Office for Product
Safety & Standards

Personal Light Electric Vehicle (PLEV) Battery Safety Research

Final Report

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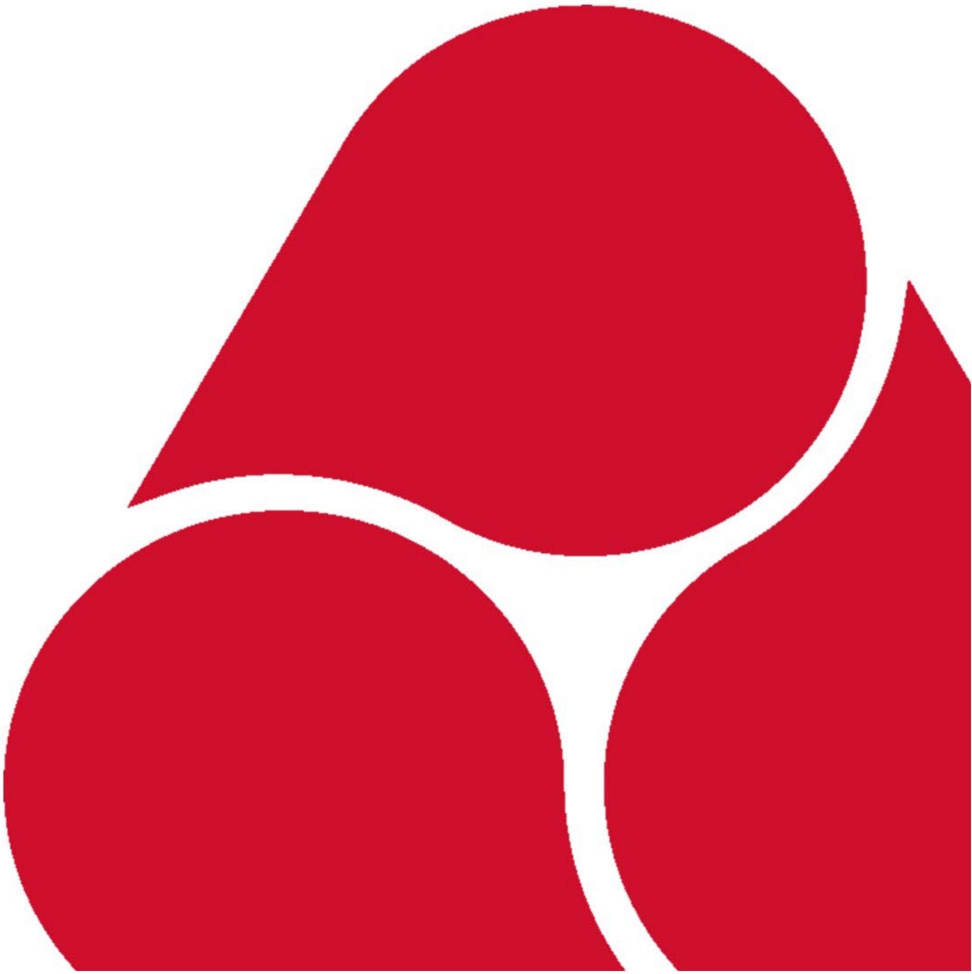

Acknowledgements

This report was prepared for the Office for Product Safety and Standards (OPSS) by James McLaggan, Mark Urbanowski, and Prof. James Marco of Warwick Manufacturing Group (WMG), a department of the University of Warwick, Coventry, CV4 7AL, UK.

The views expressed in this report are those of the authors, not necessarily those of the Office for Product Safety and Standards or the Department for Business and Trade, nor do they reflect Government policy.

The following organisations were consulted as part of this project:

- Bicycle Association
- Dyson Ltd.
- Electrical Safety First
- Exponent, Inc.
- Halfords Group plc
- London Fire Brigade
- National Fire Chiefs' Council
- Pure Electric Ltd.
- Swifty Scooters Ltd.
- UL Solutions

We are grateful to all respondents for their time and insights.

Executive Summary

The Personal Light Electric Vehicle (PLEV) market has grown rapidly in the last decade and is an important part of the electrification and decarbonisation of urban transport systems, particularly for short journeys. Electric propulsion systems are now used in a diverse range of light vehicles, from pedal-assistance in on-road and off-road electric bicycles and 3- and 4-wheeled urban delivery vehicles (e-bikes), to numerous other vehicles such as hoverboards and electric scooters (e-scooters), many of which are currently not legal for road use. The battery energy storage systems for PLEVs sold in the UK predominantly use the lithium-ion cell chemistry, which is also widespread in other market sectors such as personal electronic devices, electric passenger cars and grid energy storage. All these markets benefit from the high energy density and power density offered by Lithium-ion cells, and the rapid growth in the global market for Lithium-ion cells has resulted in manufacturing economies of scale which have significantly improved their affordability. From 2013 to 2023, the price of Lithium-ion batteries has fallen by 82%. However, Lithium-ion batteries can undergo severe failures, known as thermal runaway, wherein cells undergo a highly exothermic chemical reaction which can result in venting of large volumes of hot, toxic, flammable gas. When the gas ignites, it can cause fire and even explosions.

Like personal electronic devices, PLEV batteries are commonly charged indoors. However, PLEV batteries are much larger than those in most other consumer battery-powered devices and contain significantly more energy. PLEV batteries typically contain 30-100 cylindrical cells. When thermal runaway starts in a single cell within a battery, it can propagate to other cells in the battery. The resulting gas, fire and explosions can be extremely hazardous to the health of those in buildings where these incidents occur, resulting in severe injury or death.

This report was commissioned to improve the evidence base available to the Office for Product Safety and Standards (OPSS) on the causes of the safety risks and hazards associated with PLEV batteries and chargers. The work has included a literature study of scientific papers and reports of real world evidence of PLEV fires in the UK and other major markets. Stakeholders from emergency services, safety groups, PLEV manufacturers and retailers, standards organisations and battery experts have been consulted. A review of existing UK legislation and international standards has been conducted, and a battery assessment procedure was defined, prior to detailed inspection and testing of several e-bike and e-scooter batteries available on the UK market, covering a broad price range. This has resulted in suggestions for actions by government, standards bodies and other groups, aimed at reducing the frequency and severity of PLEV fires.

PLEV Fires: Real World Statistics and Stakeholder Evidence

Fire services across the UK have responded to PLEV fires, but London Fire Brigade (LFB) has likely the largest evidence and incident database and has documented the increase in the frequency, from two events in 2017 to at least 178 incidents in London in 2023. Since 2020, the increase has been dominated by e-bikes, rather than e-scooters. Unfortunately, despite the efforts of LFB and other fire services, the quality of incident data is constrained by the degree of destruction caused by the fires, which means that it is often impossible to determine key details such as the identity of the product or whether the battery was on charge at the time.

Stakeholders consulted for this report have highlighted perceived shortcomings in UK incident reporting systems and battery standards, the importance of cell and battery manufacturing quality, and the need to target consumer advice towards the most frequent PLEV users. PLEV supply-chain organisations who were consulted are generally supportive of improved safety requirements that are enforced to ensure a consistently high standard across the market.

Causes of PLEV Lithium-ion Battery Fires

When riding a PLEV, the battery is progressively discharged to a lower state of charge (SoC) as energy is drawn from the pack to power the motor. Subsequent charging increases the SoC. Typically, the charger will continue to charge the battery up to 100% SoC (fully charged) unless the user switches off or disconnects the charger earlier, after which the battery will then remain at 100% SoC until the PLEV is next used. The scientific literature on lithium-ion cell thermal runaway demonstrates that the likelihood and severity are both increased when the cell is at a higher SoC, and increased still further if the cell is overcharged, overheated, or mechanically damaged. The hazards to human health are exacerbated when the battery is indoors, where routes of escape from flames and ejecta may be limited, and a room can quickly fill with hot, toxic and suffocating gases.

When cells are combined into a battery, the overall likelihood and severity of a thermal incident is determined by a complex range of factors, including the effectiveness of passive and active protection systems in the cells and the battery. The battery management system (BMS) plays a critical role to monitor the state of the individual cells, and ensure that their voltage, current and temperature limits are not exceeded.

Legislation and Standards

A review of the product safety legislation has confirmed that many PLEV products, including complete e-bikes and e-scooters and conversion kits that have a motor, are covered by the Supply of Machinery (Safety) Regulations 2008 (SMSR). The SMSR contains a detailed list of essential health and safety requirements that manufacturers must comply with, including avoidance of hazards such as high temperature, fire and explosion, which are directly relevant to PLEV safety. The SMSR also requires the manufacturer to provide documentation (e.g. assembly instructions, declaration of incorporation), which can assist authorities with enforcement and can guide professionals and consumers on correct use of the product. However, separately sold batteries, often used in conversion kits, are covered by the General Product Safety Regulations 2005 (GPSR). This requires all consumer products placed on the market to be safe, but does not contain detailed health and safety requirements, or require such extensive documentation. Regulations set the legal framework which require that only products which comply with the essential requirements, as set out in the regulation, are placed on the market, these regulations place obligations on manufacturers, and others in the supply chain. Standards are a voluntary means by which those who manufacture products can assess designs. Test reports against the requirements detailed in standards are often used as evidence to support claims of compliance made for those products.

A review of the standards applicable to e-bikes and e-scooters has shown differences between the two: The latest e-bike standard specifies that, where a manufacturer wishes to claim compliance with the standard for the e-bike, they will also need to ensure that the e-bike battery conforms with the most rigorous applicable UK battery standard, but the standard for e-scooters has less stringent battery safety requirements. There is no dedicated standard to cover conversion kits, as the existing standards cover complete e-bikes or e-scooters and there is no legal or industry definition of a conversion kit for which a standard could be created. The existing standards for batteries can be used for conversion kit batteries, but the mix-and-match nature of conversion kits requires a re-examination of the relevant risks.

A review of the battery standards has highlighted several suggestions for improvement, relating mainly to the severity of test conditions and the ability of the battery to remain safe in the event of single-point failures in the protective systems and components.

Product Inspection and Testing

Several e-bike, e-scooter and conversion kit batteries, covering a range of price points, have been investigated through a process of teardown analysis, which involves disassembly and inspection of the design and manufacturing quality, and abuse testing, which tests the battery’s ability to protect itself from reasonably foreseeable misuse.

Teardown of some products has shown examples of poor manufacturing processes and quality, absence of essential safety features such as temperature sensors, and poor design choices that increase the likelihood of water ingress and cell overheating. The batteries also have widely differing sophistication in the electronic components used in their battery management systems (BMS). In some cases, the hardware restricts the ability for the battery manufacturer to configure the BMS for the operating limits of individual cell types, meaning that inappropriate generic limits are used.

The abuse testing has shown a clear correlation between the price-per-unit-of-energy of PLEV batteries and the safety outcomes. The tests have shown that many BMSs do not prevent the battery from exceeding the current and temperature limits stated on the cell manufacturers’ datasheets. This exposes the batteries to the risk of being electrically or thermally abused, by the use of an unsuitable charger or modified PLEV drive-motor. When such reasonably foreseeable misuse occurs, the tests have revealed over-heating of protective components, rendering those protections ineffective, in a way that is not apparent to the consumer. As a result, several batteries tested went into thermal runaway, leading rapidly to fire, explosions and clouds of toxic gas.

However, the tests also showed that the PLEV batteries with a higher price-per-unit-of-energy, which had better designed safety circuits, more sophisticated electronics and were better manufactured, successfully prevented thermal runaway by a combination of passive and active protection systems. Nevertheless, in the event of single-point failures in the BMS, many of the tested batteries remain reliant on passive safety devices in the cells, which only activate when the cell is already in a significantly overcharged condition, wherein the likelihood of thermal runaway is significantly increased. Greater use of secondary or “redundant” active safety systems, particularly in the charging circuit, would reduce the susceptibility to thermal runaway in the event of single-point failures. It is important that standards should include tests that introduce or mimic single-point failures, to ensure that the secondary active safety systems effectively prevent thermal runaway.

Concluding Remarks

This report has made a large number of suggestions for actions which can improve PLEV safety, spanning the following areas:

- Consistency in the legislation applicable to PLEV batteries.
- Consistency in the standards covering all PLEV batteries.
- Detailed improvements to standards, ranging from cell production quality to the abuse testing methodology and functional safety.
- Collection of real world incident data.
- Consumer advice.
- Increased obligations and sanctions for companies selling PLEVs and their batteries.

The full list of suggestions can be found in Section 12 of the report.

If these suggestions are acted on by the relevant parties in government, standards bodies and other stakeholders, WMG believes that the unacceptably high level of PLEV fires can be reduced over time. There is, however, no quick fix, due to the large number of products already in the hands of consumers and the lead-time for changes to legislation, and for updates to standards, and for manufacturers to develop, validate, productionise and introduce new products to the market.

Contents

Definitions

Acronym / Term	**Meaning**
18650	A common cylindrical cell format, 18mm diameter, 65mm long.
21700	A common cylindrical cell format, 21mm diameter, 70mm long.
A	Amperes or Amps. Unit of electric current.
ac	Alternating Current
ADR	Accord Dangereux Routier. The European Agreement concerning the International Carriage of Dangerous Goods by Road.
Ah	Amp-Hour. Unit of electrical charge. 1 Ah = 3600 Coulombs (C). See also "Capacity".
Anode	The negative electrode of a cell. In current PLEV Lithium-ion cells, the anode active material is usually graphite, sometimes with a small quantity of silicon added. Future PLEV Lithium-ion cells may use different materials, such as lithium-metal.
ANSI	American National Standards Institute
ARC	Accelerating Rate Calorimeter. A test device used to accurately evaluate the self-heating of an electrochemical cell, caused by the cell's internal chemical reactions
ASIC	Application-Specific Integrated Circuit. An integrated circuit chip customized for a particular use, such as safety monitoring of Lithium-ion cells.
BA	Bicycle Association. A trade association representing the UK cycle industry.
Battery	A combination of two of more cells, electrically connected in series or in parallel.
BMS	Battery Management System
BoL	Beginning of Life: The condition of a cell or battery at the beginning of its operational lifetime.
BS	British Standard. The prefix used for standards in the UK, such as European standards incorporated in the UK, e.g BS EN
Busbar	An electrical conductor forming part of a circuit. In this report, it is most commonly used to refer to the conductor which forms the series and parallel connections between cells in a battery.
CAN	Controller Area Network. A two-wire serial communication protocol widely used in the automotive industry to create a network connecting multiple control units in a vehicle.
Capacity	A measure of the charge that a cell or battery can store. Usually expressed in Amp-hours (Ah).

Acronym / Term	Meaning
Cathode	The positive electrode of a cell. In a Lithium-ion cell, the cathode active material is usually referred to by a three-letter acronym such as NMC or NCA or LFP. Future PLEV Lithium-ion cells may use other materials.
Cell	A self-contained electrochemical energy storage device, containing a cathode and an anode, kept apart by a separator, and infused with an electrolyte.
CE marking	Conformité Européene. European Union's (EU) mandatory conformity marking for regulating the goods sold within the European Economic Area. See also UKCA.
CEN	Comité Européen de Normalisation. The European Committee for Standardisation.
CHAdeMO	A consortium comprising mainly Japanese automotive OEMs and suppliers, which develops of electrical charging standards
CID	Current Interrupt Device. A safety feature used in many cells to protect the cell from over-charge. It comprises a thin metal diaphragm which is part of the positive terminal. Abnormally high gas pressure inside the cell pushes the diaphragm upwards, breaking the electrical connection, thereby isolating the cell's jellyroll from the external circuit.
Closed-Circuit	Continuity in the conductors of an electrical circuit. For example, if a circuit has a switch, and the switch is closed, then this results in a closed-circuit condition.
CONEBI	Confederation of the European Bicycle Industry
CPSC	Consumer Product Safety Commission. A US organisation with a similar role to OPSS in the UK
CPU	Central Processing Unit. The integrated electronic circuit in a computer that executes instructions in a computer program.
C-rate	Charge or discharge rate of a cell or battery, expressed as a fraction of its Capacity. Example: If a 5Ah battery is discharged at a current of 10A, the C-rate = 10/5 = 2.
Conversion kit	For the purposes of this report: A set of components intended to allow a conventional bicycle to be converted to an e-bike. A complete conversion requires: (1) electric motor; (2) motor controller; (3) battery; (4) Handlebar controls; (5) Wiring harness to connect the other components. The electric motor is usually built into a wheel, to replace the front or rear wheel on the bicycle. The term "conversion kit" also covers subsets of this list of components, e.g. a separately sold battery.
CoP	Conformity of Production. Part of the Type Approval process.
CSA	CSA Group (formerly the Canadian Standards Association)
dc	Direct Current

Acronym / Term	**Meaning**
DFMEA	Design Failure Modes and Effects Analysis. See also FMEA.
DfT	Department for Transport
DoC	Declaration of Conformity
DoI	Declaration of Incorporation
Drain	The terminal of a transistor from which the charge carriers (normally electrons) leave the device, when it is switched on ('on' is also referred to as 'closed', and 'off' is referred to as 'open' in this report, to give an analogy to a physical switch). See also Source and Gate. Note that conventional current is in the opposite direction to the flow of electrons, so conventional current flows from drain to source.
DUT	Device Under Test
EAPC	Electrically Assisted Pedal Cycle (UK terminology). A pedal cycle with two or more wheels, fitted with pedals capable of propelling it, and fitted with an electric motor (and no other motor) which must cut off when the vehicle reaches 15.5 mph (25 km/h) and has a maximum continuous rated motor power ≤250W. (UK Government, Jun 2015).
EASA	European Union Aviation Safety Agency
e-bike	For the purposes of this report: A bicycle, tricycle or quadricycle, equipped with pedals for the rider to propel it, and an electric motor. This includes EAPCs (UK) and EPACs (EU). It also includes L1e-A category type-approved cycles.
EC	European Commission
EESR	Electrical Equipment (Safety) Regulations 2016
EHSR	Essential Health and Safety Requirements
Electrolyte	A material which infuses the anode, cathode and separator, allowing conduction of ions between the anode and cathode. In a Lithium-ion cell, it is typically an organic carbonate liquid, with lithium hexafluorophosphate dissolved in it.
EMC	Electromagnetic Compatibility.
EN	Europäische Norm. The prefix used for European Standards.
EN 15194:2017	European Standard. Cycles - Electrically power assisted cycles - EPAC Bicycles. (Withdrawn 31/08/2023)
EN 15194:2017 +A1:2023	European Standard. Cycles - Electrically power assisted cycles - EPAC Bicycles. (Published 31/08/2023)
EN 17404-2:2022	European Standard. Cycles. Electrically power assisted cycles. EPAC Mountain bikes. - Part 2: Specific requirements applicable to electric mountain bikes.

Acronym / Term	Meaning
EN 17128:2020	European Standard. Light motorized vehicles for the transportation of persons and goods and related facilities and not subject to type-approval for on-road use - Personal light electric vehicles (PLEV) - Requirements and test methods
EN 50604–1:2016 +A1:2021	European Standard. Secondary lithium batteries for light EV (electric vehicle) applications. General safety requirements and test methods
EN 62133-2:2017 +A1:2021	European Standard. Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for portable sealed secondary cells, and for batteries made from them, for use in portable applications - Part 2: Lithium systems
EPAC	Electrically Power Assisted Cycle (EU terminology). Almost identical to the UK EAPC definition. However, the motor of an EPAC may only assist pedalling, whereas the motor of an EAPC may operate when the rider is not pedalling.
EPAC-MTB	EPAC Mountain Bike
ESA	Electrical / Electronic Sub-Assembly
e-scooter	For the purposes of this report: A personal transport device, powered by an electric motor, but not equipped with pedals for propelling the vehicle. It includes 2- and 3-wheeled electric scooters, 2-wheel self-balancing vehicles with handlebars (Segways), 2-wheel self-balancing vehicles without handlebars (hoverboards) and electric unicycles. Includes both non road-legal vehicles listed above and also those used in approved rental trials on public roads, but not L-category vehicle subject to Type Approval.
ESF	Electrical Safety First. A UK charity.
EU	European Union
eVTOL	electric Vertical Take-off and Landing. A new market sector for electrically-propelled aircraft, many using similar cells to PLEVs
FDA	Food and Drug Administration (US government department)
FMEA	Failure Modes and Effects Analysis. A methodology commonly used in many industries to assess the risk from potential single failures of a product.
FTA	Fault Tree Analysis. A methodology commonly used in many industries to assess the risk from multiple simultaneous or cascading failures.
Gate	The terminal of a transistor which is used to control the conduction of the device. In a BMS, the gate voltage of each MOSFET is controlled by the BMS to switch the MOSFET on or off. ('on' is also referred to as 'closed', and 'off' as 'open' in this report, to give an analogy to a physical switch).

Acronym / Term	Meaning
GPSR	General Product Safety Regulations 2005
GTR	Global Technical Regulation. A set of regulations developed by UNECE committees.
GTR20	Global Technical Regulation 20. Electric Vehicle Safety (EVS).
HWS	Heat Wait Seek. A test protocol used in an ARC.
IATF	International Automotive Task Force
IEC	International Electrotechnical Commission
IRS	Incident Recording System. UK system for recording data for fire and rescue authorities
ISC	Internal Short Circuit
ISO	International Standardisation Organization
ISO/TS 4210-10	Technical Specification. Safety requirements for bicycles — Part 10: Safety requirements for electrically power assisted cycles (EPACs)
Jellyroll	The physical arrangement of the main components inside a cylindrical cell, whereby the anode, cathode and separator are spiral-wound on a mandrel to create a cylindrical form, which is then housed inside the cylindrical cell casing.
K	Kelvin. Unit of absolute temperature. A temperature change of 1K is the same as a temperature change of 1 °C.
km/h	Kilometres per hour. Unit of speed.
L-Category	Motor vehicles including 2- and 3-wheelers and quadricycles.
L1e-A	Sub-category of L-Category: Powered cycles, continuous rated motor power >250W, ≤1000W. Maximum motor assistance speed = 25 km/h. Similar to EAPC/EPAC, but higher power, and subject to L-Category type approval.
LCo	Lithium Cobalt Oxide (a Lithium-ion cell cathode material)
LEV	Light Electric Vehicle. Used in EN 50604-1:2016+A1:2021 to encompass all electrically propelled vehicles of category L1 up to category L7 according to the definition of ECE-TRANS-WP29-78r6e (United Nations Economic Commission for Europe, Jul 2017) and all electrically propelled or assisted cycles
LFB	London Fire Brigade
LFP	Lithium Iron Phosphate, also known as Lithium FerroPhosphate (a Lithium-ion cell cathode material)
LIB	Lithium-Ion Battery
Li-Ion	Abbreviation for Lithium-Ion. A generic term for any cell chemistry involving the exchange of lithium ions between the anode and cathode of the cell during charge and discharge.

Acronym / Term	Meaning
LIN	Local Interconnect Network. A low-cost single-wire serial communication protocol widely used in the automotive industry to create a network in which one control unit acts as the master, which initiates all messages, and other controllers act as slaves.
LMO	Lithium Manganese Oxide (a Lithium-ion cell cathode material)
LMT	Light Means of Transport. Terminology in the new EU Battery Regulation referring to electric bikes, e-mopeds, e-scooters.
MAUDE	Manufacturer and User Facility Device Experience
M-Category	Vehicles having at least four wheels and used for the carriage of passengers (e.g., standard car with 2, 3, 4 doors).
MCU	Micro-Controller Unit. A small computer on a single chip, integrating one or more CPUs, memory and programmable peripherals.
MOSFET	Metal Oxide Semiconductor Field Effect Transistor. A type of power transistor (solid-state electronic switch) commonly used in PLEV batteries to connect / disconnect the cells from the charger and/or motor.
MSVA	Motorcycle Single Vehicle Approval
mph	Miles per hour. Unit of speed.
N-Category	Power-driven vehicles having at least four wheels and used for the carriage of goods
NBDA	National Bicycle Dealers Association. A US trade association
NCA	Nickel-Cobalt-Aluminium Oxide (a Lithium-ion cell cathode material)
NFCC	National Fire Chiefs' Council
NMC	Nickel-Manganese-Cobalt Oxide (a Lithium-ion cell cathode material)
NYFD	New York Fire Department
O-Category	Trailers (including semi-trailers)
OEM	Original Equipment Manufacturer
Open-Circuit	A discontinuity in the conductor of an electrical circuit. For example, if a fuse blows, it causes an open-circuit condition.
OPSS	Office for Product Safety and Standards. Part of the UK Government's Department for Business and Trade.
PAB	Power-Assisted Bicycle. Singapore terminology for e-bikes. Equivalent to EAPC in the UK.

Acronym / Term	**Meaning**
Parallel (electrical connection)	An electrical connection in a battery, whereby the positive and negative terminals of one cell are connected respectively to the positive and negative terminal of the neighbouring cell. The capacity of a battery is equal to the sum of the capacities of the cells connected in parallel.
PbA	Abbreviation for lead-acid. Pb is the chemical symbol for lead.
PBRA	Portable Rechargeable Battery Association. A US trade association.
PCB	Printed Circuit Board
PFMEA	Process Failure Modes and Effects Analysis. See also FMEA.
PLEV	Personal Light Electric Vehicle (used in this report to encompass all e-bikes and e-scooters)
PMD	Personal Mobility Devices. Singapore terminology for e-scooters.
Powered Transporter	Used in the UK to encompass non road-legal e-scooters and go-peds (combustion engine-powered kick-scooters).
Powertrain	The combination of systems in a powered vehicle that achieve propulsion. In the case of an electric vehicle, the powertrain includes the battery, motor controller, motor and associated cables. It may also include peripheral sensors and user controls. For example, in an EAPC it may include the sensor to detect pedalling and a handlebar control or display.
PSD	Power Spectral Density. A method of defining the magnitude of a vibration spectrum as function of frequency.
PTC	Positive Temperature Coefficient. A safety feature used in many cells to protect the cell from external short-circuit. It comprises an electrically conductive material which forms part of the positive terminal. Abnormally high current or internal heating of the cell causes the electrical resistance of the PTC device to increase dramatically, thereby limiting the cell current.
QR code	Quick Response code. A two-dimensional matrix barcode.
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals. A UK regulation, which originated in the EU.
REESS	Rechargeable Electrical Energy Storage System. Acronym used for the battery, in Type Approval legislation
Reg 100	UNECE Regulation 100. Uniform provisions concerning the approval of vehicles with regard to specific requirements for the electric power train (applies to M and N category vehicles)
Reg 136	UNECE Regulation 136. Uniform provisions concerning the approval of vehicles of category L with regard to specific requirements for the electric power train

Acronym / Term	Meaning
RMS or rms	Root mean square. A mathematical method of calculating the mean amplitude of a signal which has both positive and negative values. For alternating electric current, the RMS is equal to the value of the constant direct current that would produce the same power dissipation in a resistive load.
RoHS	Restriction of Hazardous Substances. A UK regulation, which originated in the EU.
RPN	Risk Priority Number. A numerical value, used in Failure Modes and Effects Analysis (FMEA)
RTCA	Radio Technical Commission for Aeronautics
SCC	Standards Council of Canada
SEM	Scanning Electron Microscopy
Separator	A thin, porous membrane which separates the anode and cathode in a cell, acting as an electrical insulator. In a Lithium-ion cell, it is typically a laminate of several polymer layers, with pores large enough to allow the electrolyte to transport Lithium ions back a forth between the anode and cathode.
Series (electrical connection)	An electrical connection in a battery, whereby the positive terminal of one cell is connected to the negative terminal of the next cell. The voltage of a battery is equal to the sum of the voltages of the cells connected in series.
Short-Circuit	A low electrical resistance conductive path between the positive and negative terminals of an electrical energy source. For example, a wire between the positive and negative terminals of a battery or cell.
SLI	Starting, lightning and ignition batteries, used mostly for vehicles and machinery. Primary example is 12V lead-acid car batteries.
Smart Charger	A battery charger which has a means of data communication with the BMS, allowing the BMS to dictate the maximum voltage and current delivered by the charger.
SMSR	Supply of Machinery (Safety) Regulations 2008
SoC	State of Charge. A percentage value which expresses how fully charged a cell or battery is. 100% SoC means fully charged.
SoH	State of Health. A percentage value which expresses how much of the original capacity a cell or battery has, after some amount of ageing. 100% SoH represents the as-new condition. 80% SoH means the cell or battery has permanently lost 20% of its as-new storage capacity.

Acronym / Term	Meaning
Source	The terminal of a transistor into which the charge carriers (normally electrons) enter the device, when it is switched on ('on' is also referred to as 'closed', and 'off' as 'open' in this report, to give an analogy to a physical switch). See also Drain and Gate. Note that conventional current is in the opposite direction to the flow of electrons, so conventional current flows from drain to source.
Specific Energy	Energy per unit mass. Units: Wh/kg.
Specific Power	Power per unit mass. Units: kW/kg.
TC	Thermocouple. A sensor commonly used to measure temperature
Teardown (noun) / Tear down (verb)	The disassembly and inspection of a product, performed to gain insights into the design, component selection, and manufacturing / assembly methods.
TIM	Thermal Interface Material
TP	Thermal propagation (TR spreading from one cell to other cells)
TR	Thermal runaway (highly exothermic failure of a Lithium-ion cell)
TS	Technical Specification. A "standard" which approaches an international standard in terms of detail and completeness but has not yet passed through all approval stages of an organisation such as ISO / IEC / CEN.
CEN/TS 17831	Technical Specification. Cycles. Electrically power assisted cycles. Anti-tampering measures.
UK	United Kingdom of Great Britain and Northern Ireland
UKCA marking	UK Conformity Assessed. The UK's conformity marking for regulating the goods sold within the UK, which businesses can use in place of the CE marking. Applies only to product categories specified by the UK government Department for Business and Trade.
UL	UL Solutions, formerly the Underwriters' Laboratory. A US organisation which creates many product standards for the USA and Canada (see ANSI, SCC) and conducts 3rd party certification.
UL 2271	Batteries for Use in Light Electric Vehicle (LEV) Applications. Adopted by ANSI and SCC.
UL 2272	Electrical Systems for Personal E-Mobility Devices. Adopted by ANSI and SCC.
UL 2580	Batteries for Use in Electric Vehicles.
UL 2849	Electrical Systems for e-Bikes. Adopted by ANSI and SCC.
UL 2850	Outline of Investigation for Electrical Systems for Electric Scooters and Motorcycles. Draft standard (not published)
UN	United Nations

Acronym / Term	**Meaning**
UNECE	United Nations Economic Commission for Europe
UN38.3	Section 38.3 of the United Nations Recommendations on the Transport of Dangerous Goods, Model Regulations, concerning the transport of Lithium-Ion and Lithium-Metal Cells and Batteries
USB	Universal Serial Bus, an umbrella term for a number of connector variants and communication protocols, developed by the USB Implementers Forum, Inc. (USB-IF).
USB-C or USB Type-C®	The latest iteration of the USB connector, which has 24 pins and a reversible plug orientation and supports higher power transmission, for example USB-PD. Adopted by the International Electrotechnical Commission in 2016 as IEC 62680-1-3 (BSI Group, Oct 2022)
USB-PD	USB Power Delivery. A recent addition to the USB capability, which allows charging at up to 48V and 5A, for a maximum power of 240W. It is implemented using the USB Type-C® connector, and allows the device being powered (e.g. the battery) to request intermediate voltages between 15V and up to the maximum available fixed voltage of the charger.
UV	Ultraviolet. Used in this report to refer to solar radiation (sunlight), prolonged exposure to which can adversely affect some materials, such as some plastics.
V	Electrical voltage
V_{ac_rms}	Electrical voltage for alternating current (e.g. mains supply), expressed as the root-mean-square of the current.
VCA	Vehicle Certification Agency. The designated UK Type Approval Authority for automotive products.
V_{dc}	Electrical voltage for direct current (e.g. battery)
W	Watts. Unit of Power.
WEEE	Waste Electrical and Electronic Equipment. A UK regulation, which originated in the EU.
Wettability	The ability of the cell separator, anode and cathode active materials to readily absorb electrolyte.
Wh	Watt-hour. Unit of energy. 1 Wh = 3600 Joules.
WMG	Warwick Manufacturing Group. A department of the University of Warwick, employing the authors of this report.
Ω	Ohm. Unit of Electrical Resistance
Ω/V	Ohm per Volt. Unit of Inverse Electrical Current (= 1/A). Used in Type Approval legislation to specify the insulation resistance required between HV conductors and touchable parts.

1 Introduction

1.1 Overview

This document is the final report of the “Personal Light Electric Vehicle (PLEV) Battery Safety Project”. The work was carried out on behalf of the Office for Product Safety and Standards (OPSS) by WMG, the University of Warwick between April 2023 and August 2024.

Phase 1 of the project started with research into available data on UK PLEV fires, to look for any trends that could be discerned (Section 2). This highlighted the severity of PLEV battery fires, particularly those that occur indoors, when batteries are being stored or charged using a mains-powered charger, and pointed to conversion kits (used to convert a conventional bicycle into an e-bike or, occasionally, a conventional scooter into an e-scooter) being involved in a significant number of incidents. This led the investigation to look at academic literature on the safety of Lithium-ion batteries (see Section 3) and the technology of chargers (Section 4) and conversion kits (Section 5). Phase 1 also included a review of UK legislation relating to PLEVs, alongside UK and international standards relating to PLEVs and their batteries and chargers, and a comparison to automotive Lithium-ion battery standards (Sections 6 and 7). Pre-existing work concerning PLEV fires has been reviewed (Section 8) and consultations with stakeholders were performed during the period September to December 2023 (Section 9).

Based on the information from Phase 1, WMG defined a plan for the disassembly, inspection and testing of batteries available on the UK market, and purchased several e-bikes, e-scooters, replacement batteries and conversion kits. The planned tests were conducted in WMG’s laboratories, revealing both anticipated and unexpected results which highlight the technical vulnerabilities of some existing products (Sections 10 and 11).

The test results help to explain why some PLEV products fail to meet the UK legislative requirement for safe consumer products, but also show examples of batteries which have been well engineered and manufactured, illustrating that safety in PLEVs is an achievable objective.

The report summarises all of WMG’s work and suggests numerous actions which can be taken across a variety of stakeholders to reduce the incidence and severity of PLEV fires (Section 12).

1.2 Scope of Investigation

This report investigates fires in PLEVs. The term PLEV is not formally defined in UK law, but in the context of this report, it includes several types of products:

- Electrically Assisted Pedal Cycles (EAPCs), similar to the category known in the EU as Electrically Power Assisted Cycles (EPACs). EPACs provide assistance only when the rider is pedalling, up to a maximum of 250W continuous rated motor power, and up to a maximum of 25 km/h (15.5 mph), and are not subject to Type Approval. UK legislation also allows EAPCs to use the motor when not pedalling, referred to as “twist and go” electric bikes, which are subject to Type Approval. In other geographic locations, such as the USA, the speed and power limits differ from those in the UK and EU. For simplicity, this report uses “e-bike” to refer to all electric bikes mentioned above.

- PLEVs which are not currently road-legal in the UK, primarily electric scooters. This category also includes devices such electric skateboards, and self-balancing vehicles like electric unicycles and hoverboards, but due to their relatively low market size compared to electric scooters and the similarity of the battery and charging technology, their fire hazards are considered to be adequately covered by considering only electric scooters. For simplicity, this report uses “e-scooter” to refer to all non-road-legal PLEVs.
- Conversion kits, which are sold to enable a conventional bicycle to be converted into an e-bike. These range from complete kits (comprising an electric motor; associated motor controller; battery; connecting wires; handle-bar controls; charger with cables) to individual sub-systems, such as a battery alone. These kit parts can be selected and installed by professionals, but equally can be purchased and installed by a DIY amateur, who may lack the knowledge to do so safely.

Electric bikes are also available which do not fit within the EAPC definition: L1e-A category powered cycles have much in common with EAPCs but can have a maximum continuous rated motor power up to 1000W. Along with other L-category vehicles ranging from L1 mopeds to L7 quadricycles, they are subject to Type Approval in the UK and EU and are therefore outside the purview of OPSS. However, this report will consider the implications of the differing regulatory requirements for EAPCs and L1e-A powered cycles, and whether there are aspects of the L1e-A type approval rules which should be considered for application to EAPCs, with regard to fire safety.

In addition to the motor power limit, there are other parameters of interest in scope definition. For example, standards applicable to e-bikes and e-scooters state different voltage limits within their scopes: The e-bike standard is limited in scope to EAPCs with an operating voltage up to 48 V_{dc}, which means that some UK e-bikes may not strictly be covered by the standard, whereas the e-scooter standard has a limit of 100 V_{dc}. Meanwhile, the standard for portable batteries does not specify a voltage limit, and the standard for removable LEV batteries covers up to 1500 V_{dc} since this standard covers vehicles up to Category L7 (4 wheels, up to 400kg excluding the battery, up to 15kW motor power). Some regulations also limit the scope of voltages to which they apply, notably the Electrical Equipment (Safety) Regulations 2016 which only applies to devices with voltage ratings of 50-1000 V_{ac} and 75-1500 V_{dc}. The implications of such thresholds and discrepancies will be considered in this report, insofar as they affect fire safety.

This report includes a review of existing regulations and product standards relevant to PLEVs. The e-bike and e-scooter vehicle standards include many details which are not directly relevant to fire safety, for example those that relate to the mechanical strength of pedals, frames, handlebars, saddles etc. Those sections have not been reviewed by WMG and will not be discussed in this report, except where they have the potential to affect fire safety.

Similarly, the sections of this report which cover the literature review, the review of real world incident data, the stakeholder consultation, and the methodology to assess PLEV batteries and chargers will focus on fire safety of e-bikes and e-scooters.

The evidence from real world fires (see Section 2) shows that most incidents with severe outcomes, including serious injury or death and/or substantial property damage, occur when the PLEV or its battery are inside a building, either being charged or being stored. Serious fire incidents when the PLEV is being ridden, with the battery being discharged, are relatively few. Therefore, the primary focus of this report is on the fires that occur during charging or storage.

This report will not consider how tampering to exceed the 25 km/h limit may affect riding safety, but will consider how tampering can compromise the fire safety of the battery.

The following product categories are outside the scope of this report:

- Vehicles subject to Type Approval, such as categories L1e to L7e, except as mentioned above.
- Vehicles that are considered as toys.
- Vehicles intended for competition.
- Vehicles and/or devices intend for use for medical care.
- Vehicles without an on-board driving operator.

1.3 Disclaimer

Throughout the report, specific PLEV producers, suppliers, retailers, testing and standards bodies, research entities and other organisations are mentioned by name.

A limited number of products were purchased for disassembly inspection (teardown) and testing, using criteria and information sources described in Section 10.1.

Elsewhere in the report, specific products are named or pictured to provide examples to illustrate the market or support explanations and statements made.

The inclusion or mention of any manufacturer or other organisation, or an image or data pertaining to their product, does not constitute any form of endorsement of their product or service or assurance that it is safe.

Those mentioned in this report are not a full representation of the market and alternatives are available.

The views expressed in this report are those of the authors, not necessarily those of the Office for Product Safety and Standards or the Department for Business and Trade, nor do they reflect Government policy.

Additionally, the information provided in this report is for general information purposes only and should not be construed as legal advice.

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2 Real World Evidence

2.1 Introduction

2.1.1 Background

The aim of this real world incident evidence investigation is to collate and summarise findings and recommendations from a broad range of previously collected datasets and reported incidents.

WMG has reviewed and analysed available evidence, with particular attention given to findings that:

- Inform prioritisation and selection product categories and types for teardown and testing
- Inform prioritisation and selection of e-bike and e-scooter brands, manufacturers and models for teardown and testing
- Identify real-world failure modes and potential root causes to be replicated in WMG's testing.

2.1.2 Real World PLEV Incident Evidence Sources

Evidence provided by OPSS

OPSS has given WMG access to data including:

- OPSS Fires in e-bikes and e-scooters – 2022 and 2023 (UK Government, Aug 2024)
- OPSS Product Safety Database Notifications
- OPSS Product Safety and Consumers: Wave 5 report (UK Government, Dec 2023)

International equivalent data sources

While there are high level statistics of LIB and PLEV fires from several countries, published reports or databases of incidents are limited and inconsistent.

Statistics from New York City Fire Department (USA) and New South Wales Fire and Rescue (Australia) have been included in this review.

Media reports of PLEV fires

A brief review of media reports, retailer blogs and similar online information on PLEV fires and associated risks from across the UK is included.

Stakeholder Information

In Section 9 further real-world information has been provided by industry, safety groups and battery technology experts as part of the stakeholder consultation.

2.2 OPSS Fires in e-bikes and e-scooters report

2.2.1 Introduction

Fire and rescue service (FRS) fire investigators across the UK notify OPSS of fires involving consumer products to help earlier identification of potential product safety issues. This is done on a voluntary basis using a product-related fire notification (PFN) form when fire investigation teams identify consumer products as the most probable cause of fires and incidents.

In February 2023, OPSS re-launched the procedure, engaging with FRSs and publishing guidance to support fire investigation teams in reporting product-related fires.

OPSS has published a report on this database, combining data from fire and rescue services (FRS) incidents from across the UK.

The statistics presented in this report cover incidents that occurred in 2022 and 2023, with some further, more limited, information from 2017 to 2021.

2.2.2 Trends

Trends over time show the number of incidents increasing from 2017 to 2023 with the majority of additional incidents from e-bikes.

Figure 1 below shows the total number of incidents each year, and Figure 2 shows the split between e-bikes and e-scooters each year.

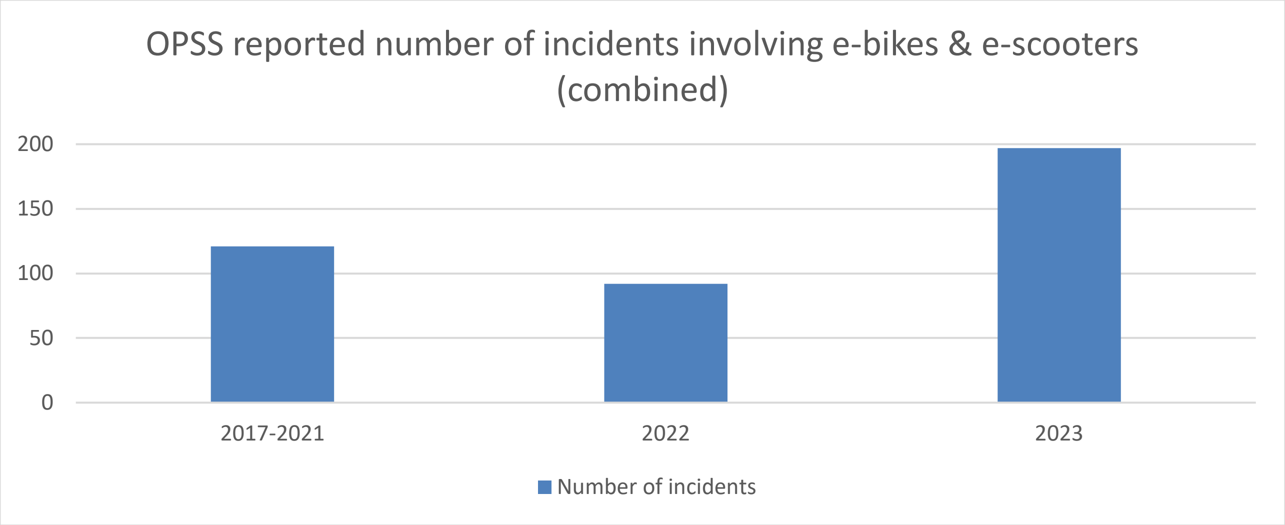


Figure 1: Number of PLEV incidents reported to OPSS by Fire Rescue Services

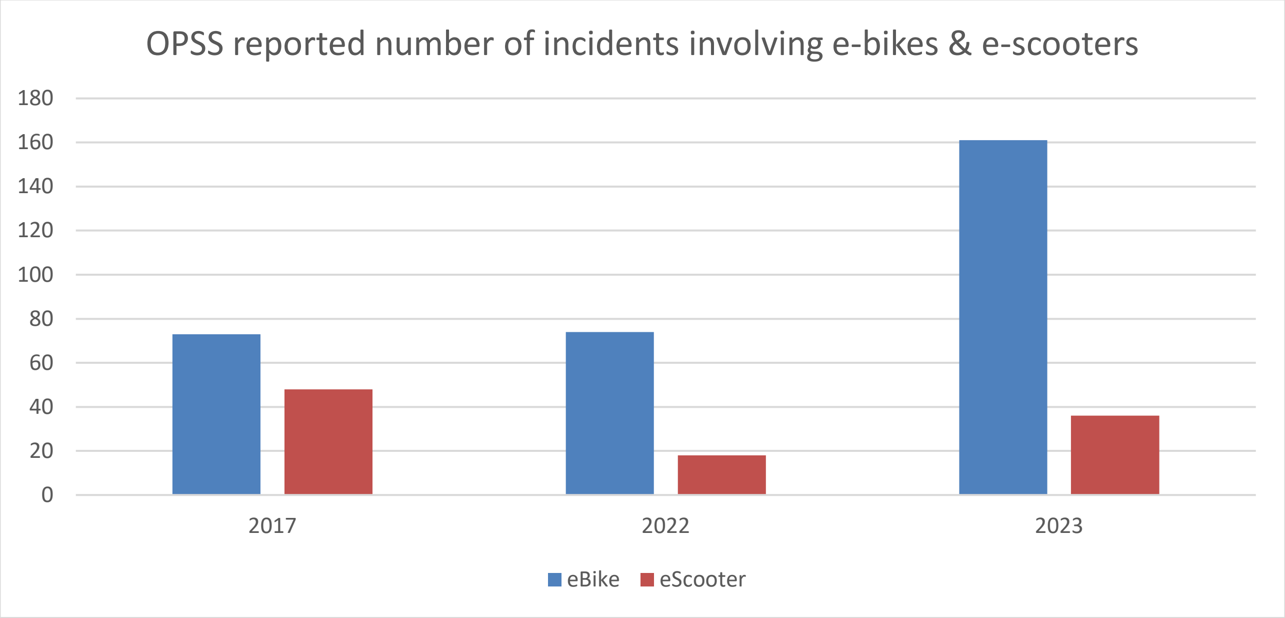


Figure 2: Number of e-bike and e-scooter incidents reported to OPSS

In 2022, 68% of the fires in e-bikes and e-scooters occurred in a dwelling, with 9% taking place in other buildings, 12% taking place outdoors and a further 5% taking place in a shed or garage.

In 2023, 50% of the fires in e-bikes and e-scooters occurred in a dwelling, with 18% taking place outdoors, 9% taking place in other buildings and a further 7% taking place in a shed or garage.

These data show that the majority of incidents occur indoors.

2.2.3 e-bike summary

FRS reported 308 e-bike incidents to OPSS from 2017 to the end of 2023:

- 48 were identified as Original Equipment Manufacturer (OEM) manufactured e-bikes. However this does not distinguish products that have been modified or have had replacement batteries or chargers.
- 149 were identified as conversion kits.
- 111 were unknown whether they are OEM manufactured or conversion kit based.
- From 2022 and 2023 data, 47% of e-bikes were reported as on charge, 31% were reported as not on charge and 22% were reported as unknown.

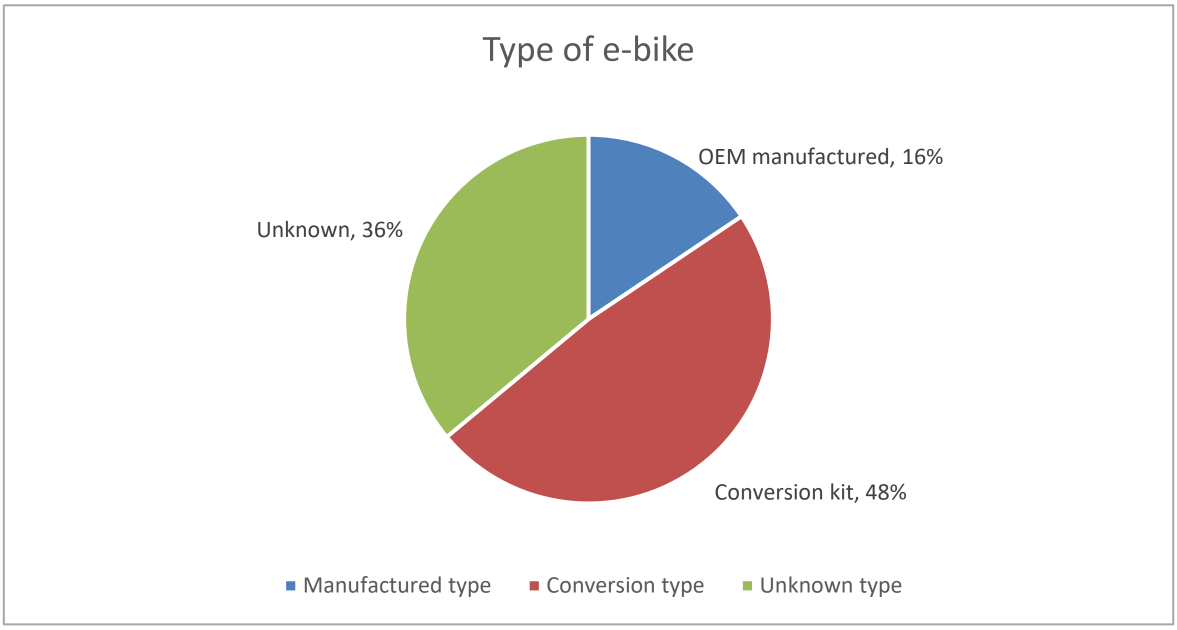


Figure 3: OEM manufactured vs conversion kit products

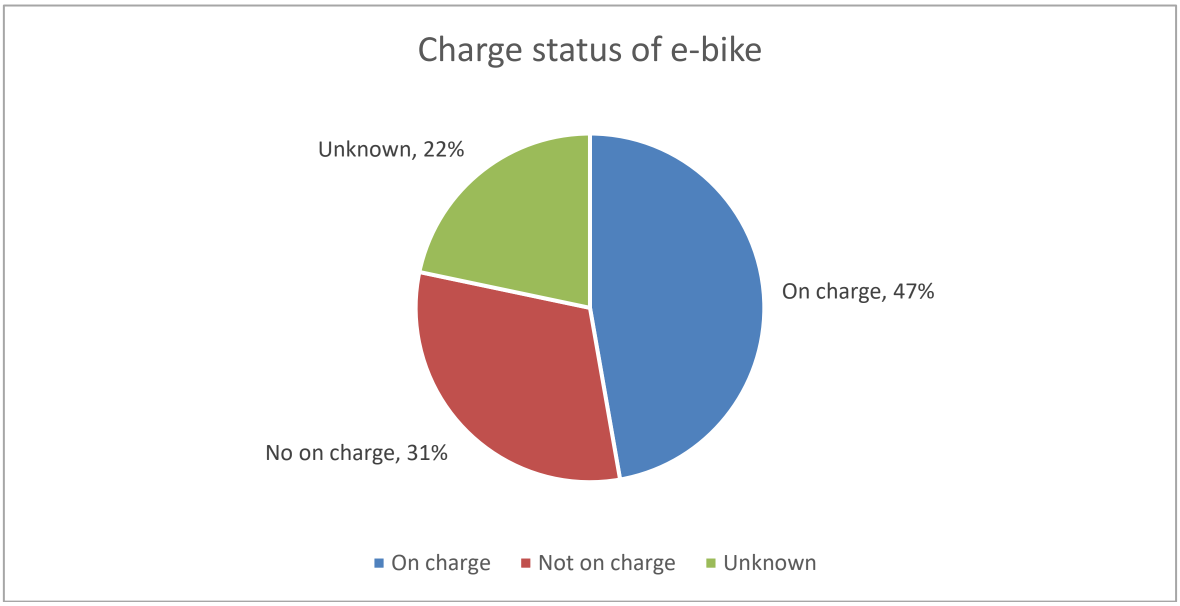


Figure 4: Charge status of e-bike incidents

2.2.4 e-scooter summary

FRS reported 102 e-scooter incidents to OPSS from 2017 to the end of 2023:

- From 2022 and 2023 data, 55% of e-scooters were reported as on charge, 31% were reported as not on charge and 13% were reported as unknown.

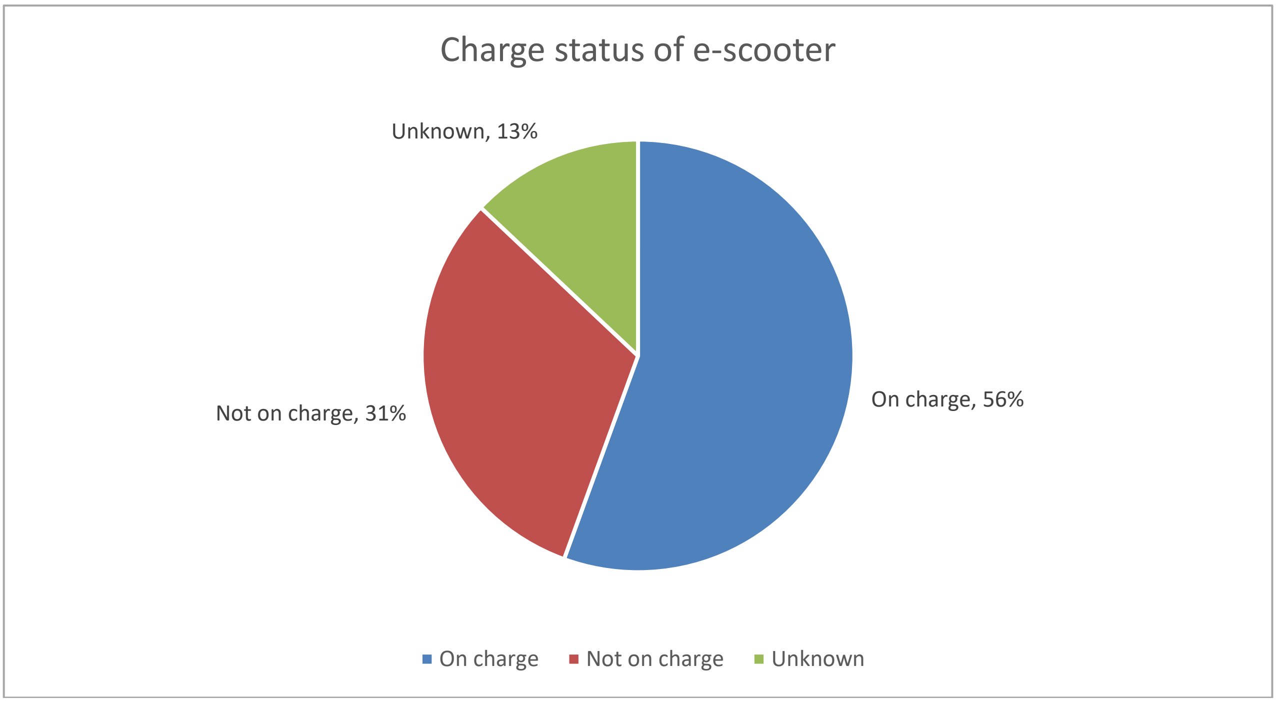


Figure 5: Charge status of e-scooter incidents

2.2.5 Use of OPSS Fire in e-bikes and e-scooters data for this Project

Identify mix of product types

Based on the review of the data, the focus of WMG's product testing needs to cover a representative range of vehicle types including conversion kits, OEM manufactured e-bikes and e-scooters.

Use to identify possible causes

It is difficult to draw any specific root cause conclusions from OPSS reported data beyond already understood electrical, thermal and mechanical failure modes.

2.2.6 Limitations

The data have a number of limitations that need to be considered before reaching conclusions regarding types of products or specific named products:

- It cannot be confirmed in all cases that the PLEV product identified caused the incident or was just present in the location of the incident.
- The responder/investigator may have limited knowledge of e-bikes, e-scooters and conversion kits and may interpret or record vehicle details incorrectly.
- The detail, consistency and reliability of reporting may vary between incidents and responders.
    - Knowing if the vehicle was on charge at time of the incident is important. It is not known from the data if a product had recently been taken off charge.
    - It may not be possible to identify whether a product was damaged, a counterfeit, copy or clone.

    - It is often not possible to identify whether the product had a replacement (and potentially incompatible or lower quality) battery or charger, or had been modified in any other way.

2.2.7 Other uses

The FRS reported data to OPSS is the most comprehensive set of incident data concerning PLEV fires in the UK.

WMG has not used the data to analyse geographic locations, building types/uses, user demographics or other human factors and societal data as this was outside the scope of the project. However, WMG believes that the data could be reviewed and analysed to help provide targeted safety information and guidance to specific user groups and communities identified in the recorded incidents.

Consistent and more detailed data collection, as well as data collection at a national level, would improve the database for this purpose.

2.3 OPSS Product Safety Data Notifications

OPSS has provided the Product Safety Database (PSD) notification data related to PLEVs from March 2019 to February 2023. 44 of the 161 entries in the database relate to fire or electric shock hazards. There are several sources of entries including:

- manufacturer reported defects and risks,
- non-compliance reports,
- tested as unsafe,
- reported by consumers as unsafe.

The majority of entries have the UK (including England, Scotland and Northern Ireland) as the notifying country, but there are a small number of entries from other countries (including Netherlands, Malta, Poland, Hungary, United States and New Zealand).

2.4 OPSS Consumer Use of PLEVs Survey Report

2.4.1 Background

OPSS conducts bi-annual consumer research, currently sub-contracted to YouGov, covering a “mixture of ‘core’ and topical or policy-focused questions”.

Each survey consists of an online survey of 10,000 consumers, a telephone survey of 250 ‘offline’ consumers and 4 focus groups.

2.4.2 Survey Statistics on PLEVs

Questions on PLEVs were included in the wave 5 survey. There are useful statistics in the report from January 2023 that confirm the extent of PLEV ownership and access, along with occurrence and severity of thermal incidents.

<u>PLEV ownership</u>

- 7% of surveyed people own, or have access to, a PLEV

<u>Safety issues</u>

- 22% of PLEV owners reported they had experienced a safety issue with the battery or charger
    - 46% of these were electrical (electric shock)
    - 14% of these were fire, explosion, smoke or over-heating

- 22% of safety issues caused physical harm
- 36% of safety issues caused damage to property or other household items
- 43% of consumers stopped using or threw the product away after the safety issue
    - 19% tried to fix themselves

Separate battery / charger

- 35% of PLEV owners had purchased a separate battery or charger
    - 41% of those who had bought a separate battery experienced a safety incident
    - 48% of those who had bought a separate charger experienced a safety incident
- 10% of those who had not bought either a separate charger or battery experienced a safety incident

Charging

- 35% charge their PLEV in the home
- 22% charge their PLEVs overnight
- 21% charge their PLEVs while they are out of the house

2.4.3 Use of OPSS Consumer Survey for this Project

There is no additional product or root cause information from the survey. However, this information suggests that occurrences of battery and charger safety related issue are more frequent than incidents documented by LFB, and often retailers, manufacturers or brands are not made aware of issues by consumers.

2.5 International Published Statistics

2.5.1 New York City Fire Department

The New York Fire Department (FDNY) records and publishes high level statistics on Lithium-Ion battery fires, including e-bike and e-scooter fires. Similar numbers per year to LFB are reported, showing that London and the UK are not unique. Figure 6 shows the total LIB incidents, injuries and deaths recorded by FDNY. The 2019-2022 data are from a report from Massachusetts Department of Fire Services (MDFS, 2023) and the 2023 data are from the International Association of Fire and Rescue Services (CTIF, 2024).

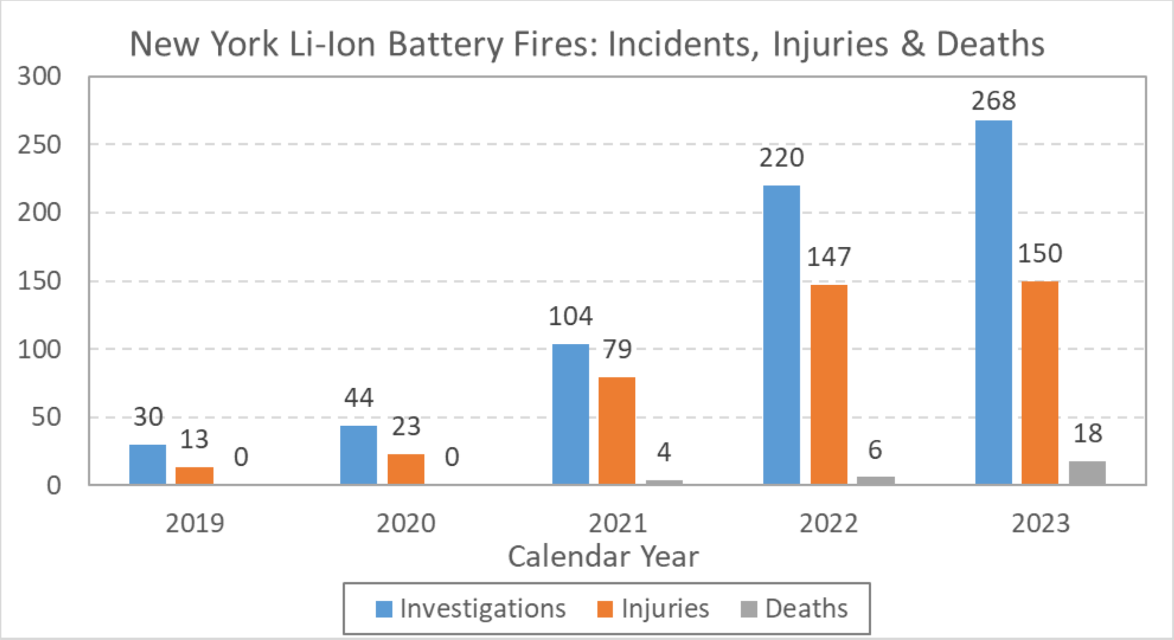


Figure 6: FDNY Reported Number of Lithium-Ion Battery Fires

The MDFS report also includes a breakdown of the FDNY data from 1 January to 25 September 2023, at which time the total number of incidents was 200. The percentage breakdown of LIB fires for those first 9 months of 2023 are shown in Figure 7.

This suggests that almost four in ten incidents involved batteries that were being charged at the time of the fire. However, like the LFB data, for the batteries that were not on charge, it is not known whether they had been charged, or were in a discharged state.

The data also show that PLEVs and other e-mobility vehicles accounted for at least seven in ten LIB fires, while of the remainder, around two thirds were unable to be identified. It is interesting that FDNY show eMopeds and eMotorcycles accounting for almost two in every ten LIB fires. This category has not been included in the shared LFB data.

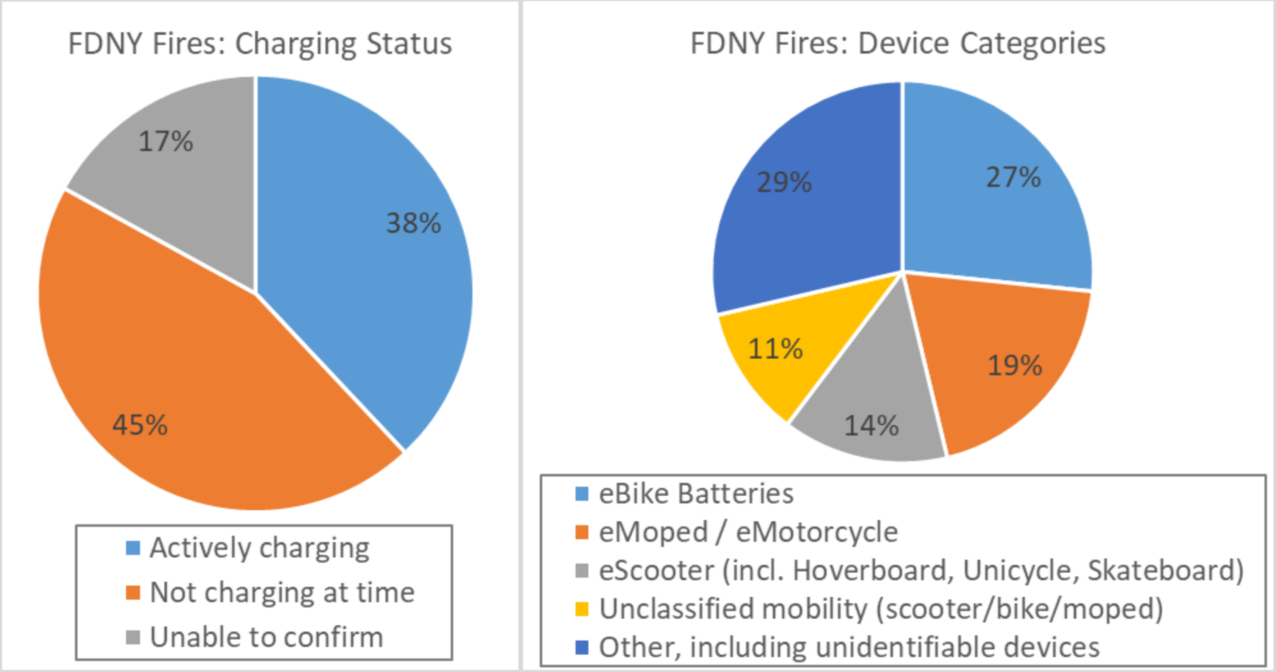


Figure 7: Percentage Breakdown of FDNY Fires, by Charging Status and Device Type

The FDNY data reported by MDFS also identify specific e-bike products involved in fires, but only for twelve of the two hundred incidents in the first nine months of 2023. In WMG's view, this does not provide a sufficiently large sample to be useful for the current project.

2.5.2 New South Wales Fire and Rescue

New South Wales Fire and Rescue (NSWFR) have published details on PLEV incidents which includes a breakdown of basic vehicle type, whether it was charging at the time of the incident and a list of identified brands/models.

This is part of a report covering all LIB fires including waste, other EVs and energy storage systems (New South Wales Fire and Rescue, 2024), prepared by the Safety of Alternative and Renewable Energy Technologies (SARET) research program.

The summary related to PLEVs (categorised as Micromobility) is reproduced below:

- *"90 (20%) incidents involved micromobility devices or their batteries.*
- *Of these, 44% of incidents were related to charging (including two incidents where the item was just taken off charging), 17% were not related to charging, and in 39% of these incidents the charging status was not reported.*
- *Micromobility device incidents mainly involved e-bikes (58%) and e-scooters (27%). In 6 of the e-bike incidents, there was evidence of tampering, or modification of the*

e-bike batteries. In 2 of the e-scooter incidents, there were multiple devices in storage within a residential setting."

Further statistics and names of product models are shown in the following tables:

Table 1: Charging status recorded by NSWFR

Type	**2022**	**2023**	**Total**
E-bike	11	41	52
E-scooter	7	17	24
Hoverboard	1	2	3
Toy car	1	1	2
Mobility scooter	0	1	1
E-motorscooter	0	1	1
E-skateboard	1	0	1
E-wheelchair	1	0	1
E-surfboard	0	1	1
Unspecified	1	3	4
Total	**23**	**67**	**90**

Table 2: Charging status recorded by NSWFR

Status	**2022**	**2023**	**Total**
Actively charging	8 (34.8%	30 (44.8%)	38 (42.2%)
Recently off-charger	1 (4.3%)	1 (1.5%)	2 (2.2%)
Not charging	2 (8.7%)	13 (19.4%)	15 (16.7%)
Unconfirmed	12 (52.2%)	23 (34.3%)	35 (38.9%)
Total	23 (100.0%)	67 (100.0%)	90 (100.0%)

The data help to show that the problem of PLEV fires is not limited to the UK, with a similar split between e-bikes and e-scooters.

2.6 Media reports of PLEV fires

2.6.1 Media

There are numerous media reports of PLEV fires, either reporting on a specific incident, or providing safety warnings due to the number of fires increasing, or other related stories including bans of PLEVs in public places and on public transport. Electrical Safety First, a UK charity focussing on electrical safety, published an extensive list of media articles covering PLEV incidents from April 2022 to March 2023 in its report "Battery Breakdown – Why are e-scooter and e-bike batteries exploding in people's homes and what can be done about it" (Electrical Safety First, Jul 2023).

It is evident that PLEV fires are occurring across cities and regions in the UK. The list below provides geographically diverse examples, but is not intended to be exhaustive:

- Belfast (Belfast Live, Feb 2023)
- Birmingham (BBC, Jul 2023)
- Bristol (BBC, Sep 2022)
- Cambridge (BBC, Jul 2023)
- Glasgow (Glasgow Live, Jul 2023)
- Lancaster (ITV, Jul 2023)
- Liverpool (Liverpool Echo, Jan 2023)
- Newcastle (Newcastle City Council, Jul 2023)
- Manchester (Manchester Evening News, May 2023)

However, based on 2022 data, it appears that the PLEV fires recorded in the UK are still concentrated in London, which accounts for 42% of all incidents. The Independent obtained the data shown in Figure 8 via Freedom of Information requests (Independent, Oct 2023). Some regions broke down the incidents into e-bike and e-scooter incidents, but other regions provided only the total of all PLEV fires. For consistency, WMG has shown the data only as totals of all PLEV fires.

In August 2023, it was reported that LFB have revealed that 40% of e-bike fires involve conversion kits (BBC, Aug 2023) LFB later explained that this figure was based on their analysis of 73 e-bike fires in the first six months of 2023, of which at least 77% were believed to involve the vehicle's battery, and 41% were thought to involve batteries that were on charge (London Fire Brigade, Sep 2023).

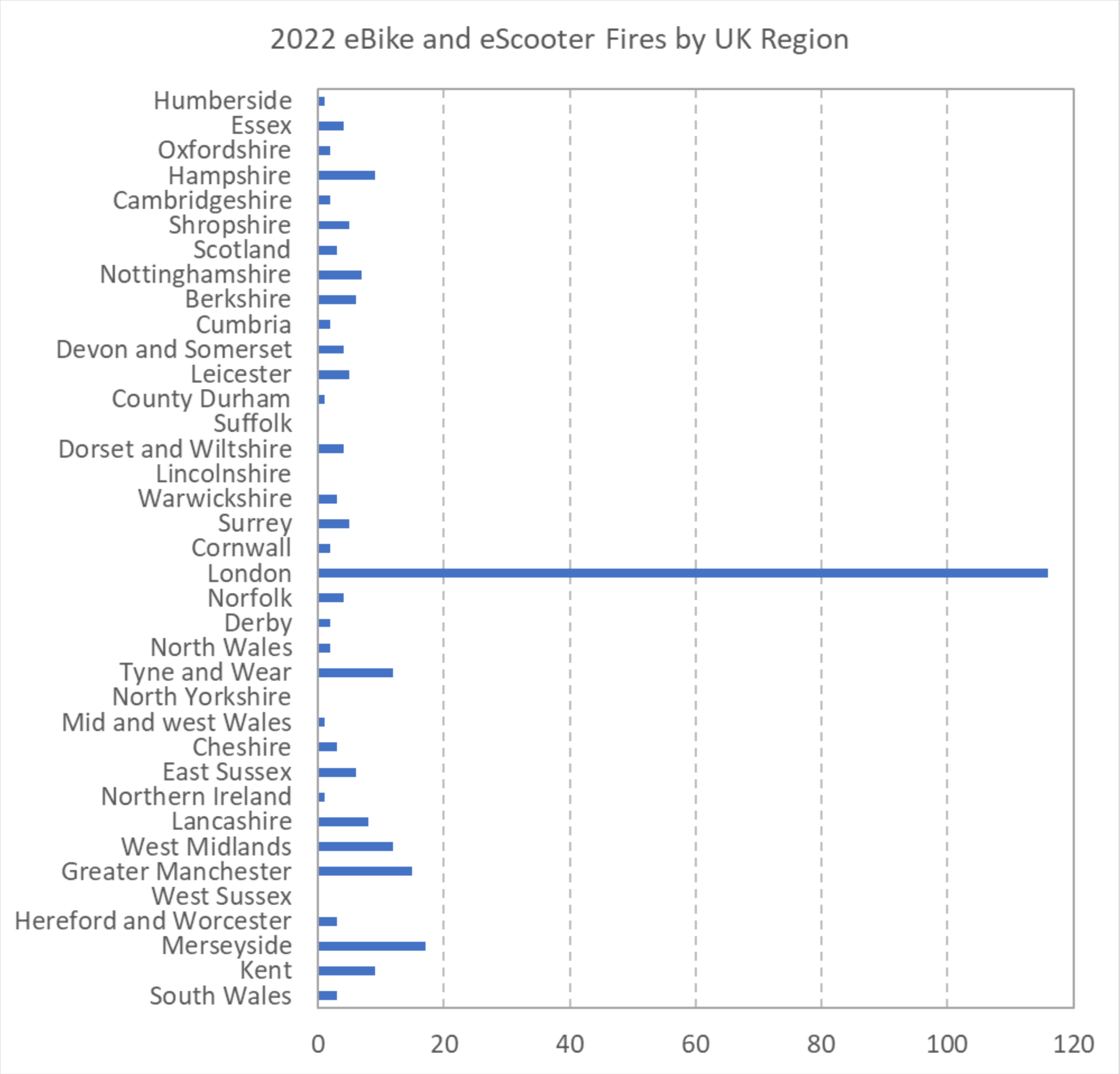


Figure 8: 2022 UK PLEV Fires by Region (adapted from Independent, Oct 2023)

Little new or additional information relevant to WMG's investigation has been found contained within the media reports.

Blog style articles by e-bike and e-scooter retailers often include more details, like this excerpt from eBikeshop.co.uk, 2023:

> *"It's imperative that your battery remains "balanced", IE, the voltages of each of the series strings remains the same (or within very tight tolerances) as the others in the pack so using the example above, at its nominal voltage (around half charged), each of the 4 parallel strings should be showing 36V each.*
> *If this isn't the case, a good quality BMS should shut the battery down and stop it from being charged or discharged.*
> *If this happens in a Bosch system for example, you may see ERROR 530 on your screen and two lights on the battery indicator light will flash if removed from the bike. In most cases, this is unrecoverable"*

2.7 Summary of Real World Evidence and Findings

WMG has considered all the available real world evidence and summarised the findings in the table below, in various categories:

Category 1: International data collection and reporting	
1.	While the largest amount and most detailed data are for London from LFB, PLEV fires are widespread across UK (from media reports) and other countries including US and Australia where fire departments have collected and published data and statistics. OPSS, and similar organisations from other countries, should consider creating a publicly available online portal, allowing consumers, fire and rescue services, and other relevant parties, to document and share details of PLEV thermal incidents.
2.	FRS reported data may be partial or inconsistent. Collection of data from PLEV fires attended by UK fire and rescue services should be improved, where possible, to assist with type of vehicle, identification of brands and models involved, as well as the circumstances prior to the fire, for example whether the battery had been on charge.
Category 2: Product categories	
3.	A large proportion of fires are due to conversion kits and modified products that warrants this type of product having its own category for WMG's investigation. OEM manufactured e-bikes and e-scooters are identified in many cases so WMG should include a broad range of product types in the investigation and testing.
Category 3: Charging	
4.	From the OPSS Fires in e-bikes and e-scooters report, e-bikes and e-scooters are more likely to be on charge (49%) than not on charge (31%). As previously noted this does not take into account whether a product had recently been taken off charge.
Category 4: Replacement chargers and/or batteries	
6.	From the OPSS consumer survey replacement batteries and chargers increase the likelihood of an incident occurring. WMG should replicate the effect of using the wrong charger (wrong voltage or for a different battery type) in the abuse testing activity.

3 Background on Battery Fires

The rapid increase in the number of PLEV battery fires, evidenced by the statistics in Section 2, shows that the hazards must be tackled urgently. However, the degree of damage caused by the fires means there is often little material evidence on which to determine the root-cause of the fires. This section aims to explain the generic causes of Lithium-ion battery fires, and how these could apply specifically to PLEVs.

3.1 Lithium-Ion Cell Thermal Runaway

Thermal runaway (TR) is a material phenomenon that manifests itself at single-cell level. It occurs when the internal temperature of the cell reaches a critical level, typically in the range 150-180 °C for the Lithium-Ion cell chemistries used in PLEVs, at which a highly exothermic (heat-generating) chemical process begins. Common causes of TR are discussed later in this section. A much lower level of self-heating caused by unwanted chemical reactions can start at lower temperatures (see Section 3.4), which can usually be suppressed with a modest amount of cooling. The chemical reactions create gas inside the cell. If the pressure is sufficient, this will cause a breach of the cell casing, known as venting. In some cases, venting does not lead to full TR, and hence may be a relatively benign failure mode, although the vented fumes can be toxic in sufficient quantities. However, once TR begins, it is almost impossible to halt it with any amount of cooling. In the context of a battery pack, the root-cause analysis of a fire relates primarily to the cause of the first cell which enters thermal runaway. The cause could be in the cell, or elsewhere in the battery, battery management system (BMS) or charger.

A Lithium-ion Battery (LIB) fire is a hazardous event because, once TR has started, it is extremely difficult to extinguish: Most LIB fires persist until the combustible material within the LIB is consumed. An LIB fire can produce flames reaching over 1000 °C, accompanied by similarly hot solid or molten ejecta, and usually produces toxic or hazardous fumes.

LIBs are produced with a variety of cathode chemistries. The cells used in current PLEV batteries most commonly use metal-oxide cathodes (e.g. Nickel-Manganese-Cobalt Oxide, NMC), because these have the highest energy-density, which translates to the best vehicle range. However, the metal-oxide chemistries also have the highest heat release during TR, and the decomposition of the cathode material liberates oxygen, which can enable burning to continue, even when the fire is starved of atmospheric oxygen, for example by using common fire extinguishers or fire blankets.

In laboratory conditions, TR can be deliberately initiated in LIBs in one of four ways:

(1) Mechanical abuse, such as crush or nail-penetration.
(2) Electrical abuse, such as over-charge.
(3) Thermal abuse, involving the use of a heat source to over-heat the LIB.
(4) Introduction of a wax-coated conductive impurity inside the cell. The wax will melt when the cell is heated, causing the conductive impurity to be in direct contact with the other components. This method is used much less frequently that the other three, because it cannot be performed on standard production cells.

Mechanical abuse leads to a short-circuit inside the cell, by damaging the separator whose function is to prevent electrical contact between the anode and cathode. In the case of nail penetration, the conductive nail directly creates a short-circuit by piercing the layers inside the cell. Electrical and thermal abuse lead to adverse chemical reactions in the cell which degrade the anode and cathode materials and the electrolyte, creating gas and heat. The heat can then damage the separator leading to a short circuit. The internal short-circuit results in a high electrical current flowing between the anode and cathode, generating sufficient heat to raise the local temperature to a level that can initiate TR. In some instances, particularly electrical and thermal abuse, the production of large amounts of gas from chemical reactions can cause the cell to vent or rupture before short-circuits can occur, releasing much of the heat energy, and the cell may not reach TR.

Similar initiation methods occur in the real world. For example:

(1) Mechanical abuse can occur from cell damage (deformation or piercing) during manufacture or assembly, or as a result of a hard impact to the battery while riding or from dropping the battery. This differs from shock and vibration during normal use.

(2) Electrical abuse can occur due to an inadequate Battery Management System (BMS), or incorrect / malfunctioning charger, which does not prevent over-charge, or as a result of a short-circuit at cell or pack level.

(3) Thermal abuse can occur due to inadequate cooling, or due to an unintended heat-source such as electrical arcing or over-heating in components close to the cell. This could be caused, for example, by a short-circuit current in a neighbouring component. It could also be caused by an external heat source, such as leaving a battery close to a domestic heater.

Figure 9 below, reproduced from Feng et al. (2018), summarises the effects that mechanical, electrical, and thermal abuse and contamination have on a Lithium-ion cell, and how these lead to thermal runaway. The green-yellow-red colouring implies only a sequence of effects and does not imply that one form of abuse is less severe than another.

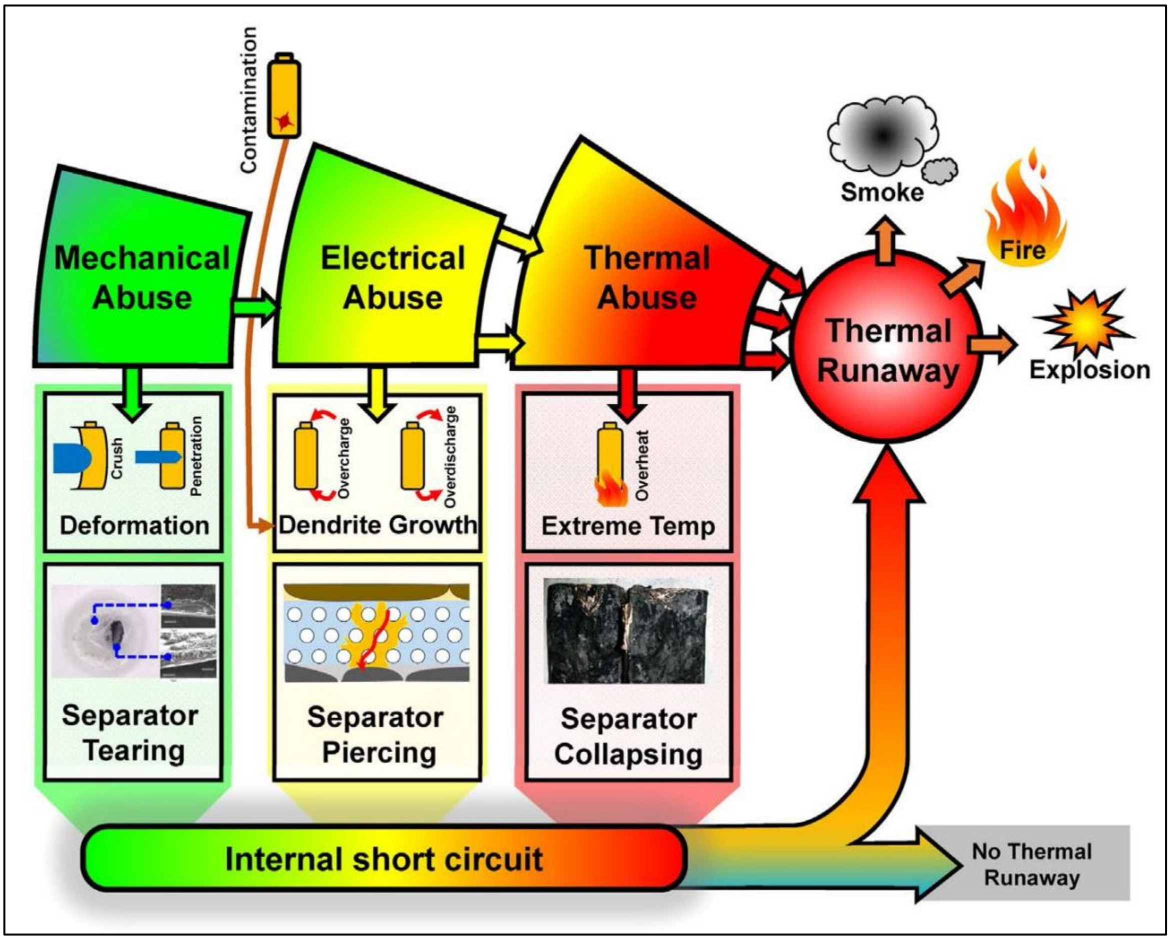


Figure 9: How Mechanical, Electrical and Thermal Abuse Lead to Thermal Runaway

In addition, TR can occur because of abnormalities inside a LIB cell: A manufacturing fault, such as contamination, can lead to an internal short-circuit (see Figure 9); or progressive chemical changes within the cell, particularly lithium plating on the anode, can lead to an internal short-circuit. This can occur, for example, during charging at cold temperatures. In either case, the internal short-circuit generates heat, which in turn leads to TR.

Some efforts have been made to mimic in-cell abnormalities in the laboratory. Two examples can be found here:

- The "nickel particle" test in Section 7.3.9 of BS EN 62133-2:2017+A1:2021 (BSI Group, 2017).
- The "copper puck" test described by Darcy, E. et al. (2015) at NASA.

However, both of these tests require bespoke assembly of cells. As a result, these methods cannot be used on standard production cells and are slow, expensive and may not yield results that are representative of standard production cells.

In the interests of practicality, nail-penetration, over-charge, and over-heating are thus the commonly used laboratory methods to initiate thermal runaway. However, each method suffers to some degree from variability in the results, particularly for nail-penetration. Repeat tests may therefore be required to achieve statistically meaningful results.

3.2 Thermal Propagation

Thermal propagation (TP) refers to any situation in which the thermal runaway of the initiating cell leads to thermal runaway of other cells in the battery pack. In fire science, the terms "fire spread" and "consecutive ignition" may also be used. In this report, the term "thermal propagation" is adopted because of its widespread use in the battery industry and associated legislation and standards. Typically, TP occurs in one of the following ways:

(1) The initiating cell develops an internal short-circuit, which acts as an external short-circuit for neighbouring cells that are electrically connected in parallel with the initiating cell. The high current in the neighbouring cells then causes them to heat up until they reach the critical onset temperature for them to enter thermal runaway.

(2) The initiating cell ejects hot gas, flames or solid matter which impinge on neighbouring cells, causing localised heating of those cells, possibly even puncturing those cells by impact or melting of their external material, causing them to reach the critical onset temperature for them to enter thermal runaway.

(3) The ejecta from the initiating cell, which often contain copper or molten aluminium, can cause external short-circuits of neighbouring cells, leading them to heat up until they reach the critical onset temperature for them to enter thermal runaway.

(4) The initiating cell is in close physical contact with neighbouring cells, such that the heat energy from the initiating cell is conducted into the neighbouring cells, causing them to reach the critical onset temperature for them to enter thermal runaway.

(5) The initiating cell is close to neighbouring cells, without an intervening thermal barrier material, such that the heat radiated from the surface of the initiating cell causes neighbouring cells to reach the critical onset temperature to enter thermal runaway.

(6) The heat or ejecta from the initiating cell can damage electrical insulation of nearby wires or electronics, causing short circuits which affect other cells, causing them to enter thermal runaway.

Thermal propagation results in more severe outcomes than single-cell thermal runaway, because:

- The total amount of heat energy and ejecta released is greater.

- The rate of release of heat and ejecta is often greater, because more than one cell may be in thermal runaway simultaneously.

With appropriate design measures, thermal runaway of a single cell can be isolated, so that it does not propagate to other cells. This is covered in Section 3.7 of this report.

3.3 Assessing the Risk of Harm from Thermal Runaway / Propagation

The existing UK and European standards for PLEV safety are underpinned by a risk assessment methodology, which has been applied to the products within their defined scope. A risk assessment is an essential requirement of the Supply of Machinery (Safety) Regulations 2008 (UK Government, 2008) (see Section 6.9 of this report), which the authors of standards aim to fulfil and ease the burden on individual companies. If compliance with the standard is deemed by the UK government to fulfil the requirements of the regulation, then the Secretary of State may choose to designate the standard under the Machinery Regulations. The standard will then confer, on any product which meets the standard, a rebuttable presumption of conformity with the essential health and safety requirements of the Machinery Regulations. Similarly, conformity with standards that are designated under other product regulations confer a presumption of conformity with the relevant parts of those regulations. However, if the standard is not designated, as is the case for the e-scooter standard BS EN 17128:2020 (BSI Group, 2020), or is designated with restrictions, then the manufacturer must consider alternative methods beyond the standard to demonstrate compliance with the essential health and safety requirements of the regulations.

The risk assessments underpinning the e-scooter standard EN 17128 and the e-bike standard BS EN 15194:2017+A1:2023 (BSI Group, 2023) are based on the methodology defined in BS EN ISO 12100:2010 (BSI Group, 2010).

In industrial companies, the typical approach used to assess the hazards associated with a particular product design is Failure Modes and Effects Analysis (FMEA), which may be performed according to BS EN IEC 60812:2018 (BSI Group, Oct 2018). This standard uses the term “criticality analysis” to describe the methodology for quantifying the risk of various failure modes and their causes. It describes various approaches to criticality analysis, one of which is to calculate a Risk Priority Number (RPN), which combines scores for the severity, likelihood and detectability of a failure to rate overall risk. Figure 10 below shows an example of the process used to determine the RPNs.

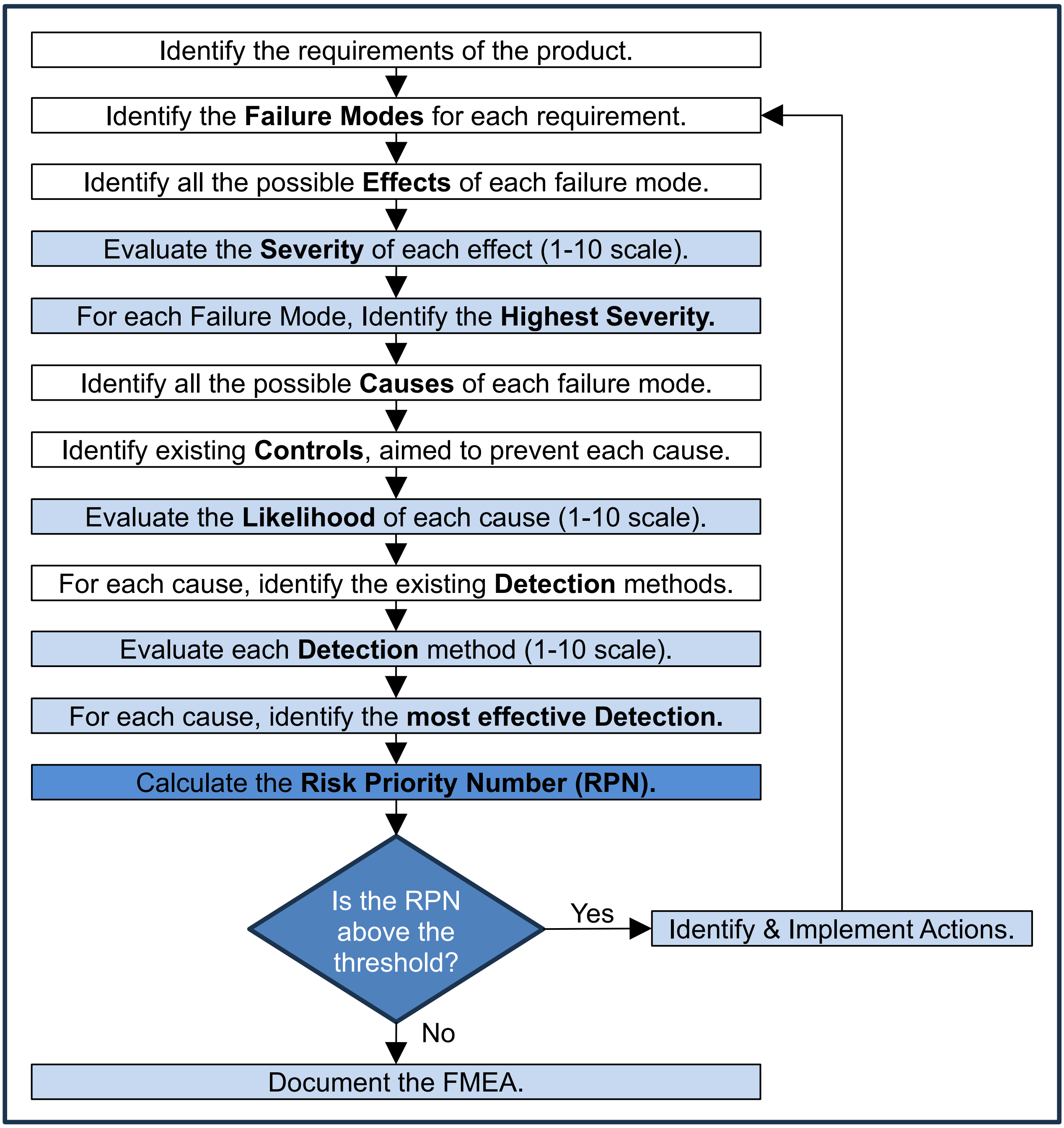


Figure 10: Example FMEA Flowchart

Table 3 shows an example of just one small part of a hypothetical FMEA for a PLEV. In the lefthand column, the FMEA process steps are shown. In the righthand column, an example is given, relating to one specific possible cause of a PLEV fire, which is over-charge of a single cell. In a complete product FMEA, this example might be one of hundreds or thousands of items.

Table 3: FMEA Process Example for PLEV Fire Safety

FMEA Process Step	**Example for PLEV Fire Safety**
Identify the requirements of the product	The product must not cause a fire
Identify all the possible failure modes for each specific requirement	The product causes a fire
Identify all the possible effects of each failure mode ("effect" means primarily the effect on human health)	• Fire results in severe injury. • Fire results in death.
Evaluate the severity of each effect. (On a 1-10 scale, where 1 is a minor inconvenience and 10 is death)	• Severe injury: 9 • Death: 10
Of all the effects of the failure mode, identify the highest severity	10
Identify all the possible causes of each failure mode	Over-charge of a single cell leading to thermal runaway, resulting in fire (this is just one possible cause)
Identify the existing design controls, aimed to prevent each cause	• Current Interrupt Device (CID) to isolate cell in case of excessive internal pressure
Evaluate the Likelihood of each cause, accounting for existing design controls. (On a 1-10 scale, where 1 is very unlikely and 10 is almost inevitable)	4
Identify the existing detection methods, to detect each cause, both in the product and in the product testing / validation process	• Design: BMS cell voltage measurement • Testing: Cell over-charge test • Testing: Pack over-charge test
Evaluate each detection method. (On a 1-10 scale, where 1 is certain to detect and 10 will almost certainly fail to detect. For a detection to be effective, it must be able to influence outcomes)	• BMS cell voltage measurement: 10 (without an isolation switch or BMS-to-charger communication, cell voltage measurement cannot influence the outcome) • Cell over-charge: 4 • Pack over-charge test: 4
Of all the detection methods for each cause, identify the most effective	4
Calculate the risk priority number (RPN) = Severity x Likelihood x Detection	10 x 4 x 4 = 160
If RPN is above a threshold (100), define actions (design changes, additional tests, etc.)	• Design control: Add BMS-controlled isolation switch, which opens if over-charge is detected.
Severity score after actions	10
Likelihood score after actions	2
Detection score after actions	2 (with an isolation switch, BMS cell voltage measurement becomes an effective detection method)
RPN after actions	10 x 2 x 2 = 40

In the example in Table 3 above, the original product has no isolation switch and no communication from the BMS to the charger, meaning that the BMS is powerless to prevent the charger from over-charging the cells, even if the BMS detects the over-charge from cell voltage measurements.

The cells are equipped with a Current Interrupt device (CID) (see Section 3.4 and Figure 15 and Figure 16 of this report), but statistically this device may not be 100% effective at preventing thermal runaway from over-charge, resulting in a Likelihood score of 4.

The pack undergoes an over-charge test as part of its validation testing, but a single over-charge test is not sufficient to cover all scenarios, so the detection score is also 4.

The original design therefore has a Risk Priority Number (RPN) of 160. Manufacturers who use this FMEA methodology must define their own threshold to determine what RPN value requires additional action. In this example, the threshold is 100, so the RPN exceeds this threshold.

The additional action identified is to add an isolation switch to the battery, controlled by the BMS. With suitable software, the BMS will open this switch if any single cell voltage exceeds the maximum allowable value. This has the effect of reducing the likelihood of cell over-charge. In this example, the detection score is also improved, because it is not relying on a single validation test, but rather detection is done on every battery. As a result, the RPN is reduced from 160 to 40.

Note that the severity of the failure mode (the product causes fire) was not changed by the corrective measures. This is often, but not always, true of design changes made to influence risk. Design changes are generally aimed at reducing likelihood and/or improving detection, rather than severity.

The example above illustrates good practice in the design and development of a product, using the FMEA process to guide design changes to improve safety. Various standards exist to define the FMEA process, including BS EN IEC 60812:2018 (BSI Group, 2018). However, the effectiveness of an FMEA is only as good as the underlying assumptions, such as the usage of the product. For example, if the FMEA was written considering only outdoor use of the PLEV, the severity score might legitimately be reduced to, say, 7 (moderate injury), on the basis that it is likely that the rider can escape from the fire without incurring severe injury. In the same scenario, the detection score might also improve from 4 to 1, because the rider would quickly become aware of smoke from the battery. The resulting RPN of 70 would be below the threshold that warranted further action. However, if the FMEA is written correctly, considering indoor storage, and charging of the battery, then the scoring would be as shown in Table 3.

A limitation of the FMEA approach is that it considers only single failure conditions. Other approaches, such as Fault Tree Analysis (FTA) tend to be better at identifying risks from multiple simultaneous or cascading failures. Later in this report, cascading failures are shown to be a real risk in PLEV batteries (see Sections 10 and 11), so the use of FTA or similar methodologies is advised.

The following sections outline the factors affecting the severity, likelihood and detection of cell thermal runaway and pack thermal propagation.

3.4 Factors Affecting the Severity of Cell Thermal Runaway

The severity of thermal runaway of a single cell can be quantified in several ways. Some examples of quantitative measurements taken during laboratory tests are:

- Peak temperature of the cell and/or vented gas/flames
- Total heat release
- Rate of heat release
- Mass loss of the cell

Other measurements, which can also help to characterise the thermal runaway include:

- Onset temperature at which thermal runaway begins.
- Determination of the gases and gas concentrations released.

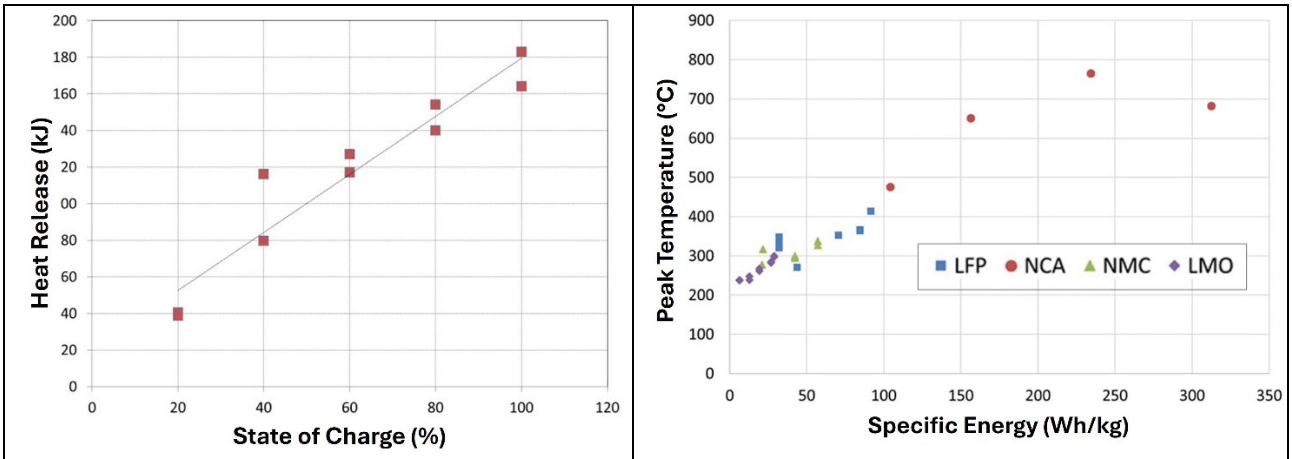
There are many factors that affect the severity of thermal runaway, including:

- Chemistry (especially the cathode chemistry)
- Cell size / capacity / total stored energy
- State of Charge (SoC)
- Internal cell pressure at which the cell starts to vent.

Thermal runaway in single cells and thermal propagation in multiple cells have been reported widely in the scientific literature, for example by Lamb *et al.* (2021), Ohneseit *et al.* (2023), Finegan *et al.* (2018), Feng, X. *et al*. (2018), He, X. *et al*. (2022), Joshi, T. *et al*. (2020), Liu, J. *et al*. (2017), Torres-Castro, L. *et al*. (2020). Consistent trends observed in laboratory experiments are summarised below:

- Total heat release is approximately proportional to cell SoC, see Figure 11(a).
- Total heat release is approximately proportional to cell capacity.
- Peak temperature measured on the cell casing increases approximately linearly with cell specific energy, see Figure 11(b).

The charts in Figure 11 are adapted from Lamb *et al.* (2021), at Sandia National Labs in the USA, which contains a summary of thermal runaway experiments done on many different capacities, formats, and chemistries of cells. In Figure 11(a), the heat energy released during thermal runaway of a specific cell-type is shown, with each data point representing a cell tested at a particular SoC. In Figure 11(b), the peak temperature during thermal runaway is shown for various cell-types, as a function of their specific energy (energy per unit mass). High specific energy is a valuable attribute, as it provides greater riding range (travel distance per full charge) for a given mass of battery. However the chart shows that it also tends to result in higher temperatures during thermal runaway.



(a) (b)

Figure 11: (a) Total heat Release vs. SoC for a 16 Ah Lithium Manganese Oxide (LMO) cathode Pouch cell and (b) Peak Temperature during Thermal Runaway vs. cell specific energy, for several cathode chemistries (LFP is Lithium FerroPhosphate; NCA is Nickel Cobalt Aluminium; NMC is Nickel Manganese Cobalt).

The charts in Figure 12 and Figure 13 are from Ohneseit *et al.* (2023), at Karlsruhe Institute of Technology in Germany. Figures and other information from the paper are used here because it reports an investigation of thermal runaway in a range of cylindrical cells similar to those used in many PLEVs, with relevant Lithium-ion chemistries, and provides a quantitative comparison of the sequence of events which result from cell self-heating, leading to thermal runaway.

The authors performed experiments on 21700 format (21 mm diameter, 70 mm long) cylindrical cells. This is a cell size increasingly used in PLEV batteries, although many still use the smaller 18650 (18 mm diameter, 65 mm long) cylindrical cells. They compared various manufacturers' cells using the three most common cathode chemistries: Nickel-Manganese-Cobalt (NMC), Nickel-Cobalt-Aluminium (NCA), and Lithium FerroPhosphate (LFP). The NMC cell used a "nickel-rich" variant of the NMC cathode chemistry known as NMC811 (approximately 80% Nickel, 10% Manganese, 10% Cobalt), which is close to the state-of-the-art in high specific-energy NMC cells. The authors tested three NCA cell types, two of which were high specific energy (very similar to the NMC cell), and one of which was a high specific-power cell, with around 20% less energy than the first two. The final cell used an LFP cathode, which cannot achieve such high energy as the NMC and NCA energy cells (around 36% less) but is widely regarded as a safer chemistry. However, LFP is rarely used in PLEVs, because the lower specific energy translates into lower range for the rider (electricbikereport.com, Dec 2023). Nevertheless, at least one PLEV product has been introduced to the UK market with LFP cells (Swifty Scooters Ltd., Mar 2024).

All the cells tested were from established suppliers and featured two safety devices:

1. PTC (Positive Temperature Coefficient). This is a component designed to protect the cell against external short-circuit. PTC materials dramatically increase their electrical resistance above a threshold temperature. If the cell is discharged with excessive current, the PTC material self-heats to a point beyond its threshold temperature, and thereby its electrical resistance increases greatly. This strongly limits the charge/discharge current if the cell is too hot. The PTC is a reversible device, so if the battery cools down, it will once more allow normal current to flow. PTC's tend to be used only on cells for relatively low-current applications such as PLEVs, because even at normal operating temperatures, they add significant electrical resistance (and hence inefficiency) to the cells. The additional resistance limits the useability of the cell for higher-current applications.
2. CID (current interrupt device). This is designed to protect the cell against over-charge. It is activated by elevated gas pressure inside the cell and acts to electrically isolate the cell, to prevent further charge or discharge. If the cell starts to experience unwanted chemical reactions, as occurs in an over-charge condition, these reactions will create gases inside the cell, which will increase the internal pressure, activating the CID. The CID is a non-reversible device, so once it has isolated the cell, it will stay isolated.

The PTC and CID are illustrated in Figure 15 and Figure 16. Neither the PTC nor the CID guarantees to prevent thermal runaway. They act only to limit or stop current through the cell. In the case of externally applied electrical abuse, this can be an effective way to prevent thermal runaway, but in the event of an internal short-circuit, they do nothing to prevent thermal runaway.

The authors performed thermal runaway tests in an Accelerating Rate Calorimetry (ARC) chamber, using a so-called heat-wait-seek (HWS) procedure, whereby the temperature in the ARC chamber is increased in steps of 5 °C, followed by a wait-time of 15-20 minutes to allow stabilisation, and then a seek-time of 10 minutes. The seek time is used to accurately detect whether the cell is self-heating due to internal chemical reactions. The temperature at which self-heating begins is shown in Figure 12(a). From that point onwards, the chamber temperature is controlled to try to match the cell temperature as the cell self-heats. This aims to achieve a quasi-adiabatic condition, meaning that the cell does not exchange heat with its surroundings: any heat generated in the cell acts only to heat up the cell, rather than being dissipated to the surroundings.

As the cell heats up, a sequence of events occurs:

1. The PTC activates. During the HWS test, this is very difficult to detect, because the cell is being neither charged nor discharged, so no change in cell voltage can be measured when the PTC activates.
2. The CID activates. This is easily detectable because the voltage between the cell terminals will suddenly drop to zero. The temperature at which this occurs is shown in Figure 12(b).
3. The cell starts to vent. This occurs when the internal gas pressure reaches a level which breaches a burst-disk in the cap of the cell. When the cell vents, the internal pressure suddenly drops, which results in a brief, small drop in the cell temperature. The temperature at which this occurs is shown in Figure 12(c).
4. The cell enters thermal runaway. The authors defined the criterion for detecting the start of thermal runaway as the point at which the rate of temperature increase exceeds 1 °C per 3 seconds (the data logging interval of their equipment). The temperature at which this occurs is shown in Figure 12(d).

It should be noted that the criterion in point 4 above, to detect the start of thermal runaway, is somewhat arbitrary, but provides a consistent means of comparison between different cells and SoCs tested. Similar criteria are reported by other researchers. In a real application, the temperature at which self-heating in the cell leads to thermal runaway will depend on the battery cooling system’s ability to dissipate that heat.

The tests were performed at five states of charge (0%, 30%, 60%, 80%, 100%) for each cell type, and two cells of each type were tested at each condition, to obtain some indication of statistical variation, shown by the error-bars in Figure 12.

Each chart in Figure 12 shows the five cell types on the x-axis. For each cell, the temperature (y-axis) is plotted against SoC (x-axis). On the far right of each chart, the mean, minimum and maximum values are shown, considering all cells tested.

Several key trends are observed in the data in Figure 12:

- In the NMC and NCA cells, the temperatures for onset, CID activation, venting and start of thermal runaway all decrease as SoC increases. In the case of the CID and venting temperatures, this implies that gas generation inside the cell is increased at higher SoC.
- In the LFP cells, the temperatures for onset, CID activation, venting and start of thermal runaway are consistently higher than for the NMC and NCA cells. This provides a greater temperature margin between normal operation and thermal runaway than is the case for the NMC and NCA cells.
- The temperature for onset of self-heating is surprisingly low, particularly at high SoC, albeit that the threshold for onset detection used by the authors is very low: 0.02 °C per minute. In the NMC cell at 80-100% SoC, self-heating is detected at around 85 °C, which is only slightly above most manufacturers’ stipulated maximum operating temperature (typically 60 °C). This illustrates that there are slow exothermic reactions which can occur inside healthy cells, well below the temperature at which thermal runaway begins. If the cells are not able to dissipate that heat to their surroundings, then they will, slowly but surely, heat up to a temperature where thermal runaway occurs, so cooling is critical to prevent this.
- Although venting occurred in all cells, thermal runaway did not start in any of the cells when they were tested at 0% SoC. Based on WMG’s extensive experience of LIB abuse testing, thermal runaway is less likely to occur in LIBs at low SoC.

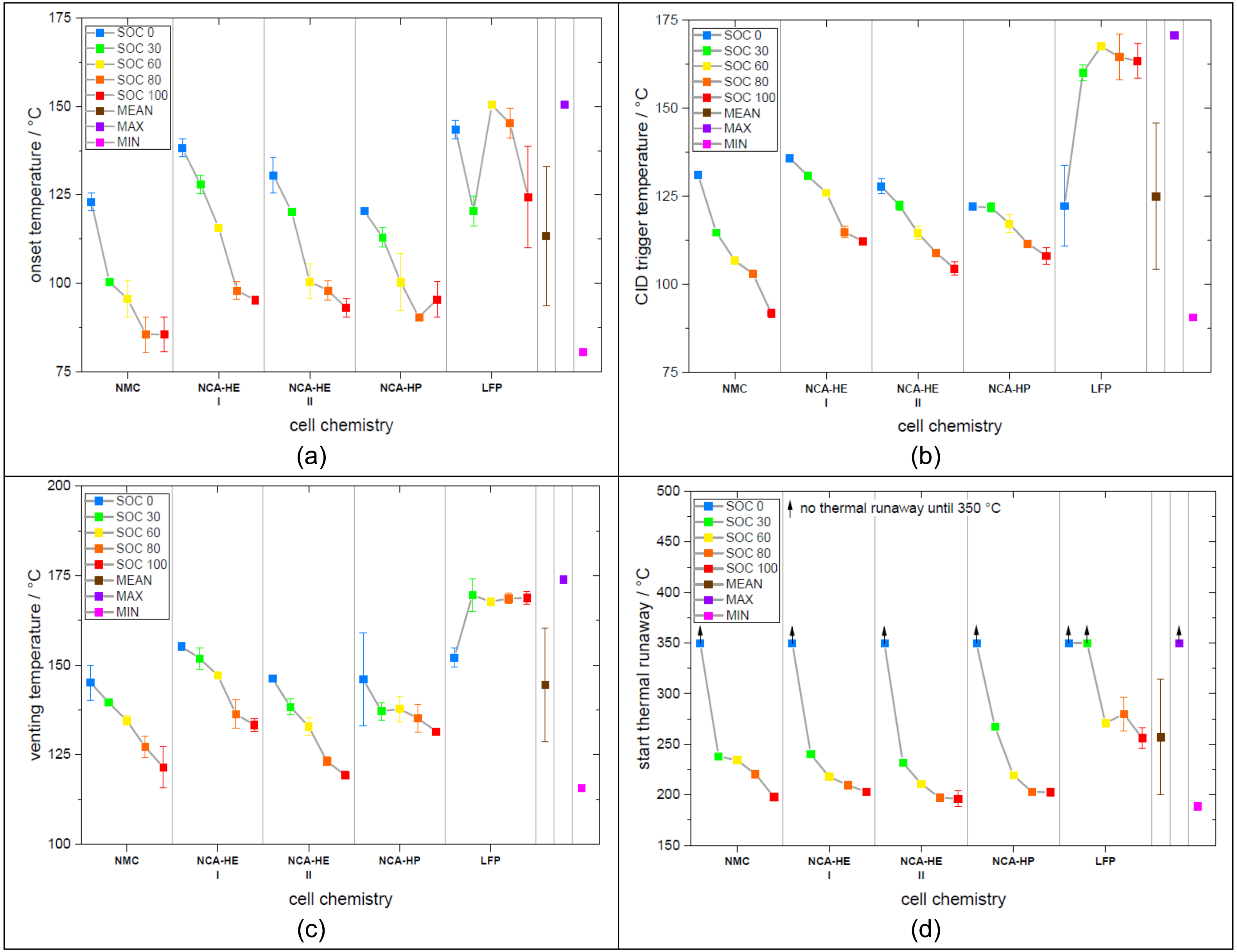
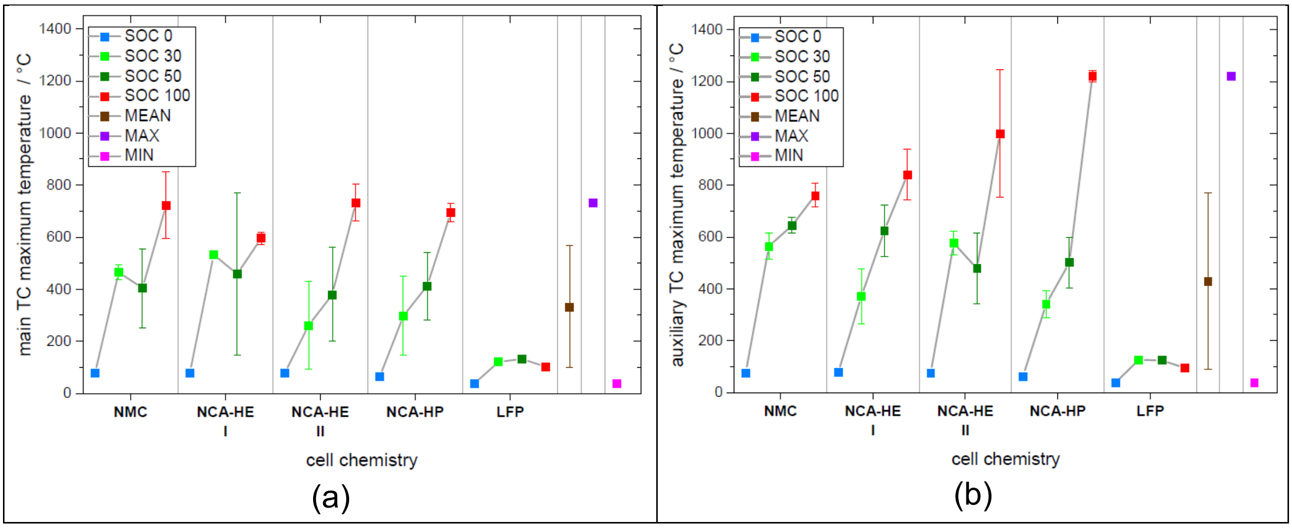


Figure 12: Temperatures for onset of self-heating, CID activation, venting and start of thermal runaway, during HWS ARC tests on 21700 cylindrical cells of various cathode chemistries, as a function of SoC

Figure 13 shows further results from the same paper. The same cell-types were again tested in an ARC chamber, but in this case, nail penetration was used to create an internal short-circuit in each cell. The charts in Figure 13 show the maximum temperature recorded in the experiment. Figure 13 (a) is a thermocouple (TC) attached to the middle of the side of the cell. Figure 13 (b) is the maximum of several auxiliary thermocouples on the top, bottom, and sides of the cell.



(a)

(b)

Figure 13: Maximum temperature as a function of SoC during nail-penetration tests in an ARC chamber, on 21700 cylindrical cells of various cathode chemistries

The main trend seen in Figure 13 is that for NMC and NCA cells (likely to represent most PLEV batteries), the maximum temperature during thermal runaway increases markedly at high SoC. In all cases, the temperature at 100% SoC was above 700 °C, and in the NCA cells, temperatures over 1200 °C were measured. By contrast, the LFP cell type used in this testing did not enter thermal runaway in any of the nail penetration tests, even at 100% SoC.

The higher temperatures at high SoCs are indicative of more vigorous exothermic reactions in the cell, more heat release and a more severe thermal hazard posed by the gases and other ejecta from the cell.

The key conclusions from the data presented in this section are:

1. The greatest thermal runaway severity from Lithium-ion cells generally occurs when they are fully charged, or nearly fully charged (close to 100% SoC).
2. The likelihood of thermal runaway is higher at high SoC, since the temperature margin between normal operation and onset of self-heating is less.
3. LFP cells represent both lower severity and lower likelihood of thermal runaway than NMC and NCA cells.

The data presented above have some limitations and caveats:

- Nail penetration is a convenient test method but creates an artificial hole in the cell casing which can act as a vent path, affecting the progression of the test. The nail itself adds significant thermal mass to the cell, which affects the temperature change in the cell. Details of the nail size, shape and penetration depth can have a significant influence on the result, so test-to-test variability can be significant.
- The tests were performed on cells of the same size, but with different energy content, depending on the cell model. Therefore, the cells are not like-for-like in terms of their performance, such as the riding range they would deliver in a PLEV.

In the context of PLEVs, batteries are regularly charged in indoor domestic locations (see Section 2 of this report) and may be left fully charged until they are next used. This means that the PLEV owner may leave their charged PLEV battery in their home in the state which, if the battery goes into thermal runaway, represents both the greatest potential hazard severity (highest peak temperature and total heat release) and the greatest likelihood of that happening. This is not misuse by the owner, and it is not reasonable to expect the owner to avoid this pattern of usage. However, it may help to explain why, when PLEV battery fires occur, they are of such high severity.

Figure 14, from the same paper by Ohneseit *et al.,* shows the mass loss of the cells, from the same tests used to generate the temperature data in Figure 12. The mass loss is highest at high SoC. For the NMC and NCA cells, around 60-70% of the cell mass is lost during thermal runaway. This indicates how much of the cell contents has either combusted or otherwise been ejected from the cell.

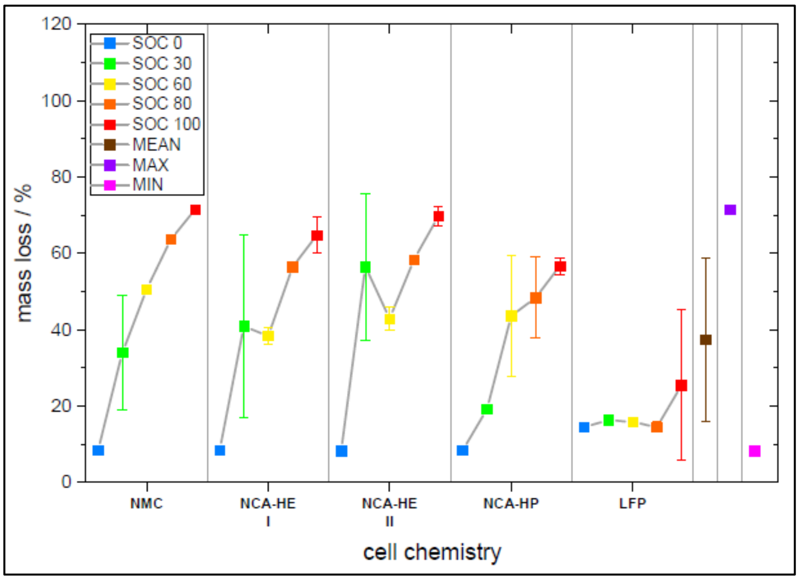


Figure 14: Comparison of Cell Mass Loss after Thermal Abuse, as a function of SoC

The photographic evidence from WMG's testing of PLEV products which ended in thermal runaway (see Figure 80 in Section 11.4.3 of this report) shows that in many cases, the complete jellyroll (see Section 2.5.1 and Figure 15) is ejected from the cell casing. This is a result of the gas pressure that develops inside the cell, which forces the cap of the cell to detach from the cell can and pushes the jellyroll out. This process was examined via high-speed synchrotron X-ray imaging at over 20,000 frames per second, in a 2018 paper by Finegan *et al.* (2018), at University College London.

The ejection of solid material from the cell during thermal runaway is a further hazard, added to the hot gases and flames. The temperatures during thermal runaway, as shown in Figure 12, frequently exceed the melting point of aluminium (~ 660 °C), so the ejecta often consist of molten aluminium as well as hot fragments of copper and other materials from within the cell.

A further aspect of thermal runaway, which is not explored in the papers mentioned above, is the phenomenon of vapour cloud explosion. In some thermal runaway events the gases, produced by decomposition of the materials inside the cell, do not combust, or only partially combust, when they exit the cell. This can lead to a cloud of combustible gas outside of the cell, which can subsequently combust violently if an ignition source is present. Such explosions can cause a pressure wave (Christensen *et al.*, 2021) and can present a severe risk of harm to human health and can be extremely damaging to property, as they which can cause structural damage to conventionally built structures (Mrozik, W, 2024).

When vapour cloud explosion risk is considered, recent research suggests that the risk from LFP cell is greater than that of NMC cells, because in LFP cells the vent gas is more likely to be emitted without combustion, leading to an increased risk of a vapour cloud (Bugryniec, P.J. *et al.*, 2024).

Therefore, while the severity of the thermal runaway behaviour of the cell itself may be significantly lower for LFP, as shown in the results of Ohneseit *et al.* above, the secondary risk of vapour cloud explosion appears to be higher. As stated by Mrozik above, vapour clouds explosion is a particular risk in enclosed spaces, so this risk is very relevant to PLEV fires, which were shown by the real-world data in Section 2 to often occur indoors.

3.5 Factors Affecting the Likelihood of Cell Thermal Runaway

As explained above, severity and likelihood of cell thermal runaway are closely correlated with one another. However, SoC is not the only factor affecting the likelihood of thermal runaway.

3.5.1 Cell Design Factors affecting the Likelihood of Thermal Runaway

There are many factors in the design of the cell which can affect the likelihood of thermal runaway. Some of these are discussed in Section 3.10 about counterfeit cells. The main design and safety features of a cylindrical cell are shown in Figure 15 and Figure 16. The examples shown include both PTC and CID safety devices, although not all cylindrical cells included these (see Section 3.4).

Inside a cylindrical cell, the thin layers of anode, cathode and separator are wound together into a “jellyroll”. The separator material plays a crucial role in preventing internal short-circuits between the anode and cathode of the cell, despite being only around 15 microns thick. A high-quality separator is made up of a laminate of polymer films and may also have a coating designed to inhibit dendrites from creating internal short-circuits and reduce shrinkage at elevated temperatures. Dendrites are microscopic tree-like structures. In Lithium-ion cells, lithium metal can grow in dendrites on the surface of the graphite anode, if the cell is charged with an excessive charging current, or if mal-distribution of current within the cell causes localised high current density. Impurities, dry spots (local lack of electrolyte) or delamination of the electrode layers can also contribute to dendrite formation. Lithium dendrites, despite their tiny size, have been shown to be sufficiently strong to pierce a separator, thereby creating an electrically conductive short-circuit between the anode and cathode. The electric current passing through the dendrite creates heat, which can then cause a small part of the cell to reach a high enough temperature to initiate thermal runaway.

Figure 15 and Figure 16 show that the separator protrudes upwards, at the top of the jellyroll, further than the anode and cathode layers. The same is true at the bottom of the jellyroll. This is necessary to ensure that the edges of the anode and cathode foils do not touch each other, which would create a short-circuit. The separator overlap looks large in the images, but in a real cell, it can be less than 1 mm.

Figure 15 and Figure 16 also show a central hollow mandrel (labelled “vent tube” in Figure 16) which serves to prevent collapse of the inner turns of the jellyroll, and is intended to provide a passage for gas at the base of the cell to reach the vent at the top of the cell. The mandrel adds some cost and weight to the cell and is not included in all cylindrical cells. The presence or absence of the mandrel can have an influence on whether the jellyroll is ejected from the cell during thermal runaway, because such ejection is caused by a build-up of gas pressure below the jellyroll, pushing it upwards. A hollow mandrel may partially alleviate that pressure, reducing the likelihood of jellyroll ejection.

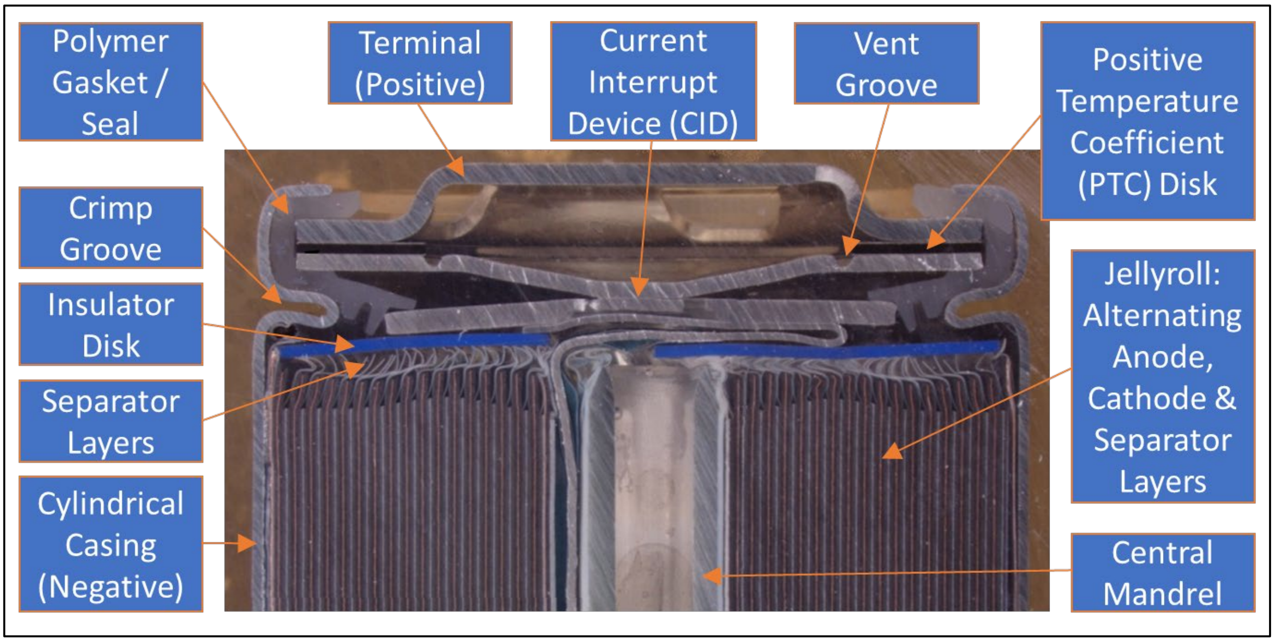


Figure 15: Cross-Section at the top of a Cylindrical Cell (adapted from Pesaran, A. et al., 2008)

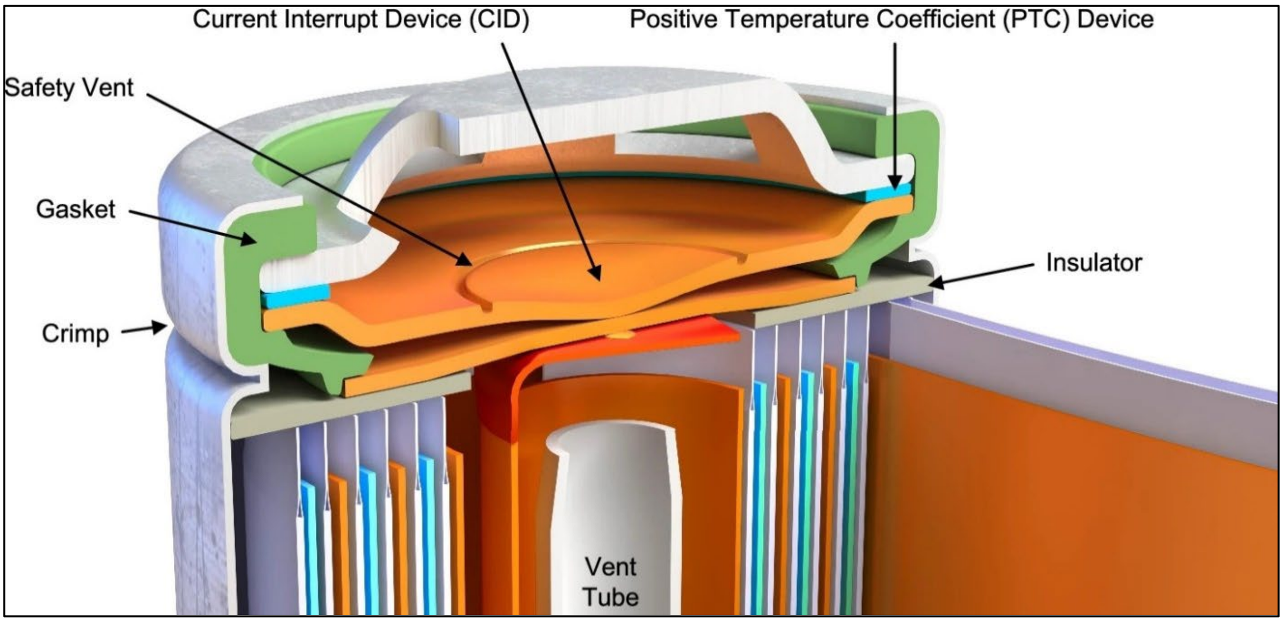


Figure 16: Safety features at the top of a Cylindrical Cell (from Nagourney, T., et al., 2021)

3.5.2 Cell Quality Factors affecting the Likelihood of Thermal Runaway

The quality of cell manufacture is another significant factor in the likelihood of cell thermal runaway. Figure 23 in Section 3.10 illustrates some examples of the microstructure of anode, cathode and separator materials resulting from poor quality production.

Quality can also affect the macro scale of the cell. The jellyroll winding is done on a specialised winding machine. As described above, at the top and bottom of the jellyroll it is crucial that the separator overlaps the edges of the anode and cathode, to prevent internal short-circuits. This relies on the layers being wound in such a way as to prevent “telescoping” whereby the middle of the jellyroll protrudes at one end (see Figure 17 for an exaggerated example of telescoping). In a typical 21700 cylindrical cell, the unwound length of each layer may be around 1.0-1.5 metres, so to wind the layers together without telescoping requires very precise control of the tension and alignment of the layers during winding. Manufacturers with little experience, or lacking care, or using inappropriate or old and worn production equipment, may be incapable of preventing telescoping of the jellyroll in some cells. As a result, there is a higher risk of internal short-circuits.

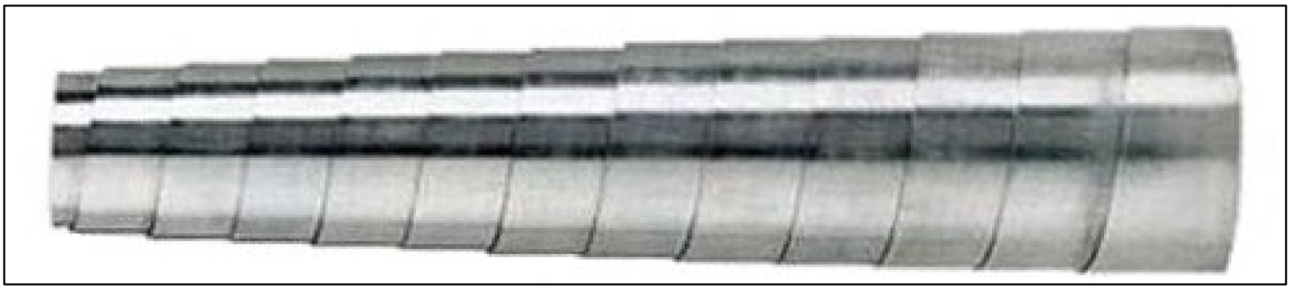


Figure 17: Exaggerated Example of a Telescoped Spiral (from Hennig (UK) Ltd., 2015)

Close inspection of Figure 15 shows that the outer anode layer of the jellyroll (copper-orange colour) protrudes much higher than the rest of the jellyroll. This likely occurred due to friction with the cell casing when the jellyroll was inserted into the casing. This is another example of telescoping, which could lead to a short-circuit.

This is just one example of how poor-quality manufacture can increase the likelihood of internal short-circuits, leading to thermal runaway. Cell manufacture involves multiple steps of creating individual components and assembling them together. Many of these steps are critical to preventing internal short-circuits. To ensure quality, manufacturers must actively monitor and control all such processes within carefully determined tolerances, and reject any components, sub-assemblies or complete cells which fail to meet stringent criteria. Further examples of cell manufacturing defects are described by Wu, Y. et al. (2018).

3.5.3 Battery Pack Design Factors affecting the Likelihood of Thermal Runaway

The battery pack design and quality can affect the likelihood of a cell entering thermal runaway, by protecting (or failing to protect) the cell from the main means of initiation:

- Mechanical abuse
- Electrical abuse
- Thermal abuse

In this context, “abuse” implies reasonably foreseeable misuse or failures.

3.5.3.1 Protection from Electrical Abuse

The BMS is responsible for protecting the cells from use outside their electrical limits. It should ensure that the charge and discharge current and voltage are always within the limits specified by the cell manufacturer. The electrical measurements it uses are:

1. Voltage of each group of parallel-connected cells
2. Current of the whole battery pack

With existing technology, it is not practical or economically viable to measure the current of every single cell. For parallel-connected cells, the BMS software will usually implicitly assume that the current is evenly distributed between the cells, so if the pack current is measured to be 30 A, and the pack has 6 cells in parallel, then it will assume that each cell is experiencing a current of 5 A. However, the current is never exactly the same between parallel-connected cells. It depends on the electrical resistance of each cell, and the connections to it.

Amongst new cells, there will be a production tolerance spread of resistance values. In high quality cells, the spread is small, but in poor quality cells, the spread may be higher. Over the life of the battery, all cells will degrade. One of the effects of degradation is an increase in electrical resistance. This may not be a problem, if all of the cells degrade at the same rate. However, the rate of degradation is temperature dependent: If some cells are hotter than others, due to differences in heat generation and cooling, the hotter ones will degrade faster, meaning their resistance increases more. So over time, the spread of current in parallel-connected cells tends to become wider. This makes it more likely that some cells will exceed the manufacturer's current limits, without the BMS being aware of this.

Nevertheless, in general, a good BMS should be capable of detecting, with acceptable accuracy, when cells in the battery are operating outside of the current and voltage limits defined by the cell manufacturer. The greater concern is whether the BMS can act on this information. In general, while the BMS may have dozens of sensors, it has very few actuators: In general the only actuators in a PLEV battery are the switches, controlled by the BMS, to close or open the charge and discharge circuits. When riding a PLEV, it is the motor that determines the battery discharge current, and during charging, it is the charger that determines the charging current. The BMS can only influence either of these by means of electronic communication. If the communication fails, or if there is no communication, the BMS has only one defence: To isolate the battery by opening a switch. Typically, in PLEV batteries, this is a MOSFET (metal oxide semiconductor field-effect transistor) switch.

The design must also consider failure of the BMS itself, including the sensors and actuators that it uses. Therefore, a purely passive protection mechanism, which is unaffected by BMS failures, is needed as a back-up. A fuse can fulfil this need. Like the MOSFET switch, this is a pack-level protective device, primarily to protect against external short-circuit (e.g. a short-circuit in the motor). The fuse must be correctly selected for the application: it must not blow (i.e. the wire in the fuse must not melt to cause an open-circuit) in normal operation, but it must blow when a failure current occurs. For batteries, the current that occurs, in the event of an external short-circuit, depends on the internal electrical resistance of the battery as well as the resistance of the short-circuit itself. This resistance varies somewhat with SoC and varies greatly with temperature (the resistance is highest at low temperature). Hence, a fuse which works fine at 25 °C might not blow at 0 °C. Typically, the short-circuit tests defined in standards and regulations are specified at only one temperature, so they fail to test the operation of the fuse across the whole operating range. Selecting a fuse which works across the whole operating range may be a challenge and may not be correctly considered by less capable suppliers.

A further failure mode which is sometimes beyond the control of the BMS is 'deep discharge'. Deep discharge means that one or more cells in the battery have been discharged significantly below the minimum allowable voltage, defined by the cell manufacturer. Deep discharge can occur because of a BMS that does not curtail discharging when the minimum allowable cell voltage is reached, but it can also occur if the battery is stored for a long period, during which self-discharge allows the cells to dip below the minimum allowable voltage. If any of the cells has an internal defect in the form of a "soft" short-circuit, this self-discharge may happen quite quickly (in a matter of hours or a few days). If the cell voltage goes very low (close to 0 V), then the copper in the anode current collector can start to dissolve in the electrolyte. The next time that the cell is charged, this dissolved copper can create dendrites, similar to the lithium dendrites described in Section 3.5.1. Just like the lithium dendrites, copper dendrites can pierce the separator to create a short-circuit, which then creates a hot spot, which can lead to thermal runaway. To prevent this from occurring, it is essential that the cells must not be charged after deep discharge. Therefore, the BMS must check the cell voltages whenever it is switched on and must permanently prevent charging if any cell voltage is below a threshold, defined by the cell manufacturer.

3.5.3.2 Protection from Thermal Abuse

Responsibility for ensuring that the cells are used within the cell manufacturer's specified temperature limits lies partly with the BMS, and partly with the design of the battery with regard to cooling. The BMS should have at least one temperature measurement in the battery, to allow the BMS to ensure that the minimum and maximum temperature limits of the cell (from the cell manufacturer) are not breached. The sensors should therefore be located in positions likely to correspond to the hottest and coldest cells, as determined from product development testing, which may point to the need for more than one sensor. Evidence from WMG's recent teardowns of e-bike batteries shows that many have only one temperature sensor, and some have no temperature sensor fitted (see Section 10.3.14).

To minimise the risk of any given cell breaching the cell manufacturer's temperature limits, the overall design of the battery pack should aim to achieve thermal homogeneity: All cells should be at very similar temperatures. All the cells generate heat as they are charged or discharged. The temperature distribution between cells depends on the amount of cooling that each one receives. In most PLEV batteries, there is no active cooling. It is likely that this is because the low charge and discharge currents do no generate sufficient heat to justify the additional complexity, weight, space and cost entailed in adding a cooling system. The only cooling effect is through passive cooling, which relies on natural convection of air within the pack, and conduction of heat from the warm air inside, through the casing, to the atmospheric air outside. Inevitably, the cells closer to the outside of the pack will be better cooled, and those furthest from the outside will run hottest.

The efficacy of convection cooling within the pack is partly dependent on the spacing between the cells, but greater gaps between cells mean that the overall size of the battery increases. According to Morin, B. (2023), CEO at Soteria Battery Innovation Group, among eight e-bike batteries that Soteria inspected, the maximum cell spacing was 1 mm, and some had no gap between cells. WMG has seen similarly small spacings in the PLEV batteries that it has torn down (see Section 10 of this report). Spacing between cells is also an effective way to reduce the thermal conduction and radiation from a thermal runaway cell to its neighbours (thermal propagation), see Sections 3.2 and 3.7. In WMG's experience from abuse testing, a spacing of ≥2 mm between cylindrical cells is often required to be effective in preventing thermal propagation, so the spacings of 0-1 mm seen in many PLEV batteries are unlikely to be an effective measure to prevent propagation.

The BMS will not be able to distinguish the spatial variation in temperature unless it has multiple thermistors. As with electrical limits, it also relies on communication with the motor controller and the charger to influence the heat generation caused by discharge and charge, and as a last resort may open the MOSFET switch to protect the cells. As mentioned in Sections 8.1 and 8.4, Soteria's recent teardown of e-bike batteries suggests that some PLEV BMS systems do not isolate the cells until a temperature well above the cell manufacturer's stated limit is reached.

The cooling that can be achieved by the type of passive cooling used in PLEV batteries is very limited. If the PLEV is used for limited durations with long gaps between rides, and if it is limited to modest power output and speeds (per the EAPC definition), and used at moderate ambient temperatures, then this may well be sufficient.

However, if the owner uses their PLEV to ride long distances or is using it for hours at a time, then the battery may progressively heat up, due to the limited cooling, until riding stops. The heat generated by the cells is proportional to the square of the current that they deliver, and the current depends on the power demand. The greatest heat generation is associated with riding patterns where the rider is frequently demanding high power. This can occur with frequent acceleration and deceleration (as tends to occur in city traffic), prolonged high speeds (as may occur if the 25 km/h speed restriction is removed or modified) or ascent of long hills. However in WMG's experience of testing PLEVs, the motor tends to reach its thermal limit and de-rate significantly before the battery would reach its thermal limit.

In automotive batteries, active cooling is normally used, whereby a cooling fluid is pumped through passages in the battery that are in thermal contact with the cells, but even this has its limitations. Automotive OEMs recognise that the BMS has a limited ability to measure the cell temperatures, due to the practical and economic challenges of implementing large numbers of thermistors. To supplement the few thermistors, they may use software to estimate the temperature of the cells. This relies on extensive development testing, to validate the accuracy of the temperature estimation in a wide range of conditions. If well validated, software estimates can be an effective way to control cell temperatures. However, in PLEVs, it is doubtful that many BMSs have the hardware and software functionality to robustly implement such a solution (See Section 10.3.15 of this report).

3.5.3.3 Protection from Mechanical Abuse

The battery pack structure, and the structure of the vehicle itself, are responsible for protecting the cells from mechanical damage, which can occur in several ways:

- Mechanical fatigue, caused by vibration.
- Mechanical shock / impact, caused for example by riding over kerbs or by dropping the battery on a hard surface.
- Penetration, caused by sharp objects puncturing the pack casing and cell(s)

As well as causing damage to cells, these occurrences may affect the battery in other ways, for example by compromising the protection against ingress of moisture and dust.

The recent "Battery Breakdown" report (Electrical Safety First, July 2023) contains a good summary of how the degree of mechanical protection differs between e-bikes and e-scooters. This relates mainly to protection from shock, impact and penetration. In general, e-bikes offer good protection from impact, as the battery is usually mounted high off the ground, and within the confines of the frame. By comparison, e-scooters that have the battery mounted below the deck present a greater risk of impact to the battery, and their small wheel/tyre diameters cause higher shock loads from kerbs and potholes.

Protection from mechanical fatigue requires absorption of vibrations. In e-bikes, this is mainly achieved by the pneumatic tyres, and a suspension system if fitted. Most e-scooters do not have suspension, so rely only on the tyres to absorb vibrations, although the absorption characteristics of different e-scooter tyres differ significantly, particularly depending whether the tyres are pneumatic or solid (see Section 7.12.1 of this report).

Vibration, shock, and impact can cause movement of parts within the cells, which can then lead to internal short-circuits. This relates mainly to the ends of the jellyroll, and the connections from the jellyroll to the cell terminals. Here it is critical that the separator and other insulation components maintain physical separation between the anode and cathode. In poor quality cells, the design and assembly of these components may not provide sufficient protection against the effects of shock and vibration.

3.5.4 Environmental Factors affecting the Likelihood of Cell Thermal Runaway

The temperature of the cells can have an influence on the likelihood of thermal runaway. As shown in Figure 12, the onset of self-heating can start as low as 85 °C, and some tests at WMG have suggested even lower onset temperatures in some cells. The closer the initial cell temperature is to the onset temperature, the greater the likelihood of thermal runaway.

3.6 Factors Affecting the Detection of Cell Thermal Runaway

As discussed in Section 3.4, in a laboratory setting, using an ARC calorimeter, the various steps leading to cell thermal runaway can be detected based on accurate voltage and temperature measurement.

In a real PLEV battery, detection can be compromised by several factors:

- The BMS is not always active. If the battery is switched off (i.e. not being discharged while riding or being charged), usually the BMS will be inactive, so it will not be measuring either voltage or temperature. However, thermal runaway can occur at any time, including when the battery is not being used.
- Although the BMS measures all cells connected in series, it cannot distinguish the voltages of cells connected in parallel. If one cell reaches the point at which the CID activates, then it will become open-circuit (electrically disconnected). However, the BMS will continue to measure the voltage of the cells in parallel with the failed cell, so it is unlikely to be able to detect any immediate change. Over a longer period of time, if the BMS has appropriate diagnostic software it may be able to detect the loss of one cell, as the remaining parallel cells will charge and discharge more rapidly than the rest of the battery, and so their voltage will change more rapidly.
- Similarly, if a cell develops an internal short-circuit, it will drain the cells which are connected in parallel to it. Depending on the resistance of the short-circuit and the number of cells in parallel, the drop in voltage may not initially be measurable by the BMS, or the BMS may lack the diagnostic software to interpret such a voltage drop as a failure condition.
- Most PLEV batteries only contain one temperature sensor (or sometimes none, see Section 10). The decision on how many temperature sensors to include is generally driven by cost. This one sensor is inevitably some distance away from most of the cells, so it will not detect the initial temperature rise of a single cell in most cases. It may only detect a significant temperature increase when the first failed cell starts to vent hot gas into the battery casing.

As discussed in Section 3.3, even if the BMS is able to detect a failure, that detection is only useful if the BMS has the means to intervene or issue an alert requiring human action. In the case of over-charge or over-discharge, detection is quite easy, using the cell voltage measurements, but only useful if the BMS can intervene by stopping the charge or discharge process.

Gas sensors have also been proposed as a means of early detection of cell thermal runaway (Swartz and Nexceris, L.L.C., 2017). WMG is not aware of any PLEV BMS that includes gas sensing. It is also relatively rare in automotive BMS hardware but is increasingly being considered for large scale battery installations, for example in stationary energy storage and in marine applications (Gully, B. *et al*., 2019).

The possibility of alerting humans to the detection of PLEV battery thermal runaway is discussed further in Section 6.15.2 of this report.

3.7 Factors Affecting the Severity of Thermal Propagation

In a complete battery pack, the severity of thermal runaway/propagation can be quantified in similar ways as for a single cell, but also with some other measurements. Some examples of quantitative measurements taken during laboratory tests of a pack are:

- Peak temperature of the pack and/or vented gas/flames
- Rupture or explosion of the battery housing.
- Mass loss of the pack.
- The time interval between successive cells entering TR (If multiple cells are simultaneously in TR, the peak rate of heat and gas release is increased).

In a complete battery pack, the severity of a fire, which may be a single-cell thermal runaway or may involve propagation to multiple cells, is dependent on several pack-level factors including:

- Severity of individual cell thermal runaway.
- Design of the cell-to-cell busbars, which are thermally conductive and may thereby promote heat transfer between cells (thereby promoting thermal propagation) but may also include fusible links to isolate cells when high electrical currents occur.
- Materials and design features to mitigate thermal propagation from cell to cell.
- Materials and design features of wiring and electronic circuits, and their protection against damage caused by ejecta from cells in thermal runaway.
- Features in the battery pack casing to allow controlled release of gases.
- Ability of the battery pack casing to contain cell ejecta and heat from TR/TP.

3.7.1 Anti-Propagation Materials

In the automotive sector, materials to slow-down or prevent thermal propagation, or to otherwise mitigate its effects, have been an active field of research and development for several years. Many chemical and material companies now offer products which are claimed to mitigate thermal propagation (see references: 3M, Rogers Corporation, Henkel Adhesives, AIS Ltd., Aspen Aerogels, and Saint Gobain).

The materials used to mitigate thermal propagation fall into several categories:

- Thermal barriers: Materials with very low thermal conductivity and very high temperature resistance.
- Thermal absorbers: Materials which can absorb a large amount of heat energy with only a modest increase in temperature.
- Thermal conductors: Materials (or devices) which conduct heat rapidly from its source to a location where it will not cause harm.

Most such materials are placed in contact with the cells, often with the intention of minimising heat conduction from one cell to its neighbour. However, there are potential downsides to this approach: If a large proportion of the cell surface is covered by a material with very low thermal conduction, cooling the cell in normal operation becomes harder. In most automotive batteries, this is overcome by having an active cooling system, which allows heat to be conducted from the cells via a surface that is not covered by the anti-propagation material (usually a surface which does not face adjacent cells). Most PLEV batteries have no active cooling but rely on passive cooling, whereby natural convection of air between the cells provides some cooling effect. This would be prevented if the space between the cells were filled with a thermal propagation preventative material.

More details on automotive anti-propagation materials are described by Torres-Castro, L. *et al*. (2020).

3.7.2 Failure of Pack Mechanical Structures

Many PLEV battery packs use plastic injection mouldings, or even simply adhesives, to hold the cells in position. Most such materials will be severely compromised by the heat from a single cell in thermal runaway, which can result in the cells no longer being held in their original positions. This makes thermal propagation harder to control and predict.

The outer casing of many PLEV batteries is also formed of plastic injection-mouldings. These materials will melt and disintegrate at temperatures well below typical thermal-runaway gas temperatures, so there is little or no chance of the casing containing the ejecta from the cells. Many plastics are flammable and so can add to the severity of a battery fire, but many fire-retardant plastics also exist. Fire-retardant properties are achieved by adding filler materials to thermoplastics. The filler materials typically work by releasing non-flammable gases, such as CO_2, which act to shield the material from atmospheric oxygen to slow the combustion, or water vapour which absorbs the heat from combustion, or are endothermic (heat-absorbing) materials. Other additives create a surface layer of char when exposed to fire, which shields the material underneath. Such fire-retardant plastics can help to prolong the integrity of battery casing during thermal runaway.

Some PLEV batteries use aluminium casings, including many used in hire fleet operations. The melting point of aluminium alloys (typically 500-600 °C) is below that of vent gases from thermal runaway, particularly at high SoC (see Figure 13).

In the aftermath of a battery fire, it is not uncommon to find that large plastic structures, which held the cells or formed the outer casing, have largely burned away or carbonised, and the cells are scattered far from their original locations.

3.7.3 Battery Pack Physical Layout

In e-bikes, there are broadly two variants of battery layout:

1. “Frame-Mounted” batteries are mounted to the e-bike frame via a bracket or straps. The cells are oriented with the axis across the width of the bike. All the cells are clustered into a single cell stack, such that the cell end-caps (vents) face to the left and right sides, towards the inner faces of the battery pack casing. See Figure 18.
2. Integrated “Tube-Mounted” batteries have a long, thin shape. They either slide into a tube of the e-bike frame from one end, or slot into a deep recess in the frame tube. The cells are oriented along the length of the tube, in a number of identical or near-identical clusters, which are arranged end-to-end, with electrical insulation between the clusters. See Figure 19.

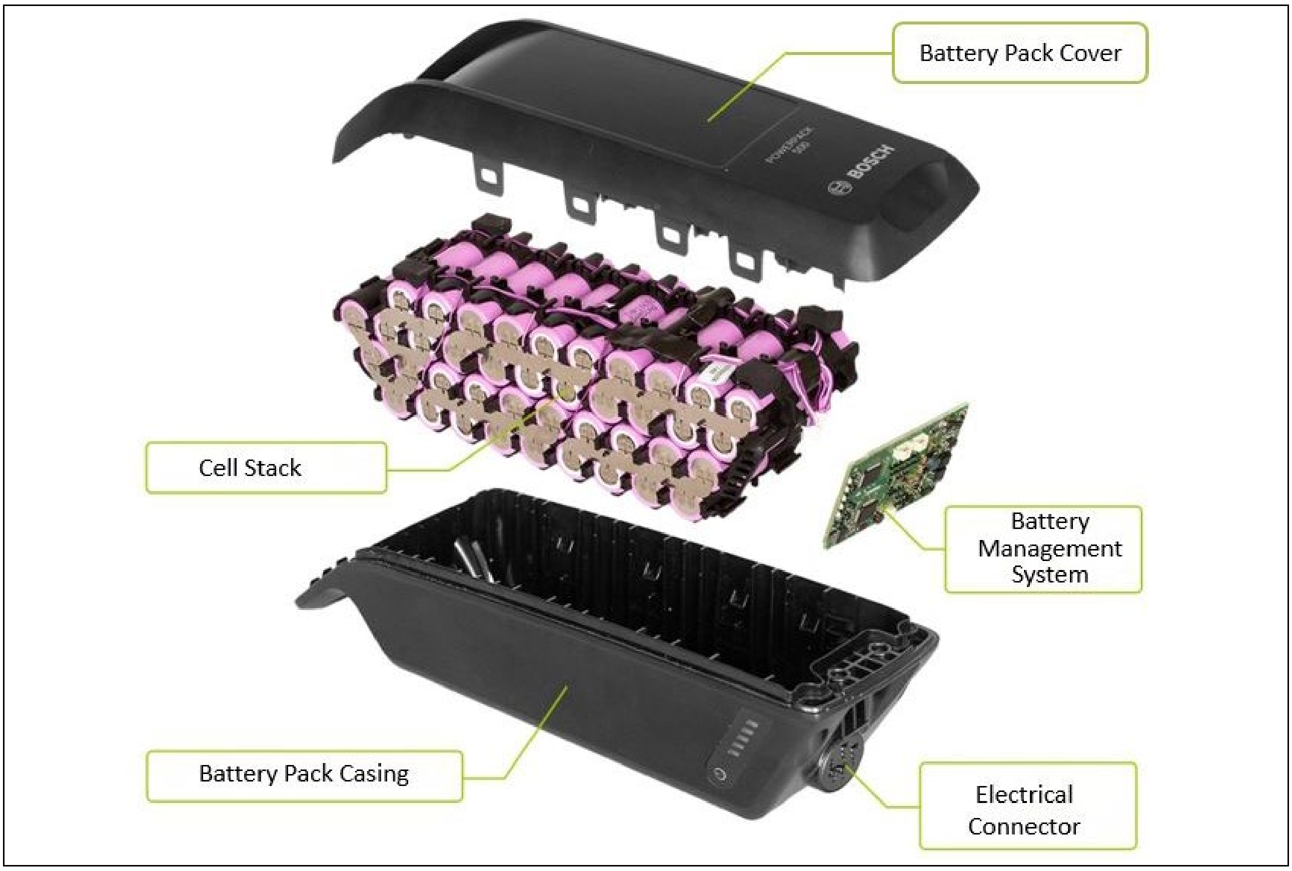


Figure 18: Example of Frame-Mounted e-bike Battery (Liofit, 2024)

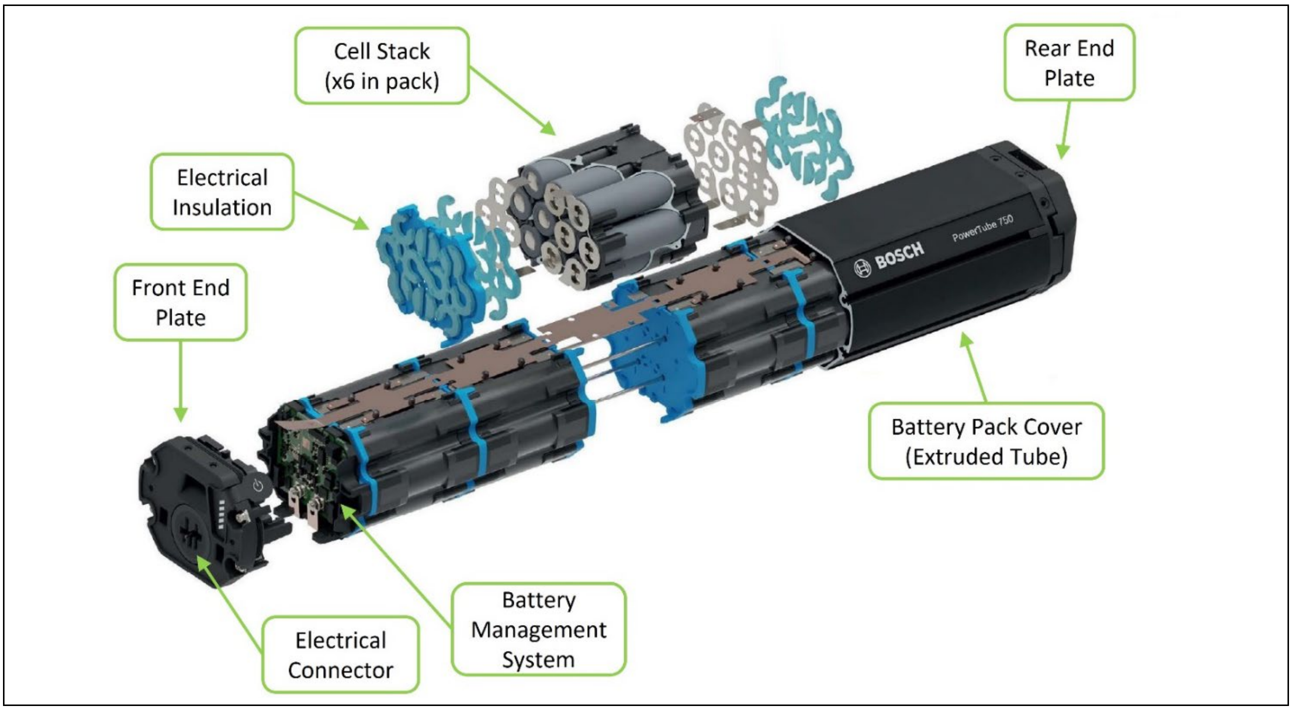


Figure 19: Example of Integrated Tube-Mounted e-bike Battery (Winograd, 2022)

In most e-scooters, the battery layout is similar to the frame-mounted e-bike battery, but the cell orientation is vertical, rather than horizontal.

In the frame-mounted battery, in the event of cell thermal runaway, the vent gas is directed at the inner face of the battery pack casing. Usually this is a plastic material which will be rapidly breached by the heat of the vent gas. The pressure inside the battery pack casing will rise rapidly, which may also cause breaching of the casing. Either way, a plastic casing will offer little resistance to the vent gas, and aluminium will be only marginally better.

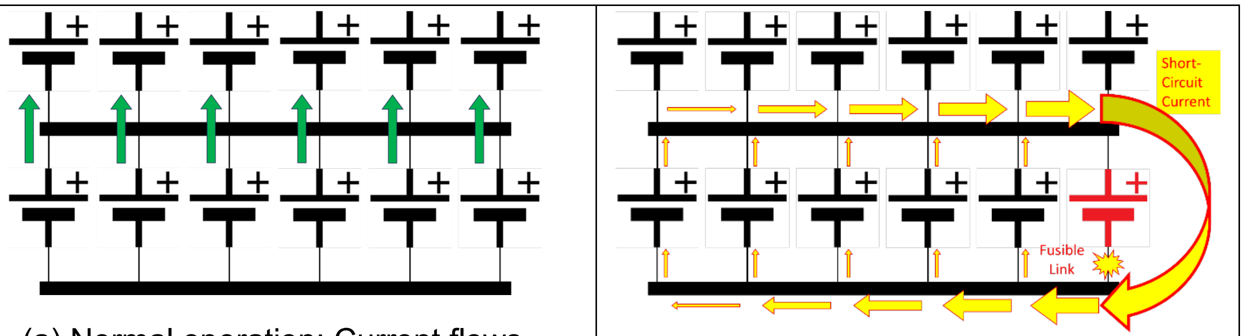
In the integrated tube-mounted battery, the vent gas is directed towards the ends of the cells in the adjacent cell cluster. The plastic electrical insulation between the adjacent clusters is likely to be rapidly vapourised by the vent gas. As a result, this layout may have an increased likelihood of thermal propagation due to impingement of the vent gas directly on to adjacent cells. Furthermore, the tubular form of the battery casing is a more effective pressure vessel, and if the tube is aluminium, it will have a higher resistance to hot gas than polymers, although even aluminium will melt relatively quickly when exposed to vent gas. The risk is that the pressure build-up in a tubular battery pack casing may be greater than for the frame-mounted battery, and the subsequent breaching of the casing may be more explosive. Retaining the heat for longer, before the casing is breached, may also accelerate the thermal propagation within the pack. However, the actual performance in a fire will depend on the detailed design of each specific product, so this needs to be tested on a case-by-case basis.

3.7.4 Fusible Links in Cell Busbar Connections

Most PLEV batteries comprise cells that are electrically connected both in series and in parallel. As shown in Figure 20(a), in normal operation, the current flow is predominantly between the cells groups connected in series. However, when one cell develops an internal short-circuit, it acts as an external short-circuit path for the cells which are connected in parallel with it. This can result in a very high current passing through the short-circuited cell, as shown in Figure 20(b). If the cells are equipped with PTC devices (see Section 3.4), then these may activate to limit the short-circuit current. However, many cells, particularly cheaper ones, do not have a PTC device. Similarly, if the cells have CID devices, then the CID may activate in the cell with the internal short-circuit, but again, not all cells have a CID.

In some batteries, the busbar connections are designed to have fusible links. Unlike the PTC which is activated by high temperature, and the CID, which is activated by high pressure, the fusible link is blown by self-heating, caused by the high short-circuit current, which melts the metal in the link. When the fusible link melts, it isolates the failed cell, and protects the parallel cells from continued short-circuit. In the best-case scenario, the battery can continue to function, albeit with reduced capacity due to the loss of one cell.

The concept of fusible links has been implemented by several automotive OEMs who use small cylindrical cells, like those commonly used in PLEV batteries (Straubel, J.B. *et al.*, 2010). The most common means of implementing this concept is to use ultrasonically joined wire bonds between the busbar and the cells, see Figure 21. At the time of writing, WMG is not aware whether any PLEV batteries use fusible links. WMG is not aware that the effectiveness of such links has been demonstrated in the scientific literature.



(a) Normal operation: Current flows predominantly between cells in series

(b) If one cell develops an internal short-circuit, it acts to short out the other cells in parallel. If the parallel links are thin, they can act as fuses

Figure 20: How fusible parallel links in cell-to-cell busbars mitigate short-circuit of parallel cells.

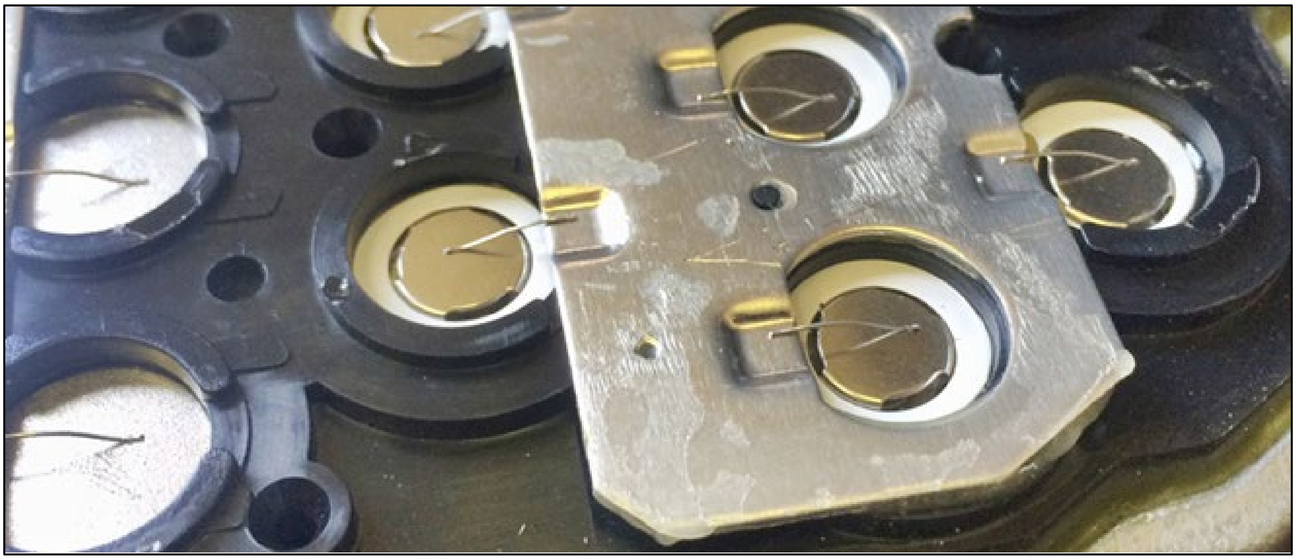


Figure 21: Fusible Connections to Cylindrical Cells, using Ultrasonic Wire Bonding (chargedevs.com, 2016)

3.8 Factors Affecting the Likelihood of Thermal Propagation

Some of the measures discussed in Section 3.7 can influence both the severity and the likelihood of thermal propagation, particularly anti-propagation materials, and the pack physical layout. Figure 22 depicts as stack of prismatic (cuboid) cells, commonly used in automotive and other applications, but similar principles apply to the cylindrical cells commonly used in PLEVs. The left-most cell is depicted as the first cell entering thermal runaway, causing heating of the neighbouring cells, potentially leading to thermal propagation.

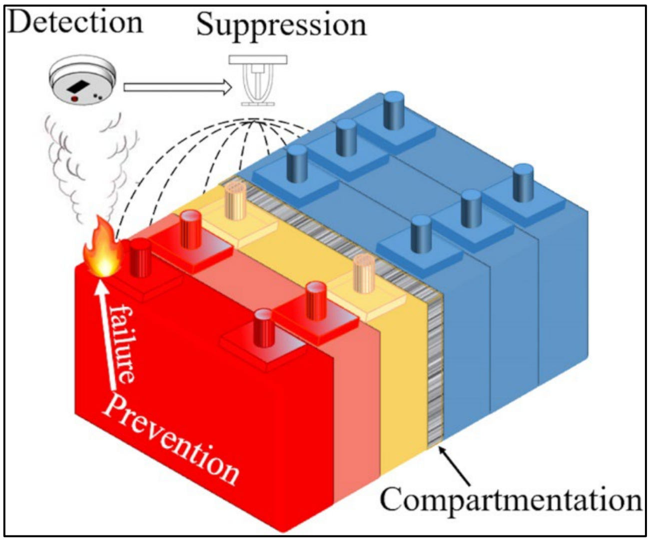


Figure 22: Four Layers of Protection for Lithium-ion Battery Fires (Bravo Diaz et al. *(2020))*

The image summarises methods of protection, including prevention (at cell level), detection, compartmentation and suppression. Detection of the first cell approaching thermal runaway may be sufficient to allow the BMS to take action to prevent or delay thermal propagation, for example by preventing charge or discharge. Compartmentation includes measures such as thermal barriers, mentioned in Section 3.7.1. Suppression can involve the use of extinguishing agents, which are unlikely to be practical in PLEV batteries due to limitations of size, weight and cost, but are increasingly used in much larger applications such as grid energy storage. However, suppression can also include thermal absorber materials, as mentioned in Section 3.7.1.

3.9 Factors Affecting the Detection of Thermal Propagation

As discussed in Section 3.5.3, detection of a failure mode is only useful if action can be taken to alter the outcome. If single cell thermal runaway occurs, then whether this progresses to thermal propagation is largely down to the design of the battery pack and cannot be influenced by the BMS. If the BMS were to detect thermal propagation, it would do so using the same methods as to detect single cell thermal runaway (see Section 3.6).

3.10 Battery Safety Malpractice: Counterfeit Cells

In her statement to the US Consumer Product Safety Commission (CPSC) hearing on Lithium-ion Battery Safety (US CPSC, Jul 2023), Dr. Judy Jeevarajan of UL Research Institutes (UL Research Institutes, no date) in the USA warned of the dangers posed by counterfeit cells (see Section 8.1 of this report).

A paper by Dr. Jeevarajan's team (Joshi *et al.*, 2023) describes a detailed comparison of three cylindrical cells in the 18650 (18 mm diameter, 65 mm long) format. Cell A was a genuine cell from an established manufacturer. Cell B was outwardly almost indistinguishable from Cell A, including all the labelling on the plastic sleeve of the cell, but was a counterfeit. Cell C was another counterfeit cell, exemplifying some of the worst discrepancies between claimed and actual performance.

The authors performed detailed teardown of the cells to ascertain their internal structure including safety devices and used microscopy techniques to examine the structure of the anode, cathode and separator materials, and conducted tests at "off-nominal" conditions, including over-charge and external short-circuit, to demonstrate the increased severity of the cell’s response to these conditions.

The paper highlights numerous design and quality differences between the genuine cell and the counterfeit cells which have the potential to increase the likelihood and worsen the severity of thermal runaway, summarised below:

- Cells A and B, which were visually similar and sold under the same brand name, were both labelled as having 3.2 Ah capacity. When tested, Cell A slightly exceeded the nominal capacity, but Cell B had only 1.8 Ah capacity. Cell C was labelled with 5.0 Ah capacity (which is impossible with current technology in this size of cell), and when tested, had a capacity of only 1.2 Ah. Cells that are below their stated capacity pose a significant safety risk: The active materials inside will be electrically over-stressed by charge or discharge current which their stated capacity implies that they should be able to withstand. This could lead to over-heating, with associated issues such as decomposition of electrolyte or active materials, or lithium plating on the anode during charging, either of which could lead to thermal runaway.
- Cell A, the genuine cell, included two safety devices: a PTC and a CID (see Section 3.4). The counterfeit cells B and C did not include these safety devices. This leaves the cell without protection from external short-circuit and over-charge.
- Cell A had an NCA (nickel-cobalt-aluminium oxide) cathode. Cell B, which was identically labelled including the brand and part-number, was found to have an NMC (nickel-manganese-cobalt oxide) cathode. While not inherently more hazardous, the discrepancy in chemistry reinforces that Cell B is a counterfeit cell.
- Cell A had a separator with consistent porosity (required to allow Lithium ions to pass between the anode and cathode during charge and discharge) and was alumina-coated on one side. The coating improves the thermal stability of the separator, making it less prone to shrink at high temperatures, thereby helping to prevent internal short-circuits. It also helps “wettability” of the separator, helping to ensure uniform distribution of electrolyte throughout the cell (good wettability of the separator enables the electrolyte to soak rapidly into the layers of the jellyroll during cell manufacture). Cells B and C had no such coating on the separator. Cell B’s separator had almost non-porous areas, while Cell C had non-uniform distribution and lower porosity. Both are therefore prone to non-uniform current distribution across the area of the electrodes. This reduces cell capacity and can cause hot spots or localised lithium plating which in turn can lead to thermal runaway.
- Cell A’s anode and cathode showed a homogeneous distribution of active material, with quite uniformly sized particles. Cells B and C displayed non-uniform distribution and large agglomerations of active material and binder, indicating poor manufacturing process control. The agglomerates can lead to non-uniform distribution of lithium between the particles, which could contribute to issues such as lithium-plating on larger anode particles. This in turn can lead to thermal runaway.

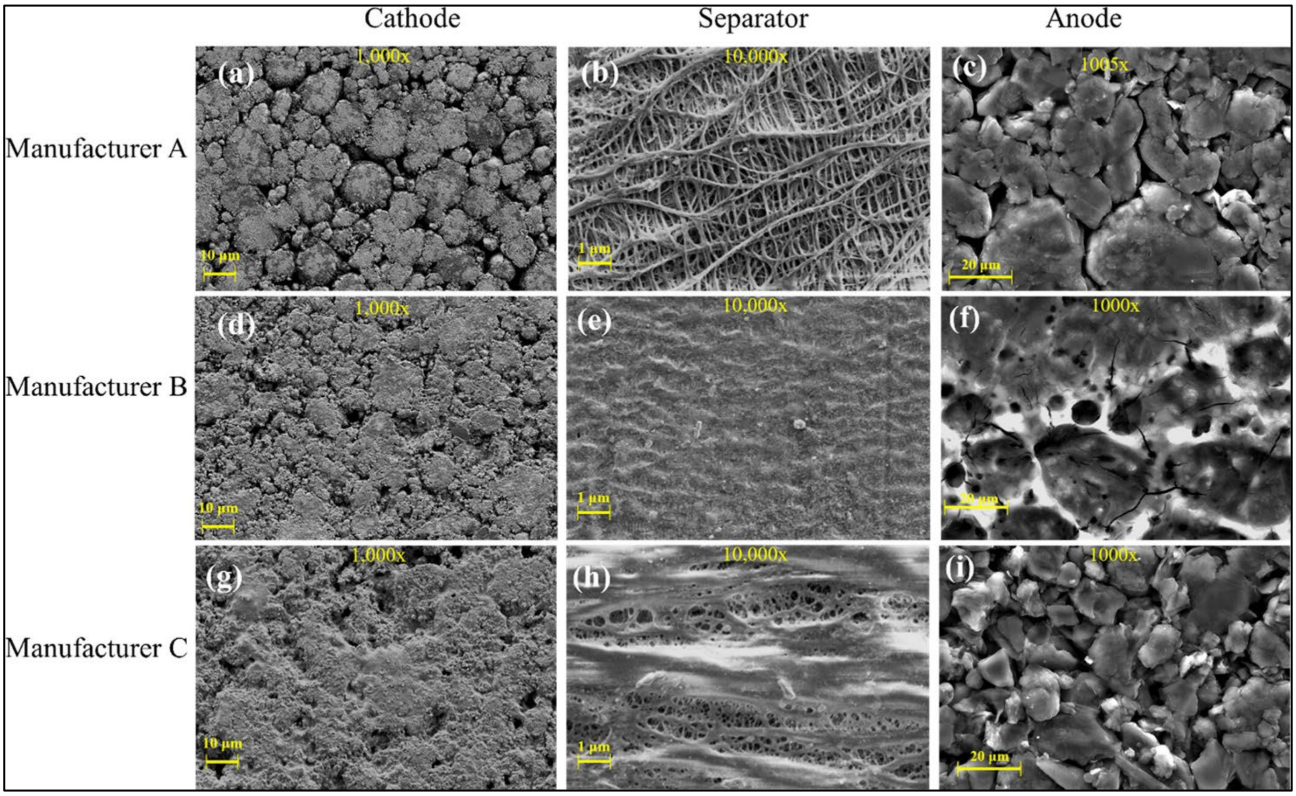


Figure 23: SEM micrographs of materials from fresh cells from three manufacturers (Joshi et al., 2023)

Unsurprisingly, when the cells were exposed to external short-circuit or over-charge, major differences in outcomes occurred. Cell A's PTC and CID devices effectively protected the cell in both tests, preventing excessive temperatures. Cells B and C both experienced excessive temperatures, and in some cases thermal runaway, flames and/or explosion.

The cells purchased and tested by UL for this study were not explicitly associated with any PLEV battery. They were obtained as individual cells from various vendors.

There have been claims of counterfeit cells in PLEVs for several years, although rigorous evidence of this is hard to find. Some in the bicycle retail industry (Lange, 2021) have claimed to have evidence that counterfeit PLEV battery packs are being advertised as containing cells from established manufacturers, but in fact contain lower quality, lower capacity cells.

In early 2023, a US consortium organisation started a project to investigate e-bike fires (Soteria Battery Innovation Group, Apr 2023). As part of this project Soteria has purchased new OEM e-bike batteries and compatible third-party e-bike batteries and has disassembled them to investigate the differences. Soteria later announced interim results of the study (Soteria, Jun 2023), in which they claim two of the battery packs contained cells strongly suspected to be counterfeit. Soteria has not yet published evidence for their claims, although a further update was provided in a February 2024 press article (Batteries and Energy Storage Technology magazine, 2024). However, during the Consumer Product Safety Commission hearing on Lithium-ion battery safety (US CPSC, Jul 2023), Drew Pereira, Research and Development Manager at Soteria claimed that the suspected counterfeit cells had the same labelling but very different performance and design.

WMG has purchased and conducted teardown analysis of e-bike and e-scooter batteries during the second half of the current project. As part of that work, WMG has aimed to identify the origin of the cells used in the batteries (see Section 10.3.8 of this report).

3.11 Battery Safety Malpractice: Poor Busbar Material & Welding

The cell-to-cell busbars carry the electric current between the cells in series and parallel. In PLEV batteries, they are usually connected to the positive and negative terminals of the cells by spot-welding. To minimise the heat-generation in the busbars, they should have low electrical resistance. The resistance is a result of both the busbar dimensions (cross-sectional area and length) and the material used. Copper has the best electrical conductivity of common busbar materials, around four times better than nickel, and is also cheaper. However, steel, which has electrical conductivity only around one eighth that of copper, is also around one tenth the price of copper. There is therefore a strong cost incentive for manufacturers to use steel.

In a 250 W PLEV, such as most e-bikes, the current in the busbars is generally low (for a 36 V battery, 250 W power requires approximately 7 A current). For these applications, steel may be acceptable as a busbar material, despite its relatively poor electrical conductivity. However, for higher power PLEVs with inadequately designed busbars, it is likely that the heat generated in steel busbars will be excessive: The heat from the busbars may be conducted into the cells, causing hotspots near the terminals, which may accelerate ageing and even risk thermal runaway. This is also a risk if e-bikes are de-restricted to bypass the 250 W power limit, or if the existing 250 W limit is significantly raised.

The choice of busbar material must also consider weldability and corrosion resistance. Steel is prone to corrosion unless the surface is protected. For example, nickel plated steel is sometimes used in e-bike battery busbars (Toll, 2019).

The welding of the busbars to the cells is also critical. The spot-welds typically used in PLEV batteries have a very small cross-sectional area, so even though the current is quite low, the current density is locally high where it passes through the welds. If the weld quality is poor, then the heat generation from the current passing through the weld may be conducted into the cells, causing hotspots near the terminals, which may accelerate ageing and even risk thermal runaway. If the weld energy is too high, there is a risk of breaking through the thin casing of the cell, with the risk of electrolyte leakage and corrosion inside the cell. This can rapidly degrade the cell, leading to thermal runaway.

Weld quality is dependent on numerous factors, such as the cleanliness and flatness of the metal surfaces, the pressure applied between the busbar and the cell during the weld, and the duration and energy of the spot weld. Achieving consistent quality is best achieved with a robotised process, which controls and monitors critical factors. In cheaper PLEV batteries, and in most repaired or remanufactured batteries, the spot-welding is done manually (Heskon BV, 2022), which leads to far greater variability in position and quality, and consequently a greater risk of thermal runaway.

3.12 Battery Safety Malpractice: Inadequate BMS

Below are some examples of poor practices associated with the BMS:

- Incorrect Voltage, Current or Temperature Limits in Software.
- Absence of temperature measurement.
- Absence of cell balancing.
- Lack of redundancy (back-up) in safety circuits.
- Poor component selection.
- Poor BMS circuit-board layout (e.g. separation of circuits at different voltages).
- Lack of consideration of thermal design (susceptibility to over-heating)

- Inadequate testing and validation of the BMS software and calibration

Real product examples are discussed in Sections 10 and 11 of this report.

The abuse tests included in Type Approval (L-Category vehicles) and certain standards (e-bike and e-scooter batteries) aim to demonstrate whether the combination of active protection by the BMS and passive protection via a fuse provide adequate battery safety. However, they do not ensure that the BMS observes the precise limits specified by the cell supplier.

3.13 Battery Safety Malpractice: Replacement of BMS

As explained in Section 3.5.3.1, in some circumstances, to be effective the BMS must permanently disable the battery, as further charge or discharge presents the risk of thermal runaway. Some ill-informed repairers may interpret the symptoms as the BMS being broken or “bricked” and may simply replace the BMS to get the battery working again. In so doing, they may lose the critical data stored in the original BMS that resulted in the permanent disabling of the battery. The BMS may also store other historical data, for purposes such as lifetime prediction, which will also be lost if the BMS is replaced.

In some situations, there may be a legitimate reason to replace the BMS. A responsible and competent supplier will ensure that there is a means of transferring the historical data from the old BMS to the new BMS, but a less sophisticated, lower cost BMS may not have this functionality. Equally, an inexperienced or negligent repairer may not take care to transfer the data.

Due to the safety-critical nature of some historical data stored in the BMS, it is important that BMS replacement should only be conducted by a suitably qualified person, following the manufacturer’s instructions. Replacing a BMS and ensuring that it meets the original functional requirements is not straightforward and requires carefully considered tests after the hardware is replaced.

3.14 Battery Safety Malpractice: Bypassing BMS

Section 6.2.2 of this report describes the 250 W power limit imposed on e-bikes by the Type Approval exemption. One potential unintended consequence of is that some consumers may desire greater power output. The power limits in a PLEV may be implemented by the BMS, the motor controller, or both. The BMS power limits exist primarily to protect the battery cells from over-current but may also be used to implement the 250 W limit to comply with the Type Approval exemption.

To independently implement battery current and/or power limits, the BMS must have:

1. A sensor to measure the battery current.
2. An actuator to limit or cut-off the battery current, such as a MOSFET switch.

The functions above can each be implemented on either the positive or negative side of the battery. The physical implementation varies between different BMS suppliers. Typically, the current sensor may be on the positive side, and the MOSFET switch on the negative side. Figure 24(a) shows a common example where the BMS has separate MOSFETS to separately switch the charger current and motor current.

There are many examples of internet videos demonstrating how to bypass the BMS limits. For example, in Figure 24(b) the negative wire to the motor has been cut and re-joined to the battery wire, bypassing the BMS MOSFET.

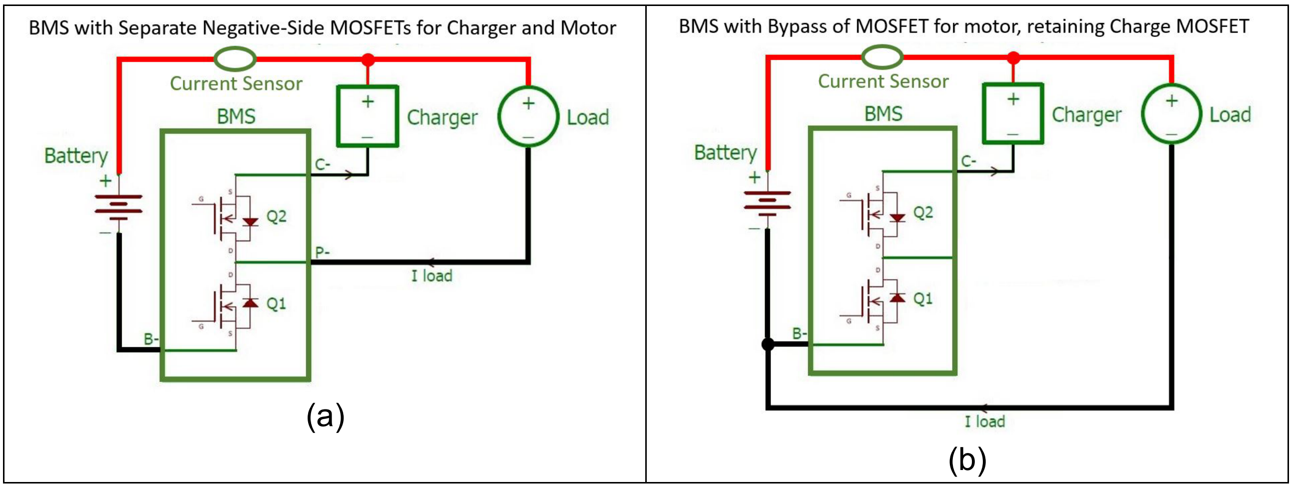


Figure 24: Example of Tampering to Bypass BMS Discharge Limits (image adapted from van Dalen, 2023)

In the example in Figure 24(b), the BMS current sensor will continue to measure both charge current and motor current, and it will retain the ability to switch off the charger current to prevent over-charge, but it is not able to switch off the motor current to prevent discharge under-voltage or over-current. Some e-bike and electric motorbike builders promote this as a means of allowing the e-bike or e-scooter to deliver more power, on the assumption that BMS discharge limits are not as important as charge limits (Moser, 2022. Note: This video includes actions which are likely to compromise the safety of a battery and must not be replicated).

Whilst it is true that charging over-current or over-voltage is generally more likely to lead to thermal runaway than over-discharge, it is not safe to bypass the BMS limits.

A second example of bypassing the BMS is for the purpose of “recovering” a deep discharged battery. As explained in Section 3.5.3.1, the BMS should prevent charging of a battery with any cell that has been deep discharged. However, it is easy to find examples of online videos demonstrating how to bypass the BMS to charge a deep discharged battery (doit_vehicles, 2022. Note: This video includes actions which are likely to compromise the safety of a battery and must not be replicated). In this example, at least two parallel cell groups were measured at below 0.1 V, which means there is a significant risk of copper dissolution leading to copper dendrites when the battery is recharged. The video shows how to charge the battery, by bypassing the BMS on both the positive and negative sides. Once the battery has been recharged to a certain level by bypassing the BMS, the BMS allows the battery to be charged via the normal charger port. This indicates that the BMS software did not permanently prevent charging, as it should have done, but rather only prevented charging as long as the cell voltages were below a threshold.

Further examples of malpractice and wrong information are shown in the same example:

- The presenter connects two chargers in parallel, one bypassing the BMS and the second via the normal charger port. This means that the cells are being charged with double the intended current, but the BMS is unaware of this, since one of the chargers is bypassing the BMS current sensor.
- The presenter claims that it is acceptable to recharge deep discharged cells if they are from a “quality” supplier. This is not true: a lithium cell is prone to copper dissolution when deep discharged, irrespective of the cell quality.

3.15 Summary of Factors Affecting Battery Safety

Section 3 of this report has covered the fundamentals of single-cell thermal runaway, thermal propagation between multiple cells in a battery pack, the severity, likelihood and means of detection of both of these phenomena, and some forms of malpractice that can worsen the severity or likelihood, such as counterfeit cells, inadequate battery management systems, and bypassing of BMS protections.

It is clear from this analysis that the potential root-causes of PLEV battery fires are diverse and complex. Many of the cell-level causes are strongly dependent on design and manufacturing quality, which inherently involves variation (tolerances) in the key parameters of materials, components, sub-assemblies, complete cells and battery packs. A typical PLEV battery contains upwards of thirty cells, and any one cell with a defect could cause a devastating battery fire. Given that such cells are typically produced in quantities of millions or even billions per year, it is impossible to eliminate such issues, but likelihood of defects can be minimised by meticulous quality control. Furthermore, cell defects can develop during the life of the cells, as a byproduct of the charge/discharge, shock/vibration and other factors that the cells experience.

It is therefore crucial to accept that:

1. It is inevitable that a small proportion of cells will contain safety critical defects.
2. Because production defects may be rare, even in sub-standard cells, certification tests on a small quantity of cells and batteries cannot reveal all such flaws.
3. Defects that emerge during the life of the product cannot be detected with tests that are performed only on as-new examples, so even 100% testing of cells and batteries at the end of their manufacturing process will not eliminate all risk.

For this reason, both the cell and the battery pack must have features to mitigate against single-cell thermal runaway and thermal propagation. It is primarily these mitigations that can be effectively proven through standardised tests in Type Approval or Standards.

The overview of academic literature that has been presented here mentions only a very small fraction of the research that has been conducted worldwide on battery safety. Several summary reviews of such research exist in the academic literature. A meta-review, covering a broad range of Lithium-ion battery safety research and input from experts in several industries to identify priorities for further research, was compiled by Bravo Diaz *et al.* (2020) and is recommended as a source for further reading.

4 Background on Battery Chargers

The statistical evidence from real world fires, presented in Section 2, shows that many of the severe PLEV battery fires tackled by fire brigades occur when batteries are being charged. The academic literature, reviewed in Section 3, confirms that the severity and likelihood of battery fires tends to be higher when they are fully charged, and potentially hazardous phenomena such as lithium-plating occur during charging. This section looks at the technology of chargers, and how they interact with the battery, to demonstrate that battery safety is a system issue: It depends on the battery itself, but also the charger that is used with the battery, and the degree to which the battery can be susceptible to reasonably foreseeable misuse by consumers.

Consumers of today are well accustomed to charging the batteries of numerous devices, from mobile phones and laptops to power tools, lawnmowers and bike lights. Almost all these devices now use Lithium-ion batteries, while older ones may have used Nickel-Cadmium (NiCad), Nickel Metal-Hydride (NiMH) or lead-acid (PbA) batteries.

These are all examples of “secondary” cell chemistries, meaning they are rechargeable, and distinct from “primary” cells which are not rechargeable, such as the replaceable cells used in a wristwatch or a TV remote control. Since secondary cells are intended to be rechargeable, the devices that use them require a charger, which converts the 230 V_{ac} mains alternating current supply to the direct current supply, at the appropriate voltage needed to charge the battery.

In some cases, the battery charger is referred to as a power supply. This term is broadly used for devices which are expected to be in use while they are being charged from the mains supply, for example laptop computers.

In other cases, the device will rarely, if ever, be in use while it is being charged from the mains supply. For these devices, the term battery charger is used. PLEVs are a good example of devices which are not used when the battery is being charged.

Each cell chemistry and each specific battery type has different requirements for charging. Due to the proliferation of devices that many consumers own, they often have multiple chargers that are outwardly similar to one another but may have different electrical specifications and different functionality.

In the case of multi-cell Lithium-ion batteries, such as those in PLEVs, the battery should always have a BMS, which monitors the battery and should be able to enable and prevent charging, by opening or closing a switch in the charging circuit of the battery.

4.1 Charging Protocol

The charging protocol describes how the voltage and current supplied by the charger vary during the charging process, from when the battery is discharged to fully charged. Numerous protocols exist, but the most common used for charging Lithium-ion batteries in consumer products is “Constant Current – Constant Voltage” (CC-CV). This describes a two-phase protocol:

1. In the first phase, the charger maintains a constant current (CC), during which time the voltage increases progressively, until the upper voltage limit is reached. The changing voltage is a result of the voltage vs. SoC curve of the battery itself (see Figure 25).

2. In the second phase, the charger maintains constant voltage (CV), so that the upper voltage limit of the battery is not exceeded. During this phase, the current decreases progressively, until it reaches a very low level, at which time the charger stops charging. At this point, the battery is deemed to be fully charged.

The CC-CV charging protocol is simple to implement, with a minimum of complexity in the charger and it suits the characteristics of Lithium-ion cells well. It is illustrated in Figure 26.

4.2 Charging Voltage

As explained in Section 4.1, the voltage varies during the charging process. The only important voltage value for charging is the upper voltage limit of the battery, or more accurately the upper voltage limit of the cells. In most PLEV batteries, using cell chemistries such as NMC (see Section 3.4), the cells have an upper voltage limit of around 4.2 V. If the battery comprises ten cells connected in series, then the upper voltage limit of the battery is 42 V. A small number of UK PLEVs use the LFP chemistry, which has a maximum cell voltage of around 3.6V.

The upper voltage limit of the cells is safety-critical, and results primarily from the stability limit of the electrolyte and the cathode material in the cells. The electrolyte is the medium that allows the Lithium ions to be transported from the cathode to the anode during charging, and from anode to cathode during discharging. The electrolyte should remain chemically inert during both charging and discharging. However, like any chemical, it only remains stable and inert over a limited voltage range. Similarly, the cathode material has a voltage stability limit. 4.2 V is the typical stability limit of the electrolytes and cathode materials used in Lithium-ion cells. Above 4.2 V, the electrolyte may start to decompose, and the cathode material will start to undergo irreversible structural changes (Guo, K. et al., 2022). These chemical changes can produce gases and heat. The higher the over-voltage, the faster the reactions, and the greater the gas and heat production. A small over-voltage is likely to mainly impact the cell life, but if it occurs repeatedly or if the over-voltage is large, it can lead to thermal runaway.

On-line marketplaces advertise Lithium-ion chargers with a wide range of voltage outputs, and with a selection of charging connectors (see example in Figure 30). This makes it easy for consumers to purchase a charger that has a plug compatible with their battery, but with a voltage output that is not suitable for the battery.

4.3 Charging Current

Most battery chargers supplied with PLEVs deliver a charging current of 1-6 A. The capacities of e-bike and e-scooter batteries vary widely from approximately 2.5 Ah (Swytch Technology Ltd., Jan 2024) to more than 25 Ah (Unit Pack Power Co., Ltd., no date).

The charge or discharge current of a battery is often expressed as C-rate. This is the current (in Amps) expressed as a fraction of the battery capacity (in Amp-hours). For example, a 1 C-rate charge implies that a fully discharged battery (0% SoC) would reach full charge (100% SoC) in 1 hour, while a 0.1 C-rate charge would require 10 hours to reach full charge. C-rate is frequently used by battery scientists and engineers to express how fast the battery is being charged or discharged. In the context of PLEV batteries, a 2 A charger current can represent anywhere from less than 0.1 C-rate (for a 25 Ah battery) to almost 1 C-rate (for a 2.5 Ah battery), depending on the battery it used for, with a resulting charging time from more than 10 hours to as little 1 hour.

However, it is also possible to find fast-chargers capable of charging a PLEV battery at up to 20 A and beyond (Battery & Accessories Store, no date). If used with anything other than the largest battery capacities, this would be likely to significantly exceed the battery's charging current limit.

For many users, fast charging is not a priority since they can charge their battery over a period of several hours between rides, often overnight. However, for some users, fast charging may be appealing, as it would enable them to recharge and use their PLEVs more frequently.

The maximum charge limit of the battery must take account of the individual limits of all the components in the charging circuit, including the cells, cell-to-cell busbars, internal cables, BMS and charging connector. Charging a battery at a current exceeding its design limit can cause serious safety concerns.

- Exceeding the cell charging current limit risks over-heating the cells and could cause lithium plating on the anode in the cells. This can lead to lithium dendrites, which can pierce the separator between the anode and cathode, causing internal short-circuits, which can then lead to thermal runaway.
- Exceeding the current limits of the conductors (busbars, cables, connectors) can lead to over-heating of these components. This can lead to melting of plastic insulator materials, compromising the electrical safety. The excessive heat may also be conducted into the cells, leading to thermal runaway.
- Exceeding the current limits of the BMS components, such as the charging MOSFET, can damage them, leading to short-circuit of those components. This means that the BMS is unable to switch the charging current off, removing a crucial layer of safety which normally prevents over-charging of the cells. This can lead to thermal runaway.

4.4 Charger Labelling

The European / UK standard for chargers is BS EN IEC 60335-2-29:2021+A1:2021 (BSI Group, May 2022). This requires chargers to be labelled with, amongst other items:

- Rated DC output voltage (output voltage assigned by the manufacturer)
- Rated DC output current (output current assigned by the manufacturer)

The definition of how to determine the voltage and current labelling is therefore left to the manufacturer, which invites inconsistencies which are likely to confuse consumers. This is discussed further in Section 10.3.3 of this report.

WMG suggests that chargers should be labelled with the maximum charging current and maximum charging voltage, as described in Sections 4.2 and 4.3 above, to ensure clear and consistent information for consumers.

4.5 Comparison of Lithium-ion and Lead-Acid Battery Charging

The main focus of this report is Lithium-ion batteries, but lead-acid batteries persist in some applications, so many consumers own a charger for a lead-acid battery, as well as Lithium-ion chargers. The two battery chemistries have very different charging requirements, which are compared in the sections below to illustrate the dangers of using the wrong specification of charger, using the example of a "12 V" battery. In this section, speech marks are deliberately used when stating the battery voltage to emphasise that this is a nominal figure, and that the actual voltage of the battery is rarely this exact value.

Most consumers are familiar with “12 V” lead-acid batteries which are used in almost all passenger cars and motorbikes, but Lithium-ion “12 V” batteries are also available.

4.5.1 Lithium-ion vs. Lead-Acid: Battery Maximum Voltage

A single lead-acid (PbA) cell has a maximum voltage of 2.12 V (Cortex Group, 2018). A “12 V” lead-acid battery comprises six PbA cells, so the maximum voltage = 6 x 2.12 = 12.7 V

A single lithium-ion cell’s maximum voltage depends on the specific Lithium-ion chemistry:

- LFP has a maximum cell voltage of approximately 3.6 V (Tran *et al.* 2021).
- NMC has a maximum cell voltage of approximately 4.2 V (Tran *et al.* 2021).

A “12 V” Lithium-ion car battery typically uses either:

- Four LFP cells in series, so the maximum voltage = 4 x 3.6 V = 14.4 V, or
- Three NMC cells in series, so the maximum voltage = 3 x 4.2 V = 12.6 V.

A summary is shown below in Table 4 and Figure 25.

Table 4: Comparison of Lead-acid and Lithium-ion Battery Maximum Voltages

Cell chemistry	Lead-Acid (PbA)	Lithium-ion LFP	Lithium-ion NMC
Maximum cell voltage	2.12	3.6	4.2
Number of cells in series for “12 V”	6	4	3
Maximum battery voltage	12.7	14.4	12.6

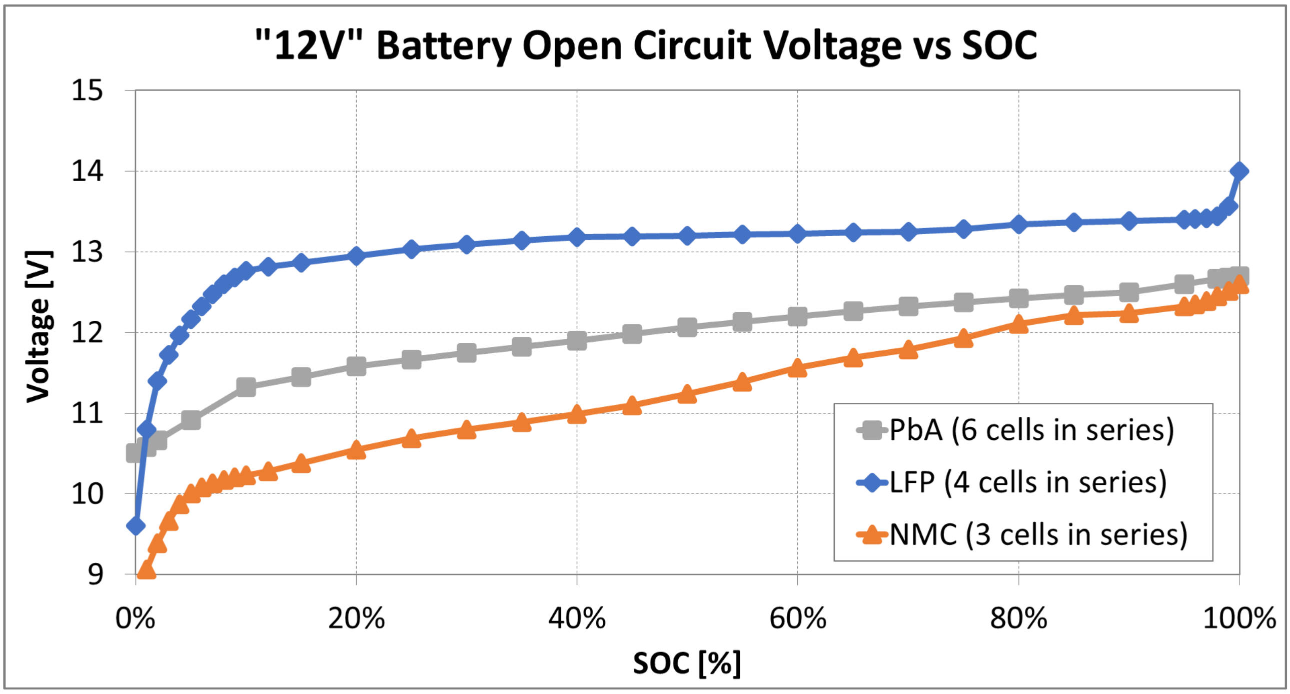


Figure 25: Comparison of Lead-acid and Lithium-ion “12 V” Battery Voltage vs. State of Charge (adapted from Tran et al. 2021 for LFP and NMC and Wikipedia.org, 2012 for PbA)

The importance of the data above is that the maximum charging voltage of “12 V” batteries differs between lead-acid and lithium-ion, and between different Lithium-ion chemistries. There is a significant risk that consumers assume that the maximum charging voltage of all “12 V” batteries is the same. The same risk applies to other commonly used nominal voltage values for PLEVs, such as “36 V” and “48 V”. These are convenient label values for manufacturers, but they can be misleading, with adverse consequences for safety.

4.5.2 Lithium-ion vs. Lead-Acid: Battery Maximum Charging Current

Lithium-ion cells can typically be charged at a much higher C-rate than PbA cells, so the fastest charging time can be much shorter.

- PbA typically requires many hours to charge.
- Lithium-ion varies greatly, from 2-3 hours for many consumer cells to as little as a few minutes for cells that are specifically designed for ultra-fast charging.

The actual maximum charge current depends on the battery capacity and many other aspects of the design, as well as external factors such as temperature. Therefore, the maximum charging current differs between PbA and Lithium-ion, and between batteries of different specifications e.g. capacity.

The maximum charge current which the battery can accept also varies with state of charge (SoC). Generally, cells can accept greater charging current when they are at low SoC, and this gradually tapers towards zero as they approach 100% SoC.

In cold conditions, cells cannot accept as high a charge current as when they are at, for example, room temperature, to avoid growth of lithium dendrites on the anode which can cause internal short-circuits and thermal runaway (see Section 3.1). Similarly, at high temperatures, the charge current must be reduced to avoid the onset of side-reactions which could lead to venting and thermal runaway. As shown in Section 10.3.9 of this report, the datasheets of cells used in PLEV batteries typically prohibit charging when the cells are above 45 °C or below 0 °C.

The safety of chargers must be considered not only for those supplied with the battery or PLEV, but for those purchased separately. In either case, it is likely that the charger has been developed and manufactured by a different supplier than the PLEV battery. This is true for all but one of the chargers supplied with the products investigated in Sections 10 and 11 of this report. This means that even the chargers supplied with batteries and PLEVs are likely not developed specifically for those products.

Chargers are labelled with a nominal output current, and it is important that this should be less than or equal to the maximum charging current of the battery, to ensure that during normal charging, the current delivered by the charger is within the limits of the battery, and therefore the BMS can allow charging to proceed. Nevertheless, since the battery current limit depends on cell temperature and the charger itself may have no information on the cell temperature, the BMS must be responsible for limiting or inhibiting charging current when necessary to protect the cells. For example, if a consumer tries to charge the battery at below 0 °C, the charger may not prevent this, so the BMS must act to prevent it, to comply with the cell datasheet limits mentioned above.

4.5.3 Lithium-ion vs. Lead-Acid: Battery Tolerance to Over-Voltage

Avoiding over-voltage is safety-critical for Lithium-ion cells, as it can cause cells to become unstable. When a Lithium-ion cell is charged, the charger should reduce the charging current as it approaches the maximum voltage, to prevent over-voltage. The charging normally follows a protocol known as Constant Current – Constant Voltage (CC-CV), described in Section 4.1, and illustrated in Figure 26.

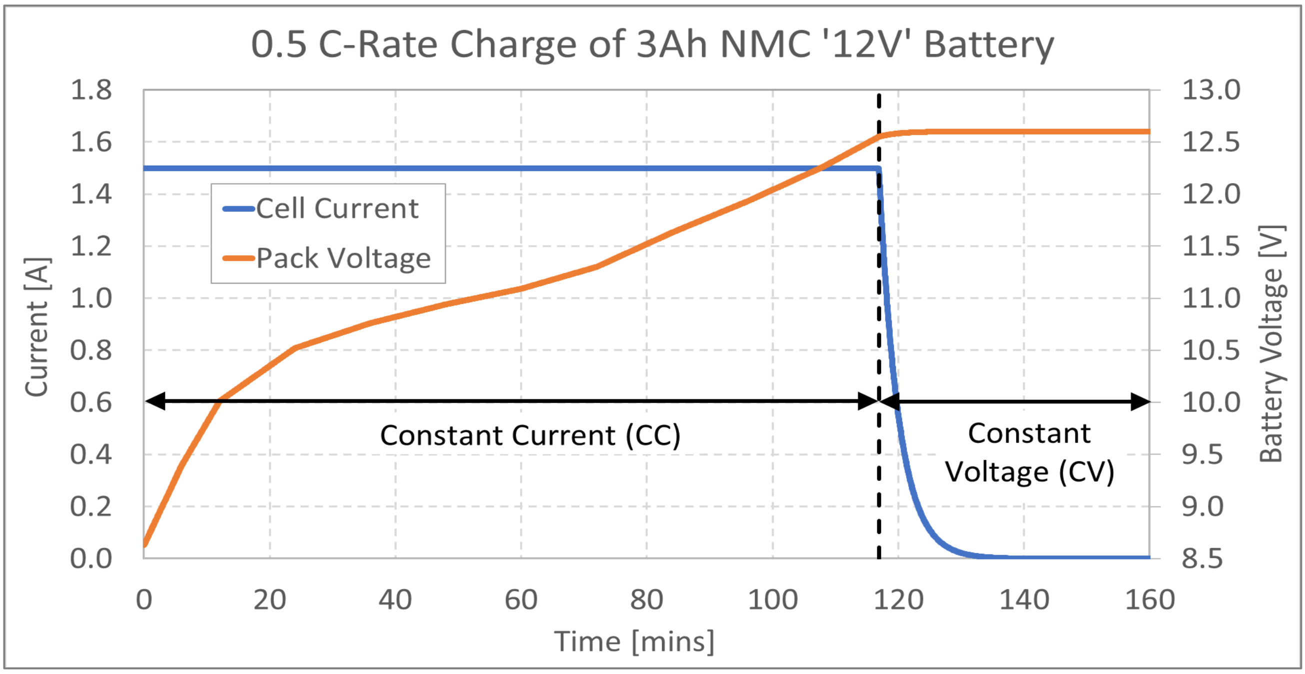


Figure 26: Example of CC-CV Charging of a Lithium-ion Cell

By contrast, PbA cells are quite tolerant to over-voltage. 12 V PbA chargers typically charge the battery up to 14.4 V for a limited duration, and then reduce to a “float” or “trickle” voltage of around 13.2 V, which is still above the notional maximum of 12.7 V. Some lead-acid chargers continue the “trickle” charge indefinitely, with no cut-off. Many feature a deliberate over-voltage feature (typically 2.5 V per cell, or 15 V for a “12 V” battery) to equalise the cells in series and remove sulphate from the PbA battery plates.

In most cars, the alternator, which serves as the battery charger when the engine is running, typically maintains the battery voltage at around 14.4 V.

If a charger (or alternator) which exceeds the maximum voltage limit of a Lithium-ion battery, or delivers an indefinite trickle charge, were used to charge the battery, it would likely create a hazardous situation that could lead to thermal runaway. It is therefore safety-critical that a charger for a Lithium-ion battery does not exceed the maximum battery voltage limit.

4.5.4 Lithium-ion vs. Lead-Acid: Cells of Differing Capacities

Even with high-quality cells, it is inevitable that the cells are not identical. One of the variables between cells is their capacity. For example, an 18650 Lithium-ion cell with a nominal capacity of 3.0 Ah may have a production tolerance between, for example, 2.8 and 3.2 Ah, equating to a difference of more than 10% between cells.

When a battery comprising cells connected in series is charged, the same current passes through each cell. If all the cells are fully discharged (0% SoC) at the start of charge, then towards the end of charge, the lowest capacity cell will become fully charged (100% SoC) first, while the highest capacity cell may still only be at, say, 90% SoC.

For Lithium-ion cells, it is safety-critical that they should never be over-charged. For an NMC Lithium-ion battery, the charging should be stopped when the lowest capacity cell reaches its maximum voltage (4.2 V), while the other cells will be at slightly lower voltage.

Figure 27 shows a simulated example of charging a “12 V” NMC battery, which comprises three cells in series, each with a slightly different capacity.

At the start of charging, all cells are at the same voltage, equating to 0% SoC. The charger follows a CC-CV profile, but accounts only for the total battery voltage, which is the sum of the three cell voltages. In accordance with Table 4, it limits the battery voltage to 12.6 V. However, due to the differing cell capacities, ranging from 2.8 to 3.2 Ah, the final cell voltages range from 4.1 to 4.3 V. The cell at 4.3 V has been over-charged to around 107% SoC. This illustrates how the cell voltage limit of 4.2 V can be exceeded by a simple charger which has no communication with the BMS, if the BMS does not intervene by opening a switch in the charging circuit. If this happens repeatedly or for extended durations, it may lead to thermal runaway of the over-charged cell.

For an LFP Lithium-ion battery, the maximum cell charging voltage is 3.6 V. Figure 25 shows that the voltage of an LFP cell rises sharply as it approaches 100% SoC. Beyond 100% SoC, the voltage curve continues at a steep gradient, meaning that even a small amount of over-charging can cause a significant over-voltage. Because of this “hockey-stick” voltage curve, charging a battery, comprising cells of different capacities (or imbalanced cells), to the nominal battery maximum charging voltage can cause significantly worse cell over-voltage for LFP than for NMC batteries. This is illustrated in Figure 28, which shows a simulated example of charging a “12 V” LFP battery. In accordance with Table 4, the battery comprises four cells in series, and the charger maximum voltage is 14.4 V.

The spread of cell capacities is the same as in the previous NMC example, from 2.8 to 3.2 Ah, but the voltage curve of the LFP cells means that there is a much wider spread of final cell voltages, from 3.36 to 4.0 V, even though the sum of the four cell voltages never exceeds the nominal limit of 14.4 V from Table 4. The cell with the lowest capacity exceeds the cell voltage limit of 3.6 V by a large margin. In terms of state-of-charge, 4.0 V represents only approximately 104% SoC, but it presents a serious safety risk, especially if it happens repeatedly or for extended durations. Conversely, the cell with the highest capacity (Cell #2) only reaches 91% SOC at the end of the charge shown in Figure 28.

As illustrated in Figure 27 and Figure 28, if the battery contains cells of different capacities, it is likely that a charger will cause over-voltage of some cells (unless the BMS intervenes), even if the charger respects the nominal battery maximum voltage. This is because the charger has no way to take account of the individual cell voltages.

To avoid this, there are three possible solutions, the first two of which should be implemented in all Lithium-ion batteries (recognised good practice, although not required by PLEV battery standards, see Section 6) and third of which provides an additional layer of protection against cell over-voltage:

1. The BMS interrupts charging, by opening a switch in the charging circuit, whenever any cell reaches the maximum cell voltage limit. If the cells are imbalanced, this means that most cells will never become fully charged, so the battery stores less energy, and therefore delivers less riding range.
2. The BMS implements cell balancing, with the aim that all the cells reach 100% SoC, as described in the next section. This should ensure that the battery is able to store the maximum amount of energy, and therefore deliver the maximum riding range.
3. The BMS has data communication with the charger, so that the charger is sufficiently informed of the cell voltages to be able to prevent over-voltage.

As explained in Section 4.5.3, lead-acid cells are relatively tolerant to over-charge. Therefore, the issue of differing PbA cell capacities can be handled without incurring safety issues in normal operation, without the need for BMS cell balancing or BMS to charger communication.

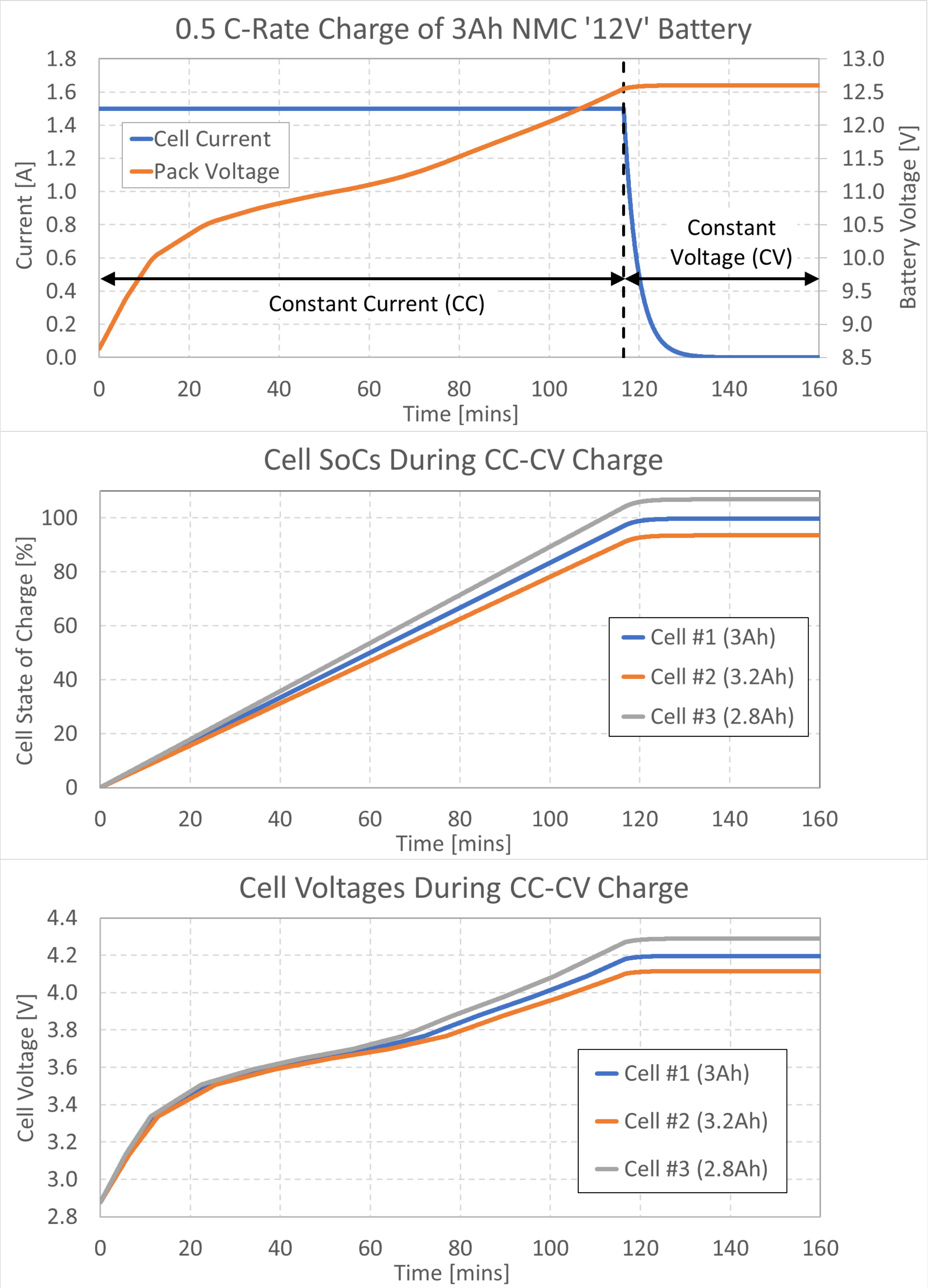


Figure 27: Cell Voltages for an NMC “12 V” Battery Comprising Cells of Differing Capacities

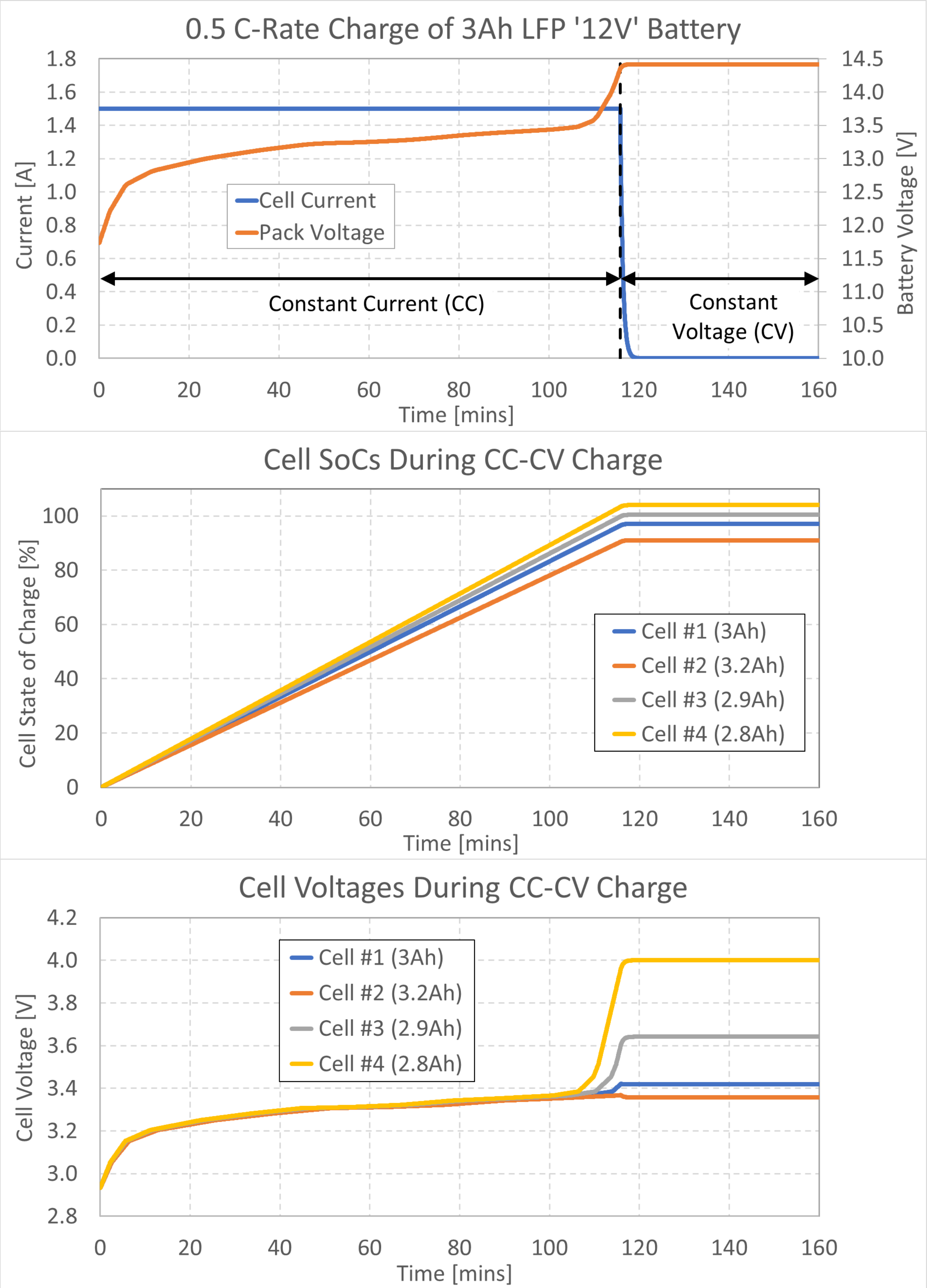


Figure 28: Cell Voltages for an LFP “12 V” Battery Comprising Cells of Differing Capacities

4.5.5 Lithium-ion vs. Lead-Acid: Equalisation of Cells in Series

A well-engineered Lithium-ion battery BMS will incorporate a balancing circuit. The aim of the balancing circuit is to allow all the cells to be charged to 100% SoC. Without this, the amount of energy that the battery can deliver in discharge is compromised.

Most commonly, the balancing is done passively. This means that the cells which reach maximum voltage first are slowly discharged through a resistor, to dissipate some of their charge as heat. This is wasteful of energy but is commercially attractive because the electronic circuit design is relatively inexpensive (Monolithic Power Systems, Inc., 2024; Andrea, 2010). A more sophisticated BMS may use active balancing. This means that the excess energy from cells at higher voltage is transferred to cells that are at lower voltage. This is more energy-efficient, but the circuit design is complex and more expensive. WMG has experience of Lithium-ion applications across multiple market sectors and has rarely seen active balancing used in practice. It is also not seen in any of the PLEV batteries investigated in this work (see Section 10.3.16 of this report).

Typically, the balancing circuit in a BMS is only sized for a low discharge current, for example 100 mA, because increasing the balancing current requires larger, more expensive components. Even with a balancing circuit, however, over-voltage of cells is possible, if the current from the charger exceeds the current of the balancing circuit. Figure 29(a) shows a simulation of the same NMC battery shown in Figure 27, but with a balancing circuit which starts to discharge a cell at 100 mA as soon as it reaches 4.2 V. However, when this first happens to cell #3, the current from the charger is still 1.5 A, so the net current into the cell is 1.4 A. As a result, the cell voltage still peaks at 4.28 V, and only slowly returns to the 4.2 V limit, once the charger current falls below 100 mA. Throughout the time that the cell is above 4.2 V, unwanted side reactions are more likely, with an increased long-term likelihood of thermal runaway.

A more sophisticated BMS balancing algorithm is simulated in Figure 29(b). In this example, the BMS uses historical data to estimate the capacity of each individual cell, so it knows that cell #3 has lower capacity. The BMS therefore starts to balance cell #3 from the very start of the charging process. It still only employs 100 mA balancing current, but by using it from the start of charging, it prevents cell #3 from exceeding 4.23 V, even though it still has no data communication to the charger.

Nevertheless, if a charger with no data communication from the BMS is to be used safely, the balancing capability of the BMS and the charging current of the charger must be compatible. The battery manufacturer should therefore ensure that the maximum charge current, stated on the battery label, is compatible with the balancing circuit capability for a reasonable worst-case assumption of imbalance between cells. If the consumer then uses a charger which does not exceed the maximum charge current stated on the battery label, then there should be no issues with cell over-voltage in normal operation. However, in the example shown in Figure 29(b), if a fast charger were used, then it would overwhelm the ability of the BMS to balance the cells, resulting in over-voltage similar to that seen in Figure 29(a).

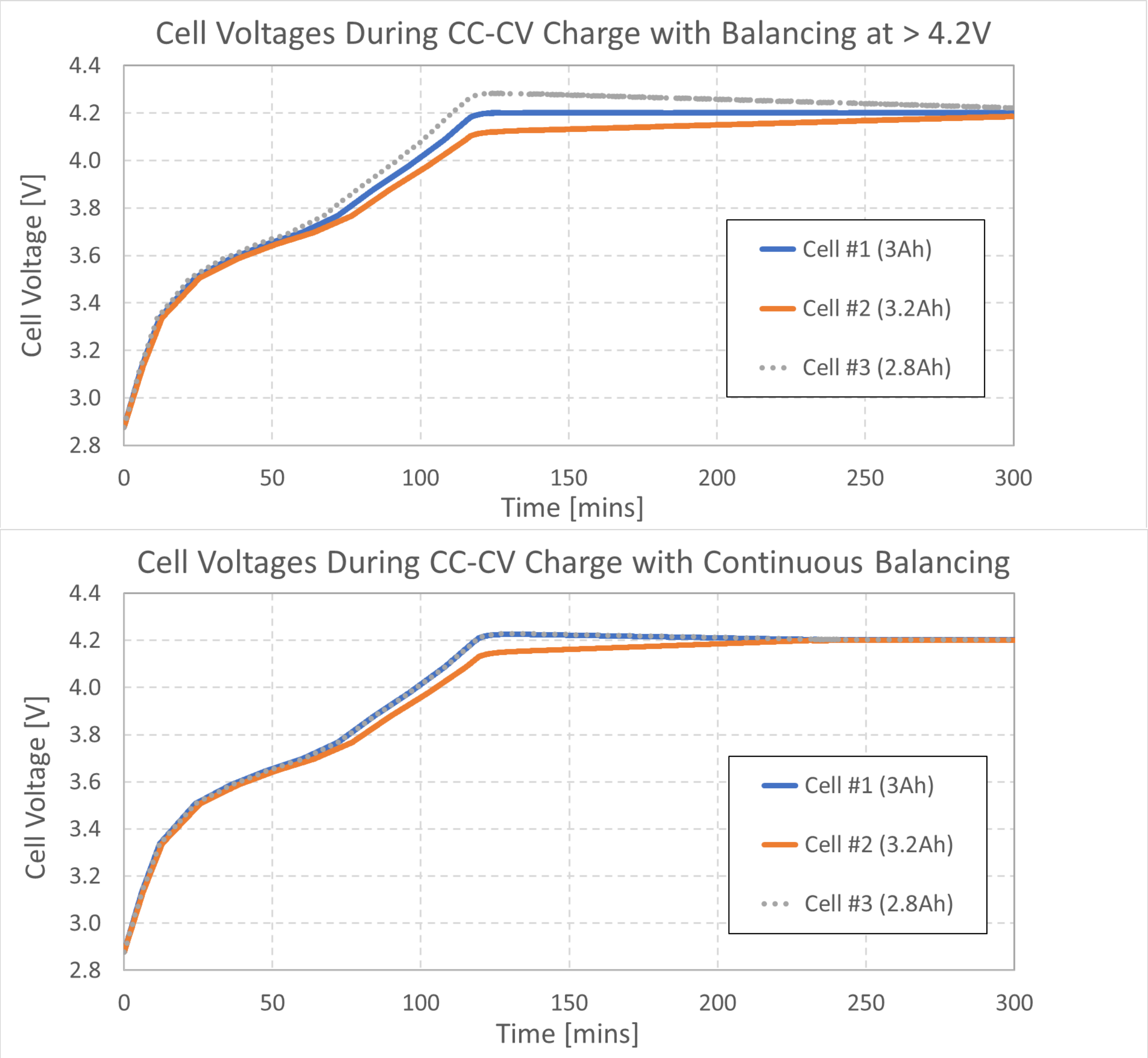


Figure 29: Comparison of Two BMS Balancing Algorithms: (a) Balancing starts when a cell reaches 4.2 V; (b) Balancing starts from the beginning of charging, based on BMS memory of historical cell capacities.

The technically preferable solution is to employ a “smart” charger, meaning that the charger has a means of data communication with the BMS, allowing the BMS to dictate the maximum voltage and current delivered by the charger. Various communication protocols exist that could fulfil this purpose, such as Controller Area Network (CAN, BSI Group, Sep 2016) or Local Interconnect Network (LIN, BSI Group, Oct 2019), both commonly used in the automotive industry, or Universal Serial Bus Power Delivery Revision 3.1 (USB-PD, USB Implementers Forum, Inc., May 2021). During charging, the BMS would continually inform the charger of the maximum voltage amongst all the cells, and/or would specify the maximum charge current allowable, within the cell limits. The charger would respond by reducing the charging current to respect the cell limits. Not only would this ensure that the cells are never over-charged, but it would also allow the charger to use a higher peak charging current, to achieve shorter charging times where possible.

By contrast, because PbA cells are tolerant to over-charge, there is no need for a balancing circuit, and no need for the end-of-charge voltage to be tailored to the actual state of the individual cells in normal operation.

4.5.6 Lithium-ion vs. Lead-Acid: Battery Charging Summary

- PbA and Lithium-ion chargers have different maximum voltages.
- PbA and Lithium-ion chargers have different maximum charge currents, and in both cases the maximum current should be appropriate for the specific battery.
- Only PbA chargers should deliberately over-volt the battery (to around 2.5 V per cell, to equalise the cells in series and remove sulphate from the battery plates).
- Over-voltage of Lithium-ion batteries is a serious safety risk.
- The Lithium-ion BMS should include a balancing circuit to minimise imbalance between cells in series, and the maximise the useable capacity of the battery pack.
- Lithium-ion chargers should be chosen to ensure that their output current does not exceed the ability of the BMS to balance out the variation in capacity and SoC between the individual cells in series.
- To facilitate this, battery labels should state the maximum charging current, which should be specified by the manufacturer taking account of the capability of the BMS balancing circuit.
- BMS-to-charger communication can significantly further reduce the possibility of cell over-voltage, and could also be used to optimise overall charging time.

4.6 Charging Connectors

Charging connectors should be designed and manufactured to meet several requirements in addition to the need to transfer electrical current:

- The battery connector should prevent moisture ingress into the battery.
- It should be protected against corrosion of the electrical pins and other parts, both when connected and disconnected.
- When connected, the resistance of the electrical contact between male and female pins should be sufficiently low to avoid over-heating, throughout its lifetime.
- Once manually connected, it should have sufficient “holding force”, or a latching mechanism, to avoid unintended disconnection.
- It should withstand sufficient connect-disconnect cycles: The mechanical and electrical parts remain intact and functional for the life of the battery and charger.
- It should meet electrical safety standards

Although there are some connector types which are commonly used in the e-bike and e-scooter industry, there is no standardisation in western markets. Some commonly used connectors are shown in Table 5 below.

The cheapest connectors are those with only two pins, such as the DC2.1. Having only two pins (power and ground) usually means that there is no signal or data connection between the battery and the charger.

Some connectors such as the XLR and ST3 have a third pin, which allows a single signal wire, typically used for a thermistor, to inform the charger if the battery temperature is excessive, or for an interlock signal to ensure that the charger does not deliver voltage to the power pins until the connector is mated to the battery. However, some chargers with three-pin connectors only use the power pins, with the third pin unused.

Due to the proliferation of connectors, many after-market chargers are advertised as “universal chargers”, meaning that they are supplied with several connector adaptors and with a choice of multiple voltage ratings (see Figure 30). This greatly increases the likelihood of charging the battery with an incompatible charger.

Table 5: Examples of Common PLEV Charger DC Connectors

Connector Name	Image	Maximum Current
DC2.1		5 A nominal 2 A continuous advised
XLR		16 A nominal 4 A continuous advised
ST3		5 A continuous

Figure 30: Example of a Universal Charger, with Interchangeable Connectors and voltage ratings ranging from 29.4 V to 96.6 V (FengXingPeng Store, no date)

Some manufacturers of e-bike powertrains (battery, motor controller and motor), such as Bosch, Yamaha and Shimano, use proprietary charge connectors which are not shared with other companies. For example, Bosch currently uses a five-receptacle socket on the battery. The battery has only one socket, which is used either for charging or for connecting to the motor on the e-bike. The charger uses only three pins: power, ground and a 5 V pin, which is used to allow the battery to verify that the correct charger is connected. When the battery is on the e-bike, the final two pins are used for CAN serial data communication to the motor controller.

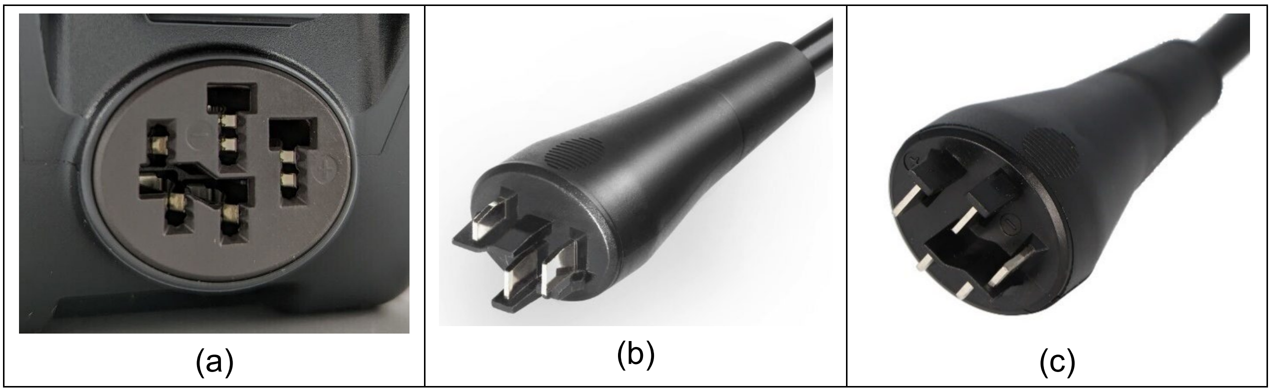

(a) (b) (c)

Figure 31: Bosch e-bike Connectors: (a) Battery 5-receptacle socket; (b) 3-pin plug; (c) 5-pin charging plug

As explained in Section 4.5.5, a data communication connection between the charger and the BMS may be used to allow the charger to adapt its behaviour to the state of the battery. In recent years, several companies have developed connector designs which allow for such a charger connection, but none has been widely adopted.

Rosenberger, a manufacturer of electrical connectivity products, developed the Power Data connector, RoPD ® (Rosenberger Hochfrequenztechnik GmbH & Co. KG, no date), which was adopted by the EnergyBus industry consortium (electricbike.com, 2013). This connector includes magnetic connector mating, with two power pins and four data pins. The power connection supports up to 60 V and 40 A current. The ingress protection rating (the ability to resist ingress of dust/particles and water) is claimed to be IP65 unmated and IP67 when mated, so is suited to outdoor use, and it is designed for 2,500 mating cycles.

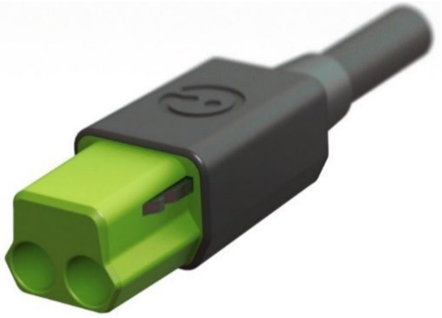
Amphenol, a manufacturer of electrical connectors, developed the DuraEV ™ connector (Amphenol Communications Solutions, 2022), comprising two power pins and up to six signal pins. The power connection supports up to 120 V and 70 A current. The ingress protection rating is claimed to be IP67 when mated, and when unmated via a rubber cap. It is designed for 10,000 mating cycles.

EnergyBus is a German-based membership organisation which developed a charger connector open standard, intended to be similar in ethos to the USB standard used for charging smaller consumer devices, and intended primarily for public charging points, rather than domestic usage (EnergyBus, no date). It uses the automotive CAN standard for communications between the BMS and the charger. They propose two different charging connectors, the first a two-pin plug for up to 60 V, and the second a three-pin plug for up to 120 V. The connectors use Near Field Communication (NFC) (nearfieldcommunication.org, 2017), whereby the communication from the charger to the vehicle is done without mating pins, but rather via a contactless method between the connector and the socket. NFC is covered in the standard BS ISO/IEC 18000-3:2010 (BSI Group, Nov 2010) which requires the devices to be within four centimetres of each other before they can transmit data, to prevent interference between similar devices in close proximity. In the EnergyBus connector, the main power transmission still relies on mating pins. The EnergyBus system assumes that the socket is on the public infrastructure, and the vehicle has the plug and cable. According to the Managing Director of EnergyBus, Hannes Neupert, experience in Germany with cables as part of the public infrastructure charger has shown that the cables only last around one year and are prone to vandalism. He also asserts that having the cable on the vehicle is the only way to ensure full interoperability (velobiz.de, 2023).

However, in WMG's view, this would add considerable weight, cost and complexity to any e-bike / e-scooter that uses the EnergyBus system, as the cable will need to be stowed on the vehicle when it is not in use for charging. This may be acceptable for rental fleet operators, who require high levels of durability and on-street charging, but consumers buying privately-owned PLEVs may prefer another solution. The EnergyBus system differs from the convention used by almost every rechargeable device that consumers are accustomed to using, from mobile phones to electric passenger cars, wherein the cable is separate from the device, or, as in the case of public chargers for electric cars, is part of the infrastructure. The EnergyBus system claims to be in accordance with PD CLC IEC/TS 61851-3-2:2023 (BSI Group, Jan 2024), but this standard also allows for the more conventional approach whereby the "EV supply equipment", i.e. the charger, is separate from the vehicle and has two cables: One to plug into the mains supply, and the other to plug into the socket on the vehicle or battery.

None of the connectors mentioned above has been accepted widely as a standard design for e-bike and e-scooter charging.

Table 6: Examples of PLEV Smart Charger Connectors

Connector Name	**Image**	**Maximum Rating**
Rosenberger RoPD ®		• Up to 60 V • Up to 40 A • 2 power pins • 4 auxiliary pins
Amphenol DuraEV ™		• Up to 120 V • Up to 70 A • 2 power pins • 4 auxiliary pins
EnergyBus		• Up to 60 V • Up to 60 A • 2 power pins • 4 auxiliary connections by Near Field Communication

PD ISO/TS 4210-10 (BSI Group, Jul 2020) dedicates almost half of its 134 pages to defining “non-proprietary” battery charging systems, meaning that the specification is intended to be adopted by multiple e-bike and charger suppliers to achieve interoperability. ISO/TS 4210-10 provides two distinct specifications, each of which includes both a connector design and a communication protocol.

The first of these, System A, was developed by the Japan-based membership association CHAdeMO, which also developed an automotive electric vehicle charging system which has been widely adopted. The ISO/TS 4210-10 System A connector uses five pins: Two are for charging power and ground, two are for communications, and the last pin is to detect connection between the battery and the charger.

In System A, the battery sends a voltage and current request to the charger, and the charger replies with an acknowledgement signal. The battery then confirms it is ready to charge, and the charger then replies with a “charge started” signal, whereupon it delivers the actual charging voltage and current on the charging power and ground pins. This allows the battery to control the output of the charger, to ensure that the charging voltage and current are within the safe limits of the battery.

The battery can optionally also send to the charger values for the battery capacity, maximum voltage, and the number of charge-cycles the battery has undergone. The charger sends data to the battery concerning the identity of the charger (such as manufacturer and serial number). The communication protocol also includes data for faults, such as over-voltage, and rules for handling communication errors.

The developer of the second specification, System B, is unknown to WMG. The connector uses only four pins: Two are for charging power and ground and two are for CAN signal communications. The protocol for the battery to control the charging voltage and current is superficially similar to System A, but in System B the battery not only sends the requested voltage and current, but also its measured voltage and current. This is to enable the charger to react to discrepancies between the values that it measures and the ones that the battery measures. In theory, the two devices should measure the same values, but in practice, small differences are inevitable due to sensor inaccuracy and other factors. Both systems aim to ensure that the charging voltage and current are within the safe limits of the battery, but System B may reduce the likelihood that the battery needs to disconnect the charger if it detects over-voltage or over-current, because the charger should continually adapt to the actual values measured by the battery. Furthermore, the resolution of the voltage and current signals in System B (10 mV, 10 mA) is ten times finer than in System A (100 mV, 100 mA), allowing for far more precise control. System B is therefore arguably a more robust protocol than System A, although the practical differences could only be determined through comparative testing.

In WMG’s view, before widespread adoption of either system, a thorough technical assessment of both systems would be required, with input from various industry stakeholders, followed by any agreed updates to the technical specifications.

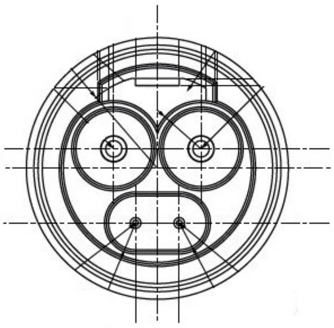
Both System A and System B are intended to allow charging voltages up to 60 V and charging currents up to 40 A, so theoretically could charge at up to 2.4 kW power.

60 V is widely recognised as a threshold distinguishing non-hazardous voltage (< 60 V) from hazardous voltage (>60 V). The implications of maximum voltage are discussed in Section 7.1.6 of this report.

As discussed in Section 4.3, most e-bike and e-scooter batteries currently do not allow charging current above around 5 A, so the 40 A limit of the ISO/TS 4210-10 specifications allows plenty of headroom for technological development towards faster charging.

The two connector types are shown in Table 7:

Table 7: ISO/TS 4210-10 Non-Proprietary Charger Connector Systems

Connector Name	Image	Maximum Rating
ISO4210-10 System A (CHAdeMO)		• Up to 60 V • Up to 40 A • 2 power pins • 3 auxiliary pins
ISO4210-10 System B		• Up to 60 V • Up to 40 A • 2 power pins • 2 auxiliary pins

Other non-proprietary battery-to-charger connection and communication standards already exist, such as the USB-C and USB-PD, developed by USB Implementers Forum, Inc. a non-profit corporation founded by the group of companies that developed the Universal Serial Bus specification (USB Implementers Forum, Inc., May 2021).

USB-C is a standardised 24-pin connector (see Figure 32), which will be mandated in the European Union for all mobile phones, tablets, digital cameras, games consoles and many other devices (European Council, 2022) sold from the end of 2024 and laptops from the end of April 2026 (European Commission, no date). This is enacted in European Union law in (EU) 2022/2380 (European Union, Dec 2022), known as the ‘common charger directive’, which is an amendment to Directive 2014/53/EU (European Union, 2014), known as the “radio equipment directive”. The common charger directive therefore only applies to equipment that intentionally transmits radio frequencies, such as Wi-Fi devices. The aim of this directive is to allow EU consumers to use a single type of charging cable, and even a single charger, to charge the majority of their mobile electronic devices.

The USB-C connector standard has existed since 2014, but the capability of the connector has been upgraded since then. In 2021, the USB-PD specification, which uses the USB-C connector, increased the power capability to 240 W (engadget.com, 2021), which is similar to the power output of many e-bike and e-scooter chargers. This power capability is only possible for charging at 48 V, whereas at 36 V it is limited to 180 W (USB Implementers Forum, Inc., no date), implying that the current is limited to 5 A. For higher charging power, it is possible to use two USB-C connectors in parallel on some devices. The specification allows the battery to control the output of the charger, in a similar way to Systems A and B in ISO4210-10 Annex C.

This means that the USB-PD is capable of meeting the charging voltage, current and power requirements of many existing PLEVs, and would offer most of the safety advantages of the ISO/TS 4210-10 Annex C non-proprietary charger specifications. However, the limitation to 48 V and 5 A means that there is likely no headroom to allow higher connector voltages and currents, unless multiple USB-C connectors are used. The standard USB-C connector is also not designed for outdoor use, although some suppliers have developed waterproof versions of the USB-C connector (Mouser Electronics, 2017). The USB-PD specification also requires that the cable attached to the USB-C connector has thicker-gauge wires within it, to deliver the 5 A current. The connector needs to contain a circuit to enable this higher current. Nevertheless, there is a small risk that manufacturers could sell such a connector attached to a cable that is not rated for this current, and the USB-C connector will not prevent them from doing so. Using an inadequately sized cable presents a risk of fire because of over-heating of the cable.

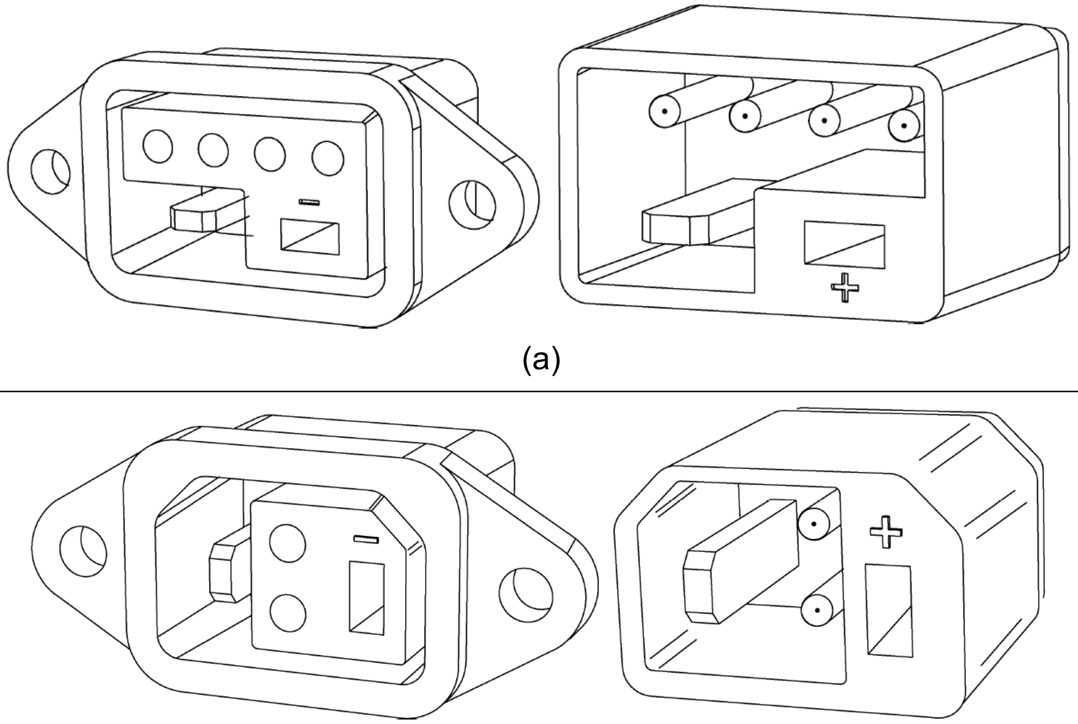
Figure 32: The USB-C (or USB Type-C) Connector

Whilst it would be very convenient for consumers if the USB-C or USB-PD standard were adopted for PLEVs, the risks outlined above must be considered. For this reason, WMG would not support any efforts that might be made to mandate USB-C or USB-PD charging for PLEVs unless these concerns are overcome.

Since work on ISO/TS 4210-10 was halted some time ago, it is not possible to make a definitive recommendation on System A or System B. Nevertheless, WMG believes that a widely-adopted charger-to-battery connection protocol, encompassing both the connector and communication, could significantly reduce the risk of over-charging.

In China, two mandatory standards were published simultaneously in late 2022, which are now being implemented. The first is “GB 42295-2022 Electrical Safety Requirements for Electric Bicycles” and the second is “GB 42296-2022 Safety technical Requirements for Chargers for Electric Bicycles” (Standardisation Administration of the People’s Republic of China, Dec 2022). These complementary standards both require “mutual recognition and coordinated charging”, whereby the battery and charger shall mutually recognise each other before charging can begin. GB 42295 contains an informative (not normative) Appendix which defines the basic rules for communication between the battery and charger. GB 42296 requires all electric bikes to use one of two new standardised connector designs, of which one is only for use with lead-acid batteries, and the other is only for use with other battery types including Lithium-ion. The two connectors are shown in Figure 33 and Figure 34.

WMG understands that the mandatory status of these standards means that e-bikes can now only be sold in China with one of these connectors. It appears that the intent of these standards is to prevent the use of lead-acid battery chargers with Lithium-ion batteries (and vice versa) and to ensure that the compatibility of the charger and battery is also implemented by electronic means. The male and female connectors are also designed to minimise the possibility of inadvertent short-circuit between the positive and negative power terminals. WMG is not aware of any plans to adopt these connectors outside China.



(a)

(b)

Figure 33: GB 42296-2022 Plug and Socket Designs for (a) Lithium-ion and (b) Lead-acid Batteries for Electric Bikes

Figure 34: Example Connectors Meeting the Chinese Mandatory Standard GB 42996-2022 (Nigat Electronics (Shenzhen) Co., Ltd., no date)

5 Background on Conversion Kits

The real-world PLEV fires statistics presented in Section 2 show that a significant proportion of severe fires are associated with conventional bicycles which have been converted to e-bikes, using kits of components purchased separately from the bicycle. This Section explores the technology of conversion kits, and how that may contribute to the severity and likelihood of fires with these products.

5.1 e-bike Conversion Kits

An e-bike conversion kit is a set of components intended to allow a conventional pedal-powered bicycle to be converted to an e-bike. With prices as low as £250 in the UK for an e-bike conversion kit including a battery (cyclotricity.com, 2024), they present a compelling proposition for many consumers who already have a bicycle. A complete conversion requires:

(1) Electric motor
(2) Motor controller
(3) Battery
(4) Battery charger (not mounted to the bicycle)
(5) Handlebar controls (sometimes including a display screen)
(6) Sensors, including for vehicle speed and pedal movement.
(7) Wiring to connect the other components on the bicycle.

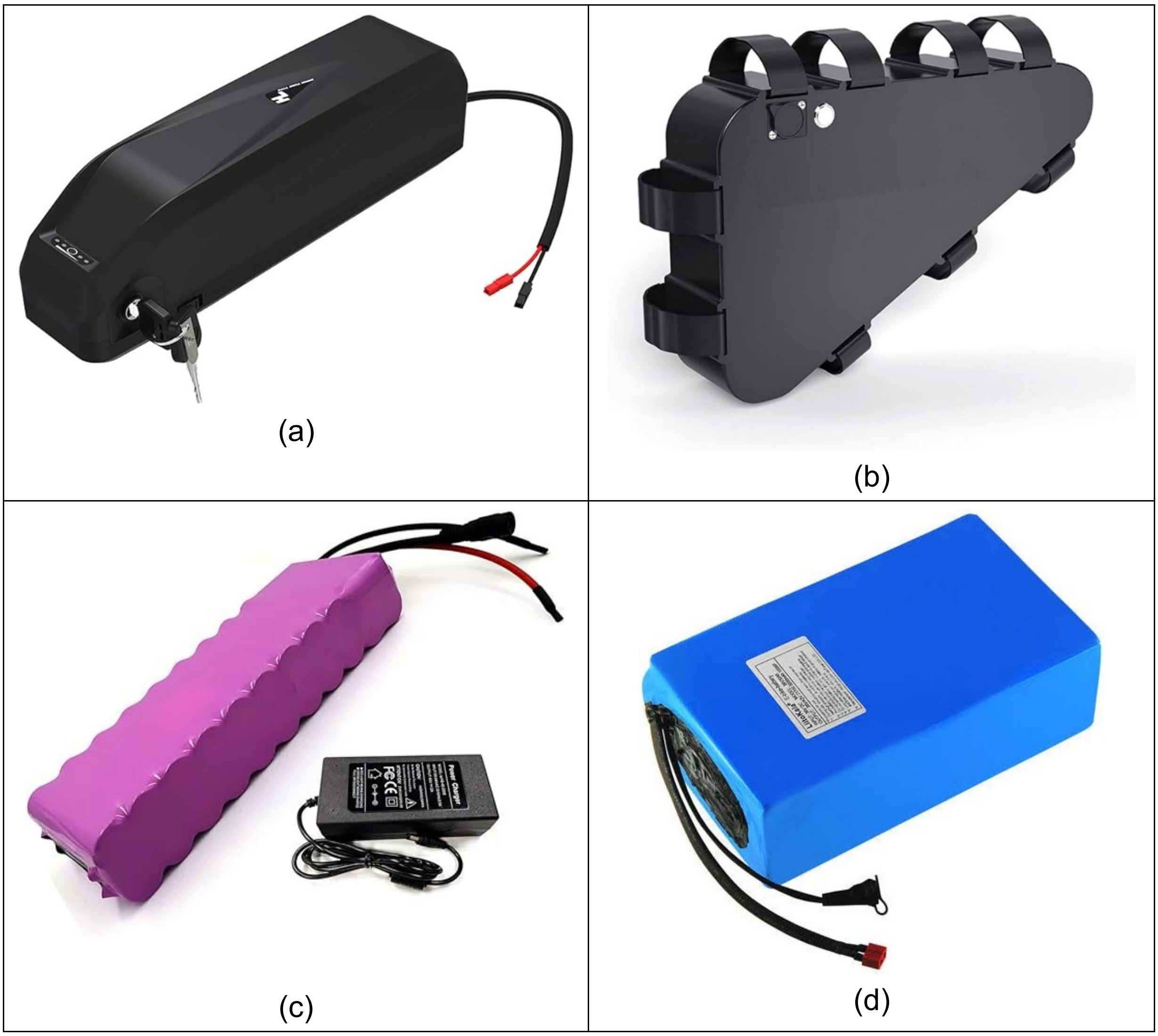
However, it is common to find conversion kits which contain only a sub-set of these components. For example, the model shown in Figure 35, does not include a battery.

Figure 35: An e-bike conversion kit comprising a replacement wheel with in-built motor; a motor controller; mounting bag; replacement handlebar grips including a twist-throttle and a display screen; replacement brake levers incorporating brake switches; and a pedal movement sensor (adapted from voilamart.co.uk, 2024)

The electric motor is often built into a wheel, to replace either the front or rear wheel on the pedal bicycle. This avoids the need to adapt the bicycle frame to attach the motor but has the disadvantage that the gear-ratio between the motor and the wheel is fixed. This means it cannot adapt to the different speeds and torques required on the flat, uphill and downhill paths, in the way that the rider can adapt the ratio from the pedals to the wheel using selectable gears.

Some kits use a “mid-mounted” motor, typically attached underneath the down-tube or the bottom bracket of the bicycle frame, where the pedal axle passes through the frame. This allows the electric motor to drive through the same gear selected by the rider, so as the rider selects different gears to be able to pedal comfortably in different situations, the motor shares the benefit. This allows the motor to be more compact but may make it more prone to impact damage, as it is typically quite close to the ground.

Some examples of e-bike conversion kit batteries are shown in Figure 36.



(a)

(b)

(c)

(d)

Figure 36: Examples of e-bike Conversion Kit Batteries

The battery is usually provided with either a mounting bracket which uses the bicycle-frame mounting points originally intended for a bottle-holder (Figure 36a), or the battery has Velcro straps which wrap around two of the bicycle frame tubes (Figure 36b). However, some are sold without a box, with the cell stack simply wrapped in a polymer heat-shrink film (Figure 36 c and d).

The motor controller is typically contained in an aluminium box. Like the battery, it has no existing mounting point on the bicycle frame, so may be attached directly to the frame using DIY methods or may be provided with a bag which attaches to the frame, e.g. with Velcro straps.

The handlebar controls and sensors vary in complexity. To be compliant with the EPAC exclusion from Type Approval (see Section 6.2.2 of this report) the controller needs to know whether the rider is pedalling and also needs to know the speed of the bicycle. The latter is also required to qualify for the UK exemption from road tax, insurance and registration for EAPCs (see Section 6.2.3). As a minimum, this requires:

(1) A sensor to detect rotation of the pedals. This typically comprises a small disc which rotates with the pedal axle. Several small magnets are embedded in the disc, and a separate sensor attached to the bicycle frame detects when the magnets pass the sensor, hence informing the controller that the pedals are turning.
(2) A sensor to measure bicycle speed. This can be achieved with a sensor which measures the rotational speed of the wheel, together with a calibrated value for the tyre diameter. Alternatively, a speed measurement such as GPS could be used, but may be prone to loss of the GPS signal.

In addition, the controller should cut off motor power when the rider is braking. This may be achieved with switches on both front and rear brakes, to detect when the rider has pulled the respective brake levers. However, typically the rider will stop pedalling when braking, so the power may be cut off based only on the pedal speed.

The level of assistance provided by the electric motor must be limited to 250 W continuous power, to comply with the EPAC exclusion from Type Approval and the UK exemption from road tax, insurance, and registration. However, to provide a predictable and intuitive riding experience, the level of assistance should vary with the rider’s needs. In most cases, this is achieved by a handlebar control which allows the rider to select between several assistance levels. In more sophisticated systems, an additional sensor is used measure the effort that the rider is applying to the pedals and adapt the motor power accordingly. However, this requires torque-sensor technology that is more expensive than a simple speed sensor.

The number of electrical connections involved in a conversion kit can be large. For example, the kit shown in Figure 35 above has 11 separate electrical connections to the motor controller. This tends to result in messy installation on the bicycle and can make the system prone to damage to wires and connectors, from general wear and tear, and from environmental effects such as rain. The complexity of the installation can also be off-putting for riders.

Some companies have endeavoured to reduce the complexity and to make the installation much neater, by integrating some components together and by minimising the number of non-integrated sensors. Figure 37 shows such a system from UK company Swytch. This system has a wheel-mounted motor, and handlebar-mounted “power pack”, which incorporates the battery and controller. The brake levers and handlebar grips from the original bicycle are retained, so the only separate sensor is the pedal sensor. A simple handlebar display unit incorporates buttons to control the motor assistance level.

Figure 37: Example of e-bike Conversion Kit with Integration of Battery and Motor Controller and only one Separate Sensor (Swytch Technology Ltd., Mar 2024)

Another example of a highly integrated e-bike conversion kit is the Rubbee X shown in Figure 38. This system avoids external wires on the bicycle completely, by integrating the battery, motor controller and motor into a single enclosure, which then delivers power to the rear wheel via a roller on the rear tyre. The only other component mounted on the bicycle is a wireless cadence sensor, which attaches to one pedal crank. Another example of an integrated system is Skarper (Blue Sky IP Ltd., 2023).

Rubbee X, with 3 battery modules

Seat-tube Bracket Attachment

Wireless pedal cadence sensor

Roller on Rear Tyre

Figure 38: Example of e-bike Conversion Kit with Integration of Battery, Motor Controller and Motor, and only one Separate Sensor (Rubbee Ltd., no date)

The examples in Figure 37 and Figure 38 show the e-bike conversion kits can be well conceived and neatly installed.

The low functional integration of many conversion kits, and the opportunity to buy different parts of the kit from different sources (potentially reducing the total price to the consumer), creates several technical compatibility issues which could contribute to the likelihood and severity of fires that may occur.

For example, the kit in Figure 35 is sold without a battery. This requires the bicycle owner to select and purchase an appropriate battery. The only advice from the kit supplier is that “The system requires a 48 Volt electrokinetic cell battery with a nominal capacity not less than 14.5 Ah”.

A buyer of this kit could easily pair it with a battery that is not compatible with the power level of the motor, even if they comply with the advised voltage and capacity values. They could also use a charger bought separately, which could be incompatible with the charging voltage and current limits of the battery. All such incompatibilities in voltage, current and power run the risk of leading to battery thermal runaway.

The kit is advertised as “48 V 1500 W and 250 W” and “Restricted to 250 W and 16 mph by default as a road-legal kit”, but the website goes on to state “Allow you to swap two power modes between the full 1500 W power or 250 W power by a single blue switch wire is embedded in controller. (Only for Twist Throttle)” and “Still remain the full 1500 W power with no speed control. (Only for Pedal Assist System, PAS)”.

The precise meaning of these statements is unclear from the poor wording, but it appears that to increase the power output from 250 W to 1500 W only requires connection of a pair of connectors supplied in the motor controller wiring (see Figure 39b).

(a) (b)

Figure 39: Voilamart motor controller: (a) label for 1000 W version and (b) road-legal switch wire (voilamart.co.uk, 2024)

The website also states that the maximum motor torque is 45 Nm. Based on this, WMG has estimated the maximum power vs. speed. Figure 40 compares the maximum continuous power allowed by the EPAC regulations with the power available from this motor when derestricted to 1000 W.

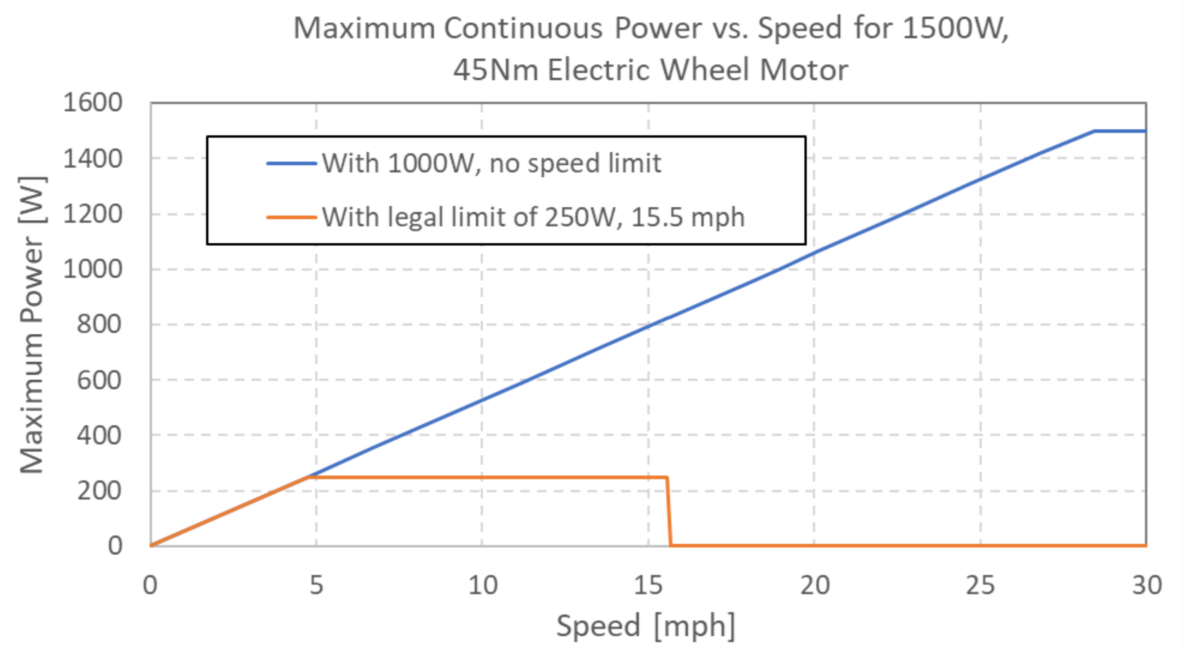


Figure 40: Comparison of the legal limit of an EPAC with the power capability of a 1500 W, 45 Nm hub-motor

It should be noted that the EAPC limit of 250 W is for continuous power. It does not restrict the short-term power, so an EAPC-compliant e-bike could (and typically does) deliver much more than 250 W for short periods. Nevertheless, the EAPC definition does require the assistance to cut off at 15.5 mph, irrespective of the duration that the power is delivered for. Therefore, the blue line shown in Figure 40 would not comply with the EAPC definition.

The potential issues relating to fire safety are as follows:

- The continuous current that the motor controller draws from the battery may be much higher than the battery or the current carrying cabling is designed to deliver. At 1500 W power, the discharge current of the cells will be more than six times what it would be for 250 W power. The heat generation in the cells, BMS components and wiring is proportional to the square of the current, so the rate of heat generation at 1500 W will be in excess of 36 times what it would be for 250 W power. While it is unlikely that most riders will sustain such high power for an extended period, it could occur for after a period of intensive use. This could lead to over-heating of the cells, BMS components and wiring. WMG estimates that, if the maximum power were sustained for 5 minutes, 250 W would result in less than 1 °C rise in cell temperature, but 1500 W would result in >25 °C increase in cell temperature if there were negligible cooling (See Appendix 1 in Section 15.1 of this report). (At 1500 W, an adult rider could achieve approximately 30 mph on a 5% gradient, covering 2.5 miles and ascending 200 m in 5 minutes. See Appendix 2 in Section 15.2 of this report.)
- There is no guarantee that an owner will choose a battery with the correct voltage, capacity, or current rating to suit the 1500 W motor controller. If the owner selects a battery with low capacity, or with poor quality cells, then it is likely that the internal resistance of the battery will be higher than assumed by the motor controller manufacturer, resulting in more rapid temperature rise, and an increased likelihood of causing cell over-current and over-discharge, increasing the likelihood of thermal runaway.

A greater concern with conversion kits is that the battery and charger may not be well matched. Both batteries and chargers are available with a wide range of voltage and current ratings.

If a battery is charged using a charger which has a higher voltage rating than the battery, this is likely to result in over-voltage of the cells, unless the BMS is able to prevent such charging from occurring. However, if the difference in voltage rating between the charger and battery is large, the protective components in the BMS may be damaged or unable to withstand the over-voltage, compromising their functionality, thereby increasing the likelihood that the BMS will fail to protect the cells.

If a battery is charged using a charger which has a higher current rating than the battery, then the charge-current limits of the cells may be exceeded if the BMS cannot limit the current draw during charging. This could over-heat the cells and increases the likelihood of lithium plating on the anode of the cells (See Section 3.1). Over time, this may lead to internal short-circuits, which can lead to thermal runaway. Furthermore, the current may also exceed the rating of the BMS components and wiring in the battery charging circuit, leading to over-heating, damage, and potential failure of these components. If such components are in close proximity to the cells, the heat from the BMS or wiring could be thermally conducted to one or more cells, causing over-heating of those cells. Overheating of a PCB can result in short circuits and propagating circuit board faults. Overheating of wires can also result in failure of insulation causing short circuits.

The quality of the design, materials and manufacturing of conversion kit components is also very variable. For example, batteries such as those shown in Figure 36c and Figure 36d may have no structure to support the cells, so the cells, busbars and the welds joining them are more prone to failure when exposed to vibration. This can lead to cell-to-cell short-circuits or hot-spots which could lead to thermal runaway. There is also inadequate protection from water and dust ingress, so the BMS electronics are vulnerable to corrosion or short-circuit / damage by contaminants. It is unlikely that most consumers will appreciate these shortcomings, and so they are unlikely to provide sufficient additional protection around the battery.

Overall, the fire safety risk of conversion kits points to a need for the complete system, comprising the motor, motor controller, vehicle sensors, battery and charger, to be specified and validated together, as required by functional safety standards (See Section 7.3). The e-bike and e-scooter standards all rely on evaluation of the complete system, including the vehicle, and are therefore not valid for components or partial systems that are paired with other components with which they were not tested.

5.2 Background on e-scooter Conversion Kits

An e-scooter conversion kit is a set of components intended to allow a conventional kick-scooter to be converted to an e-scooter. A complete conversion requires:

(1) Electric motor
(2) Motor controller
(3) Battery
(4) Battery charger (not mounted to the scooter)
(5) Handlebar controls (sometimes including a display screen)
(6) Sensors, including for vehicle speed.
(7) Wiring harness to connect the other components on the scooter.

WMG found only a handful of e-scooter conversion kits advertised on online marketplaces, compared to hundreds of e-bike conversion kits. An example is shown in Figure 41.

Figure 41: Example of e-scooter Conversion Kit, comprising a replacement wheel with in-built motor; a motor controller; replacement handlebar grips including a twist-throttle and a key-lock (Depisuta, no date)

Compared to e-bike conversion kits, e-scooter conversion kits are relatively rare. There are several factors which contribute to explaining this:

- Complete e-scooters are readily available and generally cheaper than e-bikes.
- Fewer users have existing kick-scooters compared to existing bicycles.
- Converting a kick-scooter to an e-scooter is more challenging than converting a bicycle to an e-bike, because there are few convenient locations for the bulky components such as the battery and motor controller.

None of the examples found by WMG included a battery, suggesting that the market for such kits may be limited to upgrading the motor power on existing e-scooters, rather than for converting a conventional kick-scooter to an e-scooter. The conversion kit listings found, including the one shown in Figure 41, do not provide any guidance on selecting a suitable battery to use with the conversion kit. However, there are many listings for separately sold batteries, such as the one shown in Figure 42.

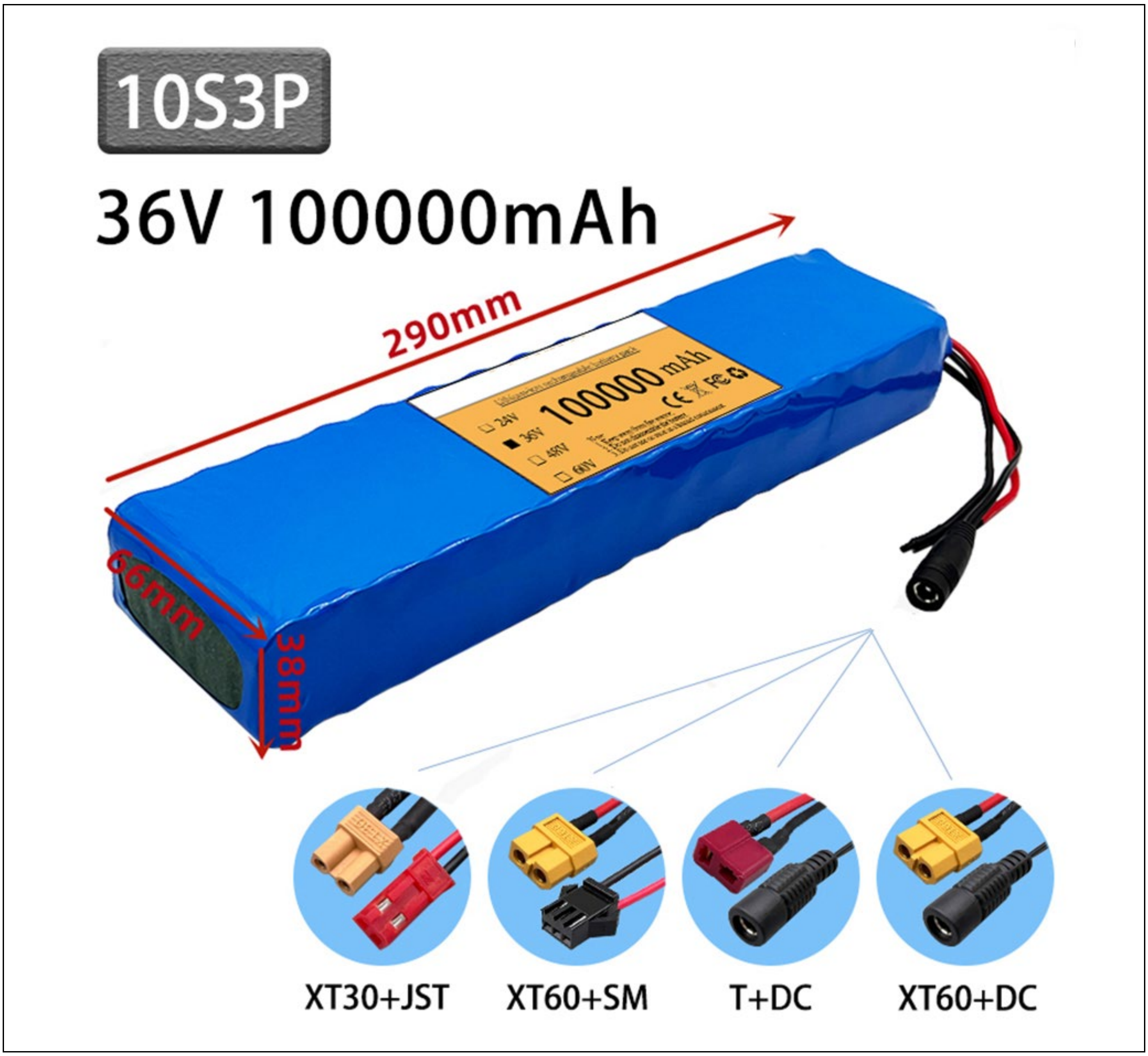


Figure 42: Example Aftermarket e-scooter Battery (Shop1103139214, no date)

The technical concerns with e-scooter conversion kits and batteries are largely the same as explained for e-bike conversion kits in Section 5.1. Therefore, they are not repeated here.

6 Existing Standards and Regulations

Sections 4 and 5 provided background on the technology of chargers and conversion kits, two of the product categories that the real world evidence in Section 2 suggested may have a roles to play in causing PLEV battery fires. However, that evidence shows that complete manufacturer-built e-bikes and e-scooters are also involved in some fires. This picture suggests that PLEV products of various types are available on the UK market that do not meet reasonable expectations of consumer product safety. This section reviews the legislation and standards that apply to these products, highlighting the fragmentation that exists, partly as a result of the large and evolving diversity of PLEV product types. It also identifies some key differences that exist in adjacent market sectors, such as automotive, and geographic markets, such as the EU, USA and China.

6.1 General Product Safety Regulations and Standards

All products placed on the market in the UK are subject to regulations to ensure their safety. The UK's product safety regulatory framework has remained largely unchanged since the UK retained relevant existing EU legislation on leaving the EU.

For some products, such as passenger cars, specific legislation applies. For products which have no specific legislation, the General Product Safety Regulations 2005 (GPSR) require all products to be safe in their normal and reasonably foreseeable usage. There are also specific regulations for some broad product sectors, setting out essential safety requirements, for example The Supply of Machinery (Safety) Regulations 2008 (SMSR) and the Electrical Equipment (Safety) Regulations 2016 (EESR). PLEV products may fall under either the SMSR, EESR or GPSR, depending on their details. This is explained further in Section 6.6 onwards.

Standards are created and published by national and international standards bodies such as BSI Group and the International Standards Organisation (ISO). Compliance with legislation is mandatory, whereas compliance with standards is voluntary. However, standards can assist manufacturers, importers and other parties to comply with these regulations, particularly if the standards are "designated" under one of the regulations (see Section 6.8.2).

Sections 6.2 to 6.14 describe the regulations and standards applicable to PLEVs.

6.2 Structure of Existing UK Regulations for PLEVs

6.2.1 Type Approved Vehicles

For most motor vehicles, such as motorcycles, passenger cars, trucks and buses, there is a regulatory framework provision called Type Approval, which must be completed before a vehicle type can be placed on the market. Type Approval legislation requires third-party approval of testing, certification, and conformity of production (CoP), to give confidence that every example of a particular product conforms to the approved specification. For products on the UK market an Approval Authority and a Technical Service (testing organisation) has been appointed to undertake the third-party approvals. The body, the Vehicle Certification Agency (VCA), performs both roles and appoints other Technical Services. The testing covers numerous aspects of the vehicle (e.g. lights, brakes, crash safety, emissions). CoP requires the manufacturer to have a Quality Management System (e.g. ISO 9001) and Control Plans, and on-site visits to the manufacturing plant at least every three years. There are also single vehicle approval frameworks which individuals or importers may wish to use to be able to register a vehicle or bring a vehicle to market.

Vehicles in various market sectors are divided into categories, some examples of which are listed in Table 69 and Table 70 in Appendix 3 (Section 15.3 of this report). For example powered two-wheelers (motorcycles, mopeds), three-wheelers- and quadricycles are in the “L-category”, which is then sub-divided, with the lowest sub-category being L1e which is two-wheelers with a maximum speed ≤ 45 km/h and maximum continuous power ≤ 4 kW.

All the L-category vehicles above are subject to Type Approval. With the exception of “Twist and Go” EAPCs (see Section 6.3), they also need to be registered, insured and taxed, and the rider must wear an approved motorcycle helmet and have the appropriate driving license.

6.2.2 Vehicles Exempt from Type Approval

The European Regulation 168/2013 (EU 168/2013) (European Union, Jan 2013), covering the Type Approval of L-Category vehicles, states in Article 2, Paragraph 2 (h) that it does not apply to:

> Pedal cycles with pedal assistance which are equipped with an auxiliary electric motor having a maximum continuous rated power of less than or equal to 250 W, where the output of the motor is cut off when the cyclist stops pedalling and is otherwise progressively reduced and finally cut off before the vehicle speed reaches 25 km/h.

This exclusion of such pedal cycles from Type Approval remains in UK law as an assimilated EU law (UK Government, Jun 2022).

EU 168/2013 Type Approval also does not apply to some other vehicle types. In the context of this report, the most relevant are:

- Vehicles with a maximum design speed ≤ 6 km/h. This is interpreted for EAPCs to permit a “start-up” mode, in which the motor can accelerate the vehicle from rest up to walking speed, or assist a person walking with the bike, without the need for the person to turn the pedals.
- Self-balancing vehicles, such as electric unicycles and hoverboards; and
- Vehicles not equipped with at least one seating position, including e-scooters.
- Vehicles equipped with any seating position of the driver or rider having an R-point height ≤ 540 mm in case of categories L1e, L3e and L4e (two-wheelers) or ≤ 400 mm in case of categories L2e, L5e, L6e and L7e (three- and four-wheelers). The R-point, or seating reference point, is the position of the seated rider’s hip joint. This includes, for example, some e-scooters equipped with a low seat.

Regular bicycles, pedal-assist e-bikes and e-scooters are therefore not subject to the Type Approval process. Instead, almost all such products fall under general product safety legislation, see Section 6.6 onwards.

6.2.3 Cycles in the UK Exempt from Registration, Road Tax and Insurance

Regular bicycles have major advantages for consumers in the UK, compared to most other road vehicles, in that they do not need to be registered, insured or taxed, and the rider is not obliged to wear a helmet. The same is true for a tightly defined category of e-bikes, called EAPCs.

In UK law, the term EAPC was defined in The Electrically Assisted Pedal Cycles Regulations 1983 UK Government (Aug 1983) which was amended in 2015 (UK Government, Apr 2015) to align more closely with EU 168/2013. Following the 2015 amendment, an EAPC is defined as follows:

- A pedal cycle with two or more wheels.
- Fitted with pedals capable of propelling it.
- Fitted with an electric motor (and no other motor) which must cut off when the vehicle reaches 15.5 mph (25 km/h).
- Which has a maximum continuous rated power which does not exceed 250 W.

An EAPC which complies with the above is not considered to be a motor vehicle within the meaning of the Road Traffic Regulation Act 1984 and the Road Traffic Act 1988. As a result, it is not required to be registered or subject to road tax and does not have to be insured as a motor vehicle. However, EAPCs must not be ridden by anyone under the age of 14 years (UK Government, Department for Transport, Jun 2015).

The UK definition of EAPC above allows the electric motor to provide mechanical power when the rider is not using the pedals. In such EAPCs, the electric motor power delivery is typically controlled via a handlebar rotary throttle, which is why they are referred to as "Twist and Go EAPCs". Since the Type Approval exemption only allows for motor assistance when the rider is pedalling, it means that "Twist and Go EAPCs" are subject to Type Approval, see Section 6.3.

6.3 Type Approval for Twist and Go EAPCs

Twist and Go EAPCs differ from non-Type Approved EAPCs only in the maximum speed up to which they can provide motor power without pedalling: Rather than the 6 km/h (walking speed) limit of most EAPCs, Twist and Go EAPCs provide power up to 15.5 mph (25 km/h), irrespective of whether the rider is pedalling.

This seemingly small difference means they that they are subject to EU 168/2013 Type Approval as L1e-A vehicles.

To obtain Type Approval, there are two possible routes, as described below by the Bicycle Association (BA) (Bicycle Association, Jul 2023):

1. Whole vehicle approval. This is intended for large production runs, has many requirements and is very expensive.
2. Motorcycle Single Vehicle Approval (MSVA) (UK Government, Sep 2022). As the name suggests, this is an approval scheme for individual vehicles, which must each be taken to a Driver and Vehicle Standards Agency (DVSA) test station, have a £55 fee paid, and be individually approved under the "250 W LPM" category. This is logistically difficult for suppliers.

The BA is not aware of any UK e-bikes with whole vehicle approval. To date, the BA is only aware of one supplier offering MSVA type-approved Twist and Go EAPCs (Wisper Bikes, 2023).

Because neither of these processes is straightforward for manufacturers, currently there are very few approved Twist and Go e-bikes available on the UK market.

6.4 Type Approval for L-Category Vehicles

As mentioned in Section 1.2 of this report, there are e-bikes on the market which do not meet the 250 W maximum continuous motor power criterion for an EAPC, but do still comply with the maximum speed for motor assistance of 25 km/h. These e-bikes fall into the L1e-A category, as defined in the EU 168/2013. L1e-A vehicles are named as “powered cycles”, a sub-category of L1e (light two-wheel powered vehicles), and are defined as:

- Cycles designed to be pedal equipped with an auxiliary propulsion with the primary aim to aid pedalling; and
- Output of auxiliary propulsion is cut off at a vehicle speed ≤ 25 km/h; and
- Maximum continuous rated or net power ≤ 1000 W; and
- A powered three- or four-wheel cycle complying with supplemental specific sub-classification criteria above is classified as being technically equivalent to a two-wheel L1e-A vehicle.

Therefore, an L1e-A vehicle is in most respects similar to an EAPC, except that the maximum continuous rated power is up to 1000 W, rather than 250 W for an EAPC. L1e-A vehicles are treated as motor vehicles in GB law, and therefore do not benefit from the advantages of EAPCs mentioned in Section 6.2.3.

Definition of Maximum Continuous Rated Power

In the Type Approval regulations for L-category vehicles, maximum continuous rated power is defined as “the maximum thirty minutes power at the output shaft of an electric engine as set out in UNECE regulation No 85”.

UNECE Regulation 85 (United Nations Economic Commission for Europe, Aug 2013) in turn defines “Maximum 30 minutes power" as: “the maximum net power of an electric drive train at DC voltage as defined in paragraph 5.3.1. of this Regulation, which a drive train can deliver over a period of 30 minutes as an average”.

Paragraph 5.3.2 (“Determination of the maximum 30 minutes power”) states: “The electric drive train shall run at the bench at a power which is the best estimate of the manufacturer for the maximum 30 minutes power. The power must be in a range of ±5 per cent of the power value at the start of the test. The maximum 30 minutes power is the average of the power within the 30 minutes period.”

This definition is different from the definition of maximum continuous rated power used in the e-bike standard EN 15194:2017+A1:2023 (BSI Group, Aug 2023), which is the “output power specified by manufacturer, at which the motor reaches its thermal equilibrium at given ambient conditions”, as “measured according to EN 60034-1:2010” (BSI Group, Nov 2010) when the motor reaches its thermal equilibrium as specified by the manufacturer” meaning that the “temperatures of motor parts do not vary more than 2 Kelvin per hour”.

Despite the difference between the two definitions, in WMG’s opinion, the power values given by the two methods are likely to be very similar.

However, it is worth noting that each definition allows for the short-term peak power to exceed the maximum continuous rated power. Indeed it is normal practice that an electric motor is specified with a peak short-term power rating and a continuous power rating. The ratio of the two values varies considerably depending on the intended application. WMG understands, based on information from various manufacturers, that EAPC motors with 250 W continuous power may have a peak short-term power in the range 500 - 800 W.

Whether the peak power is delivered in the vehicle application will depend greatly on the capability of the battery, whose maximum power output varies strongly with temperature, state of charge and state of health.

6.4.1 L-Category Regulations Relevant to Fire Safety

Annex II of the EU Regulation 168/2013 on Type Approval of L-category vehicles defines the Type Approval requirements for each sub-category of vehicles, which for L1e-A includes “electrical safety”. Annex VIII defines Enhanced Function Safety Requirements, which clarifies that, to comply with the electrical safety requirements, vehicles “shall be designed so as to avoid any risk to electrical safety, in using relevant requirements of UNECE Regulation No 100 and ISO 13063.”

At the time that EU Regulation 168/2013 was first published, UNECE Regulation 100, which covers the approval of vehicle electric powertrains, was at Revision 2 level (hereafter referred to as Reg 100.02), and this regulation applies only to category M- and N-category vehicles (passenger cars, vans and goods vehicles), and there was no equivalent for L-category vehicles. However, a few months later, the EU published Regulation 3/2014 (EU 3/2014) (European Union, Oct 2013), supplementing Regulation 168/2013 with regard to L-category vehicle functional safety. Annex IV of EU 3/2014 describes requirements regarding electrical safety, which contains broadly the same requirements as Reg 100.02 for avoidance of electric shock for high voltage systems ($> 30\ V_{ac\_rms}$ or $> 60\ V_{dc}$), but has almost no requirements to protect against fire, except for a loosely defined requirement for over-current protection. This is assimilated EU law that is mirrored in the current UK approach.

In 2016, UNECE created Regulation 136 (Reg 136) (United Nations Economic Commission for Europe, Feb 2016), based on Reg 100.02, specifically for L-Category vehicles. This regulation is also published by the EU (European Union, Jul 2019), but it has not been formally adopted as part of type approval for L-category vehicles, and it is not mentioned in the EU webpage concerning updates to regulations for L-category vehicles (European Union, Sep 2023), and therefore is not part of the regulations retained in the UK. However, it is listed as an alternative eligibility requirement to Annex IV of EU 3/2014 for the UK Government’s Plug-in Motorcycle Grant (UK Government Department for Transport, Apr 2024).

It is also important to note that, while Reg 136 (2016) is based on Reg 100.02 (2013), Regulation 100 has since been updated to Revision 3 (Reg 100.03) (United Nations Economic Commission for Europe, Mar 2022), which adds new requirements including over-current protection, low-temperature protection, warning of battery operational failure, warning of battery thermal event and a test for thermal propagation, all of which are very relevant to battery fires. These are discussed in Section 6.15.2 of this report. These additions have not yet appeared in an update of Reg 136, but it is reasonable to assume that UNECE will update Reg 136 to better match Reg 100.03 in future.

Nevertheless, since Reg 136 exists, it is worthwhile to investigate whether any lessons can be drawn from it which could be applicable to improving the fire safety of e-bikes and e-scooters which are not currently subject to Type Approval. See Section 7.

6.5 Other Technologies with Respect to the EAPC Definition

The Bicycle Association, in its Guide to UK e-bike Regulations highlights several “edge-cases”, where a product’s status regarding exemption from Type Approval requires clarification:

6.5.1 Off-road e-bikes

Some e-bikes offer a switch allowing greater motor assistance than is allowed in the EAPC definition (i.e. > 250 W and/or > 25 km/h). The Department for Transport has indicated that such bikes do not comply with the EAPC regulations, and therefore would be subject to Type Approval (UK Government, Jun 2015).

6.5.2 Series hybrid e-bikes

In a series hybrid, there is no mechanical linkage between the pedals and the driven wheel(s), such as the chain and sprockets of a conventional bike. Instead, the pedals drive a generator, which then delivers electrical power to a motor for the driven wheel(s).

The European Commission appears to have provided clarification for the EU market that such e-bikes can be exempt from Type Approval, if they meet the wording of the exemption in Article 2 Paragraph 2 (h) of EU 168/2013, on the basis that the type-approval legislation is technology neutral. Therefore, the fact of whether the vehicle has a chain or not, is irrelevant for determining if the vehicle concerned falls under the exemption (European Commission, Feb 2022).

For the GB market, the Department for Transport (DfT) advises that for a series hybrid e-bike to be classified as an EAPC, the pedals should be able to propel the vehicle unassisted, in particular if there were no charge in the battery, and if that were not the case, specific vehicles may need to be considered on a case-by-case basis. WMG suggests that complications may also occur if the battery malfunctions or is removed completely, and these cases should be considered by manufacturers in the context of the DfT advice above.

6.5.3 e-bikes with More Than One Motor

Both the UK definition of an EAPC and the EU exemption from Type Approval refer to a singular motor. WMG is aware that industry representatives are seeking clarification on whether e-bikes with more than one motor, where the total assistance is within the 250 W and 25 km/h limits, qualify for exemption from Type Approval.

6.5.4 Electrically Assisted Trailers

The BA highlights that there are cycle trailers on the market which include electric assist. Suppliers of these trailers claim that when coupled with an unassisted pedal cycle, the cycle & trailer combination meets all EAPC regulatory requirements and may therefore be used as an EAPC. WMG understands from DfT that coupling a trailer to a vehicle does not result in the combination being treated as a single vehicle, but matter has yet to be tested in court.

6.5.5 Speed Pedelecs

In some EU countries there is a class of vehicle called the “Speed Pedelec” or “S-Pedelec” which is an e-bike with a 45 km/h (ca 30 mph) cut-off speed. In the UK these must have type approval or MSVA approval and meet moped regulations to be used legally, and cannot use cycle paths. Riders must wear a motorcycle helmet.

6.6 UK Regulations for e-scooters

Under existing UK regulations, privately-owned e-scooters (officially referred to as Powered Transporters and classified as “motor vehicles”), are not legal to ride on public land such as public roads, pavements, and cycle lanes, but they can be legally used on private land with the land-owner’s permission. This is because they generally do not comply with the relevant legislation for motor vehicles (UK Government, Jul 2020). If a consumer wishes to use an e-scooter on the road, it must be approved through the Motorcycle Single Vehicle Approval (MSVA) Regulations.

It is possible to legally use e-scooters in public spaces if they are rented as part of government trials, which are taking place in various locations across England (UK Government, Jun 2024).

The safety of complete e-scooters is regulated by the Supply of Machinery (Safety) Regulations 2008 (SMSR), which are described in Sections 6.8.2 and 6.9.

Since July 2023, WMG has been supporting TRL to deliver recommendations on technical requirements for future e-scooter regulations for the Department for Transport (TRL, 2023). The related DfT report is expected to be published in due course. This research only considers technical requirements and does not cover user requirements such as regulations on insurance, licensing or helmet wearing.

6.7 UK Regulations for e-bike Conversion Kits

As explained in Section 5 of this report, e-bike and e-scooter conversion kits cover a broad range of components, which can be installed on a wide variety of conventional bicycles and scooters.

The description and content of five different types of conversion kits is shown in Table 8 and the applicable regulations and standards are shown in Table 9:

Table 8: Categories of e-bike and e-scooter Conversion Kits

#	**Kit Type**	**Components Included**			
		Motor	Motor Controller	Battery	Battery Charger
1	Conversion kit supplied with battery and charger	Yes	Yes	Yes	Yes
2	Conversion kit supplied with battery only	Yes	Yes	Yes	No
3	Conversion kit with no battery or charger	Yes	Yes	No	No
4	Battery only for conversion kit supplied with charger	No	No	Yes	Yes
5	Battery only for conversion kit	No	No	Yes	No

Table 9: Regulations and Standards Applicable to Conversion Kit Batteries and Chargers at time of report publication

#	Description	Safety Regulations	Standards
1	Conversion kit supplied with battery and charger	Supply of Machinery (Safety) Regulations 2008 (SMSR)	EN 50604-1:2016+A1:2021 EN 62133-2:2017+A1:2021 EN IEC 60335-2-29:2021+A1:2021
2	Conversion kit supplied with battery only	SMSR	EN 50604-1:2016+A1:2021 EN 62133-2:2017+A1:2021
3	Conversion kit with no battery or charger	SMSR	None
4	Battery only for conversion kit supplied with charger	Electrical Equipment (Safety) Regulations 2016	EN 50604-1:2016+A1:2021 EN 62133-2:2017+A1:2021 EN IEC 60335-2-29:2021+A1:2021
5	Battery only for conversion kit	General Product Safety Regulations 2005	EN 50604-1:2016+A1:2021 EN 62133-2:2017+A1:2021

Note: Table 9 defines the regulations and standards applicable to conversion kits as-sold, not those applicable when they are fitted to a bicycle to create an e-bike or e-scooter. They relate only to the safety of the conversion kit and not to other legislative requirements that may apply. The applicability of regulations is an indication. However any definitive interpretation would be dependent on the exact nature of the products supplied and, in some cases, the EESR may apply in place of the SMSR.

In WMG's view the first three types of conversion kits meet the definition of "partly completed machinery" under the Supply of Machinery (Safety) Regulations 2008 (SMSR), as stated in Part 2, paragraph 6 of the regulation. However, types 4 and 5 do not meet the definition of partly completed machinery, since they are not "almost machinery" per the definition of machinery in Part 2, paragraph 4 (2) of the regulation. As a result, WMG's view is that conversion kits types 4 and 5 are only covered by the General Product Safety Regulations 2005 (GPSR) or the Electrical Equipment (Safety) Regulations 2016 (EESR) (UK Government, Dec 2016), although the latter is primarily only relevant to the mains battery chargers, as most PLEV batteries are below the 75 – 1500 V_{dc} range of EESR.

The SMSR contains essential health and safety requirements (EHSRs) which are highly relevant to the fire risks of e-bikes and e-scooters and related conversion kits, whereas the requirements of the GPSR and EESR, whilst requiring the products supplied to be safe, are less specific than the SMSR about individual hazards. (See Section 6.9 of this report).

Furthermore, manufacturers of products that are within the scope of the SMSR must comply with obligations to retain particular technical documentation.

For products within the scope of the SMSR, including complete e-bikes and e-scooters, the manufacturer must:

- Compile a technical file, in accordance with Annex VII (Part 7 of Schedule 2), part A of the SMSR.
- Provide operating instructions.
- Follow a conformity assessment procedure.
- Draw up a Declaration of Conformity (DoC) in accordance with Annex II (Part 2 of Schedule 2), section A, part 1.

The technical file is required to demonstrate that the machinery complies with the SMSR, including among other things a list of standards used, the relevant EHSRs, calculations, and test results.

For partly completed machinery, including conversion kit types 1-3, the manufacturer must:

- Make available technical documentation in accordance with Annex VII (Part 7 of Schedule 2), part B.
- Prepare assembly instructions in accordance with Annex VI (Part 6 of Schedule 2) of the SMSR.
- Drawn up a Declaration of Incorporation (DoI) in accordance with Annex II (Part 2 of Schedule 2), section B, part 1.
- Deliver the assembly instructions and declaration of incorporation with the product.

The technical documentation for partly completed machinery must show which parts of the SMSR it fulfils. Like the technical file for complete machinery, it must include, among other things, a list of standards used, the relevant EHSRs, calculations, and test results.

The SMSR requires that the technical file for complete machinery, or the technical documentation for partly complete machinery, must be made available to enforcement authorities, upon request, for at least 10 years after manufacture.

By comparison, the EESR requires the manufacturer to draw up technical documentation, carry out a conformity assessment and draw up a DoC, but no DoI or assembly instructions are required. The GPSR requires producers to ensure that products are safe, but does not specify particular documentation. The manufacturer is required to provide the consumer with information on the risks inherent in the product and precautions to take against them.

In WMG's view, the fact that conversion kit types 4 and 5 do not fall under the SMSR is a significant weakness of the regulatory framework. Considering that the battery presents the greatest fire or explosion risk of any part of a conversion kit, WMG believes that the mention of these specific hazards in the EHSRs of the SMSR (see Section 6.9) is a significant benefit of the SMSR, compared to the GPSR, in that it draws manufacturers' attention to, and requires them to avoid, these hazards.

Furthermore, the weaker documentation requirements for products that fall under the EESR or GPSR rather than the SMSR mean that the absence of a DoI or assembly instructions cannot be used in enforcement activities by bodies such as OPSS, Trading Standards, and Border Force.

WMG suggests that OPSS investigate options to ensure that all conversion kit batteries can be classified as partly completed machinery under the SMSR, or another means to ensure that conversion kit batteries are subject to the same legislative health and safety requirements and standards as those in complete PLEVs.

WMG suggests that OPSS investigate whether retailers, including online marketplaces, could be obliged to provide certain documentation, such as a DoC / DoI, assembly instructions, and a UN38.3 certificate for batteries, before a product can be offered for sale. In the case of online marketplaces, an obligation to include such documents in online product listings would provide a mechanism for the marketplaces to refuse listing to, or de-list, non-conforming products.

OPSS has advised WMG that it considers that the same standards that are relevant to batteries (EN 62133-2 and EN 50604-1) and chargers (EN 60335-2-29), for complete e-bikes and e-scooters, are relevant to those parts of conversion kits, but that the vehicle standards for e-bikes (EN 15194) and e-scooters (EN 17128:2020) are not applicable to conversion kits.

Conversion kits cannot comply with some of the requirements of EN 15194 and EN 17128 until they are installed in a vehicle. Since the kits are generally designed to be able to be fitted to a wide range of vehicles, it is not realistic that the conversion kit supplier could verify compliance with the vehicle standards on all compatible vehicles.

However, in WMG's view, the conversion kit supplier should identify sections of the vehicle standards which are relevant to their products and comply with these.

The UK Bicycle Association guide on e-bike conversion kits (Bicycle Association, Jul 2022) highlights several concerns associated with fitting a conversion kit to a conventional bicycle, including inadequate frame and fork safety. For example, e-bikes tested to EN 15194 undergo more severe fatigue testing than conventional bikes frames tested to the EN ISO 4210 series of standards (BSI Group, 2024). The Bicycle Association also highlights the additional weight of the conversion kit components, their effect on vehicle handling, and their fire safety, as significant risks.

In summary, the current regulatory framework for e-bike and e-scooter conversion kits is substantially weaker than that for complete e-bikes and e-scooters, and in particular the regulations for conversion kit batteries. This lessens the obligations on the manufacturers and limits the enforcement options for authorities.

6.8 UK Regulations for PLEVs Excluded from Type Approval

The main regulations which apply to PLEVs are listed below, with a short overview of the relevance of each regulation to PLEVs. All participants in the supply chain (manufacturers, importers, distributors, retailers) have responsibilities under these rules. For these supply chain participants, complying with product safety regulations and maintaining a Technical File as evidence is important.

6.8.1 General Product Safety Regulations 2005

The GPSR requires that only "safe" products can be placed on the market. Compliance is self-certified by manufacturers and must be done before the product is placed on the market to enable a demonstration of compliance with the relevant regulatory requirements. Customers in the supply chain must be properly informed and there are supplier obligations regarding recalls. A Technical File is not mandatory but highly advisable to support the demonstration of compliance with the law.

6.8.2 Supply of Machinery (Safety) Regulations 2008

The SMSR ensures the mechanical and functional safety of machinery sold in the UK, including mobile machinery. Vehicles which are excluded from Type Approval (see Section 6.2.2) such as e-bikes and e-scooters fall under these regulations. Details of the requirements of the Machinery Regulations are provided in Section 6.9. For e-bikes, compliance can be evidenced by testing to EN 15194, which is designated under the Machinery Regulations (see Section 6.10 for details of designated standards). Designation of a standard confers a presumption of conformity with the EHSRs of relevant regulations. For e-scooters, EN 17128 is the closest equivalent standard, but is not designated under the SMSR, and so does not afford a presumption of conformity. The SMSR requires self-certified UKCA or CE marking and drawing up a Declaration of Conformity (which must be passed through to the end user, usually in the user manual).

6.8.3 Electrical Equipment Safety Regulations 2016

The EESR contain safety requirements for electrical equipment with a voltage rating of 50-1000 V_{ac} and 75-1500 V_{dc}. For PLEVs, the regulations are therefore primarily applicable to chargers. The regulations generally do not apply to the complete PLEV, unless the vehicle has a built-in mains charger, or if the battery voltage can exceed 75 V_{dc}, both of which are uncommon. Compliance can be self-certified but is generally evidenced by battery charger suppliers. The regulations require UKCA or CE marking and listing on a Declaration of Conformity (these are all usually handled by the charger manufacturer and details will be included in the supplied charger instructions).

6.8.4 REACH Regulations

The Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) regulation (UK Government, Jun 2021) applies to use of certain chemicals with potential for harm to human health or the environment. Compliance is generally evidenced by collecting conformity data from component and materials suppliers and, for larger producers, doing simple calculations to check whether totals for specific substances add up to amounts reportable to the Health and Safety Executive. In PLEVs, this is mainly relevant to components which may be in prolonged contact with the user's skin. The relevant harmful chemicals in a battery are sealed inside the cells in normal operation. The REACH regulation is of low relevance to PLEV fires because it concerns a product in its original form, not in a failure situation such as thermal runaway.

6.8.5 RoHS Regulations

The Restriction of Hazardous Substances (RoHS) regulation (UK Government, Feb 2013) controls the use of certain substances in electrical equipment (which means the whole PLEV). Compliance is generally evidenced by collecting conformity data from component and materials suppliers. It requires self-certified UKCA/CE marking and listing on the Declaration of Conformity. Separate compliance is required for the mains battery charger. The RoHS regulation is of low relevance to PLEV fires.

6.8.6 Electromagnetic Compatibility (EMC) Regulations

The Electromagnetic Compatibility Regulations 2016 (UK Government, Dec 2016) set requirements to ensure that the PLEV or charger should not interfere with other electrical equipment or be affected by interference emitted by other equipment. Compliance for the e-bike (minus charger) is generally evidenced by testing to the requirements in EN 15194, plus test lab approval. Similarly for e-scooters, EN 17128 is used. The regulations require self-certified UKCA or CE marking as a Declaration of Conformity. Separate compliance is required for the mains battery charger. In theory, it is possible that electromagnetic interference could affect safety critical electronics such as the BMS, although this very unlikely if the product complies with the relevant standards. WMG is not aware that any link has been established between EMC and PLEV fires, and such causes are not considered in this report.

6.8.7 Batteries Regulations

The Batteries and Accumulators Regulations 2008 (UK Government, Sep 2008) set some chemical limits for batteries (and "separate collection" symbol is required on the battery) but mainly set out waste batteries collection responsibilities. Product compliance is generally evidenced by battery supplier data sheets. The Batteries Regulations are of low relevance to PLEV fires.

6.8.8 Waste Electrical and Electronic Equipment (WEEE) Regulations

The Waste Electrical and Electronic Equipment (WEEE) regulations (UK Government, Jan 2014) set requirements to ensure proper handling of electrical and electronic waste. They require that PLEVs must carry the “separate collection” symbol and that “producers” (who place e-bikes on the UK market) must register on the National Packaging Waste Database among other EEE producer responsibilities. The WEEE Regulations are of low relevance to PLEV fires.

6.8.9 Radio Emissions Regulations (where relevant)

The Radio Equipment Regulations 2017 (UK Government, Dec 2017) apply only where radio features are included e.g. Bluetooth functionality. Generally self-certification is possible, and requires UKCA or CE marking and listing on a Declaration of Conformity. The Radio Equipment Regulations are of low relevance to PLEV fires.

6.8.10 Hazardous Goods Transport Regulations

The United Nations publishes the Manual of Tests and Criteria (United Nations Economic Commission for Europe, Nov 2023), which contains test methods and procedures to be used for the classification of dangerous goods according to the provisions of the “UN Recommendations on the Transport of Dangerous Goods, Model Regulations” (United Nations Economic Commission for Europe, Aug 2023). Section 38.3 of the Manual of Tests and Criteria, commonly referred to as UN38.3, defines the requirements for Lithium-metal and Lithium-ion batteries. It specifies eight types of tests, intended to demonstrate that a battery type is safe to be transported by land, sea or air. Complementing UN38.3 are the regulations and guidelines specific to certain modes of transport, such as the European Agreement concerning the International Carriage of Dangerous Goods by Road (United Nations Economic Commission for Europe, Jan 2023), commonly referred to as the UN ADR. This defines the labelling and packaging requirements for transport of dangerous goods.

The transport tests defined in UN38.3 have much in common with the tests defined in standards for the operational safety of batteries, in that they both cover topics such as vibration, mechanical shock and over-charge and short-circuit, but the details differ.

6.9 Machinery Regulation – Essential Health and Safety Requirements

Annex I of the SMSR defines the essential health and safety requirements (EHSRs) relating to the design and construction of machinery. It is the foundation of the more detailed guidance defined in application-specific specific product standards, such as EN 15194 for e-bikes and EN 17128 for e-scooters.

The requirements from the SMSR most relevant to this report are shown in Table 10:

Table 10: Summary of Relevant Health & Safety requirements in the Machinery Regulations

Essential Requirements of the SMSR Schedule 2 Part 1	**Description and Comments**
General Principles	Requires the manufacturer to perform a risk assessment, following a methodology similar to that outlined in Section 3.3 of this report (identify hazards, estimate severity, determine mitigations) taking account of foreseeable misuse. Allows for the possibility that the state of the art does not achieve all safety objectives, in which case the aim is to approach these objectives.
1.1.2 Principles of safety integration	Requires safety that encompasses operation, adjustment and maintenance, and the whole foreseeable lifetime of the product, including transport, assembly, disabling and scrapping. Defines a hierarchy of priorities: (1) Eliminate risk; (2) Implement protective measures against risks that cannot be eliminated; (3) Inform users of residual risks. Requires the design and construction to prevent abnormal use which would engender risk.
1.2.1 Safety and reliability of control systems	Requires that a fault in control hardware or software must not lead to a hazardous situation. Reasonably foreseeable human error must not lead to a hazardous situation.
1.3.2 Risk of break-up during operation	If a risk of rupture or disintegration exists, parts concerned must be contained to prevent hazards.
1.3.3 Risk due to falling or ejected objects	Precautions must be taken to prevent risks from falling or ejected objects.
1.5.1 Electricity supply	Requires electrical risks to be prevented.
1.5.5 Extreme Temperatures	Requires steps to be taken to eliminate risk form contact with very hot or very cold parts or materials.
1.5.6 Fire	Requires avoidance of the risk of fire or over-heating posed by gases, liquids, dust, vapours, or other substances produced or used by the machinery.
1.5.7 Explosion	Requires avoidance of the risk of explosion posed by gases, liquids, dust, vapours, or other substances produced or used by the machinery.
1.5.13 Emissions of hazardous materials and substances	Requires avoidance of the risk of inhalation, ingestion or contact with hazardous materials and substances.
1.7.1 Information and warnings on the machinery	Warning labels should use symbols and pictograms where possible.
1.7.2 Warnings of residual risks	Warnings of residual risks must be provided.

Essential Requirements of the SMSR Schedule 2 Part 1	**Description and Comments**
1.7.4 Instructions	Instructions must be provided.
3.5.1 Batteries	Electrolyte spillage must not occur in rollover. Must avoid accumulation of vapours.
3.5.2 Fire [extinguishers]	Built-in or easily accessible fire extinguishers to be provided for relevant hazards.

Annex I of the SMSR, paragraph 1.5.1 also states that the safety objectives set out in the Electrical Equipment (Safety) Regulations 2016 (EESR) shall apply to machinery. The requirements from Schedule 1 of the EESR which are most relevant to this report are shown in Table 11:

Table 11: Requirements from Schedule 1 of the EESR most relevant to PLEV fires

Paragraph	**Description and Comments**
2 (a)	*Persons and domestic animals must be protected against danger of physical injury caused by direct or indirect contact with electrical equipment.* The terms “direct contact” and “indirect contact” usually refer to electric shock but can also be read to include other dangers such as hot surfaces, projectiles, etc., which are relevant to battery fires.
2 (b)	*Temperatures, arcs or radiation which would cause a danger must not be produced.* These phenomena can cause direct harm but are also factors in initiation and propagation of thermal runaway (see Section 3.5.3).
3 (a)	*External mechanical influences on electrical equipment must not cause danger to persons and domestic animals.* This is relevant to mechanical damage which leads to battery thermal runaway.
3 (b)	*External non-mechanical influences on electrical equipment must not cause danger to persons and domestic animals.* This is relevant to electrical or thermal damage which leads to battery thermal runaway.
3 (c)	*Foreseeable overload of electrical equipment must not cause danger to persons and domestic animals.* This is relevant to external influences such as external short-circuit, or over-charge, which may lead to thermal runaway.

Even though the Machinery Regulations pre-date the growth of the market for e-bikes and e-scooters, and many other modern cordless electrical products with Lithium-Ion batteries, the safety requirements listed above provide good coverage of the hazards associated with the batteries used.

In WMG’s view, the essential health and safety requirements of the Machinery Regulations do not require any changes regarding PLEV fires.

However, it is clear from the incidents that have occurred (see Section 2) that some examples of PLEV products have fallen short of meeting these requirements.

It is also important to note that the EU has repealed the Machinery Directive, on which the UK Supply of Machinery (Safety) Regulations 2008 regulations are based. On 14 June 2023, the EU replaced the Machinery Directive with the Machinery Regulation (EU) 2023/1230 (European Union, Jun 2023). It is beyond the scope of this report to consider this regulation.

6.10 Machinery Regulation - Designated Standards

Designated standards (UK Government, Sep 2023) can help manufacturers demonstrate their products, services or processes comply with UK law. By following designated standards, manufacturers can claim “presumption of conformity (which can be countered by evidence)” with the corresponding essential requirements of the regulations.

If a standard is “designated” under a regulation, it means that it has been assessed by the UK Government to mean that if followed it provides a presumption of conformity with the essential safety requirements of the regulations.

While the manufacturer is still required to perform a product-specific risk assessment, a designated standard simplifies their risk assessment process, since an assessment of the hazards which exist within products that are covered by the scope of the designated standard has been performed by the standards developers and the adequacy of that standard has been accepted by the Secretary of State.

To promote consistency and guidance on the designation of standards, OPSS leads and co-ordinates the designation process across government.

For the SMSR, the Department for Business and Trade regularly issues a Notice of Publication (UK Government, Apr 2024), which lists all standards which are designated under these regulations. The Notice of Publication 0081/23 (12 April 2023), stated that EN 15194:2017 was designated, with two restrictions, the first of which is more relevant to this report:

> “Restriction 1: Designated standard EN 15194:2017 does not confer a presumption of conformity with the essential health and safety requirements set out in points 1.5.5, 1.5.6 and 1.5.7 of Schedule 2, Part 1 (Annex I) to S.I. 2008/1597, which require machinery to be designed and constructed to take into account the risks associated with extreme temperatures, fire and explosion.”

Extreme temperatures, fire and explosion are all hazards associated with battery thermal runaway (see Section 2). Therefore this restriction meant that EN 15194:2017 did not confer a presumption of conformity regarding hazards from battery thermal runaway.

Restriction 2 relates to:

> “the risks resulting from vibrations, and that machinery must be provided with the measurement of vibrations transmitted by the machinery to the operator of the machinery.”

Restriction 2 relates to the Machinery Regulations Annex I paragraph 2.2.1.1 / 3.6.3.1 requirement that the instructions provided for machinery should provide data on the vibration levels to which the rider is subjected, based on actual measurements. In EN 15194:2017, Annex ZA tabulates the relationship between the standard and the clauses of the Annex I of the Machinery Regulations, and states that vibration is “not applicable” to e-bikes, and so contains no method for measuring vibration. Restriction 2 recognises that, while vibration may not be a significant risk for consumers who only ride occasionally or for relatively short durations, it is a potential risk for intensive use, including professional use, of e-bikes.

However, in the context of this report, the risk from vibration is the effect that it may have on the safety of the battery and other parts of the electric powertrain, rather than the effect it has on the rider / operator of the PLEV.

Prior to Notice of Publication 0081/23, EN 15194:2017 was designated without restriction. The restriction followed a formal objection, from the Dutch government, that the battery safety requirements of EN 15194:2017 are insufficient (European Union, Jan 2023).

The standard has now been amended (EN 15194:2017+A1:2023) to address the first restriction above (see Section 6.12.1). For the second restriction relating to vibration, Annex ZA has been updated to state that vibration is “not covered”, rather than “not applicable”. A further amendment of the standard is expected to be published to address the second restriction. The CEN Technical Committee for cycles, TC333, will then propose to the EU that this amended standard should be harmonised without restrictions, and similarly propose to the UK Government that it should be designated under the Machinery Regulations without any restrictions.

On 30 November 2023, the Notice of Publication containing the designated standards for the Supply of Machinery (Safety) Regulations 2008 was updated, removing the restriction on the presumption of conformity for EN 15194 regarding extreme temperatures, fire and explosion. The restriction regarding vibration remains in place.

Even though the amendment has been implemented, it must be noted that EN 15194 only applies to electrically power assisted cycles (EPACs), and not to other PLEVs. The similar standard for non-road PLEVs such as e-scooters, EN 17128, is not a designated standard.

As mentioned in Section 6.9, the Machinery Regulation also encompasses the safety requirements of the Electrical Equipment (Safety) Regulations 2016. According to guidance from an expert practitioner group (National Product Safety Group, Sep 2019), this therefore means that all of the European Standards harmonised (UK designated) under the Electrical Equipment (Safety) Regulations 2016 are also designated under the Machinery Regulation.

6.11 General Product Safety Regulations – Referenced Standards

The General Product Safety Regulations 2005 have an extensive list of referenced standards (UK Government, Apr 2024) which includes the first nine parts of EN ISO 4210, which concerns safety requirements for bicycles. These nine parts cover bicycle terminology and the mechanical aspects of bicycles, including items such as brakes, steering and pedals.

There is also a tenth part titled “PD ISO/TS 4210-10:2020 Safety requirements for electrically power assisted cycles (EPACs)” (BSI Group, Jul 2020). However, this part has not been harmonised in the EU or referenced in the UK and has been given the lower status of a Technical Specification (TS), rather than a standard. This is because the draft was twice rejected by members of the ISO WG15 committee, for which the draft was developed, and under ISO rules it could not be voted on a third time LEVA-EU (October 2020), Bike Europe (Sep 2020).

6.12 Regulations and Standards Most Relevant to PLEV Fires

The evidence from real world PLEV fires shows that the majority are associated with the Lithium-Ion Battery (LIB) used to store energy for propulsion (See Section 2 of this report). Of the regulations listed in the preceding sub-sections of this report, the EHSRs of the SMSR are the most relevant to PLEV fires (see Section 6.9).

The following sub-sections describe the UK standards relevant to meeting the EHSRs of the SMSR. In general, the standards described in this section do not require the initiation of thermal runaway. On the contrary, most safety tests described in the standards have pass criteria which require the absence of signs of thermal runaway (fire, explosion). The emphasis of these tests is therefore on prevention of thermal runaway. This means that they do not assess the severity of a fire, were a fire to occur. Subsequent sections describe tests applicable in other markets which require initiation of thermal runaway, and define pass criteria regarding the survivability of these events, including the recent Chinese e-bike regulations (Section 6.14.4) and automotive regulations (Section 6.15.1).

6.12.1 Standard Relevant to e-bike Fires: EN 15194

For e-bikes, EN 15194:2017 Section 4.2.3.1 recommended that “The EPAC and battery pack shall be designed in order to avoid risk of fire and mechanical deterioration resulting from abnormal use”. The three ways in which the standard allowed conformity to be demonstrated were:

(1) By performing four tests specified in EN 15194:2017 Section 4.2.3.2; or

(2) By performing tests according to EN 62133; or

(3) By performing tests according to EN 50604-1

However, in early 2023, the Government of the Netherlands lodged a formal objection with the European Commission, that the battery safety requirements of EN 15194:2017, outlined above, were insufficient. The European Commission approached the European Committee for Standardisation (or Comité Européen de Normalisation, CEN) to assess the objection.

CEN’s Technical Committee 333, which is responsible for standardisation in the field of cycles, their components and accessories, considered the issue. An agreement was reached by CEN/TC333 to delete paragraphs 4.2.3.1 and 4.2.3.2 of EN 15194 and replace them with the following new paragraph 4.2.3:

“The battery shall comply with EN 50604-1:2016 and EN 50604-1:2016+A1:2021.”

On 31 August 2023, the updated Standard, EN 15194:2017+A1:2023, was published and the previous version, EN 15194:2017 was withdrawn.

This removes options (1) and (2) above and makes compliance with EN 50604-1 the only option for the battery of an e-bike. This is a substantial strengthening of EN 15194 with regard to battery safety.

As mentioned in Section 6.10, a further amendment of EN 15194 is expected to be published to cover vibration risks to the rider. In September 2023, CEN/TC333 decided to start work imminently on a full 'deep' revision of EN15194 too, ahead of the EU's new Machinery Regulation coming into force in 2027. The latter would not apply in the UK unless the UK government chooses to adopt it into UK law.

6.12.2 Standard Relevant to Mountain e-bike Fires: EN 17404

EN 17404:2022 (BSI Group, May 2022) is the standard for EPAC mountain bikes (EPAC-MTBs), rather than city and trekking bikes. The different categories of bicycles are defined in EN 17406:2020+A1:2021 (BSI Group, Oct 2021). EN 17404 almost fully incorporates the EN 15194 Standard. However, EN 17404 establishes specific requirements applicable only to EPAC mountain bikes, which are more susceptible to mechanical stress than conventional e-bikes. For conformity verification under EN 17404 therefore, it is necessary to supplement EN 15194 with a different set of tests with more stringent criteria, particularly regarding the mechanical and structural part.

Regarding the electric circuit, battery and battery charger, EN 17404 states that the relevant sections of EN 15194 apply without any changes to EPAC-MTBs. Regarding resistance to moisture ingress, EN 17404 requires IPx5 (resistance to water jets), whereas in EN 15194 IPx4 (resistance to water splashes) is deemed sufficient.

At the time that EN 17404 was written, the concerns about EN 15194:2017 regarding battery safety and vibration (see Section 6.10) were already known. Consequently, the Introduction of EN 17404 states that it does not cover battery and vibration issues, and Section 4.4 (List of significant hazards) states that “For intensive professional use, the risk resulting from vibrations shall be estimated and reduced if required.”

Given that EN 15194 has been amended regarding battery safety, and is expected to be updated further regarding vibration (see Section 6.12.1), it can be expected that EN 17404 will eventually be updated to refer to the amended version of EN 15194, or that users of EN 17404 should treat the latest version of EN 15194 as representing the state of the art.

In the context of this report, EN 17404 barely differs from EN 15194, so for the remainder of this report, they will be treated as equivalent and any mention of EN 15194 can be read as also referring to EN 17404, unless specifically stated otherwise. It should be noted that EN 17404 is not a designated standard, unlike EN 15194.

6.12.3 Standard Relevant to e-scooter Fires: EN 17128

For e-scooters, EN 17128 is the closest equivalent to EN 15194. Whereas EN 15194 is limited in scope to electrically assisted pedal bicycles, EN 17128 is a catch-all standard for most of the other vehicle types which are exempt from Type Approval, listed in Section 6.2.2. Examples from Annex E of EN 17128 are shown in Figure 43. The standard does not cover non self-balancing vehicles with a seat, which means that electric kick-scooters with a seat are not in scope.

Section 11.1 of EN 17128 requires that “The vehicle as well as the sets of energy storage (i.e. batteries) shall be designed and constructed such as to prevent any risk of fire and mechanical deterioration resulting from foreseeable abnormal use.” Compliance can be demonstrated in one of two ways:

(1) By performing four tests specified in EN 17128 Section 11.2; or
(2) By performing tests according to EN 62133.

In option (1), the four tests specified in Section 11.2 are essentially identical to those defined in Section 4.2.3.2 of EN 15194:2017. However, as explained in Section 6.12.1 of this report, EN 15194 has recently been amended to remove this option, and also to remove the option of using EN 62133 to show battery compliance. Instead, it allows only EN 50604-1 to be used. EN 17128 is therefore now out of step with the latest version of EN 15194, and as a result has weaker battery requirements. WMG is not aware of any plans to amend EN 17128 to align with the battery requirements of EN 15194.

Key

1	Grip
2	Brake lever
3	Accelerator
4	Control/display interfaces
5	Handlebar
6	Electric and/or brake cable
7	Handlebar height adjustment locking system
8	Steering column
9	Head tube
10	Front fork
11	Wheel
12	Frame or Structure
13	Deck
14	Rear fork
15	Main braking assembly
16	Motor
17	Transmission
18	Battery
19	Scooter folding system
20	Stabilizers
21	Handle for transportation
22	Mudguard
23	Knee-high stick

Figure 43: Examples of PLEVs Covered in EN 17128:2020: (a) 2-wheeled Electric Kick Scooter; (b) 2-wheeled self-balancing "Segway"; (c) 3-wheeled Electric Scooters; (d) Electric Unicycles and Hoverboards

Regarding chargers, EN 17128 requires that “Battery charging systems shall be in accordance with EN IEC 62485 series and EN 60204-1 or EN 60335-2-29:2004 as appropriate.”

The EN IEC 62485 series (International Electrotechnical Commission, no date) concerns secondary batteries and battery installations, and comprises:

Table 12: Standards within the EN IEC 62485 Series

Number	Subject
EN IEC 62485-1:2018	General safety information
EN IEC 62485-2:2018	Stationary batteries
EN IEC 62485-3:2014	Traction batteries
EN IEC 62485-4:2014	Valve-regulated Lead-acid batteries in portable applications
EN IEC 62485-5:2021	Safe operation of stationary Lithium-ion batteries
EN IEC 62485-6:2021	Safe operation of Lithium-ion batteries in traction applications

Of these, only EN IEC 62485-6:2021 (BSI Group, Feb 2021) is relevant to Lithium-ion batteries in PLEVs. This standard primarily concerns batteries but does have some requirements for the charger.

Regarding the other standards referred to in EN 17128:

- EN 60204-1:2018 concerns “Safety of machinery. Electrical equipment of machines. General requirements” and is designated under the SMSR. It does not contain any requirements for chargers, and therefore not discussed any further within this report.
- EN 60335-2-29:2004 has been withdrawn. The latest version of this standard is EN 60335-2-29:2021+A1:2021 (BSI Group, May 2022), see Section 6.12.6.

6.12.4 Standard Relevant to PLEV Battery Fires: EN 62133-2

EN 62133-2 covers the safety requirements for portable sealed lithium secondary cells, and for batteries made from them, for use in portable applications. It therefore covers cells and batteries for a vast range of applications, from wrist watches to laptops to garden equipment to e-scooters. It encompasses the main hazards associated with Lithium-Ion cells and batteries, but due to its very broad scope of applications, does not focus on some of the issues of PLEVs.

Since the August 2023 publication of the amended version of EN 15194 (see Section 6.12.1), EN 62133-2 is no longer recognised as an adequate Standard for e-bike batteries, but it is still referenced in the e-scooter standard, EN 17128.

6.12.5 Standard Relevant to PLEV Battery Fires: EN 50604-1

EN 50604-1 covers general safety requirements and test methods for secondary lithium batteries for light EV (electric vehicle) applications. This includes not only e-bikes and e-scooters, but also all electrified L-category vehicles.

EN 50604-1 is based on ISO 12405-3 (BSI Group, May 2014) which covers the safety of Lithium-Ion traction batteries for road vehicles. The clauses of the individual requirements in EN 50604-1 supplement or modify the corresponding clauses in ISO 12405-3. However, ISO 12405-3 has been withdrawn, and has been replaced by ISO 6469-1:2019+A1:2022 (BSI Group, Dec 2022), which has much the same scope, but reflects the latest state of the art.

The withdrawal of ISO 12405-3 leaves EN 50604-1 in a somewhat ambiguous position, because of the latter's reliance on clauses of the former. It is not clear whether EN 50604-1 will be updated to rely on ISO 6469-1, or to remove the ambiguity in some other way.

Despite this ambiguity, EN 50604-1 is now the only battery standard recognised in the e-bike standard EN 15194 (see Section 6.12.1) but is not mentioned in the e-scooter standard EN 17128.

6.12.6 Standard Relevant to PLEV Battery Fires: EN IEC 60335-2-29

EN IEC 60335-2-29:2021+A1:2021 (BSI Group, May 2022) is the EU/UK standard for battery charger safety. This is designated under the UK Electrical Equipment (Safety) Regulations 2016. It is not designated directly under the UK regulations for machinery, or general product safety. However, as noted in Section 6.10, standards which are designated under the Electrical Equipment (Safety) Regulations 2016 are commonly used to demonstrate compliance with the electrical hazards of machinery under the Supply of Machinery (Safety) Regulations 2008.

IEC 60335-2-29 is one of over a hundred sub-parts of IEC 60335-2, which covers the safety of household and similar electrical appliances. Like the other sub-parts of IEC 60335-2, it refers to EN 60335-1:2012+A15:2021 (BSI Group, Jun 2021) for most electrical safety requirements. It modifies these requirements, where necessary, for relevance to battery chargers.

6.12.7 Standards Relevant to PLEV Battery Fires: EN IEC 62485-6:2021

IEC 62485-6:2021 is one of the charger standard options stated in EN 17128, for compliance of a charger to be used with e-scooters. This standard primarily concerns batteries but does have some requirements for the charger. It requires charger-to-BMS communication and is therefore not applicable to the majority of existing e-scooter chargers, because most have no charger-to-BMS communication (see Section 4). Instead, IEC 60335-2-29 should be used (see Section 6.12.6).

Details of Standards Relevant to PLEV Fires

The details of the standards above are reviewed in detail in Section 7 of this report.

6.13 Technical Specifications and Draft Standards

PD ISO/TS 4210-10:2020 - Charging Connectors and Protocols

For battery safety, ISO/TS 4210-10 largely refers to EN 62133-2 and/or EN 50604-1. However, for the charger, ISO/TS 4210-10 is much more prescriptive than other standards:

- Charging systems are divided into “proprietary” and “non-proprietary” systems.
- A proprietary system shall have a proprietary (unique) plug/socket to ensure that the batteries can only be charged with the dedicated charger.
- A non-proprietary system must be designed with the assumption that the battery and charger come from different suppliers. To ensure safety, the e-bike shall be the master, and the charger shall act according to instructions from the e-bike.

The non-proprietary system concept evidently requires a standardised connection plug/socket and communication protocol. Annex C of ISO/TS 4210-10 provides two options for this standardisation which are described in Section 4.6 of this report.

ISO/TS 4210-10 has not been endorsed as a standard. However, in September 2023, ISO received a request from the USA to restart work on ISO/TS 4210-10, partly in light of interest from the US Consumer Product Safety Commission. If ISO were to accept the request from the USA, and if an updated version of ISO/TS 4210-10 were to be approved as a standard, then it could replace EN 15194 as the harmonised standard for e-bikes in the EU and may then also be adopted as a designated standard in the UK.

PD CEN/TS 17831:2023 EPAC Anti-tampering measures

For e-bikes, EN 15194 includes a clause on anti-tampering measures. The tampering issue is particularly relevant to e-bikes, because of the narrow definition of e-bikes that are exempt from Type Approval (see Section 6.2.2) and exempt from UK registration, road tax and insurance (see Section 6.2.3). If e-bikes are modified, for example to exceed the motor-assistance speed limit of 25 km/h or the power limit of 250 W, then they no longer comply with the rules of these exemptions. To help prevent such tampering, EN 15194 sets out the following requirements:

- Software parameters relevant to the maximum speed for motor assistance, maximum speed for start-up assistance, maximum vehicle speed, motor power and gear ratio shall only be accessible to manufacturers / authorised persons using proprietary, non-commercially available tools.
- Hardware modifications shall be detectable, for example by software plausibility checks of sensor signals, to prevent manipulation of the speed/power limits.
- “Closed” component sets, e.g. the motor will only work with the approved battery.
- Seals to reveal the presence of tampering.

PD CEN/TS 17831:2023 (BSI Group, Mar 2023) is intended to supplement the anti-tampering requirements of EN 15194. The scope section states that it “provides reproducible test methods recognized by the market aiming at protecting safety and fighting tampering of electric power assisted cycles”. In fact, the current version does not provide test methods, which it leaves to the manufacturer to define, but rather contains several requirements and recommendations which strengthen those of EN 15194 set out above.

CONEBI, the Confederation of the European Bicycle Industry, issued a statement in 2021 demonstrating the commitment of its members to compliance with the EN 15194 anti-tampering requirements (Confederation of the European Bicycle Industry, Sep 2021), and the UK Bicycle Association and its members supported this initiative (Bicycle Association, Sep 2021).

For e-scooters, EN 17128 does not mention anti-tampering measures. This reflects the absence of constraints on the maximum speed or power of e-scooters, permitted in the exemption from Type Approval (see Section 6.2.2).

Tampering is relevant to this report on PLEV fires, because increasing the power of the vehicle is likely to result in higher electrical current, resulting in greater heat generation in the battery cells, busbars, BMS components and wiring to the motor. Tampering is also relevant because it is difficult to make any modification to software and/or hardware while ensuring that the battery still meets its original safety requirements, as well as other attributes such as reliability and longevity.

Notably, the anti-tampering requirements in EN 15194 are only targeted at riding usage of the e-bike: They do not mention tampering related to charging of the battery.

In WMG’s opinion, tampering related to charging poses a more serious issue affecting PLEV fires. Increased charging power raises the likelihood of adverse effects inside the battery cells, such as Lithium plating on the anode, which can lead to internal short-circuits, which can lead to thermal runaway.

EN 17860-5 Carrier cycles. Part 5: Electrical aspects

The EN 17860 series of standards is being developed in response to increased demand throughout Europe for carrier cycles which are exempted from Type Approval. Carrier Cycles are designed to carry cargo and may have two or more wheels. Part 5 of the draft standard, EN 17860-5 (BSI Group, Sep 2023) covers electrical aspects of electrically power assisted Carrier Cycles (Carrier EPACs). The draft standard includes electrically power assisted cycle trailers (EPACTs). It also includes Series Hybrid Carrier EPACs (see Section 6.5.2 of this report).

For battery safety, the draft standard refers to EN 50604-1.

6.14 Non-UK Regulations and Standards

6.14.1 Standard Relevant to e-scooter Fires: IEC 60335-2-114

IEC 60335-2-114:2022 (BSI Group, Oct 2022) is one of over a hundred sub-parts of IEC 60335-2, which covers the safety of household and similar electrical appliances. IEC 60335-2-114 covers “Particular requirements for Personal-e-Transporters”.

It covers a similar diversity of PLEVs as EN 17128 (See Section 6.12.3 and Figure 43 of this report) but adds electric scooters with a detachable seat and electric skateboards, and allows for more than one rider as well as cargo.

Unlike EN 17128, IEC 60335-2-114 only covers the electrical safety of these PLEVs and does not include safety of riding or driving the device including aspects such as maximum attainable speed, stability, acceleration, braking, visibility, ergonomics, and reliability of driving controls such as acceleration or braking controls.

Like the other sub-parts of IEC 60335-2, it refers to IEC 60335-1 for most electrical safety requirements, including the charging of the batteries. Annex B of IEC 60335-1, which concerns battery-operated appliances and their detachable batteries, is modified somewhat by Annex B of IEC 60335-2-114. For example, a salt-water immersion test is added.

According to the quality assurance company Intertek (Intertek, no date), IEC 60335-2-114 is used in Australia, but is not applicable in Europe where EN 17128 is applicable. As stated in the Electrical Safety First report ‘Battery Breakdown’ (Electrical Safety First, Jul 2023), during a meeting of the National Committees of the European Electrotechnical Committee for Standardization (CENELEC) in October 2022, it was decided not to endorse IEC 60335-2-114 in Europe, but instead to apply EN 17128 for e-scooters and similar vehicles.

IEC 60335-2-114 lacks some of the important battery safety tests which are optionally included in EN 17128 by reference to EN 62133-2, such as over-charge, over-discharge and over-temperature. This is likely to have been a major factor in CENELEC’s decision not to adopt IEC 60335-2-114.

Many sub-parts of IEC 60335-2 are designated standards under the Electrical Equipment (Safety) Regulations 2016. However, IEC 60335-2-114 is not designated.

6.14.2 New European Battery Regulation

On 10 July 2023, the European Council of the European Union adopted a new regulation on batteries and waste batteries European Council (Jul 2023). The new regulation 2023/1542 has now been published in its final form (European Union, July 2023), and came into force on 17 August 2023.

The regulation will apply to all manufacturers, producers, importers and distributors of every type of battery placed within the EU market (defined as "Economic Operators").

The regulation will apply to all batteries including portable batteries; starting, lighting and ignition (SLI) batteries (used mostly for vehicles and machinery); electric vehicle batteries; industrial batteries (a cover-all for non-portable batteries which are not SLI, EV or LMT batteries. Stationary battery energy storage systems are a sub-set of industrial batteries); and batteries for light means of transport (LMT, e.g. electric bikes, e-mopeds, e-scooters). The LMT category therefore includes the PLEVs which are the subject of this report, and batteries for L-category type-approved electric vehicles, up to a battery weight limit of 25 kg. The categories are shown in Figure 44 below:

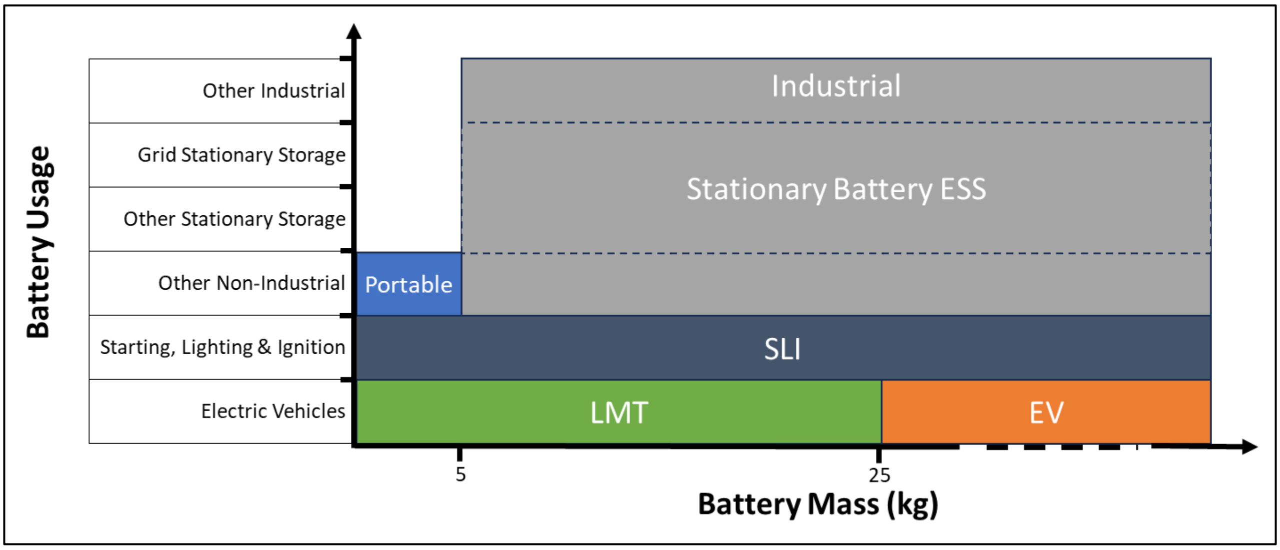


Figure 44: Battery Categories in the EU Battery Regulation 2023/1542

Timing and Implications of Requirements of the EU Battery Regulation

Much of the regulation concerns the circular economy, with requirements including a carbon footprint declaration and labelling, minimum recycled content in new batteries, supply chain due diligence, a digital battery passport and QR code, CE marking, and end-of-life management. The timeline for obligations relating to LMT batteries is set out in Figure 45.

While some obligations such as the declaration of recycled content are a decade away, others will be required much sooner. For example, from August 2024, LMT batteries must be accompanied by a document containing performance parameters (rated capacity, power, internal resistance, energy round-trip efficiency) and durability parameters (expected lifetime in years and number of charge-discharge cycles) and the BMS must be capable of calculating the degradation of the battery with usage (capacity fade, power fade, internal resistance increase, energy round-trip efficiency fade) and providing that information to the owner and other parties with a legitimate need.

Given the basic nature of the BMS in many PLEV batteries currently on the market, particularly those with relatively low purchase-price, it is likely that many do not currently meet the requirements above. To meet these requirements may require not just new software functions, but more capable microprocessor hardware and validation of both hardware and software, including re-verifying compliance with standards, and finally market introduction of updated or new products with these capabilities.

By August 2025, manufacturers must have in place due diligence policies regarding their supply chains, including third-party auditing of those policies, and maintain documentary evidence of the policies and audit verification reports for 10 years.

The Regulation also has very significant requirements for conformity assessment. This is divided into two main parts for series-manufactured batteries:

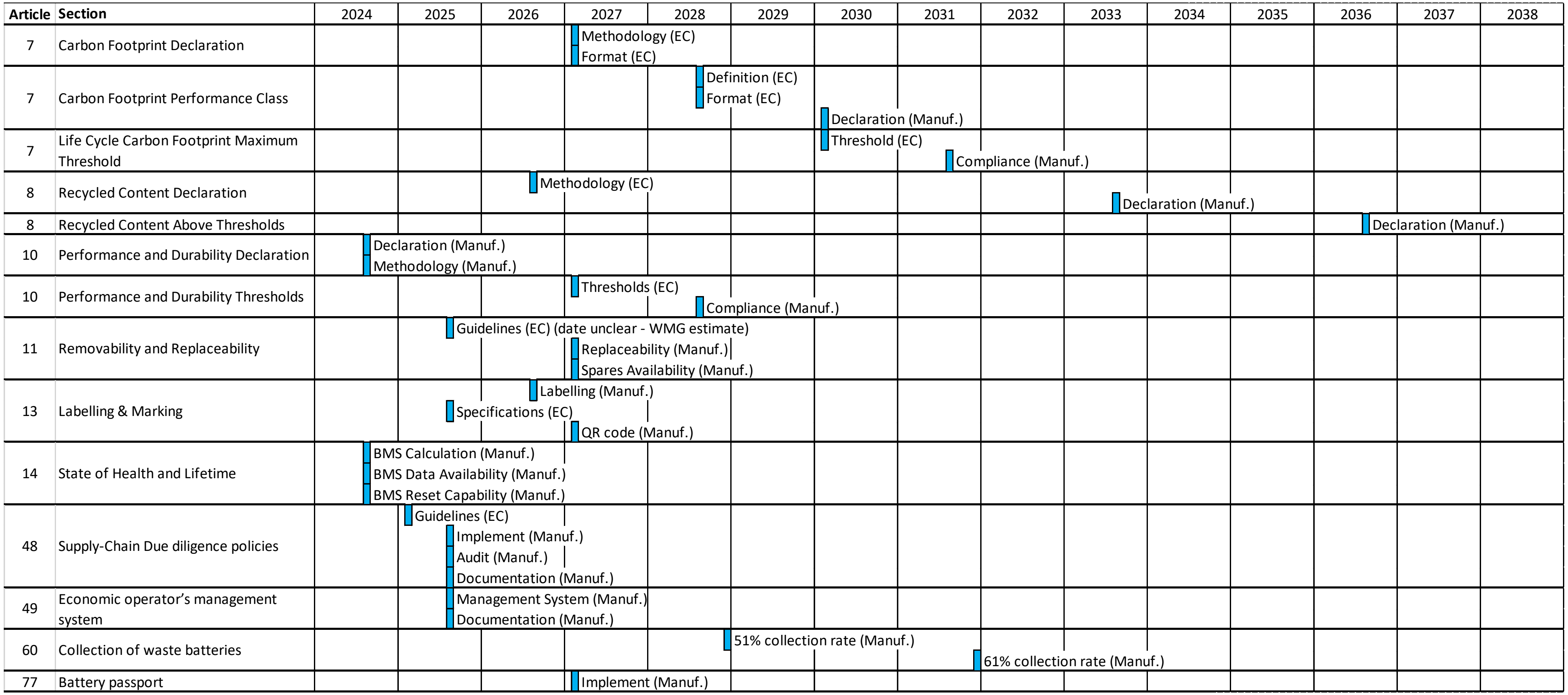
1. Internal production control
2. Quality assurance of the production processes

Item 1 can be met through processes and documentation within the manufacturer, including technical documentation, CE marking, declaration of conformity and procedures for the control of the manufacturing process. Documentation shall be kept available to national authorities for 10 years after the battery has been placed on the market.

Item 2 requires the use of a third-party notified body to assess the quality system and to perform surveillance, including periodic audits, to ensure that the manufacturer is fulfilling the obligations of the quality system. WMG views this as a significant positive step for ensuring the quality of batteries on the EU market, but also a significant additional requirement for manufacturers and notified bodies to meet.

In WMG’s view, such requirements in the EU Battery Regulation significantly raise the bar for placing batteries, and battery-containing products, on the EU market. This has both positive and negative implications for the UK market:

- It is unlikely that most manufacturers will develop different products for the EU and UK markets, so they will need to meet the requirements of both markets. Since the EU Battery Regulation requirements now exceed those of the UK, particularly with regard to the circular economy, the UK is likely to benefit from these requirements, even if it does not implement them directly.
- **However, some manufacturers may also be keen to find markets outside the EU with lower requirements, so that they can continue to sell products that do not comply with the EU Battery Regulations. This may make the UK a suitable target market for PLEV products with a lower level of regulatory control, including existing unsold stock, of which many manufacturers currently have very large quantities as a result of the downturn in the EU/UK PLEV market in the last two years** (See Section 9.5.1 and 9.7.1 of this report).
- The new EU battery regulation results in differences between the EU and GB regulatory requirements for PLEVs, with the result that CE-marking, indicating compliance with the EU regulations, will diverge from the meaning of UKCA marking, indicating compliance with GB regulations, for PLEVs and for Lithium-ion batteries generally. Since UKCA marking currently applies, amongst other product categories, to machinery (including many PLEV products) and CE marking of PLEVs is also currently accepted in the UK, this could lead to the presence of products with two different types of product safety on the UK market.
- WMG understands that OPSS is considering the implications of the divergence in product safety requirements associated with UKCA marking and CE marking of several product categories including PLEVs.



Article	Section	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038
7	Carbon Footprint Declaration				Methodology (EC) Format (EC)											
7	Carbon Footprint Performance Class					Definition (EC) Format (EC)		Declaration (Manuf.)								
7	Life Cycle Carbon Footprint Maximum Threshold							Threshold (EC)	Compliance (Manuf.)							
8	Recycled Content Declaration			Methodology (EC)							Declaration (Manuf.)					
8	Recycled Content Above Thresholds													Declaration (Manuf.)		
10	Performance and Durability Declaration	Declaration (Manuf.) Methodology (Manuf.)														
10	Performance and Durability Thresholds				Thresholds (EC)	Compliance (Manuf.)										
11	Removability and Replaceability		Guidelines (EC) (date unclear - WMG estimate)		Replaceability (Manuf.) Spares Availability (Manuf.)											
13	Labelling & Marking		Specifications (EC)	Labelling (Manuf.)	QR code (Manuf.)											
14	State of Health and Lifetime	BMS Calculation (Manuf.) BMS Data Availability (Manuf.) BMS Reset Capability (Manuf.)														
48	Supply-Chain Due diligence policies		Guidelines (EC) Implement (Manuf.) Audit (Manuf.) Documentation (Manuf.)													
49	Economic operator's management system		Management System (Manuf.) Documentation (Manuf.)													
60	Collection of waste batteries					51% collection rate (Manuf.)			61% collection rate (Manuf.)							
77	Battery passport				Implement (Manuf.)											

Figure 45: Timeline for Obligations Defined in the EU Battery Regulation 2023/1542 for LMT Batteries
(The party responsible for each obligation is shown in brackets. EC means the European Commission)

Safety Requirements in the EU Battery Regulation

The EU Battery Regulation mentions safety over one hundred times, but in general it contains few specific safety requirements. Chapter 2 is titled “Sustainability and Safety Requirements”, but it only contains safety requirements for stationary battery energy storage systems, not for other battery categories. WMG understands that further details will be covered by secondary legislation and standards, which are yet to be published.

For stationary battery energy storage systems, Annex V contains a list of tests:

- Thermal shock and cycling
- External short-circuit protection
- Over-charge protection
- Over-discharge protection
- Over-temperature protection
- Thermal propagation protection
- Mechanical damage by external forces
- Internal short-circuit
- Thermal abuse
- Fire exposure
- Emission of gases

These test categories are very similar to the categories covered in separate legislation and standards for other categories of battery-powered products, including PLEVs (see Section 7 of this report). However, Annex V does not state test methods or pass/fail criteria, but only explains the relevance of these test categories.

In WMG’s view, it would not be surprising if a future amendment of the EU Battery Regulation were to expand the applicability of Annex V to other battery categories including LMT batteries. However, in its current form, the regulation simply states in Article 5 that batteries in general “shall not present a risk to human health, to the safety of persons, to property or to the environment”. This is similar to the broad requirement that already exists for all products covered by the UK General Product Safety Regulations 2005, but does not provide the granularity on specific hazards, such as fire and explosion, that exists in the UK Supply of Machinery (Safety) Regulations 2008 which, in WMG’s view, helps manufacturers to focus on relevant risks.

WMG understands that the EU will, in time, set out greater clarity on how the high-level safety objectives of the EU Battery Regulation should be met, through secondary legislation / standards specific to particular industries and battery categories.

Repairability Requirements in the EU Battery Regulation

Relating to the circular economy and the desire to maximise the useable life of batteries, the EU Battery Regulation also includes requirements covering the right to repair and the ability to disassemble batteries at end-of-life. Article 11 paragraphs 5 and 6 state:

> 5. Any natural or legal person that places on the market products incorporating LMT batteries shall ensure that those batteries, as well as individual battery cells included in the battery pack, are readily removable and replaceable by an independent professional at any time during the lifetime of the product.
>
> 6. For the purposes of paragraphs 1 and 5, a portable battery or LMT battery shall be considered readily replaceable where, after its removal from an appliance or light means of transport, it can be substituted by another compatible battery

> without affecting the functioning, the performance or the safety of that appliance or light means of transport.

In December 2021, CONEBI issued a joint paper with ten other industry associations on the Removability and Replaceability of Portable Batteries (Confederation of the European Bicycle Industry, Dec 2021). This recommended a more stringent definition of “readily replaceable” as follows:

> A battery should be considered as readily replaceable where, after its removal from an appliance, it can be substituted by a **technically identical battery authorised by the manufacturer**, without affecting the functioning, safety or performance of that appliance. **A battery should always be exchanged as a whole. Parts of a complete, certified battery must not be replaced.**

The sections in bold above are notably absent from the final wording in Article 11 paragraphs 6 of EU Regulation 2023/1542.

The requirement to be able to remove individual cells has a major impact on the design and manufacturing of PLEV batteries, and in WMG’s view may have a detrimental effect on their safety.

This is because it is normal practice, in batteries for PLEVs and many other products including electric vehicles, that the electrical connections to individual cells are made by welding busbars to the positive and negative terminals of the cells.

Welded joints are used for several reasons:

- A welded joint requires no additional components such as screws or other fasteners, and therefore minimises the part-count and total part cost.
- A welded joint is spatially compact, so allows the overall size of the battery pack to be minimised by packing the cells and busbars efficiently into the available space.
- A well-validated weld process allows very good manufacturing repeatability. Given the large number of cell to busbar joints in a typical PLEV battery, repeatability and quality are paramount, to ensure that the final product has a low scrap rate.
- A well-engineered weld has excellent durability and is not greatly affected by corrosion. It is therefore well suited to applications, such as PLEVs, where changes in temperature and humidity are likely.
- A well-engineered weld is not adversely affected by mechanical shock and vibration. It is therefore well suited to vehicle applications, such as PLEVs, where high shock and vibration loads occur in normal operation.
- A well-engineered welded joint has very low electrical resistance, due to the intermixing of the metal in the cell terminal and the busbar. Unlike other types of metal-to-metal joint, it is not dependent on surface-to-surface contact between two separate components, since the weld process effectively combines the cell terminal and busbar into a single component. It therefore minimises parasitic heat generation and allows good operational efficiency, even with high electric current. By minimising the heat generated in the joint, the cell terminal temperature is minimised, thereby reducing the risk of heat conduction into the cell which could cause thermal runaway.

A weld can be achieved by a variety of manufacturing processes, but in all cases, it results in a joint which is intended to be extremely difficult to separate: the metallic materials of the cell terminal and the busbar become intermixed in the weld, in a way that can only be separated by processes such as machining or abrading or pulling the weld apart by applying a force that exceeds the strength of the weld, which permanently compromises the cell and the busbar. Several independent repair businesses have published videos of the processes they currently use to repair PLEV battery packs, including removal and replacement of cells and busbars. Some examples can be seen in the references (Heskon BV, 2022; AkkuZentrum (no date)).

WMG is not aware of any existing disassembly processes for welds which would allow, for example, the busbar to be returned to a pristine as-new state, to be re-used.

Furthermore, even if a welded cell could be removed and replaced, the new welds required to join the new cell to the busbar would require highly specialised welding equipment and expertise, which is likely to be well beyond the capability of most repair shops. For these reasons, to replace a single cell in a PLEV battery, it is very likely that all the cells will have to replaced. In all cases found (see references above), the professional repair businesses replace every cell in the battery (they do not mix original cells with new cells). This was also highlighted by the Confederation of the European Bicycle Industry (CONEBI) in their 2021 Position Paper on E-Bike Battery Repair. Repair businesses also appear to replace the OEM busbars with their own busbars, rather than OEM replacement parts, using multiple spot-welds to attach the busbars to each cell.

In WMG's opinion, it is therefore doubtful whether a welded cell to busbar joint is compatible with Article 11 Paragraph 5 of European regulation 2023/1542.

There are several alternatives to welding which could be used to comply with Article 11 Paragraph 5 of European regulation 2023/1542. Some of these are familiar to most consumers from other electrical and electronic devices:

- Sprung metallic contacts (e.g. in battery-powered torches, TV remotes, etc.).
- Plug-and-socket connections (e.g. for removable power-tool batteries).
- Screw contacts (e.g. inside a UK domestic mains-plug).

All these alternatives have disadvantages compared to a weld, regarding challenges such as shock and vibration, corrosion, durability, manufacturing repeatability, part-count, design complexity and cost.

However, in the context of this report, the first key disadvantage relates to the electrical resistance of the joint: It is extremely difficult to match the low electrical resistance of a weld with any alternative joint, and the part-to-part consistency of the joint resistance is also very likely to be worse. This presents the risk of unintended heat generation in the joint, with the risk that the excess heat is conducted into the cell, leading to thermal runaway.

The second key disadvantage of the requirement for replaceability of individual cells is the potential consequences for safety of mixing cells of different ages. This was highlighted by Claus Fleischer, managing director of Bosch eBike Systems (Bike Europe, Jul 2023), who stated:

> "for safety reasons, we regard the requirements for the removability and replaceability of individual cells from a battery pack as extremely critical and we see no real benefit as regards to sustainability. Replacement of individual cells leads to deteriorated performance and finally accelerated aging of the battery pack due to the onset of the de-balancing effect between the old and new cells. To put it short: the existing safety regulations work very well but we have now ended up with new conflicting requirements. Why change a safe product and good functioning system?"

In a subsequent article (Peace, Jul 2023) Hannes De Jong, managing director of Heskon, one of Europe's largest e-bike repair companies, stated:

> “In our experience, a single 'broken' cell is almost never the issue with a broken battery. In the first 1-4 years of its life an e-bike battery has issues external to the cells - a broken casing, broken connectors, broken BMS (battery management system chip) and broken fuses are the main culprits we have seen. After four years the overall performance (range potential) of a battery pack often declines meaning all cells are getting older and the full core pack needs to be changed rather than a single cell.”

WMG supports these views which can summarised as:

- Evidence suggests that the need to single-cell replacement is rare. Therefore, there appears to be little justification for requiring single cell replaceability.
- Mixing cells of different ages may accelerate aging, with possible safety risks.

Therefore, in WMG’s opinion, the requirement of Article 11 Paragraph 5 of European regulation 2023/1542 presents a high risk of unintended consequences, compromising the safety of both new and repaired PLEV batteries.

It is also notable that Article 11 Paragraph 6 refers only to the LMT battery, and not to individual cells, when specifying that a component is considered “readily replaceable” where, after its removal from an appliance or light means of transport, it can be substituted by another compatible battery without affecting the functioning, the performance or the safety. It is therefore unclear what is considered to be a “readily replaceable” cell, and leaves open the possibility that, under the new EU regulation, the safety could allowably be compromised by a replaced cell.

In WMG’s view, this needs to be clarified for the EU market, and if the UK considers adopting similar legislation for batteries, it should aim to resolve these issues.

It is stated, in the introduction to Regulation 2023/1542, paragraph (40), that:

> For repaired LMT batteries, the Commission will prepare rules on the safety of micromobility devices, building on experience at national and local levels of safety requirements, as announced in the communication of the Commission of 14 December 2021 on ‘The new EU Urban Mobility Framework’.

There is no timeline provided for this activity. However, WMG understands that the CEN standards, currently being drafted to support the EU battery regulation, take account of the points identified above, and the risks associated with single-cell replacement.

6.14.3 North American Standards and Regulations

This report focuses on the UK PLEV market, but it is instructive to consider how the regulatory environment compares in other developed markets. In the USA, an e-bike is defined in federal law as a “low-speed electric bicycle”, meaning a two- or three-wheeled vehicle with pedals and an electric motor of less than 750 W, with a maximum speed of 20mph when powered solely by the motor (US Congress, 2002). The US consumer organisation PeopleForBikes has promoted a classification of US e-bikes into three classes, which has been adopted by many US states (PeopleForBikes, Jul 2023):

Table 13: Classification of US e-bikes, adopted by most US States

Performance Parameter	Class 1	Class 2	Class 3
Maximum speed for motor power	20 mph	20 mph	28 mph
Motor activation	Only when pedalling	Throttle	Only when pedalling

Only the first two classes above meet the federal definition of a low-speed electric bicycle.

In the USA and Canada, many product safety standards are created by the Underwriters' Laboratories, which now operates globally under the UL Solutions brand.

In 2016 UL published UL 2272:2016 “Electrical Systems for Personal E-Mobility Devices”, which was developed in response to battery-related fires in self-balancing scooters (also known as hoverboards) which had recently entered the North American market. UL 2272 was updated in 2019 (UL Solutions, Oct 2019) and accredited by the American National Standards Institute (ANSI) and the Standards Council of Canada (SCC). The closest UK equivalent of UL 2272 is EN 17128.

In 2016, UL also published UL 2271 “Batteries for Use in Light Electric vehicle (LEV) Applications”, with the second edition published in 2018 (UL Solutions, Sep 2018). In this standard, the term LEV covers e-bikes, e-scooters, other PLEVs and some other categories including golf carts. UL 2271 is also accredited by ANSI and SCC. The closest UK equivalent of UL 2271 is EN 50604.

In 2022, UL published UL 2849:2022A “Electrical Systems for eBikes” (UL Solutions, Jun 2022), which was developed to provide a similar level of protections against battery-related fires in e-bikes. UL 2849 is also accredited by ANSI and SCC. The closest UK equivalent of UL 2849 is EN 15194.

The USA's regulatory regime is based around Federal legal requirements set and enforced by the Consumer Product Safety Commission (US Consumer Product Safety Commission, no date). These are, however, dated and now under review (bicycleretailer.com, May 2023). Following fire safety concerns, UL certification is now a legal requirement for e-bikes and battery packs sold in New York City (bicycleretailer.com, Mar 2023). The CPSC conducted a Forum on Lithium-Ion Battery Safety (US Consumer Product Safety Commission, Jul 2023), which has been summarised in the press (bicycleretailer.com, Jul 2023) and is discussed further in Section 8.1 of this report. Pending review of the CPSC standards, many e-bike manufacturers voluntarily comply with other standards, primarily from UL. Third-party testing of products for the North American market is performed by several accredited organisations.

6.14.4 Chinese Standards and Regulations

As described in Section 4.6 of this report, China published two mandatory standards simultaneously in late 2022, which are now being implemented. The first is “GB 42295-2022 Electrical Safety Requirements for Electric Bicycles” and the second is “GB 42296-2022 Safety technical Requirements for Chargers for Electric Bicycles”.

Notable requirements of these standards are as follows:

- The e-bike must interrupt the battery current in case of charging over-voltage, charging over-current, discharging over-current or operation outside of the minimum and maximum temperature limits for charging and discharging.
- The e-bike must have an audible alarm which will sound within 30 seconds if the internal temperature of the battery pack reaches 80 °C. The alarm sound level shall be at least 85 dB (A), measured at 2m distance left and right of the vehicle.
- “Mutual recognition and coordinated charging”, whereby the battery and charger shall mutually recognise each other before charging can begin
- The charging connector between the charger and the e-bike battery must only be of the design specified in GB 42296

The Chinese government recently released “GB 43854-2024 Safety technical specification for Lithium-ion batteries for electric bicycles” (Standardisation Administration of the People's Republic of China, April 2024). This is a new mandatory national standard, which will be implemented in November 2024. It applies to electric bicycles, as defined in the "GB 17761-2018 Safety Techncial Specifications for Electric Bicycles" (Standardisation Administration of the People's Republic of China, May 2018), which have a maximum continuous motor power up to 400W (compared to 250W for UK EAPCs) and a maximum voltage up to 60V. The new standard is complementary to the standards released in late 2022 for the safety of e-bike electrical systems and chargers.

GB 43854-2024 was released after WMG completed most of the work for this report, including the testing of UK-market products (see Sections 10 and 11), and is too recent to have undergone a thorough review in the preparation of this report. However, based on an unofficial translation of the document, the following are notable features of the GB 43854, which are highly relevant when considered together with the rest of this report:

- The standard includes 6 cell-level and 23 battery pack-level tests
- The cells-level tests include a nail-penetration test, for which the pass criterion is that the cell shall not catch fire or explode. This may be difficult to pass with many existing PLEV cells. This may oblige manufacturers to use LFP cells (see Section 3.4 of this report) or other chemistries with similar failure characteristics.
- The battery pack-level tests include a thermal propagation test (see Sections 3.7 and 6.15.1 of this report), wherein a central cell, surrounded by other cells, is overcharged or overheated to trigger single-cell thermal runaway. The battery pack shall not catch fire or explode within 5 minutes of detection of the initiated cell reaching thermal runaway. This may be difficult to pass with many existing PLEV battery packs. The standard mentions triggering of an alarm to indicate detection of single-cell thermal runaway in this test. WMG understands this to be the same alarm that is required in the mandatory e-bike electrical safety standard GB 42295 (see above).
- The standard requires three of the battery-pack tests to be performed with single faults introduced in safety components such charge/discharge switches and fuses. These tests are overcharge, external short circuit, and discharge over-current. It may not be possible to pass all these tests without redundant (back-up) components (see Section 7.3.1 of this report).
- The standard includes the same requirement as GB 42995 and GB 42996, for "mutual recognition and coordinated charging", whereby the battery and charger shall mutually recognise each other before charging can begin (see above).
- The standard requires the battery pack to "collect" data on cell voltages, pack voltage, current and temperature. The criteria for the associated test are not clear, but at the least it would prevent sale of batteries that lack these essential sensors.
- The standard requires the battery pack to be clearly and durably labelled with details including voltage, current and temperature limits. The label must remain complete and legible after wiping with water and alcohol and after 30 minutes in an oven at 950 °C. This temperature requirement means the label is likely to remain legible, even after the pack has had a fire. This would aid identification of the battery after a severe incident (see Section 9.5.2 of this report).
- The standard does not include a charging over-current test, despite this being required in the e-bike standard GB 42996 (see also Section 11.2.3 of this report).

WMG's preliminary assessment of GB 43854 is that it will require e-bike batteries on the Chinese market to achieve considerably higher safety requirements than currently exist in UK / European or North American standards. The GB 43854 tests described above have not been performed by WMG. However, WMG estimates that many of the UK-market batteries tested by WMG (see Sections 10 and 11 of this report) would not pass this new mandatory China-market standard.

6.15 PLEV Standards vs. Automotive Regulations

The evidence of PLEV fires described in Section 2 of this report shows that their severity is significantly higher than has typically been seen with other consumer products which use LIBs, with consequently greater harm to human health and damage to property. The reasons for this greater severity largely relate to the greater size of PLEV batteries, compared to other consumer products such as laptops, phones and power-tools.

Nevertheless, PLEV batteries are much smaller than those used in electric passenger cars, which accounted for >15% of UK new car sales in the first half of 2023 (Society of Motor Manufacturers and Traders, 2023). EV passenger cars are also known to suffer severe battery-related fires, but the degree of public and government concern regarding EV passenger car fires appears to be less than that for PLEV fires.

In this section, the regulatory framework for EV passenger cars is compared to that for PLEVs, to identify key differences and possible gaps / opportunities in PLEV standards.

As stated in Section 6.2.1, unlike PLEVs, passenger cars are subject to type approval. In the UK, the Driver & Vehicle Licensing Agency (DVLA) is responsible for verifying that a vehicle type complies with type approval before it can be used on the road. This gatekeeper role of the DVLA has no equivalent for vehicles that are excluded from type approval, such as most PLEVs (see Section 6.2.2), for which self-certification by the manufacturers applies.

In the EU, motor vehicle type approval is legislated in Regulation (EU) 2018/858 (European Union, May 2018), which was subsequently amended by Regulation (EU) 2019/2144 (European Union, Nov 2019). Regarding electrical safety, Regulation (EU) 2018/858 Annex II refers to UN Regulation No. 100 and Regulation (EU) 2019/2144 Annex I refers to UN Regulation No. 100, 02 series of amendments (Reg 100.02). In the UK, the GB type approval scheme uses Regulation (EU) 2018/858 which was retained in UK law on 31 December 2020 (Vehicle Certification Agency, Dec 2020), but does not use Regulation (EU) 2019/2144 (Vehicle Certification Agency, Sep 2022).

While the legislated version of UN Regulation No. 100 is Reg 100.02, as mentioned in Section 6.4.1 it has undergone a major update in Revision 3 (Reg 100.03). This in turn is heavily based on the Global Technical Regulation 20 (GTR20) (United Nations Economic Commission for Europe, May 2018), which is the result of international activity, under the auspices of the United Nations Economic Commission for Europe (UNECE), to streamline and unify global electric vehicle safety regulations.

Table 13 below provides an overview comparison of the battery-related automotive regulations (GTR20 and Reg 100.03) with the PLEV standards mentioned in Section 6.12 to 6.14.3. The detailed requirements and pass/fail criteria differ between the various documents, so this overview is based only on the headline requirement description. In some cases, the requirements can be satisfied with documentation, and in others a test must be conducted. This list is focused on battery-related items, so does not include some PLEV tests such as the blocked motor test in EN 15194. The UN38.3 transport requirements are not included in the comparison, as the table is intended to show requirements for operational use of the vehicle.

In the following sub-sections, notable differences between standards are highlighted and discussed.

Table 14: Overview of Requirements for Automotive Regulations vs. PLEV Standards

Market Sector	**Automotive**		**2,3,4 Wheel LEV**	**UK/EU PLEV-Related Standards**					**USA/Canada PLEV Standards**		**Batteries**		
Product Type	**Passenger & Goods**		**L-Category**	**eBikes**			**eScooters**		**eBikes**	**eScooters**	**LEV Batteries**	**Portable**	**LEV Batteries**
Document Title	**GTR20 (2018)**	**Reg 100.03 (2022)**	**Reg 136 (2016)**	**EN 15194: 2017**	**EN 15194: 2017 +A1:2023**	**ISO/TS 4210 -10: 2020**	**EN 17128: 2020**	**IEC 60335-2 -114**	**UL 2849: 2022A**	**UL 2272: 2019**	**UL 2271 (2018)**	**EN 62133-2 :2017 +A1:2021**	**EN 50604–1 :2016 +A1:2021**
Vibration	✓	✓	✓	(✓^{NORM})	✓^{NORM}	✓^{NORM}	✓	✓^{NORM}	✓	✓	✓	✓	✓
Thermal Cycling / Thermal Shock	✓	✓	✓	(✓^{NORM})	✓^{NORM}	✓^{NORM}	✗	✗	✓	✓	✓	✗	✓
Mechanical Shock (accel profile)	✓	✓	✓	(✓^{NORM})	✓^{NORM}	✓^{NORM}	(✓^{NORM})	✓^{NORM}	✓	✓	✓	✓	✓
Mechanical Shock (drop / impact)	✗	✗	✓	(✓^{NORM})	✓^{NORM}	✓^{NORM}	✓^{NORM}	✓^{NORM}	✓	✓	✓	✓	✓
Crush	✓	✓	✗	(✓^{NORM})	✓^{NORM}	✓^{NORM}	✗	✗	(✓^{NORM})	✓	✓	✗	✓
External Short Circuit	✓	✓	✓	✓	✓^{NORM}	✓^{NORM}	✓	✓	✓	✓	✓	✓	✓
Internal Short Circuit	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
Thermal Propagation by ISC **	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
Over-charge	✓	✓	✓	(✓)	✓^{NORM}	✓^{NORM}	(✓^{NORM})	✗	✓	✓	✓	✓	✓
Over-discharge	✓	✓	✓	(✓^{NORM})	✓^{NORM}	✗	(✓^{NORM})	✗	✓	✓	✓	✗	✓
Deep discharge				(✓^{NORM})	✓^{NORM}	✗	✗	✗	✗	✗	✗	✗	✓
Over-temperature	✓	✓	✓	(✓^{NORM})	✓^{NORM}	(✓)	(✓^{NORM})	✗	✓	✓	✓	✓	✓
Over-current Protection	✓	✓	(✓)	(✓^{NORM})	(✓)	(✓)	(✓)	✗	✓	✗	✗	✗	(✓)
Low-temperature Protection	✓	✓	✗	(✓^{NORM})	✓^{NORM}	✗	✗	✗	✗	✗	✗	✗	✓
Altitude / Low Pressure									✗	✗	✗	✗	✗
Imbalanced Charging	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓	✓	✗	✗
Dielectric Voltage Withstand	✗	✗	✓	(✓)	(✓)	✗	(✓)	✗	✓	✓	✓	✗	✗
Isolation Resistance	✓	✓	✓	(✓^{NORM})	(✓)	✗	(✓^{NORM})	✗	✓	✓	✓	✓	(✓)
Leakage Current (when Charging)	✗	✗	✗	(✓^{NORM})	✓^{NORM}	✗	✗	✓	✗	✓	✗	✗	✓
Grounding Continuity (vehicle)	✓	✓	✓	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗
Management of emitted gases	✓	✓	(✓)	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
Warning of failure	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
Warning of thermal event	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
Water Immersion	✓	✓	✓	(✓^{NORM})	✓^{NORM}	✓^{NORM}	✗	✓	✓	✓	✓	✗	✓
Exposure to Fire	✓	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓^{XXX}
Projectile Test	✗	✗	✗	✗	✗	✗	✗	✗					

✓ Item is included directly in the standard

✓^{NORM} Item is mandatory by reference to a Normative Standard

(✓^{NORM}) Item is optional by reference to a Normative Standard

(✓) Item is optional OR is indirectly covered by another test OR is mentioned but with no test defined OR the test method is inadequate

✗ Item is not included

* Only applicable for France, Japan, Korea and Switzerland

** Internal Short Circuit: Thermal Runaway of One Trigger Cell

^{XXX} Only applicable to vehicles with a passenger compartment, so not for eScooters, eBikes, etc.

^{HV} Only applicable to batteries > 60 V_{dc}

6.15.1 Thermal Propagation by Internal Short-Circuit

In the automotive industry, it has long been recognised that many battery fires start with a single cell thermal runaway, which then usually propagates to some, or all, of the other cells in the battery pack.

GTR20 and Reg100.03 require that:

> "For the vehicles equipped with a REESS [Rechargeable Electrical Energy Storage System, i.e. the battery] containing flammable electrolyte, the vehicle occupants shall not be exposed to any hazardous environment caused by thermal propagation which is triggered by an internal short-circuit leading to a single cell thermal runaway."

To satisfy this requirement, the vehicle must provide five minutes' advance warning before a hazardous situation occurs in the passenger compartment or must avoid such a hazardous situation occurring altogether.

The vehicle must also have "functions or characteristics" in the cell, battery or vehicle intended to protect the occupants from hazards resulting from thermal propagation.

GTR20 and Reg100.03 require that the manufacturer provides extensive documentary evidence of this, including a test report or validated simulation result. For the Chinese market, the equivalent legislative document is GB 38031-2020 (Standardisation Administration of the People's Republic of China, May 2020), which goes further than GTR20 and Reg100.03, in specifying the recommended test method options (nail-penetration and over-heating). Such test methods were not included in GTR20 (or in Reg 100.03) because the UNECE working group agreed that further research was needed before test methods are added to a future update of GTR20. The current version of GTR20 nevertheless suggests that OEMs could consider using the test method in GB 38031 as the basis for the documentary evidence they must submit to show compliance.

GB 38031 Annex C allows the manufacturer to choose either nail penetration or heating as the method to initiate single-cell thermal runaway, but if the first method does not cause thermal runaway, the second method must also be tested.

Partly as a result of these recent regulations, some automotive manufacturers have adopted a target of avoiding thermal propagation altogether, meaning that a single-cell thermal runaway will not result in thermal runaway in any other cells. Other manufacturers accept that propagation can occur, but nevertheless are obliged to take measures to slow the rate of propagation from one cell to the next, to meet the requirement to provide five minutes' warning before a hazardous situation occurs in the passenger compartment. This generally requires a combination of countermeasures including:

- Thermal barrier materials between neighbouring cells.
- Cells with vent features, which open reliably in the event of thermal runaway, to avoid unpredictable rupture of the cell casing.
- Channels within the battery pack, constructed from high-temperature resistant materials, to direct the vent gas from any cell which enters thermal runaway, towards the outside of the pack without impinging excessively on other cells.
- A vent feature in the casing of the battery pack, which will also open in the event of elevated pressure inside the casing, to allow the vent gases to escape into the atmosphere, to prevent unpredictable rupture of the battery pack casing.
- A battery casing which is sufficiently strong to contain the temperature and pressure caused by cell venting, without rupturing or exploding.

If a manufacturer decides to accept that thermal propagation will occur, then they must include robust detection systems to provide adequate warning to the vehicle occupants. Development and validation of sensors and software algorithms to predict and detect the onset of thermal runaway and thermal propagation are high-priority activities throughout the automotive sector.

In the aerospace sector, the advent of electric vertical take-off and landing (eVTOL) aircraft and other forms of increased aircraft electrification has led to development of requirements which are considerably more stringent than the automotive requirements, because of the severe implications of an aircraft losing propulsion power and/or suffering a fire during flight (RTCA, 2017; EASA, 2024). These tests are likely to require near-simultaneous triggering of thermal runaway in multiple cells, rather than the single trigger cell in GTR20 / Reg100.03 / GB 38031. Avoidance or containment of propagation in these aerospace tests is therefore likely to be more challenging.

Based on the evidence of real world PLEV fires (Section 2) and WMG's product testing (Section 11), it is clear that thermal propagation occurs in many cases, and that initial cause of the thermal runaway may relate to the BMS, rather than a single-cell failure.

The existing UK PLEV standards do not include any requirements or test protocols concerning thermal propagation resulting from single-cell thermal runaway.

WMG therefore suggests that OPSS explores what is required to introduce a thermal propagation requirement in existing or updated UK standards, similar to that in GTR20 / Reg100.03 or GB 43854-2024.

However, it is important to consider appropriate differences in test methodology and pass/fail criteria which are relevant to PLEVs, compared to automotive or aerospace applications.

In the automotive regulations, the pass criteria are based on the need to protect the occupants inside the vehicle cabin, by providing sufficient time to exit the vehicle before a hazard occurs inside the cabin. The unstated, but implicit, assumption is that once the occupants have exited the vehicle, they are able to achieve sufficient distance from the vehicle to avoid the associated hazards (such as fire, explosion, toxic fumes). This is generally a valid assumption, if the vehicle is outdoors, but may be more challenging in a garage, particularly in a private garage in which space around the vehicle is limited, and there may be only one exit door, or is attached or integral to an occupied house. It is notable that, in cases where automotive companies have been obliged to undertake recalls due to EV fires, they have often issued advice to owners to not park their vehicle in a garage, and to park it well away from buildings (US Department of Transportation National Highway Traffic Safety Administration, Aug 2021).

In the PLEV sector, reported incidents suggest that that the most frequently severe outcomes occur in indoor environments (London Fire Brigade, undated), where the PLEV and/or its battery are being charged or stored. This is analogous to the situation where an EV car is parked in a private garage, but with a greater likelihood of harm to humans and property, as PLEV and their batteries are often kept inside dwelling spaces. Nevertheless, a recent EV car fire in a shared parking facility under a multi-occupancy building in South Korea showed the devastating damage and harm that EV fires can cause in confirmed spaces attached to dwellings (Korea Times, Aug 2024).

Section 7 of this report considers appropriate test methodologies and pass/fail criteria relevant to the fires in PLEVs.

6.15.2 Warning of Thermal Event

As explained in Section 6.15.1 above, GTR20 and Reg100.03 require a warning to be provided to the driver if a battery thermal event occurs. GTR20 provides the following rationale for this requirement:

> “Real world data indicates that a thermal event within a battery pack is a major safety critical event associated with electric powered vehicles that can result in smoke, fire and/or explosion that can pose a safety hazard to occupants in the vehicle.”

For PLEVs, it can be argued that, while the user is operating the vehicle, a thermal event (fire and/or smoke) will be evident to the user more quickly than might be the case in a closed-cabin vehicle such as a passenger car, and that it is easier and quicker for the user to stop, dismount and escape to a safe distance from the PLEV than from a passenger vehicle. Furthermore, because PLEVs do not have closed passenger spaces, the danger from toxic fumes may be less than in a closed-cabin vehicle.

However, the evidence from real world PLEV fires (Section 2) shows that many fires occur when the vehicle is not being ridden, and either the vehicle or its battery is in an indoor space, such as a dwelling. In these enclosed spaces, the danger from fumes is likely to be higher than in an outdoor space, and escape routes are more limited. Additionally, the user cannot be expected to pay close attention to the PLEV or battery when it is stored indoors, so it is likely that their awareness of a fire will be delayed, compared with an event that occurs while riding the PLEV outdoors. Furthermore, in multi-storey buildings, such as blocks of flats, the danger is not only to those in the dwelling where the PLEV is stored, but also in neighbouring dwellings, particularly those in the floors above.

Irrespective of other measures which are intended to reduce the likelihood of PLEV fires, there will always be a risk that such events may occur, including in indoor spaces.

In the UK, landlords of rented accommodation must ensure that at least one smoke alarm is installed on each storey of a dwelling where there is a room used as living accommodation, and that a carbon monoxide alarm is fitted in any room used as living accommodation which contains a fixed combustion appliance (excluding gas cookers) (UK Government, Jul 2022). If a PLEV battery fire occurs, it is likely that smoke alarms and carbon monoxide alarms will both be triggered.

However, real world evidence shows that PLEV fires can develop extremely rapidly, such that a significant hazard to human health can occur in a matter of seconds, possibly before a domestic smoke or carbon monoxide alarm would be triggered. Furthermore, since smoke and carbon monoxide alarms are not mandatory in private dwellings, there is no guarantee of any warning to people living in private dwellings.

It is therefore worth considering whether a detection system built into the PLEV or battery could be an alternative, or supplementary, to domestic alarms, and possibly provide greater advanced warning of a fire. This would require that a sensing and warning system would be active while the PLEV is not being ridden. Ideally the system would be active at all times, but it would require some power, and so would represent a continuous, albeit slow, drain of the battery’s stored energy. If the battery were close to 0% SoC, and not being charged, then the system would need to shut itself down to prevent deep discharge of the battery cells. However, if the battery were plugged into a charger, then the system could draw power from the charger, without risk of discharging the battery.

It is important to note that the severity of thermal runaway is closely related to battery SoC: At low SoC, while thermal runaway is still possible, it is generally limited to progressive venting of smoke. At high SoC, the rate of heat release, and the total heat released during the whole event, is much higher, with a greatly increased likelihood of fire and explosion. See Section 3.4 for more details.

As described in Section 6.14.4, an audible warning is already a mandatory requirement for China-market e-bikes. The requirement must be fulfilled by the e-bike as a whole, rather than by the battery alone. If such a requirement were to be implemented in the UK, WMG believes that it should be a requirement of the battery, rather than the PLEV, in order for the alarm to be active even when the battery is removed from the PLEV, which is common practice for charging many PLEV batteries.

The sound-level required in the Chinese mandatory standard is 85 dB (A), measured at a distance of 2 m from the vehicle. For comparison, the UK standard for domestic gas detectors, EN 50291-1:2018 (BSI Group, Jan 2021) requires 85 dB (A) measured at a distance of 3 m, implying a sound intensity level significantly higher than the Chinese e-bike warning requirement. If a PLEV battery audible warning requirement were to be implemented in the UK, WMG suggests that the sound intensity level should be considered in the context of existing standards such as EN 50291-1.

WMG suggests that OPSS investigate the feasibility and practicality of audible alarms in PLEV batteries, which would sound in case of detection of thermal runaway. The circuit for the alarm would be active at all times, unless the power consumption of the circuit created a risk of deep-discharge of the battery.

6.15.3 Imbalanced Charging

Section 4.5.5 of this report explained the importance of cell balancing, to maximise the useable energy in a battery, but cell imbalance also affects safety: In the absence of effective communication between the BMS and charger, if cells become imbalanced and the BMS fails to interrupt charging, it is likely that some cells in the battery will be over-charged, creating a significant risk of thermal runaway.

In Section 4.5.4 of this report, production variation in cell capacity was identified as one potential reason for cell imbalance. This is a ‘beginning of life’ (BoL) issue. However, two further issues can exacerbate cell imbalance over the life of the battery:

1. Over their life, all cells will age, meaning that their capacity will progressively decrease and their resistance will increase. If they all age at the same rate, this will not worsen the cell imbalance, but in reality, they all age at different rates. The rate of ageing is affected by BoL cell-to-cell variations and is also temperature dependent: Hotter cells age more quickly. One factor affecting this is the uniformity of cell cooling. In a PLEV battery, the cells at the edge of the pack will be better cooled, so will age relatively slowly, while cells in the middle of the pack are surrounded by other cells, so cannot dissipate their heat effectively, and will generally reach higher temperatures, causing faster ageing. A second factor affecting cell temperature is the internal resistance of the cells. Cells with higher resistance generate more heat, so become hotter, and age more quickly. In high-quality cells, the resistance is very similar between all cells, but in poor quality cells, there may be a greater spread.
2. All cells suffer from self-discharge, because the electrical insulation between the anode and cathode, achieved by the separator, is not perfect. The rate of self-discharge in Lithium-ion cells is generally very slow, but not zero. Importantly, it also varies from cell to cell. In high-quality cells, the rate of self-discharge is very similar between all cells, but in poor quality cells, there may be a greater spread.

The on-going PLEV battery investigation being performed by Soteria in the USA has already identified that, of the first eight batteries that were disassembled:

> "Four of the battery packs had a battery management system (BMS) that specifically stated that it could not handle cell balancing, while three others did not mention cell balancing as part of the capabilities of the BMS. Only one had verified cell balancing." (Morin, 2023)

Based on these findings, WMG expects to make similar observations from disassembly of batteries purchased in the UK.

Currently, none of the EU/UK or US PLEV standards evaluate the presence or effectiveness of cell balancing capability in batteries. Neither is there any such test in the Type Approval tests for L-category or M/N-category vehicles in Europe.

For e-scooters, EN 17128 contains a test wherein a 50% imbalance is introduced in one cell of a battery, which is then charged to identify hazards. Each cell voltage is continuously monitored to determine if it has exceeded the limit condition. However, the standard does not explicitly state that exceeding the voltage limit is a fail, and states that venting of the cells is permitted. In WMG's opinion, this test is almost worthless.

The US standards for e-bikes, e-scooters and LEV batteries all include an imbalanced charging test. Crucially, this includes the requirement that the maximum voltage of the cells shall not exceed the manufacturer's specifications. While this does not test for the presence or effectiveness of a balancing circuit, it does verify that the safe operating voltage of individual cells will not be exceeded.

In WMG's view, the absence in Type Approval and standards of any test to evaluate the presence or effectiveness of cell balancing capability in batteries, is likely to be a decision based on the principle that the tests should focus only on safety outcomes, not on the technical implementation selected to achieve an outcome. The decision by a manufacturer to include a cell balancing circuit is a design decision and is not essential to achieve a safe system. Furthermore, because there are many possible implementations of a balancing circuit (see Section 4.5.5 of this report), it is challenging to define a test methodology which does not make implicit assumptions about the implementation, which may unfairly disadvantage other implementations.

Nevertheless, in WMG's view the lack of an effective Imbalanced Charging Test in the EU/UK PLEV standards and Type Approval regulations is a serious shortcoming.

WMG suggests that the standards for PLEVs and the Type Approval regulations for relevant vehicle categories should be updated to include an Imbalanced Charging Test (see also Section 7.12.6)

7 Review of Individual PLEV Standards

Section 6 explained the existing UK product safety legislation which applies to PLEVs, which relies on manufacturers to self-certify the compliance of their products. Section 6 also identifies the voluntary standards which are most applicable to PLEVs in the UK and the legislation or standards applicable in other markets such as the EU, USA and China. This section looks in greater depth at the content of these standards, to identify inconsistencies between UK standards, compare approaches in other geographic markets and other market sectors using Lithium-ion batteries such as consumer electronics, and identify shortcomings and areas of potential improvement in the UK PLEV standards.

7.1 General Scope

The electric micromobility market is characterised by a wide variety of products:

- Vehicles for recreation and for business purposes.
- Vehicles for different numbers of riders/occupants or for a driver and cargo.
- Vehicles for private ownership or for rental or owned and operated by a business.
- Vehicles with 1, 2, 3 or 4 wheels.
- Vehicle for use on-road or on shared vehicle/pedestrian areas or off-road.

Creating regulations and standards that effectively cover this diversity is challenging.

A comparison of the scope of various PLEV standards, battery standards and automotive and LEV regulations, is shown in Table 18.

The differences in scope between standards cause challenges in making direct comparisons between them. In some cases, the scope of products covered is very restrictive, with the potential for unintended consequences:

- Products that are outside of the tightly defined scope could escape the need to comply with the standards, or be denied the presumption of conformity offered by compliance with a designated standard.
- Product innovation could be stifled by the need to be within the tightly defined limits of a standard.

Further uncertainty can be caused by poorly conceived definitions for terminology used in the scope, or elsewhere in the regulations and standards.

Some key examples of narrowly defined scope, inconsistencies between documents and the poorly defined terminology are discussed below.

7.1.1 Vehicle Systems

The European/UK standard for e-bikes is EN 15194 (BSI Group, Aug 2023), which covers all the major vehicle systems, including the steering, brakes, chassis structure, wheels and tyres, mechanical drivetrain (comprising pedals, gears, chain, etc.), electric powertrain (comprising the battery, electric motor, control circuits, etc.), and ancillaries such as lights.

The European/UK standard for e-scooters is EN 17128 (BSI Group, Nov 2020), which covers a similar range of vehicle systems except for the mechanical drivetrain, which is absent from such vehicles.

By contrast, the US standards for e-bikes, UL 2849 (UL Solutions, Jun 2022), and e-scooters, UL 2272 (UL Solutions, Oct 2019), cover only the electric powertrain. This is an important distinction: Since the components of the electric powertrain are broadly similar across a wide range of vehicle types and use-cases, and represent similar hazards across all of those, it allows these US standards to be much less restrictive in the scope of vehicles and use-cases that they encompass.

The UK Type Approval legislation for cars and trucks takes a similar approach to the UL standards: Reg 100.02 covers only the electric powertrain (see Section 5.4.1).

The UK Type Approval legislation for L-category vehicles is closer in approach to that for e-bikes and e-scooters: Reg 3/2014 (UK Government, Oct 2013) contains fourteen annexes, each covering one aspect of the vehicle, with Annex IV covering electrical safety. As explained in Section 5.4.1 of this report, UNECE has produced Regulation 136 (United Nations Economic Commission for Europe, Feb 2016) for L-category vehicles' electric powertrain, but this has not been adopted in EU/UK Type Approval.

In WMG's view, placing the requirements for the electric powertrain into a separate standard, as done in the UL standards, is a preferable approach, because the same requirements can apply across numerous vehicle types.

WMG suggests that the standards bodies consider adopting an approach wherein the safety requirements of the electric powertrain for all PLEVs are placed in a single standard, separate from other vehicle system requirements.

7.1.2 Number of Wheels

The European/UK standard for e-bikes, EN 15194, only applies to bicycles, i.e. cycles with two wheels. The same applies to the technical specification ISO/TS 4210. This is more restrictive than the UK definition of an EAPC, which allows for two or more wheels (UK Government, Jun 2015), as does the exemption from Type Approval in Regulation 168/2013 (UK Government, Jan 2013).

Examples of long-established vehicle formats that do not have only two wheels are tricycles, quadricycles and handcycles which are powered by the arms rather than legs. Many recumbent cycles are tricycles, but even two-wheeled recumbents would be difficult to test according to some sections of EN 15194 which assume a conventional diamond-shaped bicycle frame. Nevertheless, the manufacturer can choose to comply with the sections of EN15194 which apply more broadly.

It is notable that the nearest equivalent standard in the USA, UL 2849, does not restrict the number of wheels.

7.1.3 User Type

The European/UK standard for e-bikes, EN 15194, only applies to "EPAC bicycles for private and commercial use with exception of EPAC intended for hire from unattended station." Likewise, for e-scooters, EN 17128 applies to PLEVs "with or without self-balancing system, with exception of vehicles intended for hire from unattended station."

Therefore, e-bikes and e-scooters for use in hire fleets, increasingly seen in UK cities, have not been considered in the standards, and any associated presumption of conformity, derived from their designation by Government, does not extend to such vehicles.

The closest equivalent US standards do not state any limitations on the type of user.

7.1.4 Environment for Vehicle Use

The European/UK standard for e-bikes, EN 15194, applies to "EPAC bicycles and subassemblies intended for use on public roads", where a public road is "any designated and adopted road, pavement, path or track on which a bicycle is legally permitted to travel", so it does not consider use on private land. In the Terms and Definitions section of the standard, it defines "city and trekking bicycle", "mountain-bicycle", "racing-bicycle", "recumbent bicycle", "young adult bicycle", "folding bicycle", but most of these terms are not used in the rest of the standard. The List of Significant Hazards notes that "the risk analysis was focused on EPAC as bicycles for city and trekking, including folding bicycles. Mountain bike and racing bike were not considered".

The EU/UK standard for e-scooters, EN 17128 applies to Personal Light Electric Vehicles, which are defined in the standard as "wheeled vehicles partially or totally motorized used for the transportation of one person in a public and/or private space", where public spaces include "roads, cycle tracks, sidewalks, public squares, parks, stations, airports…".

7.1.5 Power and Speed Limits

The definition of an EAPC specifies that the maximum continuous rated power shall not exceed 250 W. It is not clear what the rationale is behind this power threshold, although according to the former Secretary General of the European Two-Wheel Retailers' Association (ETRA) (LEVA-EU, April 2018), the 250 W limit was implemented in Regulation 168/2013 against the advice of that trade organisation, which advocated that bicycles of any power should be exempt from Type Approval, as long as the motor assistance was limited to ≤ 25 km/h.

The 250 W limit in EN 15194 exists only because of the limit in Reg 168/2013, meaning that any e-bike with power > 250 W must be Type Approved, even if its motor assistance is limited to 25 km/h.

It is notable that the nearest equivalent standard in the USA, UL 2849, does not have any restriction on the power of e-bike to which it applies, nor is it limited only to pedal-assist e-bikes; UL 2849 also applies to e-bikes that can provide motor power without pedalling.

WMG's view of current power definitions is that maximum continuous rated power is not closely representative of any safety critical performance attribute of a vehicle. Limiting continuous rated power only limits the duration a vehicle can sustain a high output power. The real world application of this are long sustained gradients or sustained high speeds, neither of which are relevant for urban duty cycles. Peak (as opposed to continuous) rated power is more representative of real world vehicle performance attributes such as maximum acceleration and speed.

The existing motor test normatively referenced by EN 15194 (EN 60034-1:2010) for continuous rated power does not test the maximum power of a motor, but determines that a motor can run at the set power for an unlimited duration without significant temperature increase (defined in EN 15194 as 2 Kelvin per hour), which any motor with a higher continuous rated power may also be able to do. When used as intended, continuous rated power is a metric that is intended to ensure that a motor can operate reliably at the power value specified by the manufacturer and does not place a cap on the maximum performance of a machine, as is the intention when a "maximum rated power" value is specified in regulation.

For e-scooters, EN 17128 does not have a power limit, but is limited to vehicles with a maximum design speed of 25 km/h. As e-scooters are purely electrically powered (no human pedalling power) they typically have higher motor power ratings than EAPCs. The e-scooters used in UK trials must meet the following definition: "fitted with no motor other than an electric motor with a maximum continuous power rating of 500W and is not fitted with pedals that are capable of propelling the vehicle". Given the absence of a power limit in EN 17128, it is unsurprising that some products for private use available on the market have power ratings well above the 500 W limit for trials in the UK and 250 W limit of EAPCs.

7.1.6 DC Voltage Limits and Risk of Electric Shock / Electrocution

The UK definition of an EAPC does not include a voltage limit, but EN 15194 is confined in scope to EAPCs with a rated voltage of ≤ 48 V_{dc} which means that some UK e-bikes may not strictly be covered by EN 15194. The relevant standard for e-scooters, EN17128 has a higher limit of ≤ 100 V_{dc}.

Meanwhile, EN 62133-2 for portable batteries does not specify a voltage limit.

EN 50604-1 is for removable LEV batteries, for vehicles up to Category L7 (4 wheels, up to 400 kg excluding the battery, up to 15 kW motor power). It states in its Scope that it covers voltage class A (≤30 V_{ac_rms} or ≤60 V_{dc}) and voltage class B (30-1000 V_{ac_rms} or 60-1500 V_{dc}). However, in the General Requirements section, it then states that “Battery packs/systems according to this document can be rated for voltage class A or voltage class B up to a maximum voltage of 200 V_{dc}”.

The US standards for e-bikes (UL 2849), e-scooters (UL 2272), and LEV batteries (UL 2271), do not state a voltage limit in their Scope sections, but some parts, such as the creepage and clearance (isolation/insulation) requirements are only specified up to 300 V_{dc}.

The limits of 48 V_{dc} in EN 15194,100 V_{dc} in EN 17128, and 200 V_{dc} in EN 50604-1, seem arbitrary and do not reflect any voltage thresholds defined in legislation. However, other standards and legislation do define a threshold to distinguish between “non-hazardous” voltage, and “high” or “hazardous” voltage.

In European/UK Type Approval legislation, including Reg 100.02 for cars and commercial vehicles and Reg 136 for L-category vehicles, an electric component or circuit is defined as high voltage if its working voltage is > 60 V_{dc} and ≤ 1500 V_{dc} or > 30 V_{ac_rms} and ≤ 1000 V_{ac_rms}.

In the USA, the UL standards for e-bikes, e-scooters and LEV batteries all define hazardous voltage as voltage exceeding 30 V_{ac_rms} or 60 V_{dc}.

UK regulations also include the Electrical Equipment (Safety) Regulations 2016 (EESR). The scope of this regulation includes electrical equipment designed for use with a voltage rating of between 50 and 1000 V_{ac_rms} for alternating current and between 75 and 1500 V_{dc} for direct current. In the context of PLEVs, this regulation is primarily applicable to chargers since they use the 230 V_{ac_rms} mains electrical supply. However, any PLEV with a battery whose voltage can exceed 75 V_{dc} is also within scope of the regulation.

The 75 V_{dc} threshold used in EESR is clearly slightly higher than the 60 V_{dc} threshold used in the UK Type Approval regulations. This may be due to different underlying assumptions. Typically, the threshold to distinguish between “non-hazardous” and “hazardous” voltage is based on the risk of electric shock / electrocution that can cause fibrillation of the human heart, i.e. a risk of severe injury or death. The voltage which can cause fibrillation depends on numerous factors, including but limited to:

- The locations on the human body which come into contact with the voltage source
- The physiology of the individual person (size, gender, body fat level, etc.)
- Environmental factors, such as the presence of moisture

Since the EESR generally cover equipment that is used indoors, environmental risk factors such as moisture, are generally less than in an outdoor setting. This may explain the

75 V_{dc} threshold. PLEVs are used both indoors (charging / storage) and outdoors, so the risk factors of both settings must be taken into account. More detail on the effect of voltage and current on the human body is provided in IEC 60479-1:2018 (BSI Group, Dec 2018).

In WMG's experience, across the vehicle electrification industry, 60 V_{dc} is widely accepted as the threshold to distinguish between "non-hazardous" and "hazardous" voltage, taking account of their use in an outdoor environment.

As a result of the hazardous nature of voltages greater than 30 V_{ac_rms} or 60 V_{dc}, Type Approval legislation for L, M and N category vehicles stipulate several stringent requirements regarding protection against electric shock. These include:

- Protection barriers than can only be opened with tools
- Non-enclosed hazardous voltage cables must be coloured orange
- Protection against contact with live parts, to IPxxD (see EN 60529:1992+A2:2013, BSI Group, Feb 2019)
- Labelling with a yellow hazard triangle with lightning-bolt symbol
- Resistance between any exposed conductive surfaces of < 0.1 Ω
- Resistance between hazardous voltage conductors and vehicle chassis > 500 Ω/V (to limit human exposure to any current to 2 mA).

These requirements do not apply if the maximum working voltage is below these threshold voltage values.

The definitions used for operating voltages are also important. The term "rated voltage" used in EN 15194 for e-bikes and EN17128 for e-scooters is defined in both standards as the "voltage declared by the manufacturer". In WMG's opinion, this is open to widely varying interpretations by different manufacturers.

In the Type Approval legislation for L, M and N category vehicles, the term "working voltage" is defined as "the highest value of an electrical circuit voltage rms, specified by the manufacturer, which may occur between any conductive parts in open-circuit conditions or under normal operating condition."

In WMG's opinion, the "working voltage" definition above is much more robust, and far less open to interpretation, than the "rated voltage" definition used in PLEV standards.

To illustrate why this definition matters, we will consider typical PLEV batteries. Most are labelled as 36, 48, 52 or 72 V_{dc}. These nominal values are usually based on the open-circuit voltage (measured with no charge or discharge current) when the battery is at 50% SoC. Most manufacturers use these voltage values because they equate to multiples of the typical Lithium-ion cell voltage. Table 14 below shows the approximate battery pack voltage at 50% SoC, for various numbers of Lithium-ion cells in series. It can be seen from this that the label values are not exactly representative of 50% SoC; they are rounded numbers, for convenience and to avoid confusing customers.

Table 15: Battery Pack Voltage for Various Numbers of Cells in Series at 50% SoC

No. of Cells in Series	1	10	13	14	20
Label voltage	3.6	36	48	52	72
Voltage at 50% SoC	3.6	36.0	46.8	50.4	72

It is not immediately obvious why manufacturers would offer packs at 48 and 52 V_{dc}, values which are so close together, and why they do not offer batteries with 15 cells or 16 cells in series (54 and 57.6 V_{dc} respectively at 50% SoC). However, with respect to the

60 V threshold for hazardous voltage, one should not consider the voltage at 50% SoC, but rather one must consider the maximum working voltage of each battery configuration. Table 15 shows the approximate battery pack voltage at 100% SoC.

Table 16: Battery Pack Voltage for Various Number of Cells in Series at 100% SoC

No. of Cells in Series	1	10	13	14	20
Label voltage	3.6	36	48	52	72
Voltage at 100% SoC	4.2	42.0	54.6	58.8	84

The 52 V_{dc} battery reaches 58.8 V_{dc} at 100% SoC, which is very close to the 60 V_{dc} threshold. This assumes a maximum cell voltage of 4.2 V_{dc}. Some cell manufacturers now offer cells with a maximum of 4.25 or even 4.3 V_{dc}. With the latter, the battery pack could reach 60.2 V, which means it would be classified as having a hazardous voltage.

For this reason, 14 Lithium-ion cells in series are the maximum possible within the 60 V_{dc} threshold, and even this is perilously close to the threshold: In a real operating electric powertrain, the “dc” voltage continuously fluctuates, due to changes in motor power demand and the high-frequency switching of the semiconductor devices in the motor controller, which cause some “ripple” on the voltage at the battery. During charging, the voltage from the charger may also contain some ripple.

These effects, together with measurement error, combine to mean that it is difficult to ensure that a battery with 14 cells in series always stays below 60 V. For this reason, a more common configuration is 13 cells in series, which ensures that the voltage is always comfortably below 60 V, in the absence of failure modes such as over-charge.

Other manufacturers, notably Bosch, use only 10 cells in series for all their PLEV batteries, with a nominal voltage of 36 V_{dc} (Robert Bosch GmbH, no date), implying a maximum voltage of around 42 V_{dc}. This may reflect a more conservative corporate safety policy, but may also reflect other legislation, some of which uses a 50 V_{dc} threshold, rather than 60 V_{dc}, or may have been determined based on the 48 V_{dc} scope limit of EN 15194.

In Table 14 and Table 15 above, batteries up to 72 V_{dc} are shown. While e-bikes typically have batteries of 36 or 48 V_{dc} nominal voltage, e-scooters have batteries up to 84 V_{dc} (electricscooterinsider.com, 2023; Dualtron Minimotors, no date). These e-scooters should therefore be compliant with the Electrical Equipment (Safety) Regulations 2016, since they exceed 75 V_{dc}. It is not known whether they do comply.

In WMG’s opinion, the 48 V_{dc} limit in EN 15194 is arbitrary and unjustified; it is not mentioned in Annex ZA of EN 15194, which tabulates the relationship between the standard and the clauses of the Machinery Regulation. Similarly, the 100 V_{dc} limit in EN 17128 is lacking apparent justification. It is unclear from the standards which parts thereof may need to be revisited or updated if the voltage limits were changed.

In general, higher battery pack voltages are used to make it easier to achieve higher motor power levels. Power is equal to voltage multiplied by current (P = V x I), so for a given power requirement, higher voltage allows lower current. Lower current allows the use of thinner conductors, such as the wires from the battery to the motor.

In the context of larger vehicles, such as passenger cars and good vehicles, this is a key consideration, particularly for fast charging, where higher battery voltage allows slimmer and lighter plug-in charging cables, and smaller semiconductor devices.

In the context of PLEVs, fast charging is not a priority for individual consumers whose typical daily journey is within the maximum riding range of the battery and have time to recharge over a period of several hours, such as overnight. Users with higher daily distance requirements, or rental fleet operators, may have a greater need for fast-charging, but since most e-bike batteries are easily removable, swapping between two or more batteries is also an option. The e-bike batteries studied for this report are not designed for fast charging (see Sections 10 and 11). Regarding discharge, motor mechanical power is currently limited for EAPCs to 250 W, equating to approximately 300 W electrical power from the battery (some power is lost as heat in the motor). E-scooters do not have a power restriction in EN 17128, which justifies this approach based on the assumption that the need for easy portability of such vehicles leads to a practical weight constraint which inherently limits the power that the battery can deliver. Meanwhile L1e-A power-cycles are limited to 1000 W. Table 16 shows the battery current required to deliver 300 W or 1000 W electrical power, for each of the common PLEV battery voltages.

Table 17: Effect of Battery Voltage on Battery Current for PLEVs

Battery Voltage	36 V	48 V	52 V	72 V
Battery Current for 300 W Power	8.3 A	6.3 A	5.8 A	4.2 A
Battery Current for 1000 W Power	27.8 A	20.8 A	19.2 A	13.9 A

While there is a significant difference in current between these battery voltages, none of these cases represents a major challenge for wire sizes or other components. For comparison, passenger car batteries typically operate up to 300 – 500 A. Therefore, based on the charging and discharging power requirements, in WMG's view there is no technical justification for why an e-bike or e-scooter would need a battery with a voltage above 60 V. It is therefore feasible that all PLEVs could have voltages below this hazardous voltage threshold.

As noted above, EN 17128 states that it covers vehicles with a rated voltage up to 100 V_{dc}. Based on the 60 V_{dc} threshold for hazardous voltage above, one would expect that the standard would include protections against electric shock / electrocution like those defined in Type Approval legislation. Annex A of EN 17128 contains a list of significant hazards that have been considered in writing the standard. This includes:

- Electrocution due to breakage of the battery during normal use.
- Electrocution due to a short-circuit or sealing defect of the battery during use.

Annex A states that these electrocution risks are addressed in Clause 10, which covers charging of batteries, but does not cover other usage such as riding or removal / insertion of a removable battery. It addresses the risk of accidental contact with charging contacts and plugs, but not the similar risk for other contacts and plugs, such as those to connect the battery to the motor. It appears that the authors intended only to address the hazard of mains AC voltage, via the charger, and did not regard the 100 V_{dc} level as hazardous. In WMG's view, EN 17128 therefore fails to completely address the risk of electric shock.

ISO/TS 4210-10 states in its Scope section that it covers systems having a Safety Extra Low Voltage (SELV) maximum voltage up to 60 V_{dc} including tolerances. It defines the SELV as voltage not exceeding ripple-free 60 V_{dc} between conductors and earth, the no load voltage not exceeding ripple-free 60 V_{dc}.

In WMG's view, it is good that this technical specification uses the 60 V_{dc} threshold, and that it attempts to address noise factors such as tolerances and voltage ripple. However, the wording used in the Scope and the definition of SELV should be improved.

In WMG's view, it is technically feasible for all PLEVs to a have a maximum working voltage of ≤60 V_{dc}, which would minimise the risk of electric shock / electrocution. This would avoid the need for protective measures against electric shock from hazardous voltages but would retain compatibility with power ratings up 1000 W and beyond.

In WMG's view, the standards for PLEVs should adopt the same approach to hazardous voltage as is used in the Type Approval legislation applicable to other types of electric vehicle. This could be done in one of two ways:

1. The standards could restrict their scope to a maximum limit of 60 V_{dc} and 30 V_{ac_rms} on the working voltage for PLEVs, avoiding the need for protection from hazardous voltage; or
2. The standards could include requirements for hazardous voltage systems regarding protection against electric shock, per those of the Type Approval documents.

It is also worth noting that ISO 6469-3:2021 (BSI Group, Nov 2021), covering electrical safety requirements for electrically propelled road vehicles, defines voltage classes A and B, with voltage class B (>60 V_{dc} and >30 V_{ac_rms}) subdivided as shown below:

Table 18: Voltage classes defined in ISO 6469-3:2021 for Electrically Propelled Road Vehicles

Voltage class	DC voltage range	AC voltage range
A	0 – 60 V_{dc}	0 – 30 V_{ac}
B1	60 – 75 V_{dc}	30 – 50 V_{ac}
B2	75 – 1500 V_{dc}	50 – 1000 V_{ac}

Voltage class B2 aligns with The EESR. It allows systems in voltage class B1 to meet lower electrical safety requirements than class B2, although still more stringent than class A. This approach could also be adopted by the PLEV regulations.

WMG suggests that standards for PLEVs should adopt the same definition for working voltage and the same thresholds to define high/hazardous voltage as are used in the Type Approval regulations for L, M and N category vehicles.

WMG suggests that the Scope section of all standards for PLEVs should unambiguously state the ac and dc voltage limits for which they are valid, and in the Rationale section should justify those limits, particularly where they do not align with thresholds defined in legislation or other electrical safety standards.

The arguments above pertain to the risk of electric shock due to hazardous voltage, which is separate from the risk of fire or explosion, which is the focus of this report. However, the ac and dc voltage of the system also relate to risk of fire: Insulation materials and isolation creepage and clearance distances must be sufficient to prevent arcing or short-circuit between components. Arcing represents a particular fire risk, because an arc comprises a very high temperature plasma, which is capable of initiating combustion of combustible gases, liquids and nearby solid materials, and can melt materials including metals.

If manufacturers follow the guidelines and normative standards referenced in EN 15194 and EN 17128, then such fire risk should be avoided. However, there are cases of reasonably foreseeable misuse, such as installing a battery with a higher voltage than the vehicle was designed for, where the insulation or creepage and clearance distances may be compromised, which would increase the risk of fire. While this risk can be addressed by warnings and instructions, mitigations inherent in the design are a more robust approach. If all PLEVs had maximum working voltage of ≤60 V_{dc} then the same insulation and creepage and clearance distances could be specified for all PLEVs. This would reduce the risk of a fire hazard from installing a battery with an inappropriate voltage.

Table 19: Comparison of the Scope of Various Standards and Regulations

Market Sector	**Automotive**		**2,3,4 Wheel LEV**	**UK/EU PLEV-Related Standards**					**USA/Canada PLEV Standards**		**Batteries**		
Product Type	**Passenger & Goods Vehicles**		**L-Category**	**eBikes**			**eScooters**		**eBikes**	**eScooters**	**LEV Batteries**	**Portable**	**LEV Batteries**
Document Title	**GTR20 (2018)**	**Reg 100.03 (2022)**	**Reg 136 (2016)**	**EN 15194: 2017**	**EN 15194: 2017 +A1:2023**	**ISO/TS 4210 -10: 2020**	**EN 17128: 2020**	**IEC 60335-2 -114**	**UL 2849: 2022A**	**UL 2272: 2019**	**UL 2271 (2018)**	**EN 62133-2 :2017 +A1:2021**	**EN 50604–1 :2016 +A1:2021**
Official vehicle categories	- M-category - N-category	- M-category - N-category	L-Category	EPAC	EPAC	- EPAC - EPAC ESAs	PLEVs not subject to Type Approval		- EPAC - Non pedal assist	Personal e-mobility devices	N/A	N/A	N/A
Number of wheels	≥ 4	≥ 4	2, 3, 4	2	2	2	Unlimited		Unstated	Unstated	N/A	N/A	N/A
Load	Unstated	Unstated	Unstated			Unstated	- 1 Person - Cargo		Unstated	- 1 Person	N/A	N/A	N/A
Users	Unstated	Unstated	Unstated	- Private - Commercial - Not hire EPACs	- Private - Commercial - Not hire EPACs	Unstated	Undefined		Unstated	Unstated	N/A	N/A	N/A
Environment	Unstated	Unstated	Unstated	- Road only	- Road only	Unstated	- Roads - Public spaces - Private spaces		Unstated	Unstated	N/A	N/A	N/A
Vehicle Systems	- e-Powertrain	- e-Powertrain	- e-Powertrain	- e-Powertrain - Steering - Brakes - Structure - Wheels & tyres - Pedals, gears, chain - Ancillaries	- e-Powertrain - Steering - Brakes - Structure - Wheels & tyres - Pedals, gears, chain - Ancillaries	- e-Powertrain - Steering - Brakes - Structure	- e-Powertrain - Steering - Brakes - Structure - Wheels & tyres - Ancillaries		- e-Powertrain	- e-Powertrain	- Battery	- Battery	- Battery
Relevant Hazard Types & Mitigations	- Fire/explosion - Thermal - Mechanical - Electrical - Chemical	- Fire/explosion - Thermal - Mechanical - Electrical - Chemical	- Fire/explosion - Thermal - Mechanical - Electrical - Chemical	- Fire/explosion - Thermal - Mechanical - Electrical - Chemical	- Fire/explosion - Thermal - Mechanical - Electrical - Chemical	- Fire/explosion - Thermal - Mechanical - Electrical	- Fire/explosion - Thermal - Mechanical - Electrical - Chemical		- Fire/explosion - Thermal - Mechanical - Electrical	- Fire/explosion - Thermal - Mechanical - Electrical	- Fire/explosion - Thermal - Mechanical - Electrical - Chemical	- Fire/explosion - Thermal - Mechanical - Electrical - Chemical	- Fire/explosion - Thermal - Mechanical - Electrical - Chemical
Mitigations				- Anti-tampering	- Anti-tampering	- Anti-tampering							
Motor Assistance Type	N/A	N/A	N/A (L1e-A = Pedal	- Pedal Assist	- Pedal Assist	- Pedal assist	N/A		- Pedal assist - Non pedal	Unstated	N/A	N/A	N/A
Motor Power Limit	Unstated	Unstated	≤ 15 kW (L1e-A ≤ 1 kW)	≤ 250 W	≤ 250 W	None	None		Unstated	Unstated	N/A	N/A	N/A
Motor Assistance Speed Limit	Unstated	Unstated	None (L1e-A ≤ 25 km/h)	≤ 25 km/h	≤ 25 km/h	None	≤ 25 km/h		Unstated	Unstated	N/A	N/A	N/A
Maximum vehicle design speed	None	None	None	None	None	None	≤ 25 km/h		Unstated	Unstated	N/A	N/A	N/A
DC Voltage Limit	≤ 1500 Vdc	≤ 1500 Vdc	≤ 1500 Vdc	≤ 48 Vdc	≤ 48 Vdc	≤ 60 Vdc	≤ 100 Vdc		≤ 300 Vdc	≤ 300 Vdc	≤ 300 Vdc	Unstated	≤ 200 Vdc
AC charging voltage limit	Unstated	Unstated	Unstated	230 Vac	230 Vac	Unstated	240 Vac		Unstated	Unstated	N/A	N/A	N/A

7.1.7 Scope of Battery Standards

The Sections above, and Table 18, focus mainly on the vehicle parameters. It is also worth noting other scope limitations of the two battery standards used in the European/UK, standards EN 50604-1 for LEV batteries and EN 62133-2 for all portable batteries.

EN 50604-1 is intended only for removable batteries for LEVs. It then divides “removable batteries” into two sub-categories:

- Portable batteries, which may be removed by hand from an LEV while in operation, having a mass of < 12 kg.
- Mobile batteries, which may be removed, with the assistance of a device, while not in operation, having a mass greater than 12 kg and equipped with wheels for moving or by using an assistance equipment or inside of a battery swap system.

In general, e-bike and e-scooter batteries are below 12 kg, but not all are removable, especially in e-scooters.

EN 62133-2 does not specify a mass limit but is intended only for portable batteries.

In WMG’s view, EN 50604-1 could easily be extended to cover non-removable batteries with very little change to the contents. This would make it more broadly applicable to PLEVs that are not e-bikes, many of which have non-removable batteries.

7.2 Risk Assessment Methodology

A risk assessment is an essential requirement of the Supply of Machinery (Safety) Regulations 2008 (SMSR, see Section 6.9 of this report), which the authors of Standards aim to fulfil, to ease the burden on individual companies. If the standard is deemed by the UK government to be such that following it will ensure a product complies with the essential health and safety requirements (EHSRs) of the SMSR, then it will become a designated standard under the Machinery Regulations. The standard then confers, on any product which meets the standard, a presumption of conformity with the EHSRs of the SMSR. However, if the standard is not designated (as is the case for the e-scooter standard EN 17128) or is designated with restrictions then the manufacturer must conduct their own risk assessment.

The risk assessments underpinning EN 15194 and EN 17128 are based on the methodology defined in EN ISO 12100:2010 “Safety of machinery. General principles for design. Risk assessment and risk reduction” (BSI Group, Dec 2010).

For e-bikes, EN 15194 includes ISO 12100 as a normative standard.

For e-scooters, EN 17128 also uses ISO 12100 as a normative standard. However Annex D, which describes the rationale for various aspects of the standard, states that ISO 12100 is oriented towards industrial usage of a product, so needed to be adapted to suit usage by normal consumers including children.

WMG has reviewed ISO 12100 and agrees with the statement above in EN 17128. The original intent of ISO 12100, to be applied to the industrial use of machines, is particularly obvious from Annex B, which provides examples of hazards, hazardous situations and hazardous events. Examples of the illustrations of hazardous situations are shown below:

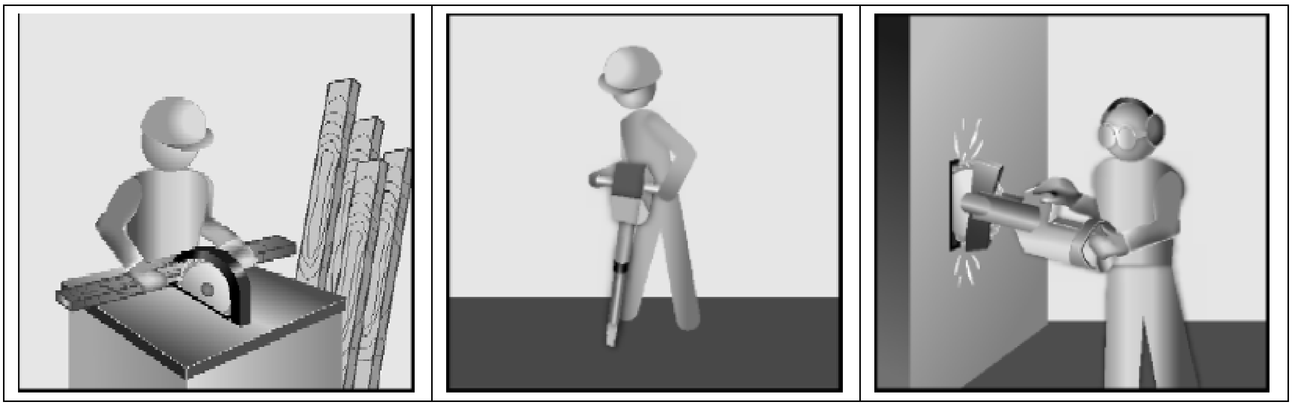


Figure 46: Examples of Hazardous Situations from EN 12100 Annex B

ISO 12100 does include examples of hazards that are pertinent to PLEV fires, including Thermal Hazards (explosion, flame, high temperature) and Material/Substance Hazards (combustible, explosive, flammable, fume) and the respective potential consequences (burns, breathing difficulties, etc.), but does not provide examples of human interaction with the “machine” (e-bike / e-scooter) which are similar to those that present the greatest risk to consumers (e.g. sleeping in close proximity to a charging battery), nor the type of environment associated with PLEV fires (confined and cluttered domestic spaces) nor of the type of device behaviour associated with thermal runaway of Lithium-ion batteries (sudden emission of flames, hot ejecta and toxic gas). This is likely a reflection of the fact that batteries are not considered to be machinery (see Section 6.7 of this report).

Hence, while the general risk assessment methodology is good, the examples provided are not sufficiently suggestive of hazards considered in this report, with the consequent risk that those following the ISO 12100 methodology to create product-specific Standards such as EN 15194 or EN 17128 may overlook some of the relevant hazard and hazardous situations and hazardous events.

7.2.1 Relevant Hazards Covered in EN 15194 (e-bikes)

For e-bikes, EN 15194 does not explicitly list the risks which have been considered, but Annex ZA tabulates the relationship between the standard and the essential requirements of Annex I of the Supply of Machinery (Safety) Regulations 2008. It lists the sections of the Regulation, and the relevant sections of the Standard pertinent to addressing those requirements, of which the most relevant to PLEV fires are listed in Section 6.9 of this report. These include extreme temperature, fire, explosion and hazardous fumes.

7.2.2 Relevant Hazards Covered in EN 17128 (e-scooters)

For e-scooters, EN 17128 states in its Rationale (Annex D) that the standard was “developed under the umbrella of the European Directive n°2006/42/EC”, which is the basis of the UK Supply of Machinery (Safety) Regulations 2008. Unlike EN 15194, it does not refer explicitly to the requirements of the SMSR. However, in Annex A, it enumerates the main sources of risks and the clauses of the standard which address these. For batteries and cables, it lists:

- Electrocution, fire outbreak or intoxication due to breakage of the battery during normal use.
- Electrocution, outbreak of fire or intoxication due to a short-circuit or sealing defect of the battery during normal use.
- Electrocution or loss of a safety function following failure of the wiring.

Notably, this list does not mention explosion or extreme temperature.

7.2.3 Relevant Hazards Covered in EN 62133-2 (Portable Batteries)

For portable lithium batteries, EN 62133-2 lists the hazards considered as:

- Fire
- Burst / explosion
- Leakage of cell electrolyte
- Venting
- Burns from excessively high external temperatures
- Rupture of battery case with exposure of internal components

7.2.4 Relevant Hazards Covered in EN 50604-1 (LEV Batteries)

For LEV lithium batteries, EN 50604-1 does not explicitly list the risks which have been considered. In the Introduction, it mentions fire and explosion risks. In Section 5, General Requirements, it mentions further hazards that can occur during battery testing, including chemicals and burns, and it specifies pass criteria for various tests including no leakage, rupture, fire or explosion. The risk assessment methodology underpinning EN 50604-1 is not explained.

In some respects, EN 50604-1 is the most comprehensive battery standard relevant to PLEVs (it is required for compliance with the latest version of the European e-bike standard, EN 15194), but the lack of explanation of the underpinning risk assessment methodology is a significant shortcoming of this standard.

7.2.5 Relevant Hazards Covered in UL Standards

The UL standards for e-bikes (UL 2849), other PLEVs (UL 2272) and LEV batteries (UL 2271) do not describe their underpinning risk assessments.

All of them mention hazardous voltage (>30 V_{ac} or >60 V_{dc}).

UL 2271 and UL 2272 both require a “post-test cycle”, meaning a charge and discharge cycle of the battery, if it is still operational after preceding electrical, mechanical and environmental tests. For the post-test cycle, the following are listed as non-compliant results, which equate to hazards:

- Explosion
- Fire
- Rupture
- Electrolyte leakage
- Electric shock hazard (only applicable for systems with hazardous voltage)

To this list, UL 2271 adds:

- Combustible concentrations
- Venting

In WMG’s view, the inclusion of “combustible concentrations” is particularly relevant to PLEV fires, because real world examples (see Section 2) show that the most severe fires occur indoors, where gases vented from a battery are not quickly dispersed, and so can reach significant concentrations that could exceed the lower flammability limit.

The implementation of these criteria is discussed further in Section 7.9 of this report.

7.2.6 Summary of Risk Assesment Methodologies

Sections 7.2.1 to 7.2.4 show diversity in the hazards and hazardous situations that are considered in the risk assessment that underpins the various standards and in the way the hazards are enumerated within the Standards.

In WMG's view, the hazards associated with batteries are very similar across all PLEV applications, and across multiple other consumer products which use Lithium-ion batteries, albeit that the size of the batteries, and thus the energy released during thermal runaway, varies markedly across product segments.

WMG suggests that a general Risk Assessment Standard, complementary to ISO 12100, should be developed with a focus on consumer products which use Lithium-ion or similar energy storage. This should provide examples of the hazards, hazardous situations and hazardous events that occur in a domestic setting, including those associated with storage and charging of batteries.

This standard could be used to underpin the risk assessment methodology for many other product-specific Standards, such as those for PLEVs, but also other existing stationary and mobile / portable consumer products which use large Lithium-ion batteries, such as home energy storage, cordless garden tools, and foreseeable future products such as domestic robots. It can also be used by manufacturers to guide their own risk assessment activities for Lithium-ion battery powered consumer products. Note: The intent of such a standard would not be to duplicate or replace existing rechargeable battery test standards such as EN 62133-2 or EN 50604-1, but to ensure a consistent approach to the risk assessment that underpins such standards.

WMG suggests that Standards for PLEVs and their batteries should use the Standard suggested above to define the risk assessment methodology, and should use a consistent approach to document hazards, including their relationship to the Essential Health and Safety Requirements of the Machinery Regulations.

7.3 Functional Safety Methodology

7.3.1 Background on Functional Safety

Functional Safety refers to the use of automatic functions to achieve safety goals, i.e. to reduce the risk of equipment causing unacceptable harm to people, damage to property or to society due to a malfunction or incorrect operation of the automatic system (Renesas, 2022). The automatic protection system should be designed to properly handle likely human errors, systematic errors, hardware failures and operational / environmental stress (Wikipedia.org, 2024).

For PLEVs, functional safety concerns the combination of hardware and software which is intended to prevent serious hazards, such as a battery fire. Functional safety methodology recognises that hardware items (such as sensors, actuators and microprocessors) can fail, including due to external influences such as power supply anomalies or electromagnetic interference. Equally, complex software can exhibit unintended behaviour.

The safety of a system may require it to be fail-safe. This may require redundant hardware, meaning that the function of a piece of hardware is duplicated, for example by using more than one temperature sensor, or more than one means to isolate the battery from the charger in case of over-charge. In software, it may require a “monitor” piece of software which checks the behaviour of the more complex application software. The former may need to run on a separate processor from the latter. The level of redundancy or other measures required depends on the specific safety goal being considered, the severity of the outcomes if the goal is not met, the likelihood of the associated failure(s) of the safety system and the possibility that those affected could avoid harm.

An extreme example of a safety-critical system is a fly-by-wire control system for a passenger aircraft. If such a system were to fail, the consequences could be devastating, so the level of hardware and software redundancy and validation testing both need to be commensurately comprehensive and robust.

Functional safety is tested by systematically introducing deliberate faults, such as a broken wire or a short-circuited switch or erroneous input data to a software algorithm, and then ensuring that the system remains safe in the event of situations such as over-charge or over-temperature.

Most industries with long-established functional safety challenges have created their own standards for the processes required to identify safety functions, goals and requirements, and for the testing of hardware and software. For example, the automotive industry uses ISO 26262 (BSI Group, 2024), which is adapted from IEC 61508 (BSI Group, 2024), which is applicable to all industries.

Across the UK, European and US e-bike and battery Standards, there is generally a consistent use of ISO 13849-1 “Safety of machinery - Safety-related parts of control systems - Part 1: General principles for design” (BSI Group, May 2023) and ISO 13849-2 “Safety of machinery - Safety-related parts of control systems - Part 2: Validation” (BSI Group (Oct 2012).

These Standards are Normative references in the European/UK e-bike and battery standards EN 15194 and EN 50604-1, and the US e-bike and battery standards UL 2849 and UL 2271.

However, ISO 13849 is not mentioned in the European/UK e-scooter standard EN 17128 (which does not mention functional safety at all) or the US equivalent UL 2272. In WMG’s view, this is concerning, as similar functional safety risks exist in non-pedal PLEVs such as e-scooters, as much as they do in e-bikes.

WMG suggests that a consistent functional safety methodology should be applied to all PLEVs, irrespective of whether they are road-legal, because safety goals such as avoiding battery fires apply equally to all PLEVs, including when they are being charged.

7.3.2 Functional Safety in ISO 13849-1

In ISO 13849-1, the performance level (PL) is a value used to define the ability of safety-related parts of control systems to perform a safety function under foreseeable conditions. The PL is expressed on a scale from a to e, and represents the probability of dangerous failure per hour, as shown in Table 19.

Table 20: ISO 13849-1 Functional Safety Performance Levels

Performance Level (PL)	Probability of Dangerous Failure per Hour (PFHd) (1/hr)	
	Value	Percentage
a	$\geq 10^{-5}$ and $<10^{-4}$	0.001% to 0.01%
b	$\geq 3 \times 10^{-6}$ and $<10^{-5}$	0.0003% to 0.001%
c	$\geq 10^{-6}$ and $<3 \times 10^{-6}$	0.0001% to 0.0003%
d	$\geq 10^{-7}$ and $<10^{-6}$	0.00001% to 0.0001%
e	$\geq 10^{-8}$ and $<10^{-7}$	0.000001% to 0.00001%

The PL_r is the required PL for a particular application to achieve its safety goals. The PL_r is determined based on three parameters:

- Severity of Injury
- Frequency and/or exposure to hazard
- Possibility of avoiding hazard or limiting harm

ISO 13849-1 defines scores for each of the three parameters, as shown in Table 20:

Table 21: ISO 13849-1 Parameter Scores for Determination of Required Performance Level

Parameter	Score	Description
Severity of Injury	S1	Slight
	S2	Serious
Frequency and/or exposure to hazard	F1	Seldom-to-less-often and/or exposure time is short
	F2	Frequent-to-continuous and/or exposure time is long
Possibility of avoiding hazard or limiting harm	P1	Possible under specific conditions
	P2	Scarcely possible

ISO 13849-1 then provides the flow-chart shown in Figure 47 to determine the required performance level, PL_r, based on the scores given to the three parameters. The Standard then allows that the PL_r may be reduced by one grade, if there is a low probability of occurrence of the hazardous event, as shown on the right side of Figure 47. The probability of occurrence should have been determined from a risk assessment according to the ISO 12100 methodology (see Section 7.1.7 of this report), but the determination is dependent upon human behaviour or technical failure and is generally very difficult to assess with the required statistical reliability (Institut für Arbeitsschutz der Deutschen Geserzlichen Unfallversicherung (IFA), 2015).

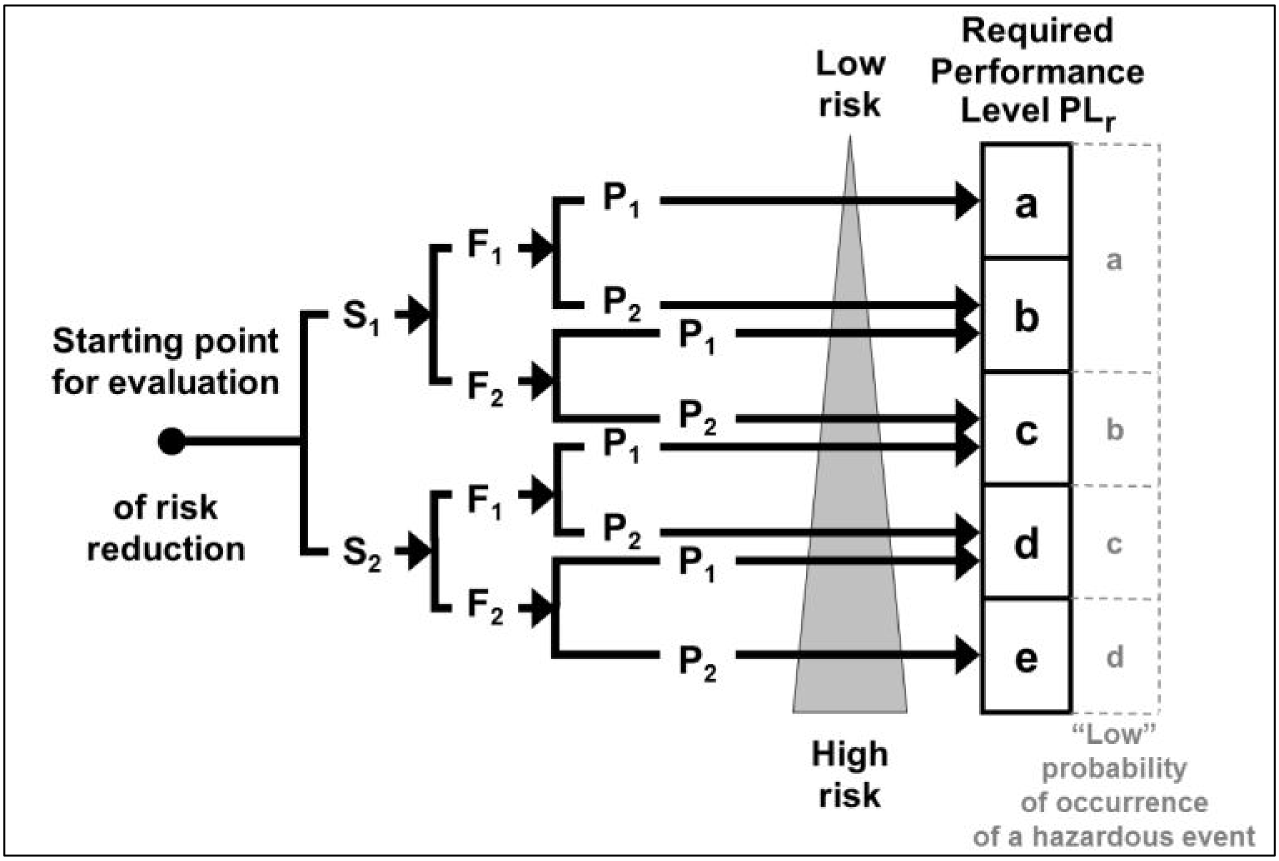


Figure 47: ISO 13849-1 Flow-chart to Determine the Required Performance Level, PL_r

It is important to note that this methodology is only to determine the required performance level of the automatic control system (e.g. the e-bike battery BMS and associated sensors and actuators), not the overall safety of the complete battery system. This is an important distinction because, as described in Section 2 of this report, there are causes of safety issues such as thermal runaway and thermal propagation which the control system cannot prevent, for example internal cell defects.

Required Performance Level for PLEV Fires

Here we consider a scenario, based on known real world PLEV fire incidents:

A consumer, living in a flat in a multi-occupancy building, stores their e-bike or e-scooter in their flat every day and night when they are not using it. They also charge the battery in their flat. The flat only has one exit route, to a communal hallway and stairwell.

We know from real world data that the severity of the hazards is high, so the Severity of Injury score, per Table 20, is S2.

The frequency of exposure is also arguably high because the owner is in close proximity to the battery for many hours per day, and while sleeping at night. However, the hazard itself is not present all the time: It only occurs in the event of a thermal runaway, which is rare. The frequency score is thus likely to be F1.

The possibility of avoiding harm depends on the situation: One could argue that it is “possible under specific conditions” (P1), such as if the person is closer to the exit door than the battery and can therefore reach the exit door without getting closer to the hazard. However, this may not always be the case. This would therefore result in a score of P2 (“scarcely possible” to avoid harm). The possibility of harm to other occupants of the same building should also be considered, which may also to lead to a score of P2.

Following the flow-chart in Figure 47, the required performance level would then be either c or d, depending on whether P1 or P2 is decided. In general, where there is doubt or disagreement about such a score, the worst case should be considered, and therefore the required performance level, PL_r = d.

7.3.3 Functional Safety in EN 15194 (e-bikes)

Section 4.3.22 of EN 15194 is titled “Performance levels (PL_rs) for control system of EPACs”. It defines functional safety requirements for three safety functions, shown in Table 21, the last of which is the most relevant to this report.

Table 22: EN 15194 Functional Safety PL_r Requirements

Safety function	Performance Level
Prevention of an unintentional self-start of the EPAC	PL_r c
Prevention of electric motor assistance functions without pedalling, and without activation of the start-up assistance mode	PL_r c
Prevention of risk of fire in case of management system failure for batteries with capacity above 100 Wh	PL_r c

The vast majority of e-bike and e-scooter batteries are well in excess of 100 Wh, so this threshold means almost all e-bike batteries should be designed to meet the requirement.

However, based on the scenario analysis presented in Section 7.3.2, WMG is concerned that the PL_r is not sufficient, and this would contribute to the frequency of fires being unacceptably high.

7.3.4 Functional Safety for LEV Batteries in EN 50604-1

EN 50604-1 approaches functional safety testing by providing three options as shown in Table 22. In addition to ISO 13849, EN 50604-1 has further normative references for functional safety:

- IEC 61508 (all parts), Functional safety of electrical/electronic/programmable electronic safety-related systems (BSI Group, 2024).
- EN 61000-6-7:2015, Electromagnetic compatibility (EMC) - Part 6-7: Generic standards – Immunity requirements for equipment intended to perform functions in a safety-related system (functional safety) in industrial locations (BSI Group, May 2015).
- EN 61326-3-1:2017, Electrical equipment for measurement, control and laboratory use – EMC requirements - Part 3-1: Immunity requirements for safety-related systems and for equipment intended to perform safety-related functions (functional safety) - General industrial applications (BSI Group, Feb 2018).

The first of these is included to allow the existing safety-related components, which have been approved to this standard, to be used in the battery without further testing. The latter two standards are to be used to test the electromagnetic immunity of safety-related components which have not previously been approved.

EN 50604-1 requires most of the battery safety tests to be performed according to one of the options defined in Table 22, including under-temperature, external short-circuit, over-charge, over-discharge and deep discharge.

In WMG’s view, it is good that EN 50604-1 considers functional safety. However, there is some concern that the individual components, whose reliability has been proved to relevant standards, may not meet the same reliability standards when incorporated into a new system. In WMG’s view, the functional safety should be demonstrated at system level, as well as at component level.

Furthermore, Option 2 in Table 22 allows system level tests to be performed and passed with no redundant protection systems: The assumption is that, if the individual protective components meet the PL c reliability level, and if the system passes the tests with all these protective components working, then it is sufficiently safe. However, in WMG’s view, single-point failure tests should be performed, even if all individual protective components meet PL c.

Table 23: EN 50604-1 Options for Evaluation of Protective Devices

Option	Description in EN 50604-1	Explanation
1	All active protective devices are bypassed unless they comply with the functional safety standard as described in option 2	For protective devices that have not been proven reliable to PL_r c, it is assumed that they are unreliable. To test the safety of the battery, all protective devices with unproven reliability are bypassed.
2	All protective devices are operating. All protective devices shall be proven to be reliable according to the EN 61508 (series) or EN ISO 13849 (all parts) PL c	For protective devices that have already been proven reliable to PL c (see Table 19 of this report), failure does not need to be induced during the battery safety tests. The battery tests can be done with all protective devices operational.
3	Active protective devices in operation with all single faults injected and tested separately. If protective devices which are not proven to reach PL c according to the EN ISO 13849 (all parts) or EN 61508 (series) are used, a design review (e.g. FMEA according to EN IEC 60812:2018 or SAE J 1739:2009) shall be performed to identify failure modes taking in consideration also EMC conditions according to EN 61000-6-7:2015 or EN 61326-3-1:2017. All single faults which could influence the test result according to the design review shall be separately injected during the tests and separately tested for each fault injection. Each protective device shall be rendered inoperative separately (common causes) e.g.: • switches of DC power circuit • controllers / microcontrollers • software • communication circuit & its power supply • heartbeat/watchdog NOTE 1 Single fault tests are conducted for the assembly. NOTE 2 If all switches of DC power circuit designed for redundancy are controlled by the same controller, then Option 3 is not applicable.	For devices that have not been proven reliable to PL c, a design analysis is done, to determine protective device failure modes which could affect the outcome of specific safety tests. This analysis should follow a Standard for Failure Modes and Effects Analysis (FMEA). The safety tests are repeated with each relevant single fault, identified from the FMEA, tested in turn. The generic protection devices, both hardware and software, are listed here. If the switches are all controlled by one controller, then a failure of this controller could lead to all switches being incorrectly controlled. This is effectively a multi-point failure, so a single-point failure test is not appropriate.

7.3.5 Functional Safety for Portable Batteries in EN 62133-2

EN 62133-2 Section 5.6.1 requires that a safety analysis must be performed on the battery safety circuitry with a test report including a fault analysis of the protection circuit under both charging and discharging conditions.

Section 6 then states that the safety analysis of Section 5.6.1 should identify those components of the protection circuit that are critical for short-circuit, over-charge and over-discharge protection, and when conducting the short-circuit test, consideration should be given to the simulation of any single fault condition that is likely to occur in the protecting circuit that would affect the short-circuit test.

Section 7.3.2, which defines the external short-circuit test, then states that a single fault applies to protective component parts such as MOSFET (metal oxide semiconductor field-effect transistor), fuse, thermostat or positive temperature coefficient (PTC) thermistor.

EN 62133-2 allows that components that meet applicable component standards (e.g. BS EN 60127 (BSI Group, 2024) for fuses, BS EN IEC 60738-1:2022 (BSI Group, Feb 2023) for thermistors, BS EN IEC 60691:2023 (BSI Group, Nov 2023) for thermal links) do not need to be subjected to single faults during the external short-circuit tests. However, these component standards are not functional safety reliability standards.

In WMG’s view, EN 62133-2 is notably weaker than EN 50604-1 regarding functional safety. It does not have normative references to functional safety standards. Functional safety conformity of safety-related components is not required. Single fault tests are only required for the external short-circuit test, and not for other safety tests such as over-charge and over-discharge and over-temperature.

The e-scooter standard EN 17128 refers to EN 62133-2 for battery safety, but not to EN 50604-1. In WMG’s view, this significantly weakens the functional safety of e-scooter batteries, compared to e-bike batteries, for which EN 15194 now requires the battery to adhere to EN 50604-1.

7.3.6 Functional Safety for e-bikes in UL 2849

UL 2849 Section 12.4 requires a safety analysis to be performed, in the form of a risk assessment, using the methodology of ISO 12100 or a similar standard. This analysis is required to consider single fault conditions in the protective circuits.

Since UL 2849 certification requires UL to perform an independent evaluation of the product, the manufacturer must provide the risk assessment to UL, and UL may modify it based on their review.

UL 2849 Section 12.6 requires that single-fault conditions shall not cause, or not cause failure to detect, a hazardous condition. This is fundamentally different from EN 50604-1, which requires only that the PL c reliability level is met by protection components, whereas UL 2849 requires that single-faults should be mitigated, irrespective of the reliability of the components.

UL 2849 Section 12.6 also requires that protective circuits shall not be relied upon for critical safety unless one of the following is met:

a) They are provided with a redundant passive protection device
b) They are provided with a redundant protective circuit that remains functional and energised upon loss of power / failure of the first protective circuit
c) They are determined to fail safe upon loss of power to / failure of the protective circuit

d) They are part of a protective circuit that has been shown to comply with IEC 61508 Safety Integrity Level (SIL) 2 or ISO 13849 PL c.

As an example of how this would be applied, we will consider a PLEV battery which is equipped with a single MOSFET to protect the battery from over-charge. If the BMS detects an over-charge condition, it should command the MOSFET to switch off, to isolate the cell stack from the charging voltage. The MOSFET is an active protective device, and is part of a protective circuit, which includes the BMS processor and software, voltage sensors, pack current sensor, and interconnecting wires. This complex system has multiple potential failure modes which could result in the MOSFET failing to isolate the cell stack. It is important to note that a key failure-mode of the MOSFET itself is to fail short-circuit, meaning that it cannot open the circuit to protect the cell stack.

Considering the options that UL 2849 provides, for this circuit to “be relied upon for critical safety”:

a) If there is no redundant passive device included in the BMS, UL 2849 §12.6 option (a) is not met. However, a passive protection circuit for over-charge could be engineered into the BMS. For example, a combination of a passive fuse and a Zener diode, suitably rated to break down just above the maximum permissible charging voltage, as shown in Figure 48. In normal operation, the Zener diode does not conduct any current. If the charge voltage exceeds the Zener voltage of the diode, it will allow current to flow backward through the diode. This will limit the voltage of the battery. If the current delivered by the charger is too high, the “avalanche” current through the diode will cause the fuse to blow, permanently isolating the battery from the charge connector.

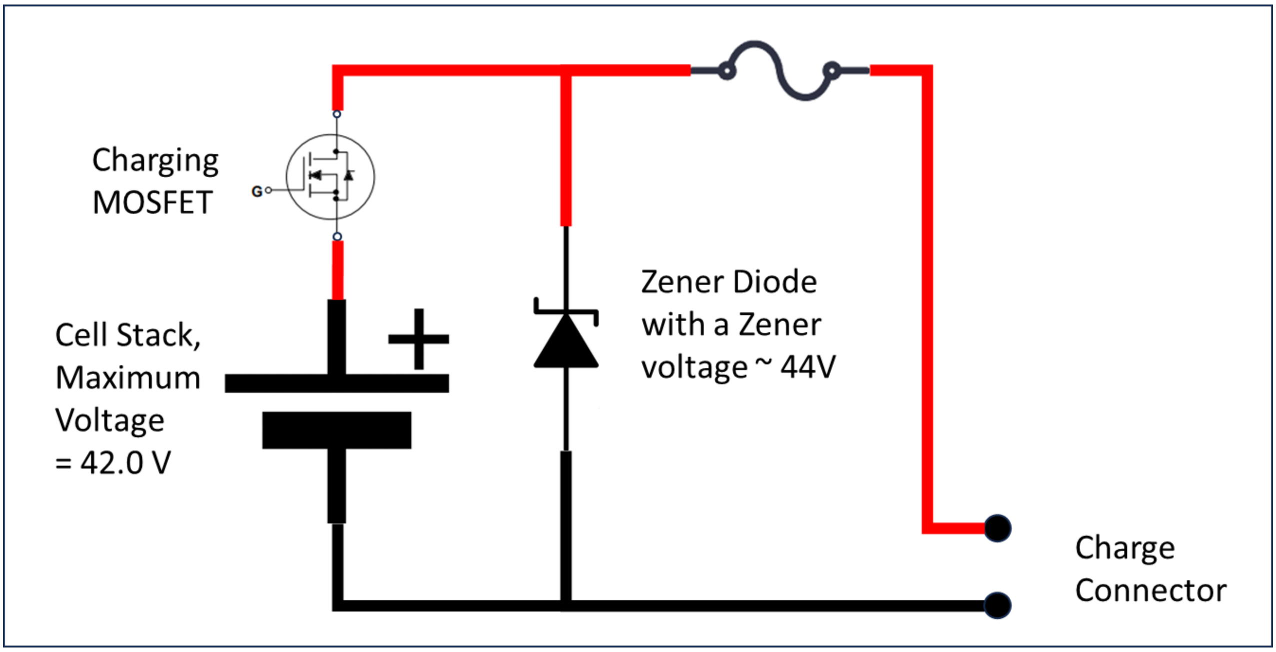


Figure 48: Example of Redundant Passive Protection Against Charging Over-Voltage

b) If there is no redundant active device included in the BMS, UL 2849 §12.6 option (b) is not met. However, an additional active protection circuit could be engineered into the BMS. For example, Figure 49 shows a system with an additional MOSFET, connected in series with the first MOSFET. For the cell stack to be charged, both MOSFETs must be switched on by their respective controllers, but to stop charging, either MOSFET #1 or MOSFET #2 can be switched off. To comply with the redundancy requirements of clause (b) from UL 2849, above, each controller has an independent power supply. In this way, with any part of the circuit to control MOSFET #1 fails, there is complete redundancy to ensure MOSFET #2 continues to operate normally, and vice versa. Either MOSFET #1 or MOSFET #2 can be used to protect the cell stack from over-charge, even if one of them fails.

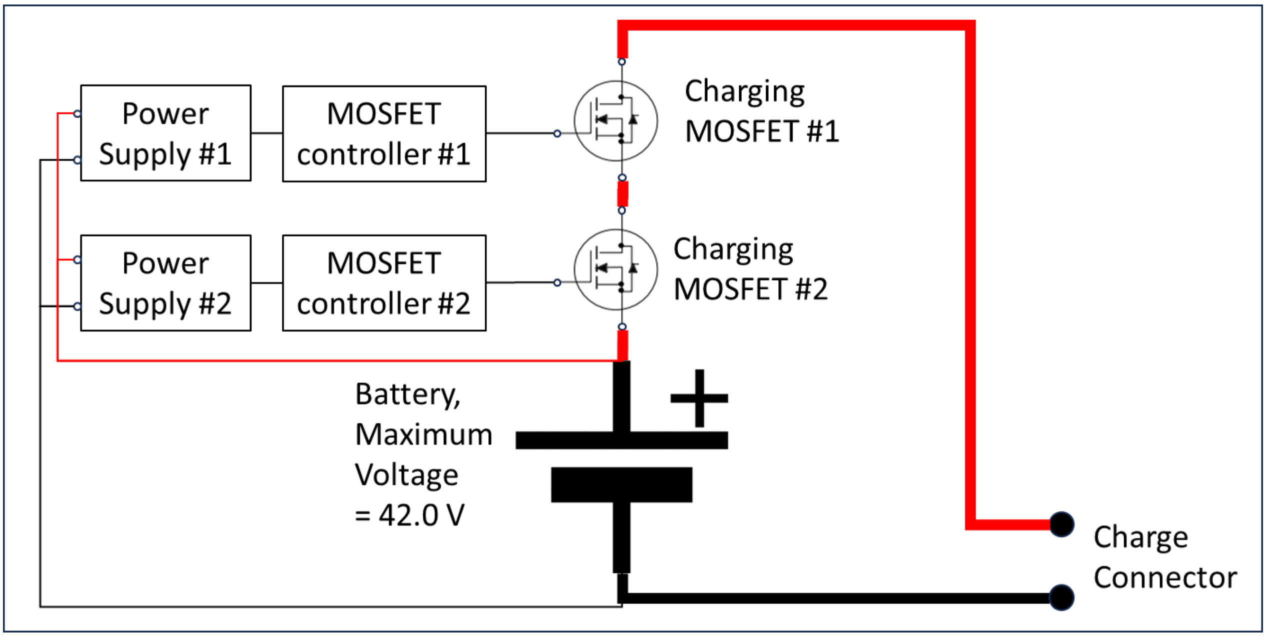


Figure 49: Example of Redundant Active Protection Against Charging Over-Voltage

c) To meet clause UL 2849 §12.6 option (c) requires the protective circuit to fail safe. This could be met, for example, if any failure mode in the protective circuit resulted in the cell stack becoming open-circuit. This cannot be met with a MOSFET because, as mentioned above, it can fail short-circuit. A physical switch, in place of the solid-state MOSFET, might be able to meet this requirement if it can be shown that it cannot fail in the closed position.

d) To meet clause UL 2849 §12.6 option (d), the circuit must be proved to meet one of the stated functional safety standards. At the very least, this requires the complete circuit to be shown to meet a high reliability standard PL c. This is more demanding than each individual component of the circuit meeting PL c.

UL 2849 then requires that the protective circuits must be tested for functionality and reliability in the relevant configuration and environment, according to a functional safety standard such as ISO 13849.

In WMG’s view, UL 2849 provides a significantly more robust approach to functional safety than EN 50604-1, because:

1) It requires that single faults shall not cause a hazardous condition, irrespective of the reliability of the components or the system; and
2) It requires testing of the complete system, irrespective of the reliability of the components.

7.3.7 Functional Safety for Personal E-Mobility Devices in UL 2272

UL 2272 (2016) pre-dates UL 2849 (2022) by several years. Section 16 of UL 2272 has some commonality with Section 12.4 of UL 2849, but it does not state so clearly the requirement for single faults not to cause a hazardous situation. Rather than requiring system-level testing of circuits which are relied on for critical safety, it only requires the individual devices to comply with relevant standards. In this respect, it is weaker than UL 2849 and is closer in equivalence to EN 50604-1.

7.3.8 Functional Safety for LEV Batteries in UL 2271

UL 2271 (2018) sits somewhere between UL 2272 and UL 2489 in the thoroughness of its functional safety approach. The same weakness exists, compared to UL 2849, as outlined for UL 2272 above. Section 15.4 of UL 2271 contains the same list of options (a) to (d) as UL 2849 Section 12.6, but applied to devices, rather than complete circuits. However, Section 18.5 of UL 2271 allows that safety tests can be performed without single device faults if they have been "determined to be reliable" by being evaluated as compliant with a relevant UL component standard, which are listed in Annex A to the standard.

7.3.9 Functional Safety in IEEE 1625 and IEEE 1725

IEEE 1625 (Institute for Electrical and Electronic Engineers, Mar 2008) is a standard for rechargeable batteries for multi-cell mobile computing devices and covers batteries comprising multiple cells in series and parallel. It is now 15 years old and, as of 2019, it is an "inactive reserved standard". WMG is not aware of any plan to update IEEE 1625, but it is described here because in some respects it provides a more comprehensive approach than current PLEV standards, and much of it could be applied to PLEV batteries.

IEEE 1725 (Institute for Electrical and Electronic Engineers, Feb 2021) is a similar standard for batteries for mobile phones. It considers batteries with a maximum of two cells in series. It was last updated in 2021 and is an active standard. It shares much in common with IEEE 1625.

WMG is not aware of the level of usage of, or adherence to, these IEEE standards in the computing and mobile phone battery suppliers. However, it is notable that these industries have achieved a good reputation for Lithium-ion battery safety, whilst also having a very large market size (much larger than the PLEV market), indicating that the safety-related failure rates of the batteries are low, so WMG surmises that the batteries and chargers used in these devices are being designed and built to generally high standards. There have been some exceptions, such as the recall of the Samsung Galaxy Note 7 following several battery fires. This issue was thoroughly investigated by Samsung, and a summary of the root cause was published (Samsung Electronics Co. Ltd., 2017), with the aim of helping the whole industry. It is notable that the identified manufacturing quality issues are described in IEEE 1625 and 1725 but are not, to WMG's knowledge, covered by other standards. These IEEE standards also mention the integration between the battery and charger, for example through the USB-C connector and charging protocol. For this reason, even though the devices and batteries covered by the IEEE standards are generally smaller and have lower energy and power than PLEVs, it is worth highlighting how these IEEE standards differ from those used for PLEVs, to see what can be learned from the computing and mobile phone industries.

Part of the credibility of these IEEE standards derives from the extensive list of high-profile companies involved in their creation. These include many of the largest cell manufacturers (Panasonic, Samsung, LG Chem, Sony/Murata, BYD, Contemporary Amperex Technology [CATL]), computing companies (Apple, Microsoft, Google, Lenovo, Motorola) and test providers (UL, Bureau Veritas) and consulting organisations (Exponent).

Both standards take a whole-system approach, graphically illustrated in a diagram showing the cell and battery pack in the context of the end-device, the interactions with the user and the environment, as shown in Figure 50 below.

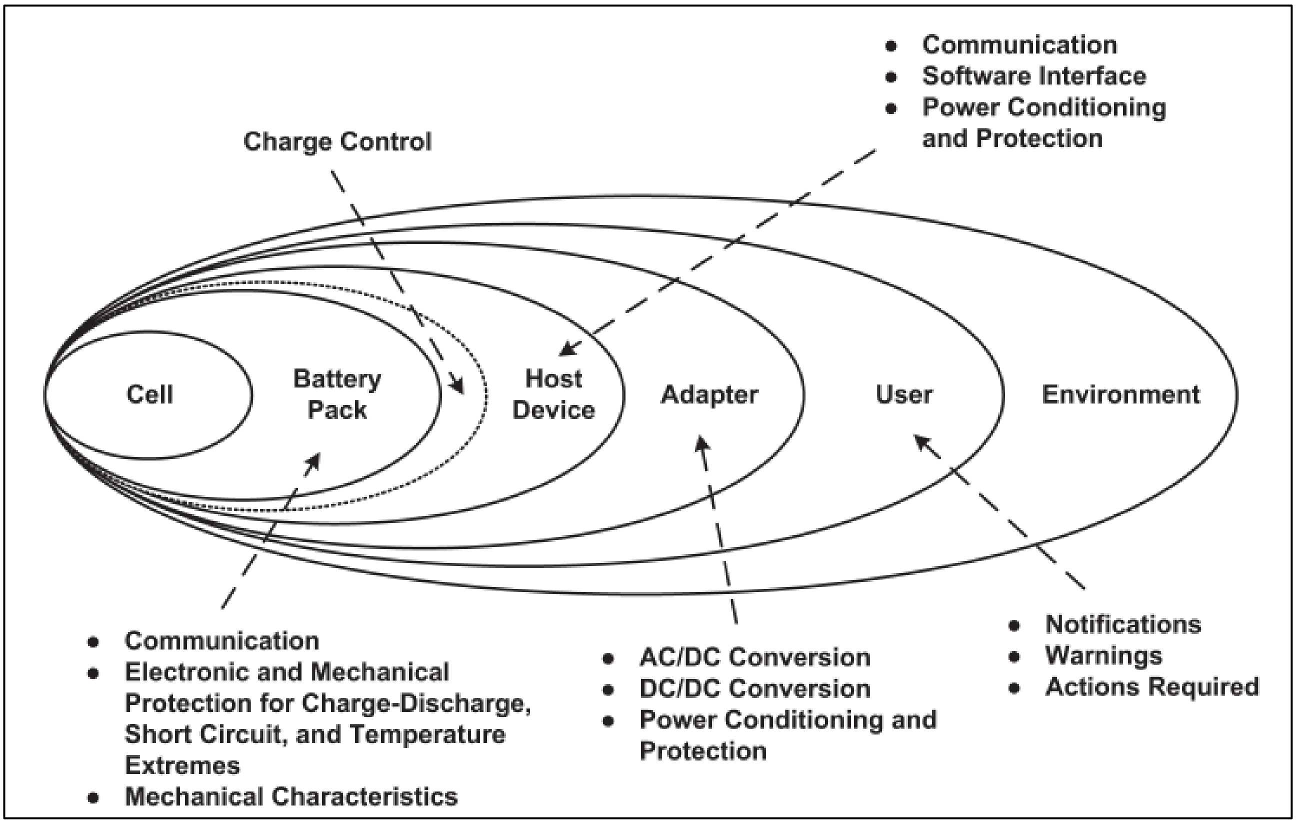


Figure 50: Conceptual Diagram of a host device and its user from IEEE 1725-2021

IEEE 1625 and IEEE 1725 provide guidance on Failure Modes and Effects Analysis (FMEA) techniques that should include consideration of two faults in reasonably foreseeable misuse, rather than just a single fault considered in the PLEV standards. Consideration of two simultaneous faults, and mitigation to ensure avoidance of hazardous conditions, is a far more conservative and robust approach. Under the complete-system approach taken in IEEE 1625 and IEEE 1725 (see Figure 50), the FMEA considers faults in the battery, host device, charger and user interaction. For example:

> “Both charge control is faulty and the primary battery safety circuit fails (double fault).”

To be safe in this failure mode, a second safety circuit is necessary to protect the cell, to prevent thermal runaway.

Further details from IEEE 1625 and IEEE 1725 are provided in Section 7.6.7 of this report.

7.3.10 Summary of Functional Safety for PLEVs

Functional Safety is an essential engineering discipline for safety-critical products that rely on automatic active systems to achieve the required safety levels. In industries such as aerospace and automotive, it is well established. In WMG’s view, any manufacturer of a consumer product that relies on Lithium-ion batteries should have a similarly rigorous approach to function safety, because of the severity of the associated hazards.

WMG suggests that a thorough review of the functional safety requirements in UK standards for e-bikes, other PLEVs and their batteries should be undertaken, using comparable standards from other countries (notably UL 2849 in North America) and other industries (notably IEEE 1625 for computers and IEEE 1725 for mobile phones and ISO 26262 for automotive) to establish good practice.

7.4 Use of Specific Words in Requirements

Words such as “should”, “shall”, “must”, “may” and “will” (and their negatives, such as “shall not”) usually have specific meanings when they are used in standards and legislation. In WMG’s experience, the terms above have the following meanings:

Table 24: Terminology Meanings in Requirements

Term	Meaning
Shall	Used to convey an obligation or a feature that is **mandatory**. If the obligation is not met, or the mandatory feature is not included, then the product is not compliant with the Standard or test. Example: “the battery shall not explode”.
Should	Used to convey **strong advice** or **guidance**. If the advice is not followed, then a documented justification is required. Example: “when testing the battery, measures to protect personnel and the environment should be taken”.
Must	This word is generally not used, to avoid possible confusion with “shall” or “should”. Consistent use of such words is vital to clear understanding.
May	Used to convey something that is **optional** or **uncertain**, without compromising compliance with the Standard. Example: “During safety tests, protective devices may be bypassed at the request of the manufacturer”.
Will	Used to convey a **declaration of intent or purpose**, that does not compromise compliance with the Standard. Example: “The standard will be updated to account for advances in the state of the art”.

Although these meanings are widely understood, within the standards they are implied but not defined, and in some cases, the terms are used interchangeably which invites misinterpretation.

WMG suggests that all Standards should include a section to unambiguously define the terms to be used and should be rigorously checked for correct usage. This may be achieved by reference to a separate document containing these definitions, such as the BSI Rules for the structure and drafting of UK standards (BSI Group, Nov 2022).

As an example of poor use of one of these terms, EN 62133-2 Section 5.6.1 states:

> “Each battery should have an independent control and protection for current, voltage, temperature and any other parameter required for safety and to maintain the cells within their operating region”.

The use of “should” in this sentence implies that control and protection of safety-critical parameters is not mandatory. In WMG’s view, this may compromise safety.

7.5 Terminology and Meanings Regarding Pass/Fail Criteria

In Standards and legislation for battery safety across various market sectors, the pass-fail criteria are often defined with terms referring to various levels of failure of the Lithium-ion cells, such as leakage, venting, rupture, explosion and fire. When tests are performed, whether in-house at a manufacturer or at a third-party facility, a clear definition of these terms is essential, to avoid the test result falling into a grey area.

Table 24 compares the definitions of these terms provided in the main European/UK PLEV battery safety standards, EN 62133-2 (used in the e-scooter standard EN 17128) and EN 50604-1 (used in the latest version of the e-bike standard EN 15194).

In WMG's view, the definitions in EN 50604-1 Section 3 (middle column of Table 24) are preferable to those in EN 62133-2. However, EN 50604-1 confuses the reader by then providing different definitions for three of the five terms in Section 5. In WMG's view, having two definitions of a term in a single standard must be avoided, and the definitions in EN 50604-1 Section 5 should be re-worded as test procedures.

The definitions of leakage and explosion in Section 5 of EN 50604-1 (final column of Table 24) are stated to be taken from "BATSO 01". WMG understands that this refers to the international test standard which was first published in 2008 by the now-defunct Battery Safety Organisation (Battery Safety Organisation, 2008). A second edition, published in 2011 (BatteryStandards.info, 2011), is no longer available but is described in a 2010 presentation Battery Safety Organisation, 2010) which provides definitions found in EN 50604-1, although this uses the term "disassembly" rather than "explosion".

Regarding the definitions in EN 62133-2:

- Venting: The definition refers to the intent of the design. In WMG's view, this is a poorly worded definition. The pass/fail criteria of a test should not be based on the intent of the design, but only on the outcome of the test.
- Rupture: The definition refers to "exposure or spillage but not ejection of materials", but the difference between ejection and spillage is not clear.
- Explosion: The definition refers to "major components" being forcibly expelled but does not explain how to distinguish major components from any other components.

Regarding the definitions in EN 50604-1 Section 3:

- Venting: The same criticism applies as above. A better wording would be "Release of excessive pressure from a DUT [Device Under test] that does not involve rupture, explosion or fire".

Regarding the definitions in EN 50604-1 Section 5:

- Leakage: The test procedure relies on measuring the change in mass of the DUT. In WMG's view, visual inspection is normally sufficient to determine electrolyte leakage, and if there is doubt, a reactant such as Litmus paper should be used.
- Explosion: The test procedure relies on construction of wire mesh screen around the DUT at a distance of 25 cm. Depending on the design of the battery and the rest of the test stand, this could present practical difficulties, and is unlikely to reveal the occurrence of pressure waves mentioned in the definition of Explosion in Section 3 of EN 50604-1. In WMG's view, this procedure may need to be re-thought, based on practical experience, possibly with addition of an illustrative drawing.
- Fire: The test procedure requires wrapping the DUT in cheesecloth. This material is also mentioned in UL 2849 as a means of detecting flame, burning oil or molten metal, and requires that there shall be no evidence of ignition, glowing or charring of cheesecloth or tissue paper. In WMG's view, cheesecloth could be used to detect both fire and explosion, which would overcome the difficulty mentioned above with the existing procedure for detection of explosion. It is possible that the cheesecloth would also be damaged by vigorous venting, but this could only be determined through experimentation. If it is affected by venting, this is probably a good thing, as there is no test procedure defined for determining venting. However, normally venting is evident visually, as the expelled gases normally include visible smoke.

Table 25: Definitions of Failure Types in EN 62133-2 and EN 50604-1

Term	EN 62133-2 Definition	EN 50604-1 Definition (§3)	EN 50604-1 Definition (§5)
Leakage	Unplanned, visible escape of liquid electrolyte	Escape of liquid or gas from a DUT except for venting	No visible escape of electrolyte or other material, or the loss of material (except battery casing, handling devices or labels) such that the mass loss of the DUT exceeds 1.0%. Leakage is evidenced by liquid or condensed electrolyte composition external to the DUT.
Venting	Release of excessive internal pressure from a cell or battery in a manner intended by design to preclude rupture or explosion	Release of excessive pressure from a DUT intended by design to preclude rupture or disassembly	-
Rupture	Mechanical failure of a cell container or battery case induced by an internal or external cause, resulting in exposure or spillage but not ejection of materials	Loss of mechanical integrity of the enclosure of the DUT resulting in openings that do not fulfil protection degree IPxxB according to ISO 20653 (BSI Group, Aug 2023)	-
Explosion	Failure that occurs when a cell container or battery case opens violently and major components are forcibly expelled	Sudden release of energy sufficient to cause pressure waves and/or projectiles that may cause structural and/or physical damage to the surrounding of the DUT	Rupturing occurred where solid parts of the DUT have penetrated a wire mesh screen (annealed aluminium wire with a diameter of 0.25 mm and a grid density of 6 to 7 wires per cm) placed 25 cm away from the DUT.
Fire	Emission of flames from a cell or battery	Continuous emission of flames from a DUT (approximately more than one second)	DUT shall be wrapped with cheesecloth e.g. see EN 60745-1:2009 (BSI Group, Feb 2010), Annex K. After the test, this cheesecloth shall remain intact. NOTE 1: Cheesecloth: bleached cotton cloth of approximately 40 g/m2 according to EN IEC 62368-1:2020 (BSI Group, Mar 2020). NOTE 2: The use of cheese cloth facilitates the detection of fire and/or extreme heat

7.6 General Safety Requirements & Considerations

Standards are generally written to avoid prescription of specific technical solutions. Instead, they define required outcomes, such as the result of safety tests. Nevertheless, they need to account for the state of the art in particular technologies, such as wiring, electronic controls and Lithium-ion batteries. Therefore, as well as defining pass/fail criteria for specific tests, they generally prescribe, or at least recommend, generic design approaches to minimise safety risks. Requirements and recommendations relevant to fire risks are discussed below.

7.6.1 General Safety Requirements for e-bikes in EN 15194

EN 15194 Sections 4.2.5 - 4.2.7 define common-sense requirements for electrical wiring and connectors, such as the use of corrosion-resistant materials, abiding by supplier temperature limits, and ensuring wires to not come into contact with sharp edges or moving parts. For wires that are flexed in normal use, or during maintenance, it specifies cyclic flexing tests to ensure durability.

Section 4.2.5.2 requires conductor cross-sections to be selected in accordance with EN 60335-1:2012+A15:2021 (BSI Group, Jun 2021) Table 11. This table requires current densities of ≤10 A/mm^2, which is a commonly used value for wires and cables in still air. However, it is based only on the operating current, and does not consider the short-circuit current. See Section 7.6.3 of this report for further comments on short-circuit current rating.

For enclosures of electrical components, EN 15194 Section 4.2.9 requires ingress protection to IPx4 (protection against low-pressure water spray / splash). The mountain e-bike standard, EN 17404, which provides a small number of additional requirements to EN 15194, requires IPx5 (protection against moderate pressure water jets), which is also required for L-category vehicles in Regulation 136 (although, as explained in Section 6.4.1 of this report, Regulation 136 is not current required for UK L-category Type Approval).

WMG suggests that the water ingress requirement in EN 15194 should be increased to IPx5: It is foreseeable that owners will spray-clean their e-bike or e-scooter, with a moderate pressure water jet, and this should not allow water ingress to the battery.

For the battery, EN 15194 Section 4.2.10 specifies two tests for the enclosure, in addition to the requirement for the battery to comply with EN 50604-1:

- Impact using a spring hammer, per EN 60068-2-75:2014 (BSI Group, Nov 2014)
- Drop-test according to EN 22248:1992 (BSI Group, Jul 1986) from 0.9m in three orientations.

The latter is arguably superfluous, given that EN 50604-1 includes a 1m drop test, repeated three times, in the most vulnerable orientation.

The introduction of EN 15194 states that the Standard does not cover the foreseeable dropping of an e-bike, which could cause impact damage to the battery, which is intended to be added in a future version of EN 15194. Section 4.2.10 advises that the manufacturer should perform their own risk analysis for the bike falling over.

In WMG's view, the impact risk from falling over is generally small, as e-bike batteries are normally mounted within the main frame triangle, or above the front or rear wheel. If the bike falls to one side, it is most likely that the main impact will be to the pedals, handlebars and/or saddle, which will generally prevent direct impact to the battery if the e-bike is dropped on a moderately flat surface. For rare cases where the battery is directly impacted, it is likely that passing the spring-hammer impact test and the drop test will be sufficient to ensure that the battery casing is robust.

However, a concern with any mechanical shock/impact test is that, even if the battery appears unharmed (no rupture, vented gas, etc.), there may be hidden damage.

WMG suggests that a full charge-discharge cycle should be performed after mechanical shock / impact tests, to ensure that the battery either operates normally, or that charge and discharge are permanently inhibited.

7.6.2 General Safety Requirements e-scooters in EN 17128

EN 17128 contains general safety requirements that are nearly identical to those described above for EN 15194. The same comments apply.

7.6.3 General Safety Requirements for LEV Batteries in EN 50604-1

EN 50604-1 provides a broad range of general safety requirements, summarised below:

Short-Circuit Withstand Current

EN 50604-1 Section 5.1.101 requires the electrical safety design to be approved according to the requirements of ISO 6469-1 and ISO 6469-3. EN 50604-1 doesn't refer to specific sections of these standards, but WMG assumes it intends to refer to ISO 6469-1 Section 5.4 "Electrical Requirements" and the whole of ISO 6469-3. Since ISO 6469-3 only covers systems of voltage class B (> 60 V_{dc} and > 30 V_{ac}), it will not apply to most e-bikes.

However, some of ISO 6469-1 Section 5.4, particularly Section 5.4.3 "Short-circuit protection" is relevant to all EPAC e-bikes. It requires the cross-section of all conductors to have a short-circuit current rating according to the maximum short-circuit current of the battery, and for these conductors to be protected by over-current protection capable to interrupt a short-circuit current. The current rating of a conductor is normally expressed in terms of the heat generated (proportional to the square of the current, I^2) multiplied by the time (t) for which this can continue before the conductor over-heats, or I^2t for short.

This means that the manufacturer must determine the maximum short-circuit current (I) and the maximum time (t) for which the short-circuit current could flow, taking account of the reaction time of the active or passive protection systems, and then refer to the current vs. time limits of each component in the DC conductive path. This is an important design requirement that aims to ensure that all conductors (busbars, cables, connectors, BMS components) will not be damaged by a short-circuit and will be protected by the protective devices.

In WMG's view, it would be unsurprising if some e-bike batteries fail this requirement, because they use conductors which appear to be selected primarily for operational current, which is far lower than the short-circuit current. For example, for a 250 W e-bike with a 36 V battery, the continuous operating current is approximately 7 A, but WMG estimates the short-circuit current for a high capacity e-bike battery could be over 1000 A. The self-heating rate of a conductor is proportional to the square of the current, so the self-heating rate in a short-circuit could be around 20,000 times greater than in normal operation and could result in conductors heating up at thousands of °C per second, meaning that they would reach their melting point in a fraction of a second, and the polymer insulation on wires would be damaged in an even shorter time. This is why the short-circuit protection must act very rapidly. If a fuse were used, this could likely be selected to act in milliseconds, which would avoid melting of other conductors. However, based on WMG's teardown of several PLEV batteries, most do not have a passive fuse, but rather rely on active protection. This requires a current sensor, an electronic logic circuit and software, and a MOSFET switch, all of which have a finite response time. The software is likely to be the slowest part of the system. The combined system must be fast enough to open the MOSFET before the conductors in the system are damaged.

BMS Requirements

EN 50604-1 uses several terms that are partly interchangeable:

Table 26: EN 50604-1 Section 3 Terminology Relating to the Battery Management System

Terminology	Definition in EN 50604-1
Battery Control Unit (BCU)	Electronic device that controls, manages, detects or calculates electric and thermal functions of the battery system and that provides communication between the battery system and other vehicle controllers (Source: ISO 12405-3:2014, 3.1)
Battery Management System (BMS)	Local energy management system for the battery system, protecting the battery system from damage, monitoring and increasing the lifetime, and maintaining the functional state (Source: IEC/TS 61851-3-4) (BSI Group, Mar 2024)
Local energy management system (Local EMS)	Active device's internal system that protects the energy buffer, source or load from damage, monitors and increases the lifetime of the buffer, source or load, maintains the buffer, and source or load in a functional state (Source: IEC/TS 61851-3-4)
Voltage Converter Unit (VCU)	Voltage converter, local EMS and communication interface

In WMG's view, these definitions are not helpful or clearly distinct from one another, and do not align with physical or functional separation of items in real applications. The confusing terminology appears to have been caused by adopting terms from multiple other standards. **In WMG's view, EN 50604-1 should adopt a single term to aid clarity.**

The EN50604-1 BMS requirements are outlined below, with WMG commentary:

Table 27: EN 50604-1 Section 5.101 Table 1 BMS Requirements

EN 50604-1 BMS requirement	Comments
The BMS shall be an integral part of the removable battery system	WMG views this as an important principle: Together with the following requirements, it means that the battery must be capable of protecting itself and shall not be reliant on external systems for its protection.
The BMS shall provide active or passive protective devices	This is good, but reliance on only active protective devices may reduce their reliability.
The BMS shall provide protective devices avoiding over-charge / over-discharge	This is good but would benefit from a clear definition of "over-charge" and "over-discharge". In WMG's view, there should be a further requirement that the BMS shall provide protection from over-current in both charge and discharge.

EN 50604-1 BMS requirement	**Comments**
The BMS shall provide controlling of charging/discharging process	This requirement is open to various interpretations because “controlling” is not defined. There are various aspects of control of charge and discharge: (1) Permit it to start or prevent it from starting. (2) Start it and set the current and voltage. (3) Monitor the current and voltage. (4) Stop it. In general, a PLEV BMS must be able to do (1), and (3) and in case of a fault it must be able to do (4), but the BMS is not capable of doing (2). In the charging situation, the charger does (2) and (4), and in discharging, the motor controller does (2) and (4). In WMG’s view, the requirement should specifically mention (1), (3) and (4).
The BMS shall provide protective devices as part of BMS [providing] detection of internal short-circuits	In WMG’s view, this is a very difficult requirement to meet, and may be unnecessarily onerous. An internal short-circuit (ISC) in a cell is difficult to detect, especially when multiple cells are connected in parallel. The main means of detection is through a sudden drop in cell voltage, but it is difficult to distinguish a voltage drop caused by ISC from a voltage drop which occurs as part of normal operation. Furthermore, BMS detection of ISC is only of use if the BMS can act to mitigate the ISC. In practical terms, the BMS cannot mitigate ISC. The only realistic mitigations against ISC are passive protective devices, which can inhibit current from the reaching the faulty cell from busbars. This may protect parallel-connected cells.
The BMS shall provide protective devices respecting temperature limits [including] at least one temperature sensor which measures the temperature of the interior of the battery pack/system as close as possible to the most critical spot according to the design	This is a good requirement. It requires both monitoring of the critical temperature(s) in the battery and protection to respect the temperature limits. It would benefit from clarification that temperature limits from the cell supplier and other component suppliers must be respected. In WMG’s view, there should also be a requirement that the manufacturer identify, by test or analysis, the critical temperature locations in the battery system.
The BMS shall provide [a] compatibility check between battery system and connected equipment	This is a good requirement. As written, it applies to any connected equipment, such as a charger or a motor controller. Subsequent sections elucidate what the compatibility check should comprise.

EN 50604-1 Table 1 then provides requirements for both “manufacturer specific solutions” and “interoperable solutions” regarding connectors and communication with connected equipment, although in WMG’s view, the separation of “BMS” requirements from “assembled removable battery system” requirements is not very clear or logical.

It is beyond the scope of this report to provide a critique of the “interoperable” protocols and connectors stated in EN 50604-1. However, bearing in mind that EN 50604-1 covers not just e-bikes, but all L-category light electric vehicles, it is clear that the content focuses on existing automotive-style interoperable charging connectors and protocols, since PLEV protocols have not yet been agreed. Further development of ISO/TS 4210-10 has the potential to resolve this gap.

Notwithstanding the absence of an agreed interoperability standard for PLEVs, some of the manufacturer-specific requirements stated in EN 50604-1 provide a good benchmark for compatibility checks:

Table 28: Selected EN 50604-1 Table 1 Manufacturer-Specific Charger Compatibility Check Requirements

EN 50604-1 Charger compatibility requirement	**Comments**
An internal switch in the DC power circuit of the battery pack/system, controlled by the BMS, able to interrupt all power flow and ensure safety. The switch shall only be closed after a successful compatibility check	This is a good requirement. It reflects WMG’s comments in the second row of Table 26 above, that the BMS must be able to permit or prevent the start of charging, and to stop the charging in case of an issue.
A compatibility check between battery system and [the charger] shall be performed based on at least two of the following: - mechanical - electrical - electronic - communication Bijective recognition of both sides is [a] requirement for successful compatibility check.	In WMG’s view, a compatibility check between the charger and battery is an essential part of battery safety. Many PLEV batteries and chargers do not currently provide this, although some higher-end products do provide manufacturer-specific compatibility checks.

Battery Enclosure Requirements

EN 50604-1 Section 5.101 also provides general requirements for the battery enclosure:

Table 29: Summary of EN 50604-1 Section 5.101 Table 1 Battery Enclosure Requirements

EN 50604-1 Enclosure requirement	**Comments**
Mechanical strength to withstand stress caused by normal use and rough handling	This refers to the vibration, mechanical shock and drop tests.
Sufficiently resistant to degradation caused by sunlight radiation	Sunlight can embrittle some materials, particularly plastics.

EN 50604-1 Enclosure requirement	**Comments**
Reducing the possibility of ignition and spread of flame	This is tested by the “exposure to fire” test, but this is only applicable to vehicles with passenger compartments. In WMG’s view, this material requirement should apply to fires that start inside the battery, as well as those that start outside
Providing suitable insulation characteristics	This is mainly applicable to batteries with hazardous voltage.
Protection against ingress of foreign objects and water: IP54	IP5x requires that any dust ingress must not interfere with safe operation. This is a good requirement. IPx4 requires that water splashing shall have no harmful effects. WMG suggests that this requirement should be increased at least IPx5, protection from water jets. It is reasonably foreseeable that owners will spray-clean their e-bike or e-scooter, with a moderate pressure water jet.
The battery pack/system housing constructed in a way that it cannot be opened without the use of tools and any opening shall be easily detectable by a broken seal	This requirement is intended to tackle tampering but is unlikely to deter the amateur DIY hobbyist. Prevention of tampering is a difficult technical issue, beyond the scope of this report.

Other Relevant Requirements

There are several other requirements in EN 50604-1 similar to the items mentioned for EN 15194 in Section 7.6.1 of this report. Three further general safety requirements in EN 50604-1 are worthy of comment:

Table 30: EN50604-1 Section 5.102 Other Relevant General Requirements

EN 50604-1 General requirement	**Comments**
In connections by soldered terminations, the conductor shall be held in position additionally to the soldering to maintain it in position.	Soldered connections are ubiquitous in Printed Circuit Boards (PCBs), for mounting and electrically connecting surface-mount components. In PLEV batteries, soldering is also widely used for sensor wire connections and power-cable connections. In these cases, the solder joint is subject to much larger forces, when the cables are subject to shock and vibration. Solder joints are not well suited to such loads, and may break, with consequences ranging from loss of sensor signal to short-circuit of the battery. This is a good requirement, but in WMG’s view it should more stringently define how the conductor should be additionally held in position. For example, a piece of adhesive tape is not a durable solution, but a mechanical clip is a good solution, if it is designed to avoid fretting of the insulation.

EN 50604-1 General requirement	**Comments**
Connection to the cells shall be made according to the specification of the cell manufacturer in a manner that does not result in damage to the cells.	This is a good requirement but relies on the cell manufacturer to provide such information. Many cell suppliers do not. Although not clear from the wording, this is assumed to refer to the electrical connections. Almost all PLEVs use sport-welded connections to the cells. If improperly specified and quality-controlled (e.g. too high weld power, or unclean surfaces), the weld can rupture the end-cap of the cell, which can lead to cell failure, by electrolyte leakage or atmospheric moisture entering the cell and reacting with the electrolyte to create hydrofluoric acid. Improper welds can also lead to hot-spots during operation, which could lead to cell thermal runaway. It is difficult to define generic requirements to cover these failure modes, but this emphasises the need for stringent quality control throughout the manufacturing life of the product.
It is strongly recommended to extend the post-test observation period for destructive tests to 24h.	It is now well known that cells and batteries can enter thermal runaway long after an abuse test has been completed. In WMG's view the longer the post-test observation period, the better. From a practical standpoint, 24 hours is a good compromise.

Finally, EN 50604-1 Section 5.110 requires non-metallic materials, used for the cell holder and battery enclosure, to have a minimum flame rating of V-2 in accordance with EN 60695-11-10 (BSI Group, Sep 2013). In this test the specimen is placed vertically and exposed to a Bunsen burner flame for two periods of 10 seconds, and after removing the burner, a V-2 material must stop burning within 30 seconds; drips of flaming particles are allowed. The highest rating for the same test is V-0, for which material must stop burning within 30 seconds, and drips particles are allowed only if they are not inflamed.

In WMG's experience, there is some debate about suitable flame-retardancy for plastics used in battery packs. However, for plastic cell holders, if cell thermal runaway occurs, the temperature of the cell in contact with the plastic is so high that the plastic will rapidly melt and burn away, irrespective of a V-0 rating. This means that all structural integrity in the cell holder may be lost, with the result that cell spacings are rapidly compromised, which may lead to thermal propagation if neighbouring cells touch.

Nevertheless, the flammability rating of plastic materials that may be ejected during a PLEV battery fire are relevant to the spread of the fire to nearby items. From this standpoint, there is scope for improvement by increasing the required rating from V-2 to V-1 or V-0.

Cell Requirements

EN 50604-1 Section 5.101, Table 1, requires that Lithium-ion cells shall be compliant with UN38.3 and either EN 62660-3 (BS EN IEC 62660-3:2022, BSI Group, Apr 2022) or EN 62133-2. Taking the latter, this means that cells must pass the tests shown in Section 7.6.5, Table 32. WMG's comments follow that table.

7.6.4 Safety Requirements for Portable Batteries in EN 62133-2

Electrical Safety

The first safety requirement in EN 62133-2, Section 5.2, concerns electrical insulation between the live parts and the battery casing, to minimise the risk of electric shock. As explained in Section 7.1.6 of this report, this is mainly relevant to hazardous voltages (> 60 V_{dc} or >30 V_{ac}). The insulation resistance (Ω) is measured, and expressed as a fraction of the maximum voltage (V) of the system, so the result is in Ω/V. The international consensus is that the value achieved should be at least 100 Ω/V for DC systems (equating to a maximum current of 10 mA) and at least 500 Ω/V for AC systems (equating to a maximum current of 2 mA), because of the different health risks posed by DC and AC. These values are used in numerous standards and legislative documents, including the Type Approval legislation for cars and L-category vehicles, and the equivalent standard ISO 6469-1. Similar values are used in the UL standards.

Voltages below the hazardous voltage threshold can still pose a health risk, so similar threshold values are commonly used.

The requirement in EN 62133-2 Section 5.2 is for an insulation resistance of 10,000 Ω/V. This is at least 20 times higher than the values used in other standards. In WMG's view, this is unnecessarily stringent, and should not be used.

Venting

EN 62133-2 Section 5.3 provides the requirements for venting shown in Table 30. This should be read alongside the terminology definitions in Table 24 of this report.

Table 31: EN 62133-2 Venting Requirements

EN 62133-2 Venting requirement	**Comments**
Battery cases and cells shall incorporate a pressure relief mechanism or shall be so constructed that they will relieve excessive internal pressure at a value and rate that will preclude rupture, explosion and self-ignition.	Regarding cells, the 18650 format used in most PLEV batteries usually includes a vent device in the cap. However, WMG experience and real world evidence shows that this does not always prevent rupture / explosion. Regarding packs, a relatively weak enclosure, such as injection-moulded plastic, is likely to comply. However, "integrated" batteries with extruded aluminium casings are more likely to rupture or explode due to the likelihood that significant internal pressure may be required to cause material failure of the enclosure.
If encapsulation is used to support cells within an outer case, the type of encapsulant and the method of encapsulation shall neither cause the battery to over-heat during normal operation nor inhibit pressure relief	Many PLEV batteries have cylindrical cells stacked close together with a shrink-wrap polymer film encapsulating the cell stack. The combination of these factors inhibits circulation of air around the cells, and therefore reduces the ability to transfer heat to the battery casing.

BMS Temperature, voltage and current management

EN 62133-2 Section 5.4 provides the requirements shown in Table 31, the first two of which effectively relate to the BMS and are comparable to those in EN 50604-1 in Table 26. The final requirement relates to documentation.

Table 32: EN 62133-2 Requirements for Temperature, Voltage and Current Management

EN 62133-2 BMS requirement	Comments
The design of batteries shall be such that abnormal temperature-rise conditions are prevented.	This is a good requirement, but there is no test in the standard to demonstrate that it is met.
Batteries shall be designed to be within temperature, voltage and current limits as specified by the cell manufacturer.	This is a good requirement, but only a small part of this is tested in the standard (over-charge test, Section 7.3.6)
Batteries shall be provided with specifications and charging instructions for equipment manufacturers so that specified chargers are designed to maintain charging within the temperature, voltage and current limits specified.	This is a good requirement. However, the standard lacks any measures to tackle the foreseeable misuse of using an incorrect or malfunctioning charger.

Section 5.6.1 and 5.6.2 of EN 62133-2 then provides further BMS recommendations, covering areas including:

- Control and protection for current, voltage, temperature and any other parameter required for safety and to maintain the cells within their operating region
- Protective components, based on a safety analysis
- Cell voltage limits and cell (or parallel cell-block) voltage monitoring
- Capacity-matching of cells (or parallel cell-blocks) in series
- Cell balancing circuitry

However, all of these are phrased with the word “should” or “recommended”, rather than “shall”, and therefore are understood not to be hard requirements (See Section 7.4 of this report). In WMG’s view, this makes EN 62133-2 much weaker than EN 50604-1.

WMG suggests that the stronger BMS requirements of EN 50604-1 should apply to all PLEVs.

Battery Enclosure and Structure

Section 5.6.3 of EN 62133-2 provides recommendations on mechanical protection of cells and design to account for cell dimensional tolerances. These are recommendations, not requirements, but the mechanical tests in Section 7.3.8 of the standard are required.

Quality Plan

Section 5.8 of EN 62133-2 requires that the manufacturer shall prepare a comprehensive quality plan for production of cells and batteries, but then states that they should institute the necessary process controls as they relate to product safety.

In WMG’s view, it is illogical for compliance with a standard to require a quality plan, but to make its implementation optional.

WMG suggests that a production quality plan and its implementation relating to product safety shall be required for all PLEV batteries to comply with relevant standards.

7.6.5 General Safety Requirements for Cells in EN 62133-2

The cell test requirements in EN 62133-2 are shown in Table 32 below:

Table 33: EN 62133-2 Cell Test Requirements

EN 62133-2 Section	Test description	Pass Criteria
7.2.1	Continuous charge at maximum voltage for seven days	No fire, explosion, or leakage
7.3.1	External short-circuit at 55 ± 5 °C, with external resistance of 80 ± 20 mΩ, cell initially at 100% SoC	No fire or explosion
7.3.4	Thermal abuse at 100% SoC, in an ambient temperature increased at 5 ± 2 °C/min from 20 °C to 130 °C, and held at 130 °C for 30 mins	No fire or explosion
7.3.5	Crush between flat plates with up to 13 kN force, or until voltage drops by one third, after which the force is released.	No fire or explosion
7.3.7	Forced discharge at 1 C-rate, starting at the minimum cell voltage, until the cell voltage is the negative of the maximum cell voltage, ending after 90 mins.	No fire or explosion

WMG’s comments on the tests above are as follows:

Continuous Charge Test

This is a test of normal operation of the cells within their intended limits, rather than reasonably foreseeable misuse. It mimics a common real world condition, where a single-cell or battery is left connected to a charger for an extended period. There is no cell-level over-charge test in EN 62133-2, but there is a battery pack-level over-charge test. This is a significant difference between EN 62133-2 and EN 62660-3, either of which is an acceptable standard for cells according to the battery standard for e-bikes, EN 50604-1. In WMG’s view, the absence of a cell-level over-charge test in EN 62133-2 is a significant omission, which places the responsibility for mitigating over-charge on the BMS rather than the cell. While the BMS should have the main responsibility for avoiding over-charge, the behaviour of over-charged cells should also be tested, to determine what additional measures may be required to ensure safety in case of a failure in the BMS’s primary protection system.

External Short-Circuit Test

The resistance value of 80 ± 20 mΩ used for the external short-circuit is essentially the same as UN 38.3, which specifies < 100 mΩ. However, WMG regards the value as quite high, being significantly higher than the internal resistance of a typical 18650 cell, which is around 20-50 mΩ. This means that the short-circuit current will be limited to less than 40 A, equating to a C-rate of 10-15 C for a typical 18650 cell. While this is much higher than the maximum operational C-rate (typically 2-5 C), it is not the worst case that hypothetically could occur in the real world with a pack-level short-circuit or a fault within a pack causing a cell-level short-circuit. Furthermore, the pass criteria mean that cell venting is permitted.

Thermal Abuse Test

WMG regards this as a severe thermal abuse test, because it reaches 130 °C, which is well above the minimum temperature at which some self-heating reactions may occur in most Lithium-ion cells (see Section 3.5.4) and is a typical temperature for the separator between the anode and cathode to melt or shrink, and could therefore lead to internal short-circuits between the anode and cathode. The 30 minute duration is short compared to some tests, but likely long enough to cause the temperature within the cell to become close to the 130 °C of the surrounding air. It is quite different from the UN38.3 thermal test, which comprises 10 thermal cycles, each of six hours at -40 °C and six hours at +72 °C.

Although cell venting is permitted, to pass the test, the separator must not break down to the point where full thermal runaway occurs. However, it should be noted that the test does not involve and charge or discharge current, so does not test for the inclusion of a PTC or CID protection device, neither of which would make a difference to the result in this test.

Crush Test

WMG regards this as a severe mechanical abuse test. It uses the same maximum crush force and flat plate as the UN38.3 crush test for small cells (<18 mm diameter), but in EN 62133-2, it is applied to all cells, whereas UN38.3 uses a different test for cells ≥ 18 mm diameter. Significant deformation and rupturing of the cell casing can be expected. However, the EN 62133-2 test has no observation period and no temperature limit, so if fire or explosion occurs after the force is released, this is not considered in the test result. Conversely, UN38.3 test has a 6-hour observation period, during which the cell surface temperature shall not exceed 170 °C. WMG considers the UN38.3 test to have more rigorous pass criteria.

Forced Discharge Test

This differs from the UN38.3 forced discharge test, which uses a 12 V power supply in series with the cell and a resistive load to discharge the cell at its maximum discharge current, for a duration equating to force discharging the cell by its rated capacity, followed by a 7-day observation period. WMG considers the UN38.3 test to have more rigorous pass criteria.

7.6.6 General Safety Requirements in UL Standards

The US standards for e-bikes, other PLEVs and LEV batteries are quite consistent in their general requirements. Here, the focus will be on the LEV battery standard, UL 2271, since it is the most relevant to the subject of this report. Since there is much overlap with the content of EN 50604-1 and EN 62133-2 (see above), this section will only highlight the aspects of UL 2271 that are notably different or superior in WMG's view.

Requirements for Plastic Parts

Section 7 of UL 2271 concerns non-metallic materials. It requires that polymeric materials (plastics) shall have a minimum flame rating of V-1, in accordance with UL 94 (UL Solutions, Feb 2023) (equivalent to EN 60695-11-10). This is a slightly better flame-retardant requirement than the V-2 rating required in EN 50604-1. WMG would expect a battery with V-1 plastics to be slightly less likely to spread fire to nearby items than one with V-2 plastics.

Section 7 of UL 2271 also requires polymeric materials to have a Relative Thermal Index (RTI) of ≥ 80 °C, determined according to UL 746B. The RTI is the maximum service temperature at which the critical properties of a material will remain within acceptable limits over a long period of time. Many polymeric materials undergo a rapid loss of structural properties above their “glass transition temperature”, changing from a hard state to a relatively soft, rubbery state. In many cases, this transition happens at lower than 80 °C, for example polyamide PA6 is typically around 60 °C (Omnexus, no date). To meet this requirement in UL 2271 requires polymer grades which retain their properties at temperatures above the operating temperature range of Lithium-ion cells. This doesn’t mean they will retain this strength in case of thermal runaway, but it aids durability of the battery. There is no equivalent requirement in the European/UK battery standards.

Requirements for Creepage & Clearance

When an electrical system contains conductors of widely differing voltages, such as the positive and negative of a PLEV battery, it is important that exposed conductors (those not enclosed by insulation) are sufficiently separated to prevent shorting between them. The distances are typically defined in two ways: (1) along a surface between the conductors, such as PCB (creepage) and (2) through air (clearance). Section 13 of UL 2271 tabulates the required separation distances, or as an alternative refers to EN 60950-1 (BSI Group, May 2006). It also requires conductors of circuits operating at different voltages to be mechanically secured to separate them, and to prevent insulation from coming into contact with uninsulated live parts (for example, insulation on a wire being able to contact the soldered terminal on another wire).

By comparison, EN 50604-1 does not mention creepage or clearance, and EN 62133-2 only advises that “adequate” creepage and clearance should be maintained, without specifying the required distances.

In WMG’s view, creepage and clearance requirements should apply to all PLEV batteries. The area of most concern, regarding battery design and manufacture, is wires and cables that are not mechanically retained to prevent them from moving and chafing on one another or on other objects which could compromise insulation between conductors.

Manufacturing and Production Line Testing Requirements

For batteries with hazardous voltage (>60 V_{dc} or >30 V_{ac}), UL 2271 requires testing of 100% of production batteries, to ensure that they comply with electrical safety. Although this is not relevant to most PLEV batteries, because they are below the hazardous voltage thresholds, this is an important principle to note.

UL 2271 also requires manufacturers to have documented production process controls that continually monitor and record elements of the supply chain and battery assembly process that can affect safety and shall include parametric (quantified) limits to enable corrective / preventative action to address defects.

This is broadly similar to the Quality Plan requirement in EN 62133-2, but is perhaps more effectively worded, particularly in its requirement to continually monitor, and to use quantified metrics with respect to safety.

As explained in Section 7.6.1 of this report, EN 50604-1 does not make any mention of production quality for the battery and has no definite requirement for cell quality either.

In WMG’s view, this is one of the most important differentiators of the UL standards, compared to the European standards. Furthermore, WMG understands that UL certification requires an on-going inspection of production facilities by UL staff, on a quarterly basis. This third-party inspection is far more robust that the self-inspection requirement for PLEV suppliers to the UK markets.

Cell Requirements in UL 2580

UL 2271 requires that Lithium-ion cells comply with the cell requirements in UL 2580 (UL Solutions, Jun 2022), meaning that cells in LEV batteries must meet the same safety requirements as those used in other electric vehicles such as cars.

Sections 16.2 – 16.4 of UL 2580 define the requirements for Lithium-ion cells. Section 16.3 requires that the cell design shall ensure sufficient safety measures to mitigate internal short-circuits and other hazardous conditions during the life of the cell. This sentence embodies a very challenging requirement, discussed in further detail in Section 2 of this report. Section 16.3 of UL 2580 goes on to provide examples of aspects of the cell design safety measures, explained in Table 33:

Table 34: UL 2580 Cell Design Requirements

UL 2580 Requirement	Comments
Appropriate choice and placement of insulation (advice to follow IEEE 1625 / IEEE 1725)	Insulation, in the form of adhesive tape, moulded plastic parts, shrink-wrap, etc., is used in several places in the cell to prevent short-circuits. IEEE 1625 requires that insulation material shall have electrochemical, chemical, mechanical, electrical, and thermal stability over the temperature range of use, storage, and transportation.
Sizing of anode to overlap cathode	The graphite active material on the anode must overlap the cathode active material along all edges, to prevent lithium plating during charging of the cell. The overlap must account for all manufacturing tolerances and any possible relative movement of the anode and cathode layers, due to shock and vibration
Proper placement of insulation and separation of parts of opposite polarity, including insulation of tabs	A typical Lithium-ion cell consists of multiple alternating anode (negative) and cathode (positive) layers. There are risks of short-circuits around the edges of the layers, and where tabs are attached to the metallic foils on to which the anode and cathode active materials are coated. Durable insulation of these areas is essential.
Appropriate protection mechanisms such as separator shutdown, protective coatings and electrolyte additives	The separator is a polymer film that electrically insulates the anode from the cathode but provides a path for Li ions to flow between the two, via microscopic pores in the material. Shutdown occurs when the separator reaches a temperature that causes the material to melt/flow, closing the pores, and preventing the flow of Li ions. Typically, a polyethylene layer provides the shutdown function at ~ 130 °C, and polypropylene layers provide mechanical integrity until they melt at ~ 160 °C. Protective coatings on the separator, for example a thin ceramic layer, typically aim to prevent Li dendrites on the anode from creating a short-circuit to the cathode, and can also counteract shrinkage of the separator, which could otherwise lead to short-circuits at the edges of the electrodes. Electrolyte additives (in small percentage quantities) are used for numerous reasons associated with cell manufacturing, safety, life and performance.

UL 2580 Requirement	Comments
Separators with sufficient strength, thermal properties and that are sized to prevent short-circuit between positive and negative electrodes	The separator is possibly the most important component within the cell to prevent short-circuits. The separator must overlap both the positive and negative electrodes along all edges. A tear or shrinkage of the separator presents a high risk of creating a short-circuit. A thinner separator allows more space for the anode and cathode, hence higher cell energy, but is a greater safety risk. The dimensions including thickness are critical for safety.

UL 2580 requires that compliance of the cell design and construction shall be determined by teardown analysis, a review of documentation and components and a series of tests. The tests are outlined in Section 7.8 of this report.

7.6.7 Battery & Cell Requirements in IEEE 1625 and IEEE 1725

As explained in Section 7.3.9 of this report, IEEE 1625 is a standard for rechargeable batteries for multi-cell mobile computing devices and covers batteries comprising multiple cells in series and parallel, while IEEE 1725 is a similar standard for batteries for mobile phones. It considers batteries with a maximum of two cells in series.

Below, WMG summarises some of the key content in these standards which does not appear in existing PLEV battery standards such as EN 62133-2, EN 50604-1 or UL 2271:

Table 35: Highlights of IEEE 1625 / IEEE 1725 Relating to Cell Safety

IEEE 1625 / 1725 Content	Comments
Annex E (Normative): Cell Specification Sheet (IEEE 1625 only)	This Annex provides a template for cell suppliers to provide fully document the cell data. Of particular importance for safety are the current and voltage limits, expressed as a function of cell surface temperature. This allows the cell supplier, for example, to specify narrower limits at lower temperatures, to prevent lithium plating.
§5.2.2: Separator Material	This section details the requirements of the separator material, including the shutdown performance, physical integrity, shrinkage allowance and general stability.
§5.2.4 Electrode capacity balance & geometry	This section requires the anode area to completely cover (i.e. overlap) the cathode active area, and to have a reversible capacity greater than the cathode. Both measures are to prevent lithium plating during charging.
§5.2.7 Cell vent mechanism	IEEE 1625 advises that the vent should open at a pressure that is significantly lower than that at which the cell case fails. IEEE 1725 requires that the cell shall be designed to include a consistent vent design or mechanism. This section also requires that the vent mechanism shall be designed to minimise/reduce projectiles and maximise/ improve retention of cell contents. This is highly relevant to preventing the spread of a PLEV fire to nearby objects.

IEEE 1625 / 1725 Content	Comments
§5.3.2 Impurity avoidance	This section requires that undesirable impurities in materials should be identified, specified, reduced to acceptable levels, and controlled throughout the manufacturing process. Impurities are a key factor in cell defects that can lead to thermal runaway.
§5.3.3 Cleanliness in manufacturing operations	This section requires that (1) management of temperature, humidity, and impurity levels shall be specified, controlled, and monitored, and (2) environmental management of materials (e.g. storage temperature & humidity), before and after manufacturing, shall be specified and monitored, and (3) introduction of metal contamination from equipment or process shall be prevented. Low humidity is essential, considering the formation of highly corrosive hydrofluoric acid that occurs from reaction of electrolyte with water. Metal contamination can lead to short-circuits and hence to thermal runaway.
§5.3.4 Manufacturing traceability	This section requires a cell traceability plan and advises that this should include methods for traceability at any date during product lifetime and after production to determine the cell production batch and performance data. IEEE 1625 goes further in recommending that the cell should have a traceability mark that is likely to survive an exothermic reaction. IEEE 1725 does not include this, probably because it is very hard to achieve with pouch cells which are universally used in mobile phones. Nevertheless, for hard-case cells, such as cylindrical cells which are almost universally used in PLEV batteries, it might be possible by etching on the cell surface. This would considerably aid post-mortem traceability.
§5.3.6.2 (IEEE 1625) / §5.4.2 (IEEE 1725) Electrode Burr Control	This section requires control in the manufacturing process of burrs (raised imperfections) in the copper and aluminium current collectors of the anode and cathode respectively. Burrs above a certain height could cause short-circuits, leading to cell thermal runaway.
§5.4 (IEEE 1625) / §5.5 (IEEE 1725) Electrode Stack Assembly	This section has numerous requirements to control the quality of jellyroll winding / electrode stacking, including tests to detect and reject damaged parts, and to prevent contamination with dust or other foreign materials. It serves as a guide to the common quality issues in this stage of cell assembly.

IEEE 1625 / 1725 Content	Comments
§5.5.5 (IEEE 1625) / §5.6.7 (IEEE 1725) Cell ageing & screening	This section requires defined processes for cell ageing (steps from the first charge to final acceptance) and screening / grading / sorting to identify and reject weak and early-failing cells, and to record all the data. IEEE 1725 requires a random sample of 100 cells from one day's production to be stored fully charged for 1 week at 45 °C, to measure charge-retention, and determine whether the statistical variation is within a certain range. Tests of this kind are essential to ensure the suitability of the process parameters, to ensure consistent cell quality.

The examples given in Table 34 give a flavour of the very detailed content of IEEE 1625 and IEEE 1725 and demonstrate that they have been written by experts who are very familiar with the operation and quality control of a cell manufacturing factory. These standards show a similarly thorough approach regarding pack integration, integration into the host application (e.g. laptop computer) and integration with the charging adapter.

Finally, Annex D of IEEE 1725 provides a useful process example for how system components (such as the battery) and their manufacturing sites can be validated against the standard, whether that be self-certification or 3rd-party certification.

WMG suggests a thorough review of PLEV battery standards alongside IEEE 1625 and IEEE 1725, to determine items that should be adopted and/or adapted from the IEEE standards, including consideration of two-fault scenarios.

7.7 Overview of Test Categories

Appendix 3 (Section 15.3 of this report) provides an overview of the categories of tests contained in the automotive and L-category Type Approval regulations, the European/UK PLEV standards, the North American PLEV standards and the battery-specific standards in Europe/UK and North America.

The test categories are repeated in Table 35 below, with an explanation of their relevance to battery fires. In some cases, the commentary refers to other sections of this report which tackle the topics in greater detail.

Table 36: Test Categories Relevant to Battery Fires

Category	Commentary
Vibration	Vibration can induce relative movement and abrasion of components within the Lithium-ion cells, and of electrical wires, leading to short-circuits which can lead to thermal runaway. See § 3.5.3.3
Thermal Cycling / Shock	Thermal cycling exposes the product to repeated large and rapid changes of ambient temperature. This causes thermal stress in components, which can result in cracking or disintegration. Welded and soldered connections are particularly vulnerable, and failures could result in short-circuits which can lead to thermal runaway. Changes of temperature also result in changes in humidity inside the battery because warm air can hold much more water vapour than cold air: As the air cools, water vapour will condense out of the air

Category	Commentary
	onto surfaces inside the battery (dewing), which may cause corrosion and could compromise electrical creepage and clearance (insulation) between exposed conductors. In extreme cases, this could cause a short-circuit leading to thermal runaway.
Mechanical Shock (accel profile)	This type of mechanical shock test imitates the more severe shock loads encountered in operation of a product, for example an e-bike hitting a kerb or pothole. The acceleration load is high, but last for only a small fraction of a second and is expected to occur only infrequently in the life of the product. It can result in movement of poorly mounted components, or breakage of poorly designed mechanical parts. This can then increase susceptibility to subsequent vibration. It could result in short-circuits which can lead to thermal runaway.
Mechanical Shock (drop / impact)	This type of mechanical shock test represents foreseeable misuse, for example dropping a battery that has been removed from an e-bike. The acceleration loads may be bigger than in the category above, and the impact may affect the integrity of the casing of the battery. Such an event is not expected to occur more than once or twice in the life of the product. The potential effects are similar to above, but casing damage presents additional hazards of exposure to internal electrical parts, susceptibility to water ingress, etc.
Crush	A crush test represents foreseeable misuse or accident, such as a vehicle crash. It is therefore more relevant to e-scooters with the battery mounted close to the bottom of the chassis, rather than e-bikes in which the battery is unlikely to encounter such loads. Whereas the real world crush may happen in a fraction of a second, the laboratory crush usually uses a slow-acting hydraulic rig to apply a crushing force between a moving and a stationary platen. The force applied is typically very high (e.g. equivalent to 1000 times the weight of the battery) and the degree of deformation can also be high (e.g. 50% of the battery dimension). With such deformation, it is expected that cells will vent, so the pass criterion is usually limited to no fire / explosion.
External Short-circuit (ESC)	ESC applies a short-circuit to the external power connections of the battery. If the battery has more than one power connector (e.g. for the motor and charger separately), then it should be applied to each in turn. The test imitates a short-circuit that could occur in a damaged connected system (motor or charger) or because of foreseeable misuse (e.g. allowing a conductive tool to touch the + and – terminals). If the ESC persists, it will result in rapid self-heating of the cells, busbars and cables in the battery, which can lead to thermal runaway.
Internal Short-circuit (ISC)	ISC imitates a failure that occurs within a cell. To perform the test, a special cell must be built, or a production cell must be modified, with an ISC trigger mechanism built into the cell. This is very difficult to do, and inherently means that the trigger cell is not representative of

Category	Commentary
	mass-produced cells, so is of dubious merit. However, it is arguably the closest that a laboratory test can get to replicating a defective cell. In general, the BMS is powerless to take any action that would mitigate an ISC. The mitigations against ISC are usually cell-level passive devices such as the PTC and CID (see §3.4). The ISC test is not used in most Standards because of the issues mentioned here.
Thermal Propagation (TP) by ISC	In many safety/abuse tests such as ESC and over-charge, the aim of the manufacturer is to prevent any cell from entering thermal runaway (TR). Conversely, the Thermal Propagation test requires that TR of a single cell is deliberately initiated. It evaluates the spread of TR from the first cell to the other cells. It is currently only used in automotive legislation and uses a trigger mechanism such as a heating pad or nail penetration to set off the first cell TR. See §6.15.1.
Over-charge	Based on real world evidence, over-charge is believed to be highly relevant to PLEV fires, for example the use of an incorrect charger for the battery. It can lead directly to thermal runaway. See §3.1, 3.5.3.1, 3.12, 3.14, 4.5.
Over-discharge	Over-discharge can occur with a poor BMS or a soft short-circuit within the battery or as a result of storing a battery for a long period without charging it. Subsequent charging can lead to thermal runaway. However, the damage to cells caused by over-discharge may take some time to manifest itself, so the real world relevance is less clear. See §3.5.3.1, 3.13.
Over-temperature	Thermal runaway begins when the cell internal temperature reaches a critical point, typically around 180 °C, but the cells can start to slowly self-heat as low as 85 °C. Therefore any mechanism that results in heating of one or more cells can lead to thermal runaway. The over-temperature test is usually aimed at ensuring that the BMS prevents charge and discharge at elevated temperatures, with a good safety margin, e.g. at 60 °C. Some tests continue to higher temperatures, e.g. 130 °C, to evaluate whether the cells can fail in a safe manner (e.g. by activating the PTC or CID, see §3.4) without causing thermal runaway.
Over-current	Over-current is a reasonably foreseeable misuse condition. In charging, it could be caused by an incorrect or malfunctioning charger. When charging at cold temperatures, it could result from inadequate BMS limits. In discharge (riding) it could result from tampering. Over-current can lead to over-heating (see above) but during charging can also lead to ISC (See §3.5.1). Either can lead to thermal runaway.
Low temperature	The ability of the cells to deliver or accept charge is reduced at low temperature. Charging at low temperature is particularly risky (See §3.5.3). A battery charging test at low temperature should be

Category	Commentary
	performed to check that the charging current is within the limit specified by the cell manufacturer.
Imbalanced Charging	Imbalance between the voltages of cells connected in series and result in over-charge of some cells. See §4.5.4, 4.5.5, 6.15.3.
Management of emitted gases	If a cell vents or reaches thermal runaway, a large volume of flammable and potentially toxic gas is released, sometimes very rapidly. Containing this gas can create different hazards, as the build-up of pressure can lead to explosive rupturing of the battery, so it is generally accepted that it is better to allow the gas to escape into the surroundings. Outdoors, the gases will quickly dissipate, but indoors they can be very hazardous due to their flammability and toxicity. Only the automotive legislation currently mentions management of emitted gases. For Lithium-ion batteries, it simply requires that all tests for which one of the pass criteria is “no venting” are passed. These include vibration, thermal shock, ESC, over-charge, over-discharge, over-temperature and over-current.
Warning of failure	Warning of failure currently only features in automotive legislation. It requires the BMS to have diagnostic capabilities, to determine the status of all sensors and actuators involved in ensuring battery safety, and to warn the driver in case of any malfunction. Compliance is determined via documentation. Testing of such diagnostics require many test-cases to ensure that false positives and false negatives do not occur.
Warning of thermal event	Warning of a thermal event currently only features in automotive legislation in the UK. It requires software to determine when any cell has entered, or is about to enter, thermal runaway. This typically relies on a combination of cell voltage and temperature sensors. As above, validation requires many test-cases to ensure that false positives and false negatives do not occur.
Water immersion	Water ingress can result in corrosion of internal parts of the battery, including the BMS. If the water is salty, it can also cause short-circuits. Either can lead to thermal runaway, but it can take weeks or months to occur. From a validation standpoint, it is sufficient to ensure that either water cannot enter the battery, or if it does enter, it can quickly and completely drain out again.

7.8 Comparison of Cell Test Requirements

7.8.1 Overview of Cell Test Categories in Each Standard

The standards used for cell testing are summarised in Table 36:

Table 37: Summary of PLEV Application, Battery and Cell Standards

PLEV Type	Battery Standard	Cell Standard
UK e-bikes – EN 15194 (also ISO-TS 4210-10)	EN 50604-1	UN 38.3 and EN 62660-3 or EN 62133-2
UK e-scooters – EN 17128	EN 62133-2	EN 62133-2
US e-bikes (UL 2849) and e-scooters (UL 2272)	UL 2271 / UL 2580	UL 2580 Annex B (equivalent to EN 62660-2 (BSI Group, Feb 2019) with some modifications) or UL 2580 Annex D

The test categories in each of the cell standards mentioned above are shown in Table 37:

Table 38: Comparison of Test Categories on Cell Standards

Test Category	Test Type	Cells (18650 cylindrical)					
		UN38.3	EN 62133-2	EN 62660-2	EN 62660-3	UL 2580 Annex B	UL 2580 Annex D
Environ-mental	Vibration	✓	✗	✓	✗	✓	✓
	Mechanical Shock	✓	✗	✓	✓	✓	✓
	Thermal Cycling	✓	✗	✓	✓	✓	✓
Mechanical Abuse	Impact / Drop	✓	✗	✗	✗	✓	✓
	Crush	✗	✓	✓	✓	✓	✓
Electrical Abuse	External Short-circuit	✓	✓	✓	✓	✓	✓
	Internal Short-circuit	✗	✓	✗	✓	✗	✗
	Over-charge	✗	✗	✓	✓	✓	✓
	Over-discharge	✓	✓	✓	✓	✓	✗
Thermal Abuse	Over-temperature	✗	✓	✓	✓	✓	✗
	Projectile	✗	✗	✗	✗	✓	✓

✓	Test is included in the standard
✗	Test is not included in the standard

Based on the summary comparison in Table 37, UL 2580 Annex B, which is based on EN 62660-2 with some modifications and additions, is the most comprehensive in terms of test categories.

For e-bikes in the UK, Table 37 shows that the two cell standards that can be used are not equivalent to each other. EN 62660-3 appears to be more comprehensive than EN 62133-2. However, it is important to consider the cell standards in the context of the battery-level tests in the battery standard EN 50604-1, see Section 7.9. For example, while EN 62133-2 does not include cell-level vibration, thermal cycling or mechanical shock tests, these are all included in EN 50604-1 at battery pack level.

7.8.2 Pass/Fail Criteria in Cell Test Standards

The pass criteria for each cell test are listed in Table 38. Fortunately, there is almost complete consistency of pass criteria between the different standards. For environmental tests, which are intended to represent normal operation of the cells, the pass criteria include no venting or leakage of electrolyte, as well as no rupture, fire or explosion. For abuse tests, the cells are permitted to vent or leak electrolyte, but no fire or explosion is permitted. The UL standards also do not permit rupture in most abuse tests.

Table 39: General Pass Criteria for the Cell Test Categories

Test Category	**Test Type**	**Pass Criteria**				
		No Leakage	No Venting	No Rupture	No Fire	No Explosion / Disassembly
Environmental	Vibration	✓	✓	✓	✓	✓
	Mechanical Shock	✓	✓	✓	✓	✓
	Thermal Cycling	✓	✓	✓	✓	✓
Mechanical Abuse	Impact / Drop	×	×	×	✓	✓
	Crush	×	×	×	✓	✓
Electrical Abuse	External Short-circuit	×	×	(✓)	✓	✓
	Internal Short-circuit	×	×	×	✓	✓
	Over-charge	×	×	(✓)	✓	✓
	Over-discharge	×	×	(✓)	✓	✓
Thermal Abuse	Over-temperature	×	×	(✓)	✓	✓
	Projectile	×	×	×	×	✓ *

✓	Criterion is included for the test category
×	Criterion is not included for the test category
✓ *	Projectile test criterion is based on ejecta piercing a wire mesh cage around the cell.
(✓)	Pass criterion is only included in UL 2580, not in the other standards.

There are some exceptions to the pass criteria shown in Table 38. In the following cases, the pass criteria are more stringent, but the test protocol is correspondingly milder:

1. In UL 2580 Annex B, the impact test requires no venting or leakage of electrolyte, as well as no rupture, fire or explosion. The protocol for this test is to drop the cells from 1 metre height, whereas the other standards’ impact tests are to hit the cell with an impact force that is generally much larger than the weight of the cell, so the damage is correspondingly more severe.
2. In EN 62660-3, the over-discharge test requires no venting or leakage of electrolyte, as well as no rupture, fire or explosion. The protocol for this test is to discharge the cell to <25% of its nominal voltage, whereas the other standards’ over-discharge tests involve force discharging the cell to have reverse polarity, with correspondingly more severe chemical reactions inside the cell.

7.8.3 Test Protocols in Cell Test Standards

A detailed comparison of the test protocols used in each cell test standard is provided in Appendix 4 (Section 15.4 of this report). This shows that there are many differences between the way that a particular type of test is specified and performed. To ascertain how the results of the test would compare for different test protocols would require an extensive test programme, which is beyond the scope of the current work. Nevertheless, based on WMG’s experience, the key is to ensure that the test categories provide a comprehensive coverage of the failure modes that could occur, due to environmental influences and potential mechanical, electrical and thermal abuse.

WMG suggests the following items to be included in the definition of any test. Some standards do not consistently provide all the items below:

1. **The number of samples to be tested.**
2. **The pre-conditioning required prior to the test (e.g. charging to 100% SoC, using the manufacturer's standard charging protocol).**
3. **The ambient temperature at the start of the test, and where appropriate, the soak duration and/or sample temperature stability criterion, to ensure the sample is stabilised at the correct temperature. In many cases, this temperature is maintained throughout the test, but some tests, such as thermal cycling, require the temperature to change during the test.**
4. **The post-test observation period and ambient temperature, during which the pass criteria must be met.**
5. **The pass criteria**

For environmental tests, which are intended to represent normal operation of the cells, it should also be demonstrated that the cell is able to perform as normal after the test. This can be done by performing charge-discharge cycles according to the manufacturer's standard protocol.

WMG suggests that at least two complete charge-discharge cycles should be performed after environmental tests, followed by an observation period, and that a criterion for the discharge capacity should also be defined (e.g. >90% of the original discharge capacity of the cell). This, together with the other pass criteria (no leakage, no venting, etc.), demonstrates that the cell has not been adversely affected by the environmental test.

In UN 2580 Annex D, the environmental tests require that the post-test open-circuit voltage (OCV) must be at least 90% of the pre-test OCV (this criterion is not included in Table 38). In WMG's view, post-test charge-discharge cycles are preferrable to this method.

For mechanical, electrical and thermal abuse, a post-test charge-discharge cycle is not appropriate, as the cell is likely to have suffered internal damage. In the real world, there is a risk that a consumer will try to charge and/or discharge a battery with one or more damaged cells (e.g. after dropping the battery). In an ideal world, a damaged cell would prevent charge and discharge. However, this is not practical to implement at cell level, except where the test has triggered a built-in fuse. At battery pack level, certain types of abuse (e.g. electrical and thermal) can be detected by the BMS, which can then act to prevent subsequent charge and discharge. This is discussed further in Section 7.9.

The post-test observation period is an important consideration, especially for abuse tests. The observation period should be defined based on real world considerations, i.e. the cell is likely to be in a location where, if it suffered a delayed failure, it could present a hazard. UN38.3 includes a 6-hour observation period for the impact and external short-circuit tests, and seven-day observation period for the over-discharge test. However, UN38.3 is specifically targeted at transportation risks, wherein damaged to cells is likely to go undetected for extended periods. In most the other standards, the observation period is either zero or unstated for most tests.

WMG suggests an observation period of at least 6 hours for abuse tests, considering that cells may remain in a domestic setting for some time after damage has occurred.

Two of the cell test categories shown in Table 37 and Table 38 are worthy of further explanation and comment, provided in Sections 7.8.4 and 7.8.5 below.

7.8.4 Cell Internal Short-Circuit Test

As explained in Section 3.1 of this report, the Internal Short-Circuit (ISC) test is a highly desirable test to have but is practically very difficult to perform in a way that is repeatable and representative of real production cells.

As explained in Section 7.7, Table 35, the Internal Short-Circuit test requires a special cell to be built, or a production cell to be modified, with an ISC trigger mechanism built into the cell. Currently, for Lithium-ion cells, this test only features in EN 62133-2 and EN 62660-3. The latter refers EN IEC 62619:2022 (BSI Group, Sep 2022), which is a standard for alkaline cells and batteries.

In either case, the intent is to use 1 mm x 1 mm L-shaped nickel “particle” to create a short-circuit between the outer anode and cathode layers of the cell. In EN 62133-2, preparation for the test requires removing the jellyroll from the cell casing, partially unwinding the jellyroll, placing the nickel particle between the cathode and the separator, then re-winding and taping the jellyroll to secure the particle inside. EN 62660-3 allows an incision to be made in the cell casing, rather than extracting the jellyroll, but practically this is almost impossible to do on cylindrical cells which are used almost universally in PLEV batteries.

Once the nickel particle is in position, an electrical servo-operated press is used to apply pressure on the cell or jellyroll, causing the sharp nickel particle to pierce the separator, causing an internal short-circuit. The press moves at only 0.1 mm/s, and as soon as a short-circuit is detected from a drop in cell voltage of > 50 mV, the press is stopped.

In EN 62133-2, the pass criterion is “no fire”, whereas in EN 62660-3 it is “no evidence of fire or explosion”.

WMG does not have direct experience of the nickel particle test method. However, based on the description in the standards, the method has several major challenges:

1. The cell must be charged to 100% SoC prior to removing the jellyroll from the cell or making an incision in the cell casing. Opening a cell and handling the jellyroll at 100% SoC is inherently risky for personnel involved.
2. Opening the cell exposes the electrolyte to atmospheric moisture. EN 62133-2 states that the procedure should be done in an atmosphere with a dew point below -25 °C, i.e. very dry air, but there is still a possibility for any moisture to react with the electrolyte, creating hydrofluoric acid.
3. Opening the cell results in electrolyte evaporation, which immediately changes the behaviour of the chemical system in the jellyroll. The procedure is fiddly, and unlikely to be completed quickly. The resulting loss of electrolyte is very likely to reduce the flammability of the cell contents.

For these reasons, in WMG’s opinion, the test is of dubious merit.

It is worth noting that several research groups internationally have developed alternative methods for creating an internal short-circuit, including NASA (Darcy *et al.*, 2015) and a collaboration between University of Michigan and Tsinghua University, Beijing (Zhang *et al.*, 2017), but these all require building bespoke cells which are necessarily different from mass-production cells.

WMG advocates only using test methods which can be performed on unmodified production cells.

7.8.5 Cell Projectile Test

The UL standard for LEV batteries UL 2271 requires that the cells comply with UL 2580. This contains a test named the “Projectile Test”, which to WMG’s knowledge is not found in other standards, although the EN 50604-1 Section 5.107 definition of “test result explosion” does bear some similarities to aspects of the Projectile Test (see Table 24).

The UL 2580 Projectile Test involves heating a cell from beneath with a Meker Burner, which is similar to a Bunsen Burner but with greater heat output. The heating continues until the cell combusts. The cell is surrounded on all sides and above by a cage of thin aluminium wire mesh, positioned at a distance of approximately 30 cm from the cell. If any ejecta from the cell penetrate the mesh, the result is deemed to be a fail.

WMG suggests considering adding the UL2580 Projectile Test to those required for cells used PLEVs in the UK. This test is very relevant to the spread of fire to adjacent objects, when a PLEV fire occurs in a domestic setting.

7.9 Comparison of Battery Pack Test Conditions

7.9.1 Overview of Battery Pack Test Categories in Each Standard

The test categories in each of the battery pack standards mentioned in Table 36 are shown below in Table 39:

Table 40: Comparison of Test Categories in Battery Pack Standards

Test Category	**Test Type**	**Battery (< 12 kg)**			
		UN38.3	EN 50604-1	EN 62133-2	UL 2271
Environ-mental	Vibration	✓	✓	✓	✓
	Mechanical Shock	✓	✓	✓	✓
	Dewing	✗	✓	✗	✗
	Thermal Cycling	✓	✓	✗	✓
Mechanical Abuse	Water Immersion	✗	✓	✗	✓
	Impact / Drop	✗	✓	✓	✓
	Crush	✗	✓	✗	✗
Electrical Abuse	External Short-circuit	✓	✓	✓	✓
	Internal Short-circuit	✗	✗	✗	✗
	Over-charge	✓	✓	✓	✓
	Over-discharge	✗	✓	✗	✓
	Deep Discharge Protection	✗	✓	✗	✗
	Imbalanced Charging	✗	✗	✗	✓
Thermal Abuse	Over-temperature	✗	✓	✗	✓
	Low-temperature	✗	✓	✗	✗
	Mold Stress Relief	✗	✗	✓	✓

✓ Test is included in the standard
✗ Test is not included in the standard

Based on Table 39, it appears that EN 50604-1 has the most comprehensive set of tests for the complete battery pack. It is the only standard that has test for dewing, crush and deep-discharge protection.

- The dewing test comprises a combination of varying humidity (55 – 98% relative humidity) and varying temperature (25 – 80 °C) and is intended to reveal electrical failures caused by condensation inside the battery pack, including those caused by transport of atmospheric moisture into the battery enclosure.
- The crush test is arguably not relevant to e-bikes but would be relevant to e-scooters and other PLEVs in which the battery is at risk from mechanical damage due to being mounted very low in the vehicle chassis. However, currently EN 50604-1 is not required for any PLEVs other than e-bikes.
- The deep-discharge protection test addresses an important potential failure mode (see Sections 3.5.3.1 and 3.14 of this report), but in WMG's view the test definition in EN 50604-1 is difficult to understand and lacking a clear rationale.
- The low-temperature test addresses the risk of damage to the cells, such as lithium plating on the anode, by charging at low temperatures. It involves cooling the battery to below the minimum permitted charge temperature, according to the supplier. Charging is then attempted. If charging is not inhibited, the test is failed.

Table 39 also shows the inadequacy of EN 62133-2, which lack many of the test categories which are present in EN 50604-1 and UL 2271.

UL 2271 contains most of the tests that are in EN 50604-1, although it lacks the dewing and deep-discharge tests. Table 39 also shows it not having a crush test, because the crush test in UL 2271 is "only applicable to on road LEVs such as scooters and motorcycles that could be involved in a crash". Therefore WMG deems that it is not applicable to e-bikes and non-road-legal e-scooters.

UL 2271 has one test that does not feature in the other standards: Imbalanced Charging (see Sections 4.5.4, 4.5.5, 7.12.6 of this report). However, although this requires the BMS to prevent cell over-voltage due to imbalance, it falls short of requiring the BMS to include a cell voltage balancing function. Meanwhile, EN 50604-1 mentions cell balancing, but does not have any tests for this function. In WMG's view, a test that expands on the UL 2271 test, to validate the functionality of a cell balancing circuit, would be a worthwhile addition.

UL 2271 and EN 62133-2 contain one test that is not included in EN 50604-1: The "case stress at high ambient temperature" or "mold stress relief" test. This test is targeted at moulded thermoplastic battery enclosures. It is well known that the injection-moulding process can result in stresses in the material. If the material is subsequently heated (outside of the manufacturing mould), these stresses can cause the part to distort. If this happens to a battery casing, it could lead to loss of sealing or exposure of electrical parts, presenting a hazard to the user. The tests in UL 2271 and EN 62133-2 both involve heating the battery to 70 °C for 6 hours, then allowing it to cool to room temperature, and then inspecting the housing to check for distortion. The test accelerates a process that could take place in the real world at lower temperatures over an extended time.
EN 62133-2 requires the test to be done on a fully charged battery, while UL 2271 requires the battery to be fully discharged prior to the test. WMG advocates the UL 2271 procedure, as heating the cells to 70 °C runs the risk of inadvertently causing thermal runaway.

Most of the battery standards listed above do not include tests to validate the protection against over-current, other than the short-circuit test and the EN 50604-1 low temperature charging test. EN 62133-2 does provide Annex A (Normative) "Charging and discharging range of secondary lithium-ion cells for safe use" which provides an explanation of the failure modes associated with charging and discharging outside the limits defined by the cell supplier but does not define a test methodology to ensure operation within the limits.

EN 62133-2 provides an example of how the charging and discharging limits can be shown graphically. The charging example is shown in Figure 51:

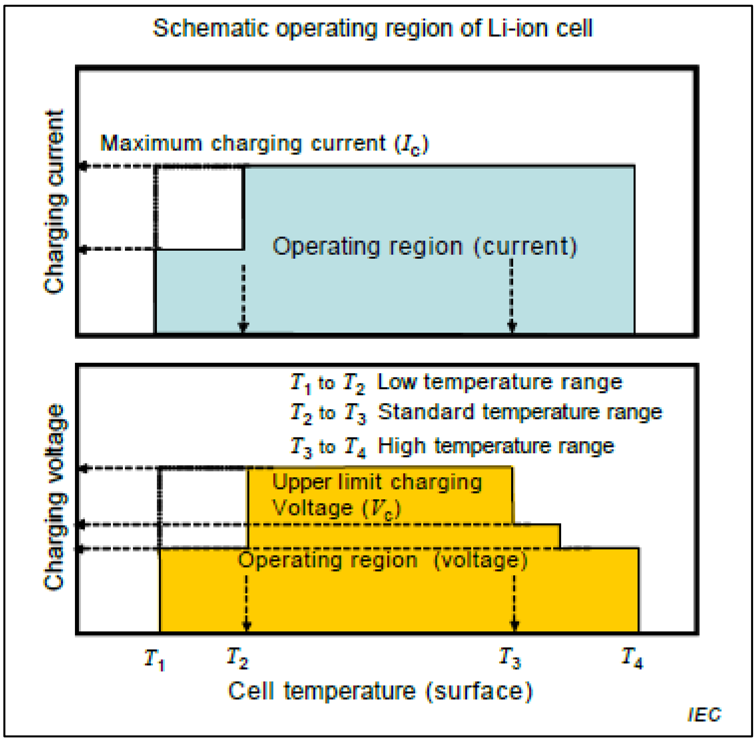


Figure 51: EN 62133-2 Annex A Figure A.1 – Representation of lithium-ion cells

It may be impractical for a standard to specify in detail how to validate the BMS protection limits against the charging and discharging current and voltage limits, which can be a function of temperature, duration, battery state of health and other factors. Nevertheless, in WMG's view, the battery standards should require the manufacturers to define their own test protocol to validate the limits, and to include the test description and results in a technical file.

Of the existing standards considered here, UL 2271 comes closest to a robust validation of the charge and discharge limits: The over-charge and short-circuit tests state that "if a protective device in the circuit operates, the test is repeated at 90% of the trip point of the protection device or at some percentage of the trip point that allows charging [or discharging] for at least 10 minutes." This is evidently intended to validate that the protection device activates at the intended current or voltage, but it leaves open the interpretation of what the "trip point" means. This really requires detailed system knowledge that is only available to the manufacturer.

WMG suggests that all PLEV batteries should undergo all of the tests listed in Table 39, with the exception of the Crush test, which should only apply for applications where physical damage can be anticipated from vehicle crash or from close proximity to the ground.

WMG suggests that standard organisations should consider a requirement for validation of current and voltage limits in the BMS, with reference to the limits defined by the cell supplier and suppliers of protective components such as the BMS MOSFETs. This includes any definition in limits as a function of temperature.

7.9.2 Pass/Fail Criteria in Battery Pack Test Standards

The pass criteria for each cell test are listed in Table 40. Unfortunately, unlike the cell standards, there is little consistency in pass/fail criteria between the various standards, which is reflected in the long list of notes beneath Table 40.

EN 50604-1 is particularly inconsistent in the pass criteria it specifies for each test, see Table 41. In WMG's view, the key points of concern are:

- The "no electrolyte leakage" and "no venting" criterion should apply to all the environmental tests, electrical abuse and thermal abuse tests.
- There is a clear mistake with the pass criteria for the crush test: One of the pass criteria is "no rupture", but rupture is inherent to a crush test.
- The isolation resistance criterion, for batteries with hazardous voltage (> 60 V_{dc}) should apply to all tests, with the exception of crush.

For comparison, the pass criteria in UL 2271 are shown in Table 42. These are more consistent between test categories, and the rationale is more intuitive.

In UL 2271, the "no venting" criterion applies in some tests, but the "combustible concentrations" criterion applies in all tests. This test criterion is not found in the European UK standards. The presence of combustible concentrations of gas can be determined in two ways: (1) By measuring the concentration of relevant gases directly or (2) by installing spark sources adjacent to the battery.

In WMG's view, this criterion is highly relevant to the hazards posed by PLEV batteries in an indoor environment, for example when they are on-charge or being stored.

WMG suggests adopting the UL 2271 "combustible concentrations" criterion for all battery tests in future UK standards for PLEV batteries.

Table 41: General Pass Criteria for the Battery Pack Test Categories

Test Category	**Test Type**	**Pass Criteria** No Electrolyte Leakage	No Venting (1) (2)	No Rupture	No Fire	No Explosion / Disassembly	Isolation Resistance ≥ 100 Ω/V (3)	Post-Test Operating State (4) (5)
Environmental	Vibration	✓	✓	✓	✓	✓	✓	Operational
	Mechanical Shock	✓	✓	✓	✓	✓	✓	Operational
	Dewing	✓ (6)	✗	✓ (6)	✓ (6)	✓ (6)	✓ (6)	Operational
	Thermal Cycling	✓	✓	✓	✓	✓	✓	Operational
Mechanical Abuse	Water Immersion	✗	✗	✗	✓	✓	✓ (7)	✗
	Impact / Drop	✓ (8)	✓ (8)	✓ (8)	✓	✓	✓ (8)	✓ (8)
	Crush	✗	✗	(✓)	(✓)	✗	✗	✗
Electrical Abuse	External Short-circuit	✓ (9)	✓ (9)	✓ (9)	✓	✓	✓ (9)	✓ (9)
	Internal Short-circuit	✗	✗	✗	✗	✗	✗	✗
	Over-charge	✓ (10)	✓ (10)	✓ (10)	✓	✓	✓ (10)	✓ (10)
	Over-discharge	✓	✓ (11)	✓	✓	✓	✓ (11)	✓ (11)
	Deep Discharge Protection	✗	✓ (6)	✓ (6)	✓ (6)	✓ (6)	✗	✗
	Imbalanced Charging	✓ (12)	✓ (12)	✓ (12)	✓ (12)	✓ (12)	✓ (12)	✓ (12)
Thermal Abuse	Over-temperature	✓ (13)	✓ (13)	✓ (13)	✓ (13)	✓ (13)	✓ (13)	✓ (13)
	Low-temperature	✗	✓ (6)	✓ (6)	✓ (6)	✓ (6)	✗	✗
	Mold Stress Relief	✗	✗	✓ (14)	✗	✗	✗	✓ (14)

✓ Criterion is included for the test category.

✗ Criterion is not included for the test category.

(✓) Only EN 50604-1 has a pack-level crush test. The "no rupture" requirement is clearly a mistake.

(1) For UL 2271 only, Venting is quantified by combustible gas concentration.

(2) EN 50604-1 only requires "no venting" for low-temperature; over-charge; deep-discharge protection, not for other tests.

(3) Isolation Resistance ≥ 100 Ω/V is only required for batteries with Hazardous Voltage (> 60 V_{dc}).

(4) Post-test operating state is only required in EN 50604-1 and UL 2271.

(5) In UL 2271 only, only protection controls are required to still be operational post-test.

(6) Only for EN 50604-1. No other standards contain the Dewing, Deep-discharge Protection and Low-temperature Protection tests.

(7) For water immersion, Isolation Resistance ≥ 100 Ω/V after the test is only required in UL 2271.

(8) For Impact/Drop, EN 62133-2 requires only no fire, no explosion. UL 2271 also requires no leakage, Isolation R ≥ 100 Ω/V, post-test operation.

(9) For ESC, EN 62133-2 and EN 50604-1 require only no fire, no explosion. UL 2271 also requires no leakage, Isolation R ≥ 100 Ω/V, post-test operation.

(10) For over-charge, EN 62133-2 and UN38.3 require only no fire, no explosion. UL 2271 also requires no leakage, Isolation R ≥ 100 Ω/V, post-test operation.
(11) For over-discharge, only UL 2271 requires no venting, Isolation Resistance ≥ 100 Ω/V, post-test operation of protection controls.
(12) Only UL 2271 has an imbalanced charging test.
(13) Only EN50604-1 and UL 2271 have over-temperature test. UL 2271 requires all components below their temperature limits.
(14) Only EN62133-2 and UL 2271 have a mould stress-relief test. UL 2271 requires ingress protection to IP3xB and Isolation Resistance ≥ 100 Ω/V.

Table 42: EN 50604-1 Pass Criteria for the Battery Pack Test Categories

		EN 50604-1 Pass Criteria						
Test Category	**Test Type**	No Electrolyte Leakage	No Venting	No Rupture	No Fire	No Explosion / Disassembly	Post-Test Operating State	Isolation Resistance ≥ 100 Ω/V (1)
Environmental	Vibration	✓	✗	✓	✓	✓	Operational	✓
	Mechanical Shock	✓	✗	✓	✓	✓	Operational	✓
	Dewing	✓	✗	✓	✓	✓	Operational	✓
	Thermal Cycling	✓	✗	✓	✓	✓	Operational	✓
Mechanical Abuse	Water Immersion	✗	✗	✗	✓	✓	✗	✗
	Impact / Drop	✗	✗	✓	✓	✓	✗	✗
	Crush	✗	✗	(✓)	✓	✗	✗	✗
Electrical Abuse	External Short-circuit	✗	✗	✗	✓	✓	✗	✗
	Over-charge	✗	✓	✓	✓	✓	✗	✗
	Over-discharge	✓	✗	✓	✓	✓	✗	✗
	Deep Discharge Protection	✗	✓	✓	✓	✓	✗	✗
	Imbalanced Charging	-	-	-	-	-	-	-
Thermal Abuse	Over-temperature	✓	✗	✓	✓	✓	✗	✓
	Low-temperature	✗	✓	✓	✓	✓	✗	✗
	Mold Stress Relief	-	-	-	-	-	-	-

✓ Criterion is included for the test category.
✗ Criterion is not included for the test category.
(✓) For the pack-level crush test, the "no rupture" requirement is clearly a mistake.
(1) Isolation Resistance ≥ 100 Ω/V is only required for batteries with Hazardous Voltage (> 60 V_{dc})

Table 43: UL 2271 Pass Criteria for the Battery Pack Test Categories

Test Category	Test Type	UL 2271 Pass Criteria						
		No Electrolyte Leakage	No Venting (1)	No Rupture	No Fire	No Explosion / Disassembly	Post-Test Operating State (2)	Isolation Resistance ≥ 100 Ω/V (3)
Environmental	Vibration	✓	✓	✓	✓	✓	Protection	✓
	Mechanical Shock	✓	✓	✓	✓	✓	Protection	✓
	Dewing	-	-	-	-	-	-	-
	Thermal Cycling	✓	✓	✓	✓	✓	Protection	✓
Mechanical Abuse	Water Immersion	✗	✗	✗	✓	✓	✗	✓
	Impact / Drop	✓	✓	✓ IP3xB	✓	✓	Protection	✓
	Crush	-	-	-	-	-	-	-
Electrical Abuse	External Short-circuit	✓	✓	✓	✓	✓	Protection	✓
	Over-charge	✓	✓	✓	✓	✓	Protection	✓
	Over-discharge	✓	✓	✓	✓	✓	Protection	✓
	Deep Discharge Protection	-	-	-	-	-	-	-
	Imbalanced Charging	✓	✓	✓	✓	✓	Protection	✓
Thermal Abuse	Over-temperature	✓	✓	✓	✓	✓	Protection	✓
	Low-temperature	-	-	-	-	-	-	-
	Mold Stress Relief	(✓)	(✓)	✓ IP3xB	(✓)	(✓)	✗	✓

✓ Criterion is included for the test category.
✗ Criterion is not included for the test category.
(✓) Although not stated, these requirements are implicit in the mould stress-relief test.
(1) In UL 2271, Venting is quantified by combustible gas concentration
(2) In UL 2271, only protection controls are required to still be operational post-test
(3) Isolation Resistance ≥ 100 Ω/V is only required for batteries with Hazardous Voltage (> 60 V_{dc})

7.9.3 General Comments on EN 50604-1

As explained in Section 6.12.5 of this report, EN 50604-1 states that it must be read in conjunction with ISO 12405-3 and that the clauses of EN 50604-1 supplement or modify the corresponding clauses in ISO 12405-3. However, ISO 12405-3 has been withdrawn and replaced by ISO 6469-1.

Appendix 6 (Section 15.6 of this report) provides a comparison of the test categories and relevant section numbers in EN 50604-1, ISO 12405-3 and ISO 6469-1. This makes it clear that ISO 6469-1:2019 does not cover all the same test categories as ISO 12405-3 and is therefore not a direct replacement for it. This leaves the user of EN 50604-1 with no choice but to refer to the withdrawn ISO 12405-3 for some of the tests.

There are other issues with EN 50604-1. Some of these have already been mentioned in Sections 7.5 and 7.6.3 of this report. Other general issues are summarised below:

- The standard is difficult to navigate because of its incomplete contents list, haphazard section numbering and illogical structure (e.g. over-temperature and under-temperature tests are under Section 8 “Simulated vehicle accidents”).
- There are some references to Sections in other standards which do not exist.
- Some sections refer to tests in two other standards which are incompatible.
- Some of the sections unique to EN 50604-1 are written ambiguously such that the correct interpretation and the rationale are unclear.

Unfortunately, the inconsistencies are numerous and detract from the useability of the standard. The issues that WMG has identified (a non-exhaustive list) are shown in Appendix 7 (Section 15.7 of this report).

WMG suggests that EN 50604-1 should undergo a thorough revision to address the errors and inconsistencies in the current version.

There are also some important requirements missing from EN 50604-1:

EN 50604-1 does not make any mention of production quality for the battery. It requires the cell to comply with either EN 62660-3 or EN 62133-2. If the latter is used, the cell quality is covered by the Quality Plan requirement of that standard, but if EN 62660-3 is used, this also contains no Quality Plan requirement.

EN 50604-1 also does not mention creepage and clearance distances.

WMG suggests that EN 50604-1 should be updated to include requirements for production quality of the cells and the battery pack.

WMG suggests that EN 50604-1 should be updated to include creepage and clearance distances.

7.10 Comparison of PLEV Test Conditions

7.10.1 Overview of Battery Pack Test Categories in Each PLEV Standard

The battery test categories in each of the PLEV vehicle standards mentioned in Table 36 are shown below in Table 43:

Table 44: Comparison of Battery Test Categories in PLEV Standards

Test Category	**Test Type**	**PLEV Vehicle**					
		e-bikes	e-bikes	e-bikes	e-scooters	e-bikes	e-scooters
		EN 15194 :2017	EN 15194 :2017 +A1:2023	ISO/TS 4210-10 :2020	EN 17128 :2020	UL 2849 :2022A	UL 2272 :2019
Environ-mental	Vibration	(✓NORM)	✓NORM	✓NORM	✓	✓	✓
	Mechanical Shock	(✓NORM)	✓NORM	✓NORM	(✓NORM)	✓	✓
	Dewing	(✓NORM)	✓NORM	✓NORM	✗	✗	✗
	Thermal Cycling	(✓NORM)	✓NORM	✓NORM	✗	✓	✓
Mechanical Abuse	Water Immersion	(✓NORM)	✓NORM	✓NORM	✗	✓	✓
	Impact / Drop	(✓NORM)	✓NORM	✓NORM	✓NORM	✓	✓
	Crush	(✓NORM)	✓NORM	✓NORM	✗	(✓NORM)	✓
Electrical Abuse	External Short-circuit	✓	✓NORM	✓NORM	✓	✓	✓
	Internal Short-circuit	✗	✗	✗	✗	✗	✗
	Over-charge	(✓NORM)	✓NORM	✓NORM	(✓NORM)	✓	✓
	Over-discharge	(✓NORM)	✓NORM	✗	(✓NORM)	✓	✓
	Deep Discharge Protection	(✓NORM)	✓NORM	✗	✗	✗	✗
	Imbalanced Charging	✗	✗	✗	✓	✓	✓
Thermal Abuse	Over-temperature	(✓NORM)	✓NORM	(✓)	(✓NORM)	✓	✓
	Low-temperature	(✓NORM)	✓NORM	✗	✗	✗	✗
	Mold Stress Relief	✗	✗	✗	(✓NORM)	✓	✓

✓NORM Item is mandatory by reference to a Normative Standard.
(✓NORM) Item is optional by reference to a Normative Standard.
(✓) Item is mentioned but with no test defined.

In general, the European/UK PLEV standards for e-bikes and e-scooters do not themselves contain battery tests, but refer to other standards.

For e-bikes, EN 15194:2017 referred optionally to EN 62133-2 and EN 50604-1, but the 2023 update to EN 15194:2017+A1:2023 now makes EN 50604-1 the required normative battery standard and removes the option to use EN 62133-2. Since EN 15194 now refers to EN 50604-1 in its entirety, all of the same comments apply as have been made in Sections 7.2.4, 7.3.4, 7.6.3 and 7.9.3 of this report.

ISO/TS 4210-10, the e-bike technical specification which has not been adopted as a standard, but may be revived (see Sections 6.11 and 6.13 of this report), refers to some parts of EN 50604-1, but not to the whole standard. In WMG's view, it would be better to refer to EN 50604-1 in its entirety.

For e-scooters, EN 17128 refers optionally to EN 62133-2 for all battery tests other than general mechanical strength, for which it requires an impact test according to EN 60068-2-75 and a drop test according to EN 22248. If EN 62133-2 is not used, then EN 17128 includes tests for short-circuit and imbalanced charging. There is also a vehicle-level vibration test.

The UL standards for e-bikes (UL 2849) and e-scooters (UL 2272) contain all relevant tests directly within the standard, but also refer to other battery standards, primarily UL 2271.

EN 17128 is, by comparison, inadequate in its coverage of battery hazards.

WMG suggests that EN 17128 should be updated to ensure that non-e-bike PLEVs use equivalent battery safety requirements as EN 15194, while also recognising that the relevant battery standard EN 50604-1 has shortcomings which needs to be addressed.

7.10.2 Pass/Fail Criteria in Battery Pack Test Standards in Each PLEV Standard

Since the UK e-bike standard EN 15194 refers to the battery standard EN 50604-1, all the comments on pass/fail criteria in Section 7.9.2 apply.

7.11 Comparison of Charger Standards in Each PLEV Standard

7.11.1 Charger Standards for UK e-bikes

Regarding chargers, EN 15194 states “For external chargers with d.c. output less than 42.4 Volt, e.g. EN 60335-2-29:2021+A1:2021 is applicable”.

In WMG’s view, the 42.4 V limit should be removed. EN IEC 60335-2-29:2021+A1:2021 (BSI Group, May 2022) covers chargers both above and below this threshold. The 42.4 V limit only applies to battery chargers for use by children, which are covered in Annex AA of the standard. EN 15194 covers e-bikes without user age restriction, so there is no justification for the 42.4 V threshold.

WMG suggests that EN 15194 should be updated to require that all e-bike battery chargers shall comply with EN 60335 2 29:2021+A1:2021 as a minimum, irrespective of their output voltage, as an interim step prior to requiring battery-to-charger communication.

As described in Section 4.6 and 6.13 of this report, ISO/TS 4210-10 takes a completely different approach, describing a communication protocol between the battery and the charger, to ensure that the charger does not exceed the battery voltage and current limits.

In WMG’s view, an approach similar to those described in ISO/TS 4210-10 should be adopted for battery chargers for all PLEVs in the future, but this requires alignment across the industry to agree a charging connector and communication protocol.

7.11.2 Charger Standards for UK e-scooters

For e-scooters, EN 17128 refers that “Battery charging systems shall be in accordance with EN IEC 62485 series and EN 60204-1 or EN 60335-2-29:2004 as appropriate.”

The EN IEC 62485 series concerns secondary batteries and battery installations. As explained in Section 6.12.7 of this report, only EN IEC 62485-6:2021 is relevant to Lithium-ion batteries in PLEVs. This standard contains the following in Section 6:

> It is of prime importance that the charging current during the last portion of the charging procedure is kept at a level appropriate for the battery type used. Therefore the use of a controlled charger, which considers the cells operating region (e.g. by the BMS communication) is essential otherwise batteries run the risk of total destruction, explosion or thermal runaway.

The requirement for BMS communication is not met by the majority of existing e-scooter chargers, and therefore according to EN 17128, they would need to comply with

EN 60335-2-29:2004. This standard has been withdrawn. The latest version is EN IEC 60335-2-29:2021+A1:2021.

EN 60204-1:2018 (BSI Group, Jul 2021) concerns “Safety of machinery. Electrical equipment of machines. General requirements” and is designated under the SMSR. It does not contain any requirements for chargers.

7.11.3 Safety Requirements in EN 60335-2-29:2021+A1:2021

Based on the charger requirements in EN 15194 and EN 17128, EN IEC 60335-2-29 is the most relevant standard for UK PLEV chargers.

EN IEC 60335-2-29 is one of over a hundred sub-parts of IEC 60335-2, which covers the safety of household and similar electrical appliances. Like the other sub-parts of IEC 60335-2, it refers to IEC 60335-1 for most electrical safety requirements.

In WMG’s view, the objective of EN IEC 60335-2-29 is primarily the electrical safety (avoidance of electric shock) of the charger itself but does not address the safety of the charger and battery as a system. This is reflected in Annex ZZA, which explains the relationship between the standard and the EU Low Voltage Directive 2014/35/EU, which is the basis of the UK Electrical Equipment Safety regulations 2016 (EESR). The safety requirements of the EESR, as applied in EN IEC 60335-2-29, do not consider the safety of the battery which is connected to the charger.

In WMG’s view, any charger intended for use with Lithium-ion cells or batteries should have safety requirements defined in a standard which considers the charger and the battery as a system. This would therefore require the charger to respect the maximum charging current and voltage of the individual cells (or cell blocks) connected in series, as well as the measured temperature of the cell stack.

In WMG’s view, the battery must ultimately be capable of protecting the cells from charging over-current or over-voltage, but the only way it can do this is by opening a switch (e.g. MOSFET). In other words, it cannot regulate the voltage or current, it can only start or stop it. Regulating the current and voltage can only be done by the charger.

7.11.4 Charger Standards for US e-bikes and e-scooters

UL 2849 (e-bikes) and UL 2272 (other PLEVs) require the charger to comply with one of several UL standards. It is beyond the scope of this report to consider the various UL charger standards. However, in WMG’s understanding, the UL standards for PLEVs have a similar shortcoming to the UK standards. They do require the charger sold with the PLEV to be compatible with the PLEV battery, but do not require the charger to adjust the charging current and voltage to respect the limits of any connected battery.

Since WMG is not aware of any significant benefit of the UL charger standards over the UK charger standards, they are not discussed any further in this report.

WMG recognises that a non-proprietary (industry-standardised) charger connector and communication specification, as suggested in ISO/TS 4210-10 Annex C, and mandated in the China-market standard GB 42296-2022, would significantly enhance the safety of e-bike and e-scooter charging.

WMG suggests that standards for batteries and chargers for UK PLEVs should consider and address the risks associated with unsuitable battery and charger pairing and consider the safety of the battery and charger as a system, to ensure that the charger abides by the current, voltage and temperature limits of the connected battery.

7.12 Individual Battery Test Categories

In this section, commentary is provided on some of the battery test categories for which WMG has specific suggestions.

7.12.1 General – Mechanical Vibration

The standard used in the UK, EN 50604-1 and EN 62133-2, both use the same vibration test specification as UN 38.3, which defines tests to prove a cell or battery is safe for transportation. The origin of this profile is not known to WMG. However, it seems likely that a vibration profile specific to transport safety will not be suitable for safety in a PLEV.

The e-bike standard EN 15194 does not contain a vibration profile, other than by reference to EN 50604-1 for the battery.

The e-scooter standard EN 17128 defines three random vibration profiles, all spanning frequencies from 5 to 500 Hz, of which one must be selected for a vehicle-level test, based on the following factors:

- Whether the e-scooter has suspension
- Whether the e-scooter is equipped with pneumatic or solid rubber/elastomer tyres
- Whether the wheel diameter is above or below 10 inches (254 mm)

The selected vibration profile is used to evaluate the robustness of the “electric functions” on the e-scooter: Following the 15-hour vibration test, the e-scooter must undergo a “function test” to ensure that it still functions correctly, but this function test is undefined.

The EN 17128 e-scooter vibration test only uses vibration in the z-axis (vertical). Other standards require vibration test to be done in x, y and z axes. There is a wide variety of vibration parameters in the various standards, as shown in Table 44:

Table 45: Comparison of Vibration Test Parameters for Different Standards

Standard	Device Under Test	RMS Acceleration	Directions	Duration per Direction	Total Duration
		m/s^2		hours	hours
UN 38.3 Test T3 / EN 50604-1 / EN 62133-2	Cell / Battery < 12 kg	32	x, y, z	3	9
UL 2271 §30 - x-direction	LEV battery	9	x	21	63
UL 2271 §30 - y-direction		12	y	21	
UL 2271 §30 - z-direction		14	z	21	
UL 2580 Annex D Test 3.6	Cells	28	x, y, z	1.5	4.5
BS IEN IEC 62660-2:2019 § 6.2.1.2	Cells	28	x, y, z	8	24
BS EN 17128:2020 §6.5.2 - Profile A	e-scooter - soft	19	z	15	15
BS EN 17128:2020 §6.5.2 - Profile B	e-scooter - medium	30	z	15	15
BS EN 17128:2020 §6.5.2 - Profile C	e-scooter - hard	44	z	15	15

The harshest of the EN 17128 profiles, applicable for e-scooters with no suspension, small wheels and solid rubber tyres, has the highest RMS (root mean square) acceleration of any of the standards, but the 15-hour duration of the test is toward the lower end.

EN 17128 also requires that, before and after the random vibration test, a logarithmic frequency sweep is performed from 5 to 500 Hz, at a sinusoidal acceleration magnitude of 0.5 G_{peak} and a sweep rate of ≤1 octave per minute, meaning the frequency doubles around once per minute. Each of these sweeps will take approximately 7 minutes. For these sweeps, accelerometers must be fixed to the e-scooter. The signal from these accelerometers must be recorded during the sweep, to identify the resonant frequencies of the e-scooter. Any change in the resonant frequencies is to be recorded. However, there is no requirement for these data to be used in a pass/fail criterion.

This type of frequency sweep is a widely used technique. Changes in the frequency or amplitude of the resonances of a product are usually associated with changes in the mechanical integrity. For example, a welded joint that fails, or a mounting bracket for a component such as a battery that breaks, will result in a change in one or more resonances. Therefore, comparison of the frequency-sweep results before and after the vibration test can be used to identify structural failures.

WMG cannot comment on the suitability of the EN 17128 vibration profiles, but clearly the authors of EN 17128 have considered the vibration likely in the application, although the absence of vibration testing in the x and y directions is a surprising omission.

The vibration magnitudes and frequencies in any PLEV are strongly influenced by whether the vehicle has suspension, the size of the wheels and the tyre characteristics.

WMG suggests that the e-bike standard EN 15194 would benefit from a similar approach to vibration requirements as EN 17128, with different vibration spectra, dependent on the design (suspension, wheel size, tyre characteristic) of the e-bike.

WMG suggests that consideration is given to defining pass criteria for the vibration tests for all types of PLEVs, based on pre- and post-test low-magnitude sine-sweeps with accelerometers attached to the PLEV, as follows:

- **A limit on the change in amplitude and frequency of the resonances**
- **A clearly defined functionality test after the vibration test, with relevant safety-based criteria. For example, two complete charge-discharge cycles of the battery, following by an observation period, with pass criteria of no venting, leakage, rupture, fire or explosion and no loss of electrical isolation.**

7.12.2 Battery Electrical – External Short-Circuit

An external short-circuit test involves attaching the battery to an external circuit which must fulfil the following requirements:

- Able to withstand the anticipated short-circuit current for the time taken to drain the energy from the fully charged battery, without damage to the external circuit.
- Able to close and open the circuit as required by the test personnel, via a switch which is sufficiently sized to avoid the risk of welding the switch when it is closed.
- Able to measure the short-circuit current to a reasonable accuracy (e.g. 1% of the maximum anticipated value)
- Able to provide an external circuit resistance that complies with the requirements of the relevant standard, throughout the short-circuit test.

The last of these requirements is, in some cases, difficult to meet. One must define the resistor based on the following:

- The minimum anticipated internal resistance of the battery
- The maximum open-circuit voltage of the battery

- The maximum anticipated short-circuit current, taking account of the resistance of both the battery itself and the external circuit (Current = V/R_{total}).
- The heat generation in the resistor (Resistor heat generation = $I^2.R_{resistor}$)
- The estimated duration of the short-circuit, assuming that the battery is completely drained of energy.
- The initial resistance of the resistor.
- The maximum permissible amount of self-heating of the resistor, due to its heat generation, to keep the resistance within the permissible limits.

For example, consider the short-circuit in EN 50604-1, which requires the external circuit resistance to be “20 +0/-10 mΩ”, i.e. between 10 and 20 mΩ.

If we consider a large PLEV battery, the internal resistance of the battery might be around 40-50 mΩ at room temperature. However, the battery will heat up very quickly when it is short-circuited. As it heats up, then resistance will steadily drop to perhaps 30 mΩ, before it starts to increase dramatically when the separators in the cells start to shut down.

The total circuit resistance is therefore 40 mΩ, assuming that the external circuit resistor is 10 mΩ at room temperature and allowed to increase up to 20 mΩ during the test. If we assume the battery has a maximum voltage of 42 V, then the maximum short-circuit current will be 42 V / 0.04 Ω = 1050 A.

Then the average heat-generation in the external circuit resistor will be 1050^2 * 0.015 = 16.5 kW.

If the battery has a capacity of, say, 20 Ah, then the total stored energy = 840 Wh = 3 MJ. Approximately two-thirds of this will be dissipated in the battery, and one-third in the external resistor, so the latter needs to absorb 1.0 MJ, which at a rate of 16.5 kW will take around 61 seconds.

Assuming the external resistor is made of a metal such as copper, its resistivity will increase approximately linearly with absolute temperature, so a resistor that is 10 mΩ at room temperature (298 K) will be 20 mΩ at approximately 600 K = 327 °C. Therefore, the resistor must be sized to heat up by less than this amount.

Based on the specific heat capacity of copper, this would require a resistor weighing approximately 9 kg if it must absorb all of the heat generated, with a length of 25 metres and a cross-section of 40 mm^2 to achieve the required resistance. In other words, it would need to be a long length of cable. Alternatively, it could be small if it were actively cooled. This is a simplistic calculation but illustrates a point.

The only practical way to obtain such a resistor is to make a bespoke one.

However, the problem would be much easier if the restriction on the external resistance value were different. For example, UL 2271 requires it to be <20 mΩ, rather than between 10 and 20 mΩ. To comply with UL 2271, the nominal resistance can be much lower. It is possible to buy shunt resistors with a resistance of around 0.2 μΩ, rather than 20 mΩ, i.e. one hundred thousand times lower. These will result in a higher short-circuit current (around 2000 A) but will generate much less heat (around 1 W, rather than 22 kW).

Such practical considerations are an important part of defining usable test requirements in standards.

7.12.3 Battery Electrical – Over-charge

The existing battery pack standards vary in the current that is used to over-charge the battery, but almost all of them terminate the over-charge when the applied voltage reaches 1.2x the maximum allowed battery voltage.

It is easy to find chargers advertised on online marketplaces ranging from 42V (most common) to 96 V, often available with a variety of connector types (See Figure 30 in Section 4.6).

In WMG's view, it is reasonably foreseeable that an ill-informed consumer could connect a charger rated at 2x the maximum battery voltage, particularly where the battery uses a non-bespoke connector type and there is no communication between the BMS and charger.

Therefore, WMG intends to perform the over-charge test by progressively increasing the applied over-voltage up to 84 V maximum on battery samples that will be purchased for testing in the second phase of the current work.

It is foreseeable that the BMS will initially protect the cell stack when the applied voltage exceeds the 42 V maximum allowable value. However, most MOSFETs used in such PLEV batteries are rated to withstand a maximum of around 60 V. Therefore, WMG anticipates that the MOSFETs will breakdown at higher voltages, allowing an in-rush of current which is likely to severely damage the cells.

7.12.4 Battery Electrical – Deep-discharge

Currently, the only standard to include a deep-discharge test is EN 50604-1. In WMG's view, this type of test should be included in standards for all types of PLEV. However, the test definition and pass criteria in EN 50604-1 are not clear.

WMG suggests that the deep-discharge test in EN 50604-1 should be reviewed and updated, and a rationale should be provided.

7.12.5 Battery Electrical – Over-Current

In WMG's view, it is essential to test the battery to ensure that the BMS correctly protects the cells from charge and discharge over-current, based on the cell manufacturer's definition of current limits, as a function of temperature and other parameters.

WMG suggests that charge and discharge over-current tests should be added to standards for all PLEV batteries, with tests performed at various temperatures, covering the operating temperature range of the battery and 5-10 K above and below that range.

7.12.6 Battery Electrical – Cell Imbalance

Currently, the only battery standard to include an imbalanced charging test is UL 2271, and the only European/UK standard to include such a test in EN 17128. These tests only validate that the BMS prevents charging when a single cell exceeds the maximum allowable cell voltage. They do not test for the presence or operation of a balancing circuit.

WMG suggests that an imbalanced charging test should be included in all standards for PLEV batteries.

WMG suggests that all PLEV battery standards should include a BMS design requirement to include a cell balancing circuit. An accompanying test should be devised to validate the operation of the balancing circuit.

7.12.7 Battery Thermal – Low-temperature

Currently, the only battery standard to include a low-temperature test is EN 50604-1. This test validates that charging is prevented when the temperature is below the minimum allowed charging temperature for the cells.

WMG suggests that a low-temperature test should be included in all PLEV battery standards, to ensure that charging is prevented by the BMS when the temperature is below the minimum allowed value for charging the cells.

7.12.8 Labelling

The voltage labelling of PLEV batteries and chargers is currently unnecessarily misleading.

EN 50604-1 and EN 62133-2 (via EN 61960-3:2017, BSI Group, Nov 2017) both require batteries to be marked with their nominal voltage, but do not define how the nominal voltage is determined. The convention followed on all examples that WMG has seen is that the nominal voltage is the open-circuit voltage at approximately 50% SoC. For example, a typical PLEV battery is labelled as 36 V, but the maximum charging voltage of 42 V is not shown on the label.

EN IEC 60335-2-29 requires that the charger is labelled with the rated DC output voltage and the rated DC output current. These terms are not defined other than to say they are “assigned to the charger by the manufacturer”. There is no test to check these values in the standard.

EN 15194 does not contain any requirements for e-bike battery labelling, other than the requirement for the battery to comply with EN 50604-1. Similarly for the charger, the only requirement is from EN IEC 60335-2-29.

EN 17128 requires that for e-scooter batteries, “Information concerning the battery shall comply with existing corresponding standards” and requires that the battery is labelled with the output voltage, charging voltage, power and warning on the risks. No explanation of any of these is provided. As above, the only labelling requirement for the charger is via EN IEC 60335-2-29.

The US standard for LEV batteries, UL 2271 requires only that the battery is marked with the electrical ratings in V_{dc} and Ah or Wh, but not specify what these values should be.

In WMG’s view, the most critical information for the consumer is the maximum charging voltage of the battery, because this is critical for ensuring that the charger output voltage is compatible with the battery. By contrast, the nominal voltage is relatively meaningless information for the consumer.

WMG suggests that labelling requirements for all PLEV batteries should be changed, to require the maximum charging voltage to be shown, and the nominal voltage should be removed, to avoid potential confusion for the consumer.

As noted in Section 6.14.4, in China the mandatory standard GB 43854-2024 requires the label to be durable legible after exposure to water, alcohol and extreme temperature (950 °C). The latter would significantly improve the ability to identify a battery after a fire, which could assist investigators with gathering data from real world incidents.

WMG suggests that OPSS consider an investigation of the technical and commercial feasibility of battery markings that are able to withstand battery fires, to aid post-fire identification.

8 Previous Work to Address PLEV Fires

The real world evidence in Section 2 included statistical data from the USA and Australia, as well as the UK. These and other geographic markets have made efforts to address PLEV fires in recent years. This section reviews some significant recent developments from the UK and overseas.

8.1 US Consumer Product Safety Commission Perspective

Fires caused by e-mobility devices have become a major issue in North America, just as they have in the UK and EU. From 1 January 2021 through 28 November 2022, the United States Consumer Product Safety Commission (CPSC) received reports of at least 208 micromobility fire or over-heating incidents from 39 states, resulting in at least 19 fatalities, including five recorded as associated with e-scooters, 11 with hoverboards and three with e-bikes. As a result, in December 2022, the CPSC sent a letter to more than 2,000 manufacturers and importers, calling on them to adhere to the UL 2272 and UL 2849 standards (US Consumer Product Safety Commission, Dec 2022).

New York has suffered a particularly acute rise in the frequency of these fires. It was reported in June 2023 that in the first few months of that year alone, 13 people have been killed in New York, from a total of 108 LIB fires (New York Times, Jun 2023).

On 23 May 2023, the United States Consumer Product Safety Commission (CPSC) opened a 60-day comment period, inviting views on the safety of e-bikes (bicycleretailer.com, May 2023).

On 27 July 2023, the CPSC held a hearing, titled the “Forum on Lithium-ion Battery Safety” (US Consumer Product Safety Commission, Jul 2023). The hearing opened with pre-recorded statements from New York Senators Chuck Schumer and Kirsten Gillibrand, and from New York Congressman Ritchie Torres, who had recently filed a new legislative bill titled the “Setting Consumer Standards for Lithium-Ion Batteries Act” (Ritchie Torres, March 2023), which is supported in the US Senate by the aforementioned New York Senators (bicycleretailer.com, Apr 2023). If passed, this bill would require the CPSC to promulgate a consumer product safety standard for rechargeable Lithium-ion batteries (US Congress (2023).

The CPSC hearing was led by the four CPSC commissioners, who had invited a variety of stakeholders to sit on three panels, to provide statements and answer questions from the commissioners (US Consumer Product Safety Commission, Jul 2023). The panellists represented organisations in the following domains:

- New York City Fire Department
- Battery standards development and third-party certification
- Battery manufacturing-quality and safety research and testing
- Associations for e-bike and battery manufacturers, importers, retailers and dealers
- One individual e-bike company
- Consumer product safety

Below, WMG has summarised some of the key facts and opinions voiced in the hearing:

- The New York City Fire Department (NYFD) is clearly the leader among such US regional fire departments and keeps detailed data on all fires it tackles. In this respect, there are close parallels to the London Fire Brigade (LFB).

- NYFD highlighted the difficulty in identifying the manufacturers and model types of e-bikes and batteries involved in fires, due to the degree of destruction, although they do have a list of devices that have most often been involved in fires.
- NYFD noted the inability to tell whether a battery is safe, stating they had multiple experience of batteries re-igniting after a fire had stopped.
- NYFD called for mandatory e-bike battery safety standards, including:
  - Anti-tampering devices and the ability to detect tampering.
  - Automatic shut-offs at the end of charging, including redundant shut-offs.
  - Means to ensure batteries can only be charged with the intended charger.
- NYFD stated that Singapore has seen a 33% drop in fires related to e-mobility devices, attributed to their introduction of mandatory standards. This is confirmed by a Singapore media report (Straits Times, Feb 2023).
- Dr. Judy Jeevarajan, Vice President and Executive Director of the Electrochemical Safety Research Institute at UL (UL Research Institutes, no date) advised that an electronic communication “handshake” between the battery and charger should be mandated, to ensure that the charger has data on the battery’s chemistry, voltage, maximum charge current, state of health, temperature and any history of “off-nominal” conditions such as over-charge. She also advised that universal chargers should never be used.
- Dr. Jeevarajan also urged that the battery should be independently fault-tolerant and should not be dependent on the charger to ensure its own safety.
- Dr. Jeevarajan also highlighted the risk posed by low quality and counterfeit cells, which have been found not to have the same safety devices as genuine cells from established suppliers. She warned that visual inspection is not sufficient to distinguish between genuine and counterfeit cells. See also Section 3.10 of this report.
- Dr. Michael Pecht, Director and Distinguished Professor at the Center for Advanced Life Cycle Engineering (University of Maryland, no date) emphasised the need for auditing of the quality control in Lithium-ion cell manufacture, and that battery pack manufacturers must be held accountable for this. He opined that supply chain quality, rather than pack-level or BMS issues are the main problem.
- Dr. Drew Pereira, Research and Development Manager at Soteria (Soteria Battery Innovation Group, no date) presented a short summary of Soteria’s recently started on-going project to tear down and analyse PLEV batteries. They purchased five OEM e-bikes, including the OEM batteries, and five third party batteries that were compatible with the same e-bikes. Dr. Pereira gave the example of one e-bike battery, for which the third-party equivalent was $500 cheaper. It was outwardly almost identical, but inside casing, the construction was inferior and more likely to suffer thermal propagation in the event of single-cell thermal runaway. The third-party pack’s cells had the same labelling as the OEM pack’s cells but differed greatly in performance and design. This raised the possibility that they were counterfeit cells.
- Dr. Pereira also highlighted BMS issues: Firstly that many e-bike batteries, whether OEM or third-party, lacked cell balancing, and secondly that some BMS either lacked a temperature sensor, or had incorrect calibration such that the temperature cut-off did not operate until well above the upper temperature limit of the cells.
- Dr. Pereira stated that only three of ten batteries purchased had any form of certification, stating the benefit of certification but also emphasising that consumer must be protected from counterfeit certification labels.

- Matt Moore, General and Policy Counsel at PeopleForBikes (PeopleForBikes, no date), the trade association for 335 US bicycle manufacturers, suppliers and distributors, stated that “PeopleForBikes urges a broad response by CPSC that would require testing and certification of all Lithium-ion batteries for all e-mobility devices, including emerging categories of battery-powered off-road devices. This would ensure that these products have a robust battery management system. The agency should adopt established consensus standards for batteries such as those referenced under UL 2849 and EN 15194". This would require use of 3rd party laboratories and create a general certificate of conformity to establish their compliance with the mandatory regulation. This is the consensus view of PeopleForBikes members, but Mr. Moore mentioned there are over 400 sellers of e-bikes in the US which are not PeopleForBikes members.
- Michael Fritz, Chief Technology Officer at Human Powered Solutions (Human Powered Solutions, no date), which is on retainer to the US National Bicycle Dealers Association, proposed the need for an e-bike equivalent of the “check engine light” which is required in all passenger cars.
- Robert Slone, Senior Vice President and Chief Scientist at UL (UL Solutions, no date) emphasised the need for a systems approach to safety: the whole e-bike system must be safe to ensure that the battery is safe. He explained that standards can reduce the likelihood / frequency of e-bike fires, but will not necessarily reduce the severity of an incident. UL has therefore started to develop the UL 1487 standard, for battery containment enclosures (UL Solutions, Feb 2023), which would provide containment for a battery fire, and could be used, for example, for charging batteries in a workplace or domestic environment.
- Mr. Slone stated that UL had performed a comparison of UL 2849 and EN 15194. He estimated 85% similarity but stated that UL 2849 is more rigorous on the electrical system safety.
- Mr. Slone stated that global harmonisation of e-bike standards must happen in future, as has been done for passenger cars under GTR 20 (United Nations Economic Commission for Europe, May 2018).
- Mr. Slone emphasised the speed with which PLEV fires develop and create life-threatening hazards. He stated that, in two separate incidents, NYFD had reached the location of reported PLEV fires within 3 minutes of being notified, but in both incidents, people had been killed: 4 people in one incident and 2 people in the second incident.
- Michael Becker, Tech Specialist Energy Storage at CSA Group (formerly the Canadian Standards Association) (CSA Group, no date), highlighted CSA’s development of a standard for Battery Management Systems, CSA/ANSI C22.2 NO. 340:23 (CSA Group, 2023). Based on the CSA webpage, it is not clear to WMG whether this is applicable to PLEVs.
- Jeff Jambois, Electrical Compliance Engineer at Trek Bicycle (LinkedIn, no date) outlined two major lessons learned by Trek, and the related recommendations to CPSC:
    - That safety standards work; they promote safety and promote market growth. He stated that markets that require certification to minimum safety standards have seen far fewer issues with fires and general battery safety with e-bikes. Trek recommended that CPSC should mandate UL 2849, clauses 11.1 and 11.2 for battery safety and clause 23 for battery charger safety.
    - It is necessary to ensure consistent application of these standards, and close existing loopholes in US rules, such as the “de minimis” rule which exempts

products being sold for less than $800. Trek recommended that the standards should be applied equally across the whole industry, either by testing with an accredited lab and self-certification or by testing and certification by an accredited lab.

- Mr. Jambois also stated that LIBs are far too complex for the average consumer or even the average repair shop, therefore repair and refurbishment should only be done by the OEM.
- Mr. Jambois agreed with Dr. Jeevarajan that the safety of the battery should protect itself, and should not depend on the charger. This would emulate the approach of the automotive industry.
- George Kerchner, Executive Director at the Portable Rechargeable Battery Association (PRBA) (LinkedIn, no date), whose members he claimed manufacture approximately 55% of the Lithium-ion cells produced worldwide, requested CPSC to use UL 2849 as a mandatory safety standard.
- Mr. Kerchner stated that consumers do not fully understand the hazards, especially when it comes to repairing a product containing a Lithium-ion battery, or the implications of modifying the design of Lithium-ion batteries. Such repairs can compromise the safety components and cause a fire. This is the primary reason why PBRA has often opposed right to repair legislation over the last 5 years.
- Heather Mason, President, National Bicycle Dealers Association (Nation Bicycle Dealers Association, no date), which represents 700 US retail organisations, urged compliance with UL 2849 and recommended CPSC to emulate ISO 4210-10, or EN 15194 or enforce UL 2849.
- Ms. Mason also pushed for approved safe storage and charging cabinets for retailers and wanted to see a standardised user manual for e-bikes.
- Gabe Knight, Safety Policy Analyst at Consumer Reports (Consumer Reports, no date), the US equivalent of Which? in the UK, mentioned their report “Fire! Fire! Fire!” (Consumer Reports, Dec 2022), highlighting that currently, there are no mandatory US safety standards for e-bikes, e-scooters, hoverboards, or any other micromobility products. Companies may choose to certify to UL Solutions’ voluntary standard for e-bikes, but only 13 companies did so. Non-compliant companies cited cost as a major reason for not certifying to the UL standard. The report also states that the CPSC, the US governmental agency responsible for e-bike safety amongst some 15,000 other product categories, is underfunded and lacking in authority to legislate, reliant on voluntary standards except if “the current voluntary standard does not adequately reduce the risk” or “there is not likely to be substantial compliance”. This appears to be part of the reason why Rep. Torres filed a bill which would force CPSC to legislate on Lithium-ion battery safety.
- Ms. Knight also highlighted that the lack of industry-wide acceptance for these standards may leave lower income individuals at a greater risk than those who are able to afford high-end devices that are currently more likely to be UL certified.

8.2 Singapore Stakeholder Perspective

As mentioned in Section 8.1 of this report, during the US CPSC hearing held on 27 July 2023, New York Fire Department drew attention to the regulations in Singapore, which appear to have achieved a significant reduction in the number of e-mobility related deaths.

The Singapore authorities introduced new e-bike regulations, effective from July 2021 (One Motoring, 2021). Under these regulations, e-bikes, referred to as Power-Assisted Bicycles (PABs) in Singapore, must meet the following requirements:

- PABs must be type-approved, sealed and registered before they can be used on public roads and cycling paths in Singapore.
- Only PABs that meet all the technical requirements can be registered.
- To register or ride a PAB, you must be at least 16 years old. You must also wear protective gear when riding a PAB.

The key technical requirements for PABs are:

- The PAB must comply with European Standard, EN15194
- The maximum continuous power output of the PAB must not exceed 250 Watts
- The motor power of the PAB can only cut in when the rider starts to pedal
- The motor power of the PAB must be progressively reduced and finally cut off as the bicycle reaches 25 km/h, or sooner, if the cyclist stops pedalling
- The maximum weight of the PAB must not exceed 20 kg

Every PAB in Singapore must be approved and sealed by the Singapore Government (Singapore Government Land Transport Authority, 2017). The seal takes the form of a tamper-proof device, similar in appearance to a small padlock, which is affixed to the frame of the PAB. Each seal has a unique number, which is stored in the LTA One Motoring database (Teoh Yi Chie, 2021). Any significant modification of the PAB is illegal.

Once the PAB is approved and sealed, it can be registered with the LTA, and will receive a registration plate matching the number of the seal, displayed on the rear of the PAB.

Riders of PABs in Singapore must be at least 16 years old and must pass a theory test (Singapore Government Land Transport Authority, Apr 2021).

The penalties for non-compliance with Singapore's PAB regulations are severe: up to 20,000 Singapore dollars (~ £12,000) or a jail term of up to 24 months for the first offence, and up to double for a second offence.

Separate from the PAB rules, Singapore has also introduced new rules for e-scooters (One Motoring, 2019), which are classified in Singapore as Personal Mobility Devices (PMDs). Since July 2020, only UL2272 certified motorised PMDs are allowed for use on cycling paths. According to the Singapore authorities' website "non-UL2272 certified motorised PMDs are fire risk and should be properly and safely disposed of."

e-scooters must be registered with the LTA, and the registration number must be displayed on the e-scooter. The e-scooter is then subject to a mandatory inspection every 2 years.

As for e-bikes, the LTA publishes a mandatory theory test for e-scooter riders (Singapore Government Land Transport Authority, Apr 2021).

The penalties for non-compliance with the e-scooter regulations are less harsh than for e-bikes, but can still be significant. For example, for using a non-compliant e-scooter, first-time offenders may face a fine of up to $5,000 and/or imprisonment of up to 3 months.

A report in February 2023 claims that fires involving PMDs and PABs in Singapore dropped from 63 cases in 2021 to 42 cases in 2022 (Straits Times, Feb 2023). The Singapore Civil Defence Force, which operates the Singapore fire service, attributed the decrease to the implementation of regulatory measures, but said that such fires continue to be a concern for the authorities as such devices are often used by those with walking difficulties. It is too early to determine the trend in 2023, but media reports continue to highlight further PAB / PMD fires, so the issue is still a concern in Singapore.

When considering how the Singapore experience relates to the UK, it is important to mention the difference between the two nations. Singapore is a small, densely populated city-state of just 735 square kilometres and a population of 5.9 million, compared to the UK at 242,700 square kilometres and 68 million people (Wikipedia.org, 2024). Greater London alone is more than twice the land area of Singapore with a population approximately 57% larger.

Given its small size, it is easier for Singapore to provide access for its population to the government agency facilities for vehicle certification and registration. It is also likely easier to enforce the regulations. Therefore, although the Singapore regulations appear to have delivered a significant reduction in PLEV fires, it would not necessarily translate easily to the UK. However, some aspects of the Singapore system may translate well to larger conurbations. It appears that New York may have taken inspiration from Singapore in implementing its own approach, such as mandating compliance with UL standards.

8.3 Electrical Safety First

Electrical Safety First (ESF) is a UK charity dedicated to reducing the number of injuries and deaths caused by electricity. On 27 July 2023, ESF published a report titled “Battery Breakdown - Why are e-scooter and e-bike batteries exploding in people’s homes and what can be done about it?” Electrical Safety First (Jul 2023). The ESF report covers a multitude of topics relating to PLEV fires including:

- Recent statistics and media reports from the UK and US for PLEV fires
- Perceived shortcomings of the UK Incident Recording System (IRS) (UK Government Home Office, no date) regarding PLEV fires
- PLEV categorisation challenges, and legislative inconsistencies
- e-bike conversion kits, and the lack of standards for them
- Compatibility issues between chargers and batteries
- e-scooter design shortcomings which risk battery damage
- Disposal of end-of-life Lithium-ion batteries
- Legislation and Standards relevant to PLEVs
- Shared e-micromobility in the UK
- Safety tests commissioned by ESF on PLEV batteries
- Strategies to mitigate fire risk, such as bans, regulation, design, labels, certification

The ESF report makes 30 recommendations under the following topics:

- Consumer education
- Policy
- Data Collection
- Standards and Regulations
- Online marketplaces

Overall, WMG supports many of the suggestions made in the ESF report. However, WMG has some observations as follows:

Table 46: WMG Observations on the Suggestions in the Electrical Safety First "Battery breakdown" Report

ESF Suggestion / Observation	WMG comments
OPSS should adopt the technical specification ISO/TS 4210-10:2020 as a designated standard to mitigate risks of dangerous compatibility and charging.	ESF made this recommendation largely because of the comprehensive requirements for charger-to-BMS communication, to improve battery charging safety. WMG agrees that such communication could significantly benefit safety. WMG notes that this technical specification failed to become a standard because the draft was twice rejected by members of the ISO WG15 committee, for which the draft was developed, and under ISO rules it could not be voted on a third time. **WMG suggests that a consensus needs to be achieved before the technical specification is adopted as a standard, and that efforts by standards organisations should be accelerated to revisit ISO/TS 4210-10:2020 alongside other standards such as EN 15194 and EN 17128.**
UK standardisation bodies should consider the marking requirements for the e-micromobility standards, so that the battery or charging port is marked with the voltage required for charging	The key issue here is to match the charger and battery voltages. The voltage markings on PLEV batteries and chargers are currently not aligned, because most PLEV batteries are marked with their “nominal” voltage (typically this is the voltage when they are approximately 50% charged), whereas the chargers are marked with the maximum charging voltage. In WMG’s view, the anomaly should be removed, to avoid consumer confusion and to align with other product categories, by marking batteries with their maximum voltage.
Currently, there is no requirement for the type of cell chemistry used to be marked on a battery. Doing so could help ensure consumers make informed purchasing decisions where safety is a key consideration. It would also facilitate more effective recycling. The Department for Environment, Food and Rural Affairs and the regulators should consider introducing regulatory measures requiring more prominent markings on batteries to include cell chemistry.	While cell chemistry does affect safety, there are many other important factors which determine PLEV battery safety. Furthermore, consumer understanding of the complex underlying details of cell chemistry is generally poor. It is unwise to expect consumers to make informed decisions based on limited information and understanding. WMG believes it is preferable to ensure that all cells and batteries comply with safety standards, so that consumers can buy them, confident that the cells are safe.

On 2 November 2023, ESF published “The Safety of Electric-Powered Micromobility Vehicles and Lithium Batteries Bill”, a private members’ bill addressed to the UK parliament. This bill calls for:

- Third-party assessment by a government-approved body, for all e-bikes, e-scooters, and their Lithium-ion batteries before they enter the UK market.
- Responsible disposal of used Lithium-ion batteries.
- Government action to specify safety standards for micromobility vehicle conversion kits and associated components.
- Legislation requiring micromobility vehicles to have either a non-proprietary charging system with a communications protocol or a proprietary charging system with a matched charger.
- Government consultation on whether to ban universal chargers.

The Bicycle Association (BA), which has supported WMG in the creation of this report, responded to the ESF bill, on behalf of the BA members, with the following recommendations:

- While introducing mandatory third-party testing could definitely be part of the solution, it must run alongside much stricter enforcement of product safety for products supplied to UK consumers direct from overseas sellers, often via online marketplaces.
- Any Bill aiming to meaningfully address fire risk must impose responsibility on food delivery app operators to ensure that the equipment used by their riders is safe.
- More practical arrangements for the mandatory approval of e-bikes and batteries would be required, with a transition period for the establishment of approval capability and for approvals of existing models to be granted.

WMG supports the BA response to the ESF bill.

8.4 Soteria Battery Innovation Group

Soteria Battery Innovation Group is a US-based consortium of organisations involved in the development, manufacture and use of batteries. Soteria has already been mentioned in Section 8.1 of this report, as they provided testimony to the US Consumer Product Safety Commission hearing on battery safety.

In early 2023, Soteria started a consortium project titled “Transform e-bike battery safety” (Soteria Battery Innovation Group, Apr 2023). The Soteria project has many parallels with the work performed by WMG to generate this report. Soteria’s project comprises the following activities:

- Disassembly of new e-bike batteries, to identify good practice.
- Disassembly of used e-bike batteries, to identify potentially dangerous wear and abuse.
- Understand use conditions of e-bikes, through surveys, interviews and on-e-bike data recording.
- Interviews with e-bike OEMs about safety and design considerations.
- Identify and categorise design features that lead to enhanced safety.
- Produce public and consortium-only reports.

WMG is not a member of the Soteria consortium. Therefore, the following is based only on the press release that Soteria made in June 2023, to explain their initial findings (Soteria Battery Innovation Group, Jun 2023); Morin, 2023).

Several points in Soteria's work will be examined by WMG during the teardown of e-bike and e-scooter battery packs for OPSS:

- Cell balancing. Soteria reported that 4 of the first 8 packs that they disassembled had no capability for cell balancing. WMG will visually inspect the BMS of disassembled batteries to check for presence of a balancing circuit.
- Battery pack venting: Soteria reported that none of their disassembled battery packs had provision for pack venting. WMG will also check for pack vents.
- Cell spacing: Soteria reported that no battery packs had more than 1 mm between cells. WMG will also measure cell spacing, where practical to do so.
- Thermal propagation barriers: Soteria reported that none of the battery packs had protective materials placed between the individual batteries. WMG will also check for evidence of materials to counter thermal propagation.
- Counterfeit cells: Soteria reported that two of eight battery packs contained cells strongly suspected to be counterfeit. WMG will check the cell markings of disassembled batteries, and check them against manufacturer websites, and against the UL public database of UL-certified cells.

8.5 Media Articles on Battery Safety

Numerous media articles have been published about PLEV fires, particularly those in consumer residences. Annex A of Electrical Safety First's "Battery Breakdown" report provides an extensive list of such reports.

WMG has reviewed articles and publicly available CCTV footage of many PLEV fires. While these sources provide a clear insight into the devastating damage and danger to life that PLEV fires represent, they do not provide any scientific data to help understand the root-causes. Therefore, they are not discussed any further here.

9 Stakeholder Consultation

9.1 Introduction and Objectives

The aim of the stakeholder consultations is to provide evidence and opinions about PLEV fires from a broad spectrum of stakeholders, including manufacturers, retailers, industry associations, fire & rescue services, standardisation bodies, safety advocates and battery experts. The consultation is intended to complement WMG's own expertise in battery safety, based on first-hand experience of PLEVs, covering their development, certification, volume manufacture, shipping, sale to end-users, customer experience and feedback, and the aftermath of fires including root-cause analysis.

9.2 Selection of Stakeholders

WMG divided the stakeholders into three groups:

1. PLEV supply-chain companies
2. Safety advocates and fire & rescue services
3. Standards organisations and battery experts

WMG and OPSS worked together to agree an initial list of stakeholder organisations, and added to this list as further information came to light. The final list of stakeholders, agreed with OPSS, provides an equal split of numbers across the three categories.

9.2.1 PLEV Supply-Chain Companies

In the tender for this project, OPSS requested that the consultations should predominantly involve PLEV battery and charger manufacturers. However, almost all the manufacturers are in Far-Eastern countries, presenting challenges of contact and communication. Furthermore, some supply-chain companies may be resistant to engaging constructively in this consultation.

WMG therefore decided to engage with UK-based stakeholders which have relevant experience of designing, assembling, marketing and retailing PLEV products, as well as sub-contracting supply of components including chargers and batteries from Far-Eastern manufacturers, and are responsible for the relationship with the UK consumers, and therefore have direct experience of PLEV battery fires in the UK. The companies selected are:

- Halfords (PLEV developer and retailer, with large UK distribution network, and around 25% of the overall cycle market in the UK (Halfords Group plc (2023))
- Pure Electric (e-scooter developer, manufacturer and seller)
- Swifty (e-scooter developer, manufacturer and seller)

9.2.2 Safety advocates and fire & rescue services

In the UK, the greatest concentration of documented PLEV fires has occurred in London. London Fire Brigade (LFB) has thus been involved in tackling many of the fires caused by PLEV thermal incidents and has collated a large quantity of data from these incidents. The published LFB data underpins some of the analysis presented in Section 2 of this report. However, to answer questions not addressed by the incident data, LFB were also included in the stakeholder consultation.

The National Fire Chiefs' Council (NFCC) is the independent membership association for fire and rescue services across the UK and acts as their collective professional voice. The

NFCC therefore represents a much larger geography than LFB and was included to provide a broader UK perspective.

Electrical Safety First (ESF) is a campaigning charity that provides expertise in the safety of electrical consumer products. ESF has been very active advocating for improved safety of PLEVs, and in 2023 published the “Battery Breakdown” report on this topic (Electrical Safety First, Jul 2023), which includes outcomes from testing of PLEV batteries commissioned by ESF. Two months after their stakeholder interview, ESF also published “The Safety of Electric-Powered Micromobility Vehicles and Lithium Batteries Bill” (Electrical Safety First, Nov 2023), a private members’ bill addressed to the UK parliament (see Section 8.3 of this report). ESF is therefore the UK’s highest profile safety advocacy organisation with direct experience of PLEV fires.

To summarise, the safety advocates and fire & rescue service stakeholders consulted are:

- London Fire Brigade
- National Fire Chiefs’ Council
- Electrical Safety First

9.2.3 Standards organisations and battery experts

UL (formerly Underwriters’ Laboratory) is a global independent safety science company which creates safety standards for diverse sectors and products, and offers testing, inspection, and certification services in over 100 countries covering products and the manufacturing plants that produce them. UL is particularly well known in the North American market, in which many UL standards are adopted by the American National Standards Institute (ANSI) and the Canadian Standards Association (CSA). UL standards are developed with input from many companies from around the world in the relevant market sectors and are widely regarded as representing a consensus on good practice. For example, UL stated that UL 2271 (Batteries for Use in Light Electric Vehicle (LEV Applications) has over 50 companies on its technical panel. Some of the UL standards relevant to PLEVs and their batteries are discussed in Sections 6.14.3 and 7 of this report. UL was approached as a stakeholder because it represents an international perspective and has direct experience of safety testing of PLEV products and monitoring the quality processes in their manufacture.

Exponent is an international engineering and scientific consulting firm. Exponent is frequently contracted by manufacturers / service providers to assist them to understand the root-cause of in-market product failures and has investigated a variety of PLEV issues including thermal incidents. Exponent has presented publicly on some of their research findings and was contacted by OPSS to volunteer their assistance as a stakeholder in this project.

Dyson is a manufacturer and retailer of various electrified household products, including vacuum cleaners, air treatment systems and more. For several years Dyson undertook to develop an electric passenger car, before cancelling the project in 2019. Dyson retains many of the staff with an automotive background who were recruited for that project. Dyson does not make PLEVs, but because many of its products are powered by Lithium-ion batteries, it has relevant experience of the safety of such devices.

To summarise, the standards organisations and battery expert stakeholders consulted are:

- UL
- Exponent
- Dyson

9.3 Stakeholder Engagement Format

Each Stakeholder organisation was approached through existing contacts of WMG or OPSS, or contacts provided by the Bicycle Association, who supported WMG with parts of this project.

Each stakeholder consultation interview was performed as an on-line video call, typically two hours long. In some instances, the original call was of insufficient duration to cover all topics, or the stakeholder wished to introduce additional colleagues to supplement their answers, in which case a follow-up call was arranged and conducted in the same manner. With the consent of the stakeholder, the audio from the calls was recorded and an automatic transcript was generated and subsequently shared with the stakeholder, to allow them to check the accuracy and any information that they wished to be kept confidential or redacted. The vetted transcripts form the basis of the collated stakeholder responses that follow.

9.4 Consultation Questionnaire

In accordance with the introductory letter from OPSS, the questions posed in the interviews were framed in the context of the following topics:

- PLEV product knowledge: To increase understanding of PLEV products on the UK market and their respective levels of battery and electrical safety, with a focus on those known to have undergone fires.
- Fire root cause analysis: To describe investigations into causes of PLEV battery fires that the stakeholder conducted, or of which they were aware.
- PLEV battery standards and regulation: Awareness and discussion around relevant standards in relation to PLEV / Lithium-ion batteries and fire safety.
- Good practice, covering quality assurance, design, manufacturing, supply chain and consumer guidance for product use and maintenance.
- Market intelligence: Information on current size and trends of UK PLEV market.
- Consumer feedback: Information from customers regarding reviews, faults, complaints and returns.

The generic question list is shown in Appendix 8 (Section 15.8 of this report)

Given the diversity of stakeholders, the relevance of each of the above topics to their organisation varied considerably, and so the weighting of time spent on each topic varied accordingly. Similarly, prior knowledge of the activities of each organisation was used to tailor the generic questions. For example, in the case of Electrical Safety First, it was known from their publications that they had commissioned testing of PLEV batteries, so the questions were focused in this direction.

The following sections are structured according to the topics listed above, and further sub-divided by the three groups of stakeholders defined in Section 9.2.

9.5 Stakeholder Responses: PLEV product knowledge

9.5.1 PLEV supply-chain companies

Halfords has large network of retail and service outlets in the UK and aims to use this to maintain close contact with its customers. Halfords stated that they have had no direct thermal incidents involving e-bikes or e-scooters in their premises. There have been times when they have been contacted by LFB after their products have been involved in fires. However, in all cases no further investigation or action was required from Halfords.

Similarly, Swifty Scooters has had no knowledge of any battery safety thermal incidents related to their products.

Pure Electric stated that an earlier generation of products, which were manufactured by a Chinese supplier, did experience a small number of thermal incidents, after which the remains of the batteries were recovered from customers. A few incidents were caused by water ingress and corrosion due to weak structural strength of the plastic wrap around battery. This resulted in corrosion of contacts and cell enclosures. A couple of examples showed that a cell had vented and melted nearby components. Thermal propagation did not occur in those thermal incident cases.

Pure Electric also described an issue with a third-party manufactured scooter for children, sold by them. A manufacturing error results in a chassis screw that was found to have entered the battery pack but missed the cells and BMS. In another example, the fuse activated, and the unit was returned without causing a thermal incident. Pure Electric stated that children's scooters have inferior manufacturing quality & quality of the design, which may be due to the customer expectation of a lower price point.

Other than the e-bikes and e-scooters, some other PLEV products have been mentioned by the stakeholders. For example, around 2015, Halfords had an issue with a hoverboard product, which was manufactured by third-party, with no input from Halfords in the design. Use of the product resulted in a fault in the internal circuitry, leading to fires. Halfords worked closely with Trading Standards, which led to a global recall for the product a week later. Another case involved a power-bank product in the shape of a soft-drink can. This experienced thermal incidents during charging and was quickly withdrawn from sale.

A common product issue identified by all interviewed stakeholders in the supply-chain category relates to self-discharge of the battery. Batteries left uncharged for a significant period exhibit a voltage drop a very low level, referred to as deep discharge. Swifty related this to the quiescent current draw of the battery management system (BMS): Even when the battery is not in use or is switched off, there may be a very small electric current drawn by the BMS from the cells. Swifty estimated 6-12 weeks was the maximum time allowable between battery charges, and that the issue mainly occurs with stock held at dealers. Swifty has had to send some batteries to a third-party company to be recovered from a discharged state. Halfords stated that the high level of stock held by the cycle industry in the 2022-23 had required the batteries in PLEV products to be charged several times. Halfords referred to a "deep sleep" BMS mode, from which the battery was unrecoverable, to avoid the safety issues associated with deep discharge (see Section 3.5.3.1 of this report)

The problem of third-party manufactured aftermarket, or counterfeit, products is also another concerning factor that has raised by many stakeholders, including the main PLEV product itself, batteries, chargers, and spare parts. Swifty mentioned that there are many online marketplace platforms that sell PLEVs or related products. In the e-scooter market, they referred to poorly manufactured copies or counterfeits of a popular Asian e-scooter.

9.5.2 Safety advocates and fire & rescue services

London Fire Brigade (LFB) has documented the number of PLEV-related fires that it has tackled each year since 2017. In that year, the number of significant incidents was just seven. In 2022, this had increased to 116 PLEV related fires, and the number has grown further in 2023. At the time of the stakeholder meeting (October 2023), 145 incidents had been reported, and in an article published subsequently by LFB on 15 December, they reported 150 e-bike fires and a further 28 e-scooter fires (London Fire Brigade, Dec 2023).

As these numbers show, LFB stated that e-bikes are a greater concern than e-scooters. They also stated that e-bike conversion kits are a greater concern than OEM-manufactured e-bikes.

LFB stated that, compared to PLEV incidents, fires involving electric cars or vans (EVs) are virtually non-existent: at the time of the interview, there had been just two significant incidents in London in 2023. They were not aware of any EV fires causing significant property damage. Amongst other products that use Lithium-ion batteries, LFB opined that the next highest risk, after PLEVs, was likely to be consumer devices such as smart watches, phones, and laptops. They also have some concerns about domestic energy storage systems, particularly if they have amateur-built batteries.

LFB stated that the PLEV battery pack is entirely consumed by fire in 99% of incidents it attends. This makes it hard to determine the origin of the battery. If the battery can be identified, LFB raises a Product Fire Notification (PFN). LFB does not have strong data regarding whether PLEVs involved in fires have been bought new or second-hand but believes that sales from online marketplaces are significant. LFB stated that they rarely, if ever, see fires involving “high quality” PLEV brands. However, even where the owner has retained a purchase receipt, it is difficult to definitively tie that receipt to the burned product.

The capacity of the batteries is becoming larger. LFB stated it has seen PLEV batteries as high as 3000 Wh (more than twice the energy of the battery in a non-plug-in hybrid electric vehicle Toyota Prius).

When asked whether there are any signs of PLEV batteries improving, LFB said there was no clear evidence of this, one way or the other. They also highlighted that counterfeit batteries are causing them a lot of trouble.

NFCC stated that London has a huge concentration of PLEV incidents, but they expect the number of incidents to grow in other cities. Looking beyond London at the whole UK, NFCC said that it is hard to establish the PLEV incident data due to the low-quality information gathering system in most areas, which do not have LFB’s resources. LFB are the exception in the UK, having seen the emerging trend of PLEV fires before other fire services, and applied significant resources to gathering data. Other fire and rescue services are not capturing incident information appropriately and so the evidence base is low. For example, an incident report may only be collected as free-form text or a brief incident report (i.e. no specific data categories) unless the severity of the incident is high, or a full forensic investigation is required. NFCC is sending out surveys to fire rescue services, aiming to improve the quality and efficiency of data collection, as well as working on increasing the data collection rate. NFCC stated that a new National Fire Data Collection System is intended to go live in the summer of 2024.

NFCC raised the topic of the gig economy. They stated that PLEV fire fatalities are not seen in areas of affluent housing, but rather in multiple-occupancy dwellings in socially deprived areas, often with one or more occupants involved in the gig economy, such as food/parcel delivery riders. It is very common to see people within the household share similar work throughout the day, which may lead to dangerous behaviours, such as sharing chargers, multiple charging, non-stop charging, insufficient charging space and blocking of escape routes. There are great health and safety issues within those households. NFCC stated that most nationally-published PLEV-related safety guidance is only published in English, which is often not the first language of gig economy workers. Because of the diversity of languages and backgrounds of such workers, NFCC suggested that tailored translation and dissemination may be required for different localities.

NFCC also mentioned the existence of café/bar properties that operate a battery-swap offering for courier riders, so that they can continue deliveries with minimal interruption for battery charging. Such operations also present a potential battery fire risk.

Both LFB and NFCC share similar frustrations regarding incident investigation and data gathering. Part of this relates to a lack of knowledge amongst first responders who attend fires, and shortcoming of the system that they work with, or inadequate connection to those responsible for collating data. However, other factors relate to the occupants of the dwellings affected, such as language barriers and fear from the victims (e.g. fear of self-incrimination) which lead to unwillingness to share information.

LFB, NFCC and Electrical Safety First (ESF) all expressed an intent to engage in education, to be able to promote and bring awareness to people for the dangers of Lithium-ion batteries and incorrect charging.

ESF's published "Battery Breakdown" report highlighted several factors contributing to the occurrence of fires and was accompanied by videos from product testing that ESF commissioned at a test service provider. The products tested were selected by ESF from online marketplaces, based on images in the product listings that suggested they may not have undergone formal laboratory testing. There is no implication that these products have been involved in real world fires. However, ESF has used the videos and test results to raise awareness of the risk and severity of thermal incidents involving PLEV batteries.

9.5.3 Standards organisations and battery experts

UL started by highlighting that any Lithium-ion battery, or a product containing one, is classified by the United Nations as dangerous goods for transport purposes. UL stated that many smaller consumer products, such as earbuds, power-banks and electronic vaping devices, have logged thousands of thermal incidents, illustrating the risk of Lithium-ion batteries. However, while these were a cause for concern, the individual incidents do not cause the severity of harm or damage that PLEV battery fires do. UL identified the key difference with PLEV batteries as the number of cells and the quantity of energy stored in a single device. The difference is mainly in the severity of outcomes, rather than the probability or likelihood of a fire.

UL also referred to the "fire triangle", a graphical representation showing that a fire requires three elements needed for a fire to ignite: Fuel, Oxygen and Heat (see Figure 52). They explained that when a Lithium-ion battery goes into thermal runaway, the fire triangle is "always complete", because the Lithium-ion cell provides the fuel, the heat and also the oxygen, because the decomposition of most cathode materials liberates oxygen.

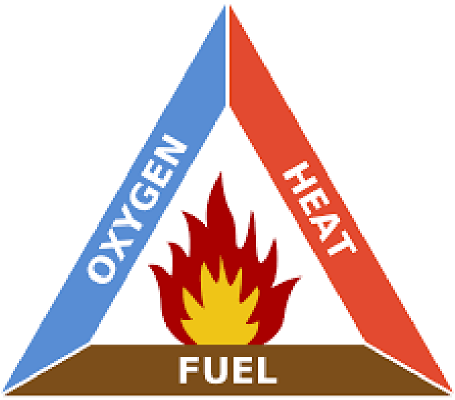


Figure 52: The Fire Triangle

Addressing the question of why PLEV fires are more frequent than passenger car EV fires, UL pointed to the fact that the bicycle community is very do-it-yourself (DIY) orientated: Many consumers feel comfortable undertaking DIY servicing, repairs and modifications on a bicycle or similar product, and the design of the components facilitates this. By comparison, relatively few electric vehicle owners do their own servicing or modifications. However, due to the inherent risks of Lithium-ion batteries, UL stated that it is necessary to “draw the line” at DIY on e-mobility products. For that reason, UL’s view is that the “right to repair” should be limited for PLEV products.

UL were not able to state good or bad examples of PLEV manufacturers or models but referred to their publicly available list of UL-certified products, for manufacturers who have undertaken the due diligence to achieve the UL standard and have had that certified by a third party. UL stated that many of their product tests end with non-compliance, and the process will end there unless the manufacturer corrects the non-compliances. UL “certified” status also requires that the factory where the product is made passes quarterly inspections, and UL has the policy that a battery pack can only be UL certified if UL has also certified the cell that it uses.

Exponent’s product knowledge derives in part from those products for which it is contracted to perform root-cause analysis. Typically, such work is requested by the larger manufacturers or where substantial disputes may be present, and where it is necessary to identify and/or rectify possible causes of product failure. Often, the failures can occur after several years of service life with customers, so the failure mechanisms can be ageing-related (or compounded by ageing effects), as well as related to design or manufacture. Exponent’s experience of products from less established OEMs, at the lower price end of the market, is less extensive, aside from some internal research studies.

Dyson’s experience of battery thermal incidents is not in the PLEV market, but rather in other Lithium-ion battery powered consumer products. Although their products are designed and supplied with Dyson-specific battery packs, competition law prohibits Dyson from preventing compatibility with third-party batteries. There are several third-party batteries available that replicate the shape and physical interfaces of the original Dyson batteries. In Dyson’s experience, fires have only occurred with these third-party batteries.

While Dyson’s experience is in adjacent market sectors, it clearly illustrates the risks of third-party Lithium-ion batteries being fitted to OEM products.

Dyson also stated that availability of third-party batteries is significantly lower in the USA than in other markets, including the UK, Europe and Canada. Dyson believe this is related to the size of insurance claims for property damage in the USA (partly a result of widespread wooden house construction), which the insurance companies try to claim back from the manufacturer or importers. Dyson assume that the fear of large claims, or being sued, is sufficient to discourage third-party battery manufacturers from that market.

9.6 Stakeholder Responses: Root-Cause Analysis of Fires

This section provides information on root-cause analysis (RCA) investigations into causes of PLEV battery fires that have been carried out by different stakeholders.

9.6.1 PLEV supply-chain companies

Because Halfords has not experienced thermal incidents involving e-bikes or e-scooters that have required further investigation, they were not able to provide information about the root-cause analysis that would be undertaken for such incidents. Halfords do not conduct any tests or benchmarking on competitor’s product or get involved in the investigation competitor thermal incidents. Halfords requires that all PLEV products that it sells need to have a certification by the OEM or accredited third party companies.

Similarly, Swifty Scooters has never had any customer report with thermal incident related to their batteries or products, and therefore has not needed to undertake root-cause analysis.

Pure Electric has conducted abuse testing, aiming to replicate some customer battery failures. They used two initiation methods: nail penetration and heating with a Nickel-chromium (Nichrome) wire to heat the cell. They found nail penetration to be the most effective and repeatable approach.

In addition, Pure Electric have set up tests for the effect of water ingress causing thermal runaway events. They found it challenging to predict and achieve thermal runaway for the cell. It was unclear how cell corrosion led to thermal runaway.

Although inconclusive on root-cause, Pure Electric's tests led to concern about thermal propagation from a single cell to the entire battery pack. Pure Electric are investigating methods to prevent thermal propagation in the event of single cell thermal runaway.

Pure Electric has also done mechanical abuse testing of battery enclosures, for the battery alone, and for the battery mounted in the e-scooter. This includes drop test and abusive riding to ensure the casings are robust, and the batteries are safely enclosed. Results did not show any damage on the battery enclosure.

Pure Electric highlighted an issue for e-scooters, where customer replace the original pneumatic tyres with solid tyres, to avoid punctures. This significantly changes the stiffness of the tyres, and hence the vibration frequencies and magnitudes transmitted to the e-scooter chassis and battery. Similarly, the level of impact/shock that the e-scooter experiences with some customers has been found to exceed what Pure Electric originally anticipated. There is no evidence that these factors have resulted in battery thermal runaway, but it must be accounted for in the product validation testing.

All three companies are aware that the misuse of incompatible chargers could lead to severe thermal incident. Halfords have put clear messages on the official website stating that only compatible chargers approved by the original bike supplier should be used or purchased by customers. Halfords does not encourage or sell universal chargers in their shop. Pure Electric has demonstrated the similar approach by putting information for the best use of their batteries on the official website.

9.6.2 Safety advocates and fire & rescue services

Among the three stakeholders interviewed in this grouping, LFB and NFCC have very limited resources for root-cause analysis: Both stated that fire and rescue services don't have sufficient budget for frequent forensic investigations.

If a scientific advisor is employed to examine the evidence, then a greater insight is possible, but this is not done in every case: Given the high number of incidents, the cost-benefit of an investigation must be weighed for each case.

LFB stated that it is very hard to identify issues such as misuse and over-charging without scientific advisors' detailed investigation. The level of destruction caused by the fire makes root-cause analysis very challenging, even for forensic investigators.

ESF commissioned over-charging and nail penetration tests on battery products selected at the lower price end of the market, purchased through online marketplaces. The objective of the testing was to highlight the hazards of battery fires, rather than to perform a root-cause analysis. These battery units came in various conditions: Some came with a charger, some without. Some came with an aluminium or plastic enclosure around the battery cells, but some also came with no enclosure with the cells and BMS, normally unbranded, wrapped in heat-shrink plastic.

Phase-1 of ESF's charging test aimed to charge the sample battery at an over-voltage, for example 36 V batteries were charged using a universal 54 V charger, which came with options of different connectors. Tests showed that the BMS protected the battery from over-voltage and stopped the charging. The Phase-1 tests failed to achieve thermal runaway on any of the battery samples.

Taking experience from Phase-1, Phase-2 aimed to simulate a fault condition in the BMS circuit, to allow uninterrupted charging with an over-voltage. Two fault conditions were introduced: The first fault condition involved bypassing components on the circuit board, such as the MOSFET switches. The second fault condition involved bypassing the discharge side of the BMS to allow over-discharge (this was not effective). The first method did manage to achieve thermal runaway with the 54 V charger.

Other tests were also conducted and managed to achieve thermal runaway, including nail penetration test and the use of external heat source using infrared heating plate, causing the surface of the battery to reach 200 °C. This did eventually cause thermal runaway, but was regarded as a very extreme test, possibly not representative of foreseeable misuse.

ESF also commissioned a 13 kN crush test (the force specified in UN 38.3 for cell-level crush tests) of a battery and were surprised that this did not result in thermal runaway. ESF expressed interest in investigating further into crush tests and more towards water ingress short-circuiting test. Test chamber time and financial costs limited the abuse testing that ESF were able to procure.

9.6.3 Standards organisations and battery experts

UL has had the opportunity to conduct root cause analysis for real world thermal incidents caused by PLEVs and related products. In common with the UK fire and rescue services, UL found that it is difficult to discern the root cause in many incidents, but gleaned some information from interviewing owners, residents, etc. UL estimates that in 50% of incidents, the battery is stated as having been "left on charge", but it's challenging to get more detail about when charging started or the state of the battery prior to the incident. UL said they rarely have information on whether the charger is the one the originally came with the product. Nevertheless, they said that charging is a "huge indicator" associated with thermal runaway, based on the frequency with which it is mentioned after incidents.

UL also emphasised that the usage history of the PLEV is important, for example whether the owner has used the battery in a situation where it's exposed to mechanical or water damage. However, accurate information on the usage history and state of health of the battery is almost never available.

As a company that creates standards and performs many compliance and certification tests, UL has good insights into the shortcomings of cells and batteries that fail to meet the UL standards. They emphasised several points that frequently come up during UL testing of PLEV battery packs and vehicles.

- The battery/BMS, vehicle and charger all need to respect the voltage, current and temperature limits of the cell. It is not uncommon for UL to find, during testing, that these cell limits are not respected in the application.

- Repeated small excursions outside the cell limits can cause cell materials to be cumulatively “weakened”, which can lead to cell failure. However, the standards do not test for this type of weakening, but rather involve single large excursions.
- Functional safety is essential: The control hardware and software must be reliable and have built-in redundancy in case a critical component fails.
- Temperature protection must cover not only the cells, but all of the components in the battery, including the BMS, to ensure that none of them exceed their limits.

Testing the aging of batteries has been considered for inclusion in standards, but UL said it would be very difficult to get a consensus on how long and what conditions to subject a cell to, for ageing studies.

For Exponent, root-cause analysis is a core competence. When a customer organisation contracts Exponent to conduct an investigation into a battery that has undergone thermal runaway, there is not always much left from the incident, because much of the material has been damaged, lost or destroyed. If anything remains of the pack, Exponent typically starts with X-rays or CT-scans of the entire battery pack, followed by disassembly and looking for signs of over-heating and short-circuiting and attempting to identify any evidence of the cause of the fire, such as melted materials.

Because of the difficulty of working with the remains from the incident, Exponent can sometimes work to acquire intact samples of the same product, of the same age and produced in the same production batch, with a similar customer usage profile, which Exponent then uses for laboratory testing. The premise of this is that the intact samples may display the precursor failures, such as loose fasteners, corrosion, or other forms of manufacturing faults or ageing damage, which could highlight the likely root cause of the fire.

Exponent has seen evidence of fasteners such as screws which have come loose, causing resistive heating effects from poor electrical contact, which can result in subsequent pack thermal damage. Exponent may also test the battery or BMS, for example passing current through the conductors to identify signs of over-heating.

CT scanning and disassembly can reveal signs of ohmic heating of conductors such as copper, nickel or steel busbars and PCB tracks. PCBs may be pyrolised, causing the insulative substrate material to become conductive.

Exponent stated that the most frequent issue identified for long term commercial e-mobility use is generally moisture ingress, particularly when the moisture reaches the BMS. They emphasised that moisture ingress can be a very slow process, happening gradually during the customer usage of the product. This type of long-term effect is not identifiable from the Ingress Protection (IP) tests that are typically performed during product development, since these tests only last for minutes or hours and are carried out on new devices. Exponent believe the IP tests can give consumers a false confidence, because they fail to capture long-term effects that can be caused by thermal cycling, consumer usage (e.g. washing / cleaning), mechanical damage and exposure to ultraviolet (UV) radiation from sunlight, such as delamination of materials and degradation of seals.

Some of Exponent’s work is under contract to established manufacturers or suppliers who have a vested interest in making sure their products are well built. However, Exponent has also conducted its own research, purchasing conversion kit batteries from online sources.

Exponent has found there is a big difference between OEM and conversion kit batteries. Conversion kit batteries that they have investigated have not had O-rings or gaskets (seals) that OEM products would have. Some have had “zero waterproofing”. Some have had pinched / damaged wires. They have had much smaller BMS boards than would be expected for the electric currents present, leading to questions over the ability of the BMS to carry high current for long periods.

Exponent has performed its own research into PCB failures, in the presence of moisture, which they presented at a meeting of the Electrochemical Society in October 2023 (Electrochemical Society, 2023). This showed that:

- Full immersion of cells results in slow discharge of the cells, not thermal runaway.
- Moisture on exposed copper tracks / busbars can lead to growth of a bridge of material between the tracks, comprising mainly copper oxides. A voltage as low as 8.4 V (equivalent to two Lithium-ion cells in series) between tracks separated by 2 mm was sufficient to cause bridging that led to localised sparking / electrical arcing, and local temperatures of approximately 100 °C. Increased separation can prevent this behaviour: at 4 mm separation, to copper completely corroded away before a bridge could form.

Although it is too early to draw clear conclusions or design recommendations from Exponent's work, the implication is that the distance required between exposed copper conductors, to avoid corrosion bridging, is likely greater than the separation required by "creepage and clearance" distances that are defined in existing standards, which only consider the risk of electrical arcing between conductors. If the conductors are not exposed, for example if they have a conformal coating, then the issue will not occur, as long as the coating remains intact throughout the life of the product.

Exponent believe that, while most PCBs will have a protective coating over the copper tracks, delamination of that coating could expose the tracks to moisture and lead to the type of damage seen in their experiments.

Exponent has also done experiments with nickel, rather than copper tracks. With Nickel, the bridging-sparking issue did not appear to occur as readily. They intend to continue the experiments with other materials.

Exponent has also seen corrosion on the top of 18650 cylindrical cells (the size most commonly used in PLEV batteries) where moisture has been present: At the top of the cell, the positive and negative parts of the cell are only separated by approximately 1 mm of gasket polymer material. Moisture exposed to the voltage of a single cell can cause corrosion in this location. The implication of this could be a soft short-circuit, bridging across the gasket between the positive and negative of the cell. Severe corrosion could result in the hermetic seal of the cell being compromised, allowing electrolyte leakage. If sparking occurred, as Exponent saw with copper track experiments, then this could ignite the flammable electrolyte, although Exponent have not investigated this.

Dyson highlighted third-party replacement batteries as the main source of fires in their products. They believe most incidents occur when the battery is fully charged, and not when the product is in use. Often, all six cells in the battery have undergone thermal runaway. The root cause is not clear, but some potential factors identified by Dyson are:

- The third-party batteries have been found to have poor quality soldering.
- They often lack individual cells voltage sensing, which is essential for Lithium-ion safety.
- They may have a thermistor, but not necessarily located at the hottest cell.

9.7 Stakeholder Responses: PLEV battery standards and regulation

9.7.1 PLEV supply-chain companies

Halfords stated that they generally start by ensuring that their battery products comply with the UN38.3 regulations for transport of dangerous goods. Halfords view UN38.3 as covering most safety concerns.

Since EN15194 for e-bikes was updated to require that, for an e-bike to comply with EN15194, the e-bike battery shall comply with EN50604-1 (see Section 6.12.1), Halfords are working with suppliers to ensure that future batteries will comply. They stated that the main challenges with meeting EN50604-1 are the number of sample batteries required and the costs involved. Their battery suppliers do not see a technical challenge in meeting the standard.

Halfords also stated that the current market conditions are unhelpful in making the transition to EN50604-1 compliance within the required timeframe, because of high levels of unsold stock of existing products. Ideally, they want to be compliant 6-12 months before the deadline. In normal times, when stock is sold within 6 months, this would not be an issue, but with higher-than-normal stock levels, it is more of a challenge.

Halfords did not highlight any shortcomings with existing standards but noted that they do place some additional requirements on their battery suppliers. For example, relating to deep discharge, Halfords has requirements for how long the battery must be able to be stored without any charging, which requires a very low self-discharge level.

Pure Electric, who produce e-scooters, stated compliance with EN 17128 for the vehicle, and EN 62133-2 and UN38.3 for the battery. Pure Electric stated that they do not feel the European regulations go far enough in some areas. They exceed the ingress protection standard, and now achieve IPx7 for water ingress. They have also implemented mechanical tests that are beyond the requirements of standards, in light of knowledge of the extreme use that e-scooters can experience in the hands of customers.

Pure Electric also stated that “EN 17128 is nowhere near sufficient” to avoid reliability issues that they have seen, and they are moving towards e-bike or even motorbike levels of mechanical testing. They also mentioned the importance of testing a large sample-size during product validation, and the challenge of maintaining adherence to quality standards when production volumes are ramped up.

Regarding the battery, Pure Electric goes beyond the requirements of EN 62133-2, and has considered adopting EN 50604-1, because of its higher requirements. However, it is a challenge to justify such examples of going beyond existing standards, while also needing to remain price competitive with other manufacturers who do not exceed existing standards.

At the time of the interview (26 September 2023) Pure Electric was in the process of obtaining UL 2271 and UL 2272 compliance, to enable them to enter the US market. This required adding redundant safety features in the BMS hardware and software. They had to adopt different solutions in two different batteries. In the first case, a hardware redundancy was added. In the second, this was not feasible, but a software redundancy solution was identified, and was agreed with the test house that undertook the compliance testing.

This underscores the current absence of functional safety requirements in EN 17128 and EN 62133-2 for UK/EU market e-scooters, in contrast to the UK/EU e-bike requirements and the US requirements for both e-bikes and e-scooters.

Pure Electric are also keen to see standards adopt a more stringent requirement on thermal propagation, to prevent a single cell thermal runaway from propagating throughout the battery pack.

Swifty stated that they rely heavily on EN 14619:2019 “Roller sports equipment - Kick scooters - Safety requirements and test methods” (BSI Group, Jul 2019) and also use EN 17128. For some parts of the vehicle, such as brakes and handlebars, they use the e-bike standard EN 15194. Since Swifty have not had experience of battery fires, they did not have any comments on the suitability of the standards in this regard.

9.7.2 Safety advocates and fire & rescue services

LFB stated that they do not get involved in standards, but they highlighted the concern over incompatible chargers, which they see as a major contributor to PLEV fires and stated that they would like to see an enforced standard which tackles this issue.

NFCC likewise are not normally involved in standards. They stated that they had been approached by Electrical Safety First (ESF), to review a private members’ bill (see Section 9.2.2). NFCC commented that they provided feedback to ESF that NFCC does not advocate the use of charging bags as a means of improving charging safety. NFCC advocate that the focus must be on PLEV product safety and standards.

ESF highlighted several issues regarding standards for e-bikes and e-scooters:

Firstly, ESF outlined their own experience of trying to identify the relevant legislation and standards. They highlighted that some devices fall under the Electrical Equipment (Safety) Regulations 2016, whereas others fall under the Supply of Machinery (Safety) Regulations 2008. ESF believe this could create confusion as to whether the risk is primarily electrical or mechanical. They came across some of the standards “by chance” by an “iterative process”, and found overlaps between standards in some cases, and gaps in other cases. Their impression was “it just causes uncertainty from a manufacturer’s standpoint as to what the requirements actually are”. They also referred to “technical specifications which aren't recognised as standards at all, which seem to do a far better job of keeping people safer than the standards that are designated”. This was a reference to ISO/TS 4210-10, which ESF advocate because of the detail it provides regarding non-proprietary charging connectors and protocols, to provide communication between the charger and BMS (see also Section 6.13 of this report).

Secondly, ESF highlighted that an e-bike that has been created by installing a conversion kit on a conventional bicycle is covered by legislation and standards for complete e-bikes, but there is no standard that a manufacturer of conversion kits can follow, to ensure that all the sub-systems, such as the battery, motor and controller, are safe when combined as a powertrain system. ESF urged that a standard for the system-level safety of conversion kits is needed.

ESF’s third point relates to the discrepancy in voltage marking between chargers and batteries. As ESF said “You should be buying a 42 Volt charger for a 36 Volt battery, which is not intuitive. So the chances are you will buy the wrong charger because you're not quite sure what voltage you should be getting and because of the compatibility of the universal connectors that also makes it possible to connect the wrong voltage, so you've not got those safeguards that you would have otherwise in other Lithium-ion battery powered devices.”

Fourthly, ESF had done some research into fire-containment enclosures. They found some products for the aviation industry, which were not suitable for e-bike / e-scooter users due to their high purchase price. Others that were affordable for consumers seemed not to have any standards for them. ESF urged that a standard is needed for fire containment products for Lithium-ion battery fires, taking account of factors such as the size of the battery, the peak temperatures, the quantity of gas produced, the toxicity of the gas and the possibility of explosion.

9.7.3 Standards organisations and battery experts

UL raised their concern that many national markets have “zero regulation, zero oversight for consumer protection” regarding consumer products with Lithium-ion batteries. They highlighted Singapore as an exception, where mandatory third-party certification of PLEVs was introduced in 2019, leading to reduction in PLEV fires, and the more recent change in the law in New York City, requiring that PLEVs must be certified to UL standards. UL is also supporting California to create a model regulation that aims to maintain commonality with the New York approach. UL advocates product safety regulations and standards that require third party certification and market surveillance and emphasised that such regulations should apply to all consumer products with Lithium-ion batteries.

UL shared information about the studies conducted by European Commission’s Coordinated Activities on the Safety of Products (CASP) (European Commission, no date). CASP enables all authorities of EU countries, which are responsible for market surveillance, to cooperate to reinforce the safety of products placed on the European markets. CASP projects typically focus on one market sector and involve the testing of a selection of products against existing standards, to ascertain the level of compliance. In 2019, CASP performed three projects that are relevant to this report, on batteries (power-banks, smartphone/tablet batteries, 18650 cells) (European Commission, 2020), chargers (USB chargers, laptop/tablet chargers, single-cell chargers) (European Commission, 2020) and personal transporters (e-bikes, e-scooters, hoverboards, uni-wheels) (European Commission, 2020). Perhaps the most striking results came from the personal transporter testing: Out of 46 products tested, 80% were found to be non-compliant (92% of e-bikes and 74% of e-scooters). Overall, the largest non-compliance related to partial immersion in water (56% of products tested), while 11% failed the over-charging test. All chargers supplied with the PLEVs were compliant with the relevant charger standards. The separate CASP battery study (which did not cover PLEV batteries) found much higher compliance: 89% of 92 products tested complied with relevant standards, but in UL’s view, the relevant standard “is a very easy one to pass”. Meanwhile, the separate charger study found 65% non-compliance.

UL used the example of the CASP results to illustrate their view that self-certification is not sufficiently effective in ensuring consumer product safety. UL said, of the EU and UK, that with “a programme that has no market surveillance, no requirement for the certification company, you wrote your own ticket for disaster.”

UL suggested that the UK could adopt a similar approach to New York City, with the use of their existing standards UL 2271 , UL 2272 and UL 2849.

UL acknowledged that these standards do not have a requirement regarding thermal propagation, although a suitable requirement and test methodology could be developed. UL does have thermal propagation tests in their existing standard for large stationary energy storage systems, UL 9540A (UL Solutions, Nov 2019).

Regarding the detailed content of the standards, UL highlighted two areas in which they believe their own standards set more robust requirements and test methodology than the EU/UK standards.

The first is in the approach to functional safety, and the criteria for foreseeable misuse conditions. Unlike the EN standards, UL 2271 and UL 2849 assume that safety-critical components could fail during the life of the product, even if those components have been validated for reliability. Abuse tests are run with each critical component shorted-out, to check that the battery still behaves in a safe manner.

The second relates to temperature limits of the non-cell components, for example the BMS electronics and the plastic casing parts. According to UL, “very little of that kind of testing or evaluation is being done in the EN standards, and that's absolutely critical because in normal operation, you should make sure that everything's within the limits”.

Exponent expressed a similar view to ESF, that the standards landscape can be confusing for OEMs, because there are so many different standards. The two Exponent scientists involved in the stakeholder interview with WMG both sit on standards committees with bodies such as BSI and CEN. In their experience, it can be challenging when a fast-acting standards body, such as UL, publishes standards for a particular type of product before slower moving standards bodies which are more aligned with national/international regulation (such as CEN). Some standards organisations require a great deal of consensus building, and cannot move as quicky, but their standards may become legislation and so can require more political and legal consideration. Those slower moving bodies may already be in the process of developing their own standards when the fast-acting body publishes, which can then cause difficulties where differences exist between the two standards. Changing the standards to be followed (e.g. a voluntary standard being superseded by a different legislated standard) can present technical difficulties and costs for OEMs.

To avoid this confusion, Exponent suggests that internationally agreed and consistent standards would be beneficial if developed for PLEVs and other battery products.

As described in Section 9.6.3, Exponent have extensive experience of moisture ingress as a cause of battery failures. In their view, the generic ingress protection tests, for example EN 60529, may be insufficient for the ingress challenges present in PLEVs. Exponent suggests that a specific ingress protection requirement should be developed for PLEVs, to ensure protection from moisture over the life of the product.

Like UL, Exponent conducts audits of factories that manufacture PLEVs and their sub-systems, including Lithium-ion cell manufacturers. Exponent suggests that a manufacturing quality standard could be developed for PLEVs, similar to IATF 16949:2016 (International Automotive Task Force, undated; Society of Motor Manufacturers and Traders, no date), which was developed by the International Automotive Task Force, and aligns and supersedes US, German, French and Italian automotive quality standards as well as the earlier ISO/TS 16949:2009 (BSI Group, Jul 2009). IATF 16949 is based on EN ISO 9001:2015 (BSI Group, Sep 2016), the international standard for quality management systems across many industries (Note: No quality standard is required in the e-bike standard EN 15194, the e-scooter standard EN 17128, the LEV battery standard EN 50604-1 or the portable battery standard EN 62133-2. The last of these is the only one that requires a manufacturing quality plan).

Exponent drew attention to the new EU Battery regulation 2023/1542 (see Section 6.14.2 of this report), which they believe is likely to have a significant effect on battery safety in the EU. Exponent emphasised particularly the requirements that economic operators that place batteries on the market or put them into service, and any battery suppliers, shall have their battery due diligence and manufacturing policies verified and periodically audited by a third-party notified body (See also Section 6.14.2). This is a major increase in oversight compared to the current situation and would appear to address the concern raised by UL at the start of this section.

Exponent has experience of other market sectors that involve safety-critical products, such as medical devices and the automotive sector. They explained that the Medical Devices Regulations 2002 divides such devices into classes, depending on the health risks associated with them. Lower risk medical devices (class I) can be self-certified by the manufacturer, but classes IIa, IIb and III require approval by a notified body. Exponent suggested that such third-party approval approach could be considered for Lithium-ion battery-powered consumer products but cautioned that lessons should be learned from the introduction of the Medical Devices Regulations with regard to third party certification: Initially, there was insufficient capacity in the newly created notified bodies to approve the large number of devices on the market, which created a bottleneck. As a result, the deadline for compliance with the new system was repeatedly pushed back.

The final point that Exponent made is that compliance with standards does not necessarily mean that a product will perform safely throughout its lifetime. They emphasised that individual manufacturers may wish to understand the use-cases of their product in the hands of consumers and apply some standard engineering tools such as Failure Modes Effects Analysis for the Design and manufacturing Process (DFMEA and PFMEA), or Fault Tree Analysis, and adapt the design and the validation / verification testing plan accordingly.

Dyson is not involved in the PLEV market, so did not have views on the legislation and standards for PLEVs. However, they made a similar point to Exponent, that not everything can be put in a standard without over-constraining the OEM design, for example component spacings and multiple layers of protection.

As noted in Section 9.5.3, Dyson highlighted the lower availability of third-party batteries in the USA than in many other major markets. As well attributing this to the size of insurance liabilities for fires, Dyson also noted the influence of UL certification, and the ability for anyone, from border forces to consumers, to check the validity of a product certification on UL’s database. The accuracy of this database relies on the third-party testing done by UL. The implication for the UK is that, firstly, a public database of approved products would be a significant benefit but that such a database is impractical without third-party testing.

9.8 Stakeholder Responses: Good Practice

9.8.1 PLEV supply-chain companies

Halfords’ main input on good practice was the avoidance of deep discharge on batteries. They achieve this by implementing several low- power consumption modes in the BMS, with the lowest being for shipping. The BMS automatically transitions into lower consumption modes after defined periods of inactivity. This helps Halfords to avoid the need to recharge batteries in warehouses or retail stores and would have a similar benefit for consumers. It also has an important safety benefit, as charging following deep discharge can result in hazardous damage to Lithium-ion cells (see Section 3.5.3.1 of this report).

Pure Electric’s design and development team includes many people who previously worked at Dyson, including Dyson’s car project, who know the risks involved with Lithium-ion batteries. They have also had experience from previous-generation Pure Electric products which have had thermal incidents. As a result, Pure Electric is pursuing technical developments which could significantly reduce the severity of thermal runaway. They stated that “we're reducing this to a one in a million event”. These technical developments concern the filler material between the cells, with the aim of preventing thermal propagation, so that if a single cell thermal runaway does occur, it does not spread to the other cells in the battery pack.

In WMG’s view, Pure Electric’s approach has parallels to the state-of-the-art in the automotive and aerospace industries, which are influenced by standards and legislation in those markets. WMG has not seen any evidence of such measures to prevent thermal propagation in currently available PLEV batteries.

Pure Electric also implements design measures to discourage or prevent tampering: The fasteners used are “security” type screws, which require specialist tools to unscrew, and the battery enclosure is glued together, so it will be destroyed if someone tries to open it. They also use encrypted firmware in their control units, so it is not possible to hack into the software to change parameters such as the maximum speed or power. The engineering software required to make such changes is only available to Pure Electric personnel. This prevents tampering and ensures that the product remains compliant with legislation and standards. Pure Electric claim that this is in contrast to some popular competitor e-scooter brands, where software apps are readily available to allow adjustment of parameters.

Swifty scooters have had experience of customer e-scooters which, left unused for long periods, have reached a deep discharge state and have been unrecoverable. As part of the solution to this, Swifty are implementing a CAN-bus serial communication system between control-units on their e-scooters. This will provide more BMS data to consumers and is also important for their corporate customers, some of whom have fleets of e-scooters operating, for example, in large warehouses and datacentres. The CAN-bus system will also allow over-the-air software updates of control units on the e-scooter.

In existing products, Swifty have used a battery mounted on the stem of the e-scooter, above the front wheel. In future, they will move the battery to the footplate/deck, which they state achieves a big improvement to the stability of the e-scooter. They mitigate against the possible effects of mechanical damage of a low-mounted battery by housing it in a steel tray, part of the chassis, which ensures a significant gap to protect the battery from impact or penetration.

Swifty also stated that some courier companies, which ship Lithium-ion batteries under the UN dangerous goods regulations, place a 300 Wh limit on the energy in each individual battery. As a result, Swifty plan to keep their batteries under this limit. Where a product requires more than this, they may need to have two batteries, electrically connected in parallel. The courier limit is a safety-related limit for transport, but keeping the battery energy down can also reduce the severity if a fire occurs.

9.8.2 Safety advocates and fire & rescue services

The input from LFB and NFCC, regarding good practice, mainly concerned two areas: The first is reporting on incidents that fire services attend, and the second is good practice by consumers and owners of PLEVs.

For the first of these, both LFB and NFCC made it clear that the skills/training of fire service personnel, and the resources available to crews that attend fires, are not well suited to the task of root-cause analysis or gathering accurate data which can be used in studies such as the one covered by this report. PLEV fires constitute only a fraction of the incidents that fire services attend, but there is clearly room for improvement in the gathering of data from fires. The National Fire Data Collection system, mentioned by NFCC, is aimed to improve this.

Both LFB and NFCC have been active in tackling the second topic, consumer good practice, through engagement with the public through their websites, press releases and other media for education.

LFB also mentioned instruction manuals as an important topic for education. In common with other stakeholders, they suspect that most consumers rarely, if ever, read an instruction manual. However, insofar as an instruction manual will ever be opened, LFB believe that good pictures, with a minimum of words, are the most effective way to educate the consumer on good practice. LFB also believe that clear warnings on the outside packaging of products, similar to the mandatory labelling of cigarette packets, could be considered, to reinforce the dangers associated with Lithium-ion batteries.

ESF's recommendations for good practice were concerned with legislation and standards. These are covered in Section 9.7.2.

9.8.3 Standards organisations and battery experts

UL's suggestions for good practice relate primarily to the certification testing of products (see Section 9.7.3) and market surveillance, through frequent audits of the manufacturing supply chain for products, and intermittent testing of randomly selected examples of the product against the certification test standards.

In the certification process, UL creates a Critical Components List (CCL), which documents details of all the critical components in the battery, listing their material, manufacturer, certification record, and more. During quarterly factory inspections, UL check the components being used in the production parts against the original CCL. Approximately annually, UL takes a product from the factory, which will then undergo a sub-set of the relevant standards tests, at UL's laboratories, to check that it still complies. If a non-compliance is found, this will need to be explained. In serious cases, a non-compliance may lead to a public release notice stating that UL no longer considers the product to be certified, and possibly a recall of products in the market. UL also uses a holographic UL mark on the product, as a way to determine genuine certification, and actively monitors for counterfeit marks.

Overall, UL suggests their certification process, comprising initial product certification against relevant standards, followed by quarterly surprise factory inspections and annual spot-checks of product compliance to standards, as the good practice to ensure that products sold to consumers meet the required safety levels.

Exponent's input on good practice relates firstly to possible product design choices, to minimise the severity of thermal runaway and propagation. Exponent conducted thermal propagation tests on a 48 V 20 Ah e-bike conversion kit battery, comprising 104 cylindrical cells in a 13-series 8-parallel configuration. They used a small heater, placed on one cell at the end of the cell block, to initiate thermal runaway. The battery had been charged to 100% SoC. The fire propagated to the whole battery over the course of 7 minutes. In a similar test with the initiating cell in the middle of the cell block, the thermal propagation occurred much more quickly, over a period of approximately 30 seconds.

They then prepared a second battery, with thermal insulation applied to two cells at one end of the battery, which would be used as initiating cells. The first was potted in urethane, and the second was wrapped with ~1 mm of Nomex ®, a flame and high-temperature resistant material (DuPont de Nemours, Inc., no date). Thermocouples were placed on these initiating cells and on neighbouring cells. In a first test, the potted cell was set into thermal runaway using a heater. This cell reached over 550 °C, but the nearest neighbouring cell reached only 132 °C. No cells other than the initiating cell entered thermal runaway. In a second test, the Nomex-wrapped cell was set into thermal runaway using a heater. This cell reached over 350 °C, but the nearest neighbouring cell reached only 50-60 °C. Again, no cells other than the initiating cell entered thermal runaway.

These proof-of-concept tests demonstrate the effectiveness of thermal insulation to prevent thermal propagation.

Exponent also performed tests with fire blankets (Torelli, D.A. *et al.*, 2024). In the first test, a fire blanket was laid over the battery prior to thermal runaway, and held down with weights, on two opposite sides of the battery. The thermocouple results show that the fire blanket prevented heat from escaping, which resulted in a much more rapid thermal propagation, and the blanket acted as a conduit for the flames, causing them to jet out four metres from each of the two sides where the blanket was not weighted down. Within 15 seconds of the first cell entering thermal runaway, the fire blanket had a hole in it, and soon afterwards it had split into several pieces.

In a second test, Exponent used a different type of fire blanket, “specifically advertised as a Lithium-ion battery e-mobility battery pack fire blanket”. This was deployed over the fire approximately one minute after the first cell entered thermal runaway, by which time approximately five cells had entered thermal runaway. Within one second of being pulled over the burning battery, this blanket had a hole in it. Ten seconds later, flames were jetting out from underneath the blanket, 4 meters away from the pack. Inspection after the tests found the remains of projectiles up to 16 metres away.

These tests appear to show that fire blankets may exacerbate some of the hazards of a PLEV battery thermal runaway, rather than mitigate them.

The second aspect of Exponent’s input on good practice relates to the product development and validation process. They emphasise the need for a full DFMEA and PFMEA, based on a series of questions such as “How might the product break?”, “How might it hurt someone?”, “How do we design that out of our product?”. Exponent make the point that a standard can provide guidance on the process of how to perform an FMEA, but it cannot provide the OEM with all the answers on how to design the product and how to manufacture it with sufficient quality.

For example, regarding moisture ingress, Exponent state that, once moisture is inside a battery casing, it is likely to stay there, and it is difficult to guarantee the ingress protection of a housing over its full life, so it is prudent to assume that moisture ingress is a possible failure mode. With changes in temperature, the moisture will evaporate and then condense on colder surfaces, for example on BMS components, which could possibly lead to corrosion or short-circuits, which are a safety concern. If the DFMEA concludes that exclusion of moisture cannot be guaranteed, then it may be beneficial for the BMS to be able to detect the presence of moisture, to provide a warning to the user or to inhibit battery use. This may then require a moisture sensor.

Dyson’s input on good practice relates to two main areas. The first is to have multiple layers of protection. Dyson try to have three layers of protection against failure modes, through a combination of hardware and software measures. The second is to maximise spacings between components and conductors, to minimise the risk of short-circuits. Dyson also cover their circuit boards with silicon, to protect them from moisture and dust, in addition to the ingress protection provided by the battery casing.

9.9 Stakeholder Responses: Market intelligence

This section concerns information on current size and trends of UK PLEV market, and on approaches to safety amongst existing manufacturers.

9.9.1 PLEV supply-chain companies

Halfords stated that it does not test or benchmark competitor products, so was not able to comment on the safety approach of non-Halfords products. Halfords has approximately a 25% share of the overall UK cycle market (Halfords Group plc, 2023). No statistic is available for their share of the PLEV market, but it is likely to be substantial. Given that Halfords has experienced no PLEV fires with consumers that warranted further investigation, this is a clear sign that it is possible to manufacture and sell large numbers of PLEVs with acceptable safety.

Pure Electric has looked at products from a variety of e-scooter competitors and e-bike manufacturers which it believes represent good practice. In general, Pure Electric believes that they achieve similar levels as these other companies regarding BMS protection and redundancies for over-voltage, undervoltage, temperature, and good quality plastic enclosures, but Pure Electric stated that these are in contrast to products from some online sellers and the conversion kits seen being used by many delivery riders.

Pure Electric also mentioned the Estonia Äike e-scooter brand, which claims to be the only e-scooter with USB-C charging, and the only one built outside China, and has a removable battery which is relatively unusual in e-scooters. Pure Electric sees innovations such as USB-C charging as topics that should be explored, in terms of good practice.

Swifty did not provide market intelligence information.

9.9.2 Safety advocates and fire & rescue services

The fire and rescue services, LFB and NFCC, and the charity Electrical Safety First, were not able to provide market intelligence information.

9.9.3 Standards organisations and battery experts

The standards organisations, UL and Exponent, and the consumer products manufacturer Dyson, were not able to provide market intelligence information.

9.10 Stakeholder Responses: Consumer feedback

This section concerns information from customers regarding product reviews, faults, fires, complaints and returns.

9.10.1 PLEV supply-chain companies

Halfords stated that, through their network of shops, they have a very good conduit for feedback from customers, as well as for servicing, repairs, spare parts and end-of-life disposal. Halfords looks at customer reviews of their products, and they study return rates, and trawl through all the customer complaints that they receive. They are confident that, if they had any indication of any ongoing trend or issues that were more than a one off because of some misuse or abuse, they would identify it very quickly. Halfords detects certain key words such as “dangerous” or “safety” in reviews left on their website, which will automatically direct the review feedback to Halfords’ head of quality. These data channels show that they have had very few incidents, and no discernible pattern of product failures with e-bikes or e-scooters.

Pure Electric also emphasised the benefit of strong links with their customers. With previous generations of products, when customer e-scooters have had thermal incidents, Pure Electric has arranged to recover those products for return to their workshops, to investigate the root-cause. This is how they have established issues with water ingress, and they have successfully recreated issues in the laboratory, to prove the causal link. Similarly, customer returns have enabled Pure Electric to identify issues of mechanical damage to the battery, from extreme use of the e-scooter, for example at a skatepark. Pure Electric stated that “having that good point of contact [with the customer] is essential to make sure that where you can recover products that might be on the cusp of being a serious problem”.

Similarly, Pure Electric received customer feedback on early products that highlighted a premature loss of riding range, which led the company to focus on the manufacturing quality of the cells, and only purchasing good quality cells.

Pure Electric has also used communication to their customer base, for example through their website, to help customers to get the most from their product. For example, they have added website information about operating temperature range, because of complaints of reduced range or performance in winter. Similarly, they have added advice to the website and user manuals, on how to charge the battery safely.

Pure Electric also takes measures in customer communication, to discourage tampering. For example, the warranty is void if non-OEM parts are used.

Swifty also maintains a close relationship with its customers. Swifty has an ambition to implement “live analytics” in the battery, including temperature and moisture sensing, and allowing proactive messaging to customers, through a mobile phone app. For example, the customer could be reminded to charge the battery, to avoid deep discharge, or to put the battery in a warm environment if it is too cold.

For customer returns of e-scooters, Swifty provides a service, through its website, to order a shipping box that is correctly labelled (including dangerous goods labels) for the Swifty product. They have experience of some people ordering and using that box with a non-Swifty product, which means the labelling is not appropriate for that product. This emphasises the importance of OEMs providing their customers with the means to ship returned products safely, adding to the point from Pure Electric, above, that OEMs should be obliged to provide service support to their customers.

9.10.2 Safety advocates and fire & rescue services

The fire services, LFB and NFCC, are not recipients of customer feedback on e-bikes and e-scooters but are strongly involved in communication to end-users. LFB attended its first PLEV-related fire of 2023 on 1st January, and this acted as a springboard for a social media campaign, #chargesafe, that became a national campaign.

Social media are the biggest platforms for LFB to use for communication campaigns, because they believe that the target audience is predominantly teenagers and people under 30 years old. However, they have also undertaken campaigns on national television. LFB also has a community engagement team, which works directly in less privileged areas of London, to communicate more directly with the most vulnerable groups.

NFCC described the challenges in obtaining meaningful information from end-users who experience PLEV fires. They described an incident where a gig-economy courier rider had converted a conventional bicycle using a conversion kit, which caused a fire in his residence, a multiple-occupancy house with several other residents with similar jobs. The local fire service attended within 2-3 minutes, and fortunately no one was hurt. The fire service then tried to obtain information from the e-bike owner, but there was a language barrier, and the person was fearful of arrest because he feared he had done something wrong, and perhaps culturally had a fear of uniformed services. NFCC stated that similar problems are seen across the UK.

NFCC see PLEV fires happening mainly in socially deprived areas. They see many fires associated with gig-economy courier riders, who are generally using conversion kit e-bikes. NFCC suggested that there could be a case for provision of e-bikes, in a similar way to fleet-hire bikes, with public outdoor charging provided, for use by gig-economy riders. The benefits of this would be that the e-bikes (or batteries) would not be taken into their homes for charging, the riders would not need to pay the purchase price of their own e-bike, and the condition of the e-bikes would be under the control of an organisation which could ensure adherence to a maintenance schedule.

ESF has undertaken some consumer survey work, to obtain consumers' perspective about PLEV safety, how they charge their bikes, whether they have used a conversion kit, etc. However, ESF was not able to provide results of the survey during the stakeholder interview.

9.10.3 Standards organisations and battery experts

UL does not have consumers as direct customers (although consumers can access the UL database of certified products), and therefore was not in a position to provide information on customer feedback on PLEVs.

Exponent made a comparison between the post market surveillance environment for PLEVs and the one for medical devices. For the latter, there is a requirement that end users be provided with a means of informing the manufacturer when the device malfunctions, and for the manufacturer to log and act on that information. In the USA, the Food and Drug Administration (FDA) operates the Manufacturer and User Facility Device Experience (MAUDE) database which is accessible to medical professionals and end-user members of the public, to log issues that are experienced with medical devices. Exponent made the point that the risk of a public-access database is that the information provided may be of poor or inconsistent quality, but nevertheless, Exponent believe that MAUDE may be a good example of a database for collating data on issues with safety-critical products.

Dyson does not produce PLEV products, and therefore was not in a position to provide information on customer feedback on PLEVs.

9.11 Summary of Stakeholder Consultations and Suggestions

WMG has considered all the stakeholder input, and summarised the stakeholder observations in the table below, in various categories:

Category 1: Collection of incident data	
1.	WMG suggests that collection of data from PLEV fires attended by UK fire and rescue services needs to be improved, to assist with identification of brands and models involved, as well as the circumstances prior to the fire, for example whether the battery had been on charge. The National Fire Data Collection System, intended to go live in the summer of 2024, is expected to help. The impact of this system should be monitored.
2.	WMG suggests that OPSS should consider creating a publicly available online portal, allowing consumers, fire and rescue services, and other relevant parties, to document PLEV thermal incidents.
Category 2: Consumer Guidance	
3.	WMG suggests that advice for consumers, about actions to reduce the likelihood of a PLEV fire, should be targeted at the societal groups found to be most at risk, for example gig-economy courier/delivery riders. This targeting should include translation of the advice into languages most relevant in local areas.
4.	WMG suggests that OPSS should consider increased promotion of the publicly available "product recalls and alerts" database of unsafe and non-compliant products.
5.	WMG suggests that third party testing or certification organisations should consider greater promotion of their publicly available databases of PLEV products which have passed third-party assessment for compliance with specific battery-safety standards. Other stakeholders, including PLEV retailers, trade bodies and safety advocacy organisations should also promote these databases, to encourage public awareness.
Category 3: Enforcement	
6.	WMG suggests that OPSS should consider the development of regulatory powers, to identify and prevent sale of unsafe products. Examples include: • High financial penalties for products that cause fires (e.g. through insurance claims or enforcement procedures). • Legal requirements for product certification by third party notified bodies. • Legal requirements for quality management systems, assessed by third party notified bodies (as seen in the EU Battery Regulation). • Legal requirement to provide UK customer support, such as the means to return faulty products to the vendor at a UK address, including provision of suitably labelled shipping boxes.
Category 4: Legislation	
7.	WMG suggests that the UK government, when developing legislation concerning the right of the consumer to repair a product, or to have it repaired by a third party, should consider restricting these rights when applied to PLEVs containing Lithium-ion batteries. This restriction should also apply to the right to convert a conventional bicycle into an e-bike, using a conversion kit.

Category 5: Standards	
8.	WMG suggests that PLEV shock and vibration standards should consider the reasonably foreseeable case that consumers fit aftermarket parts, such as solid rather than pneumatic tyres, which are likely to significantly change the frequency and magnitude of vibrations and the duration and magnitude of shocks.
9.	WMG suggests that PLEV standards should recognise the fact that existing ingress protection tests only evaluate the product in the brand-new condition. To evaluate possible deterioration of ingress protection over the life of the product, new test methodologies should be considered, for example by introducing a defined moisture content inside the battery casing, and then performing thermal cycling.
10.	WMG suggests that battery electrical tests, including abuse tests, should include measurement of critical component temperatures on the BMS, busbars, cables and housing/structure, to ensure that all components are maintained within their limits, and do not pose a risk of over-heating adjacent Lithium-ion cells.
11.	WMG suggests that an appropriate standard should exist to ensure the safety of conversion kits, including the system-level safety when separate components are combined into a system.
12.	WMG suggests that the discrepancy between voltage markings of chargers and batteries should be eliminated, to minimise the risk of consumer confusion and mistakes
13.	WMG suggests that a standard is required for fire containment / suppression products such as charging bags and fire blankets.
14.	WMG notes that a 2019 European Commission Coordinated Activities on the Safety of Products (CASP) project determined that 80% of products tested were not fully compliant with relevant standards. This suggests that the self-certification regime in the EU (and UK) for PLEVs is insufficient to ensure compliance with standards.
15.	WMG suggests that the UK Government and Standards Bodies should work with international partners to work towards internationally harmonised standards for Lithium-ion battery safety in consumer products. There is precedent for such harmonisation, for example in automotive standards developed under the United Nations as Global Technical Regulations (GTRs).
16.	WMG suggests that the standards for PLEVs, their batteries and chargers should require compliance with an internationally recognised quality management systems standard such as ISO 9001:2015.
17.	WMG suggests that the Standards Bodies should assess the adequacy of ISO 9001:2015, with regard to manufacturer of PLEVs. If necessary, a PLEV-specific standard for quality management systems should be developed, in a similar way that IATF 16949 was developed by the automotive industry.
Category 6: Products to Test	
18.	Regarding e-scooters, there are popular established brand products and cheaper imitations from other brands. The selection of e-scooters tested by WMG should include both, to compare their safety.

19.	Regarding e-bikes, the greatest concern of stakeholders is around conversion kits. WMG should test several conversion kit batteries, as well as batteries from complete OEM-built e-bikes.
Category 7: Test Methodology	
20.	The greatest concern of stakeholders is around charging. WMG's test methodology should examine the ability of the battery to withstand over-charge.
21.	WMG's test methodology should include temperature instrumentation of critical components, to determine whether the component limits are exceeded and whether those component temperatures present a risk of over-heating adjacent Lithium-ion cells.

10 Product Teardown Analysis

The second phase of WMG's investigation of PLEV fires involved the purchase and testing of several products available on the UK market. The purpose of this activity was to provide an engineering critique of the design and manufacturing quality of the products, and then to expose them to test conditions representing the types of reasonably foreseeable misuse that could occur in consumer usage. This section covers the purchase, unboxing and disassembly (teardown) or each product to investigate their shipment packaging, product design and manufacturing quality. Section 11 will cover the testing.

10.1 Products Tested

The criteria for selecting products to be tested were as follows:

- Up to ten product types in total
- Include batteries from OEM e-bikes, OEM e-scooters, OEM replacement batteries and e-bike conversion kits
- Products to span a range of purchase prices, within each product category
- Include some products known to have been involved in real world fires
- If possible, include products from UK and overseas manufacturers

Several sources of information were used to create a list of potential products for testing:

- WMG knowledge of the UK micromobility market
- Stakeholder input (see Section 9)
- OPSS Product Safety Database

Table 45 below lists the products that have been purchased and tested. The rows of the table have been colour-coded by product type. The same colour coding is used in other tables in this report section.

Table 47: PLEV Batteries Purchased and Tested in this Project

#	Product Type	Relative Price	Number Purchased
1	e-scooter (complete)	Low	5
2	e-scooter (complete)	High	5
3	e-bike (complete)	Low	5
4	e-bike (complete)	High	1
5	e-bike Replacement Battery	Low	4
6	e-bike Replacement Battery	High	5
7	e-bike Conversion Kit Battery	Low	5
8	e-bike Conversion Kit Battery	Low	5
9	e-bike Conversion Kit Battery	Low	5

Table 46 below shows the purchase price of each product. Product #4 was purchased as a complete e-bike, and products #5 and #6 as replacement batteries, but all are available as complete e-bikes or replacement batteries. The complete e-bikes are shown in Table 46 as products 4a, 5a, 6a and replacement batteries as 4b, 5b, 6b.

Table 48: Price and Relative Battery Value of Products Purchased

#	Product Type	Purchase Price	Capacity (Wh)	Price per kWh of Battery	Price per kWh High or Low
1	e-scooter (complete)	£258	270-362 *	£713 - £956 *	Low
2	e-scooter (complete)	£400	187	£2,137	High
3	e-bike (complete)	£390	222	£1,757	Low
4a	e-bike (complete)	£599	218	£2,742	Medium
5a	e-bike (complete)	£1399	470	£2,974	Medium
6a	e-bike (complete)	£2199	410	£5,363	High
4b	e-bike Replacement Battery	£280	218	£1,282	High
5b	e-bike Replacement Battery	£385	470	£819	High
6b	e-bike Replacement Battery	£340 **	410	£828	High
7	e-bike Conversion Kit Battery	£230	749	£307	Low
8	e-bike Conversion Kit Battery	£226	523	£432	Low
9	e-bike Conversion Kit Battery	£163	367	£444	Low

* Product #1 has an apparent discrepancy in the battery capacity, see Section 10.3.8

** Product #6 was bought in a sale. The recommended retail price (RRP) is £500.

The fifth column of Table 46 shows the price per kWh (energy) of battery, and the final column ranks these as high or low within each category. Price per kWh is a commonly used metric in the battery industry, as energy is the probably the most valued parameter of a battery for many pure electric vehicles. The energy of the battery translates directly to the range that can be achieved.

For products 1 – 4a, the price includes the whole vehicle (e-scooter or e-bike), so the price per kWh values cannot be compared like-for-like with those for products 4b – 9, which are based on the price for the battery alone.

The key observations from this comparison are:

- The two e-scooters have a 3:1 ratio in price per kWh. These are visually similar products, but product #2 is regarded as an established Asian e-scooter brand, whereas product #1 is regarded as a low-price visually similar alternative.
- The two complete e-bikes have a smaller difference between them, but the more expensive one (product #4) is at the lower price end of the in-house brand e-bike products from a UK bricks-and-mortar store, whereas the cheaper one (product #3) is from an online-only seller.
- The e-bike replacement batteries are approximately 2-3 times as expensive as the conversion kit batteries, based on price per kWh.

Figure 53 below shows the price per kWh plotted against the battery energy. Although the data are quite scattered, they show a general trend for lower energy batteries to have a higher price per kWh. WMG believes that this is likely to be because the price of the BMS, casing and connectors, as well as other costs such as shipping and storage logistics, do not vary greatly with battery energy: It is likely to be similar for a small battery and a large battery. The main variable cost is the cost of the cells. As a result, the overall price per kWh is lower for larger batteries. This partially explains why the lower-energy batteries can appear “worse value”, based on the price per kWh.

Figure 53 also shows a clear difference between the e-bike conversion kit batteries and e-bike replacement batteries: The conversion kit batteries, on average, have higher energy and much lower price per kWh.

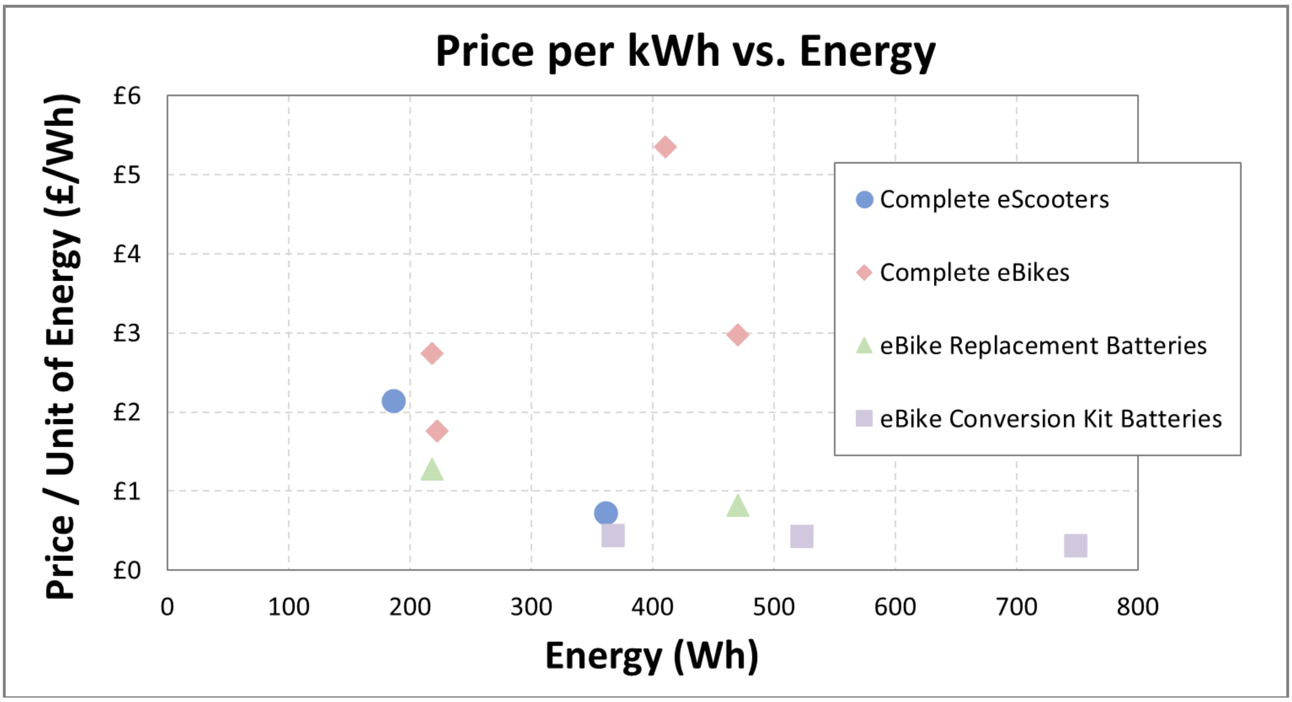


Figure 53: Price per kWh vs. Energy for the Purchased Products.

10.2 Teardown Methodology

Teardown is a process of methodical disassembly, inspection and measurement of a product, to better understand the design, component selection and manufacturing methods and quality. In OEMs, it is an essential part of benchmarking the OEM's own products against competitors.

The purpose of performing teardown in this project is to compare and contrast the design of various batteries, as it relates to their fire safety. The process covers the following:

- Quality of packaging used to ship the product.
- Package labelling, with respect to rules on shipping of dangerous goods.
- Charger labelling and fusing.
- Battery labelling.
- Construction and sealing of the battery casing, regarding water ingress.
- Physical support / location of the Lithium-ion cells.
- Cell-to-cell busbar welding.
- Cell Identity, including a check of whether the cell is UL certified (As far as WMG is aware, the UL certification database is the only one which is publicly available).
- Cell datasheet implications for the battery pack.
- Internal wiring (signal wires and power cables).
- Power-circuit layout, with emphasis on the safety-critical components such as MOSFETs, fuses, diodes. The power-circuit includes all components that deliver current from charge port to the cells, or from the cells to the discharge port.
- Identity and suitability of power-circuit MOSFETs.
- Identity and suitability of and ASICs (Application-Specific Integrated Circuits) and MCUs (Micro Control Units) used to monitor the safety of the Lithium-ion cells.

Within the scope of this project, the teardown has been limited to visual inspection and simple electrical measurements, such as cell voltages and using a multimeter to verify electrical connections on PCBs. The teardown has included visible-light digital photography of the main components and notable features of each battery. As far as possible, the teardown has been non-destructive, but in several cases, some damage has been unavoidable, particularly to the battery casings. Where possible, the example used for teardown has been reassembled for use in later abuse testing.

The project has not involved teardown of individual cells, or any advanced imaging techniques such as CT-scanning. Individual cells have not been removed from the structure, as the busbar welds to the cells make this impossible to do without the use of cutting or abrading tools. Such work would introduce additional hazards, because of the likelihood of damaging the cells, which could leak electrolyte or enter thermal runaway while being handled.

Close-up photography has been used to identify PCB-mounted components, which are often labelled with a part-number and supplier name which are too small to read with the naked eye. Often, the PCB components are covered in a “conformal coating”, intended to protect the components from corrosion by atmospheric moisture. The conformal coating usually obscures the part markings, so has been removed, as necessary, to allow part identification.

Similarly, it is common to find soft, opaque sealants used to cover exposed electrical connections on PCBs and connectors. Where necessary, such sealants have been removed to help confirm electrical connection paths.

In most cases, the cell markings have been sufficiently visible without disassembling the cell stack. In a couple of cases, the structure holding the cells has obscured the markings. To enable the marking to be read, the structure holding the cells has been cut away around one cell.

Where it has been possible to read the part-number and manufacturer name or logo from a component, an internet search has been conducted to find datasheets for these components. The datasheets have not been thoroughly reviewed, but where specific questions have arisen, the datasheets have been used to confirm the specification or functionality of components.

The cell datasheets have been used to document the voltage and current limits defined by the cell manufacturer. During the abuse testing phase of the project (see Section 11), these values have been compared with the limits imposed by the BMS, to check whether the BMS complies with the cell manufacturer’s limits.

Beyond electrical continuity measurements, no other tests (e.g. waterproofing) have been conducted: WMG has relied primarily on visual evidence.

10.3 Teardown Results

10.3.1 Quality of Packaging

All of the products were delivered to WMG by couriers, and all had cardboard outer packaging. No serious concerns were identified with the quality of the packaging, and no significant visible damage had been sustained to any of the packaging.

10.3.2 Package Labelling

Lithium-ion batteries are classified by the United Nations (UN) as dangerous goods for shipping. The UN publishes Model Regulations (United Nations Economic Commission for Europe, Aug 2023) covering the transport of all types of dangerous goods. Under these regulations, each category of dangerous goods has a UN number. Some examples relevant to Lithium-ion batteries are provided in Table 47 below:

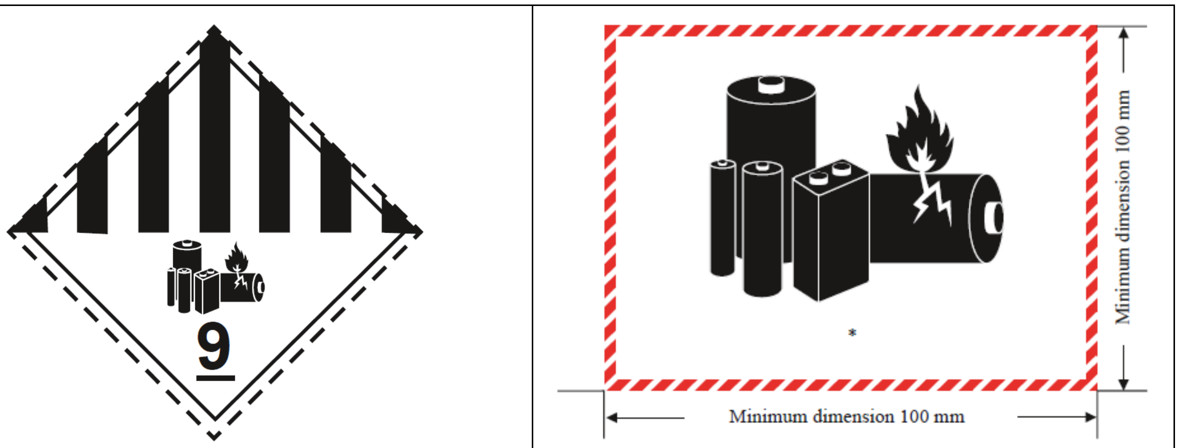
Table 49: UN Dangerous Goods Numbers Relevant to Lithium-ion Batteries

UN No.	Description	Class
3171	Battery-powered Vehicle or Battery-powered Equipment	9
3480	Lithium-Ion Batteries	9
3481	Lithium-Ion Batteries Contained in, or Packed with, Equipment	9
3556	Vehicle, Lithium-Ion Battery Powered	9

UN No. 3556 was only introduced in the most recent revision (rev 23) of the Model Regulations. Prior to that, an e-bike or e-scooter would have fallen under UN No. 3171. It is possible that some of the products purchased in this project were packed and shipped before rev 23 came into effect in December 2022.

All of the categories above fall under “Class 9 – Miscellaneous dangerous substances and articles, including environmentally hazardous substances”.

For each UN number, the Model Regulations define the options for packaging and the requirements for labelling. Since the introduction of UN No. 3556, WMG would expect to see the label in Figure 54(a) on the packaging of a battery or e-bike or e-scooter, and a battery alone (UN No. 3480) or battery with equipment (UN No. 3481) additionally requires the label in Figure 54(b).



(a) Label 9A for Class 9 Batteries

(b) Lithium or Sodium Ion Mark

Figure 54: UN Model regulations Packaging Labels

Prior to the creation of UN No. 3556, e-bikes and e-scooters would have fallen into UN No. 3171, which did not specify such labelling requirements, and only applied to transport by sea or air. However, a battery alone, or a battery with equipment (e.g. with a charger) would still have required these labels.

A summary of the outer packaging labels of the products received is shown in Table 48:

Table 50: Dangerous Goods Labelling on Outer Packaging of Products

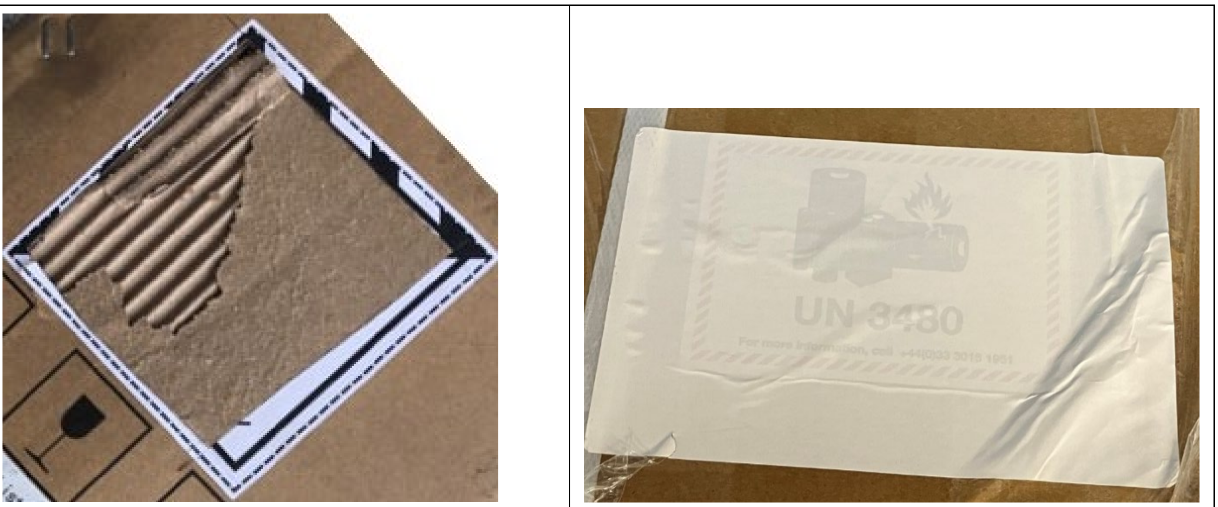
#	UN Number	Class 9 Diamond Label	Lithium-Ion Mark
1	None	Label 9 (non battery-specific)	None
2	UN 3171	Label 9 (non battery-specific)	None
3	None	Label 9 / 9A removed	None
4	None *	None *	None
5	UN 3480	Label 9A	None
6	None *	None *	None
7	None	None	None
8	None	None	None
9	UN 3480 covered up	None	Covered up

* Products 4 and 6 had UN number 3480 and Label 9A on the inner packaging, but this was not visible until the outer packaging was removed.

In addition to the Model Regulations, the UN publishes the ADR (Accord Dangereux Routier) (United Nations Economic Commission for Europe, Jan 2023), which concerns the transport of Dangerous Goods by Road. There are similar documents published by international bodies responsible for rail, sea, and air transport.

In the UK, only drivers who hold and are in possession of an ADR Driver Training Certificate can legally drive a transport vehicle carrying dangerous goods (UK Government, no date). The cost of transport by and ADR certified driver is generally higher than a normal courier cost, because of the additional training and insurance costs that they incur. WMG believes it is possible that some organisations may try to avoid the additional expense by attempting to avoid correct labelling, giving couriers the impression that a package does not contain Dangerous Goods.

This may explain why some of the packages received showed signs that Dangerous Goods labels had been removed or obscured. Figure 55 below shows examples of this.



(a) Class 9 Diamond removed from Product 3 Packaging

(b) UN3480 & Lithium-ion Battery mark covered up on Product 9 Packaging

Figure 55: Examples of removed or obscured Dangerous Goods labels

Equally, it is possible that some dispatchers are unaware of the UN Model Regulations and ADR, and hence fail to label battery packages correctly.

10.3.3 Charger Labels & Fusing

All of the products were supplied with a charger, except for product #4, for which the charger was ordered separately from the same manufacturer. All chargers were CE-marked (some were also UKCA marked).

The charger electrical ratings (mains AC input and charging DC output) are shown in Table 49, along with the mains plug fuse ratings and the battery maximum voltages.

Table 51: Electrical Ratings of the Chargers

#	Charger Mains Rating				Charger DC Rating		Battery Voltage (V)	
	Voltage (V)	**Frequency (Hz)**	**Current (A)**	**Mains Plug Fuse Rating (A)**	**Voltage (V)**	**Current (A)**	**Nominal (label)**	**Maximum ***
1	100-240	50-60	2	3	42	2.0	36	42
2	100-240	50-60	2	13	41	1.3	36	42
3	100-240	50-60	2	13	42	1.5	36	42
4	100-240	47-63	1.4	5	29.4	2.0	24	29.4
5	100-240	50-60	1.2	3	48	2.0	48	54.6
6	100-240	50-60	1.6	3	36	2.0	36	42
7	100-240	50-60	2.5	3	42	3.0	36	41
8	110-240	-	2	13	42	2.0	36	42
9	100-240	50-60	1.4	13	42	2.0	36	42

* Based on the cell maximum voltage multiplied by the number of cells in series

All the supplied chargers have quite a low current rating, equating to a full charge of the battery in between 4 and 8 hours. If these chargers are used, and remain within their stated ratings, then in WMG's opinion they are unlikely to exceed the current ratings of the respective batteries.

The mains plug fuse ratings vary significantly, but this may be legitimate, since the fuse rating should be based on the cross-section of the supply cable and should be used only to protect the supply cable, not to protect the charger. WMG has not checked the cross-section of the supply cables to check that the fuse ratings are appropriate, as this was outside the scope of this work.

Comparing the DC output voltage of the chargers with their respective batteries, it is clear that most manufacturers state the charger DC voltage as the maximum value, equating to the maximum battery voltage. However, two manufacturers (products 5 and 6) state the charger DC voltage as equal to the nominal battery voltage.

In WMG's view, this inconsistency between manufacturers is likely to add to consumer confusion about how to ensure a compatible charger is being used with a particular battery.

10.3.4 Battery Labels

There is little consistency in the labelling used on the batteries investigated in this project. This is likely because of the lack of clarity and consistency in the standards. The latest amendment of the e-bike standard EN15194 requires e-bike batteries to comply with EN50604-1, which provides a list of data and symbols which must be displayed on the battery. However, before the 2023 update to EN 15194, battery labelling requirements were ambiguous at best, because EN 15194 itself contains no battery labelling requirements, and in the original 2017 version, compliance with other battery standards (EN50604-1, EN62133) was an option in seeking to demonstrate compliance with EN 15194.

The current e-scooter standard EN17128-2020, states only that “Information concerning the battery shall comply with existing corresponding standards” and that the battery shall be labelled with output voltage, charging voltage, power and warning on risks.

EN62133-2 requires that batteries shall be labelled as specified in IEC 61960 (BSI Group, Nov 2017). This requires the battery to be labelled with “secondary (rechargeable) Lithium-ion”, the polarity, date of manufacture, name of the manufacturer or supplier, rated capacity and nominal voltage, as well as a “designation” comprising a combination of numbers and letters which specify the number of cells in series and parallel, the chemistry and cell dimensions. For example, product #6 is labelled “10INR19/66-4”, which means it comprises 10 cells in series, 4 in parallel, with cylindrical cells (R) of dimensions of approximately 19 mm diameter, 66 mm long (these are rounded up to the next whole number of millimetres) with a carbon-based anode (I) and nickel-based cathode (N). Products 1, 4 and 5 comply with this designation format.

EN50604-1 does not require such “designation” but does require various graphical symbols and “maximum charge current/voltage and maximum discharge current in Amps/Volts”. In WMG’s view, the latter requirement is ambiguous, as it’s not clear whether both maximum charge current and maximum charge voltage are required or whether the manufacturer can choose between the two. In WMG’s understanding, none of the purchased batteries conforms with the EN50604-1 labelling requirements.

Almost all of the purchased batteries state the capacity (Ah) and energy (Wh). The exceptions are product #8, which states only the capacity and product #9 which provides no battery data on the label. In most cases, the claimed capacity and energy are within a small margin of the calculated values. The exception is product #1. This discrepancy was seen on all examples of product #1 that were purchased. Further comments on this are provided in Section 10.3.8.

Table 50 below shows a comparison between the label values and the values calculated from the cell datasheets. In the cases where the battery label does not provide the data, values from the product online listing have been used.

In most cases, the claimed capacity and energy are within a small margin of the calculated values. The exception is product #1. This discrepancy was seen on all examples of product #1 that were purchased. Further comments on this are provided in Section 10.3.8.

Table 52: Battery Ratings

#	Battery Capacity			Battery Energy (Wh)		
	Label (Ah)	Calculated * (Ah)	Error *** (%)	Label (Wh)	Calculated ** (Wh)	Error *** (%)
1	7.5	10.1	-25%	270	362	-25%
2	5.2	5.2	0%	187	187	0%
3	6.0	6.0	0%	216	222	-3%
4	8.7	8.6	2%	208	218	-5%
5	10.5	10.1	4%	504	470	7%
6	11.0	11.4	-4%	400	410	-3%
7	20.0	20.8	-4%	720	749	-4%
8	15.0	14.3	5%	540	523	3%
9	10.0	10.2	-2%	360	367	-2%

* Calculated as the cell datasheet value multiplied by the number of cells in parallel

** Calculated as the cell datasheet value multiplied by the total number of cells.

*** Errors are shown as positive where the label appears to overstate the capacity / energy, and negative where the label appears to understate the value.

10.3.5 Construction and Sealing of the Battery Casing

The two e-scooters share similar chassis designs, with the battery located under the footplate of the e-scooter, protected on each side by the metallic chassis structure, and accessible from the underside by a screw-on unsealed cover. With the cover removed, product #2 has a battery that is in a moulded plastic box, which appears likely to be water-tight, whereas product #1 has a battery wrapped in a shrink-wrap material. However, examples of product #1 bought a few months later had a construction more like product #2, with a sealed plastic box.

The two complete e-bikes have very different construction. Product #3 has an irremovable battery, built into a plastic box that is bolted to the e-bike frame. This box is clearly not waterproof, having large gaps around cables passing through the box (see Figure 56), and neither was the shrink-wrapped battery within the box. Product #4 is based on a non-electric bicycle, with a conventional diamond-shaped frame. The manufacturer / retailer makes an e-bike version of the bicycle by fitting a hub-motor to the front wheel and a battery in the shape of a drinks bottle, attached to the frame in the same position as a bottle cage. It is likely that some other changes have been made to ensure compliance with the e-bike legislation and standards, together with validation testing, which clearly differentiates this from a DIY conversion kit. Although this e-bike is at the lower end of the price range from this manufacturer / retailer, the battery has a superior construction to the one in product #3. The battery in product #4 has an extruded aluminium tube and moulded plastic ends, with compressible seals between the three parts. Compressible seals, usually moulded from a rubber-like material, are able to conform to small irregularities in the surfaces of the two mating parts of a casing, thereby minimising the occurrence of gaps where moisture can penetrate. They may also be re-usable, meaning that the quality of sealing would not be compromised by disassembly and re-assembly. This type of seal is therefore likely to provide good waterproofing.

The e-bike replacement batteries have similarly good construction, but with plastic casings. Product #6 has a compressible seal between the two halves of the casing and is likely to be waterproof. Product #5 does not have a compressible seal, but the two halves of the casing have a thin layer of adhesive between them that is likely to at least provide some protection from water ingress.

Each of the three conversion kit batteries has no compressible seals between the parts of the casing. Product #7, like product #3, has large gaps around cables passing through the box, meaning that water ingress is likely.

In general, the trend is that the higher priced products have superior housing construction and sealing.

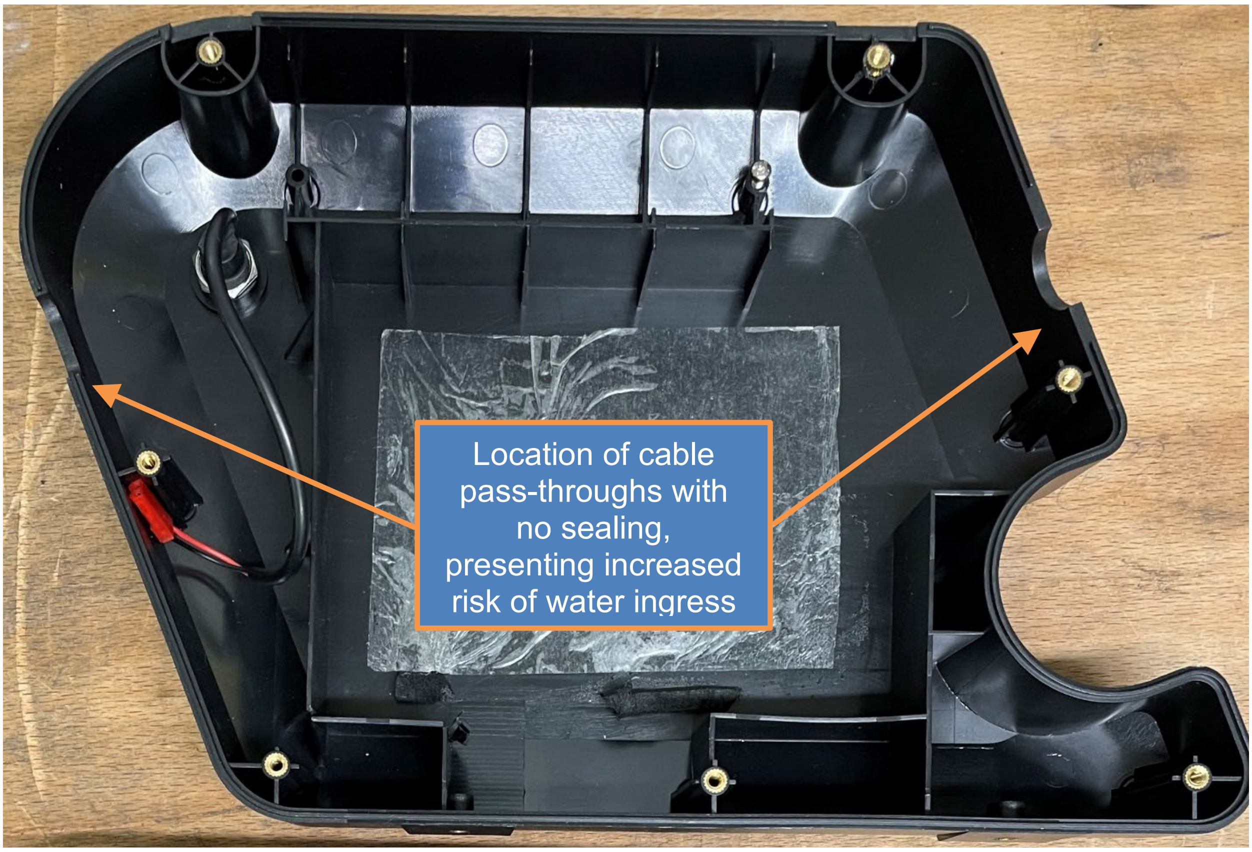


Figure 56: Half of the Battery casing from Product #3, showing holes for cables with no sealing

10.3.6 Physical support / location of the Lithium-ion cells.

All but one of the products have plastic mouldings to hold the cells in a fixed position relative to one another. The exception is product #3, in which the cells are only secured to one another by the busbars, with no other structure present other than cardboard and shrink-wrap around the block of cells. With the latter removed, modest manual force applied to the block of cells caused obvious distortion. This design means that the inertial forces on the cells, caused by shock and vibration, are transmitted only though the busbars and through direct contact between the cells which have little or no gap between them.

In WMG's view, it is not good practice to pass mechanical loads through the busbars, because this is likely to place excessive stress on the busbar-to-cell welds that may lead to premature weld failure, which could lead to resistive heating and cell failure.

In the examples that use plastic mouldings to locate the cells, the quality of execution varies. In most cases, the moulding is in two parts, one supporting each end of the cells. In WMG's view, the best example is product #6, wherein the plastic mouldings secure the cells axially by overlapping the ends of the cells, and the two plastic mouldings are secured to each other to form a single semi-rigid structure, which minimises the mechanical loads on the cells (see Figure 57).

The two plastic mouldings are bolted together to form a semi-rigid structure.

The plastic mouldings support the cells over a broad area, likely with an internal taper to ensure good radial contact.

The plastic mouldings have protrusions which engage with features on the battery casing, to prevent movement of the cell block.

The two plastic mouldings overlap the ends of the cells, to locate them axially as well as radially.

Figure 57: The Cell Support Structure in Product #6

In other examples, the two plastic mouldings are only joined to each other by the cells themselves. Figure 58 shows Product #1, where the plastic mouldings do not overlap the ends of the cells, and a bead of adhesive has been applied between the plastic mouldings and the insulation sleeves around the cells. This means that the axial loads are being transmitted via shear of the insulation sleeves, which risks damage to the sleeves from prolonged shock and vibration. The sleeve material is ill-suited to transmit mechanical shear loads. Its main purpose is to electrically insulate the cell to prevent inadvertent short-circuits, particularly during battery pack assembly.

The support structure may also play a key role in aligning the cells prior to placement and welding of the busbars. In Product #6 (Figure 57), the accurate axial and radial location of the cells minimises any misalignment that may affect the busbar welding. By contrast, in Product #1 (Figure 58) the absence of axial alignment from the plastic mouldings means that a separate tooling fixture would be required during assembly, to ensure axial alignment prior to busbar welding.

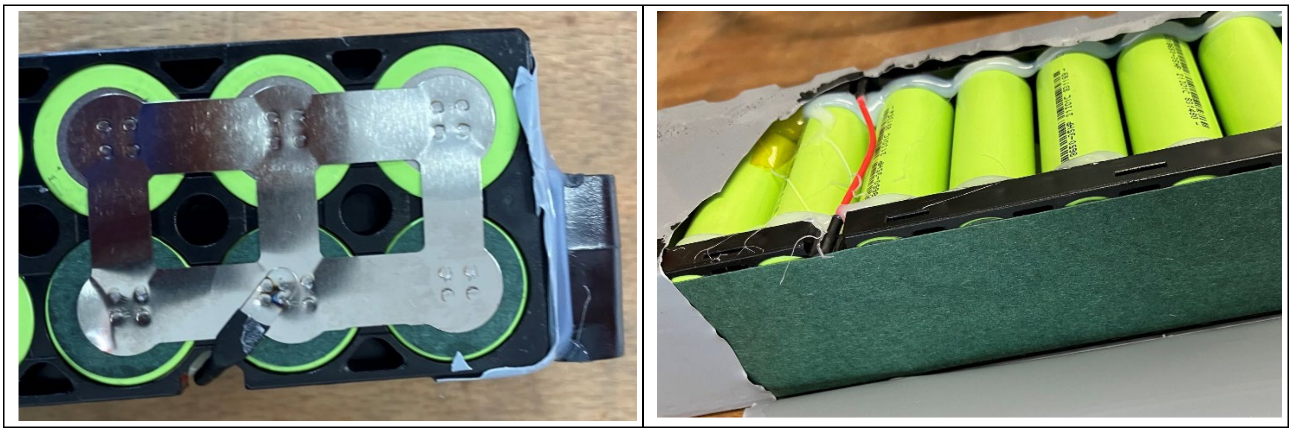


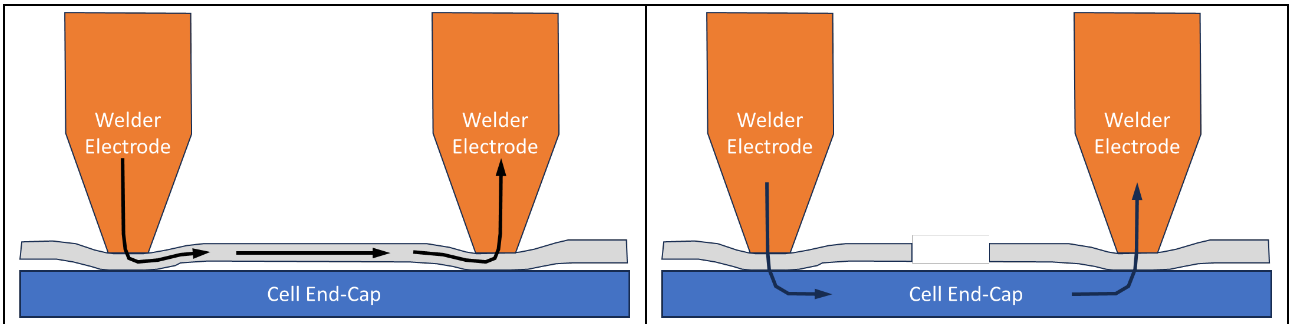
Figure 58: The Cell Support Structure in Product #1

These issues are perhaps somewhat peripheral to the fire-safety theme of this report but are illustrative of differences in engineering rigour in the design and manufacturing process, which may also affect the approach to fire safety.

10.3.7 Cell-to-cell Busbars and Welding

In all of the products purchased in this work, the busbars are welded to the cells, using spot-welding. In this manufacturing process, the busbar is placed on to the cell, and then two electrodes of the welder press down on to the busbar, to achieve a firm mechanical contact between the busbar and the cell end-cap. Then a pulse of high electrical current is passed between the electrodes, via the busbar and cell. This current pulse is sufficient to locally melt the material of the busbar and cell, achieving the fusion weld of the two parts.

For the spot-welding process to be effective, the current must pass through the cell end-cap. To ensure this, there should be a slot in the busbar between the welder electrodes, such that the current does not simply pass through the busbar alone, bypassing the cell end-cap (see Masomtob et al., 2017), as illustrated in Figure 59.

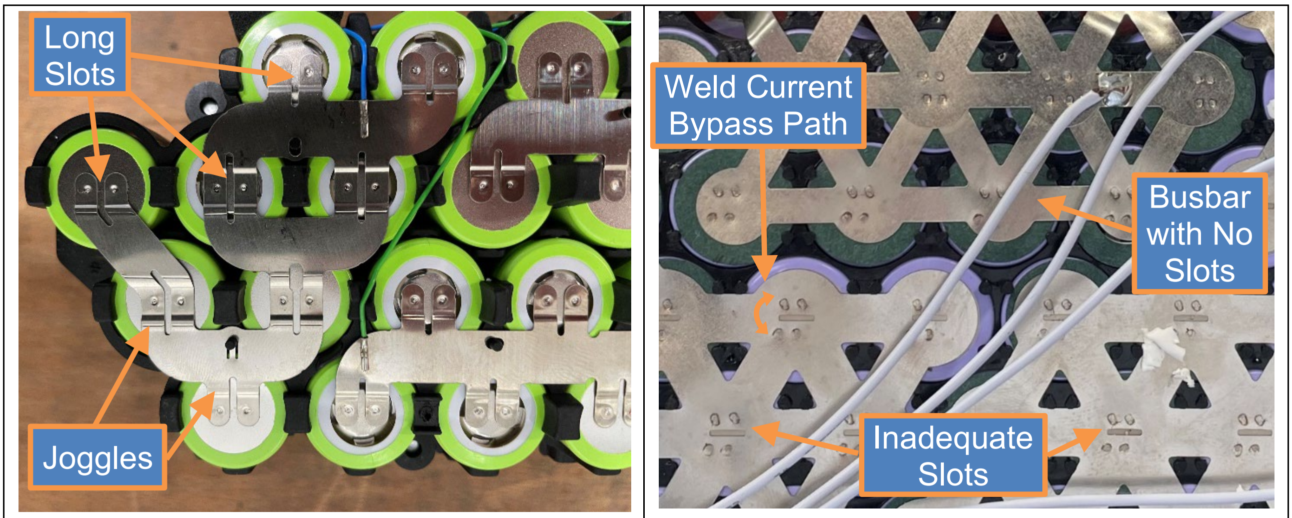


(a) Without a slot, current bypasses the cell end-cap, through busbar

(b) With a slot, the current is forced to pass through the cell end-cap, thereby achieving the weld between the busbar and end-cap

Figure 59: Cross-Section of a Spot-Weld Process, to Illustrate why Busbar Slots are Preferred for a Successful Spot-Welding

The slots should be sufficiently long that any path through the busbar around the ends of the slot is too long to experience any significant current. Figure 60 shows good and poor examples. Figure 60(a) shows the busbars in Product #6, which have long slots and a single weld (two spots) per cell, located symmetrically around the centre of each cell. Figure 60(b) shows those in product #7, in which there are two welds (four spots), but these are not consistently positioned, and the busbar slots are not long enough to avoid some of the spot-weld current bypassing around the slots. It can also be seen that one of the busbars has no slots at all, which may result in poor welds.



(a) Product #6: Good design practice, with a long slot between the welder electrode positions

(b) Product #7: Poor design & manufacturing, with insufficiently long or completely absent slots

Figure 60: Examples of Busbar Welds from Products #6 and #7

In Figure 60(a) some other features are also worth noting:

- The busbars are deliberately not flat: There is a joggle in the busbars, adjacent to each weld. This provides two benefits:
  1) It avoids the risk of the busbar shorting between the positive centre and negative shoulder of each cell. In other batteries with flat busbars, it is necessary to add insulator disks under the busbars (dark green in Figure 60(b)).
  2) It provides stress-relief to mitigate thermal expansion that occurs when busbars heat up, which could impose excessive mechanical stress on the cell welds.
- At the location of the spots of the spot-weld, the busbars are dimpled downwards. This means that the busbar is only in contact with the cell at the position of the spot weld. This acts to concentrate the spot-weld current more locally, allowing for more consistent weld quality, and potentially allowing for a lower weld current.

In most of the products purchased, the busbars were stamped metal, with various shapes according to the layout of the cells in series and parallel. However, in two of the products, #1 and #8, some or all of the busbars were simply cut from standard strips of metal.

The clearest example of inconsistent welding is product #8, shown in Figure 61. Here, the complex busbar shapes have been achieved by cutting metal strips and overlaying them, spot-welding them one at a time. The individual strips do not have slots to ensure good weld penetration, and the process results on welds on top of welds. This is poor practice, because the first weld causes distortion of the first busbar, such that it is not flat, so the second weld is less likely to be successful because of poor contact between the two surfaces.

Figure 61 also clearly shows that the positioning of the welds is inconsistent: The welds have likely been performed manually, rather than by a robot. The number of spot welds made on each cell appears to vary between two (on a cell that only has one strip of metal welded to it) to five or more. In some cases, it is not possible to make a precise count, because of the overlapping busbars.

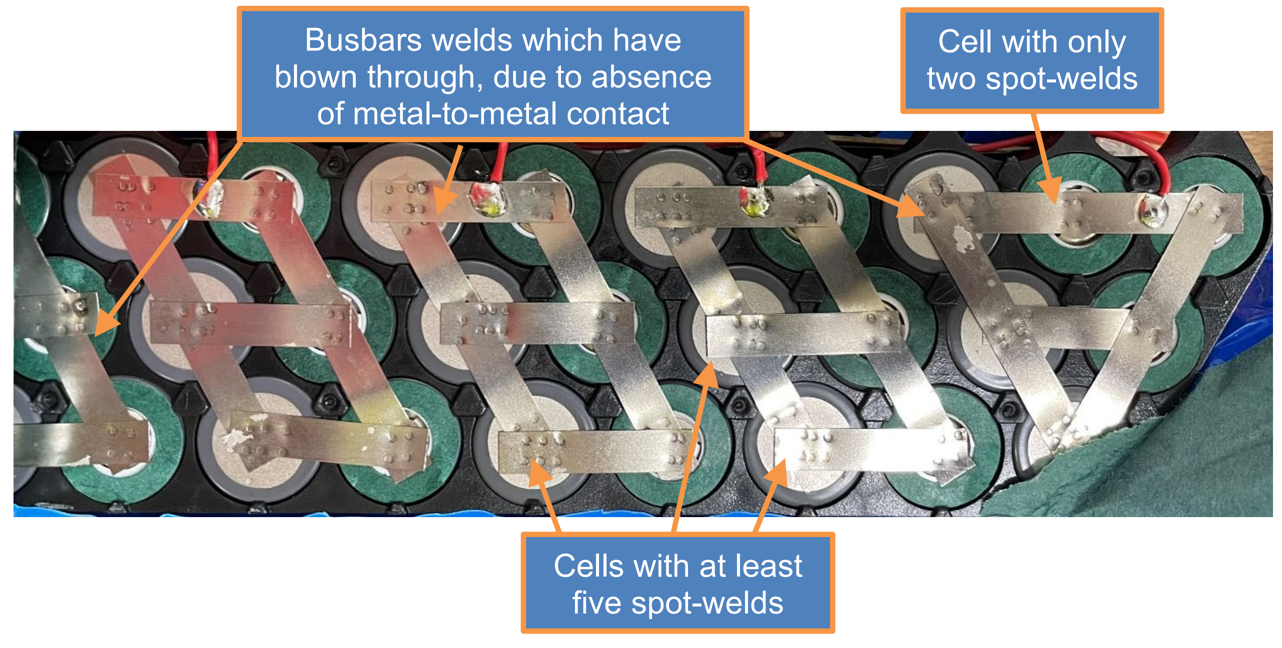


Figure 61: Cell-to-cell Busbars in Product #8

Figure 62 shows the busbars in Product #9. All four spots of the busbar weld to one cell have been broken. This damaged was caused simply by removing the adhesive-backed thin plastic sheet which covered the busbars, indicating that the welds were weaker than the adhesive, which was easy to peel off by hand. The minimal area of the weld to the cap at the top of the cell can be seen. These symptoms may be indicative of insufficient weld penetration into the cell cap, possibly due to poor weld machine set-up. Such welds may be susceptible to resistive heating and also breaking during operation, when subjected to shock and vibration.

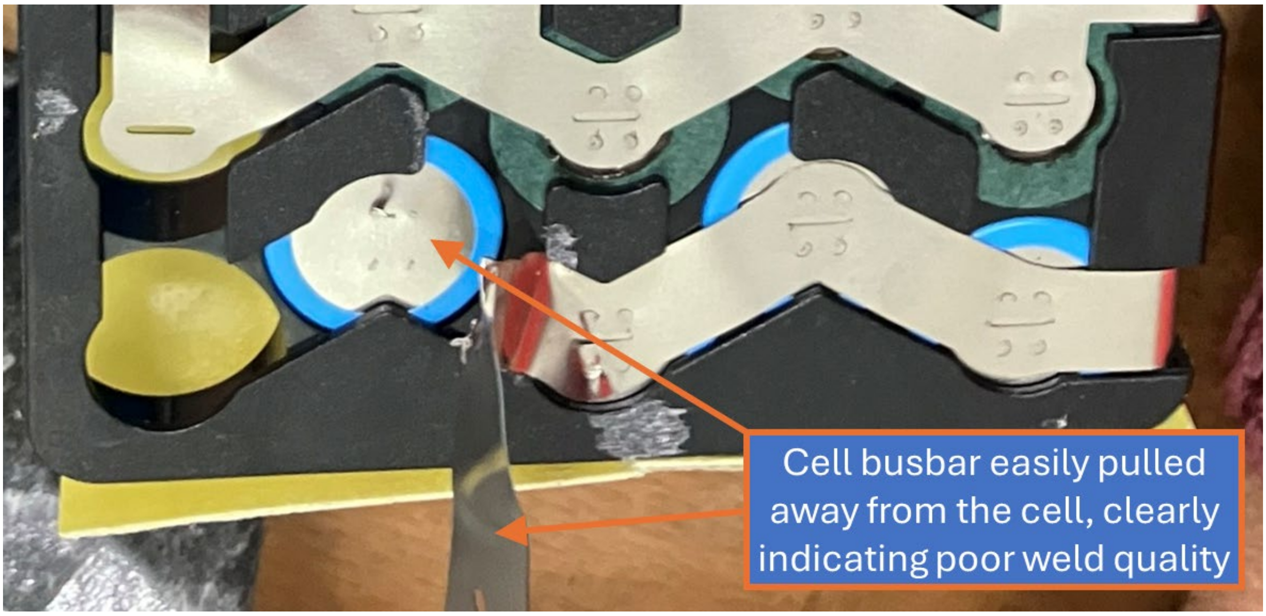


Figure 62: Damaged Busbar Weld of Product #9

The concerns with the design and manufacturing approach shown in Figure 61 are:

- Inconsistent weld quality. Poor welds can lead to hot spots, where the operational current results in locally excessive heat generation, due to the high electrical resistance of a poor weld. This heat can then be conducted back into the cell, potentially causing premature ageing, and in the worst case, thermal runaway. Inconsistent welds cause differences in the electrical resistance path through each cell, so can result unequal current distribution between parallel cells.
- Poor durability. A poor weld may fracture as a result of shock and vibration, and the mechanical stress caused by thermal expansion which can be exacerbated by the hot spots mentioned above.
- Heat damage to the cells during assembly. The end-cap material of the cell is thin (typically < 0.5 mm). The weld process parameters must be selected to ensure that the material melts sufficiently to fuse the busbar to the cell, but not so much that it causes a hole in the busbar or end-cap. The end-cap is part of the hermetically sealed container that prevents moisture ingress and electrolyte leakage, so any hole in the end-cap risks such failure modes. When multiple spot-welds are applied in rapid succession, the cumulative heating increases the risk of such damage. This may not be easily detectable visually.
- Melting of busbars, resulting in spatter of molten metal. In Figure 61, there are three welds where one spot is located where there is no contact between the upper busbar and either the underlying busbar or the cell. The result is a hole in the upper busbar, with localised scorch marks where the molten material has spattered. This material could cause issues such as short-circuits or heat damage to plastic parts.

When a product is manufactured in significant quantities, there is a strong requirement for consistent quality, which requires repeatability in every aspect of the product, such as the material of the busbars, their geometry, and the location, number and process parameters of each weld. The greater the variability, the greater the likelihood of undesirable outcomes. In batteries, the worst-case outcome may be thermal runaway.

If a busbar becomes detached from a cell, the implications can vary:

- Intermittent busbar-to-cell contact can result in arcing, which can damage the cell.
- If a parallel connection is broken, but the series connections of all cells remain intact, over time the affected cell will become out of balance with the cells with which it should be connected in parallel. The BMS will be unable to measure the voltage of one of more of these parallel cells, and also unable to balance them, but all cells will remain actively used in charge and discharge. Since the cells will become imbalanced, there is a high risk, increasing over time, that certain cells will become over-charged or over-discharged, potentially leading to thermal runaway.
- If a series connection of a cell is broken, then it will no longer be charged or discharged. The pack current will then be shared between fewer cells. For example, if the pack has four cells in parallel (4P), and one cell is disconnected, then the current will pass through only three cells. This increases the current per cell. Diagnosis of such a breakage requires sophisticated BMS software, calibration and validation during pre-production testing. If the BMS is unable to diagnose such a fault, it is likely to result in cell current limits being exceeded, which could lead to thermal runaway. It also reduces the effective capacity of the pack. In the case of a 4P pack that loses one cell, the capacity will be reduced by 25%, so the riding range will be reduced by a similar amount.

The quality of busbar-to-cell welds is summarised in Table 51:

Table 53: Busbar to Cell Weld Quality for Each Product

#	Style of Busbar	Busbars slotted for cell welds?	Are slots judged adequate?	Consistent Spot-Weld Positions?	Number of welds (pairs of spots) per cell	Weld failure seen ?
1	Combination of Bespoke Stamped and cut from strip	No	No	Yes	2	No
2	Bespoke Stamped	Yes	Yes	Yes	2	No
3	Bespoke Stamped	Yes	No	No	2	No
4	Bespoke Stamped	Yes	Yes	Yes	2	No
5	Bespoke Stamped	Yes	Yes	Yes	2	No
6	Bespoke Stamped	Yes	Yes	Yes	1	No
7	Bespoke Stamped	Yes (1 unslotted)	No	No	2	No
8	Cut from Strip	No	No	No	2 to 6	No
9	Bespoke Stamped	Yes	No	Yes	2	Yes

In summary, the poorest busbar-to-cell weld quality is seen in the e-bike conversion kit batteries and the low-price complete e-bike and e-scooter. The more expensive products all have busbar-to-cell welds that WMG would judge to be of higher quality, based on visual inspection. A full analysis of weld quality would require mechanical testing, weld sectioning and microscopy, which is beyond the scope of this project.

10.3.8 Cell Identity, Certification

All the purchased products use small cylindrical cells. Most use the 18650 size (18 mm diameter, 65 mm length), while Product #8 uses the 21700 size (21 mm diameter, 70 mm long).

In all cases, the cells are individually wrapped in a polymer shrink-wrap, which provides electrical insulation. This is mainly to prevent inadvertent short-circuits during handling of the cells and battery pack assembly. Printed on the polymer wrap are identifying markings, comprising text, and sometimes a bar-code or QR-code. The latter are intended for automated scanning by the manufacturer, so could not be used by WMG. Therefore, identification of the cells relied on the alphanumeric text markings.

In general, the alphanumeric markings, combined with the colour of the polymer wrap, are sufficient to identify the manufacturer and model of the cell (although wrap colour is the less dependable of the two factors). Where possible, the appearance of the markings has been compared with an image of the cell on the manufacturer's website to increase confidence in the identity, and the datasheet has been obtained, either from the manufacturer or from a third-party vendor website. The datasheet values for charge and discharge current limits have been used in the testing phase of this project, to ascertain whether the BMS in each battery abides by the cell manufacturer's operating limits.

It is beyond the scope of this project to perform cell-level testing of any kind. However, many cells undergo third-party testing, which provides a good proxy to provide confidence in the cell. UL Solutions (formerly Underwriters' Laboratory) is one of several global organisations who provide product certifications and third party testing across a wide range of product sectors, including cells. Their certification process involves rigorous testing of the cells and regular audits of the factories that produce the cells. UL provides a publicly accessible database, searchable to confirm whether cells are certified by UL.

Table 52 below provides a summary of the findings.

Table 54: Summary of Cell Identities and Certifications

#	UL Certified? (assuming cell correctly identified)	Confidence in identifying cell	Comments
1	Yes	Low	Discrepancy between battery and capacity. Mismatch of cell sleeve vs. internet images.
2	Yes	Medium	Discrepancy in marking appearance between manufacturer images and vendor images.
3	No	Medium	Manufacturer website provides no data or image. Reliant on vendor websites & datasheet in Chinese.
4	Yes	High	Good match to internet sources
5	Yes	High	Good match to internet sources
6	Yes	High	Good match to internet sources
7	Yes	Low	Discrepancy between cell marking model & capacity vs. manufacturer data
8	Yes	Low	Cell appearance does not match internet sources. Cell has been discontinued by manufacturer.
9	Yes	High	Good match to internet sources

There is a strong correlation between the ranking of the price per kWh (see Table 46) and the confidence in the cell identity: In general, the confidence in the cell identity is highest for the higher priced products. However, there are exceptions, such as product #9, which has a low price per kWh, but high confidence in the cell identity.

Based on the analysis above, the high confidence in cell identity (products #4, #5, #6 and #9) also correlates with widely known, established cell suppliers such as Samsung and EVE Energy (companies that supply cells to Western automotive manufacturers), whereas the lower confidence (products #1, #2, #7 and #8) correlates with lesser-known suppliers such as SinoWatt and CHAM.

The main implication of low confidence in the cell identity is that the UL certification of the cells is more questionable. The UL certification provides confidence that the cell type has been third-party tested according to the UL safety standards.

The greatest discrepancy of all the cells in the products tested is for Product #1. The internet product listing for this e-scooter claims that the battery capacity is 10.5 Ah. The markings on the cell agree with this: The cell nomenclature indicates a 3.5 Ah capacity, and the battery has three cells in parallel, which would result in a battery capacity of 10.5 Ah. However, the label on the battery itself states that the capacity is 7.5 Ah, 28% less than advertised.

Within this project, WMG has not performed accurate capacity measurements on any of the batteries or cells, because the capacity is not directly relevant to safety. However, during the course of the abuse tests, various discharge tests have been performed that approximate to a discharge capacity test. Of the eight products that underwent abuse testing, an estimate of capacity could be made for six of them, see Table 53:

Table 55: Comparison of Capacity Claimed, Calculated and Estimated from Testing

#	Claimed Capacity	Capacity Calculated from Cell Data *	Capacity Estimated from Testing	Does testing estimate match claim?
1	10.5	10.1	7.5 – 8.0	No
2	5.2	5.2	4.9 – 5.2	Yes
3	6.0	6.0	5.0 – 6.0	Yes
4	8.7	8.6	8.6 – 9.1	Yes
5	10.5	10.1	-	-
6	11.1	11.4	-	-
7	20.0	20.8	20 – 24	Yes
8	15.0	14.3	-	-
9	10.0	10.2	9.4 – 10.1	Yes

* Assuming the cell has been correctly identified

Product #1 is the only one for which the capacity estimated from the abuse tests was significantly different from the advertised capacity. The value estimated from testing is 7.5-8.0 Ah. This correlates more closely to the capacity stated on the battery label (7.5 Ah) than to the capacity (10.5 Ah) advertised on the manufacturer’s website or the capacity implied by the cell nomenclature (10.1 Ah). This raises the possibility that the cell marking is misleading, and that the actual capacity is significantly less than the advertised capacity. This could either be because a different cell type has been used, or because the cells used have already undergone substantial ageing, for example if they are second-hand. WMG was not able to determine which of these is the case. This in turn means that customers are potentially receiving less value and a less capable product than they may expect from the manufacturer’s website.

The discrepancy in capacity does not directly imply any safety concern. On the one hand, lower capacity cells tend to have slightly less severe thermal runaway than higher capacity cells of the same size. On the other hand, for a given pack power and current, lower capacity cells will be operating at a higher C-rate, which could increase the risk of exceeding the cell current limits, particularly if the owner increases the discharge power by fitting a different motor, or increases charging power by using an aftermarket charger. However, the discrepancy does mean that the identity of the cell is uncertain, and hence the certification status of the cell is also uncertain.

10.3.9 Cell Data Implications for Battery Pack

This section presents cell datasheet values, and their consequences for the battery pack, on the assumption that the cell identity, discussed in Section 10.3.8, is correct.

The cell datasheets typically provide minimum and maximum cell voltage and maximum charge and discharge current. When WMG is testing cells, it regards any operation outside of the datasheet values as abuse testing and takes appropriate precautions in light of the elevated risk of such testing.

The current limits are generally specified for various temperature ranges, but the approach is far from consistent between cell datasheets. This makes comparison between cell datasheets challenging. However, a battery pack supplier should always abide by the cell datasheet limits in the pack application, unless they have reached an agreement with the cell supplier to permit them to use different limits.

Typically, the cell current limits are based on either safety requirements or durability / longevity requirements, or a combination of both. In some cell datasheets, different limits are specified, depending on whether longevity is a key consideration in the application. However, sometimes the limits with and without longevity considerations are not specified over the same temperature ranges. For example, the cell datasheet for Product #2 provides charge current limits “For cycle life” in four temperature zones between 0-45 °C, and a higher “Not for cycle life” limit for 25-45 °C. This creates some difficulties in interpretation. In this report, WMG has selected the “not for cycle life” current limits, where available, since this report is concerned with safety, not with longevity.

Figure 63 compares the charging C-rate limits in the cell datasheets for all nine products. All of them specify that charging can only occur in the range 0-45 °C, except for product #7, for which no complete datasheet was found. The dotted lines are for cell datasheets that only specify a single charge-rate limit, with no temperature zones defined.

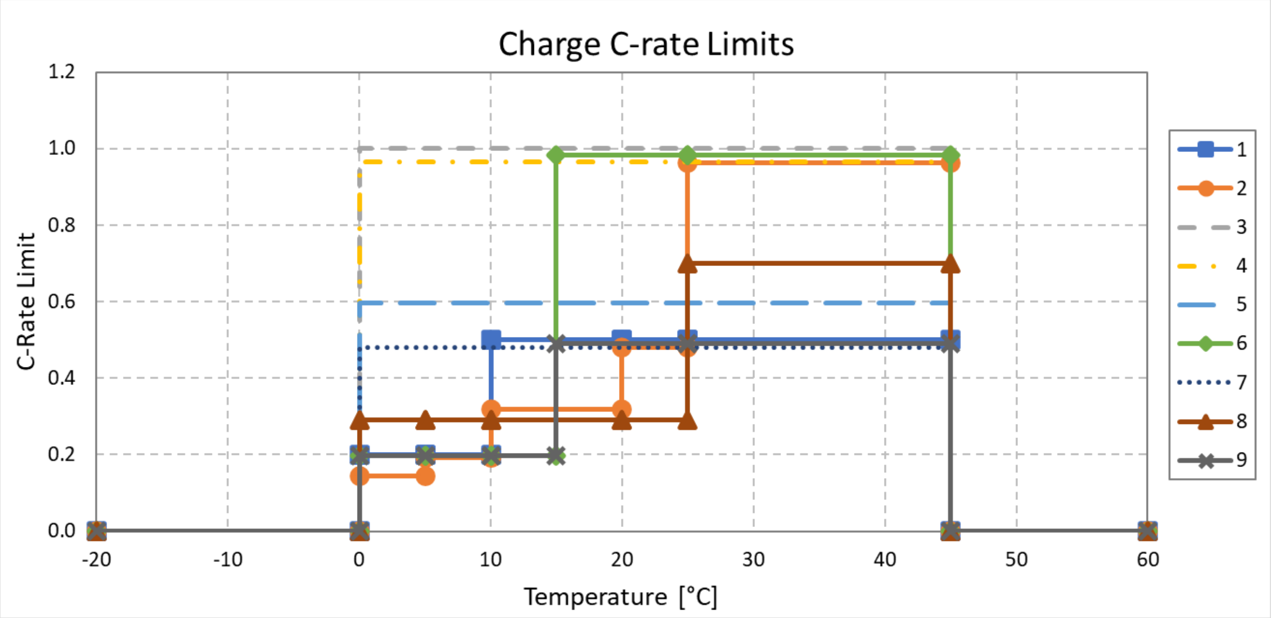


Figure 63: Charge C-Rate Limit Comparison based on Cell Datasheets

It is clear from Figure 63 that the approach to temperature zones differs markedly between cell manufacturers. The most detailed cell datasheet, for product #2, specifies different current limits in four temperature zones between 0 and 45 °C. Other cells specify only two temperature zones, with the temperature breakpoint between low and high charging current limits varying between 10 and 25 °C.

The implication of this variety, particularly the datasheets that have only a single charging current limit, is that either the cell supplier has supplemental information, which is not stated on the publicly available datasheet, but should be provided to their customers, or that some cell suppliers appear to believe that there is no detrimental effect of high-rate charging at low temperatures. In general, this is well known to be a cause of lithium-plating on the anode, and potentially growth of lithium dendrites which can pierce the separator between anode and cathode, thereby causing short-circuits within the cells.

Cell suppliers employ a variety of methods to minimise the risk of lithium plating and dendrites. It is to be expected that different cells will have different C-rate limits, but in WMG’s view it is somewhat concerning to see a cell datasheet that provides only a single charge-rate limit between 0 and 45 °C, particularly if that rate is relatively high, as in the case of the cells for products #3 and #4. It is possible that the suppliers would provide more detailed charge-rate limits if asked, but it is far preferable to provide the detail in the standard cell datasheet. Annex A (normative) of EN 62133-2, the standard for portable batteries, goes into some detail to guide cell suppliers on this topic, as discussed in Section 7.9.1 of this report.

Figure 64 compares the discharge C-rate limits in the cell datasheets for all nine products. Discharge current is less of a safety issue than charge current. Only two of the cell datasheets, for products #2 and #8, provide discharge current limits that vary across the operating temperature range. Most of the cell datasheets permit discharge between -20 and 60 °C, which is almost twice the range permitted for charging. The peak discharge current permitted is also much higher: A C-rate of 2 – 4, compared to 0.5 – 1 for charging.

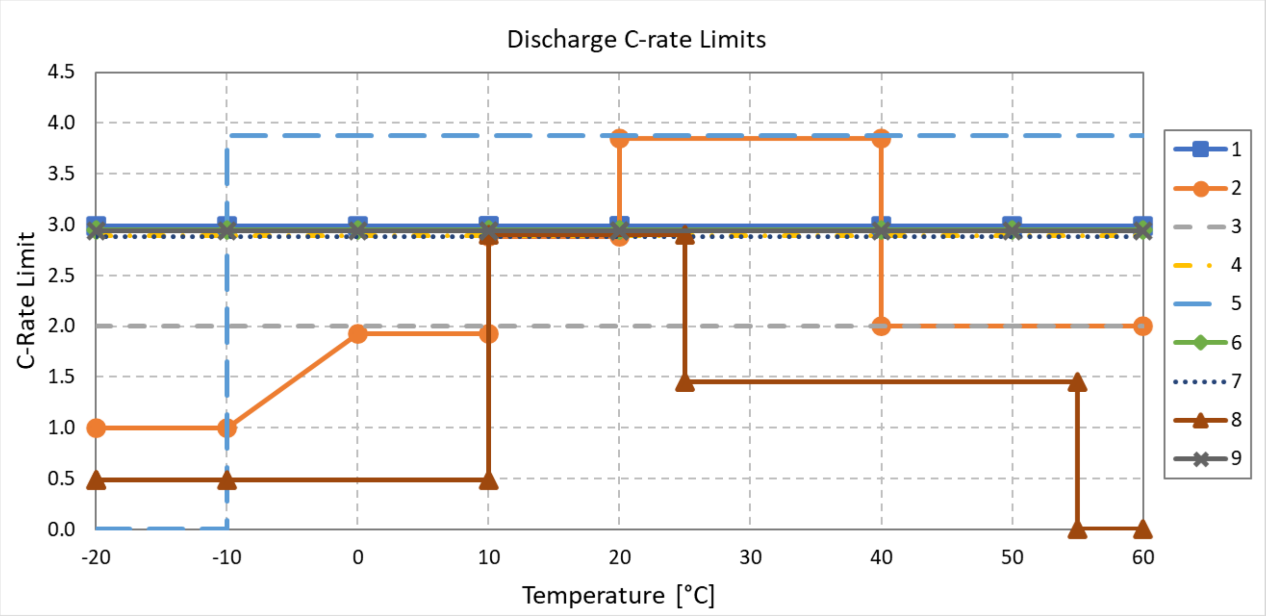


Figure 64: Discharge C-Rate Limit Comparison based on Cell Datasheets

Although discharging current does not pose a risk of lithium plating or dendrite formation, the higher discharge rates generate much more heat within the cell, so the main risk in discharge is over-heating. This leads to accelerated ageing, and if the cell is put on charge while it is hot, that may contravene the maximum safe charging temperature.

As with the charge limits, it is important that the battery pack ensures that the cell datasheet limits are not exceeded. This will be examined further in the abuse testing phase of this project.

10.3.10 Internal wiring (signal wires and power cables)

The internal wiring of the battery comprises two main categories:

- Signal wires, which carry minimal current. This includes the voltage sensing signals from each group of parallel-connected cells, and the thermistor wires, to the BMS.
- Power cables, which carry the charge and discharge current for the entire pack.

All of the purchased products have voltage sensing on every group of parallel-connected cells, which is an essential part of Lithium-ion battery safety. Two approaches to voltage signal wiring are seen:

- In products #3, #4, #6, #7 and #8, a wire is joined to each cell-to-cell busbar, with all wires leading to a single connector which plugs to the BMS.

- In products #1, #2, #5 and #9, each busbar is joined directly to the BMS. In these products, the BMS board extends along one entire side of the battery, to allow each busbar to be joined to a connection along the edges of the BMS board.

The second of these approaches is arguably the simpler and more elegant solution, involving fewer connections, but it also has disadvantages:

- The BMS PCB is typically several times larger than is necessary to house the BMS components. This may increase the cost of the BMS.
- The BMS is not replaceable, because the direct connections from the busbars to the BMS cannot be un-joined. Therefore, repairability is significantly reduced.

The first of these approaches results in significant lengths of wire which, if unrestrained, could cause unwanted loads on the joints at each end of the wires during shock and vibration, and could chafe on sharp edges. The relevant battery standards provide the following guidance:

- EN 62133-2 §5.2 advises that “solder alone is not considered a reliable means of connection”.
- EN 50604-1 requires that “In connections by soldered terminations, the conductor shall be held in position additionally to the soldering to maintain it in position”.

In products #3, #4, #7 and #8, the only features to restrain the wires between the soldered busbar connections and the BMS connector are adhesive tape or cardboard, which are unlikely to be durable. In products #6, the voltage sense wires are restrained at frequent intervals, using clip features on the plastic mouldings that locate the cells, see Figure 65:

Figure 65: Voltage Sense Wire and Thermistor Wire Restraining Features in Product #6

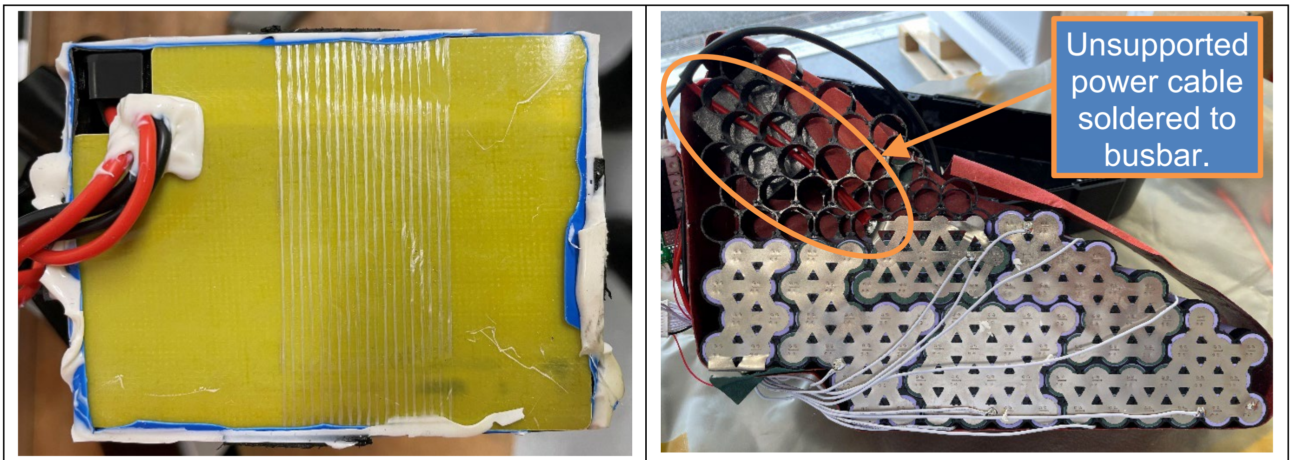
Regarding the power cables, all of the products use conventional cables to transmit the battery power between the cell-block / BMS and the connectors on the external casing. In most cases, there is significant slack length in these cables, to facilitate final assembly and closure of the casing. This presents a risk of chafing and fatigue to joints, particularly solder connections on the BMS board.

In general, the higher-priced products show greater evidence of efforts in design and manufacture to protect the cables, such as sleeving over the cables to prevent chafing, or minimising the cable lengths to reduce the potential for the cables to move around in use.

The lower priced products, particularly the e-bike conversion kit batteries, have more slack unsupported length in the cables, and show less evidence of additional measures to reduce the load on solder joints.

Cable chafing or failure of solder joints presents a risk of short-circuits. In some of the products, fuses are included to protect against short-circuits (see Section 10.3.11), but in some cases, the location of the fuses means that they will protect only against external short-circuits, not against shorts of the internal cables.

Examples of poor practice in the routing and protection of cables are shown in Figure 66:



(a) In product #9, the power cables are routed past the sharp edge of a plastic sheet, with only silicone sealant holding them in place

(b) In product #7, the voltage sense wires are unrestrained, and the power cable is supported only by the solder joint to the positive busbar.

Figure 66: Examples of Poor Cable Routing in Conversion Kit Batteries

10.3.11 Power Circuit Layout, including MOSFETs, Fuses and Diodes

Figure 67 shows a generic schematic layout of the power-circuit in PLEV batteries. The products investigated in this project broadly follow this layout, although the details differ between them. For example, not all of them have charge or discharge fuses. The purpose of each of the major components is explained below:

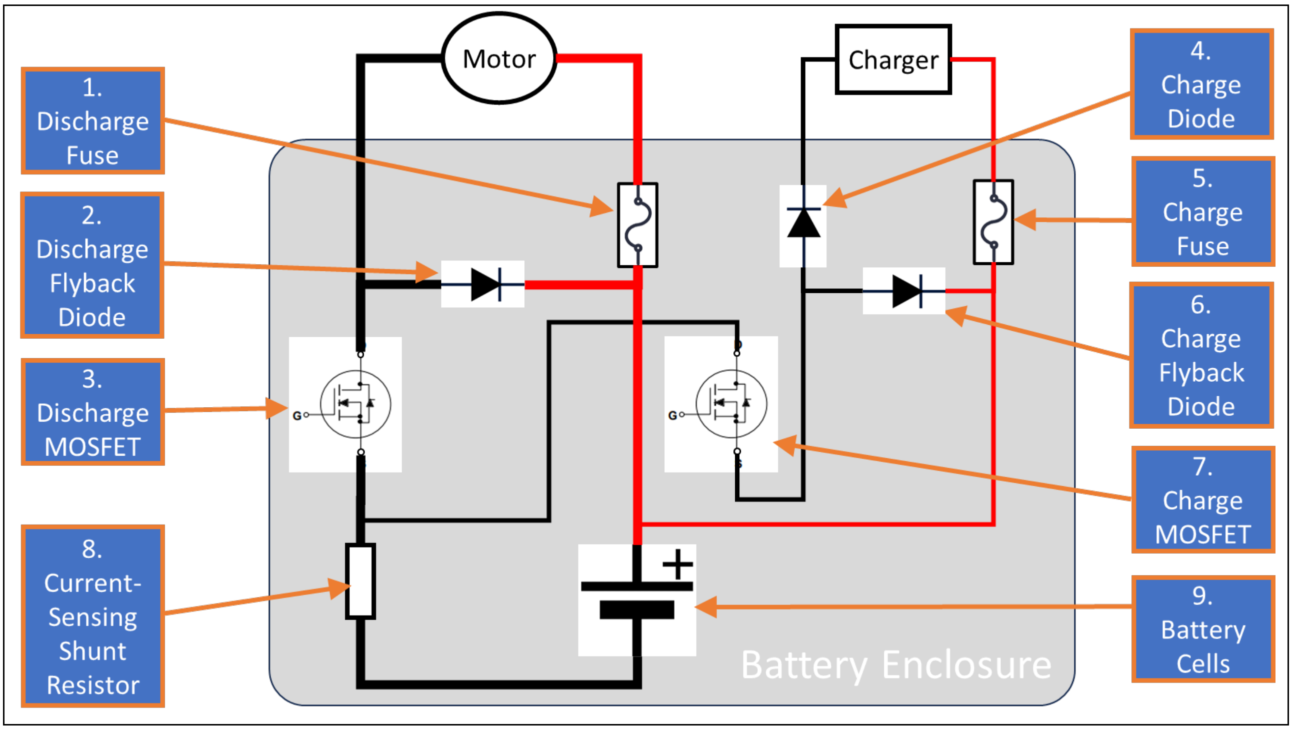


Figure 67: Generic Power-Circuit Layout of PLEV Batteries

Discharge Fuse: To protect against excessive current in the discharge circuit. The fuse is rated to be able to deliver the maximum operational current (e.g. 30 A) but will blow in case of a severe over-current, such as would be caused by a short-circuit. Fuses are commonly used to protect cables from over-heating. This is their main function in household wiring. In a battery, the fuse also protects the BMS and the battery cells. Once a fuse blows, it cannot be reset, so the battery discharge circuit is permanently disabled unless the fuse is replaced.

Discharge Flyback Diode: To protect the battery and BMS from the inductive characteristic of the motor. An inductor, such as the coils in a motor, acts to resist any change in current. When the motor current is suddenly switched off, for example by the discharge MOSFET (see below), the inductance of the motor resists this sudden drop in current, and would cause a voltage spike, if it weren't for the flyback diode, which allows the current through the motor to continue to flow in a loop until it decays to zero. This only takes a fraction of a second, but without the flyback diode, the voltage spike could exceed the limits of some BMS components, damaging them.

Discharge MOSFET: The MOSFET is a solid-state switch, which can be opened by the BMS to prevent discharge current (see Figure 68). The voltage at the gate G of the MOSFET is set by the BMS to control whether the MOSFET is switch on (current can flow from drain D to source S, analogous to physical switch being closed) or off (current cannot flow from drain to source, analogous to a physical switch being open). If the BMS has the require capability, it may also be able to control the discharge MOSFET by Pulse Width Modulation (PWM). This means the BMS opens and closes the MOSFET at high frequency, thereby effectively allowing it to limit the discharge current (analogous to partially closing a tap). Its primary purpose is to protect the cells from excessive discharge current. Unlike the fuse, a MOSFET can do this repeatedly and controllably, so the BMS can determine when to open the MOSFET based on a multitude of factors. For example, it can implement different discharge current limits at different temperatures, according to the limits specified by the cell manufacturer. The downside of a MOSFET is that it can only block the current in one direction. MOSFETs have an “intrinsic diode”. When the MOSFET is in the off state (open), current can flow in the reverse direction through the intrinsic diode. So, for example, the discharge MOSFET alone cannot prevent charging through the discharge port.

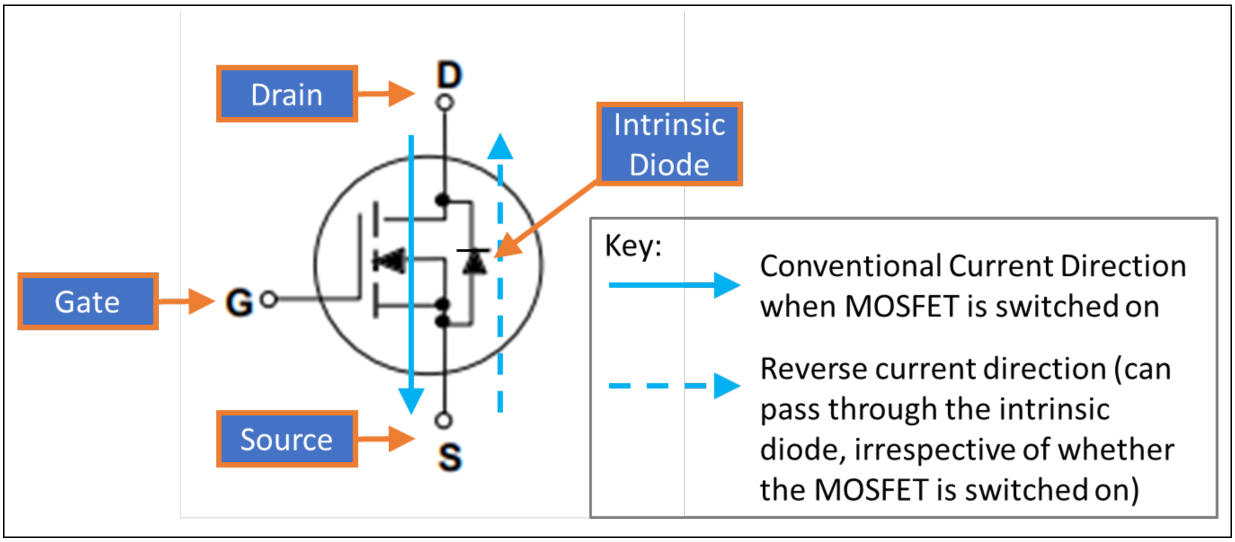


Figure 68: MOSFET Explanatory Diagram

Charge Diode: A diode acts like a one-way valve. It allows current in one direction, but blocks reverse current flow. This protects the battery from connection of a charger that inadvertently has its polarity reversed, i.e. it prevents discharge through the charge connector.

Charge Fuse: To protect against excessive current in the charge circuit. The fuse is rated to be able to deliver the maximum charge current (e.g. 5 A) but will blow in case of a severe over-current, such as would be caused by a short-circuit.

Charge Flyback Diode: Serves a similar purpose to the discharge flyback diode, but this is protecting sensitive battery components from the inductance in the charger.

Charge MOSFET: As with the discharge MOSFET, the charge MOSFET enables the BMS to prevent or limit the charge current. Its primary purpose is to protect the cells from excessive charge current. Like the discharge MOSFETs, the charge MOSFET is only able to block the current in one direction. Note, in Figure 67 that it is mounted in the opposite sense to the discharge MOSFET, so that it blocks charge current, rather than discharge current. As for the discharge MOSFET, a suitably capable BMS could apply PWM control to control the charge current. If the charge diode is also present, the discharge through the charge port is prevented.

Current-Sensing Shunt Resistor: One of the key parameters required by the BMS is the current passing in or out of the battery. The easiest way to measure current is to pass the current through a known resistor and measure the voltage across the resistor. Using Ohm’s Law (V=IR), the current is calculated.

Battery Cells: The cells store energy provided by the charger and provide discharge current to the motor.

With the exception of the cells, motor and charger, all of the major components shown in Figure 67 can be surface-mounted on a PCB. Most of the purchased products use this method, although products #5 and #8 have fuses that are not PCB-mounted, but are instead mounted on the battery casing, to allow them to be easily replaceable.

Surface-mounted components are typically quite small, and most are not intended to deliver continuous high current. To overcome this limitation, a BMS supplier can choose one of two routes: Either select a larger component which is capable of delivering the required current, or mount several identical components in parallel, so they share the current. The latter is commonly seen in the purchased products, particularly for components in the discharge circuit, which experiences significantly higher current than the charge circuit. It is likely that using several smaller MOSFETs or resistors is a more cost-effective solution than using one larger component, partly because the smaller components are produced in greater quantities and so have economies of scale. Several smaller components also typically have a greater combined surface area for heat dissipation than one large component, so thermal management is likely to be easier.

Table 54 summarises the number of Discharge and Charge MOSFETs and the number of shunt resistors used in the BMS of each of the purchased products. “P” indicates that the components are connected in parallel, and “S” indicates that they are connected in series:

Table 56: Numbers of Parallel and Series MOSFETs and Resistors in Each BMS

#	Number of Discharge MOSFETs	Number of Charge MOSFETs	Number of Shunt Resistors
1	4P	1	2P
2	2P	2S	1P
3	3P	1	2P
4	3P	1	1
5	5P	2	5P
6	1	1	1
7	4P	1	4P
8	5P	1	2P
9	4P	1	2P

Although multiple parallel components likely have cost and thermal advantages, there are downsides associated with their failure-modes, outlined below:

- MOSFETs tend to fail short-circuit. This is a significant safety issue, given that their most important function is to be able to open the circuit. So even if the circuit has just one MOSFET, if it fails then the ability to open the circuit is lost. If several MOSFETs are used in parallel, then the implication of a single MOSFET failure is essentially the same, because whilst the remaining healthy MOSFETs will continue to be able to open, the current will simply bypass those, passing through the one failed MOSFET. However, the risk is a combination of both severity and likelihood. The likelihood depends on the failure-rate of the component. For mass-produced components like these, the failure rate is typically expressed as parts per million (ppm). If one assumes that the ppm failure rate of a large MOSFET is the same as that for a small MOSFET, then using several smaller MOSFETs increases the likelihood of a single failure, compared to using a single large MOSFET. However, the ppm failure rate of smaller components may be different from larger components, so to evaluate the likelihood accurately would require failure rate data for all MOSFET types considered.
- Conversely, if MOSFETs are mounted in series (see product #2 in Table 54), then to lose the ability to open the circuit, both MOSFETs must fail short-circuit. This is a much lower likelihood event than failure of one MOSFET. Furthermore, the total voltage drop is divided between the two MOSFETs. This is an example of “redundancy” in the design: Each of the series-connected MOSFETs acts as a backup for the other one. However, when one MOSFETs fails, it may increase the voltage drop across the second one, which could cause it to fail too. This must be considered in the design, to ensure that the redundancy is effective. WMG considers this to be

good practice. There is only one example of series-connected MOSFETs in the products tested here: The charge circuit of product #2 has two MOSFETs connected in series to serve this purpose.

- Unlike MOSFETs, shunt resistors tend to fail open-circuit, acting like a fuse, so they cannot conduct current after failure. If one of several parallel resistors fails, then the circuit continues to operate, but the current now passes through one fewer resistor. This means that the voltage-drop across the resistors is higher. It is unlikely that the BMS has any means of detecting a failed resistor, so it will interpret the higher voltage-drop as a higher current. It may therefore cause the BMS to limit the battery performance more than is necessary, but it is preferable for the BMS to over-estimate than to under-estimate the current. Therefore, whilst it may inconvenience the rider, it is a safe failure mode.

Figure 69 provides an example of one of the more complex schematics from the products purchased for this project:

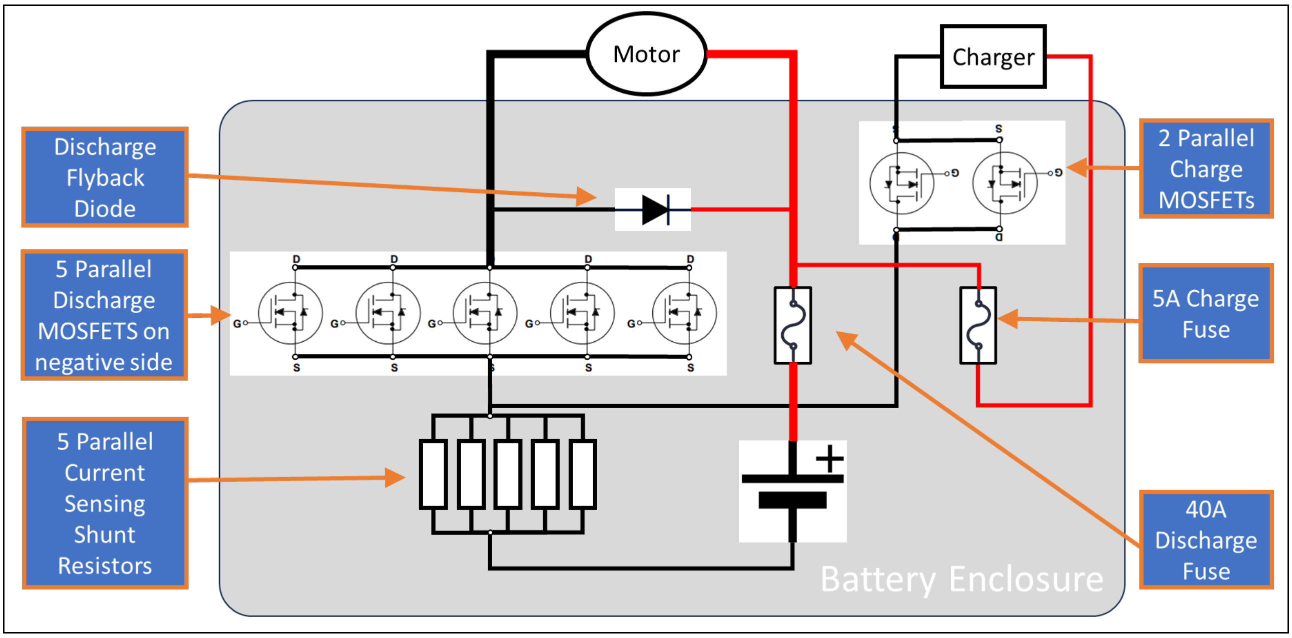


Figure 69: Power-Circuit Schematic of Product #5

Product #5 has 5 parallel discharge MOSFETs, 2 parallel charge MOSFETs and 5 parallel shunt resistors. This proliferation of parallel components may increase the likelihood of a single-point failure, to the detriment of safety.

Product #5 also has a discharge fuse and charge fuse which are accessible via removable rubber covers on the outside of the battery casing. These externally accessible fuses have been installed, even though the BMS has spaces allocated for surface-mounted charge and discharge fuses. It is assumed that the choice to have user-replaceable fuses was judged to be preferable for the user. However, there is a safety risk with this: The fuses are of the standard automotive type, which are available in multiple different ratings in the same physical size. This invites the risk that the user deliberately or accidentally replaces a fuse with one that is not the correct rating. This is a particular risk on the charge circuit, where the user could insert a higher-rated fuse to allow them to use a charger with greater current output, thereby potentially exceeding the current limit of the cells and BMS. In this case, there would be a trade-off between repairability and safety. Having to replace a PCB-mounted fuse may be significantly more expensive, as it's likely to require a completely new PCB. The alternative of attempting to unsolder a fuse from the existing PCB and then solder a new fuse to replace it, carries risks of overheating the PCB during soldering or causing spatter of stray solder which could cause short-circuits elsewhere. In general, it is challenging to accommodate repair and replaceability whilst retaining as-new product safety, so easily replaceable fuses may appear a good solution. Nevertheless, for the reasons stated above, in WMG's opinion, user-replaceable fuses in non-unique sizes are a significant risk.

Figure 70 shows the power circuit schematic of product #2, which is unique amongst the product purchased here in having series-connected MOSFETs in the charge circuit. Two of the three MOSFETs (labelled 1 and 2) are oriented to be able to prevent charge current (the conventional charge current flows from drain to source), while the third (labelled 3) is oriented the opposite way and can prevent discharge through the charge port (the conventional charge current flows from source to drain). In WMG's view, the redundancy provided by the two MOSFETs that can prevent charging is a safety benefit, significantly reducing the likelihood of over-charging.

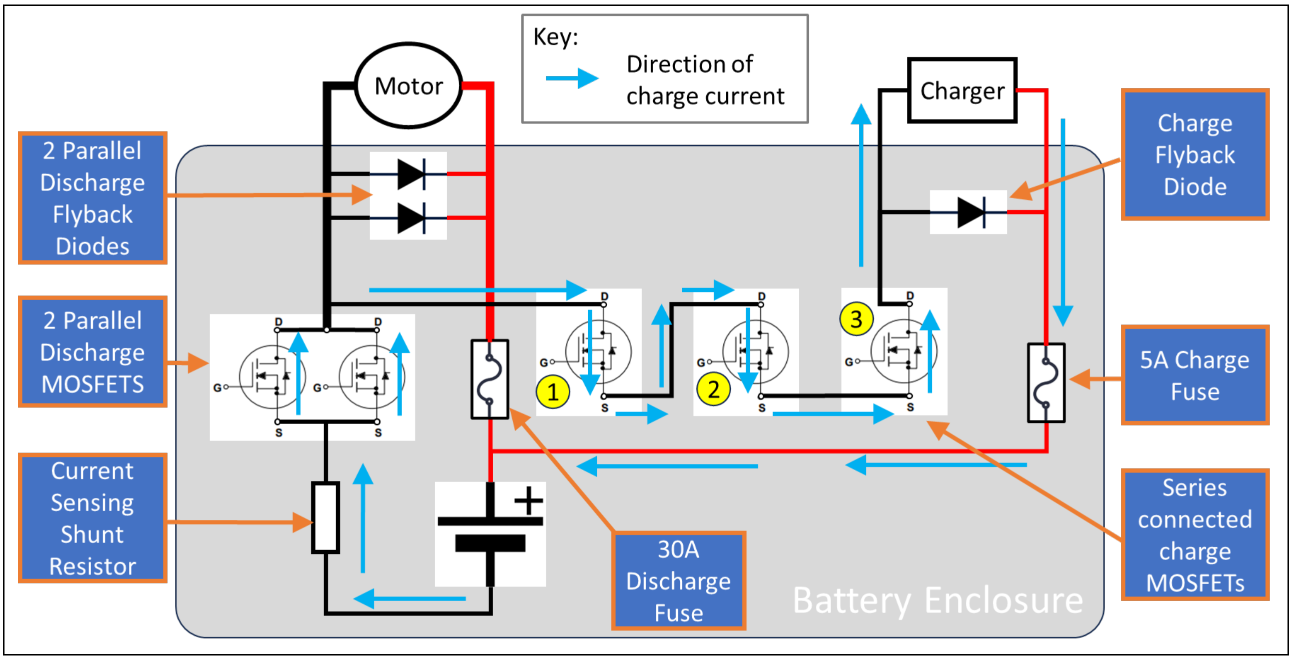


Figure 70: Power-Circuit Schematic of Product #2

Figure 71 shows the power circuit schematic of product #6.

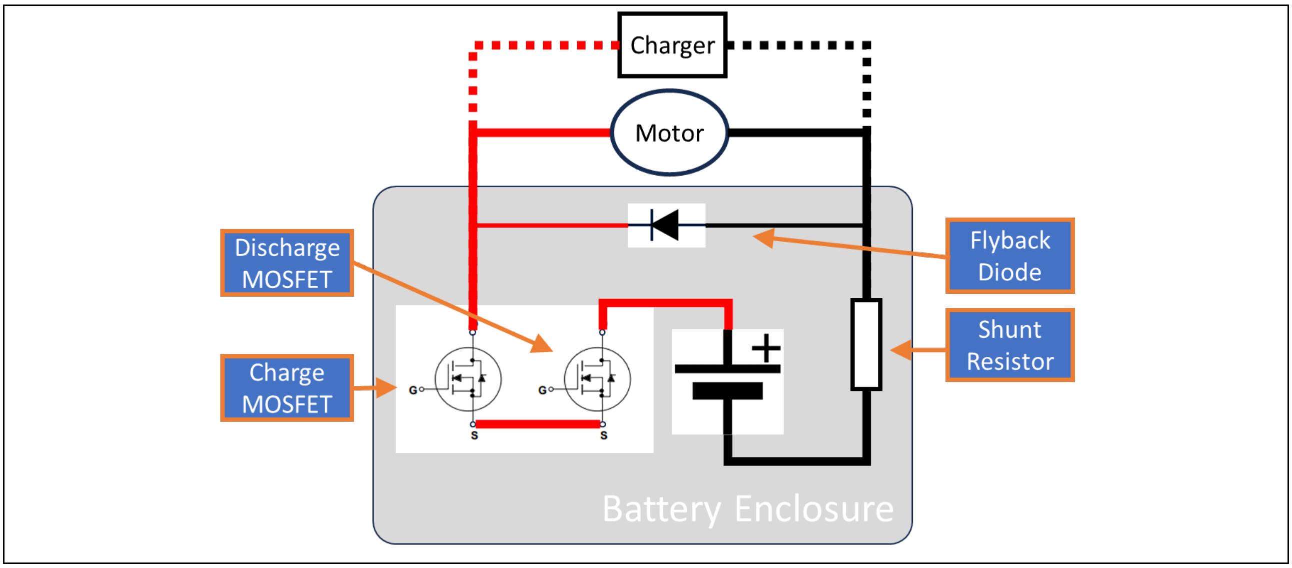


Figure 71: Power-Circuit Schematic of Product #6

This is unusual, compared to the other PLEV products purchased, for several reasons (although WMG understands it is a commonly used layout in personal electronic devices):

- There is only one electrical power connection to the battery, rather than having separate charge and discharge connections. The connector is used either to connect to the e-bike motor or to connect to the charger.
- There is only one discharge MOSFET and one charge MOSFET.
- The current passes through both MOSFETs, whether for charge or discharge.

The charge and discharge MOSFETs are oriented in the opposite sense to one another. Each one acts as a one-way valve, but in opposite directions.

The advantage of this layout is its simplicity. The minimal number of components reduces the number of potential points of failure, so reduces the likelihood of failure. However, it is notable that there is no fuse on either the charge or discharge circuit, so short-circuit protection must be provided either by opening the MOSFETs or by a fuse elsewhere in each circuit (such as in the charger or motor controller). There is also no redundancy in this layout, so safety is affected by a single-point failure just as much as other systems.

As discussed in Section 7.3 of this report, Functional Safety standards (e.g. ISO 13849-1) place high importance on the probability of dangerous failure of safety-critical components, i.e. their reliability. WMG has not found any failure rate data in any of the MOSFET datasheets used in the BMS of the purchased products. However, the datasheets for the MOSFETs used in four of the products (from two MOSFET suppliers) have disclaimers stating:

> “Unless otherwise specified in the datasheet, the product is designed and qualified as a standard commercial product and is not intended for use in applications that require extraordinary levels of quality and reliability, such as automotive, aviation/aerospace and life-support devices or systems. Any and all semiconductor products have certain probability to fail or malfunction, which may result in personal injury, death or property damage. Customers are solely responsible for providing adequate safe measures when design their systems”.

PLEVs, including e-bikes and e-scooters, are not listed in this disclaimer. However, in WMG’s view the large PLEV market size and the fire safety issues seen in the real world mean that the comments above, about the responsibility for providing adequate safety, apply equally to PLEV manufacturers as they do in sectors such as automotive, and producers are responsible in UK law for selling only safe products.

The datasheet for the MOSFETs used in Product #6 has a different statement:

> “[The] component described in this Data Sheet may be used in life-support devices or systems and/or automotive, aviation and aerospace applications or systems only with the express written approval of [the manufacturer] if a failure of such components can reasonably be expected to cause failure of that life-support, automotive, aviation and aerospace device or system or to affect the safety or effectiveness of that device or system.”

This implies that this MOSFET can meet the reliability requirements of sectors such as automotive, aerospace and medical, albeit that the customer would need to seek the MOSFET supplier’s approval for such use. It is possible that the supplier of product #6 has justified the absence of redundant components based on reliability assurances from the MOSFET supplier.

It is important to note that there is more than one way to meet the high level of reliability needed to minimise the number of safety-critical product failures. One option is to use components, including MOSFETs, which are manufactured to achieve very high reliability (low rates of failure). An alternative is to provide redundancy, as shown in Figure 70 for the charge circuit in product #2. This addresses the component reliability by ensuring that a single component failure can be overcome by having another similar component as a backup. A third option is multiple layers of protection, each using a different approach.

10.3.12 Identity and suitability of MOSFETs

All of the purchased products use surface-mounted MOSFETs for the charge and discharge circuits. In all cases except from Product #2, the same type of MOSFET is used on both the discharge and charge circuits.

MOSFET datasheets typically include extensive data to assist the application engineer to integrate them correctly. For the purposes of this report, the following parameters listed in Table 55 are the most relevant:

Table 57: Key MOSFET Parameters Affecting Safety

Parameter	Explanation
Maximum drain-source voltage (V)	This is the maximum voltage difference between the drain and source that the device can withstand.
Maximum drain current (A)	The power circuit current passes from the drain to the source of the MOSFET. This is the maximum continuous current that the MOSFET can deliver. However, this can be highly misleading because it does not consider the thermal limit.
Maximum Junction Temperature (°C)	This is the maximum permissible temperature of the semiconductor junction.
Drain-source on-state resistance (mΩ)	This is the resistance of the MOSFET when conducting current from drain to source. It can be used to calculate the heat generated in the MOSFET: Heat Generation (W) = I^2R
Thermal resistance, junction to ambient (K/W)	The thermal resistance quantifies how much hotter the semiconductor junction of the MOSFET will be than the ambient, to reject a certain amount of generated heat. A low thermal resistance means it is easy for the heat to dissipate from the MOSFET to the ambient air, and therefore the MOSFET temperature will not be too high. The figures provided on the datasheets are indicative only, as the real temperature will depend greatly on details such as heat-sink dimensions, whether there is any moving airflow, etc.

In Table 56 below, the above values are shown for each purchased product. For the first three values (maximum drain-source voltage, maximum drain current and maximum junction temperature), a higher value is preferable. For the final two values (drain-source on-state resistance and thermal resistance from junction to ambient), a lower value is preferable.

Table 58: MOSFET Parameters

#	Maximum drain-source voltage (V)	Maximum drain current (A)	Maximum Junction Temperature (°C)	Drain-source on-state resistance (mΩ)	Thermal resistance, junction to ambient (K/W)
1	60	80	150	6.5	62
2	80	110	150	6.0	91
3	68	83	150	6.8	91
4	60	100	150	3.6	35
5	80	120	175	4.0	31
6	60	100	175	3.4	62
7	85	120	150	4.6	62
8	80	120	150	5.3	63
9	80	110	150	6.0	62

The maximum drain-source voltage is at least 60 V in all cases. This is expected to be adequate, even considering the most extreme foreseeable misuse, in terms of connection of an incorrect charger. The maximum drain current for each MOSFET type is also well in excess of what the MOSFETs will experience in these applications.

Most of the MOSFETs have a maximum junction temperature of 150 °C. The only two products that have a higher maximum junction temperature are the replacement e-bike batteries. This may be a sign that these suppliers have opted for more capable MOSFETs.

Since each product has MOSFETs connected in parallel, the total pack current is divided between them, and the total electrical resistance is equal to the single-MOSFET value divided by the number of parallel MOSFETs. Similarly, considering the heat generated in all the MOSFETs combined, the total thermal resistance is also equal to the single-MOSFET value divided by the number of parallel MOSFETs. Figure 72 shows these combined values for the discharge and charge circuits of each product.

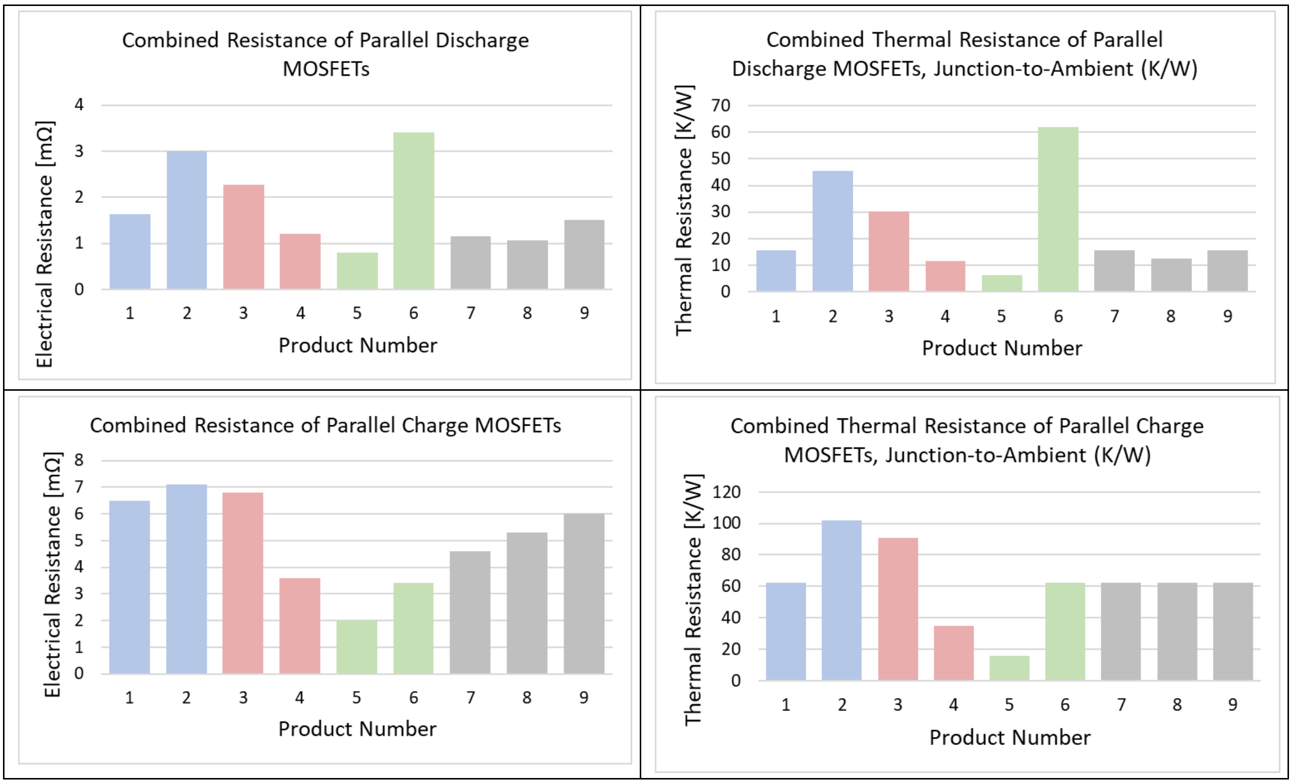


Figure 72: Total Discharge and Charge MOSFET Electrical and Thermal Resistances

In Figure 72, there is no discernible trend in terms of product category. Based on this MOSFET data alone, there is no reason to raise a concern about any product or product category.

In the discharge charts, Product #6 is notable in having the highest electrical and thermal resistance, because it only has one discharge MOSFET. This means that, for a given current, it will generate the most heat in the discharge MOSFET(s) and that it will be more difficult to dissipate that heat. This is not necessarily a safety issue, as long as the current is strictly limited to ensure that the single MOSFET never over-heats.

In the charge charts, Product #6 does not stand out, because many of the other products also have only one charge MOSFET.

In all of the charts, Product #5 is notable in having the lowest electrical and thermal resistance, meaning that its MOSFETs will generate the least heat, and will run cooler because it is easier for them to dissipate the heat generated.

In Figure 73 and Figure 74 below, the above data are translated into a calculation of how hot the MOSFET semiconductor junction temperatures will be, depending on the pack current. This is only an indicative estimate, because as noted in Table 55, the real thermal resistance values depend greatly on how the MOSFETs are installed, particularly the design of any heatsink to dissipate heat more effectively. Nevertheless, Figure 73 gives a reasonable indication of the relative temperatures of each product.

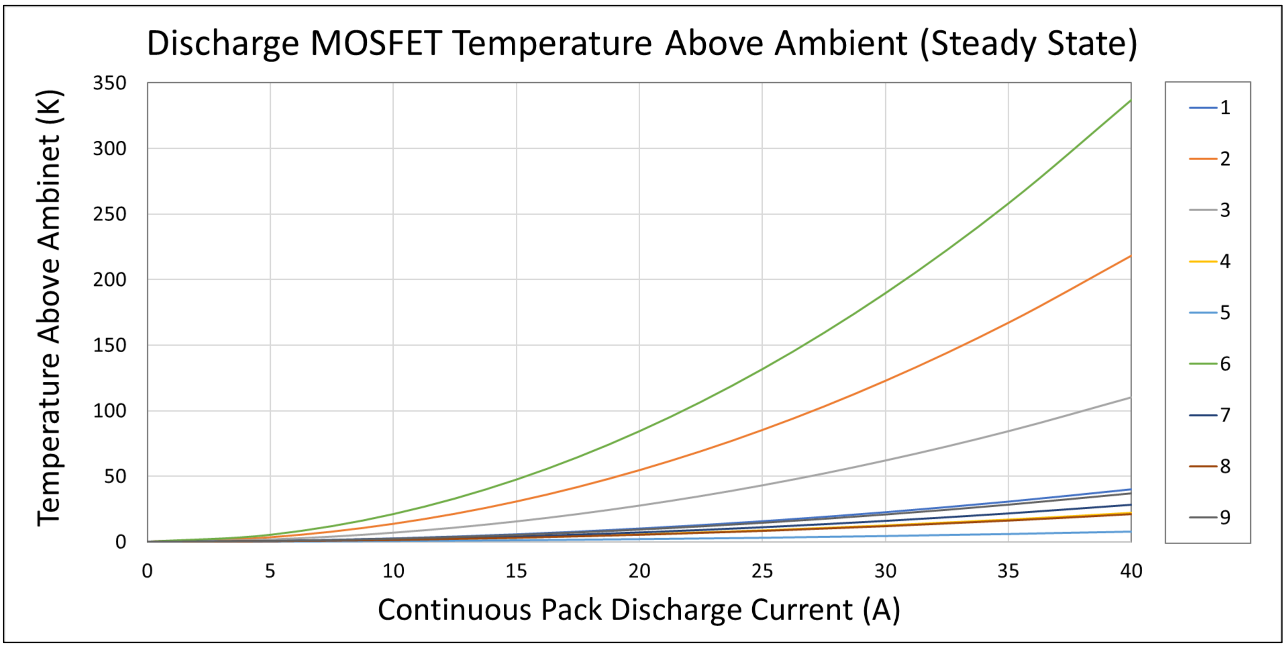


Figure 73: Estimated Temperature Above Ambient of the Discharge MOSFET Junction

In Figure 73, an enormous spread can be seen between the estimated discharge MOSFET temperatures of the different products, with product #5 being the coolest and #6 the hottest. These values must be seen in the context of the maximum allowable junction temperature (150-175 °C), but also the likely maximum continuous current that will occur in each application. e-bikes should be limited to 250 W continuous motor mechanical power, which likely equates to approximately 300 W electrical power from the battery. Depending on the battery voltage, this will require a current of no more than 14 A. The two e-scooters tested here have higher rated power of 300 and 350 W, but would still require no more than 14 A, given the voltages of their respective batteries. If the power output is kept below this level, then none of the products should experience over-heating of the discharge MOSFETs. Therefore, while product #6 might look concerning in Figure 73, it would only be concerning if it were used outside of its intended maximum current. However, if an e-bike is modified to achieve greater power, or if a conversion kit is used with a higher-power motor, then the MOSFET temperatures could become a concern.

It is also important to consider that e-bikes and e-scooters are typically capable of peak power much higher than 250 W. During a pulse of high power, such as when the rider needs to accelerate or climb a hill, the time for the temperature to reach the steady-state value shown in Figure 73 will depend mainly on the thermal inertia of the MOSFETs and any heatsink to which they are mounted. In general, because of their small size, MOSFETs have a much smaller thermal inertia than the cells of the battery, which change temperature relatively slowly, so MOSFETs change their temperature quickly, and can approach the steady-state values shown in Figure 73 after only a few seconds. There can also be thermal interaction between MOSFETs that are mounted in close proximity on the PCB, meaning for example that a discharge MOSFET can cause heating of a neighbouring charge MOSFET. The measurements during abuse tests of the products will demonstrate these effects.

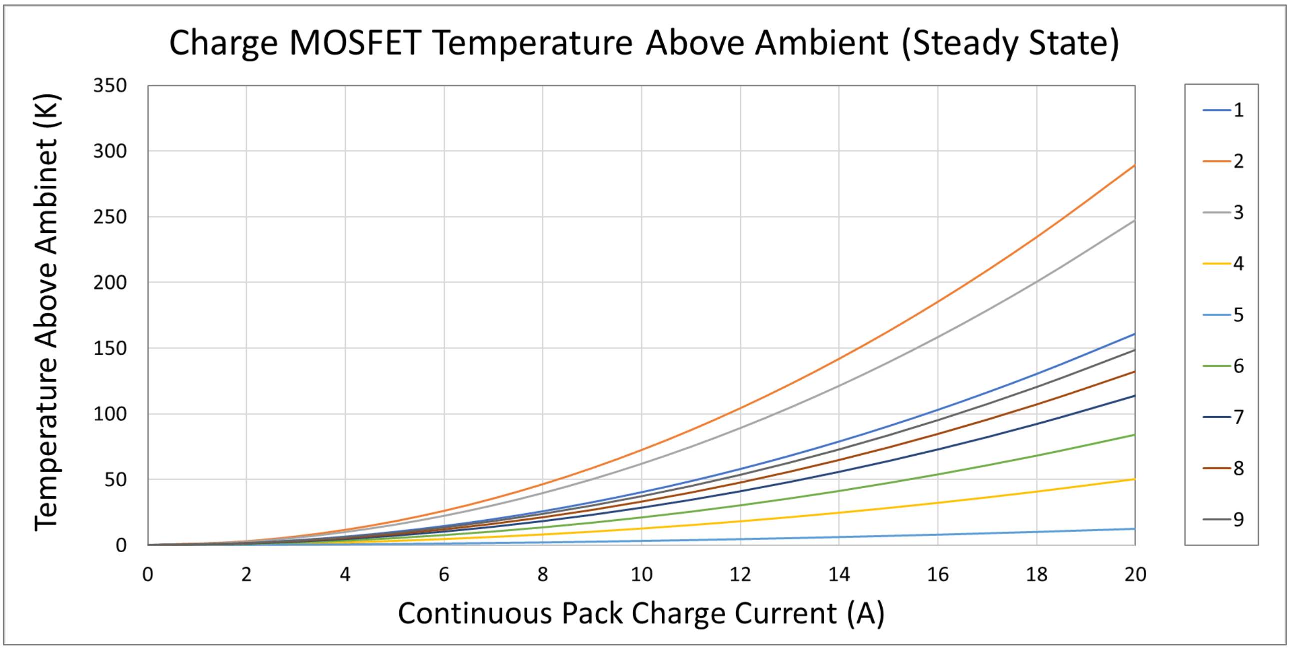


Figure 74: Estimated Temperature Above Ambient of the Charge MOSFET Junction

In Figure 74, a large spread can also be seen in the estimated charge MOSFET temperatures, albeit that the spread is less pronounced than for the discharge MOSFETs. Again, if a standard charger (1.5 – 5 A) is used, then there is no reason to be concerned about the charge MOSFET temperatures, but if a higher-rated charger is used and if the BMS does not prevent its use, then the charge MOSFET temperatures could become a concern.

In summary, the temperature of MOSFETs is a key consideration, and is strongly influenced by the current that is conducted through the MOSFETs. Managing their temperature depends on several key factors: The MOSFET specification, the number of parallel MOSFETs, the power output in the application, and the BMS software's ability to limit the battery current. If improperly managed, not only could the MOSFET maximum temperature be exceeded, but a hot MOSFET in close proximity to a Lithium-ion cell could transfer heat to that cell, causing it to go into thermal runaway, and/or cause a propagating failure in the BMS circuit board.

10.3.13 BMS PCB Layout Regarding Thermal Management

The MOSFETs are not the only sources of heat in the BMS. The copper tracks on the PCB that carry the current of the power circuit can also generate significant heat if they are insufficiently dimensioned. The balancing circuit can also generate heat, as it functions by dissipating excess energy from some of the cells through PCB-mounted resistors.

Thermal management of the BMS PCB and its components is therefore an important design consideration, and it must be ensured that the heat generated by the BMS does not overheat the BMS itself (with the risk of propagating circuit failure) and is not conducted into the cells to a degree that jeopardises their safety.

As noted in Section 10.3.10, there is great variety in the size and shape of BMS PCBs. Table 57 shows the approximate dimensions and surface area of the PCB in each product.

Table 59: BMS PCB Dimensions and Thermal Design Factors

#	BMS PCB Dimensions (mm)	BMS PCB Area (mm^2)	Heatsink on MOSFETs?	Air Movement Possible?
1	37 x 256	9,500	No	No
2	35 x 340	11,900	No	Yes
3	61 x 32	2,000	Yes	No
4	Ø 54	2,300	No	No
5	62 x 255	15,800	No	No
6	75 x 55	4,100	No	Yes
7	78 x 58	4,500	Yes	No
8	65 x 33	2,100	Yes	No
9	64 x 200	12,800	No	No

The largest PCB has almost eight times the area of the smallest. However, in almost all of the BMSs, the MOSFETs are mounted close together in a small area, rather than being spread around the available area, as shown in Figure 75. This is likely done to make the electrical layout simpler but has the downside of concentrating the MOSFET heat generation in a small area.

The MOSFETs used in these products are all designed with the drain electrical connection as a large metallic pad on the underside of the device, by which it is soldered to the PCB. Copper, used for the conductive tracks in PCBs, is an excellent thermal conductor. Large copper areas will help to dissipate the heat from the MOSFETs over a wide PCB area. Products #5 and #9 are examples of generous areas of copper track to spread the heat.

In the smaller PCBs, the is very little area to spread the heat around the PCB. In most of these (Products #3, #7 and #8), an additional aluminium heatsink plate is screwed over the top of the MOSFETs, with a soft Thermal Interface Material (TIM) sandwiched between the plate and the MOSFETs. The TIM is an electrical insulator, to prevent the aluminium heatsink from causing inadvertent short-circuits between MOSFETs but is also intended as a thermal conductor, albeit that its thermal conductivity is far less than, say, aluminium. The heatsinks are a worthwhile addition, but the heat from the semiconductor junction of the MOSFET has to be conducted through the MOSFET's plastic casing, which is a poor thermal conductor, so it is not an ideal thermal path.

Given that all of these batteries are in enclosures with no forced air circulation, there is limited scope for the heat from the BMS to escape. In Table 57 above, the final column gives WMG's subjective judgement on whether air circulation around the MOSFETs of the BMS is possible. In most cases, the BMS is wrapped in shrink-wrap, adhesive tape or similar, making air movement very difficult. The exceptions are Products #2 and #6.

In WMG’s view, allowing sufficient space around the BMS MOSFETs for some air circulation is beneficial for dissipating heat from them. When heat is conducted into air, it causes the air to become buoyant, so it rises. If there is sufficient space, this gives rise to convective circulation of the air, whereby the hotter air rises, dissipates its heat to the battery casing, then falls back down. Convective flow is encouraged if the BMS is mounted vertically, when mounted in the e-bike / e-scooter, as it is in Product #6. However, if there is no space for air circulation, then BMS orientation is unlikely to make much difference.

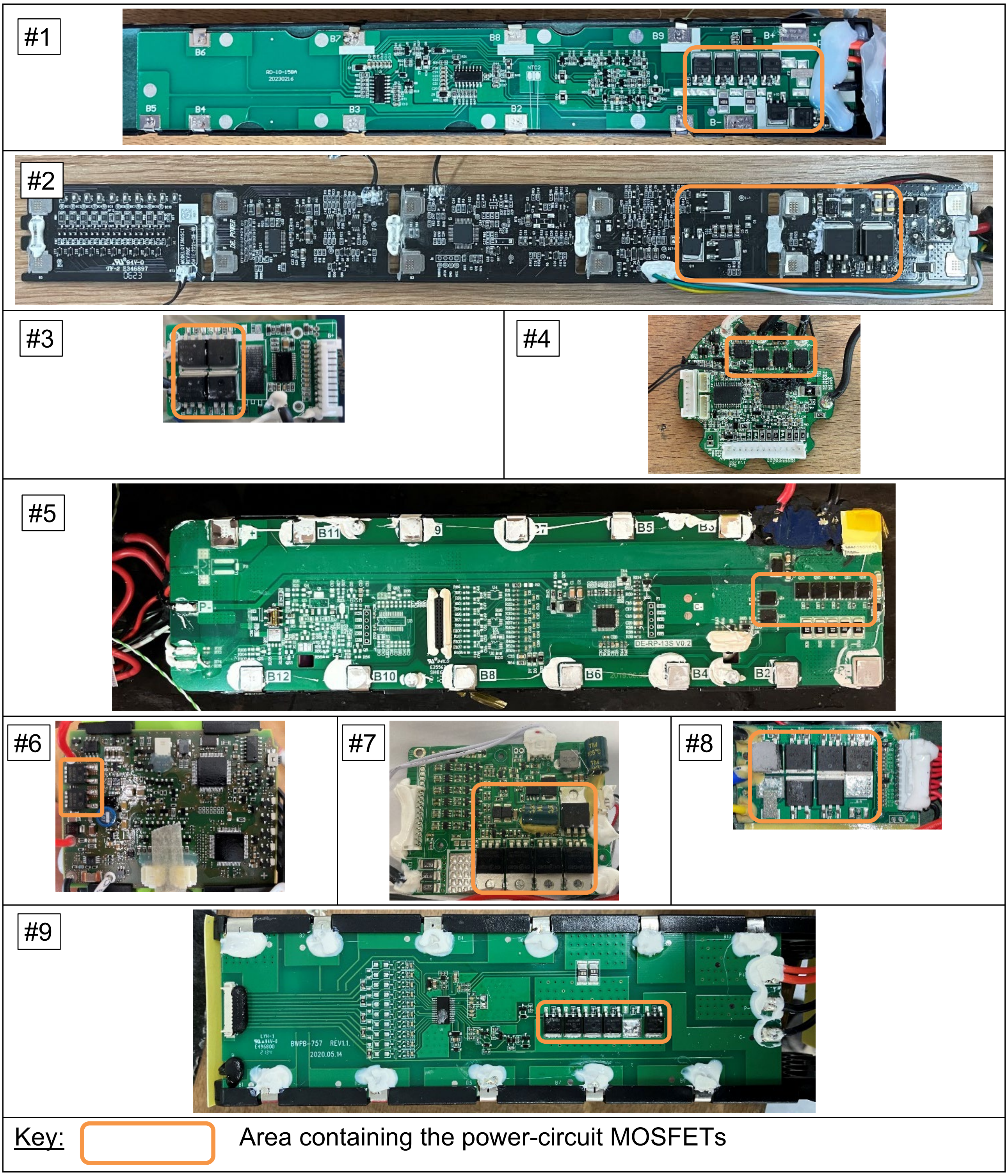


Figure 75: Photos of the BMS PCBs from Each Product (approximately to the same scale)

In these products, the discharge MOSFETs are generally mounted very close to the charge MOSFETs. The only exception is Product #2. The risk of mounting the charge and discharge MOSFETs close together is that thermal conduction through the PCB can heat the other MOSFETs, even when they are not in use. For example, if a discharge MOSFET over-heats because of excessive current (perhaps due to modification of the PLEV), then the charge MOSFETs may reach almost the same temperature. In extreme cases, this could result in damage to both discharge and charge MOSFETs, causing them to fail short-circuit. This may not be apparent to the user, but will prevent the BMS from isolating the cells, for example in the event of a subsequent over-charge.

WMG suggests that design guidelines in standards should encourage a significant spacing between charge and discharge MOSFETs, to reduce the likelihood of cascading thermal failures between the two circuits.

10.3.14 BMS Thermal Sensors

Temperature measurement is critical to the safety of batteries containing Lithium-ion cells. Temperature data is an input to several BMS functions:

- Determination of current limits, as a function of temperature
- Low-voltage protection, to prevent charging below the minimum charging temperature limit stated by the cell manufacturer (for the cells here, 0 °C. See Section 10.3.9)
- High temperature, to prevent charging at above the maximum charging temperature limit stated by the cell manufacturer (for the cells here, 45 °C) and discharging above the maximum discharge temperature limit stated by the cell manufacturer (for the cells here, 55-60 °C. See Section 10.3.9)

Temperature is such a critical parameter that reliability of the temperature measurement system (comprising the sensor(s) and the circuit in the BMS) is just as important as the reliability of the MOSFET switches that disconnect the battery. This does not necessarily mean that redundant temperature sensors are required, but if there is only one sensor, then a robust plausibility check must be done on the signal. For example, some of the cell-monitoring ASICs have a built-in measurement of their own temperature, which can be compared with the cell temperature sensor value, to determine whether they are within a plausible margin of one another.

Another factor to consider in selecting the number of temperature sensors is the spatial variation of temperature between all of the cells in the battery. In general, if the cells are arranged in a tight cluster, the ones near the middle of the cluster will be the hottest, as they are furthest from the external surfaces from which heat can be dissipated to the ambient air. However, since low-temperature protection is just as important as over-temperature protection, it is prudent to know both the minimum and maximum cell temperatures, which suggests the need for at least two sensors. However, if appropriate product testing shows that the cells always remain within a small temperature band in normal use, then a single sensor is likely to be sufficient.

Table 58 below shows the maximum number of thermistor inputs that each BMS PCB allows, and the number of thermistors actually fitted:

Table 60: Thermistors in Each Product

#	Number of Thermistor Inputs on the BMS PCB	Number of Thermistors Fitted for Cell Temperatures
1	1	0
2	3	3
3	1	1
4	2	2
5	2	1
6	1	1
7	0	0
8	2	1
9	1	1

Two of the products, #1 and #7, have no thermistors fitted. Product #7 appears to have no thermistor inputs possible on the BMS, while #1 has a vacant thermistor location on the BMS PCB. For the reasons outlined above, in WMG's view, the absence of temperature sensing in these products is a major safety concern.

However, it is possible that the chips on the BMS PCB, which for products #1 and #7 could not be identified, have internal temperature measurement, which they may use to implement thermal limits, in the absence of a separate thermistor measuring cell temperature.

10.3.15 Identity and suitability of Battery Management Chips

One of the clearest visual differences in BMS sophistication between the purchased products is in the integrated circuits (chips) that they employ. Table 59 below describes the integrated circuits for each product, under two categories.

The first is a "cell monitoring" chip. This is an ASIC designed specifically for the monitoring of Lithium-ion cells. All cell monitoring ASICs measure the cell voltages and most measure several thermistors and the pack current. The ASIC will also typically control cell balancing, and will implement voltage and current limits, with driver circuits to control charge and discharge MOSFETs.

The second integrated circuit listed in Table 59 is a Micro Controller Unit (MCU). This is a general-purpose programmable controller, which includes a central processing unit (CPU), memory, communications and various generic input / output capabilities. An MCU permits far greater flexibility to the battery pack supplier, to implement bespoke software functions, whereas a cell-monitoring ASIC alone has no programmable software, and only limited options for calibration of key values such as voltage and current limits.

Table 61: Multi-Pin Integrated Circuits in Purchased Products

#	Cell Monitoring Integrated Circuit	Micro Controller Unit
1	2x 16-pin ASIC for 5 cells in series	None
2	30-pin ASIC for 6-10 cells in series	48-pin Micro Control Unit
3	28-pin ASIC for 8-10 cells in series	None
4	30-pin ASIC for 6-10 cells in series	30-pin Micro Control Unit
5	48-pin ASIC for 5-16 cells in series	None
6	64-pin ASIC for up to 12 cells in series	64-pin Micro Control Unit
7	None identifiable	None
8	28-pin ASIC for 10 cells in series	None
9	28-pin ASIC for 10 cells in series	None

In eight products, a cell-monitoring chip was found on the BMS. In product #1, the cell monitoring is split between two identical chips, each monitoring 5 of the 10 cells in series. In all products, the part number could be seen on the chip, and the relevant datasheet was found.

In product #7, no cell monitoring chip was found. There were two 8-pin chips, on which no part markings could be discerned. In WMG's view, this pin-count seems insufficient for a cell monitoring system for 10 cells in series. It is therefore unclear how this BMS would implement cell voltage and current limit functionality.

Only products #2, #4 and #6 include an MCU. In WMG's view, this is likely to add significant cost to the BMS and is a sign that the supplier has determined that a cell monitoring chip alone is insufficient to achieve the functionality and safety that they require in their products, which may include support for data communication to other systems on the PLEV or support for diagnostic data logging during servicing. An MCU is no guarantee of superior safety, but in WMG's view it is nevertheless likely that these products will have superior protection.

Table 60 below summarises the options for selecting the voltage, current and temperature limits implemented in the cell monitoring ASICs, based on the datasheets found. An explanation of the terminology used is provided below the table. The colours used indicate WMG's judgement of the ability of the ASIC to comply to cell datasheet limits as follows:

- Green: The hardware offers sufficient flexibility to comply with cell datasheet limits
- Amber: The hardware offers limited flexibility to comply with cell datasheet limits
- Red: The hardware has no flexibility to comply with cell datasheet limits or lacks the functionality to implement limits

Table 62: Cell Monitoring ASIC Protection Function Calibration Options

#	Programmable cell voltage min limits?	Programmable cell voltage max limits?	Programmable pack discharge current limits?	Programmable pack charge current limits?	Programmable Over-Temperature Protection?	Programmable Low Temperature Protection?
1	No (2 options per part number)	No (3 options per part number)	No (2 options per part number)	No (no limit)	No (Set by external resistor)	No
2 *	Yes (single value)	Yes (single value)	Yes (single value)	No (done by MCU)	No (done by MCU)	No (done by MCU)
3	No (4 options per part number)	No (4 options per part number)	No (fixed value)	No (3 options per part number)	No (Set by external resistor)	No (Set by external resistor)
4 *	Yes (single value)	Yes (single value)	Yes (single value)	No (done by MCU)	No (done by MCU)	No (done by MCU)
5	Yes (single value)	Yes (single value)	Yes (single value)	Yes (single value)	Yes (single value)	Yes (single value)
6 *	Yes (single value)	Yes (single value)	No (done by MCU)	No (done by MCU)	No (done by MCU)	No (done by MCU)
7	N/A	N/A	N/A	N/A	N/A	N/A
8	No (3 options per part number)	No (2 options per part number)	No (fixed value)	No (fixed value)	No (2 options per part number)	No (2 options per part number)
9	No (3 options per part number)	No (2 options per part number)	No (fixed value)	No (fixed value)	No (2 options per part number)	No (2 options per part number)

* Products that include an MCU (see Table 59)

Some of the cell-monitoring ASICs provide some ability to specify the cell-voltage, pack current and temperature limits. In some cases, this is only possible by selecting part-number variants, indicated in Table 60 by “No (xx options per part number)”. For example, the datasheet for the ASIC used in product #8 provides the following options:

Table 63: Part-Number Variants for the ASIC used in product #8

Part Number Variant	Cell voltage min limit (V)	Cell voltage max limit (V)	Low Temp. Charging Limit (°C)	High Temp. Charging Limit (°C)	High Temp. Discharging Limit (°C)
1	2.7	4.25	0	50	70
2	2.8	4.25	-7	55	75
3	2.8	4.2	-7	55	75
4	2.7	4.2	0	50	70
5	2.5	4.25	-7	55	75

This shows that there are three options for cell minimum voltage (2.5V, 2.7V, 2.8V) and two options for cell maximum voltage (4.2V, 4.25V) and two options for the minimum and maximum charging temperatures and the maximum discharging temperature. However, because of the limited number of part-number variants, only a few combinations of limits values are available. This is quite typical of ASICs with limits defined by the part-number.

As a result, it may not be possible to identify an ASIC part-number variant which matches all of the cell datasheet limits. It is notable that in product #8, which uses ASIC variant 2 in Table 61, none of the ASIC temperature limits comply with the cell datasheet limits, which are 0 °C, 45 °C and 55 °C respectively.

The current limits are generally implemented by the ASIC measuring the voltage drop across a shunt resistor, which is a separate component selected by the BMS manufacturer. The ASIC limit is therefore a voltage limit. For example, an ASIC limit of 0.1V, used together with a 4 mΩ shunt resistor, would equate to a current limit of 25A (= 0.1V / 0.004Ω).

In some ASICs, there are part-number options for this limit, but in others the limit is a single fixed value for all part-number variants (indicated by “No (fixed value)” in Table 60). The manufacturer may select the shunt resistor value such that the ASIC voltage limit equates to the desired current limit. In the example above, the manufacturer could use a 2 mΩ shunt resistor instead of 4 mΩ, to achieve a current limit of 50A instead of 25A.

However, the same shunt resistor is used to implement both charge and discharge current limits, so the manufacturer cannot select the two limits independently.

In other ASICs, such as found in products #2, #4, #5 and #6, the BMS manufacturer is able to programme the ASIC limits. This generally provides greater flexibility on the values used. For example, in product #5, the voltage limits can be set anywhere between 0V and 5V, in increments of 5mV. However, generally these are still single values (indicated by “Yes (single value)” in Table 60). This means, for example, that the current limits do not vary with temperature, as required by many of the cell datasheets.

In some ASICs, temperature limits are defined by the resistance value of a separate resistor, which the BMS manufacturer can select (indicated by “No (Set by external resistor)” in Table 60). This provides greater flexibility than those ASICs where the temperature limits are defined by the ASIC part-number variants.

The greatest flexibility is provided in ASICs which allow limits to be defined via a data communication link with a separate microprocessor (indicated by “No (done by MCU)” in

Table 60). This means the BMS manufacturer can implement their own bespoke software in the MCU. This would allow them for example, to implement limits which vary with temperature.

Based on WMG's understanding of the datasheets for the cell-monitoring ASICs in these products, none of them can implement cell voltage limits or pack current limits that vary as a function of temperature, when used as a stand-alone solution without an MCU. Referring to Section 10.3.9, this is a requirement to be able to comply with most of the cell supplier datasheets, and therefore the ASICs alone do not permit the battery supplier to comply fully with the cell datasheets.

Products #2, #4 and #6, which use an MCU in addition to a cell-monitoring ASIC, could implement voltage, current and temperature limits in a much more flexible way, by using bespoke software functions in the MCU, which can then communicate limit values to the cell-monitoring ASIC. It is not possible to tell how well this has been done from a visual inspection. The quality of implementation can only be judged from testing.

The cell-monitoring ASICs also do not have protection functionality for any components other than the cells. As discussed in Section 10.3.12, the power-circuit MOSFETs and other BMS components could over-heat if the current is excessive. By adding an MCU, the battery supplier has the option to implement additional protection functions, such as temperature estimation or monitoring for the MOSFETs and other critical components.

10.3.16 Balancing Circuits

As discussed in Section 3.5, balancing of cells connected in series can achieve a significant benefit in the usable capacity of a battery, by allowing all cells to charge to 100% SoC, even if they have slightly different capacities.

Visual inspection of the BMS provides an indication of the whether a balancing circuit is present. Typically, the balancing circuit comprises multiple components and interconnecting tracks on the PCB, some of which may be too small to be identified visually.

All of the products inspected appear to have provision for a balancing circuit on the BMS PCB. In some cases, WMG had doubts about whether the circuit was fully populated with the necessary components, but a definitive determination of the circuit layout and behaviour would require further testing which is beyond the scope of this project.

10.3.17 Summary of Teardown Results

The main observations and suggestions from the teardown are shown below:

- None of the products received appeared to have the outer packaging labelled in accordance with the requirements of the UN Model Regulations for shipping of Dangerous Goods and the specific requirements for transport by road (ADR). Some had such labels covered up or removed.
- There is a lack of consistency between manufacturers, regarding whether the charger DC voltage rating is stated as matching the maximum voltage or the nominal voltage of the battery. In WMG's view, this inconsistency between manufacturers is likely to add to consumer confusion about how to ensure they correct charger is being used with a particular battery. As stated in Section 7.12.8, **WMG suggests that only the maximum voltage should be shown on labels, and the nominal voltage should be removed, to avoid ambiguity.**
- There is little consistency in battery labelling between the nine purchased products. One of the e-bike conversion kit batteries contained no battery data, only warnings and

markings for recycling etc. The battery label requirements of EN 62133-2 (portable batteries) and EN 50604-1 (removable LEV batteries) differ significantly, which is likely to contribute to the lack of consistency. **WMG suggests that the battery label requirements of EN 62133-2 and EN 50604-1 should be aligned.**

- The battery casings of the purchased products use plastic mouldings, sometimes combined with an aluminium extrusion for the main body of the casing. Only two of the products (both e-bike OEM batteries) have compressible rubber seals between the casing parts, which are likely to ensure that they are waterproof. Both e-scooter batteries have non-openable plastic housings, where the two halves are glued together and the cable exit has sealant, which likely means that they also are waterproof (in one case, the later versions of the product had this design, but an earlier one had only a shrink-wrap). In WMG's view, none of the e-bike conversion kit batteries have adequate sealing to prevent moisture ingress. Two e-bike batteries (one OEM, one conversion kit) had large gaps around cables which would certainly allow water ingress. **WMG suggests that all PLEV and battery standards should include ingress protection requirements to ensure that moisture ingress is protected against.**
- The structure supporting the cells varies in execution quality. In one product, the cells were held together only by the busbars. In WMG's view, it is not good practice to pass mechanical loads through the busbars, because this is likely to place excessive stress on the busbar-to-cell welds that may lead to premature weld failure. **WMG suggests that PLEV battery standards should include design guidelines to encourage the use of a structure separate from the cell-to-cell busbars to retain the cells in their intended positions.**
- There is a clear correlation between the price per kWh of products and the quality of busbar-to-cell welds. The e-bike conversion kit batteries and the lower-priced e-bike and e-scooter batteries all had visual signs of poor design for spot welding (inadequate or absent busbar slots) and/or poor manufacturing quality (inconsistent spot position & number).
- There is a strong correlation between the price per kWh of products and the confidence in the cell identity: In general, the confidence in the cell identity is highest for the higher priced products. However, there are exceptions, such as product #9, which has a low price per kWh, but high confidence in the cell identity.
- The cell supplier datasheets provide cell current limits. Of the nine products, only five of the cell datasheets specify the charge limits as a function of temperature. In WMG's view, charging current limits are an important safety parameter, for the avoidance of lithium plating and dendrite formation on the anode. **WMG suggests that EN 62133-2 should make the requirement, for cell charge limits as a function of temperature, clearer and more prominent than it is currently (it appears only in Annex A).**
- There is a correlation between price per kWh of products and the quality of internal wiring, particularly the retention of wires and cables to avoid chafing and undue stress on soldered joints. **WMG suggests that the existing wording in EN 62133-2 and EN 50604-1, on retention of wires and cables to avoid chafing and undue stress on soldered joints, should be strengthened and aligned between the standards.**
- In the power-circuit layout, only one of the nine products appears to have redundant charging MOSFETs to enable the BMS to protect the cells. None of the MOSFET datasheets provides reliability data, and some have disclaimers stating that the devices should not be used in safety-critical applications requiring high levels of reliability. **WMG suggests that standards for PLEV batteries should require reliability / safety fault tree analysis to demonstrate sufficient safety with the**

selected components comprising MOSFETs with certified reliability levels, and/or redundancy in the safety system to address the reliability of single devices.

- The MOSFETs used in these products do not cause reason for concern, based on their electrical and thermal characteristics. However, if a PLEV were modified for greater charge or discharge power and the BMS did not prevent this, then in some cases, it could be expected that the MOSFETs would reach temperatures that could endanger adjacent cells or exceed the maximum limit of the MOSFETs.
- All but one of the products have a BMS PCB layout that places the charge and discharge MOSFETs close together. **WMG suggests that design guidelines in standards should encourage a significant spacing between charge and discharge MOSFETs and other power-circuit components, to reduce the likelihood of cascading thermal failures between components.**
- Two of the products, #1 and #7, have no cell temperature sensors fitted. In WMG's view, this is a serious safety concern. All the other products have at least one thermistor to measure cell temperature. One product, #2, has three thermistors. It is not clear why the supplier chose this number, but an increased number of thermistors is beneficial for safety. One possible reason to use a greater number of sensors is to have them located where to coldest and hottest cells are known to be, based on product development testing.
- There is a clear correlation between price per kWh of products and the sophistication of the integrated circuits (chips) used in the BMS. Based on the datasheets of the cell-monitoring ASICs used in these products, in WMG's view such ASICs do not offer the battery manufacturer sufficient software functionality and flexibility in calibration to comply with cell datasheets, particularly current limits that vary as a function of temperature. However, the higher-priced products that use an MCU in tandem with a cell-monitoring ASIC enable the suppliers to create bespoke software and calibration to enable them to fully comply with cell datasheets and to implement additional software functions such as estimation / monitoring of temperatures of other safety-critical components such as MOSFETs.

11 Product Abuse Testing

11.1 Objectives of Product Abuse Testing

Battery abuse testing is a critical step in ensuring the safety of Lithium-ion batteries, especially given the recent widespread incidents reported in London (London Fire Brigade, Sep 2023) and by other fire and rescue services. By subjecting these batteries to extreme conditions in controlled environments, it is possible to evaluate their safety. In Section 2, analysis of real world data showed that the majority of serious incidents occur indoors, and that many occur during charging. As described in Section 3 of this report, many factors can contribute to the onset of thermal runaway in the real world. In Section 10, teardown analysis of PLEV batteries has shown where shortcomings in hardware and software of the battery can contribute to the onset of thermal runaway. In this section, WMG describes abuse tests that have been conducted on the same products, following a methodology intended to reveal such weaknesses in hardware and software, in scenarios that could occur in real world usage.

11.2 Relevant Battery Failure Modes

11.2.1 Under-Voltage

Cell manufacturers specify the minimum voltage during discharge, primarily to prevent over-discharge, which could lead to adverse reactions that affect safety. As explained in Section 3.14 of this report, when a cell is deep-discharged, copper, from the foil on which the anode is coated, can dissolve in the electrolyte. Subsequent charging can cause this copper to form dendrites on the anode, which can cause internal short-circuits. The tests performed here will include determination of the voltage at which the BMS interrupts discharging.

11.2.2 Over-Voltage & Over-Charging

Real world data shows that many of the severe incidents occur when the battery is being charged or is stored after charging (See Section 2 of this report). As explained in Section 3.4 of this report, the severity of thermal runaway is greatest when cells are at a high state of charge (SoC), and over-charging (charging to beyond 100% SoC or above the maximum allowable cell voltage) can induce self-heating which leads to thermal runaway. Exceeding the cell upper voltage limit by even 0.1 V can cause exothermic side-reactions involving the electrolyte, which generate gas and can lead to cell venting. Therefore, the tests performed here will include determination of the voltage at which the BMS interrupts charging. Although it is anticipated that the BMS on all products will interrupt charging if over-voltage is detected, it is possible that a severe over-voltage, caused by a charger delivering a voltage far above the rated voltage of the battery, will damage the BMS protective circuit. Chargers can be purchased with a broad range of voltage outputs and connector types (see Figure 30 in Section 4.6), which presents a risk that consumers inadvertently purchase and use chargers with output voltages unsuitable for their batteries. Over-voltage tests will therefore be conducted at up to double the rated voltage of each battery. Over-charging will be conducted, either by continuation of normal charging if the BMS fails to intervene, or by bypassing the BMS.

11.2.3 Charging Over-Current

Cell manufacturers specify charging current limits, primarily to avoid lithium plating and lithium dendrite formation on the anode, which can lead to cell internal short-circuits (See Section 3.1 of this report). The current above which this occurs depends on the temperature of the cell: at lower temperatures, it occurs with a lower current. The datasheets for the cells used in the products purchased for this project all specify that charging should be limited to temperatures above 0 °C. They also prohibit charging above 45 °C, to prevent rapid ageing and to provide a temperature margin to ensure the cells do not experience side-reactions which could result in self-heat leading to thermal runaway.

As explained in Section 10.3.15 of this report, some BMSs may lack the ability to vary the charge current limit as a function of temperature and may not correctly implement the upper and lower temperature limits for charging. This increases the safety risk.

The testing here will include progressively increasing the charging current, while the battery is at a sufficiently low SoC to avoid the maximum voltage limit, to determine whether, and at what current, the BMS interrupts charging.

11.2.4 Discharging Over-Current

Cell manufacturers also specify discharging current limits, primarily to limit the internal temperature of the cells and to prevent cracking of particles in the active materials, which can lead to premature reduction of battery capacity. As explained in Section 10.3.9 of this report, the discharge current limits are significantly higher than the charge limits, because there is no risk of lithium plating during discharge. However, the higher current in discharge leads to more heat generation, as it is proportional to the square of the current. The temperature at the centre of the cells can be significantly higher than on the surface, where a BMS thermistor may be positioned. The discharge current limit ensures that the cell core temperature remains within the safe range.

The testing here will include progressively increasing the discharging current, while the battery is at a sufficiently high SoC to avoid the minimum voltage limit, to determine whether, and at what current, the BMS interrupts discharging.

11.2.5 Battery External Short Circuit

An external short circuit is typically caused by a fault in a connected system, such as a motor or charger. It has the effect of shorting the positive and negative terminals of the whole battery pack through a very low electrical resistance, causing a very high discharge current, which results in very rapid heating of the cells and other parts of the power circuit in the battery, including the BMS. It acts on all the cells simultaneously.

In PLEV batteries, the short circuit current is typically much higher than the maximum normal operational current. For example, an e-bike with a 36 V battery, and a peak power output of around 500-800 W, will have a peak operational current of approximately 15-30 A, but an external short-circuit might result in a current of 300-1000 A, which is around 20-30 times the peak operational current. This is because the resistance of an external short-circuit can be close to zero, so the only significant resistance to the flow of current is the resistance of the battery itself, which is very low.

Since the heating caused by electric current is proportional to the square of the current, the heat generated during a short-circuit can be 400-1000 times what it is in normal operation. The conductive components in the power-circuit (busbars, cables, connectors, BMS PCB tracks, MOSFETs, diodes, etc.) are not able to survive such rapid heating for long.

Under a short-circuit, WMG estimates that cells in a PLEV battery will typically heat up at a rate of 10-15 °C per second, but in the same situation, a MOSFET may heat up at 1,000-10,000 °C per second, so will likely fail much more quickly.

In some batteries, power-circuit components are protected by a fuse, which should be sized to blow before any of the other components would be damaged. A 40 A automotive blade fuse, such as that used in Product #5, should blow within 0.02 seconds with a current of 500 A (Littelfuse Inc., undated). In other batteries, no fuse is installed, in which case one of the other power-circuit components will almost inevitably fail, typically within well under 1 second. This will usually open the circuit, just as a fuse would, but less predictably than a fuse, as they are not typically designed and validated for this purpose.

The main difference between a fuse and any other component that fails is subsequent risk. Fuses use a thin section of metal, which forms part of the power circuit, which will melt/vaporise when the short-circuit occurs. The fuse casing is designed to contain the molten/vaporised metal. Other components will undergo similar melting but may not be designed to contain the molten material, which could be ejected from the component. There is a small risk that this molten material may land in a place that causes a secondary short-circuit. An example is the voltage sensing wires, to allow the BMS to measure the voltage of each parallel group of cells (see Section 10.3.10). These are typically very thin, because in normal operation they carry very little current, but if they are part of a short-circuit, they will rapidly melt.

External short-circuit tests will be conducted to confirm the benign failure-modes expected from the explanation above.

11.2.6 Battery Internal Short-Circuit

A short-circuit within the battery casing could be caused by a loose internal conductor or by mechanical damage to the battery which causes two internal conductors to come into contact. Water ingress and the associated corrosion can also cause a battery internal short-circuit. BMS component failures can also propagate to cause a short-circuit. It has a similar effect to an external short-circuit but may affect only part of the power-circuit and may only affect a proportion of the cells. For example, if a short-circuit occurs between two cell-to-cell busbars, it could result in a short-circuit through just one or a few cells. A pack-level fuse cannot protect against this type of fault, so the short-circuit may be sustained for longer than in the case of an external short-circuit. Nevertheless, the likelihood is that a component such as a busbar, if appropriately designed, will act as a fuse before the cells reach a critical temperature.

The locations at which a battery internal short-circuit could occur are too numerous to be tested exhaustively here. Therefore, only external short-circuit tests will be conducted.

11.2.7 Cell Internal Short Circuit

A cell internal short circuit may be more likely to lead to a severe outcome than a battery pack-level short-circuit, because it may sustain for a longer time and will initially concentrate the current within a small region of the cell. It is therefore more likely to cause the cell to reach a temperature which will lead to thermal runaway.

Cell internal short-circuits can result from physical damage, over-charge, lithium dendrite formation, over-heating or manufacturing defects. In this test programme, over-charging will be the primary means of inducing this failure mode.

11.2.8 Over-Heating

In the real world, over-heating can occur because of an external heat source (e.g. the battery is stored close to a domestic heater) or because the battery self-heats and cannot dissipate that heat (e.g. while charging, particularly if it is covered by an insulative layer, such as a coat or blanket). The battery may already be warm before charging, following a preceding ride. The initial source of heat does not need to be at a temperature which would directly cause thermal runaway (typically around 180 °C). The scientific literature shows that slow self-heating, without charge or discharge current, can occur at as low as 85 °C, without over-charging (See Section 3.4 of this report). With over-charging, the onset temperature for self-heating could be lower. If this self-heating occurs and the heat cannot be dissipated to the surroundings, the cells may eventually reach the temperature for thermal runaway.

Over-heating does not apply only to the cells: All components in the battery have temperature limits, albeit that those limits are typically rather higher than for the cells. However, if the components are not specified appropriately, they may exceed their temperature limits, for example during high-current charging or discharging. In the case of safety-critical components such as MOSFETs, over-heating may render them incapable of performing their safety function (to interrupt charge or discharge the battery).

Since the MOSFETs are the most safety-critical active safety components, and vulnerable to such failure modes, their temperatures will be measured during testing.

11.3 Test Methodology

All tests were conducted in one of the WMG abuse test-chambers. This chamber is lined with high temperature resistant, non-flammable materials, and equipped with a gas extraction system to remove harmful battery vent gases from the chamber and pass them through a wet scrubber before they are vented to atmosphere.

The test chamber is not temperature controlled, so the test chamber temperature varies between tests, in the range 5-15 °C.

The majority of tests were performed using a power-supply, capable of charge and discharge in a range of 0-80 V and 0-50 A. The power-supply is manually configured with target values for minimum and maximum voltage and current. The power-supply automatically restricts the charge or discharge to whichever limit is reached first. For example, during charging, it will limit the actual current to the target charging current, until either the target maximum voltage is reached, or the battery restricts or interrupts the current. In either case, the power-supply will then hold the actual voltage at the target maximum voltage.

The external short-circuit test is the only test which does not use the power-supply. A test circuit comprising a contactor (large relay), current sensor and a heavy-duty shunt resistor, is connected to the battery by heavy-duty cables. The contactor is used to close the circuit, creating the short-circuit of the battery.

Temperatures were measured using K-type thermocouples and recorded via a Pico data logger. Both temperatures and voltage / current data from the power-supply were logged simultaneously in a single time-synchronised CANalyzer file for each test, and post-processed using purpose-written scripts in the Mathworks MATLAB software.

No BMS internal data were logged during these tests.

Further details of the test procedures are in Section 15.9 (Appendix 9).

Due to the research nature of this project, WMG maintained flexibility in the test procedure, partly to adapt the test parameters to the voltage and current characteristics of the individual products, but also to enable unexpected results to be investigated more thoroughly. Therefore the procedure described in Appendix 9 allows the test-engineer some flexibility, and the order of tests was sometimes altered, or tests were repeated to verify or clarify a result. In cases where the battery failed prematurely, a second or third example of the product was tested.

11.4 Abuse Test Results

11.4.1 Preparatory testing

The first step with each product was to check that it could be charged using its own charger, and then that it could be charged and discharged using the WMG power-supply.

For all but one of the products, this process was straightforward. For product #6, however, discharging the battery via the BMS required replicating the CAN communication interface between the BMS and the same-brand motor controller. Similarly, although charging from the supplied charger was possible, charging from the WMG power-supply relied on replicating the signal interface between the BMS and the charger. In the absence of public-domain information about this signal interface, WMG attempted to reverse-engineer the interface to allow charging to occur but was unable to do so. Without the ability to charge or discharge the battery using the power supply, no useful testing could be completed, so product #6 was excluded from the test programme. This result is an example of the success achieved by product #6 in countering tampering.

The remaining eight products underwent testing, the results of which are described below.

11.4.2 Voltage, Current and Temperature Limit Functionality

Table 64 summarises the BMS safety protection functions which were found to be operating during the testing.

- “Yes” indicates that evidence of the BMS function was found, but not necessarily that it occurred at the appropriate value of voltage / current / temperature.
- “No” indicates that the functionality appeared absent, or if present was not encountered within the range of the WMG tests and was therefore not appropriately calibrated. In product #3, charging was not performed to as high a current as desired, because the BMS charging MOSFET repeatedly failed before higher currents could be tested. This value is shown in black text.
- “-“ in the final two columns indicates that the cell temperatures never reached a value at which BMS intervention would have been expected (45 °C for charging, and 60 °C for discharging). It is therefore not possible to confirm whether the functionality is present or not. However, the fact that over-temperature was never induced is a positive sign that the cells are unlikely to reach their upper temperature limit in real world use.

Table 64: Voltage and Current Limit Functionality Found in Testing

#	Charging Over-voltage Cut-out	Discharging Under-voltage Cut-out	Charging Over-Current Cut-out	Discharging Over-Current Cut-out	Charging Over-Temperature Cut-out	Discharging Over-Temperature Cut-out
1*	Yes	Yes	No	No	No	No
2+	Yes	Yes	Yes	Yes	-	-
3	Yes	Yes	No	No	No	-
4+	Yes	Yes	Yes	Yes	Yes	-
5	Yes	Yes	Yes	Yes	Yes	Yes
7*	Yes	Yes	No	No	No	No
8	Yes	Yes	Yes	Yes	No	No
9	Yes	Yes	Yes	No	Yes	-

* No thermistor fitted

\+ MCU fitted, in addition to cell-monitoring ASIC

All eight products had functioning over-voltage and under-voltage protection. When the batteries were charged continuously, the BMS interrupted charging at the upper voltage limit by opening the charging MOSFET(s). Similarly, when the batteries were discharged continuously, the BMS interrupted discharging at the lower voltage limit by opening the discharging MOSFET(s).

Minimum and maximum voltage limits are the bare minimum of safety functionality expected of any Lithium-ion BMS. They are usually implemented based on individual cell voltages, so the BMS interrupts charging or discharging when the first cell reaches the respective limit. WMG did not measure individual cell voltages during most of the tests, but based on measurement of pack voltage, it is clear that the limits were operational in all products, and the pack voltages at which the cut-out occurred reflected appropriate cell limits in all cases.

Only four of the eight products showed definitive evidence of current limits for both charging and discharging. Of the other four products, three showed no evidence of either charge or discharge limits. Product #9 showed evidence of a charging current limit, but no interruption of discharging occurred up to 40 A, even though the part-label on the BMS stated that it is rated to a maximum of 20 A in discharge, and the cell datasheet allows a maximum of 30 A for this product’s four cells in parallel.

The final two columns of Table 64 show whether evidence was found that the BMS would interrupt or inhibit charge and discharge due to over-temperature. Three products (#4, #5 and #9) showed clear evidence of a charging temperature limit. In each case, this became apparent after a prolonged high-current discharge, which increased to cell temperatures above 45 °C. The BMS then prevented charging until the cell temperature had dropped to a lower value.

Of the remaining five products, four showed no evidence of BMS temperature limits, meaning that the cell temperature during testing exceeded the value at which it would be expected for the BMS to interrupt charge of discharge. In products #1 and #7, this was unsurprising, as neither was fitted with a thermistor.

Product #3 is fitted with a thermistor, but during a continuous charge, the cell temperature stabilised at around 51 °C for approximately 45 minutes during a continuous 5 A charge. This is significantly above the 45 °C limit stated in the cell datasheet. WMG recognises that some allowance must be made for sensor inaccuracy and small differences in temperature between the location of the BMS thermistor and the test thermocouple. However, in WMG's view, exceeding the cell datasheet limit by 6 °C over such a long period is not an acceptable result.

In product #8, which is also fitted with a thermistor, the cell temperature reached 65 °C during discharge and 60 °C during charging, which are respectively 10 °C and 15 °C above the limits on the cell datasheet (unlike the cells in the other products, this one has a discharge limit of 55 °C rather than 60 °C).

The battery from product #2 has a casing which proved impossible to open without permanently damaging it. For this reason, no thermocouples were placed on the cells or on the BMS MOSFETs for most of the charge and discharge testing. Instead, thermocouples were placed on the surface of the casing. It was therefore not possible to determine the cell temperature during most of the tests. Only after the majority of the testing was complete was the casing opened, to allow the BMS to be bypassed. At this stage, thermocouples were placed on the cells. During the subsequent test, the battery was charged at up to 10 A, more than three times the limit that the BMS had permitted. Even then, the cell temperatures took over fifteen minutes to reach 45 °C. Based on this result, in WMG's opinion, with the BMS in the circuit, the cell temperature would be unlikely to reach 45 °C during charging because charging is limited to just 3 A.

In summary, among the products tested here, there is a strong correlation between the price per kWh of the product and the comprehensiveness of the BMS protective limit functionality. The higher price per kWh e-scooter (#2) and e-bikes (#4 and #5) have the most comprehensive protection functions. Two of these (products #2 and #4) have a micro control unit (MCU) in addition to the cell-monitoring ASIC, and the third (product #5) has a higher specification of ASIC than the remaining products. Product #6 also has an MCU in addition to a high-specification ASIC. Unfortunately, as explained in Section 11.4.1, product #6 could not be tested to confirm whether the hardware specification results in successful protection.

Conversely, the lowest price per kWh e-scooter (#1), e-bike (#3) and conversion kit battery (#7) have the least effective BMS protection, with only voltage limits in evidence.

The remaining two conversion kit batteries (#8 and #9) sit in the middle-ground in their BMS protective functionality.

11.4.3 Actual vs. Expected Voltage, Current & Temperature Limit Values

Table 65 shows the extremes of voltage, current and temperature measured during testing when the BMS was not being bypassed, i.e. when the BMS should have been implementing appropriate limits:

- Minimum discharge voltage and maximum charge voltage
- Maximum current during charge and discharge
- Maximum temperature during charge and discharge

The values in Table 65 are colour-coded as follows:

- Green: The value is within the acceptable limits, based on the cell datasheet and BMS label, allowing small deviations to account for measurement error.
- Amber: Testing provided evidence that the BMS would interrupt the charge or discharge if a limit value was exceeded, but the implemented limits exceeded the cell datasheet values to a degree cannot be attributed only to measurement error.
- Red: Testing showed that the BMS had no limit, or the limit was outside the range tested or well outside the cell datasheet or BMS label limits (see next page), or a severe failure mode negated the BMS's ability to interrupt the charge or discharge.

Table 65: Extremes of Voltage, Current and Temperature Measured During Testing

#	Lowest Pack Discharge Voltage (V)	Highest Pack Charge Voltage (V)	Highest Pack Discharge Current (A)	Highest Pack Charge Current (A)	Highest Cell Discharge Temperature (°C)	Highest Cell Charge Temperature (°C)
1*	27.3	43.0	25	10	68	54
2+	27.5	42.3	14	4	-	-
3	26.7	43.4 / 53.7 **	25	5	40	51 / 176 **
4+	19	30.1	30	5	53	28
5	36.3	54.6	40	14	68	48.5
7*	30.7	42.7 / 55.0 **	40	40	38	53 / 120 **
8	26.7	44.4	45	14	65	60
9	29.7	42.7	40	10	42	38

* No thermistor fitted
\+ MCU fitted, in addition to cell-monitoring ASIC
** Values after " / " are following MOSFET failure, prior to thermal runaway

In Table 66, the data from Table 65 are converted to percentages of the relevant component limits, which in most cases are from the cell datasheet. In products #7, #8 and #9 the BMS label states current limits, which are lower than the cell limits, so these are used instead. The temperature values in Table 66 are expressed as a percentage of the values in °C, rather than absolute temperature.

Table 66: Extremes of Voltage, Current and Temperature, as a Percentage of the Component Limits

#	Lowest Pack Discharge Voltage	Highest Pack Charge Voltage	Highest Pack Discharge Current	Highest Pack Charge Current	Highest Cell Discharge Temperature	Highest Cell Charge Temperature
1*	109%	102%	83%	199%	113%	120%
2+	100%	101%	70%	160%	-	-
3	97%	103 / 128% **	208%	83%	65%	113 / 391% **
4+	109%	102%	121%	61%	88%	62%
5	105%	100%	103%	233%	113%	108%
7*	97%	104 / 134% **	160%	400%	63%	118 / 267% **
8	107%	106%	180%	280%	118%	133%
9	119%	102%	200%	200%	70%	84%

* No thermistor fitted
\+ MCU fitted, in addition to cell-monitoring ASIC
** Values after " / " are following MOSFET failure, prior to thermal runaway

The lower pack voltage limit (column 2 in Table 65 & Table 66) is a minimum limit, whereas as the other limits are all maximum values. Hence, in Table 66 column 2, a value of >100% is safe, whereas for the other columns, a value <100% is safe. To determine the green / amber threshold, WMG has allowed small deviations from the nominal limits, based on possible measurement error in both the WMG instrumentation and the BMS. The thresholds between amber and red have been decided based on the safety-criticality of each limit. In general, WMG regards charging voltage, current and temperature limits as more critical for safety than the equivalent discharge limits. Further justification for the red/amber/green thresholds are provided in the following paragraphs.

The values for "Lowest Pack Discharge Voltage" (column 2) are shown as green for all eight products: They all have appropriately calibrated under-voltage cut-off values, allowing a small margin for measurement error. The lower voltage limit is not as safety critical as the upper voltage limit, so a wider margin has been used for the green category.

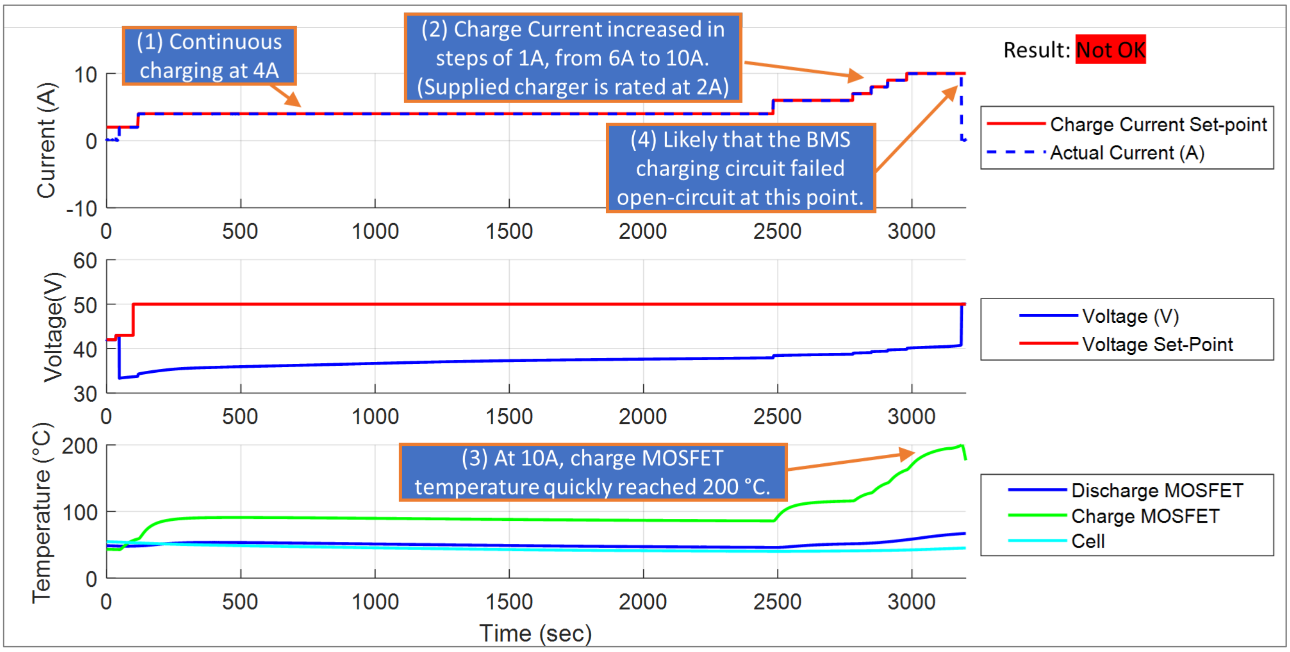
As mentioned in Section 11.2.2, the "Highest Pack Charge Voltage" (column 3) is particularly critical for safety, to avoid electrolyte reactions. Therefore, only values up to 102% have been categorised as green, up to 104% as amber, and 105% upwards as red. Most products have reasonably effective charging voltage limits, but products #3 and #7 are both categorised as amber, even before their MOSFET failures. After the MOSFET failures induced by abuse testing, neither could prevent over-voltage and therefore both are categorised as red. Product #8's limit was too high at 44.4 V (4.44 V/cell): In WMG's view, repeated charging to this voltage could eventually lead to cell failure.

For the "Highest Pack Discharge Current" (column 4), all the conversion kit batteries and the cheaper e-bike battery exceeded the limits by a concerning amount. The conversion kit batteries are the only ones for which the BMS label states a discharge current limit, and in each case this limit is lower than the pack limit calculated from the cell datasheet: The limits shown on the BMS labels of products #7, #8 and #9 are 25 A, 25 A and 20 A respectively, whereas the limits calculated from their cell datasheets are 60 A, 41 A and 30 A respectively. It is surprising and perhaps misleading that a BMS label should state a current limit, and yet the BMS does not implement that limit. The implication is that the BMS manufacturer expects the battery manufacturer to ensure that the BMS limit is respected by some other means, for example by placing the responsibility on to the charger and/or motor manufacturer. In WMG's view, this is an unreasonable expectation.

For the "Highest Pack Charge Current" (column 5), the story is similar: the conversion kit batteries and the cheaper e-scooter battery showed no evidence of a charge-current limit. In the more expensive e-scooter battery (product #2), the BMS limited the current to 4 A which is 60% higher than the limit calculated from the cell datasheet. This is partly a reflection of the conservative limits on the datasheet of the cell used in this product but is nevertheless somewhat concerning. In the cheaper e-bike battery (product #3), charging was not performed to as high a current as desired, because the BMS charging MOSFET repeatedly failed closed due to over-voltage before higher currents could be tested (See Figure 81).

In products #1 and #7, the absence of a charging current limit resulted in over-heating of the charging MOSFET, such that the MOSFET exceeded its temperature limit of 150 °C, resulting in the MOSFET failing short-circuit, but with a much higher resistance than before it failed. This failure mode has very severe consequences: It means that the BMS is no longer able to open the MOSFET, so it continues to conduct current from the charger, irrespective of whether voltage, current or temperature limits are exceeded. The increased resistance, after MOSFET failure, results in even more rapid self-heating of the MOSFET: In product #1, the MOSFET reached 200 °C, and in product #7 it reached over 400 °C. In both products, the charging MOSFET failure allowed uncontrolled over-charging of the cells. In product #7 this eventually led to thermal runaway which destroyed the entire battery. It is important to note that such a MOSFET failure will likely not be apparent to the consumer, unless the BMS has a means to diagnose the failure and inform the consumer, for example by displaying an error on a handlebar-mounted display screen. In cases of extreme over-temperature of the MOSFET, the consumer may become aware due to the unpleasant odour of pyrolised BMS components and circuit-board (as occurred in product #7), but this is not guaranteed. The battery will continue to be able to power the PLEV and to be charged, but without the protection of the MOSFET, the battery is far more vulnerable to over- or under-voltage, over-current and over-temperature. MOSFET failure also increases the likelihood of the consumer being exposed to the battery voltage by touching the battery terminals, for example when removing the battery from the PLEV to attach it to a charger. In the case of PLEV batteries that contain hazardous voltages (see Section 7.1.6), this could present a severe risk to human health.

Figure 76 shows the data recorded during the charging over-current test on Product #1. The supplied charger for this product is rated at 2 A, and the maximum pack charging current based on the cell datasheet is 5 A. However, the BMS did not intervene when the charging current exceeded this level. For the first 2500 seconds, charging is performed at 4 A. At this temperature, the charging MOSFET temperature already reaches 90 °C. Given the close proximity of the BMS MOSFETs to the cells, this risks heat conduction which could over-heat the closest cells. At around 2500 sec, the charging current is increased in steps, and from 3000 sec onwards it is 10 A. Each step of current increases the charging MOSFET temperature, which quickly reaches 200 °C at 10 A. This is well over the MOSFET's maximum allowable temperature of 150 °C. In this test, a link component in the charge circuit of the BMS became open circuit, because one of the solder joints melted. This prevented further charging but is not a robust protection mechanism. After testing was completed, the solder joint was found to have reconnected, and charging would have been possible.


(1) Continuous charging at 4A

(2) Charge Current increased in steps of 1A, from 6A to 10A. (Supplied charger is rated at 2A)

(3) At 10A, charge MOSFET temperature quickly reached 200 °C.

(4) Likely that the BMS charging circuit failed open-circuit at this point.

Result: Not OK

Figure 76: Product #1 Charging Over-Current Test

Figure 77 shows a similar charging over-current test performed on product #7. The supplied charger for this product is rated at 3 A. The product's on-line listing stated that the maximum charging current should be 5 A, and the maximum pack current based on the cell datasheet is 10 A. However, as with product #1, the BMS did not intervene when the current was increased beyond this level. In Figure 77, it can be seen that the charging current was increased in steps up to 35 A, to determine whether any BMS intervention would occur. This caused the charging MOSFET temperature to reach 150 °C, at which point the MOSFET failed short-circuit, but its resistance increased by approximately 2000%. This caused the sudden increase in MOSFET temperature at around 2930 seconds. The temperature continued to increase to over 400 °C, well above the typical 300 °C temperature for circuit-board pyrolysis, which would render any other BMS safety measures ineffective. In this test, the solder joint at the charge cable connection to the BMS failed, which prevented further charging. The pack voltage had already reached 44.5 V, well above the maximum allowable 42.0 V.

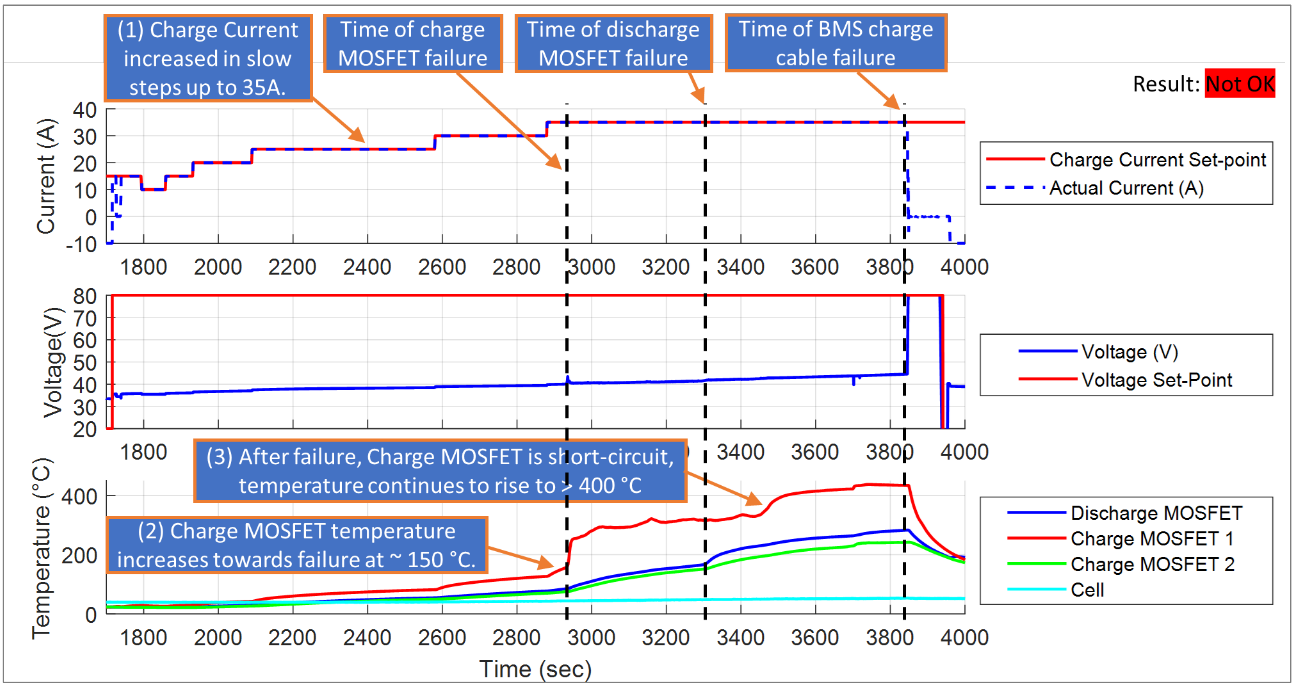


Figure 77: Product #7 Charging Over-Current Test

The damage to the BMS is shown in Figure 78, after the BMS heatsink was removed:

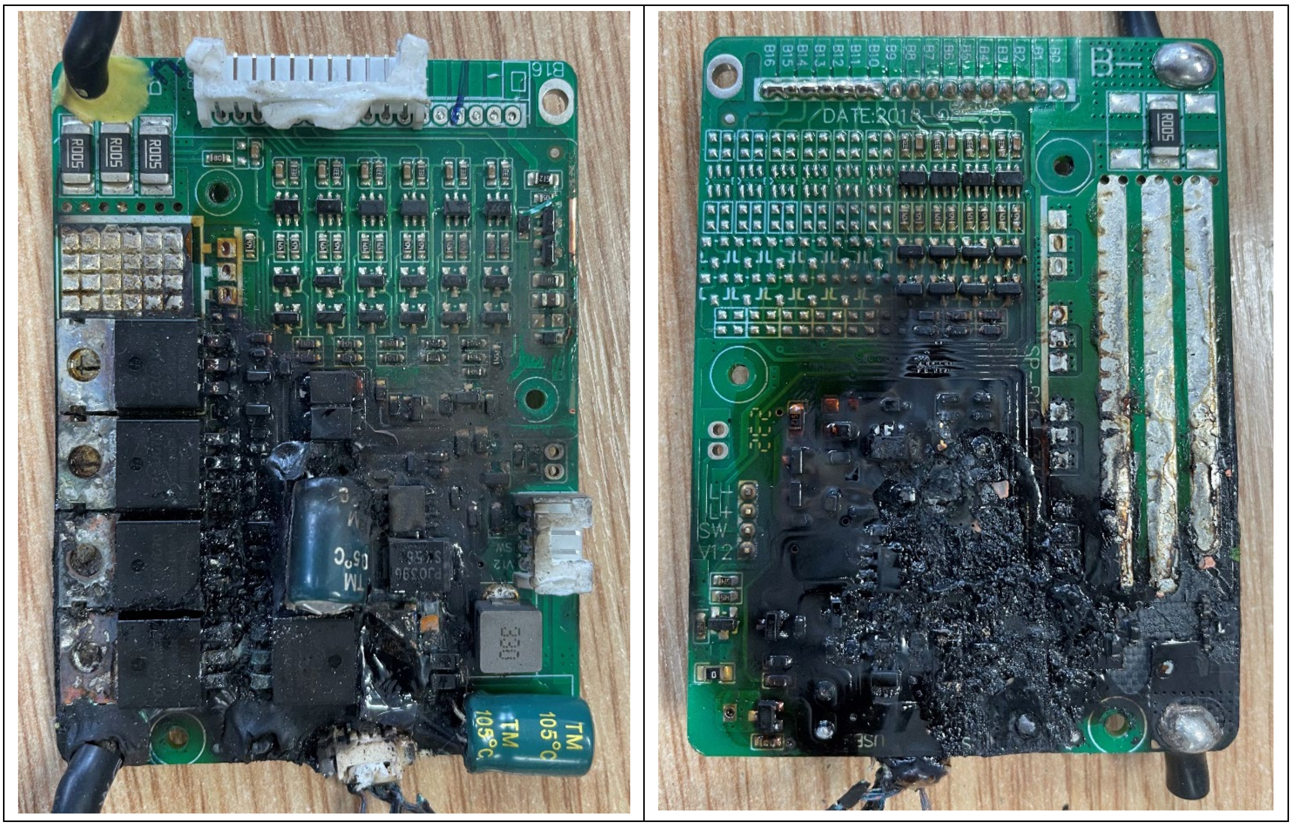


Figure 78: Heat Damage to the BMS of Product #2 after the Charging Over-Current Test

WMG recognises that the 35 A charging test condition above is extreme. Whilst there are many chargers available which are have current ratings higher than the chargers supplied with these products (1.3 A to 3.0 A), there are few that exceed 25 A. It could therefore be argued that the failure seen in product #7 above is unlikely to happen in the real world. However, the absence of a BMS current limit means that the cell datasheet limit would be exceeded with any current over 10 A. Furthermore, the proximity of the BMS MOSFETs to the cells, in product #7 and many of the other products here, means that the elevated MOSFET temperatures could heat adjacent cells to above their safe limits, even if the MOSFETs were well below their own temperature limits. Therefore, even if the MOSFETs themselves did not initially fail, there are at least two ways in which the absence of current limits could be expected to lead to cell failure.

In slightly different circumstances from the test in Figure 77, the pack voltage could have been significantly higher and resulted in thermal runaway. In an earlier test on another example of product #7, a similar MOSFET failure is believed to have occurred (although in that example, the MOSFET temperatures were not measured) and the pack voltage reached around 53 V, precipitating thermal runaway. In a later test on a third example of product #7, the pack reached around 52 V, but the pack did not initially undergo thermal runaway. However, over the following 50 minutes, during which there was no charging, the cells self-heated from 50 °C to 120 °C, at which point thermal runaway occurred.

This demonstrates that an over-charged battery can eventually go into thermal runaway, even after charging has been stopped. This is an important observation, because of the implications for consumers. Information campaigns and manufacturer advice already advise that PLEV batteries should not be left on charge unattended, but this advice may give consumers the impression that the battery is safe, once the charger is switched off or unplugged. However, the result above shows that, if the cells have become over-charged prior to the end of charging, they may undergo thermal runaway a considerable time later.

Figure 79 below shows images extracted from the video taken of the thermal runaway of the third example of product #7 that was tested. The first image illustrates the rapid evolution of smoke. Although small wisps of smoke had been visible for over forty seconds earlier, this image is within 1 second of the first audible explosion. The second image, around one second later, shows sparks ejected through the battery casing from one of the cells undergoing thermal runaway. It is common for small cylindrical cells in thermal runaway to eject their contents from the steel cell casing. In this example, these punched multiple holes in the plastic casing of the battery. The final two images, around forty seconds later, show the ferocity of the flames and flying debris, as well as the dense smoke that has filled the test chamber.

Figure 80 shows photos taken after the test chamber extraction system had cleared the smoke and it was safe to enter the chamber. Some cells remain in clusters, attached together by the busbars, but remains of small clusters and individual cells were scattered across the test chamber, along with fragments of the jellyroll of various cells. Typically, the cathode and anode active materials are burned away, the aluminium foil has melted or burned (aluminium alloys typically melt at 500-600 °C), and only the copper foil remains recognisable, due to its higher melting temperature of approximately 1085 °C. The products of combustion left a residue of soot all over the floor of the chamber. Such residue may be harmful, and after such tests, it is carefully removed while wearing appropriate personal protective equipment.

Subsequent to the test above, thermocouples were installed around the periphery of the test chamber, to measure the temperature of the gas in the room. During a test on product #8, which went into thermal runaway during a test to bypass the BMS protective circuits, the chamber temperature was measured at above 200 °C, while the surface temperature of the cells reached >1300 °C during some thermal runaway tests. This, combined with the toxicity of the gas ejected from cells, illustrates how hazardous an enclosed space can become when a PLEV battery undergoes thermal runaway.

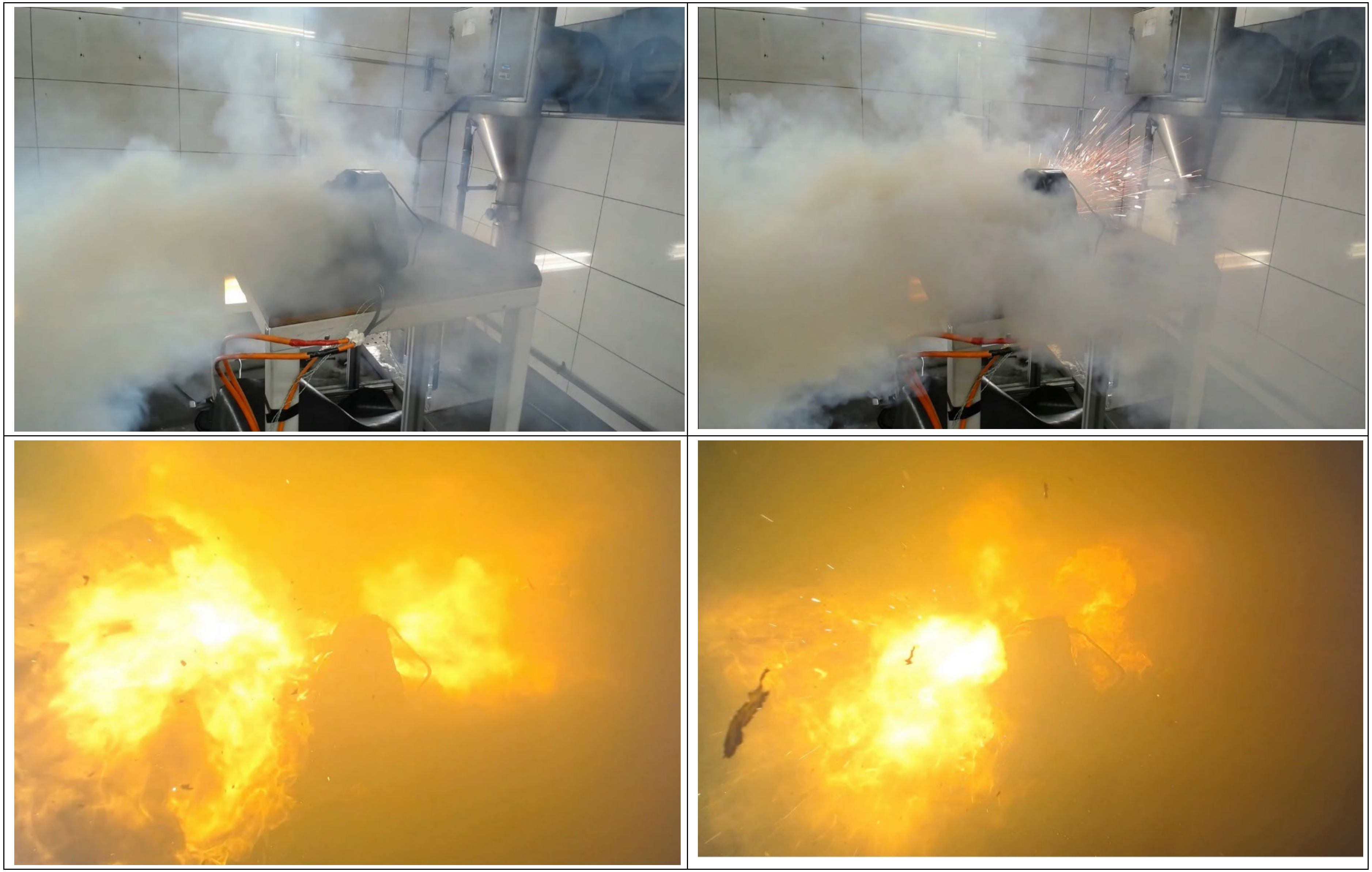


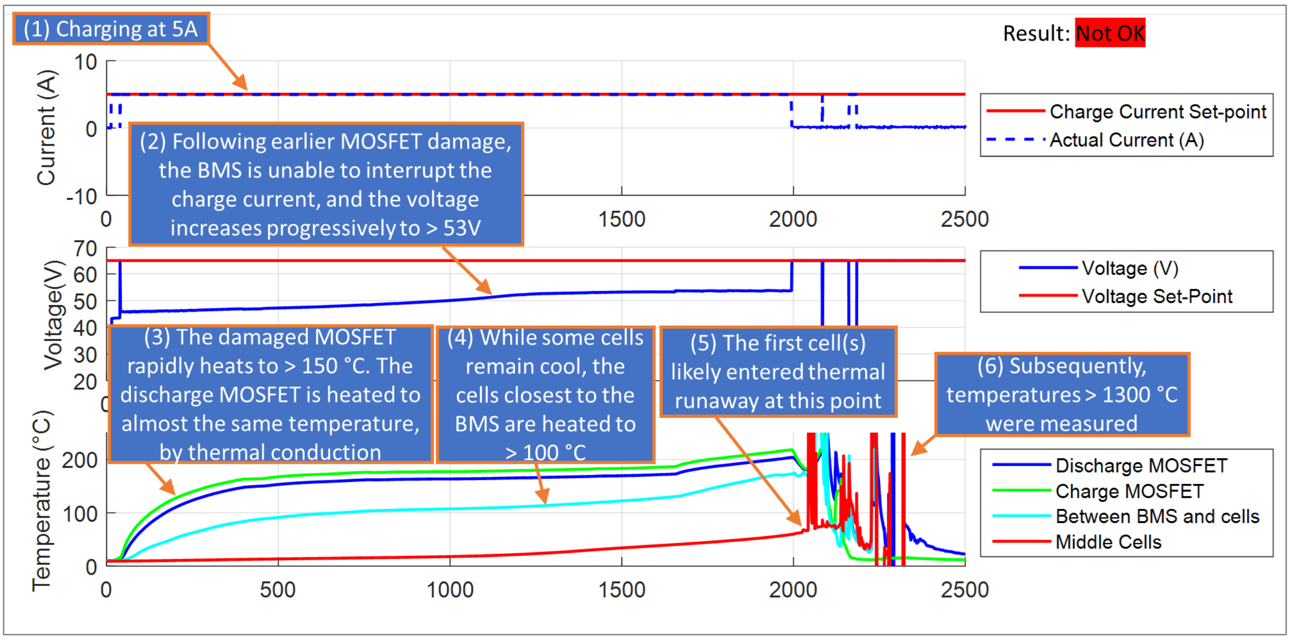
Figure 79: Still Images Extracted from Video of Example 3 of Product #7 in Thermal Runaway
(at intervals of 1 sec, 2 sec, 40sec and 41 sec after the first audible explosion)

Figure 80: Photos of the Remains of Example 3 of Product #7, After Thermal Runaway

In product #3, the charging MOSFET appeared to become damaged as a result of exposure to high voltage from the power supply, rather than due to over-heating. The over-voltage test imitates what would happen if the battery were charged with an incorrect charger, rated for a voltage that is double the maximum charging voltage of the battery (limited by the 80 V upper limit of the test equipment). This test was conducted on all batteries. All of them interrupted charging when over-voltage was applied (see Table 65 & Table 66), but product #3 was the only one to sustain obvious MOSFET damage from exposure to excessive voltage. This was first observed when the battery was exposed to 70 V (167% of the maximum battery voltage). The test was then repeated on a second sample of the battery, increasing the applied voltage in 5 V increments from 45 V up to 65 V. This second example failed in the same way as the first, after exposure to 65 V (155% of the maximum battery voltage). There is no clear explanation for this, as the MOSFET datasheet suggests that it should have survived. Nevertheless, the symptoms shown by the charge MOSFET in product #3 were similar to those in products #1 and #7 that were damaged by over-heating: The MOSFET failed short-circuit with an increased resistance by approximately 650%. As with products #1 and #7, this allowed the battery to be over-charged until thermal runaway occurred and destroyed the entire battery.

In the second example of product #3 that was tested, instrumentation thermocouples were inserted in two cell locations, one remote from the BMS and one adjacent to the BMS. The latter was close to the thermistor used by the BMS. This allowed an evaluation of how over-heating of the BMS affected the temperature of the adjacent cells.

Figure 81 below shows the results of the over-charge test after the charge MOSFET was damaged by over-voltage. The test ends with thermal runaway that destroyed the battery. The temperature data show that the temperature of the cells close to the BMS was far higher than the cells that are further from the BMS and tracks the temperature of the BMS MOSFETs. This clearly illustrates that BMS temperature can have a strong influence on the temperature of adjacent cells.



(1) Charging at 5A

Result: Not OK

(2) Following earlier MOSFET damage, the BMS is unable to interrupt the charge current, and the voltage increases progressively to > 53V

(3) The damaged MOSFET rapidly heats to > 150 °C. The discharge MOSFET is heated to almost the same temperature, by thermal conduction

(4) While some cells remain cool, the cells closest to the BMS are heated to > 100 °C

(5) The first cell(s) likely entered thermal runaway at this point

(6) Subsequently, temperatures > 1300 °C were measured

Figure 81: Product #3 Over-charge Test, Following Charge MOSFET Damage Caused by Over-Voltage

In product #5, no thermal runaway occurred, but the BMS permitted up to 14 A continuous charging (it interrupted 16 A charging within 2 seconds), compared to the pack limit of 6 A calculated from the cell datasheet. 14 A charging caused the cells to reach over 48 °C before the BMS intervened. This exceeds the 45 °C limit from the cell datasheet. The BMS allowed the cell current limit to be exceeded by 133%, which in WMG's view is very concerning. It is also notable that the 14 A charging current did not cause the charging fuse, marked as a 5 A fuse, to blow. Based on typical fuse characteristics (Littelfuse Inc. (undated), WMG would have expected the fitted fuse to blow in less than 1 second when subjected to 14 A, but during testing 14 A was sustained for approximately 10 minutes without blowing the fuse. This calls into question the quality of the fuses fitted.

Product #5 did exhibit charging and discharging over-temperature protection. In a test during which the temperature was too high for the BMS to allow charging, the power-supply voltage was inadvertently set slightly lower than the battery voltage, while it was connected to the charging port. This resulted in discharge through the charge port, as the BMS in this product does not have a diode to prevent reverse current in the charge circuit. Although the discharge current was low (3-5 A), it caused significant heating of the charge MOSFETs which quickly reached 75 °C (see Figure 82). This is well below the MOSFET temperature limit of 175 °C but had the power-supply been set to a lower voltage, the current would have been higher, and the MOSFETs could have over-heated. **While the test was unintentional, it illustrated a potential failure mode which could occur in the real world, if an owner tried to charge a battery with a charger which had too low a voltage rating for the battery.**

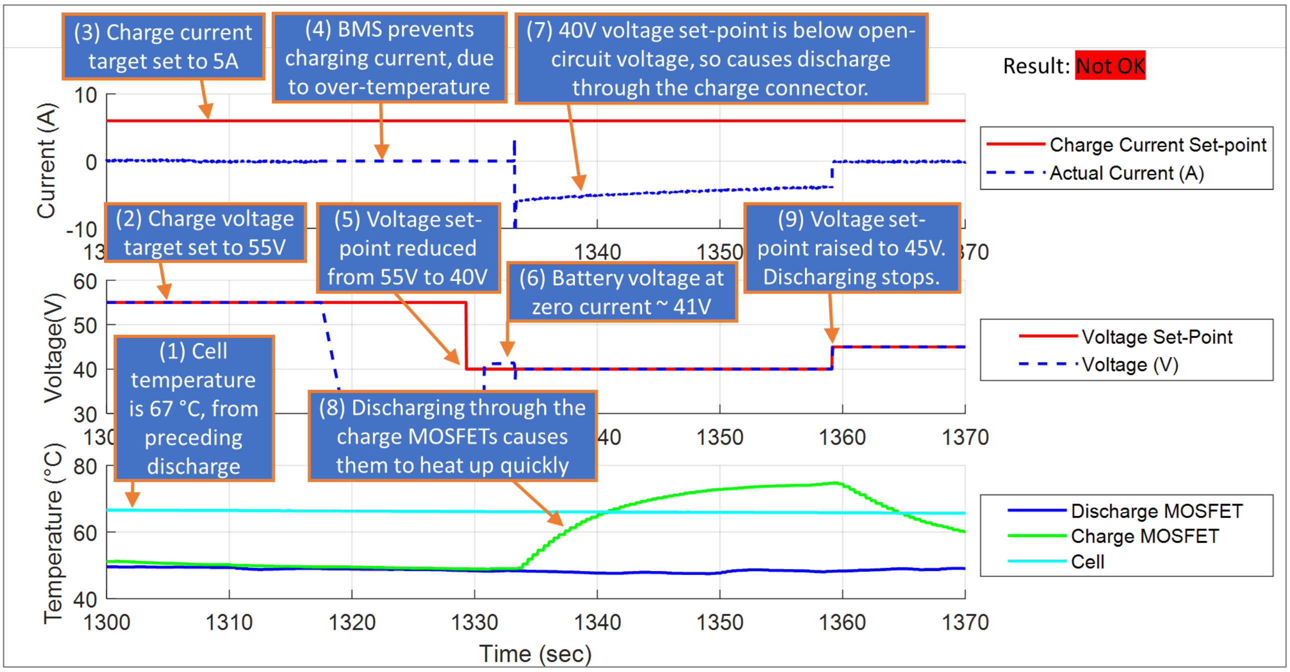


Figure 82: Product #5 Discharge through the Charge Connector, Due to Absence of Charging Circuit Diode

In product #9, no thermal runaway occurred, but the BMS permitted up to 10 A continuous charging (it interrupted 12 A charging within 1 second). The cell datasheet implies that charging current should be limited to 5 A. The cell datasheet also implies a 30 A discharge limit, but the BMS permitted 40 A (the highest value tested), during which the MOSFET temperatures were increasing rapidly. The 40 A discharge was not continued for long enough to determine the temperature the MOSFETs would have reached. A label on the BMS states that it is rated for a maximum of 5 A in charge and 20 A in discharge. It is therefore very concerning that the BMS permitted current that was double its rated limit in both charge and discharge.

In product #8, the cell datasheet charge and discharge current limits (10 A and 41 A respectively) were also exceeded but by smaller amounts. However, as with product #9, the limits stated on the BMS label (5 A charge and 25 A discharge) were grossly exceeded, since the currents measured during testing were 14 A in charge and 45 A in discharge. Furthermore, although the BMS was fitted with a thermistor, there was no evidence from the testing that the BMS interrupted either charge or discharge due to over-temperature. During charging, the cell temperature reached 60 °C, well above the datasheet limit of 45 °C. The final test of product #8 involved charging via the discharge connector, which is a way to deliberately bypass the normal BMS protection. In this test, the pack underwent thermal runaway.

Only products #2 and #4 came close to complying with all the cell datasheet limits. Both of these batteries were also subjected to final tests for which the BMS protection was bypassed. In both cases, it appears that protective mechanisms in the cells (likely Current Interrupt Devices (CID) or Positive temperature Coefficient (PTC) devices) acted to prevent thermal runaway.

Amongst all the tests that were conducted, when data indicated that the CID or PTC had activated in some cells, this did not occur until the cells had reached 4.8 - 5.1 V. WMG considers cells at such elevated voltage to be potentially hazardous. When cells did go into thermal runaway, this typically occurred at around 5.2 V, so the CID/PTC activation appears not to occur until the cell is very close to a thermal runaway condition. As explained in Section 3.4, the CID is activated by a build-up of gas pressure in the cell. This build-up occurs over an extended period, depending on the rate of chemical reactions within the cell, so if over-charge occurs rapidly, the pressure build-up and the CID activation may lag behind. However, in the WMG tests, the over-charge occurred slowly over an extended period, so WMG does not believe the lag effect would have been significant. While it is true that these cell-level safety devices prevented thermal runaway in some tests, in WMG's opinion they should not be relied upon.

Table 67 below summarises the outcome of the tests of voltage, current and temperature limits, including the BMS bypass over-charge tests.

Table 67: Outcome of Voltage, Current and Temperature Limit Tests

#	Final Test Outcome	Comments
1*	BMS damaged. Cell CIDs likely activated.	MOSFET damaged due to lack of over-current protection. In BMS bypass test, current dropped to zero at 5.0 V/cell.
2+	BMS not damaged. Cell CIDs likely activated.	BMS protected cells successfully. In BMS bypass test, current dropped to zero at 5.1 V/cell.
3	BMS damaged. Battery destroyed by TR.	MOSFET damage caused by exposure to over-voltage. This allowed over-charge leading to thermal runaway.
4+	BMS not damaged. Cell PTCs likely activated.	BMS protected cells successfully. In BMS bypass test, current dropped to 0.25 A at 5.1 V/cell.
5	BMS not damaged. Cell PTCs likely activated.	BMS charge current limit too high, but no MOSFET damage. In BMS bypass test, current dropped to zero at 5.1 V/cell.
7*	BMS damaged. Battery destroyed by TR.	MOSFET damaged due to lack of over-current protection. This allowed over-charge leading to thermal runaway.
8	BMS not damaged. Battery destroyed by TR.	BMS current limits too high, but no MOSFET damage. In BMS bypass test, cells were not protected from TR.
9	BMS not damaged. Cell PTCs likely activated.	BMS current limits too high, but no MOSFET damage. In BMS bypass test, current dropped to zero at 4.8 V/cell.

* No thermistor fitted

\+ MCU fitted, in addition to cell-monitoring ASIC

Once again, there is a clear correlation between product price per kWh and whether the product complies with the expected voltage, current and temperature limits. The lower-cost e-scooter and e-bike and all of the conversion kit batteries exceeded various limits by very concerning amounts. Although only three products (#3, #7 and #8) underwent thermal runaway, WMG believes that the poor implementation of voltage, current and temperature limits in products #1, #5 and #9 means that there is a significantly elevated risk that those products might also undergo thermal runaway if further repeat testing were performed. Only product #2 (the higher price per kWh e-scooter) and product #4 (higher price per kWh e-bike) demonstrated acceptable BMS active protection and both also demonstrated effective passive protection from the cell-level protective devices.

11.4.4 Effectiveness of Cell Passive Protection Devices

While the effectiveness of the BMS active protection has been covered thoroughly above, it is also important to review the effectiveness of the passive protection mechanisms in the cells. In the scope of this project, WMG has not performed CT-scans or disassembly of the cells to determine what safety devices are present. However, the results of the BMS bypass tests provide a good insight into these devices. Typically, WMG would expect to find a Current Interrupt Device (CID) and possibly a Positive Temperature Coefficient (PTC) device. The CID is activated by elevated internal pressure in the cell and disconnects the internal positive electrode of the cell from the external positive terminal. The CID is non-reversible: Once activated, the cell is permanently electrically isolated. The PTC is activated by elevated temperature. It increases the electrical resistance to substantially limit the current passing through the cell. It is reversible: If the temperature reduces, then the resistance will drop again.

Since the PLEV products have cells connected in parallel, the CID of all parallel-connected cells in one group need to activate for the pack current to drop to zero. It is unlikely that they will activate simultaneously, but when one activates, the current in the parallel cells will increase, accelerating the over-charge of those cells. Activation of their own CIDs may lag behind somewhat, as explained above, but since parallel cells are inherently at the same voltage, they would all already be over-charged, so the lag is not expected to be large, and when the CIDs in all parallel cells have activated, the pack current will drop to zero. The same applies to PTCs, except that the pack current will not drop to zero but will nevertheless be substantially reduced.

In products #1, #2, #5 and #9, the evidence suggests that some of the cell CIDs activated: In each case, during the BMS bypass tests, when the pack had been over-charged at around 4.8 to 5.1 V per cell, the current abruptly dropped to zero. In product #4, the current dropped from 2 A to 0.25 A, which suggests that the PTCs activated. In each of these products, the activation of the cell passive protection devices was sufficient to prevent thermal runaway.

In products #3, #7 and #8, the cells did go into thermal runaway. It cannot be determined from the results whether they had no cell passive protection, or whether such protection was ineffective.

It is important to emphasise that, in the products where the cell passive protection prevent thermal runaway, that the internal voltage of the cells was still around 5 V, at which condition the cells are in a hazardous over-charged state. As seen with product #7, over-charged cells can undergo thermal runaway when they are no longer being charged. The same could theoretically have happened with the cells in products #1, #2, #4, #5 and #9 after the BMS bypass tests. If the CID has activated, the cells can be neither charged nor discharged. In the laboratory environment, WMG has protocols for handling and disposing of batteries in this condition. However, a consumer could not be expected to know the hazardous condition of the battery nor to know how to handle or dispose of it safely. The consumer would find only that their battery could no longer function, but it is likely that they would have no more information than this. Therefore, while CID and PTC devices are undoubtedly a good feature, they are not a substitute for comprehensive BMS active protection, which should prevent over-charge from ever occurring.

The BMS bypass tests demonstrate what could happen if the BMS active protection fails, or if a consumer tampers with the battery to bypass the BMS. It is encouraging that the cell passive protection prevented thermal runaway in five of the eight products, including the cheaper e-scooter (product #1) and one of the conversion kit batteries (product #9). However, the products in which cell passive protection did not prevent thermal runaway were the cheaper e-bike (product #3) and two of the conversion kits batteries (#7 and #8). Once again, this appears to show some correlation between price per kWh and safety.

11.4.5 Short-Circuit Test Results

As explained in Section 11.2.5, the current during a short-circuit test far exceeds any operational current. As a result, in each short-circuit test conducted, whether or not a fuse was fitted, a component in the power-circuit acted as a fuse within a very short time. Whilst it would be preferable to have a fuse that blows to protect the rest of the components, none of the batteries tested exhibited hazardous behaviour during the short-circuit test. The batteries can therefore be said to fail safely in an external short-circuit test.

Figure 83 shows an example of a typical short-circuit test result, from product #3: The current peaks at around 400 A but persists for less than 0.1 seconds before part of the circuit fails. For this example, Figure 84 shows that one of the BMS MOSFETs ruptured during the brief short-circuit current pulse, although this did not open the circuit. In this and other examples, a busbar or cable solder connection acted as the fuse.

Overall, WMG has no further observations as a result of the short-circuit tests.

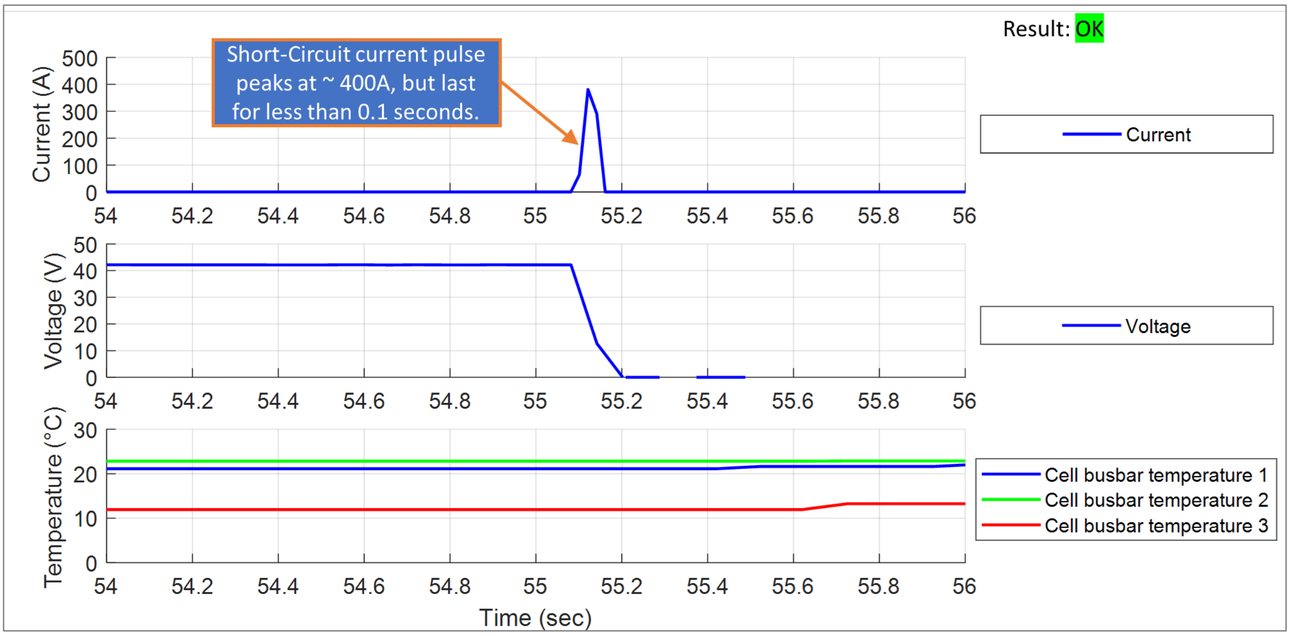


Figure 83: Short-Circuit Test Result from Product #3

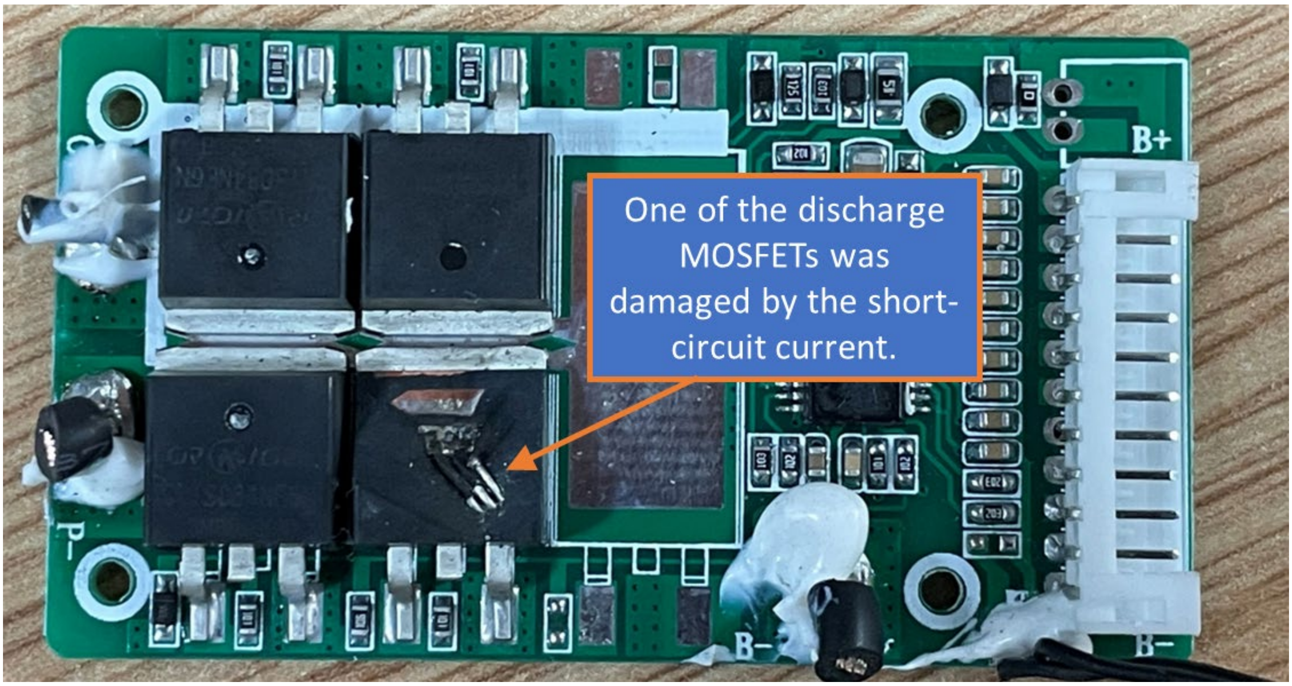


Figure 84: BMS from Product #3, showing the MOSFET that failed during the Short-Circuit Test

11.5 Product Abuse Testing Summary

Abuse testing was conducted on eight of the nine products purchased. The remaining product was not able to be tested, because charge and discharge was inhibited by the BMS unless the communication interface of the e-bike system was present. Unfortunately, WMG was unable to replicate the communication interface since it is proprietary.

The key outcomes and lessons learned from the testing are as follows:

- Only one product (#6) had a communication interface which prevented efforts to charge and discharge the battery without it being connected to the matching PLEV system. While the other BMS protection mechanisms on this product were not able to be tested, the communication protocol was an effective “first line of defence”.
- Only three of the eight tested products (#2, #4 and #5) showed clear evidence that the BMS had the expected functionality to implement limits for voltage, current and temperature. These three were the higher price per kWh e-scooter and the two higher price per kWh e-bikes. The lower price per kWh e-scooter and e-bike and the three conversion kit batteries all had significant shortcomings in BMS safety functionality.
- None of the products adhered strictly to all the cell datasheet limits. Only two products (#2 and #4) implemented limit values which gave no cause for serious concern.
- The greatest concern relates to current and temperature limits. In several products, the absence of suitable current limits resulted in the cell datasheet limits being exceeded by large margins, but also caused over-heating of the BMS MOSFETs.
- In all the products tested, the MOSFETs are the only means by which the BMS can actively interrupt the charge or discharge current. They are the “first line of defence”. Only product #2 has any redundancy in the MOSFETs, to ensure that the BMS can interrupt the current in the event of a single-point MOSFET failure.

- Some of the products include a charge and/or discharge fuse to act as a “second line of defence”. However, none of the fuses blew during over-current testing: They only blew during short-circuit tests.
- The test data from three of the batteries (#1, #3 and #7) demonstrated what may happen when a MOSFET is damaged by over-temperature or over-voltage: In these test cases, it fails closed, meaning that the BMS can no longer interrupt the current. Although the MOSFET is no longer able to open, the electrical resistance of the MOSFET increases significantly compared to before the failure, so it then generates more heat, and its rate of temperature rise increases. The temperature continues to rise until either another part of the battery fails open-circuit (interrupting the current) or the cells enter thermal runaway. In theory, this could even occur in normal use due to a defective MOSFET, rather than in conditions of foreseeable misuse, although this is expected to be a statistically rare occurrence.
- The test data also show that in most products there is “close thermal coupling” between the charge and discharge MOSFETs, because they are located close together on the BMS PCB. This means that, for example, if a charge MOSFET over-heats, it is also likely that the discharge MOSFETs will over-heat, even though they are not delivering any current at the time. This may also cause over-heating of other nearby BMS components, although the testing only measured MOSFET temperatures.
- Over-heating of the MOSFETs therefore has very severe implications: In most products, a single MOSFET failure means that the only line of active defence against electrical abuse is lost, and the single-point failure often cascades to become a multi-point failure. For batteries in which the MOSFETs are located close to some of the cells, tests showed that the MOSFETS may also cause excessive heating of the cells, potentially causing them to enter thermal runaway.
- In two of the eight products (#5 and #8), the layout of the power-circuit means that, with an undamaged BMS, discharging through the charge connector is possible. A test on product #5 showed that this results in rapid heating of the charge MOSFET. In theory, this is another way that the MOSFETs could fail through over-heating.
- In five products, cell temperatures were measured that exceeded the charge or discharge limit, as applicable, from the cell datasheet. In most cases, this did not lead to thermal runaway, but it nevertheless constitutes abuse of the cells.
- The BMS bypass tests showed that in five of eight products, the cell passive protection (CID and/or PTC) was effective in preventing thermal runaway. However, these passive protections did not activate until the cells had reached approximately 5 V. In this condition, the cells could potentially still undergo thermal runaway, even though the charging current has been interrupted. This was shown in one of the tests on product #7, which underwent thermal runaway approximately one hour after the charging current was stopped.

The charging failure modes that have been revealed by the abuse testing would not occur in normal use of the battery with the correct charger, if the BMS is fault-free. However, if an owner of some PLEV products were inadvertently or deliberately to use an incorrect charger (one that supplies too low or too high voltage, or too high current), or if a single-point failure occurs in the BMS, then the charging failure modes could occur. Similarly, if an owner fitted a motor that exceeds the discharge current for which the battery is intended, discharge over-current could occur in many of the products.

The key suggestions emerging from the abuse testing are:

- **WMG suggests that standards for PLEV batteries, such as EN 50604-1, should be updated to require that all PLEV batteries shall be tested to demonstrate compliance with the voltage, current and temperature limits provided on the datasheets for the cells and the power-circuit components such as the BMS MOSFETs. If the battery manufacturer wishes to exceed these limits, they should obtain written consent from the component manufacturer or be required to produce testing results that support the decision.**
- **WMG suggests that standards for PLEV batteries, such as EN 50604-1, should be updated to require that all PLEV batteries should be tested to demonstrate protection against reverse current-flow through the charge and discharge circuits, or if reverse current flow is permitted, it should be demonstrated that this does not result in over-heating of the power-circuit components or contravening the cell voltage, current and temperature limits.**
- **WMG suggests that standards for PLEV batteries, such as EN 50604-1, should be updated to require that all PLEV batteries should be tested with temperature measurement of the cells located closest to the main sources of heat in the power-circuit, such as MOSFETs, to demonstrate that the heat transfer from these power-circuit components does not cause the adjacent cells to exceed the cell charge or discharge temperature limits. This should include test conditions with foreseeable single-point failure of these heat sources, such as a short-circuit failure of a MOSFET.**
- **WMG suggests that standards for PLEV batteries, such as EN 50604-1, should be updated to include design guidelines for PLEV batteries which recommend that at least one BMS thermistor should be placed on the cell(s) closest to the critical power-circuit components such as MOSFETs, or other locations identified through testing to be experience the highest temperatures, to maximise the likelihood that cell hot-spots are identified by the BMS, and the cell limits are respected accordingly.**
- **WMG suggests that standards for PLEV batteries, such as EN 50604-1, should be updated to include design guidelines for PLEV batteries which state that cell passive protection devices, such as CID and PTC, should not be seen as a substitute for comprehensive BMS protection, because cells can still be in a hazardous condition after these devices have activated. This emphasises the value of redundancy in the BMS, to ensure that single-point BMS failure does not result in reliance on the cell passive protection to prevent thermal runaway.**

12 Summary of Suggestions in this Report

The table below collates all the WMG suggestions and related observations in this report:

#	Section Reference	Suggestion
1	6.7	WMG suggests that OPSS investigate options to ensure that all conversion kit batteries can be classified as partly completed machinery under the SMSR, or another means to ensure that conversion kit batteries are subject to the same legislative health and safety requirements and standards as those in complete PLEVs.
2	6.7	WMG suggests that OPSS investigate whether retailers, including online marketplaces, could be obliged to provide certain documentation, such as a DoC / DoI, assembly instructions, and a UN38.3 certificate for batteries, before a product can be offered for sale. In the case of online marketplaces, an obligation to include such documents in online product listings would provide a mechanism for the marketplaces to refuse listing to, or de-list, non-conforming products.
3	6.15.1	The existing PLEV standards do not include any requirements or test protocols concerning thermal propagation resulting from single-cell thermal runaway. WMG therefore suggests that OPSS explores what is required to introduce a thermal propagation requirement in existing or updated UK standards, similar to that in GTR20 / Reg100.03 or GB 43854-2024.
4	6.15.2	WMG suggests that OPSS investigate the feasibility and practicality of audible alarms in PLEV batteries, which would sound in case of detection of thermal runaway. The circuit for the alarm would be active at all times, unless the power consumption of the circuit created a risk of deep-discharge of the battery.
5	7.1.1	WMG suggests that the standards bodies consider adopting an approach wherein the safety requirements of the electric powertrain for all PLEVs are placed in a single standard, separate from other vehicle system requirements.
6	7.1.6	WMG suggests that standards for PLEVs should adopt the same definition for working voltage and the same thresholds to define high/hazardous voltage as are used in the Type Approval regulations for L, M and N category vehicles.
7	7.1.6	WMG suggests that the Scope section of all standards for PLEVs should unambiguously state the ac and dc voltage limits for which they are valid, and in the Rationale section should justify those limits, particularly where they do not align with thresholds defined in legislation or other electrical safety standards.

#	Section Reference	Suggestion
8	7.2.6	WMG suggests that a general Risk Assessment Standard, complementary to ISO 12100, should be developed with a focus on consumer products which use Lithium-ion or similar energy storage. This should provide examples of the hazards, hazardous situations and hazardous events that occur in a domestic setting, including those associated with storage and charging of batteries.
9	7.2.6	WMG suggests that Standards for PLEVs and their batteries should use the Standard in suggestion 8 above to define the risk assessment methodology, and should use a consistent approach to document hazards, including their relationship to the Essential Health and Safety Requirements of the Machinery Regulations.
10	7.3.1	WMG suggests that a consistent functional safety methodology should be applied to all PLEVs, irrespective of whether they are road-legal, because safety goals such as avoiding battery fires apply equally to all PLEVs, including when they are being charged.
11	7.3.10	WMG suggests that a thorough review of the functional safety requirements in UK standards for e-bikes, other PLEVs and their batteries should be undertaken, using comparable standards from other countries (notably UL 2849 in North America) and other industries (notably IEEE 1625 for computers and IEEE 1725 for mobile phones and ISO 26262 for automotive) to establish good practice.
12	7.4	WMG suggests that all Standards should include a section to unambiguously define the terms to be used and should be rigorously checked for correct usage. This may be achieved by reference to a separate document containing these definitions, such as the BSI Rules for the structure and drafting of UK standards (BSI Group, Nov 2022).
13	7.6.1	WMG suggests that a full charge-discharge cycle should be performed after mechanical shock / impact tests, to ensure that the battery either operates normally, or that charge and discharge are permanently inhibited.
14	7.6.1, 7.6.3	WMG suggests that the ingress protection requirement in EN 15194, for enclosures of electrical components in e-bikes, and the related requirement in EN 50604-1 for batteries, should be increased from IPx4 to at least IPx5, to ensure protection against jets of water. WMG further suggests that, subject to investigations to verify the factors most relevant to aging of PLEV battery casings, the EN 50604-1 ingress protection test on batteries should be conducted after a battery has completed and passed the environmental tests in Section 6 of the standard (vibration, shock, drop, exposure to sunlight) and Section 7 of the standard (dewing, thermal shock), to ensure that ingress protection is tested in a condition that approximates an aged battery.

#	Section Reference	Suggestion
15	7.6.4	WMG suggests that the stronger BMS requirements of EN 50604-1 should apply to all PLEVs.
16	7.6.4	In WMG's view, it is illogical for compliance with a standard to require a quality plan, but to make its implementation optional. WMG suggests that a production quality plan and its implementation relating to product safety shall be required for all PLEV batteries to comply with relevant standards.
17	7.6.7	WMG suggests a thorough review of PLEV battery standards alongside IEEE 1625 and IEEE 1725, to determine items that should be adopted and/or adapted from the IEEE standards, including consideration of two-fault scenarios.
18	7.8.3	WMG suggests the following items to be included in the definition of any test. Some standards do not consistently provide all the items below: 1. The number of samples to be tested. 2. The pre-conditioning required prior to the test (e.g. charging to 100% SoC, using the manufacturer's standard charging protocol). 3. The ambient temperature at the start of the test, and where appropriate, the soak duration and/or sample temperature stability criterion, to ensure the sample is stabilised at the correct temperature. In many cases, this temperature is maintained throughout the test, but some tests, such as thermal cycling, require the temperature to change during the test. 4. The post-test observation period and ambient temperature, during which the pass criteria must be met. 5. The pass criteria
19	7.8.3	WMG suggests that at least two complete charge-discharge cycles should be performed after environmental tests, followed by an observation period, and that a criterion for the discharge capacity should also be defined (e.g. >90% of the original discharge capacity of the cell). This, together with the other pass criteria (no leakage, no venting, etc.), demonstrates that the cell has not been adversely affected by the environmental test.
20	7.8.3	WMG suggests an observation period of at least 6 hours for abuse tests, considering that cells may remain in a domestic setting for some time after damage has occurred.
21	7.8.5	WMG suggests considering adding the UL2580 Projectile Test to those required for cells used PLEVs in the UK. This test is very relevant to the spread of fire to adjacent objects, when a PLEV fire occurs in a domestic setting.

#	Section Reference	Suggestion
22	7.9.1	WMG suggests that all PLEV batteries should undergo all of the tests listed in Table 39, with the exception of the Crush test, which should only apply for applications where physical damage can be anticipated from vehicle crash or from close proximity to the ground.
23	7.9.1	WMG suggests that standard organisations should consider a requirement for validation of current and voltage limits in the BMS, with reference to the limits defined by the cell supplier and suppliers of protective components such as the BMS MOSFETs. This includes any definition in limits as a function of temperature.
24	7.9.2	WMG suggests adopting the UL 2271 “combustible concentrations” criterion for all battery tests in future UK standards for PLEV batteries.
25	7.9.3	WMG suggests that EN 50604-1 should undergo a thorough revision to address the errors and inconsistencies in the current version.
26	7.9.3	WMG suggests that EN 50604-1 should be updated to include requirements for production quality of the cells and the battery pack.
27	7.9.3	WMG suggests that EN 50604-1 should be updated to include creepage and clearance distances.
28	7.10.1	WMG suggests that EN 17128 should be updated to ensure that non-e-bike PLEVs use equivalent battery safety requirements as EN 15194, while also recognising that the relevant battery standard EN 50604-1 has shortcomings which needs to be addressed.
29	7.11.1	WMG suggests that EN 15194 should be updated to require that all e-bike battery chargers shall comply with EN 60335 2 29:2021+A1:2021 as a minimum, irrespective of their output voltage, as an interim step prior to requiring battery-to-charger communication.
30	7.11.4	WMG recognises that a non-proprietary (industry-standardised) charger connector and communication specification, as suggested in ISO/TS 4210-10 Annex C, and mandated in the China-market standard GB 42296-2022, would significantly enhance the safety of e-bike and e-scooter charging.
31	7.11.4	WMG suggests that standards for batteries and chargers for UK PLEVs should consider and address the risks associated with unsuitable battery and charger pairing and consider the safety of the battery and charger as a system, to ensure that the charger abides by the current, voltage and temperature limits of the connected battery and the cells therein.
32	7.12.1	WMG suggests that the e-bike standard EN 15194 would benefit from a similar approach to vibration requirements as EN 17128, with different vibration spectra, dependent on the design (suspension, wheel size, tyre characteristic) of the e-bike.

#	Section Reference	Suggestion
33	7.12.1	WMG suggests that consideration is given to defining pass criteria for the vibration tests for all types of PLEVs, based on pre- and post-test low-magnitude sine-sweeps with accelerometers attached to the PLEV, as follows: • A limit on the change in amplitude and frequency of the resonances • A clearly defined functionality test after the vibration test, with relevant safety-based criteria. For example, two complete charge-discharge cycles of the battery, following by an observation period, with pass criteria of no venting, leakage, rupture, fire or explosion and no loss of electrical isolation.
34	7.12.4	WMG suggests that the deep-discharge test in EN 50604-1 should be reviewed and updated, and a rationale should be provided.
35	7.12.5	WMG suggests that charge and discharge over-current tests should be added to standards for all PLEV batteries, with tests performed at various temperatures, covering the operating temperature range of the battery and 5-10 K above and below that range.
36	7.12.6	WMG suggests that an imbalanced charging test should be included in all standards for PLEV batteries.
37	7.12.6	WMG suggests that all PLEV battery standards should include a BMS design requirement to include a cell balancing circuit. An accompanying test should be devised to validate the operation of the balancing circuit.
38	7.12.7	WMG suggests that a low-temperature test should be included in all PLEV battery standards, to ensure that charging is prevented by the BMS when the temperature is below the minimum allowed value for charging the cells.
39	7.12.8, 10.3.17	WMG suggests that labelling requirements for all PLEV batteries should be changed, to require the maximum charging voltage to be shown, and the nominal voltage should be removed, to avoid potential confusion for the consumer.
40	7.12.8	WMG suggests that OPSS consider an investigation of the technical and commercial feasibility of battery markings that are able to withstand battery fires, to aid post-fire identification.
41	8.3	In response to ESF Report recommendation: "OPSS should adopt the technical specification ISO/TS 4210-10:2020 as a designated standard to mitigate risks of dangerous compatibility and charging." - WMG suggests that a consensus needs to be achieved before the technical specification is adopted as a standard, and that efforts by standards organisations should be accelerated to revisit ISO/TS 4210-10:2020 alongside other standards such as EN 15194 and EN 17128.

#	Section Reference	Suggestion
42	9.11	WMG suggests that collection of data from PLEV fires attended by UK fire and rescue services needs to be improved, to assist with identification of brands and models involved, as well as the circumstances prior to the fire, for example whether the battery had been on charge. The National Fire Data Collection System, intended to go live in the summer of 2024, is expected to help. The impact of this system should be monitored.
43	9.11	WMG suggests that OPSS should consider creating a publicly available online portal, allowing consumers, fire and rescue services, and other relevant parties, to document PLEV thermal incidents.
44	9.11	WMG suggests that advice for consumers, about actions to reduce the likelihood of a PLEV fire, should be targeted at the societal groups found to be most at risk, for example gig-economy courier/delivery riders. This targeting should include translation of the advice into languages most relevant in local areas.
45	9.11	WMG suggests that OPSS should consider increased promotion of the publicly available "product recalls and alerts" database of unsafe and non-compliant products.
46	9.11	WMG suggests that third party testing or certification organisations should consider greater promotion of publicly available databases of PLEV products which have passed third-party assessment for compliance with specific battery-safety standards. Other stakeholders, including PLEV retailers, trade bodies and safety advocacy organisations should also promote these databases, to encourage public awareness.
47	9.11	WMG suggests that OPSS should consider the development of regulatory powers, to identify and prevent sale of unsafe products. Examples include: • High financial penalties for products that cause fires (e.g. through insurance claims or enforcement procedures). • Legal requirements for product certification by third party notified bodies. • Legal requirements for quality management systems, assessed by third party notified bodies (as seen in the EU Battery Regulation). • Legal requirement to provide UK customer support, such as the means to return faulty products to the vendor at a UK address, including provision of suitably labelled shipping boxes.
48	9.11	WMG suggests that the UK government, when developing legislation concerning the right of the consumer to repair a product, or to have it repaired by a third party, should consider restricting these rights when applied to PLEVs containing Lithium-ion batteries. This restriction should also apply to the right to convert a conventional bicycle into an e-bike, using a conversion kit.

#	Section Reference	Suggestion
49	9.11	WMG suggests that PLEV shock and vibration standards should consider the reasonably foreseeable case that consumers fit aftermarket parts, such as solid rather than pneumatic tyres, which are likely to significantly change the frequency and magnitude of vibrations and the duration and magnitude of shocks.
50	9.11	WMG suggests that PLEV standards should recognise the fact that existing ingress protection tests only evaluate the product in the brand-new condition. To evaluate possible deterioration of ingress protection over the life of the product, new test methodologies should be considered, for example by introducing a defined moisture content inside the battery casing, and then performing thermal cycling.
51	9.11	WMG suggests that battery electrical tests, including abuse tests, should include measurement of critical component temperatures on the BMS, busbars, cables and housing/structure, to ensure that all components are maintained within their limits, and do not pose a risk of over-heating adjacent Lithium-ion cells.
52	9.11	WMG suggests that an appropriate standard should exist to ensure the safety of conversion kits, including the system-level safety when separate components are combined into a system.
53	4.4, 9.11	WMG suggests that the discrepancy between voltage markings of chargers and batteries should be eliminated, to minimise the risk of consumer confusion and mistakes.
54	9.11	WMG suggests that a standard is required for fire containment / suppression products such as charging bags and fire blankets.
55	9.11	WMG notes that a 2019 European Commission Coordinated Activities on the Safety of Products (CASP) project determined that 80% of products tested were not fully compliant with relevant standards. This appears to show that the self-certification regime in the EU (and UK) for PLEVs is insufficient to ensure compliance with standards.
56	9.11	WMG suggests that the UK Government and Standards Bodies should work with international partners to work towards internationally harmonised standards for Lithium-ion battery safety in consumer products. There is precedent for such harmonisation, for example in automotive standards developed under the United Nations as Global Technical Regulations (GTRs).
57	9.11	WMG suggests that the standards for PLEVs, their batteries and chargers should require compliance with an internationally recognised quality management systems standard such as ISO 9001:2015.
58	9.11	WMG suggests that the Standards Bodies should assess the adequacy of ISO 9001:2015, with regard to manufacturer of PLEVs. If necessary, a PLEV-specific standard for quality management systems should be developed, in a similar way that IATF 16949 was developed by the automotive industry.

#	Section Reference	Suggestion
59	9.11	Regarding e-scooters, there are popular established brand products and cheaper imitations from other brands. The selection of e-scooters tested by WMG should include both, to compare their safety. *(This suggestion has already been addressed as part of this research, see Sections 10 and 11)*
60	9.11	Regarding e-bikes, the greatest concern of stakeholders is around conversion kits. WMG should test several conversion kit batteries, as well as batteries from complete OEM-built e-bikes. *(This suggestion has already been addressed as part of this research, Sections 10 and 11)*
61	9.11	The greatest concern of stakeholders is around charging. WMG's test methodology should examine the ability of the battery to withstand over-charge. *(This suggestion has already been addressed as part of this research, see Section 11)*
62	9.11	WMG's test methodology should include temperature instrumentation of critical components, to determine whether the component limits are exceeded and whether those component temperatures present a risk of over-heating adjacent Lithium-ion cells. *(This suggestion has already been addressed as part of this research, see Section 11)*
63	10.3.17	WMG suggests that the battery label requirements of EN 62133-2 and EN 50604-1 should be aligned.
64	10.3.17	WMG suggests that all PLEV and battery standards should include ingress protection requirements to ensure that moisture ingress is protected against.
65	10.3.17	WMG suggests that PLEV battery standards should include design guidelines to encourage the use of a structure separate from the cell-to-cell busbars to retain the cells in their intended positions.
66	10.3.17	WMG suggests that EN 62133-2 should make the requirement, for cell charge limits as a function of temperature, clearer and more prominent than it is currently (it appears only in Annex A).
67	10.3.17	WMG suggests that the existing wording in EN 62133-2 and EN 50604-1, on retention of wires and cables to avoid chafing and undue stress on soldered joints, should be strengthened and aligned between the standards.
68	10.3.17	WMG suggests that standards for PLEV batteries should require reliability / safety fault tree analysis to demonstrate sufficient safety with the selected components comprising MOSFETs with certified reliability levels, and/or redundancy in the safety system to address the reliability of single devices.
69	10.3.17	WMG suggests that design guidelines in standards should encourage a significant spacing between charge and discharge MOSFETs and other power-circuit components, to reduce the likelihood of cascading thermal failures between components.

#	Section Reference	Suggestion
70	11.5	WMG suggests that standards for PLEV batteries, such as EN 50604-1, should be updated to require that all PLEV batteries shall be tested to demonstrate compliance with the voltage, current and temperature limits provided on the datasheets for the cells and the power-circuit components such as the BMS MOSFETs. If the battery manufacturer wishes to exceed these limits, they should obtain written consent from the component manufacturer or be required to produce testing results that support the decision.
71	11.5	WMG suggests that standards for PLEV batteries, such as EN 50604-1, should be updated to require that all PLEV batteries should be tested to demonstrate protection against reverse current-flow through the charge and discharge circuits, or if reverse current flow is permitted, it should be demonstrated that this does not result in over-heating of the power-circuit components or contravening the cell voltage, current and temperature limits.
72	11.5	WMG suggests that standards for PLEV batteries, such as EN 50604-1, should be updated to require that all PLEV batteries should be tested with temperature measurement of the cells located closest to the main sources of heat in the power-circuit, such as MOSFETs, to demonstrate that the heat transfer from these power-circuit components does not cause the adjacent cells to exceed the cell charge or discharge temperature limits. This should include test conditions with foreseeable single-point failure of these heat sources, such as a short-circuit failure of a MOSFET.
73	11.5	WMG suggests that standards for PLEV batteries, such as EN 50604-1, should be updated to include design guidelines for PLEV batteries which recommend that at least one BMS thermistor should be placed on the cell(s) closest to the critical power-circuit components such as MOSFETs, or other locations identified through testing to be experience the highest temperatures, to maximise the likelihood that cell hot-spots are identified by the BMS, and the cell limits are respected accordingly.
74	11.5	WMG suggests that standards for PLEV batteries, such as EN 50604-1, should be updated to include design guidelines for PLEV batteries which state that cell passive protection devices, such as CID and PTC, should not be seen as a substitute for comprehensive BMS protection, because cells can still be in a hazardous condition after these devices have activated. This emphasises the value of redundancy in the BMS, to ensure that single-point BMS failure does not result in reliance on the cell passive protection to prevent thermal runaway.

13 Conclusions

13.1 Real World Data

Personal Light Electric Vehicle (PLEV) fires have become a significant UK-wide problem, with severe incidents causing particular challenges for fire and rescue services in the UK. While UK-wide data has not been collated for long enough or with sufficient detail to be analysed, London Fire Brigade (LFB) data from 2017 to 2023 shows a rapid increase in the annual number of incidents. The annual number of e-scooter incidents has not increased since 2021, but the number of e-bike incidents has continued to climb. WMG analysed the e-bike data to ascertain how many incidents involved conversion kits compared to Original Equipment Manufacturer (OEM)-made e-bikes. Of the 56% of incidents where this could be ascertained, over three quarters were conversion kits. The data on brand and model type of e-bikes and e-scooters has been used to inform some of the products purchased for teardown and abuse testing in this project.

Almost all incidents recorded by LFB occurred indoors, either in domestic or commercial properties. The LFB data on whether a battery was being charged at the time of the fire are not definitive, due to the high proportion of incidents where this could not be determined. However, there is evidence to suggest that some consumers use incompatible chargers, rated at up to twice the voltage of the battery involved in the fire.

The OPSS Product Safety and Consumers Wave 5 survey data (UK Government, Dec 2023) imply that issues around PLEV fire safety are more widespread than the LFB data suggest: Of the 7% of respondents who owned or had access to a PLEV, 22% had experienced a safety issue, and 14% of these involved fire, explosion, smoke or over-heating.

The survey also showed 35% of PLEV owners had purchased a separate battery or charger, and the proportion of such PLEV owners who had experienced a safety incident (41% of separate battery purchasers and 48% of separate charger purchasers) was much higher, compared to safety incidents reported by owners who had not bought a separate charger or battery (10%). This suggests that mixing batteries and chargers that are not supplied together increases the likelihood of safety incidents.

The UK is not alone. New York City Fire Department has recorded a rapid annual increase in incidents since 2019, and in early 2024, the New York City Council voted to pass new safety regulations which require businesses that sell e-bikes and e-scooters to post safety information about Lithium-ion battery storage in stores and online and prohibits the sale of batteries that are not certified as meeting the relevant UL standards.

13.2 Scientific Data on Causes of Lithium-ion Cell Thermal Runaway

Thermal runaway is a highly exothermic (heat-generating) chemical process. Once it starts, it proceeds rapidly and is almost impossible to halt with any amount of cooling. To reach thermal runaway, some part of a cell must reach an abnormally high temperature of around 150-180 °C. In a battery, thermal runaway invariably starts in a single cell and can propagate to other cells, multiplying the severity of the incident. In laboratory conditions, thermal runaway can be started by three main causes:

1. Mechanical abuse, such as crushing or penetration of cells.
2. Thermal abuse, meaning over-heating.

3. Electrical abuse by over-charging (over-voltage or charging over-current) or over-discharging (under-voltage or discharging over-current). Over-charging is generally much more likely to cause thermal runaway than over-discharging.

Defects within a cell, resulting from manufacture or the effects of long-term use, are also known causes, but are much more challenging to reproduce in the laboratory.

Considering the high severity of thermal runaway, even with a low or limited likelihood of it occurring, cells and batteries must be designed based on the assumption that single-cell thermal runaway will happen. It is essential that the battery as a whole should be designed and manufactured to:

(1) Minimise the likelihood of thermal runaway.
(2) Ensure detection of the potential causes of thermal runaway.
(3) Act to prevent thermal runaway when potential causes are detected.
(4) Mitigate against single points of failure.
(5) Mitigate against the severity of thermal runaway when it does occur.

Point (1) above relies firstly on manufacturing quality and secondly on ensuring that the cells are only used within the voltage, current and temperature limits stated by the cell manufacturer.

Point (2) above requires the Battery Management System (BMS) to be equipped with appropriate sensors for voltage, current and temperature, and that its software is appropriately calibrated and validated to ensure that, when the cell manufacturer's stated limits are exceeded, this is detected.

Point (3) above requires that, upon detection of abnormal conditions, the BMS can reliably protect the cells and other components. This requires circuitry which can limit or interrupt the charge or discharge current, including prevention of reverse current flow in charge and discharge circuits unless the battery can operate safely in such conditions.

Point (4) above requires tolerance to single-point failures in hardware and software: There should be secondary or "redundant" features to ensure that the protection system is failure-tolerant. These may include passive protection components in individual cells (e.g. current interrupt device) or at battery-level (e.g. fuse), but these generally cannot offer the effectiveness of prevention that the active systems in the BMS can provide across a range of single-point failures. It is also essential that single-point failures shall not cause cascading failures to other critical components.

Point (5) above requires design measures in the battery to prevent, minimise or slow down propagation from cell to cell, including effective venting of the gas and other ejecta from the initiating cell and features to protect other cells from the electrical, thermal and mechanical effects that can cause a cascading failure. The ejecta from a single cell can cause damage to property and human health, but this will generally be far less than if multiple cells enter thermal runaway.

If the whole battery is at a high State of Charge (SoC), or worse still, overcharged, then the likelihood, rapidity and severity of thermal propagation are substantially increased.

13.3 Literature Review

A review of public domain sources has shown the easy availability of guidance on how to bypass BMS protection mechanisms, to liberate more performance from a battery, or to recover a deeply discharged battery. Such tampering has been highlighted as a serious safety concern. Prevention of tampering is a major technical challenge, but notably one of the batteries purchased in this project had protections which prevented it from being charged other than when connected to the originally supplied charger. Discharge using laboratory equipment was also prevented. No publicly available information was found on how to defeat this system. The work did not include an exhaustive attempt to defeat these protections, but this product demonstrates that anti-tampering measures can be effective against reasonable attempts at misuse.

The literature review included a review of statements made by stakeholders in the USA to the US Consumer Product Safety Commission (CPSC). Several stakeholders pushed for mandatory certification of PLEV batteries. A bike manufacturer asserted that markets that require certification to minimum safety standards have seen far fewer issues with fires and general battery safety with e-bikes and went on to opine that the battery should protect itself and should not depend on the charger. This view is shared by WMG.

ISO 4210-10, a technical specification for e-bike safety including details for battery-to-charger communication protocols intended to ensure that over-charging cannot occur, was mentioned in the CPSC hearing, and has been promoted in the UK by the safety charity Electrical Safety First. It has not been adopted as standard in Europe or the UK, but in WMG's view, an appropriate battery-charger protocol would have significant safety benefits.

Singapore is a market that has recently implemented laws requiring type-approval and registration of e-bikes, which must be fitted with a tamper-proof seal. Harsh financial penalties and/or jail terms apply to individuals found not to comply. Related rules also apply to e-scooters. In early 2023, reports indicated that the number of PLEV fire incidents had started to fall. Singapore's fire service attributed the fall to the new laws.

13.4 Stakeholder Input

Stakeholders from the PLEV supply-chain, safety experts, fire services, and standards organisations have been consulted for this report. The fire and rescue services highlighted the perceived shortcomings in UK incident reporting and the challenge for firefighters to gather incident data. This is not their primary role, they are not trained as experts in forensic examination of incident scenes and the physical evidence is often so damaged by the fire that it is difficult to obtain meaningful data. Nevertheless, while data collection itself will not reduce the number of incidents, it is an important tool to monitor progress to reduce the number of incidents, and to identify products which are unsafe and consumer usage patterns that correlate with occurrence of fires.

Stakeholders also highlighted shortcomings with some battery standards, the importance of manufacturing quality, and the need to target consumer advice at the most frequent PLEV users, such as gig-economy riders and couriers. The supply-chain organisations, including UK manufacturers and retailers, are supportive of improved safety requirements that are enforced to ensure a consistently high standard for all market players.

The stakeholders highlighted the international dimension of the PLEV market, and the similar thermal incidents that occur in other market sectors which use Lithium-ion cells and batteries. PLEVs should not be seen in isolation, and measures to tackle the fire safety of products with Lithium-ion batteries should be coordinated at international level, as has been done in, for example, the automotive sector.

13.5 Product Inspection and Testing

Several e-bike, e-scooter and conversion kit batteries, covering a breadth of price points, have been investigated through a process of teardown analysis and abuse testing.

Teardown of some products has shown examples of poor manufacturing processes and quality, absence of essential safety features such as temperature sensors, poor design choices that increase the likelihood of water ingress and cell overheating. The batteries also employ a wide variety of sophistication in the electronic components used in their battery management systems. In some cases, the hardware restricts the ability for the battery manufacturer to configure the BMS for the operating limits of individual cell types, meaning that inappropriate generic limits are used.

The abuse testing has shown a clear correlation between the price-per-unit-of-energy of PLEV batteries and the safety outcomes. The tests have shown that many BMSs do not prevent the battery from exceeding the current and temperature limits stated on the cell manufacturers' datasheets. This exposes the batteries to the risk of electrical abuse, by the use of an unsuitable charger or modified PLEV drive-motor. It is even possible that the cell limits may be exceeded when the battery is used with the vehicle system and charger for which it was intended.

When such abuse occurs, the tests have demonstrated over-heating of protective components, rendering those protections ineffectual, in a way that is not apparent to the consumer. The over-heated components were seen to directly heat neighbouring cells and they failed to prevent over-voltage or over-current, which then resulted in the cells becoming overcharged. As a result, several batteries tested went into thermal runaway, leading rapidly to fire, explosions and clouds of toxic gas that would be extremely hazardous to anyone in the same space.

However, the tests also showed that the PLEV batteries with a higher price-per-unit-of-energy, which had better designed safety circuits, more sophisticated electronics and were better manufactured, successfully prevented thermal runaway by a combination of passive and active protection systems. Nevertheless, in the event of single-point failures in the BMS, many batteries remain reliant on passive safety devices in the cells, which only activate when the cell is already in a significantly overcharged condition, wherein the likelihood of thermal runaway is significantly increased.

The testing demonstrated that over-charged cells can enter thermal runaway sometime after the charging has stopped. This is because the damage that had already been done to the cells causes gradual self-heating, which eventually caused the cells to reach the critical temperature for thermal runaway to occur. Prior to thermal runaway, there may be no outward indication that the battery is compromised.

13.6 Combining Real World Evidence with Scientific Data

The scientific literature shows a clear correlation between high SoC and increased likelihood and severity of thermal runaway. Taken together with the real world evidence, we conclude that charging is likely to be a significant contributor to thermal incidents.

There are also numerous other factors which can cause thermal runaway, including manufacturing defects, mechanical damage, and over-heating.

The state of the art in cell manufacturing quality-control enables almost all defects to be avoided or detected by in-process checks but cannot completely eliminate the possibility of defects in cells. Many types of cell manufacturing defects can result in internal short-circuits. However, they may only manifest themselves after some period of use, for example because of shock and vibration causing slight movement of internal parts or the microstructural changes resulting from repeated charge and discharge. If undetected during manufacture, they could over time contribute to causing thermal runaway. It is therefore essential that all Lithium-ion cells for PLEVs are manufactured to consistently high quality standards to reduce defect occurrence to the lowest possible level.

Mechanical damage, caused by severe shock, vibration, or impact could result in thermal runaway. Stakeholder input confirmed that consumer use of some PLEVs, particularly e-scooters, can include such mechanical stresses, but while manufacturers have evidence of mechanical damage to cells inside customer batteries, there is no clear evidence that these have resulted in severe real world thermal incidents.

Mechanical damage or poor design or manufacture can result in moisture entering inside the outer casing of the battery. Long-term exposure to environmental factors such as Ultraviolet (UV) radiation from sunlight can also compromise the sealing of the battery housing. Stakeholder experience has shown that moisture ingress can result in corrosion of electrical components, particularly in the BMS, but also the cells. These can potentially lead to thermal incidents. Most product validation and certification tests fail to detect these long-term effects, because the tests are conducted on new batteries. Accelerated environmental ageing tests, followed by water ingress tests, can improve detection.

Over-heating could be caused by certain consumer actions, such as leaving a battery close to a domestic heat source, or tampering, such as altering the motor power with a consequent increase in discharge current, or by using an inappropriate charger which provides excessive charging current. While the first of these causes is beyond the reasonable control of the battery itself, the latter two can be addressed by appropriate BMS design. Stakeholder experience and WMG's product teardowns show that some products are not fitted with temperature sensors, which are essential for the BMS to detect and act upon over-heating.

This includes preventing over-voltage (meaning that the battery reaches > 100% SoC), but also over-current, which can happen at any SoC, especially in colder conditions where the charging current that the cells can safely accept is substantially reduced. The battery must also prevent other potential causes that are well established from scientific knowledge, such as over-heating. The BMS plays a key role in implementing such active protection.

When cells are combined in a battery, the overall likelihood and severity of a thermal incident is determined by a complex range of factors, including those stated above and the effectiveness of passive and active protections in the cells and the battery. The BMS should play a critical role to monitor the state of the individual cells, and ensure that their voltage, current and temperature limits are not exceeded.

13.7 Existing Legislation and Standards

A review of the product safety legislation has confirmed that many PLEV products, including complete e-bikes and e-scooters and conversion kits that have a motor, are covered by the Supply of Machinery (Safety) Regulations 2008 (SMSR). This contains a detailed list of essential health and safety requirements, including avoidance of hazards such as high temperature, fire and explosion, which are directly relevant to PLEV safety. The SMSR also requires the manufacturer to provide documentation (e.g. assembly instructions, declaration of incorporation), which can assist authorities with enforcement and can guide professionals and consumers on correct use of the product. However, separately sold batteries, often used in conversion kits, are not in the scope of the SMSR, and are therefore covered by the General Product Safety Regulations 2005 (GPSR) or the Electrical Equipment (Safety) Regulations 2016 (EESR). This requires all consumer products to be safe, but does not contain detailed health and safety requirements, or require such extensive documentation.

A review of the standards applicable to e-bikes (EN 15194) and e-scooters (EN 17128) has shown differences between the two: EN15194 requires that, for an e-bike to comply with that standard, the e-bike battery shall comply with the most rigorous applicable UK battery standard (EN 50604), but the standard for e-scooters has a less stringent requirement. There is no dedicated standard to cover conversion kits, as the existing standards cover complete e-bikes or e-scooters and there is no industry definition of a conversion kit for which a standard could be created. The existing standards for batteries can be used for conversion kit batteries, but the mix-and-match nature of conversion kits requires a re-examination of the relevant risks.

A review of the battery standards has highlighted several areas for improvement, relating mainly to ensuring manufacturing quality, the severity of test conditions and the ability of the battery to remain safe in the event of single-point failures in the protective systems and components.

13.8 Concluding Remarks

In WMG’s view, battery safety should not need to be a factor in consumers’ PLEV purchase decisions: Safety should be inherent to all products offered for sale, irrespective of their price and other attributes, as is required by existing UK legislation. To achieve this, PLEV batteries must be designed to protect themselves against reasonably foreseeable misuse and manufactured to consistently high quality levels. However, evidence of the growing number of serious PLEV fires in the UK shows that some manufacturers are failing to achieve the level of safety required in UK consumer product legislation.

Product testing for this report showed that the PLEV batteries with a higher price-per-unit-of-energy, which had better designed safety circuits, more sophisticated electronics and were better manufactured, successfully prevented thermal runaway by a combination of passive and active protection systems.

However, product testing has also shown that some PLEV battery management systems fail to respect the current and temperature limits specified for the cells that they use. Both the cells and the BMS protective circuits are thereby susceptible to damage, which can lead to thermal runaway, especially if the battery is used with an incompatible charger. These susceptibilities can and should be addressed by improved BMS design and testing.

Inspection of the general design and manufacturing quality of the tested products has shown examples of other deficiencies, such as lack of waterproofing and poor weld quality, which manufacturers should also address.

Enforcement of legislation and market surveillance may currently be compromised by a lack of consistency in the consumer safety legislation which applies to PLEV products, particularly separately-sold batteries. Further inconsistency and shortcomings in the supporting standards also undermine the need for clarity, uniformity and technical robustness to help manufacturers to comply with legislative requirements.

This report has made a large number of suggestions for actions which can improve PLEV safety, spanning the following areas:

- Consistency in the legislation applicable to PLEV batteries.
- Consistency in the standards covering all PLEV batteries.
- Numerous detailed improvements to standards, ranging from cell production quality to the abuse testing methodology and functional safety.
- Collection of incident data.
- Consumer advice.
- Increased obligations and penalties for companies selling PLEVs and their batteries.

If these suggestions are acted on by the relevant parties in government, standards bodies, manufacturers and other stakeholders, WMG believes that the unacceptably high level of PLEV fires can be reduced over time. There is, however, no quick fix, due to the large number of products already in the hands of consumers and the lead-time for changes to legislation, and for updates to standards, and for manufacturers to develop, validate, productionise and introduce new products to the market.

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15 Appendices

15.1 Appendix 1: Calculation of Cell Temperature Rise

Table 68: Assumed Cell Characteristic (typical of the cells in the PLEV batteries tested by WMG)

Parameter	Units	Value
Format	-	18650
Capacity	Ah	2.5
Nominal voltage	V	3.7
Mass	Kg	0.048
Specific heat capacity	J/kg.K	1000
Heat capacity	J/K	48
DC Resistance	mΩ	75

Table 69: Assumed Battery Pack

Parameter	Units	Value
Cells in Series	-	13
Cells in Parallel	-	6
Total number of cells	-	78
Open-Circuit Voltage (OCV)	V	48 (= 3.7V * 13)
Capacity	Ah	15 (= 2.5Ah * 6)
DC resistance	mΩ	163 (= 75 mΩ * 13 / 6)
Heat capacity, C	J/K	3744 (= 48 J/K * 13 * 6)

Assumed power output:

For 1500W mechanical power, with 80% motor/inverter efficiency, battery power = 1875W

For 250W mechanical power, with 80% motor/inverter efficiency, battery power = 312W

Current under load is calculated by solving the following equations:

(1) Voltage drop: $dV = OCV - V = I.R$
(2) Power: $P = VI$

Combined, these equations give:

(3) Power: $P = (OCV - V).I = I.OCV - I^2.R$

Solving this quadratic equation gives:

(4) Current: $I = OCV - \frac{OCV - \sqrt{OCV^2 - 4.R.P}}{2.R}$

This results in a current of 6.7A for 250W motor power and 46.3A for 1500W motor power.

The heat generation is given by $H = I^2.R$

The heat generation is 7.2W for 250W motor power and 348.8W for 1500W motor power.

The rate of temperature rise (K/min) is given by $\frac{dT}{dt} = \frac{H}{C}.60$

The rate of temperature rise is 0.12 K/min for 250W motor power and 5.6K/min for 1500W.

In 5 minutes, the temperature rise is 0.6K for 250W motor power and 28K for 1500W.

15.2 Appendix 2: Calculation of Speed and Distance

Table 70: Assumed Rider & e-bike Characteristics:

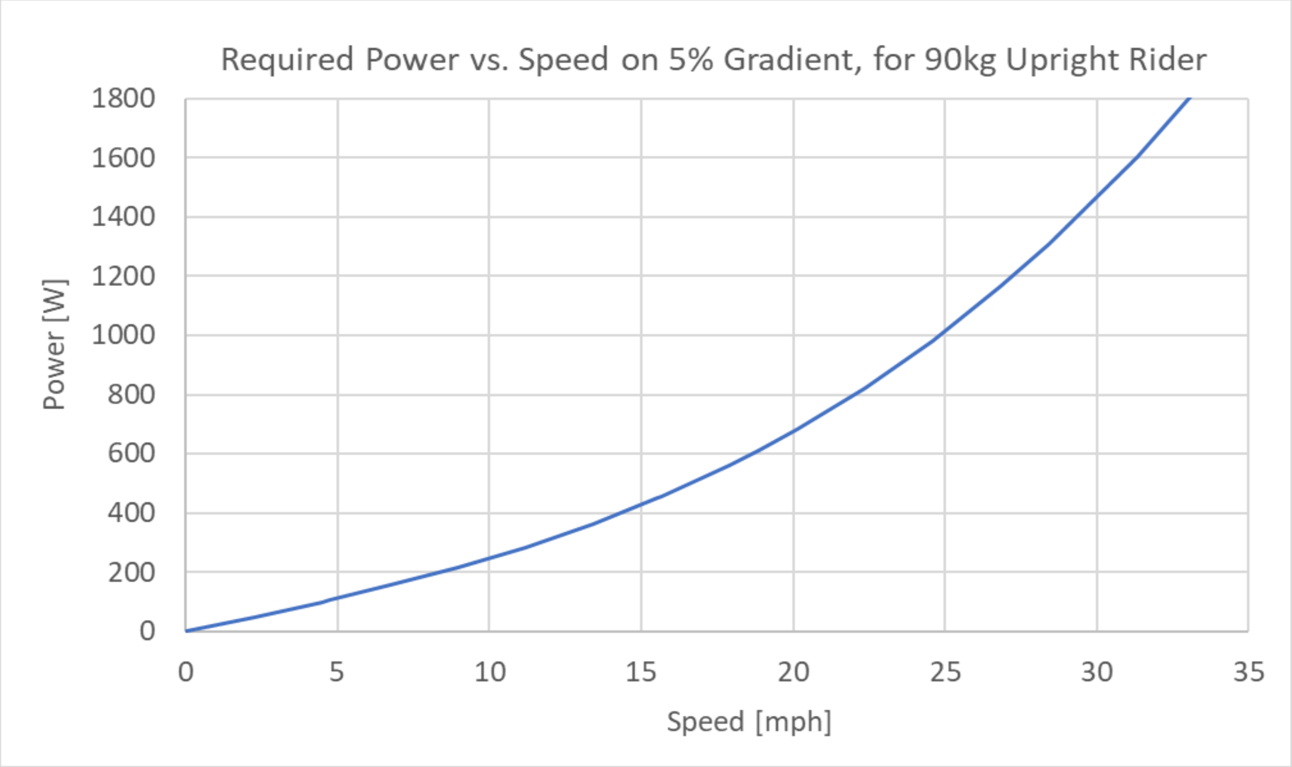
Parameter	**Units**	**Value**	**Data Source**
Air density, ρ_{air}	kg/m^3	1.2	Value at std. temperature and pressure.
Drag Coefficient, C_d	-	1.1	Munson *et al.*, 2013 (for upright commuter)
Frontal Area, $A_{frontal}$	m^2	0.51	Munson *et al.*, 2013 (for upright commuter)
Tyre rolling resistance coefficient, C_{RR}	-	0.005	sciencedirect.com (no date)
Mass, m	kg	90	Assume 70kg rider, 20kg e-bike
Road gradient, θ	0.05	radians	Equal to 5% gradient

Total resistance force calculated as the sum of (1) Aerodynamic drag force, (2) Tyre rolling resistance force, and (3) Gradient force. These are calculated as follows:

(1) Aerodynamic drag force $F_A = \frac{1}{2}.\rho_{air}.v^2.C_d.A_{frontal}$
(2) Tyre rolling resistance force $F_{RR} = 9.81.m.C_{RR}$
(3) Gradient Force $F_G = 9.81.m.sin\theta$

The required power (W) is then calculated as force (N) * speed (m/s).

The required power is plotted in the figure below, as a function of speed. This shows that 1500W mechanical power is sufficient to maintain 30 mph on a 5% gradient, with the assumptions stated above:



At 30mph, the distance covered in 5 minutes is 2.5 miles. On a 5% gradient, the height gained in this time and distance is approximately 200m.

15.3 Appendix 3: Type Approval Vehicle Categories

Table 71 provides an overview of some of the main road vehicle categories, based on the Consolidated Resolution on the Construction of Vehicles (United Nations Economic Commission for Europe, Jul 2017):

Table 71: Examples of the main Vehicle Categories for Type Approval

Vehicle Type	**Category**
Powered 2-wheelers (motorcycles, mopeds), 3-wheelers and quadricycles	L
Passenger vehicles with ≥4 wheels (e.g. passenger cars, taxis)	M
Goods vehicles with ≥4 wheels (goods vans, trucks, etc.)	N
Trailers	O

The L-Category has many sub-divisions, including both combustion and electric powered vehicles. The electric-powered sub-divisions are summarised in Table 72 below, based on Annex I of Regulation 168/2013 of the European Parliament and of the Council on the approval and market surveillance of two- or three-wheel vehicles and quadricycles (UK Government, Jan 2013):

Table 72: L-Category Type Approval Sub-categories

Vehicle Type	**Category**
2-wheelers, max. speed ≤ 45 km/h, max. cont. power ≤ 4 kW	L1e
3-wheelers, max. speed ≤ 45 km/h, max. cont. power ≤ 4 kW	L2e
2-wheel motorcycles,	L3e
2-wheel motorcycles with side-car	L4e
Powered tricycles	L5e
Light quadricycles, max. speed ≤ 45 km/h, max. cont. power ≤ 6 kW, mass ≤ 425 kg, max. 2 seats including driver	L6e
Heavy quadricycles, max. cont. power ≤ 15 kW, mass ≤ 450 kg (passenger vehicles) / 600 kg (goods vehicles)	L7e

15.4 Appendix 4: Detailed Comparison of Cell Test Protocols

Table 73: Comparison of Cell Environmental Test Protocols

Test Category	Test Type	Units	Cells (18650 cylindrical)					
			UN38.3	EN 62133-2	EN 62660-2	EN 62660-3	UL 2580 Annex B	UL 2580 Annex D
Vibration	Number of samples tested	-	5 new, 5 cycled	0	Undefined	-	3	2
	State of Charge	%	100%	-	100%	-	See EN 62660-2	Undefined
	Discharge Rate	C-rate	0	-	0	-		0
	Temperatures	°C	Undefined	-	25	-		Undefined
	Type	-	Log Sweep	-	PSD Random	-		Linear Sweep
	Frequency Range	Hz	7 - 200	-	10 - 2000	-		10 - 55
	Directions	-	3	-	3	-		2
	Total Duration	hours	9	-	24	-		4.5
	RMS Acceleration	m/s^2	45.4	-	27.8	-		38.9
	Observation time	hours	0	-	0	-		0
Mechanical Shock	Number of samples tested	-	5 new, 5 cycled	0	Undefined	Undefined	3	2
	Temperature	°C	Undefined	-	25	25	See EN 62660-2	20
	State of Charge	%	100%	-	100%	100%		Undefined
	Type	-	Half-sine	-	Half-sine	Half-sine		Undefined
	Peak acceleration	m/s^2	150	-	500	500		150 ±25
	Shock pulse duration	ms	6	-	6	6		Undefined
	Directions	-	6	-	6	6		2
	Shocks per Direction		3	-	10	10		3
	Total number of shocks		18	-	60	60		6
	Observation time	hours	0	-	0	0		0
Thermal Cycling	Number of samples tested	-	5 new, 5 cycled	0	Undefined	Undefined	3	2
	State of Charge	%	100%	-	100%	100%	See EN 62660-2	Undefined
	Temperatures	°C	-40 / +72	-	-40 / +20 / +85	-40 / +20 / +85		-40 / +20 / +85
	Time at Temperatures	hours	6 / 6	-	1.5 / 1.5 / 1.83	1.5 / 1.5 / 1.83		4 / 2 / 4
	Transition time	hours	0.5	-	~ 2.0	~ 2.0		0.5
	Number of Cycles	-	10	-	30	30		10
	Total Duration	hours	130	-	240	240		144
	Observation time	hours	0	-	0	0		0

Table 74: Comparison of Cell Mechanical Abuse Test Protocols

			Cells (18650 cylindrical)					
Test Category	**Test Type**	Units	UN38.3	EN 62133-2	EN 62660-2	EN 62660-3	UL 2580 Annex B	UL 2580 Annex D
Impact	Number of samples tested	-	5 new, 5 cycled	3	0	0	3	2
	Temperature	°C	20	20	-	-		Undefined
	State of Charge	%	50%	100%	-	-		Undefined
	Type	-	Mass drop	Cell drop	-	-	Cell drop	Mass drop
	Directions	-	1	3	-	-	3	1
	Indenter shape	-	Semi-cylinder	-	-	-	-	Semi-cylinder
	Indenter diameter	mm	15.8	-	-	-	-	15.8
	Mass dropped	kg	9.1	-	-	-	-	9.1
	Drop height	m	0.61	1.0	-	-	1.0	0.61
	Peak Speed at Impact	mm/s	2446	3132	-	-	3132	2446
	Release condition - Force	kN	-	-	-	-	-	-
	Release condition - Voltage	V	-	-	-	-	-	-
	Release condition - deformation	%	-	-	-	-	-	-
	Observation time	hours	6	1	-	-	1	0
Crush	Number of samples tested	-	0	5	Undefined	Undefined	3	2
	Temperature	°C	-	20	25	25	See EN 62660-2	Undefined
	State of Charge	%	-	100%	100%	100%		Undefined
	Number of Orientations	-	-	1	1	1		1
	Indenter shape	-	-	Flat Plate	Semi-cylinder	Semi-cylinder		Semi-cylinder
	Indenter diameter	mm	-	-	150	150		150
	Mass dropped	kg	-	-	-	-		-
	Drop height	m	-	-	-	-		-
	Peak Indenter Speed	mm/s	-	Undefined	Undefined	0.1		Undefined
	Release condition - Force	kN	-	13	$1000 * m_{cell}.G$	$1000 * m_{cell}.G$		$1000 * m_{cell}.G$
	Release condition - Voltage	V	-	$V < V_{max}$ *2/3	$V < V_{max}$ *2/3	$V < V_{max}$ *2/3		$V < V_{max}$ *2/3
	Release condition - deformation	%	-	-	15%	15%		15%
	Observation time	hours	-	0	24	24		0

Table 75: Comparison of Cell Electrical Abuse Test Protocols

Test Category	Test Type	Units	Cells (18650 cylindrical)					
			UN38.3	EN 62133-2	EN 62660-2	EN 62660-3	UL 2580 Annex B	UL 2580 Annex D
External Short Circuit	Number of samples tested	-	5 new, 5 cycled	5	Undefined	Undefined	3	2
	Temperature	°C	57	55	25	25	See EN 62660-2	55
	State of Charge	%	100%	100%	100%	100%		Undefined
	External short-circuit resistance	mΩ	<100	80 ±20	<5	<5		<20
	Observation time	hours	6	24	0	0		0
Internal Short Circuit	Number of samples tested	-	0	5	0	Undefined	0	0
	Temperature	°C	-	20	-	25	-	-
	State of Charge	%	-	100%	-	100%	-	-
	Type	-	-	Ni particle	-	Ni particle	-	-
	Press dimensions	mm	-	10 x 10	-	10 x 10	-	-
	Press speed	mm/s	-	0.1	-	0.1	-	-
	Press termination Force	N	-	800	-	800	-	-
	Press Termination Voltage Drop	mV	-	50	-	50	-	-
	Press hold time	sec	-	30	-	30	-	-
	Observation time	hours	-	0	-	0	-	-
Over-charge	Number of samples tested	-	0	0	Undefined	Undefined	3	2
	Temperature	°C	-	-	25	25	Undefined	Undefined
	Initial State of Charge	%	-	-	100%	100%	Undefined	Undefined
	Charge Rate	C-rate	-	-	Undefined	0.33C or 1C	Charge I_{max}	Charge I_{max}
	Termination Voltage	V	-	-	Undefined	1.2x V_{max}	1.2x V_{max}	1.2x V_{max}
	Termination SOC	%	-	-	Undefined	130%	130%	130%
	Observation time	hours	-	-	0	0	0	0
Over-discharge	Number of samples tested	-	10 new, 10 cycled	5	Undefined	Undefined	3	0
	Temperature	°C	20	20	25	25	See EN 62660-2	-
	Initial State of Charge	%	0%	0%	0%	0%		-
	Discharge Rate	C-rate	Discharge I_{max}	1C	1C	1C		-
	Termination voltage	V	-	$-V_{max}$	-	-		-
	Termination SOC	%	-100%	-	-	25%		-
	Max discharge duration	hours	Capacity / I_{max}	1.5	1.5	0.5		-
	Observation time	hours	168	0	0	0		-

Table 76: Comparison of Cell Thermal Abuse Test Protocols

Test Category	Test Type	Units	Cells (18650 cylindrical)					
			UN38.3	EN 62133-2	EN 62660-2	EN 62660-3	UL 2580 Annex B	UL 2580 Annex D
Over - temperature	Number of samples tested	-	0	5	Undefined	Undefined	3	0
	Initial Temperature	°C	-	20	25	25	See EN 62660-2	-
	State of Charge	%	-	100%	100%	100%		-
	Heating Method	-	-	Oven	Oven	Oven		-
	Temperature Rate	°C/min	-	5	5	5		-
	Charge / Discharge Rate	C-rate	-	0	0	0		-
	Charge / Discharge Repeats	-	-	0	0	0		-
	Final Temperature	°C	-	130	130	130		-
	Final Temperature Hold Time	mins	-	30	30	30		-
	Observation time	hours	-	0	0	1		-
Projectile Test	Number of samples tested	-	0	0	0	0	3	2
	Cell support	-	-	-	-	-	Steel wire mesh	Steel wire mesh
	Cell support wire spacing	-	-	-	-	-	20 per inch	20 per inch
	Cell support wire diameter	mm	-	-	-	-	0.43	0.43
	Heating method	-	-	-	-	-	Meker burner	Meker burner
	Cell support height above burner	mm	-	-	-	-	38	38
	Cage type	-	-	-	-	-	Octagonal	Octagonal
	Cage diameter	mm	-	-	-	-	610	610
	Cage Height	mm	-	-	-	-	305	305
	Cage screen wire material	-	-	-	-	-	Aluminium	Aluminium
	Cage screen wire spacing	-	-	-	-	-	16 - 18 per inch	16 - 18 per inch
	Cage screen wire diameter	mm	-	-	-	-	0.25	0.25

15.5 Appendix 5: Detailed Comparison of Battery Pack Test Protocols

Table 77: Comparison of Battery Pack Environmental Test Protocols (1 or 2)

Test Category	Test Type	Units	Battery (< 12 kg)			
			UN38.3	EN 50604-1	EN 62133-2	UL 2271
Vibration	Number of samples tested	-	4 new, 4 cycled	Undefined	3	1
	State of Charge	%	100%	100%	100%	100%
	Discharge Rate	C-rate	0	C/3 to 25% SOC	0	0
	Temperatures	°C	Undefined	Undefined	20	25
	Type	-	Log Sweep	Log Sweep	Log Sweep	PSD Random
	Frequency Range	Hz	7 - 200	7 - 200	7 - 200	5 - 200
	Directions	-	3	3	3	3
	Total Duration	hours	9	9	9	63
	RMS Acceleration	m/s^2	45.4	45.4	45.4	x:9.4/y:12.1/z:14.1
	Observation time	hours	0	0	0	1
Mechanical Shock	Number of samples tested	-	4 new, 4 cycled	Undefined	3	1
	Temperature	°C	Undefined	Undefined	20	Undefined
	State of Charge	%	100%	100%	100%	100%
	Type	-	Half-sine	Half-sine	Half-sine	Half-sine
	Peak acceleration	m/s^2	90 - 150	150	150	50
	Shock pulse duration	ms	6	6	6	11
	Directions	-	6	6	6	6
	Shocks per Direction		3	3	3	3
	Total number of shocks		18	18	18	18
	Observation time	hours	0	0	0	1

Table 78: Comparison of Battery Pack Environmental Test Protocols (2 or 2)

		Battery (< 12 kg)			
Test Category	**Test Type**	UN38.3	EN 50604-1	EN 62133-2	UL 2271
Dewing	Number of samples tested	0	3	0	0
	State of Charge	-	Undefined	-	-
	Temperatures	-	+25 / +80	-	-
	Time at Temperatures	-	0.75 / 0.75	-	-
	Temperature Transition time	-	2.0	-	-
	Relative Humidity Levels		55 / 80 / 98	-	-
	Time as Relative Humidity Levels		~0 / 0.5 / 3	-	-
	Transition time	-	~1.5	-	-
	Number of Cycles	-	5	-	-
	Total Duration	-	25	-	-
	Observation time	-	1	-	-
Thermal Cycling	Number of samples tested	4 new, 4 cycled	4	0	1
	State of Charge	100%	100%	-	100%
	Temperatures	-40 / +72	-40 / +85	-	-40 / +85
	Time at Temperatures	6 / 6	6 / 6	-	Per SAE J2464
	Transition time	0.5	0.5	-	Per SAE J2464
	Number of Cycles	10	5	-	Per SAE J2464
	Total Duration	130	65	-	Per SAE J2464
	Observation time	0	1	-	1

Table 79: Comparison of Battery Pack Mechanical & Ingress Abuse Test Protocols

Test Category	**Test Type**	Units	Battery (< 12 kg)			
			UN38.3	EN 50604-1	EN 62133-2	UL 2271
Water Immersion	Number of samples tested	-	0	Undefined	0	1
	Ambient Temperature	°C	-	RT	-	RT
	Water Temperature	°C	-	20	-	RT
	State of Charge	%	-	100%	-	100%
	Water Depth	m		Submersion	-	Submersion
	Water Salt Mass Fraction	%	-	5%	-	5%
	Immersion Duration	hours	-	2	-	2
	Observation time	hours	-	1	-	0
Impact	Number of samples tested	-	0	Undefined	3	1
	Temperature	°C	-	Battery T_{min}	20	0 (4)
	State of Charge	%	-	100%	100%	100%
	Type	-	-	Battery Drop	Battery Drop	Battery Drop
	Directions	-	-	3	3	1 x3 (5)
	Drop height	m	-	1.0	1.0	1.0
	Peak Speed at Impact	mm/s	-	3132	3132	3132
	Observation time	hours	-	6	1	1
Crush	Number of samples tested	-	0	Undefined	0	0
	Temperature	°C	-	RT	-	-
	State of Charge	%	-	Undefined	-	-
	Number of Orientations	-	-	2	-	-
	Indenter shape	-	-	Semi-cylinder	-	-
	Indenter diameter	mm	-	150	-	-
	Peak Indenter Speed	mm/s	-	15	-	-
	Release condition - Force	kN	-	1000 * $m_{battery}$.G	-	-
	Release condition - Voltage	V	-	Undefined	-	-
	Release condition - deformation	%	-	50%	-	-
	Observation time	hours	-	6	-	-

Table 80: Comparison of Battery Pack Electrical Abuse Test Protocols (1 of 2)

Test Category	**Test Type**	Units	Battery (< 12 kg)			
			UN38.3	EN 50604-1	EN 62133-2	UL 2271
External Short Circuit	Number of samples tested	-	4 new, 4 cycled	Undefined	5	1
	Temperature	°C	57	RT	20	Undefined
	State of Charge	%	100%	100%	100%	100%
	External short-circuit resistance	mΩ	<100	10 - 20	80 ±20	<20
	Observation time	hours	6	6	24	
Over-charge	Number of samples tested	-	4 new, 4 cycled	Undefined	5	1
	Temperature	°C	Undefined	≥RT	20	Undefined
	Initial State of Charge	%	Undefined	100%	0%	0%
	Charge Rate	C-rate	2x Charge I_{cont}	Undefined	2C	Charge I_{max}
	Termination Voltage	V	1.2x V_{max}	1.2x V_{max}	1.2x V_{max}	1.1x V_{max}
	Termination SOC	%	Undefined	130%[++]	Undefined	Undefined
	Observation time	hours	192	0	Undefined	2
Over-discharge	Number of samples tested	-	0	Undefined	0	1
	Temperature	°C	-	20[+++]	-	Undefined
	Initial State of Charge	%	-	Undefined[+++]	-	100%
	Discharge Rate	C-rate	-	< Disch. I_{max}[+++]	-	Disch. I_{max}
	Termination voltage	V	-	0	-	0
	Termination SOC	%	-	Undefined[+++]	-	Undefined
	Max discharge duration	hours	-	Undefined[+++]	-	Undefined
	Observation time	hours	-	0	-	1

Table 81: Comparison of Battery Pack Electrical Abuse Test Protocols (2 of 2)

		Battery (< 12 kg)			
Test Category	**Test Type**	UN38.3	EN 50604-1	EN 62133-2	UL 2271
Deep discharge Protection	Number of samples tested	0	1	0	0
	Temperature	-	Undefined	-	-
	Initial State of Charge	-	Undefined	-	-
	Discharge Rate	-	Undefined, CC-CV	-	-
	Termination voltage	-	0.9 * Cell V_{min}	-	-
	Termination SOC	-	Undefined	-	-
	Max discharge duration	-	Undefined	-	-
	Observation time	-	0	-	-
Imbalanced Charging	Number of samples tested	0	1	0	1
	Temperature	-	-	-	25
	Initial State of Charge	-	-	-	50%
	Imbalanced Cell Block Initial SOC	-	-	-	0%
	Charge Rate	-	-	-	Charge $I_{Nominal}$
	Termination voltage	-	-	-	Undefined
	Termination SOC	-	-	-	Undefined
	Max discharge duration	-	-	-	Undefined
	Observation time	-	-	-	Undefined

Table 82: Comparison of Battery Pack Thermal Abuse Test Protocols

			Battery (< 12 kg)			
Test Category	**Test Type**	Units	UN38.3	EN 50604-1	EN 62133-2	UL 2271
Over - temperature	Number of samples tested	-	0	Undefined **	0	1
	Initial Temperature	°C	-	50 **	-	Charge T_{max}
	State of Charge	%	-	Undefined **	-	0%
	Heating Method	-	-	Charge-Discharge	-	Charge-Discharge
	Temperature Rate	°C/min	-	Undefined **	-	Undefined
	Charge / Discharge Rate	C-rate	-	Chg. / Dschg. I_{max}	-	Ch/Dschg I_{max}
	Charge / Discharge Repeats	-	-	Undefined **	-	5
	Final Temperature	°C	-	Undefined **	-	Undefined
	Final Temperature Hold Time	mins	-	Undefined **	-	Undefined
	Observation time	hours	-	0	-	0
Low-temperature Protection	Number of samples tested	-	0	Undefined	0	0
	Initial Temperature	°C	-	T_{min} - 10K	-	-
	State of Charge	%	-	80%	-	-
	Attempted Charge Rate	C-rate	-	Chg. I_{max}	-	-
	Observation time	hours	-	0	-	-
Mold Stress Relief	Number of samples tested	-	0	0	3	1
	Initial Temperature	°C	-	-	70	70
	State of Charge	%	-	-	100%	0%
	Heating Method	-	-	-	Oven	Oven
	Temperature Rate	°C/min	-	-	0	0
	Charge / Discharge Rate	C-rate	-	-	0	0
	Charge / Discharge Repeats	-	-	-	0	0
	Final Temperature	°C	-	-	70	70
	Final Temperature Hold Time	mins	-	-	420	420
	Observation time	hours	-	-	Cool to RT	Cool to RT

15.6 Appendix 6: Comparison of Tests in EN 50604-1, ISO 12405-3 and ISO 6469-1

Table 83: Comparison of Test Categories in EN 50604-1, ISO 12405-3 and ISO 6469-1

Test Category	**EN 50604-1:2016 +A1:2021 Section Number**	**ISO 12405-3:2014 Section Number**	**ISO 6469-1:2019 Section Number**
Vibration	6.101	6.1	5.1 / 6.2.2
Mechanical Shock (accel profile)	6.102	6.2	5.1 / 6.2.3
Mechanical Shock (drop)	6.103	-	-
Resistance to Sunlight	6.104	-	-
Dewing (temperature change)	ISO 12405-3 § 7.1	7.1	-
Thermal Cycling / Shock	ISO 12405-3 § 7.2	7.2	5.2.1 / 6.3.1
Crush	8.101	8.2	6.4.1.1.3
Water immersion	8.3	8.3	5.3.2 / 6.4.2
Over-temperature	8.102	-	6.6.4
Low temperature	8.103	-	-
External Short Circuit (ESC)	9.1	9.1	5.4.3 / 6.5.1
Leakage current when battery is switched off	9.101	-	-
Thermal Propagation (TP) by ISC	-	-	5.7 / 6.7
Over-charge	10.1	10.1	5.5.2 / 6.6.2
Over-discharge	10.2	10.2	5.5.3 / 6.6.3
Loss of thermal control / cooling	10.3	10.3	5.5.4 / 6.6.4
Deep discharge	10.4	-	-
Over-current	-	-	-

15.7 Appendix 7: Errors and Inconsistencies in EN 50604-1

Table 84: Errors and Inconsistencies in EN 50604-1

Section	Quote	WMG comment on Error
Contents	(all)	The contents page shows some, but not all, of the 2nd-level sections. This makes it very difficult to navigate the document.
6.102 Mechanical Shock	This subclause of ISO 12405-3:2014 is applicable.	There is no Section 6.102 in ISO 12405-3:2014. This sentence should be deleted
6.102 Mechanical Shock 6.102.2 Test procedure	Adjust the SOC to 100 % before starting the vibration test	This is not a vibration test.
7.1 Dewing (temperature change)	This subclause of ISO 12405-3:2014 is applicable	Because of this, an isolation measurement has to be done, even on a battery of voltage class A.
8.102 Over-temperature condition test	Tests the safe behaviour of the battery system in a condition of over temperature	Why is this in Section 8 “Simulated vehicle accidents”? It should be in Section 10 “System functionality tests”
8.102 Over-temperature condition test	Tests the safe behaviour of the battery system in a condition of over temperature	This section is duplication of Section 10.3 Loss of thermal control/cooling.
8.103 Under-temperature condition test	Tests the safe behaviour of the battery system in a condition of under temperature	Why is this in Section 8 “Simulated vehicle accidents”? It should be in Section 10 “System functionality tests”
10.1 Overcharge protection 10.1.101 Purpose	Option 1: The VCU is directly connected to the cell assembly	It is completely unclear what this means, and how it affects connection to the short-circuit test rig.
10.1 Overcharge protection 10.1.102 Test procedure	According to ISO 12405-1:2011, 9.3.2, or ISO 12405-2:2012, 9.3.2, as appropriate for the DUT.	The subsequent test procedure vs. the ISO 12405-x procedure is not clear. E.g. Do the limits of 130% SOC limit and 55 °C from 12405-1:2011 apply?
10.1 Overcharge protection 10.1.102 Test procedure	Compliance is checked by a valid certificate.	It’s unclear what this statement applies to.

Section	Quote	WMG comment on Error
10.1 Overcharge protection 10.1.102 Test procedure	The voltage shall not exceed 1.2 times the maximum allowed cell voltage as defined by the supplier unless EV supply equipment is limited in voltage. Then the voltage applied to the DUT shall be set to the maximum output voltage of the EV supply equipment that can occur.	The meaning of "EV supply equipment" is not clear, because it is not included in Section 3 Definitions. Does it refer to a charger that is supplied with the LEV? Does it refer to a grid charger? Does it refer to any charger?
10.2 Over-discharge protection	For Option 2 or Option 3: ISO 6469-1:2019, 5.5.3 is applicable.	What is applicable for Option 1?
10.2 Over-discharge protection	NOTE For further information see also ISO 12405-3:2014, 10.2.	ISO 12405-3:2014, 10.2. conflicts with ISO 6469-1:2019, 5.5.3 in several details: - Ambient temperature - Initial SOC - Termination voltage - Termination time limit
10.3 Loss of thermal control/cooling	(all)	This section is duplication of Section 8.102 Over-temperature condition test
10.4 Deep discharge protection 10.4.102 Test procedure	10.4.102.1 Test procedure Option 1 (see 5.104.2):	Section 5.104.2 does not exist. Should be corrected to 5.103.2
10.4 Deep discharge protection 10.4.102 Test procedure	10.4.102.2 Test procedure Option 2 or 3 (see 5.104.3 or 5.104.4):	Sections 5.104.3 and 5.104.3 do not exist. Should be corrected to 5.103.3 and 5.103.3
10.4 Deep discharge protection 10.4.103 Requirements	10.4.103.1 Requirements Option 1 (see 5.104.2):	Section 5.104.2 does not exist. Should be corrected to 5.103.2
10.4 Deep discharge protection 10.4.103 Requirements	10.4.103.2 Requirements Option 2 or 3 (see 5.104.3 or 5.104.4)	Sections 5.104.3 and 5.104.3 do not exist. Should be corrected to 5.103.3 and 5.103.3
10.4 Deep discharge protection 10.4.103.2 Requirements Option 2 or 3	Compliance is checked by the review of the design and/or the software	If the check is done in this way, then why is a test needed? WMG suggests to delete this sentence.

Section	Quote	WMG comment on Error
10.4 Deep discharge protection 10.4.103.2 Requirements Option 2 or 3	Test result for 2a of 10.4.102.2: — this shall result in the single cell voltage reaching the 1 V level after 30 s	Does this mean: “single cell voltage must reach ≥1 V in ≤30sec” or “single cell voltage must reach ≥1 V in ≤30sec” ? The meaning is very unclear, and the rationale is also unclear. WMG suggests to re-word this.
10.4 Deep discharge protection 10.4.103.2 Requirements Option 2 or 3	Test result for 2a of 10.4.102.2: — if this is not the case, charging shall be terminated, and the battery pack/system permanently disabled for further use.	Does this mean: “the charging test shall be terminated” or “the BMS shall terminate charging” The meaning is very unclear, and the rationale is also unclear. WMG suggests to re-word this.
10.4 Deep discharge protection 10.4.103.2 Requirements Option 2 or 3	Test result for 2b of 10.4.102.2: — this shall result in the single cell voltage reaching the 3 V level after 6 min.	Does this mean: “single cell voltage must reach ≥3 V in ≤6min” or “single cell voltage must reach ≥3 V in ≤6min” ? The meaning is very unclear, and the rationale is also unclear. WMG suggests to re-word this.
10.4 Deep discharge protection 10.4.103.2 Requirements Option 2 or 3	Test result for 2b of 10.4.102.2: — this shall result in the single cell voltage reaching the 3 V level after 6 min.	What happens if this does not occur? Should charging not be permanently inhibited?

15.8 Appendix 8: Stakeholder Questionnaire

Questions on Product Knowledge

1. Please tell us about experience you have of thermal incidents (fires) involving PLEV products. These could be your own products, or those from another company. Your experience could be direct (e.g. in your own facilities) or indirect (e.g. your customers).

Questions on Root-Cause Analysis of Fires

With reference to question (1) above:

2. Was a root-cause analysis conducted, and if yes, what did it reveal?
3. What changes have you implemented, based on the lessons learned? e.g. Changes to your processes and procedures, or your product design / testing, or your facilities, or how you interact with customers (retailer advice, written instructions, training, service schedule, etc.)

Questions on PLEV Battery Standards and Regulation

4. Please tell us about your experience of applying Standards to the design, development, and certification of your products
    - 4.1. Which standards do you follow for the vehicle, battery and charger? e.g. EN 15194:2017 (e-bikes); EN 17128:2020 (non-road PLEVs); EN IEC 62133-2:2017 (batteries); BS EN 50604-1:2016+A1:2021 (LEV batteries)
    - 4.2. Which aspects of the standards are most challenging to comply to?
    - 4.3. Do you aim to exceed the safety requirements of the Standards in any respects?
        - 4.3.1. If yes, which, and why?
    - 4.4. Are there aspects of the Standards which you find inadequate?
        - 4.4.1. If yes, which, and in what way?
    - 4.5. Are there aspects of the Standards which you find unnecessary or too stringent?
        - 4.5.1. If yes, which, and in what way?

Question on Good Practice

6. Please tell us about your experience of good practice in PLEV product design, testing, manufacture, and delivery, insofar as it affects safety (primarily fire safety)
    - 6.1. What design features do you regard as critical to this goal?

      e.g. battery monitoring (voltage, current, temperature, etc.); specific battery management system functions; communication (e.g. between battery and charger); passive protection components such as fuses or thermal cut-outs; active protection components such as switches / relays; ingress protection (protection against moisture, dust, etc.); creepage / clearance distances; anti-tampering features; anti mis-use features (e.g. unique charger connectors); thermal propagation mitigation features; vent devices; etc.
    - 6.2. What testing / validation / certification practices do you regard as critical to this goal?

      e.g. Specific standards to be followed; other tests that aren’t in the standards.
    - 6.3. What manufacturing practices do you regard as critical to this goal?

e.g. Cell manufacturing quality good practice (incoming material checks, cleanliness levels, specific in-line quality checks and/or end-of-line quality checks, traceability data, etc.); pack assembly processes (e.g. busbar -to- cell welding; application of adhesives; wiring harness terminal crimping; etc.); pack assembly quality good practice (e.g. cell matching based on SOC / capacity / impedance; weld quality checks; ingress protection checks such as housing vacuum leak-down test; end-of-line BMS functionality / sensor checks; end-of-line energy capacity checks; self-discharge checks; etc.)

  6.4. What delivery practices do you regard as critical to this goal?

    e.g. Shipping packaging to protect parts; parts handling procedures; pre-delivery inspection / test; pre-delivery charging / discharging / cell balancing; customer communication / demonstration; documentation / instructions for the customer; etc.

7. Please tell us about your experience with your supply-chain for batteries and chargers
    7.1. What supply-chain issues have you encountered which may have affected the safety of your products?
    7.2. What supply-chain choices have you made, based on safety considerations?

    e.g. deliberately not selecting a supplier, or deliberately selecting another supplier

    7.3. Please tell us about the basis of those decisions

Questions on Market Intelligence

8. Please share information on current size and trends of UK PLEV market

Questions on Consumer feedback

9. Please tell us about your experience of customer usage of PLEVs, regarding their safety (primarily fire safety), including customer misuse
    9.1. What experience do you have of customers returning products, or complaining about products, due to issues that may relate to safety?
    9.2. Have customers used the incorrect charger for the PLEV / battery?
    9.3. Have customers replaced original-equipment batteries or chargers with alternatives that were not from the original equipment supplier?
    9.4. Describe any other customer behaviour which may affect the safety of the PLEV, particularly the battery and charger.
    9.5. Describe any actions you have taken to mitigate customer misuse, or otherwise to improve the customer experience with regard to product safety

15.9 Appendix 9: Abuse Test Methodology Details

15.9.1 Preparation

Step	
1	Determine the expected minimum battery pack voltage, V_{min}, based on (1) Battery label, (2) Manufacturer website and (3) Cell manufacturer data. If there is a conflict between sources or some sources do not exist, use the highest value.
2	Determine the expected maximum battery pack voltage, V_{max}, based on (1) Battery label, (2) Manufacturer website and (3) Cell manufacturer data. If there is a conflict between sources or some sources do not exist, use the lowest value.
3	Determine the expected maximum battery pack discharge current, I_{max_disch}, based on (1) Battery and BMS label data, (2) Manufacturer website and (3) Cell manufacturer data. If there is a conflict between sources or some sources do not exist, use the lowest value.
4	Determine the expected maximum battery pack discharge current, I_{max_ch}, based on (1) Battery and BMS label data, (2) Manufacturer website and (3) Cell manufacturer data. If there is a conflict between sources or some sources do not exist, use the lowest value.
5	Determine the expected maximum battery pack discharge temperature, T_{max_disch}, based on (1) Battery label, (2) Manufacturer website and (3) Cell manufacturer data. If there is a conflict between sources or some sources do not exist, use the lowest value.
6	Determine the expected maximum battery pack charge temperature, T_{max_ch}, based on (1) Battery label, (2) Manufacturer website data and (3) Cell manufacturer data. If there is a conflict between sources or some sources do not exist, use the lowest value.
7	Determine the expected maximum BMS MOSFET temperature, T_{max_MOSFET}, based on the MOSFET datasheet.

15.9.2 Discharge Over-Current Test with BMS

Step	
1	Use the test-chamber power-supply to charge the battery via the charging connector, as necessary, until the state of charge is above 50% (open-circuit voltage is above nominal)
2	Use the test-chamber power-supply to discharge the battery via the discharging connector. Set the initial discharge current to a value below 50% of I_{max_disch}. Increase the discharge current in steps, at intervals of 1-5 A (at the discretion of the test engineer), up to a maximum of 40 A. The test may be stopped at any time, at the discretion of the test engineer, based on factors such as: - BMS interrupts discharging. - BMS MOSFET temperatures increasing at alarming rate.
3	Continue the discharge until either the BMS interrupts the discharge, or the pack voltage is 5 V below the expected minimum battery pack voltage V_{min} determined previously.

Pass criteria:

- No venting, rupture, fire or explosion.
- BMS interrupts discharge when discharge current > I_{max_disch} + 2 A.
- Cell temperature < T_{max_disch} + 2 °C.
- BMS MOSFET temperature < T_{max_MOSFET}.

15.9.3 Under-Voltage Test with BMS

Step	
1	Use the test-chamber power-supply to charge the battery via the charging connector, as necessary, until the state of charge is above 50% (open-circuit voltage is above nominal)
2	Use the test-chamber power-supply to discharge the battery via the discharging connector. Discharge current to be determined to ensure that the BMS does not interrupt discharge based on either over-current or over-temperature.
3	Continue the discharge until either the BMS interrupts the discharge, or the pack voltage is 5 V below the expected minimum battery pack voltage, V_{min}.

Pass criteria:

- No venting, rupture, fire or explosion.
- BMS interrupts discharge when pack voltage is $> V_{min} - 1$ V.
- Cell temperature $< T_{max\_disch} + 2$ °C.
- BMS MOSFET temperature $< T_{max\_MOSFET}$.

15.9.4 Charge Over-Current Test with BMS

Step	
1	Use the test-chamber power-supply to discharge the battery via the discharging connector, as necessary, until the state of charge is below 50% (open-circuit voltage is below nominal)
2	Use the test-chamber power-supply to charge the battery via the charging connector. Set the initial charge current to a value below 50% of I_{max_ch}. Increase the charge current in steps, at intervals of 1-2 A (at the discretion of the test engineer), up to a maximum of 40 A. The test may be stopped at any time, at the discretion of the test engineer, based on factors such as: - BMS interrupts discharging. - BMS MOSFET temperatures increasing at alarming rate.
3	Continue the discharge until either the BMS interrupts the discharge, or the pack voltage is 5 V below the expected minimum battery pack voltage V_{min} determined previously.

Pass criteria:

- No venting, rupture, fire or explosion.
- BMS interrupts charge when charge current > I_{max_ch} + 2 A.
- Cell temperature < T_{max_ch} + 2 °C.
- BMS MOSFET temperature < T_{max_MOSFET}.

15.9.5 Over-voltage Test with BMS

Step	
1	Use the test-chamber power-supply to discharge the battery via the charging connector, as necessary, until the state of charge is below 50% (open-circuit voltage is below nominal)
2	Use the test-chamber power-supply to charge the battery via the charging connector. Set the charge current target to a value below the BMS cut-off current, determined from the charge over-current test. Set the charge voltage target to a value of 2x V_{max}.
3	Continue the charge until either the BMS interrupts the charge, or the pack voltage is 2 V above the expected maximum battery pack voltage V_{max} determined previously. At this point, the power-supply will default to the charge voltage target. This is to test the ability of the charge MOSFET to withstand over-voltage.
4	Use the test-chamber power-supply to discharge the battery via the discharging connector, as necessary, until the state of charge is below 80%.
5	Use the test-chamber power-supply to charge the battery via the charging connector. Check that the charging MOSFET behaviour is similar to previously, indicating that it has not been damaged.

Pass criteria:

- No venting, rupture, fire or explosion.
- BMS interrupts charge when pack voltage is $< V_{max} + 1$ V.
- Cell temperature $< T_{max\_ch} + 2$ °C.
- BMS MOSFET temperature $< T_{max\_MOSFET}$.
- BMS charge MOSFET resistance unaffected by over-voltage, or charging is permanently inhibited.

15.9.6 Over-voltage Test, bypassing BMS

Step	
1	Use the test-chamber power-supply to discharge the battery via the charging connector, as necessary, until the state of charge is below 80%
2	Reconfigure the power-supply connection to the battery, either to charge via the discharge connector or to bypass the BMS completely. The intention is to ensure that the BMS cannot interrupt charging.
3	Use the test-chamber power-supply to charge the battery. Continue the charge until the charging curent is interrupted by the battery (e.g. cell CIDs) or until thermal runaway

Pass criteria:

- No rupture, fire or explosion.

15.9.7 External Short-Circuit with BMS

Step	
1	Connect the discharge connector of the battery to an external circuit comprising the following components mounted electrically in series: - Heavy-duty contactor (initially with contacts open) - Heavy-duty current shunt / sensor (< 20 mΩ). The external circuit components should be rated for at least 1000 A.
2	Using a suitable power-supply, activate the coil of the contactor to close the circuit.
3	Allow the current to continue to flow until the discharging current is interrupted by the battery or thermal runaway occurs. Then deactivate the coil of the contactor to open the circuit.

Pass criteria:

- No venting, rupture, fire or explosion.
- Cell temperature < T_{max_disch} + 2 °C.

15.9.8 External Short-Circuit, bypassing BMS

Step	
1	Reconfigure the external circuit connection to bypass the BMS.
2	Using a suitable power-supply, activate the coil of the contactor to close the circuit.
3	Allow the current to continue to flow until the discharging current is interrupted by the battery or thermal runaway occurs. Then deactivate the coil of the contactor to open the circuit.

Pass criteria:

- No rupture, fire or explosion.

Contact us if you have any enquiries about this publication, including requests for alternative formats, at: OPSS.enquiries@beis.gov.uk

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