SPEED-EMISSION/ENERGY CONSUMPTION CURVES FOR ULTRA-LOW EMISSION VEHICLES AND NON-FUEL OPERATING COSTS FOR ALL VEHICLES

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EXECUTIVE SUMMARY

The UK Department for Transport uses several modelling tools to estimate the direct and indirect impacts of road transport policies. The ability of these tools to predict environmental and economic outcomes rely on the accuracy of the input data and assumptions feeding into them. The challenge, therefore, is to keep these assumptions up to date as the nature and behaviour of the UK fleet changes.

The National Transport Model (NTM) and Transport Analysis Guidance (TAG) currently use a set of equations that describe how emissions of nitrogen oxides (NOx) and fine particulate matter (PM), fuel and energy consumption vary with average speed for different ultra low emission vehicle (ULEV) types. These equations are based on a study carried out by Ricardo in 2015 using information available at the time which was fairly limited due to the low number of ULEVs in the fleet and lack of emission test data. The factors were therefore subject to high uncertainty.

Since then, a greater number of ULEVs have entered the fleet and with it an expanding database on emissions and fuel/energy consumption under real-world conditions has emerged. This report describes the development of an updated set of speed-emission and fuel/energy consumption curves for a wider range of ULEV types derived from a more substantial evidence base from measurements made across Europe. The ULEV types include hybrid, plug-in hybrid, battery electric and hydrogen fuel cell electric vehicle types in the passenger car, light goods vehicle (LGVs), heavy goods vehicles (HGVs), buses and coaches fleets, as well as catenary battery electric vehicles in the HGV fleet.

The measurements data have been processed by TU Graz in Austria for various European studies using the PHEM simulation model to provide factors that underpin the transport emission inventories used in many countries. Data from this source have been available for this study to generate the emission curves in the format required for the NTM and TAG for each of the various ULEV types requested by DfT. In addition, various assumptions have been made to fill some data gaps and in estimating the emissions and consumption of future generations of these ULEV types. Then using the latest fleet turnover model used in the UK's National Atmospheric Emissions Inventory compiled for Defra, a set of fleet-weighted emission curves have been developed for each main ULEV type in different years out to 2060. The derivation of the fleet-weighted emission curves is described in this report and the curves themselves, the underlying data and fleet weightings are provided in an accompanying Excel spreadsheet. This allows DfT to change any of the input parameters such as fleet-weightings for future years when such data become available or for modelling alternative scenarios and assumptions.

In addition, emission factors have been provided from the latest evidence on PM emissions from non-exhaust processes, i.e. from tyre and brake wear and road abrasion and estimates for the fraction of NO_x emissions emitted directly in the form of nitrogen dioxide (NO_2).

The provenance of the data from an established and well-respected source and the fact that the data are derived from a larger evidence base should give greater confidence in the emission and consumption curves developed in this study compared with the previous 2015 study. Nevertheless, there remains uncertainty in the curves, particularly for ULEV technologies less established in the fleet such as those for heavy duty vehicles and curves for future generations of vehicles where changes in emissions and efficiencies are still uncertain and assumptions have been made. The report describes the main areas of uncertainties and summarises the assumptions made.

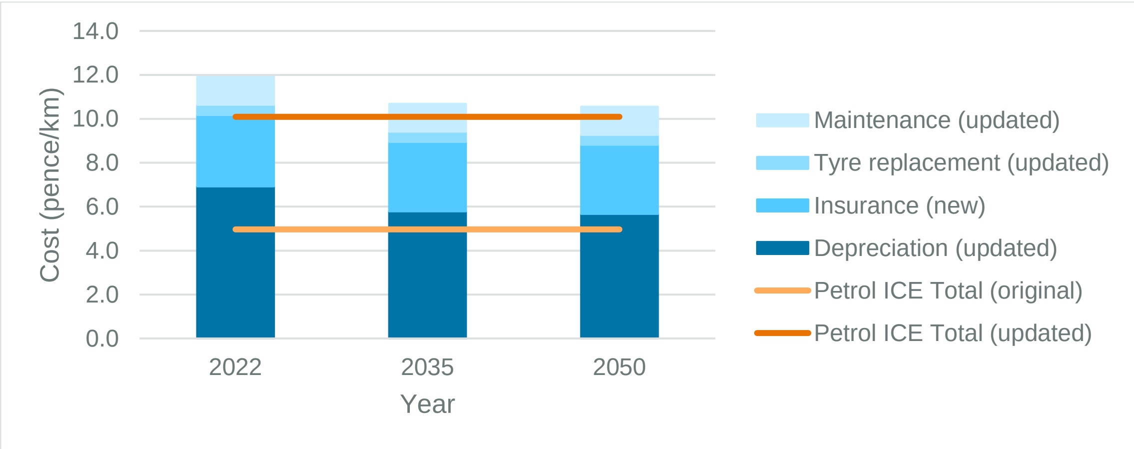
The report shows a comparison of how the new emission curves developed in this study compare with those developed previously. In some cases, the emissions or consumption factors for a specific ULEV type are higher than previously estimated and in other cases are lower. The differences are discussed and are largely due to the fact that the data come from a different, but more robust data set than before, based on a larger number of vehicles and tests, but may also reflect genuine changes in emission performance and energy efficiencies of these vehicles as technologies have advanced.

In spite of these uncertainties, we recommend the emission and consumption curves for use in the NTM and TAG as being based on the most robust and up-to-date information available providing the limitations and assumptions made are recognised. We also recommend that the curves are periodically updated, as new ULEV types and generations of existing ULEV types enter the fleet and the evidence base on their emissions and energy performance expands.

As well as updates to emission curves for TAG, the Non-fuel vehicle operating costs (NFVOCs) used in TAG were updated for both conventional internal combustion engine (ICE) vehicles and ULEVs. NFVOCs were updated for conventional powertrains based on the most recent publicly available operational data identified in the UK, covering cost factors such as vehicle maintenance, tyre replacement and distance-related depreciation. An additional cost factor not previously considered in NFVOCs was also included, i.e. the premium paid to insure vehicles on UK roads. These updated NFVOCs were then extended to estimate costs for ULEVs utilising Ricardo's proprietary analysis of ULEV capital costs, also including a cost factor for the replacement of batteries and fuel cells in relevant vehicles.

In comparison to the NFVOCs currently used in road transport modelling for conventional vehicles, which are based on estimates originally made in the 1990s, the costs estimated in this study are often significantly higher - for example, see difference between original and updated estimates for working petrol cars in Figure 1 below. Differences between the two estimates are due to the **addition of insurance payments** (an additive element for each vehicle type), **changes in fleet activity** (increasing estimated per kilometre costs for some vehicles), and **increases in capital costs** (affecting both insurance payments and vehicle depreciation). NFVOCs for ULEVs are higher across the board than conventional powertrains, but this differential is projected to fall over time as high initial ULEV purchase costs fall due to technological improvements and increases in the scale of production (see example below for BEV passenger cars).

Figure 1: NFVOC update example: BEV passenger car, with Petrol ICE for comparison (Units: 2010 pence/km)



We recommend that all of the emission and energy curves and NFVOCs developed are periodically revisited as more ULEVs enter the market and improved real-world evidence comes to light.

CONTENTS

1. INTRODUCTION

The National Transport Model (NTM) is the Department for Transport's (DfT) analytical and policy-testing tool used to provide road traffic forecasts and means of comparing the national consequences of alternative national or widely applied local transport policies. The NTM has the capability of calculating fuel and energy consumption and emissions of carbon dioxide (CO_2), nitrogen oxides (NO_x) and fine particulate matter (PM) from road vehicles in different years using a set of equations that relate emission or fuel/energy consumption factors for different vehicle types to average vehicle speed. These equations are used together with forecasts of traffic levels and vehicle speed to predict future quantities of fuel or energy use and road traffic emissions. DfT's Transport Analysis Guidance (TAG) also provides a methodology for assessing the impacts of road schemes and public transport schemes and uses similar speed emissions curves to characterise the emissions of different vehicle types in different traffic conditions.

The UK vehicle fleet is continuously evolving with new vehicles and technologies entering the fleet. With this, the evidence base on emissions from the current and future fleet is developing. In 2015, Ricardo Energy & Environment developed a set of speed emission/energy consumption curves for a range of ultra-low emission vehicle technologies (ULEVs) for use in the NTM and TAG based on the evidence available at the time. These were provided in the same format as those also provided by Ricardo for more conventional petrol and diesel internal combustion engine (ICE) vehicles.

Since 2015, the evidence on emissions and energy consumption for ULEVs has further developed and DfT requires an update of the factors and assumptions used in the NTM and TAG for these vehicle types based on the latest evidence to ensure these tools are better able to predict the impact of policies on emissions and energy consumption. The objective of this project was to develop updated fuel/energy consumption and emission speed curves for the ULEV technology types shown in Table 1.

Table 1 Ultra Low Emission Vehicles covered in this study

Vehicle Type	***Fuel/Technology Type***
Cars	Battery Electric Vehicle (BEV) Non plug-in hybrid (HEV) Plug-in Hybrid (PHEV) Hydrogen Fuel Cell Vehicle (HFCV)
Light goods vehicles	Battery Electric Vehicle Non plug-in hybrid Plug-in Hybrid Hydrogen Fuel Cell Vehicle
Heavy goods vehicles: Each of rigid and artic Each of OGV1 and OGV2	Battery Electric Vehicle Plug-in Hybrid Catenary Battery Electric Vehicle (catenary BEV) Catenary Plug-in Hybrid (catenary PHEV) Hydrogen Fuel Cell Vehicle
For each of buses and coaches	Battery Electric Vehicle Plug-in Hybrid Hydrogen Fuel Cell Vehicle

The general approach to the development of new speed emission curves is described in this report, but the main source of data was simulations from the Passenger Car and Heavy Duty Emission Model (PHEM) developed by the University of Technology Graz (TU Graz, Institute for Thermodynamics and Sustainable Propulsion Systems) in Austria. PHEM is an instantaneous vehicle emissions model based on an extensive European set of vehicle measurements and covers passenger cars, light duty vehicles and heavy duty vehicles from city buses up to 40 tonne HGVs. It is validated against portable emissions measurement systems (PEMS) for real-world vehicle emission test data and is used to support most of the models used in Europe to develop city scale and national emission inventories. These models include the average speed-related emission factors in COPERT, the source of emission factors used in the UK's national atmospheric emissions inventory (NAEI).

Further details on how data from PHEM were used to develop the speed-curves for the NTM and TAG are described in Section 2. This includes the assumptions made such as the utility factors for plug-in hybrid vehicles that define the emissions, fuel and energy consumed by these vehicles from the combustion engine and mains electricity source.

The scope for the update in emission curves has been expanded from the previous work to cover non-exhaust emissions of PM from tyre and brake wear as well as exhaust emissions. The source of data for these emissions is also discussed in Section 2. In the case of HGVs, additional consideration has been given to energy consumption of vehicles powered by a network of catenary cables above major roads which have been proposed to electrify a significant proportion of the distance travelled by the long-haul HGV fleet.

Section 3 sets out the exhaust emission factor results for cars and light goods vehicles (LGVs) and section 4 sets out the exhaust emission factor results for the heavy goods vehicles, buses and coaches. Section 5 describes the emission factors developed for non-exhaust sources of PM. In section 6, we provide an overview of the tools developed for the aggregation of the emission functions for use in the NTM including the fleet weightings used to develop a series of curves for each vehicle and technology type specific for different model years from 2015 to 2060.

In addition to new speed-emission and fuel/energy curves for these vehicles, DfT also requires an update and extension to the existing evidence base for non-fuel vehicle operating costs (NFVOCs), covering conventional ICE vehicles and ULEVs. This was to cover a number of operating cost components, and has also utilised approaches and datasets used by Ricardo in more recent (currently unpublished) studies for the European Commission (Ricardo et al., 2021 forthcoming) (Ricardo et al., 2023 forthcoming). Section 7 discusses the updates to the non-fuel vehicle operating costs (NFVOCs), the sources of data used for the updates, assumptions made, and the methodology used to develop them.

Section 8 provides a brief discussion on the uncertainty and robustness of the results and what the major limitations are likely to be.

Accompanying this report are spreadsheets with the final emission curves functions and aggregation tools as well as the NFVOCs.

2. DATA SOURCES, METHODOLOGY AND ASSUMPTIONS

2.1 OVERVIEW

The current speed-emission/energy curves used in the NTM and TAG were derived in the 2015 study from a fairly limited set of data and evidence on the real-world performance of ULEVs. The curves were generated using data from various literature sources available at the time, including emissions inventory guidebooks, data from research studies and vehicle manufacturers, some raw emissions/energy data from Portable Emission Monitoring Systems (PEMS) where emissions tests had been carried out on ULEVs in real traffic situations and from PHEM model simulations. However, since many of the technologies were new or not even in production at the time detailed real-world data were not readily available. Most of the available data were on light duty vehicles, with far less data available for heavy duty vehicles. In general, it was then necessary to do some gap filling, extrapolations, merging and rationalisation of data from these different sources to derive the most optimum set of curves for each detailed vehicle category. Fleet compositional weightings were then done to take account of changes in emission and energy performance over time due to technology improvements and emission regulations to provide a single curve for each year, pollutant and main vehicle technology types.

To update the speed-exhaust emission curves for this study, a number of data sources were used. The key data sources were:

- Simulation data from the PHEM model provided by TU Graz
- Data on light and heavy duty vehicle technology performance from previous work undertaken by Ricardo
- Road transport emission factors from the EMEP/EEA Inventory Guidebook
- Literature evidence on the share of electric driving (i.e. the utility factor) for plug-in hybrid electric vehicles

Real-world emission factors of PM from non-exhaust sources such as tyre wear and brake wear are sparse at present. Research is on-going including through a programme being undertaken by Ricardo, funded by DfT, though this is not specifically looking at ULEV sources of non-exhaust emissions. However, factors are available for these sources for compiling emission inventories from the latest version of the EMEP/EEA Emissions Inventory Guidebook. This Guidebook does now provide factors for hybrid and battery electric vehicles separate from factors provided for ICE vehicles that take into account the impact of regenerative braking and differences in vehicle weight for hybrids and BEVs which can both influence the quantity of tyre and brake wear emissions.

Further details on the assumptions and curve development specific to individual vehicle categories will be given in the following sections. Having developed speed curves for individual Euro standards or generations of vehicles of a given category, information on fleet turnover defining the proportion of vehicle kilometres travelled by each sub-category (Euro standard or generation) was used to provide weightings and development of speed curves for each main vehicle category representative of a given year in the UK.

2.2 OUTLINE METHODOLOGY FOR THE DEVELOPMENT OF SPEED EMISSION AND ENERGY CURVES

2.2.1 PHEM model simulations of ULEV emissions and energy consumption

The main source of emissions data for this study was from detailed simulations from the Passenger car and Heavy duty Emission Model (PHEM) model. The PHEM model was developed by the Technical University of Graz (TU Graz) in Austria who provided the simulated emissions data for this study.

Through the PHEM model, TU Graz provides the main input to the European Research for Mobile Emission Sources (ERMES) group. ERMES is a permanent network of mobile emission modellers and model users, coordinated and partly funded by the EC Joint Research Centre (JRC) and brings together the knowledge produced in Europe, to facilitate information exchanges and promote cooperation in the measurement and modelling of mobile emissions, energy consumption and transport decarbonisation. As well as being the source of speed-related factors for the COPERT model which are made available in the EMEP/EEA Emissions Inventory Guidebook for official inventory reporting, the PHEM model provides the traffic-situation based factors that underpin the Handbook Emission Factors for Road Transport (HBEFA), widely used for modelling road traffic emissions in Europe.

The basic approach used by the PHEM model is to model the components of the vehicle in relation to a drive cycle[1] in order to generate an engine speed/power (torque) profile. This is then related to an engine emission map generated on an engine test bed to provide engine out emissions. These can then be corrected by exhaust treatment modules to provide full vehicle emission results. This allows detailed modelling of vehicle technology combinations and vehicle drive cycles, from which emission results can be aggregated to give emission factors.

PHEM simulations are designed to be representative of the vehicle fleet in the EU and already exist for conventional ICE, hybrid (HEV) and electric vehicle classes as they are included in HBEFA. The emissions and energy data assessed here were consistent with the vehicle simulations and drive cycles generated for HBEFA 4.2, the latest version of HBEFA. New PHEM simulations were run for this study to provide updated BEV energy consumption data. These new simulations incorporated the latest evidence on real-world energy consumption from BEVs (Helms, et al., 2022), including the power demand of auxiliaries such as air conditioning and heating, into the engine maps used for simulations.

The simulation outputs provided average speed, tailpipe emission factors of NO_x and PM (where relevant), and energy or fuel consumption for over 300 traffic situations and drive cycles for each detailed vehicle class by vehicle type, fuel, technology, Euro standard and size or weight class. The traffic situations cover driving on urban, rural and motorway roads and account for state of flow (free-flow, heavy, saturated and stop-start) and the speed limit of a road (Ericsson, Nolinder, Persson, & Steven, 2019). For each traffic situation, TU Graz provided a weighting factor that reflects the typical prevalence of a particular driving condition in Europe at a given average speed. With this information, statistical fits of the emissions or energy consumption data versus average speed could be carried out to develop the sixth-order polynomial speed functions in the formats required by DfT.

2.2.2 Speed emission, fuel and energy consumption curves for battery electric and hybrid vehicles

The PHEM simulations discussed above provided good quality speed related data for ICE (internal combustion engine), BEV and hybrid vehicles. BEV and hybrid vehicles were the core technologies that provided the basis of the curve fitting for all other ULEV vehicle technologies. Table 2 summarises the data available from the PHEM simulations. The PHEM simulations provide fuel consumption for hybrid vehicles and energy consumption for BEVs. The simulations provide NO_x and PM emissions from ICE vehicles, but NO_x and PM emissions are not provided separately for hybrid vehicles because there is currently insufficient evidence from vehicle measurements to do so. TU Graz recommended assuming that NOx and PM emissions from hybrid vehicle are the same as from the equivalent ICE vehicle of the same type, fuel, weight class and Euro standard.

The data from the PHEM simulations were fit with a sixth-order polynomial speed function of the format required for the speed emission/energy curves to be used by DfT in the NTM and TAG. As noted above, the simulation outputs were provided for hundreds of traffic situations and each traffic situation needed to be weighted according to its prevalence. UK traffic data was not available to enable it to be allocated according to the HBEFA drive cycles and it was beyond the scope of this work to develop these detailed weightings. Instead, TU Graz provided the traffic situation weighting for Austria that were developed for HBEFA and these weightings were used to develop speed emission and energy curves.

Figure 2 shows an example of the fits to the PHEM simulations. This figure shows the average speed and emissions data from the PHEM simulations plotted in the open circles, where the size of the circle indicates the weighting attributed to a traffic situation, and the red line shows the sixth-order polynomial fit to the data.

[1] A drive cycle represents a set of vehicle speed points versus time and is used to provide a standardised assessment of fuel consumption and emissions. In PHEM a set of more than 100 drive cycles can be simulated to represent driving under a range of conditions, such as urban driving on a trunk road under stop-start or free-flowing conditions.

Figure 2 Example sixth-order polynomial fit to PHEM simulations

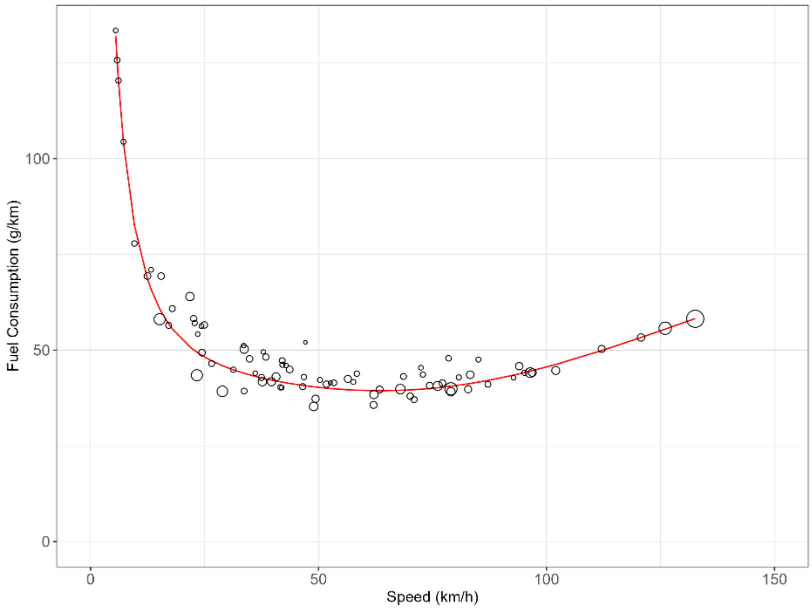


Table 2 shows that PHEM simulations provided emission and fuel/energy consumption curves for a number of weight classes of ICE, BEV and hybrid buses, coaches and HGVs. The weight classes for NO_x and PM simulations are aligned with the weight classes for buses, coaches and HGVs in the fleet compositions developed for the NAEI. The BEV energy and hybrid fuel consumption simulations, however, were available only for a subset of the weight classes. Speed emission, energy and fuel consumptions curves for all weight classes of BEV and hybrid buses, coaches and HGVs that were not available from the PHEM simulations were estimated based on the available data for BEV and hybrid vehicles and fuel consumption curves that were available for all size classes. This methodology is discussed further in Section 4.

Table 2 Summary of data available from the PHEM simulations

Vehicle class	Weight class	ICE vehicle NOx, PM & FC	BEV EC	Hybrid FC
Car	One size	✓	✓	✓
Van	N1(I)[a]	✓	✓	✓
	N1(II)[a]	✓	✓	✓
	N1(III)[a]	✓	✓	✓
Rigid HGV	3.5-7.5 t	✓	✓	✓
	7.5-12 t	✓	✓	✓
	12-14 t	✓	×	×
	14-20 t	✓	✓	✓
	20-26 t	✓	×	×
	26-28 t	✓	✓	×
	28-32 t	✓	×	×
	>32 t	✓	×	×
Articulated HGV	14-20 t	✓	×	×
	20-28 t	✓	×	×
	28-34 t	✓	×	×
	34-40 t	✓	✓	✓

Vehicle class	Weight class	ICE vehicle NOx, PM & FC	BEV EC	Hybrid FC
	40-50 t	✓	×	×
	50-60 t	✓	×	×
	>60 t	✓	×	×
Bus	<15 t	✓	✓	✓
	15-18 t	✓	✓	✓
	>18 t	✓	✓	✓
Coach	<15 t	✓	✓	×
	15-18 t	✓	✓	×
	>18 t	✓	✓	×

a) The weight classes of vans are defined based on the reference mass of the vehicle, where the reference mass is the mass in running order less the uniform mass of the driver of 75 kg and increased by a uniform mass of 100 kg. The weight classes are defined as N1(I) – RW≤1305 kg, N1(II) – 1305 kg <RW≤1760 kg, and N1(III) – 1760 kg < RW. All vans are less than 3,500 kg gross vehicle weight.

The curves developed for the core BEV and hybrid technologies were the basis for the calculation of curves for all other technologies. The curves for PHEVs, HFCVs and catenary HGVs were calculated based on the data for the core technologies:

- PHEVs – developed from the curves for HEVs and BEVs using the concept of a utility factor (UF) which provides an estimate of the proportion of time a PHEV operates in electric mode.
- HFCVs – derived from BEVs using a factor to convert required electric consumption into hydrogen consumption
- Catenary BEV HGVs– derived from BEV curves, accounting for the energy losses through plug-in charging of the battery at a depot and from drawing power from an external road system (ERS, e.g. overhead power lines) and the share of driving done on the ERS.
- Catenary PHEV HGVs – derived from BEV and hybrid curves and based on a similar methodology to catenary BEVs, but additionally accounting for the share of driving on the diesel engine.

The remainder of this section provides details of the methodology to calculate curves for these ULEV classes.

Section 3 sets out the resulting curves for the three core technologies for cars and LGVs, and the methods to derive curves for the remaining technologies. Section 4 sets out the detailed method and resulting curves developed for ULEV buses, coaches and HGVs.

2.2.3 Battery charging efficiency

Simulations can predict the energy required for vehicles (both LDV and HDV) for pure electric (battery) vehicles in units of kWh/km. These are especially valuable for ULEVs that currently do not exist, and for which there are no real-world data.

However, in terms of total power consumption, there are charger efficiencies (converting the AC mains electricity into a DC charging current) and internal battery loses to be taken into account also.

For HDVs the data within the VECTO model[2] assumes a charger efficiency of 90% and 2% battery charging losses (i.e. that is 98% efficient). Together this amounts to an overall efficiency of 88.2%, i.e. there are 11.8% losses.

The literature supports these values, though putting them towards the more efficient end of the spectrum (lower efficiencies, i.e. higher losses are often reported). These data come from peer reviewed scientific studies

[2] The Vehicle Energy Consumption calculation Tool (VECTO) is a simulation tool developed by the European Commission and is used for determining CO_2 emissions and fuel consumption from heavy duty vehicles (trucks, buses and coaches) with a gross vehicle weight above 3500 kg, Vehicle Energy Consumption calculation TOol - VECTO (europa.eu)

(Apostolaki-Iosifidou, Codani, & Kempton, 2017), practical testing (ADAC, 2023), and summaries in popular motoring journals (go-e, 2022).

In this study, we will assume the losses for all BEVs are 11.8%. This applies to depot charging, rapid charging, and ultrarapid charging. An uplift factor of 1/0.882 = 1.13 should be applied to the BEV battery to wheel energy consumption curves derived from the PHEM model to account for charging losses.

Catenary BEV and PHEV HGVs, when connected to external power lines, can be charged in motion. The data within the VECTO model assumes an in-motion charging efficiency of 85% and 2% battery losses which amount to an overall efficiency of 83.3%. This charging efficiency has been assumed in this study for catenary BEV and PHEV HGVs while connected to the external road system.

2.2.4 Utility factors for plug-in hybrid cars and vans

2.2.4.1 Introduction and definition

The “utility factor”, UF, concept is used for plug in hybrid electric vehicles, PHEV, which can use either a liquid fuel through an internal combustion engine, or external electricity supply, to provide its energy. It is defined as: Utility factor = Fraction of total mileage driven using electric only (power depleting) mode.

Therefore, for a PHEV used for short commuting, that drives only using the vehicle’s electric battery, which keeps being topped up from the mains electricity supply, its UF would be 1.00. For a PHEV which is never plugged in to the mains, and uses only pump fuel, its UF would be 0.00.

When modelling a fleet of PHEVs, an average UF is used, which lies between these two extremes.

2.2.4.2 Original values

UF values have evolved as driver behaviour has been quantified. Originally the Regulations were defined based on the electric range over the regulatory New European Drive Cycle (NECD). The algorithm below was used to define a vehicles UF:

UF = Electric only range over NEDC / (Electric only range over NEDC + 25km)

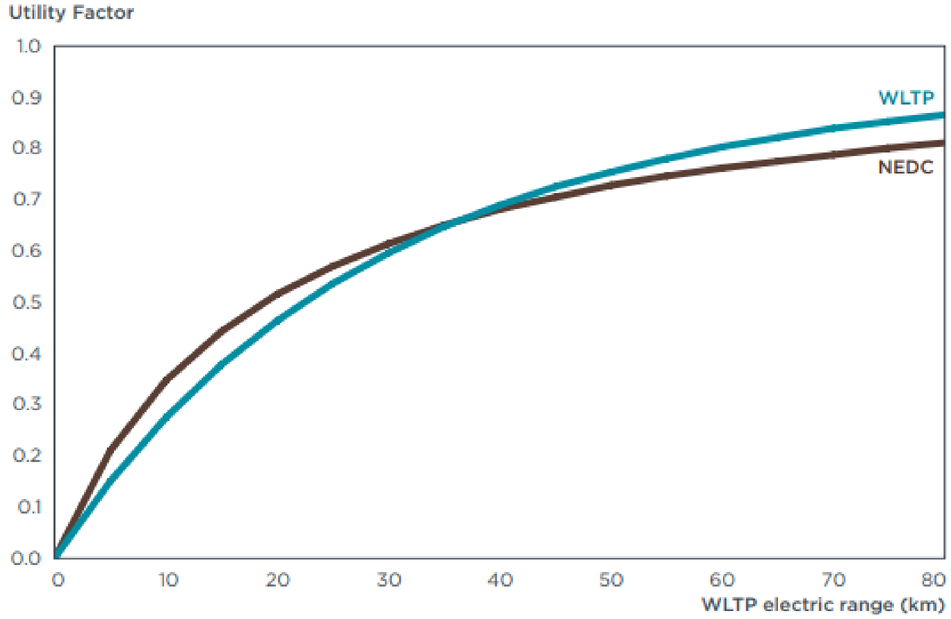
- Ranges from 50% for E Range = 25 km
- To 80% for E Range = 100 km
- To 90% for E Range = 225 km

This was revised when the regulatory drive cycle changed from the NEDC to the World Harmonised Light Vehicle Test Procedure (WLTP), becoming:

UF = Electric only range over WLTP / (Electric only range over WLTP + 25km)[3]. The UF can be plotted for vehicles as a function of their electric only range, see below.

[3] Taken from EU-PHEV_ICCT-Briefing-Paper_280717_vF.PDF

Figure 3 Utility factor in the EU Regulations as a function of electric range

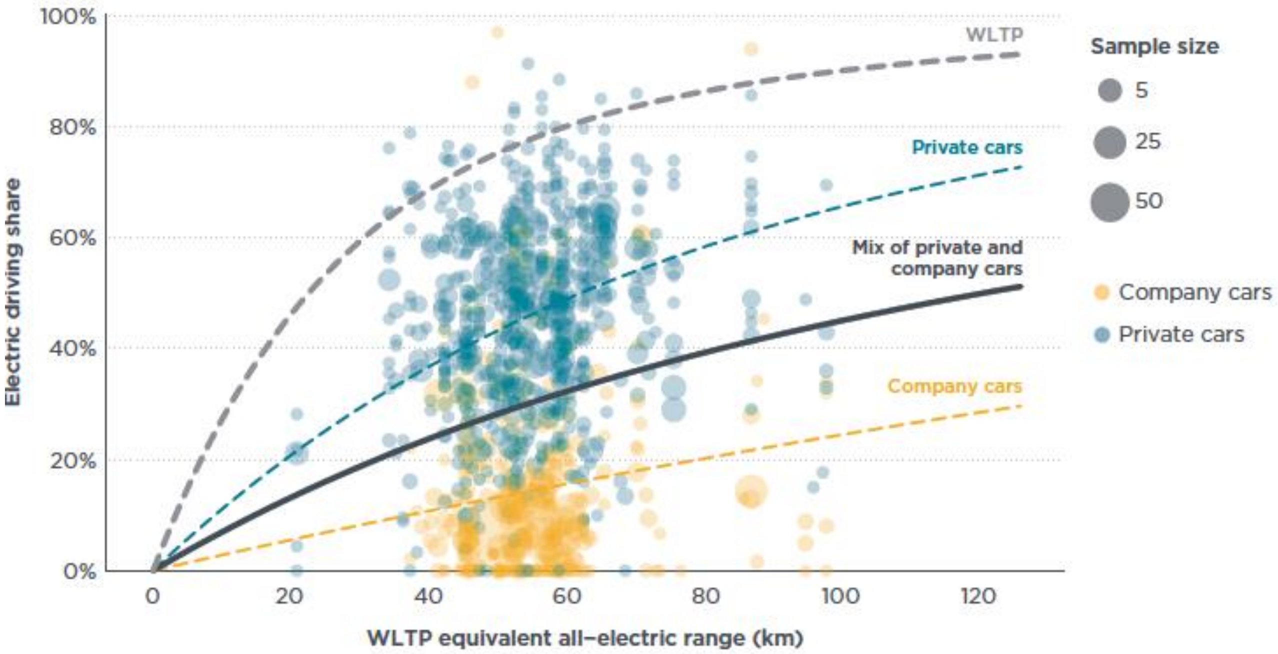


2.2.4.3 *Commission's latest proposal and supporting evidence*

With the passage of time, there being an increasing number of PHEVs in the fleet, and an increasing body of evidence on how they are actually being used, the value of the UF has been re-evaluated.

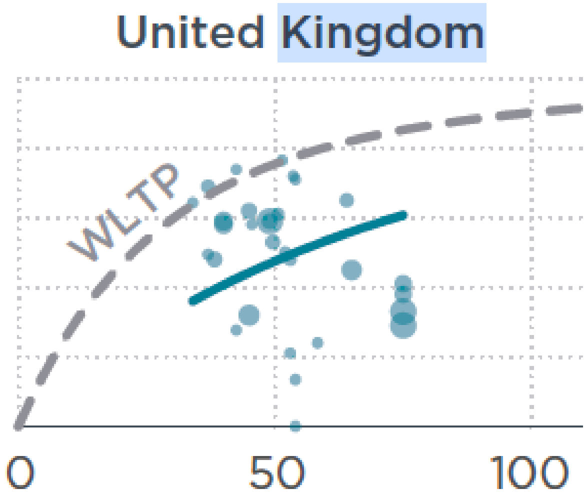
A very relevant report for this study, is a 55 page report from the Fraunhofer Institute for ICCT (Plotz, et al., 2022). It looked at the real-world share of electric driving for many thousands of PHEVs. These were subdivided into private and company cars (with the latter tending to travel longer distances) and by nation.

Figure 4 Real world electric driving share compared to WLTP assumption on charge depleting mode driving share from around 6,000 PHEVs within Europe



From Figure 4 the mean WLTP equivalent all electric range is 56 km. For this electric range the WLTP Regulatory UF = 80%. However, the real-world mix UF is around 33%. This study for the ICCT also gives UK data (taken from Figure 7 from the main report).

Figure 5 Real world electric driving share compared to WLTP assumption on charge depleting mode driving share from only the UK share of PHEVs. The x-axis shows electric driving share from 0 to 100%.



For the UK mean all Electric range, over the WLTP, is 56 km, for which the current regulatory UF is 80%. But the real world value is around 50%. This is important because in terms of liquid fuel consumption this increases from 20% for WLTP certification to 50% real world. This is an increase of 250%. There have been a number of other, less detailed studies that have reached similar conclusions.

This recent evidence has led the European Commission to publish an amendment to its Regulation for the type approval procedure for the CO_2 emissions of light passenger vehicles (EU Amending Regulation 2022). The Commission note: “Recent studies show a significant difference between the average real-world CO_2 emissions of plug-in hybrid electric vehicles and their CO_2 emissions determined by WLTP.” It added that the utility factors used during type approval tests, which determine the percentage of journeys driven in battery or ICE mode, should be revised to ensure that the CO_2 emissions of PHEVs are representative of real driver behaviour.

As a first step, it said new utility factors should be specified on the basis of available data; from 2025 it suggests the utility factor should assume only **50% of PHEV journeys in private cars are driven electrically**, and the same 50:50 split will be applied to company cars from 2027. It also said that the utility factor should be reviewed again in 2024 and 2026, based on data from on-board fuel consumption monitoring devices fitted to all new cars since 2021.

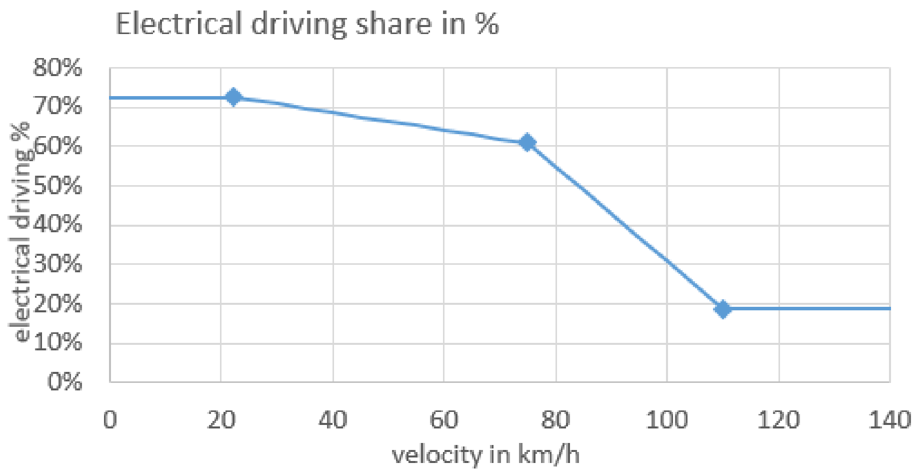
For this study for the DfT it is recommended that we follow the published evidence, and the plans of the EC, and use the reduced UF of 50% for passenger cars.

2.2.4.4 Speed related value

Certification and most analysis are focused on the (real) utility factor for PHEVs as a function of their electric only range.

However, for this DfT study, what is more important is how the UF varies with different speeds. This is poorly studied. TU Graz have undertaken an analysis which they have shared with Ricardo. It notes that longer journeys are more likely to include more higher speed driving. Whilst the whole analysis is somewhat complex, TUG derive a graph of “Electrical driving share (%)” as a function of speed. Their results are shown in Figure 6:

Figure 6 Modelled electric driving share on charge depleting mode for journeys of different average speed



If the overall average speed of all vehicle-km were around 83 km/hr, then the average electrical driving share would be 50%, close to the figure arrived at here.

2.2.4.5 Conclusions and recommendations for DfT study

The following have been found:

1. The original algorithm for generating utility factors (UFs) presumes the fraction of PHEV veh-km driven under electric power (certification UF) is around 80%.
2. All studies of real driver behaviour find this is too high, and in reality the ICE is used to drive a higher fraction of km.
3. Consideration of the UK fleet as analysed in a report by the Fraunhofer Institute for the ICCT indicates that a good figure for the UK is as above, i.e. assume a PHEV UF of 50%.
4. The EU are going to make future values of UF based on data from the on-board fuel consumption monitoring of PHEVs (required to be fitted to all cars since 2021). In the interim, from 2025 the Commission suggests the UF should assume only 50% of PHEV distances are driven under electric power.
5. There is a case for making the UF for PHEVs a variable for different average trip speeds.

Overall, it is recommended that a utility factor of 50% is used for cars and vans following the published evidence on real-world use of PHEV cars and the plans of the EC. However, an alternative approach for consideration would be to use a speed related function based on the TU Graz analysis above, or three discreet UFs covering average speeds for urban, rural or motorway driving speeds.

2.2.5 Utility factors for plug-in hybrid HGVs, buses and coaches

The concept of a utility factor that defines the fraction of total mileage driven by PHEVs using electric only (power depleting) mode was introduced in the previous section, and recommendations for utility factors for PHEV cars and vans were provided. Utility factors are also required for PHEV HGVs, buses and coaches.

PHEV HGVs, buses and coaches are new technologies and are not yet in widespread use in the UK or in Europe. Therefore, there is little evidence available on in-use utility factors for fleets of heavy-duty PHEVs, in particular evidence on real-world utility factors is lacking. Recent modelling undertaken by Ricardo included calculations of the anticipated electric driving share (UFs) for PHEV HGVs, buses and coaches based on the vehicle weight, expected battery capacities and electric ranges of PHEV vehicles. Calculations were performed under a number of different drive cycles that were consistent with the cycles used in the VECTO model. The drive cycles represented different driving conditions typical for each vehicle class, for example calculations for articulated HGVs were performed for regional delivery and long-haul drive cycles. The drive cycles consider the typical distances travelled per trip and typical vehicle speeds. Calculations were undertaken for a number of different vehicle weight classes.

Table 3 summarises the range of utility factors calculated for each vehicle class and drive cycle. Significant differences are sometimes seen between the UFs developed for vehicles under different drive cycles and these differences can be understood in terms of the driving conditions. For example, the UFs for rigid and articulated HGVs under a long-haul drive cycle are low compared to regional delivery cycles because long-haul drive cycles consist primarily of long-distance motorway driving with infrequent stops, whereas regional delivery cycles represent shorter journeys between depots where the PHEV can be plugged in to charge the battery.

The data in Table 3 shows evidence for using different UF assumptions for heavy-duty vehicles operated under different drive cycles. However, in the absence of real-world data, there is considerable uncertainty over the in-use UFs for heavy duty vehicles. The table also provides recommended utility factors that should be used for rigid and articulated HGVs, buses and coaches. These utility factors sit between the UF estimates under different drive cycles and can be used without the need to consider the weighting between drive cycles within a vehicle class. This straightforward approach is in-line with the recommendations made for UFs for cars and vans and these UF values are recommended for this study. The recommended UFs in Table 3 are used in the accompanying spreadsheet aggregation tool, however the assumptions made can be changed in the spreadsheet by the user.

Table 3 Utility factors for HGVs, buses and coaches

Vehicle class	Drive cycle	Utility factor
Rigid HGVs	Urban delivery	0.57-0.74
	Regional delivery	0.43-0.80
	Construction	0.45-0.56
	Long haul	0.16-0.18
	Recommended	**0.5**
Articulated HGVs	Regional delivery	0.40-0.44
	Long haul	0.18
	Recommended	**0.2**
Bus	Heavy urban	0.47-0.55
	Urban	0.55-0.58
	Suburban	0.53
	Recommended	**0.55**
Coach	Coach (regional)	0.25-0.32
	Interurban	0.47-0.54
	Recommended	**0.35**

2.2.6 Hydrogen consumption from Hydrogen Fuel Cell Vehicles

Fuel cell vehicles are essentially BEVs but powered by a fuel cell with a secondary battery, rather than a prime motive power battery. Many of the processes in the HFCV are directly comparable to BEVs, however the fuel cell conversion efficiency must be taken into account, similar to the battery charging efficiency that must be taken into account for BEVs. The energy requirements for starting and maintaining the fuel cell at its operating temperature must also be considered.

The approach taken was to derive speed energy and hydrogen fuel consumption curves for HFCVs from the speed energy curve for the corresponding BEV. It was assumed that the shape of the speed energy curve for a HFCV was the same as for a BEV, but a scaling factor was applied to uplift energy consumption and account for the fuel cell conversion efficiency, energy requirements of the fuel cell, and differences in weight between HFCVs and BEVs. Scaling factors were derived from Ricardo’s proprietary modelling by considering the energy consumption of HFCVs relative to the energy consumption of the same class of BEV. These scaling factors were applied to the BEV energy consumption curves derived from the PHEM simulations to estimate speed energy curves for HFCVs. The scaling factors developed are summarised in Table 4. Fuel cells are a less efficient means of providing energy to run a vehicle than charging the battery from the grid, therefore the uplift factors in the table are greater than the uplift factors required to account for charging losses from BEVs see Section 2.2.3).

Table 4 Uplift factors to apply to BEV battery to wheel fuel consumption to estimate speed energy curves for HFCVs

Vehicle	Weight class	Uplift factor
Car and van	All size classes	1.840
Bus	<15t	1.880
Bus	15-18t	1.961
Bus	>18t	1.746
Coach	<18t	1.791
Coach	>18t	1.691
Rigid HGV	>7.5t	2.005
Rigid HGV	7.5-12t	1.944
Rigid HGV	12-14t	1.987
Rigid HGV	14-20t	1.778
Rigid HGV	20-26t	1.771
Rigid HGV	26-28t	1.771
Rigid HGV	28-32t	1.768
Rigid HGV	>32t	1.768
Artic HGV	All weight classes	1.680

Speed hydrogen consumption curves (in g H_2 / km) can be calculated from energy curves using the energy content or calorific value of hydrogen fuel of 120 MJ/kg.

2.2.7 Trends in LDV and HDV technology performance

The PHEM model is based on simulations of emissions and energy consumption for currently available ULEV technologies in the fleet. Future trends in emissions of NO_x and PM are driven by the requirements of European regulations on emissions from vehicles (“Euro standards”). PHEM model simulations were available for current Euro standards, including the latest Euro 6d and Euro VI D for light and heavy-duty vehicles respectively. In general, newer vehicles are required to meet more stringent NO_x and PM emission standards and this is reflected in the PHEM simulations. However, the simulations also account for real-world evidence from vehicle emission measurements so will reflect the observed change in emissions between Euro standards and not just the requirements of the emission regulations. Euro 7 emission standards are still under consideration by the European Parliament and the UK Government and therefore have not been taken into consideration in this study.

Additional information and assumptions were required to take into account efficiency improvements and further technology developments for future vehicles in the fleet so that curves representative of future years could be developed. Ricardo have previously undertaken detailed calculation of energy consumption and fuel-related CO_2 emissions for new vehicles entering the fleet between 2020 and 2050 and these calculations were made available for this project. This work covered both light and heavy-duty vehicles and the following powertrains:

- Plug-in hybrids
- Battery electric
- Hydrogen fuel cell
- Catenary battery electric (HGVs only)

Ricardo’s calculations were based on a bottom-up assessment that took account of anticipated mass reductions due to improvements in powertrain components (particularly battery energy density), improvements to efficiency of electric motors and fuel cells, and took account of some additional electric range and increases in battery capacity.

Ricardo's calculations were used to provide future trends in energy and fuel consumption for new vehicles entering the fleet for use in this study. Furthermore, the calculations provide a means to estimate average energy consumption from hydrogen fuel cell vehicles relative to battery electric vehicles and therefore an estimate of the energy efficiency of hydrogen fuel cells.

2.2.8 Validation of the speed emission/energy consumption curves

The 2019 EMEP/EEA Inventory Guidebook, henceforth the Guidebook, is the primary sources of emission factors for the development of emission inventories by countries in Europe (EMEP/EEA, 2019). The transport emission factors recommended for use by the Guidebook are consistent with COPERT and are the road transport emission factors used in the UK National Atmospheric Emissions Inventory (NAEI). The transport emission factors cover exhaust emissions and energy consumption from internal combustion engine (ICE) cars, LGVs, HGVs, motorcycles, buses and coaches. There is limited coverage of exhaust emissions and energy consumption from ULEVs as data is provided for petrol HEV cars, petrol and diesel PHEV cars, and diesel PHEV buses only. This data has been used to validate speed emission curves developed from PHEM simulations.

2.2.9 Non-Exhaust Emissions

The Guidebook also provides a methodology to calculate non-exhaust emissions of PM from brake wear, tyre wear and road abrasion and this was the main data source for the development of non-exhaust emission factors for ULEVs. Emission factors for brake and tyre wear show a dependence on speed within a limited range and, for heavy duty vehicles, are dependent on load and the number of axles, but are independent of fuel type. Road abrasion factors are provided for each main vehicle type and do not depend on speed. A recent update to the Guidebook consistent with COPERT v5.6 introduced new non-exhaust emission factors for BEV, HEV and PHEV cars that take account of vehicle weight and regenerative braking. Unlike the exhaust emissions, not all the PM emitted from these sources are within the 2.5 µm range, i.e. some particulates are coarser and emitted in the 2.5-10 µm range. The Guidebook provides factors that express the mass fraction of PM_{10} emitted as $PM_{2.5}$ for each non-exhaust source.

Non-exhaust emission factors were developed based on the latest emission factors and methodologies in the EMEP/EEA Inventory Guidebook, consistent with COPERT version 5.6. The resulting PM_{10} brake wear, tyre wear and road abrasion emission factors are presented in Section 5.

3. EMISSION CURVES FOR LIGHT DUTY VEHICLES

The detailed analysis and results for each of the car and van technologies is set out in the following sections.

Sections 3.1 to 3.5 present the speed emission, fuel and energy curves for ULEV cars. The core vehicle technologies petrol HEV, diesel HEV and BEV that provided the basis of the curve fitting for all other ULEV vehicle technologies are presented in the first three sections. The curves developed for PHEV and hydrogen fuel-cell cars from the three core technologies are then presented in sections 3.4 and 3.5.

The curves developed for ULEV vans are presented in sections 3.6 to 3.10. The core vehicle technologies petrol HEV, diesel HEV and BEV vans are presented in sections 3.6 to 3.8, and the curves for PHEV and fuel-cell vans derived from the core technologies are presented in sections 3.9 and 3.10.

Section 3.11 provides recommended values for the fraction of NO_x emitted as primary NO_2 for relevant ULEV technologies and Section 3.12 provides a discussion of how the curves developed compare to alternative sources.

3.1 PETROL HEV CARS

Speed emission curves and fuel consumption curves were developed from PHEM simulations developed for HBEFA. The HBEFA makes the assumptions that speed NOx and PM emission curves for petrol HEV cars are the same as the curves for conventional petrol cars. This is a conservative assumption that is made because there is little evidence available from vehicle measurements collected under the ERMES program to support the development of separate emission factors for HEV cars. Figure 7 and Figure 8 present the speed emission factors for NO_x and PM_{10} emissions from Euro 4 to Euro 6 petrol HEV cars developed from the PHEM simulations. In each plot the open circles show the underlying average speed and emissions for each traffic situation simulated, with the size of the circle representing the weighting allocated to each traffic situation. The red line shows the 6th order polynomial fit to the data. The simulations for Euro 6 vehicles are presented separately for four stages of Euro 6 that align with the changes to regulated Euro 6 test procedure to introduce improved tests closer to real-world driving.

Figure 7 Speed NOx emission curves for Euro 4, 5 and 6 petrol HEV cars

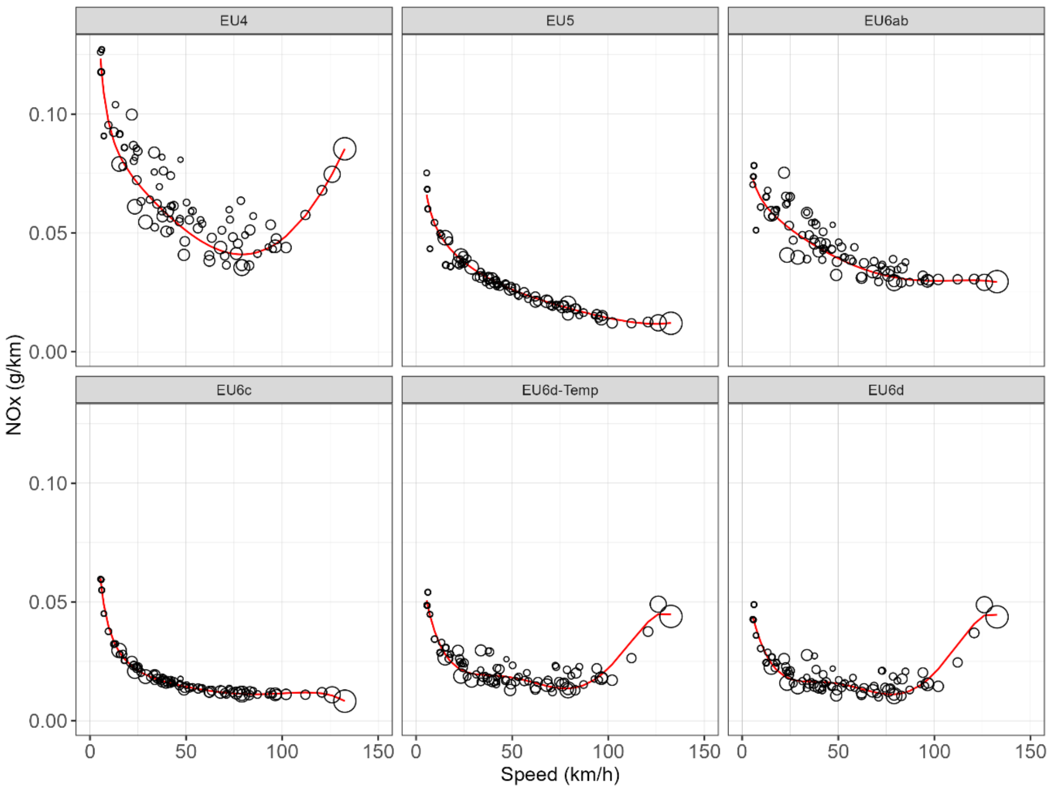
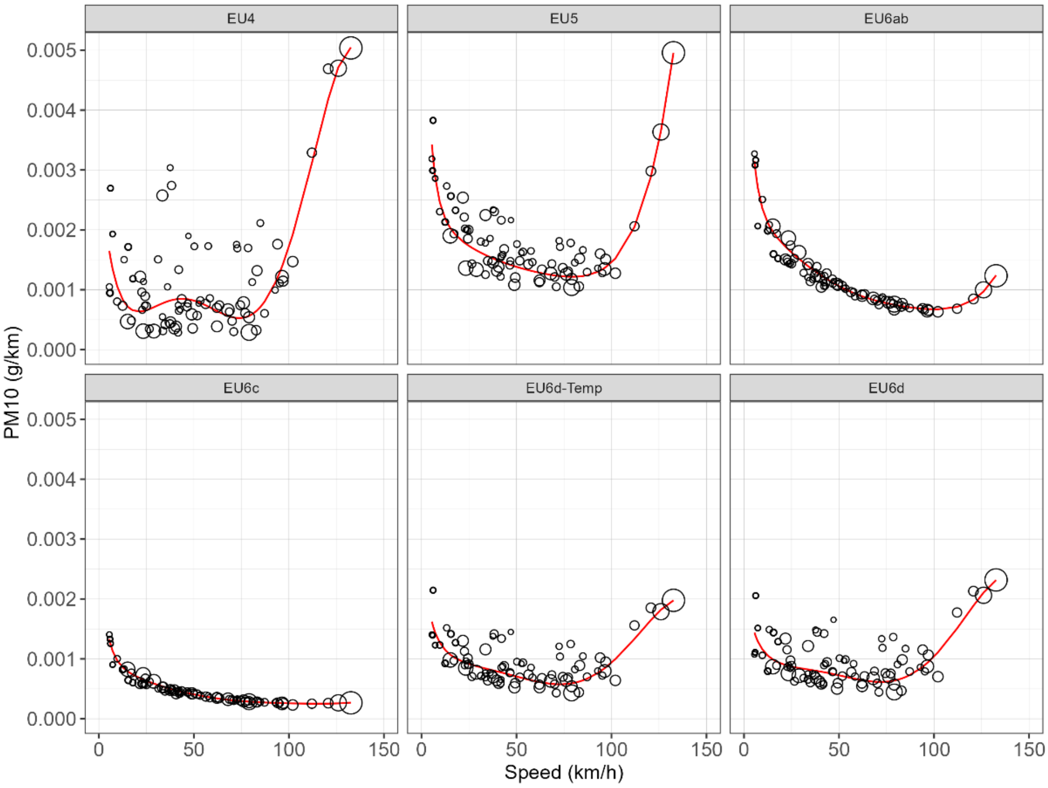
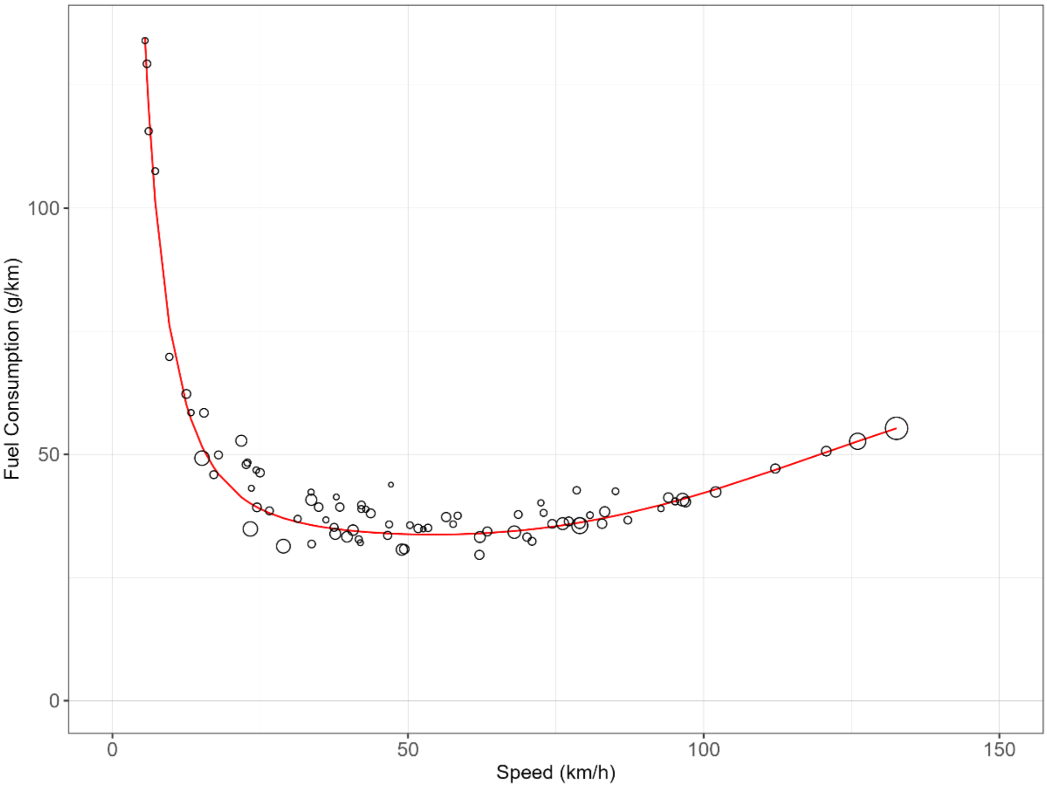


Figure 8 Speed PM emission curves for Euro 4, 5 and 6 petrol HEV cars



A speed related fuel consumption curve was developed for petrol HEVs and is presented in Figure 9. The curve takes into account improvements in fuel efficiency compared to conventional petrol cars. The curve generated is representative of a HEV car currently available in the fleet. Evidence on the expected historic and future trends in fuel consumption was sought, however HEV cars were not covered in Ricardo's previous work on ULEV energy consumption. Therefore, the speed fuel consumption curve for petrol HEV cars presented in the figure is assumed to be applicable for all generations (past, present and future) of petrol HEV cars in this study. If data or assumptions about future trends in fuel consumption for petrol ICE cars are used by DfT in modelling, it is recommended that DfT assume the same trends for petrol HEV cars. The aggregation tool provided to DfT allows the user to update the trends in fuel consumption if information is available.

Figure 9 Speed fuel consumption curve for petrol HEV cars



3.2 DIESEL HEV CARS

Speed emission curves and fuel consumption curves were developed from PHEM simulations developed for HBEFA. As for petrol HEV cars, the HBEFA makes the assumptions that speed NOx and PM emission curves for diesel HEV cars are the same as the curves for conventional diesel cars. Figure 10 and Figure 11 present the speed emission factors for NO_x and PM_{10} emissions from Euro 5 and Euro 6 diesel HEV cars developed from the PHEM simulations.

Figure 10 Speed NOx emission curves for Euro 5 and 6 diesel HEV cars

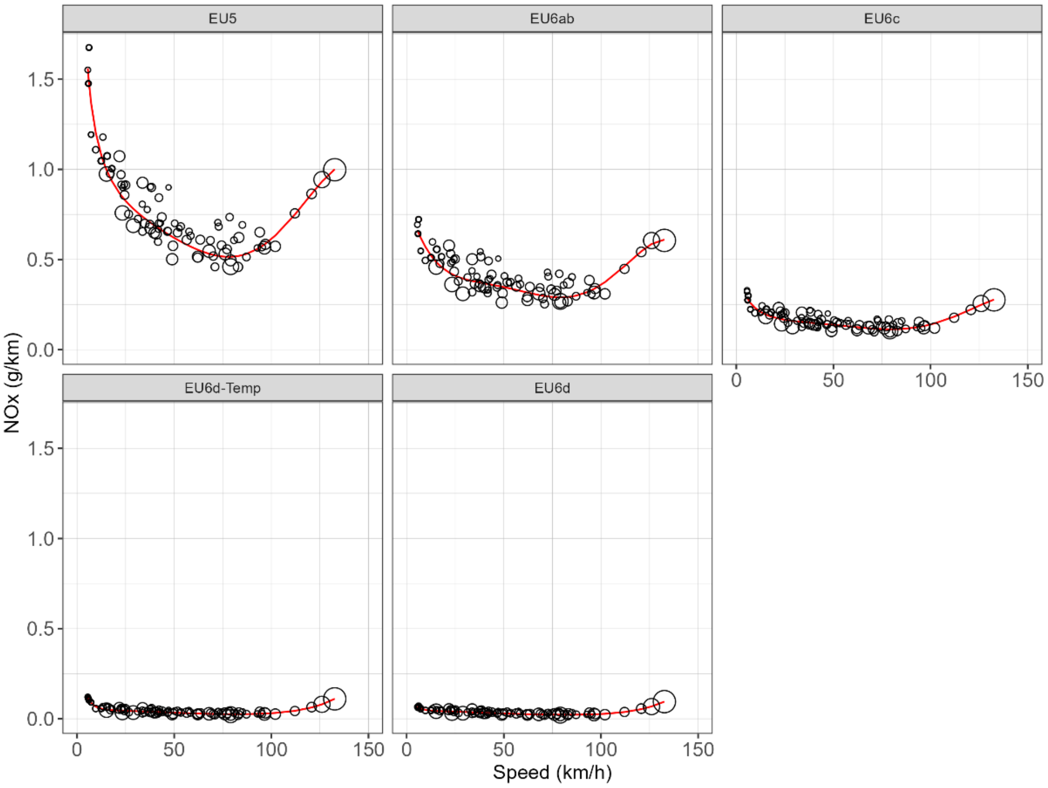
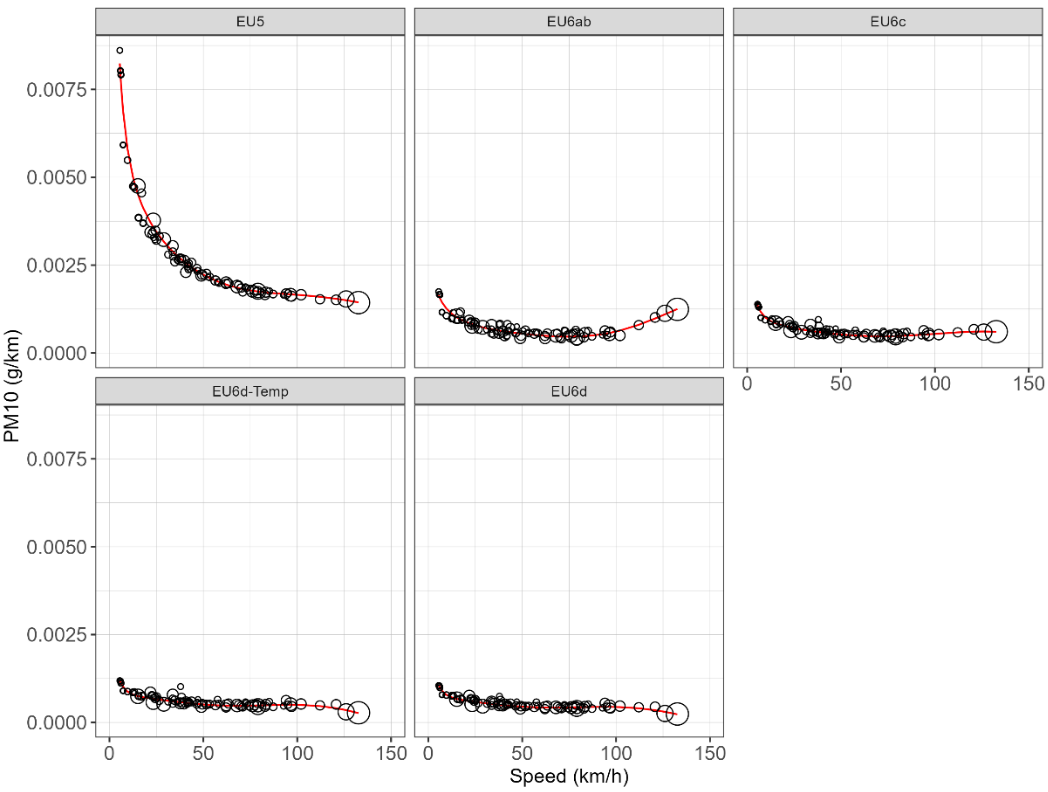
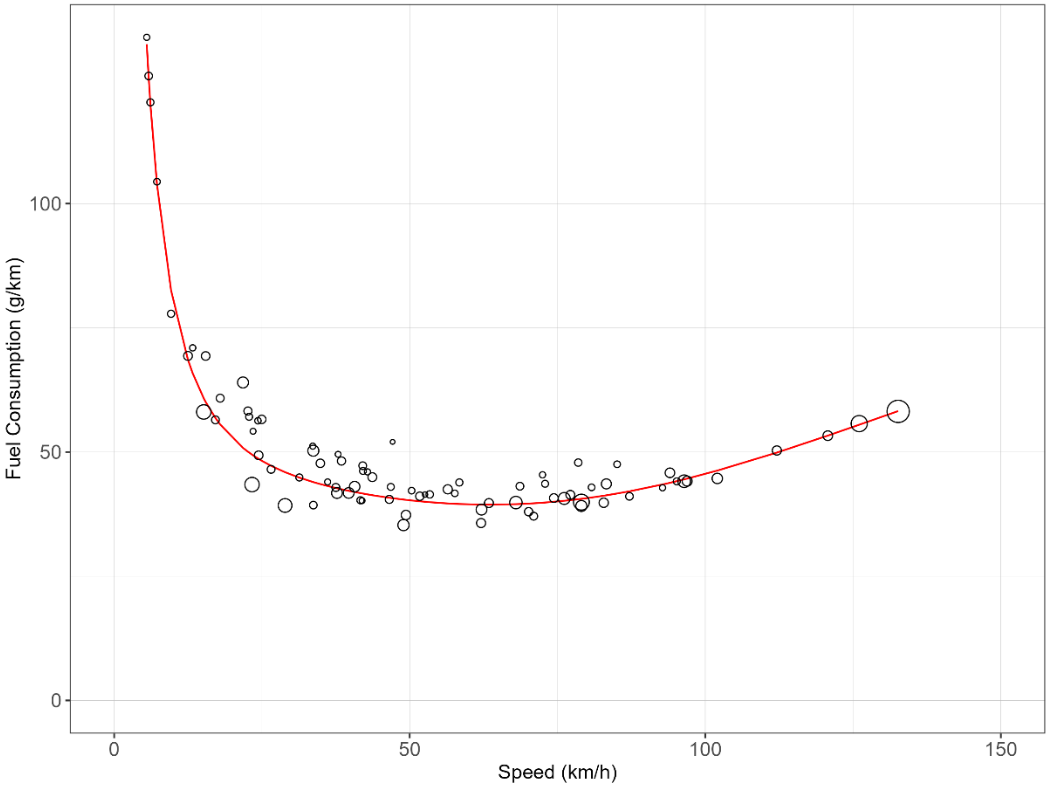


Figure 11 Speed PM emission curves for Euro 5 and 6 diesel HEV cars



A speed related fuel consumption curve was developed for diesel HEVs and is presented in Figure 12. The curve takes into account improvements in fuel efficiency compared to conventional diesel cars and is representative of a HEV car currently in the fleet. Evidence on the future trends in fuel consumption for HEV cars was not available from Ricardo's previous work on ULEV energy consumption separate from ICE diesel technologies. In the absence of quantitative information on trends in fuel consumption for diesel HEV cars, it is recommended that DfT assume the future trends are the same as the trend for ICE diesel cars. In the absence of quantitative information on trends in improvements on energy consumptions for diesel HEV and ICE cars, it is assumed in this work that there is no future improvement in fuel consumption. This assumption can be updated if quantitative information becomes available.

Figure 12 Speed fuel consumption curve for diesel HEV cars



3.3 BATTERY ELECTRIC (BEV) CARS

The base data for the development of speed energy curves for BEV cars was derived from the updated PHEM model simulations that were undertaken by TU Graz for this project (see section 2.2.1). Figure 13 presents the speed energy curve developed for BEV cars. The base emissions data from the PHEM model simulations provide energy consumptions from battery to wheel. The curve in Figure 13 accounts for a grid to battery conversion efficiency and therefore provide energy use in terms of kWh/km at the power supply socket. A grid to battery conversion efficiency of 88.2% was assumed, consistent with literature evidence.

Future improvements in the energy efficiency of BEV cars were derived from the Ricardo's calculations based on anticipated BEV mass reduction and other powertrain efficiency improvements. The energy consumptions trends are presented relative to vehicles sold in 2020 are presented in Figure 14.

Figure 13 Speed energy curves for BEV cars

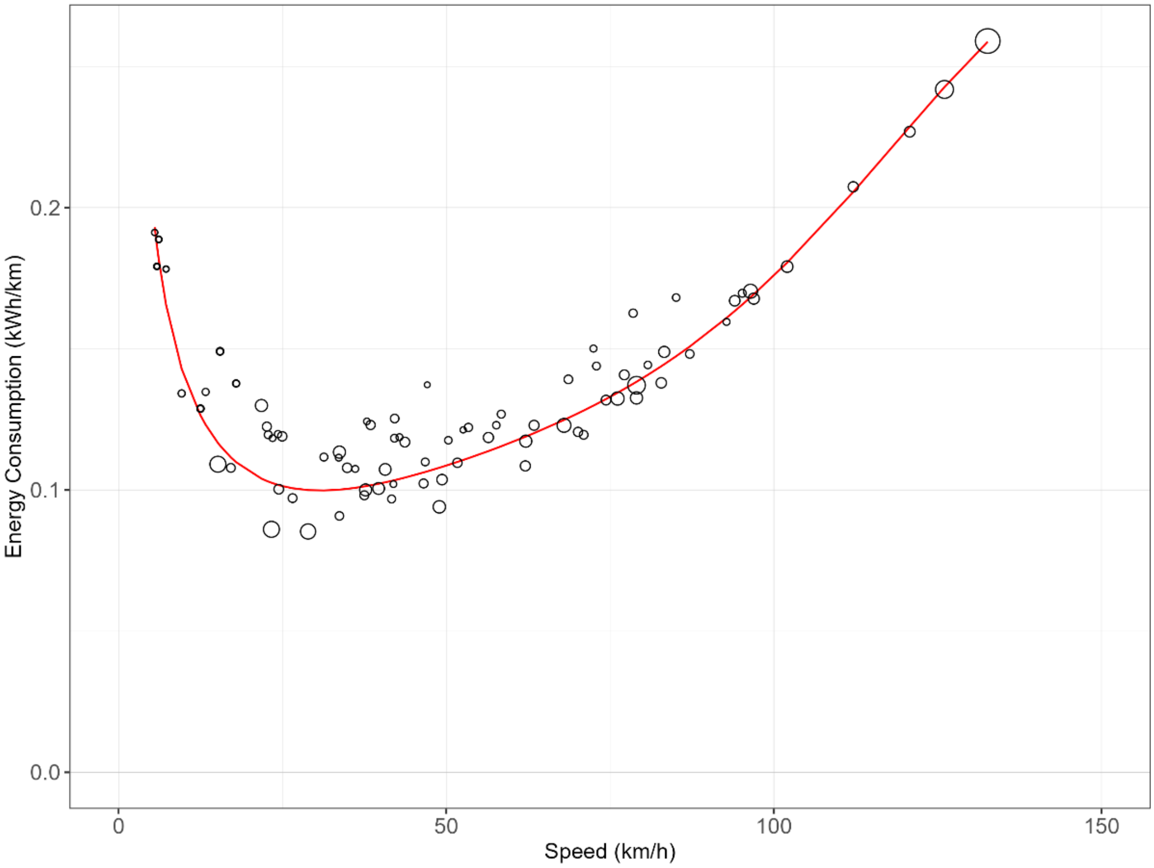
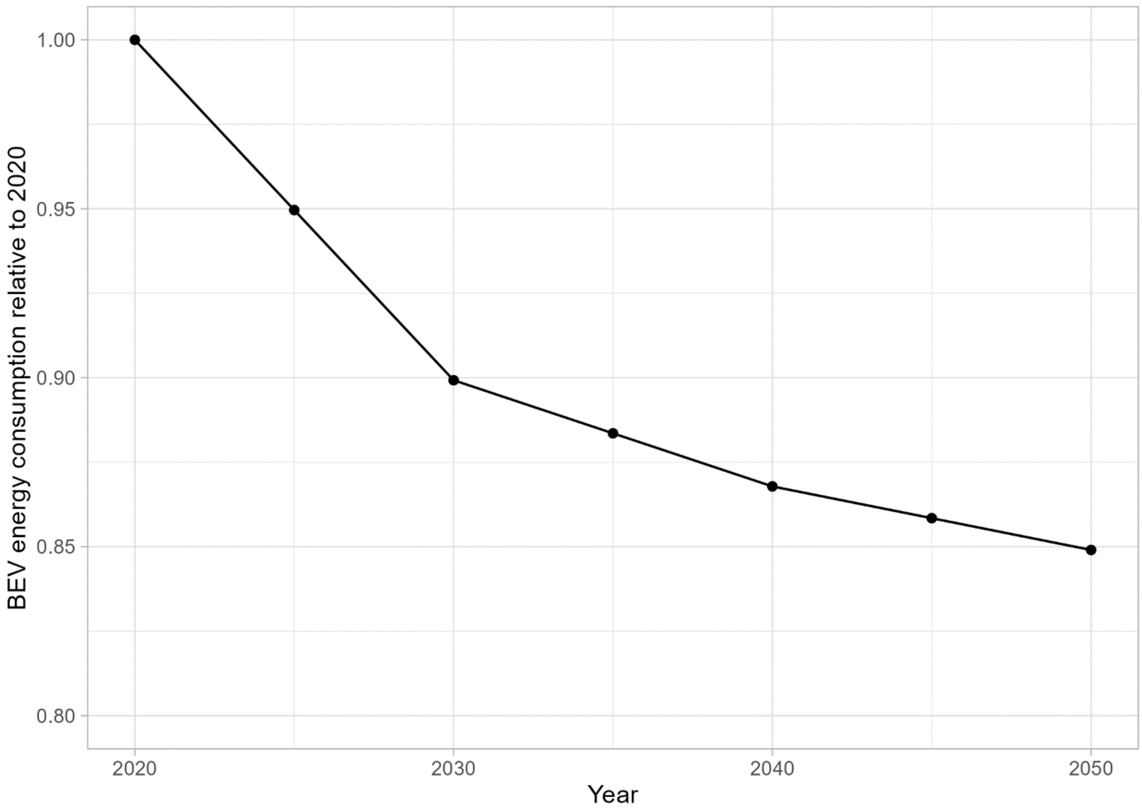


Figure 14 Future trends in energy consumption for BEV cars

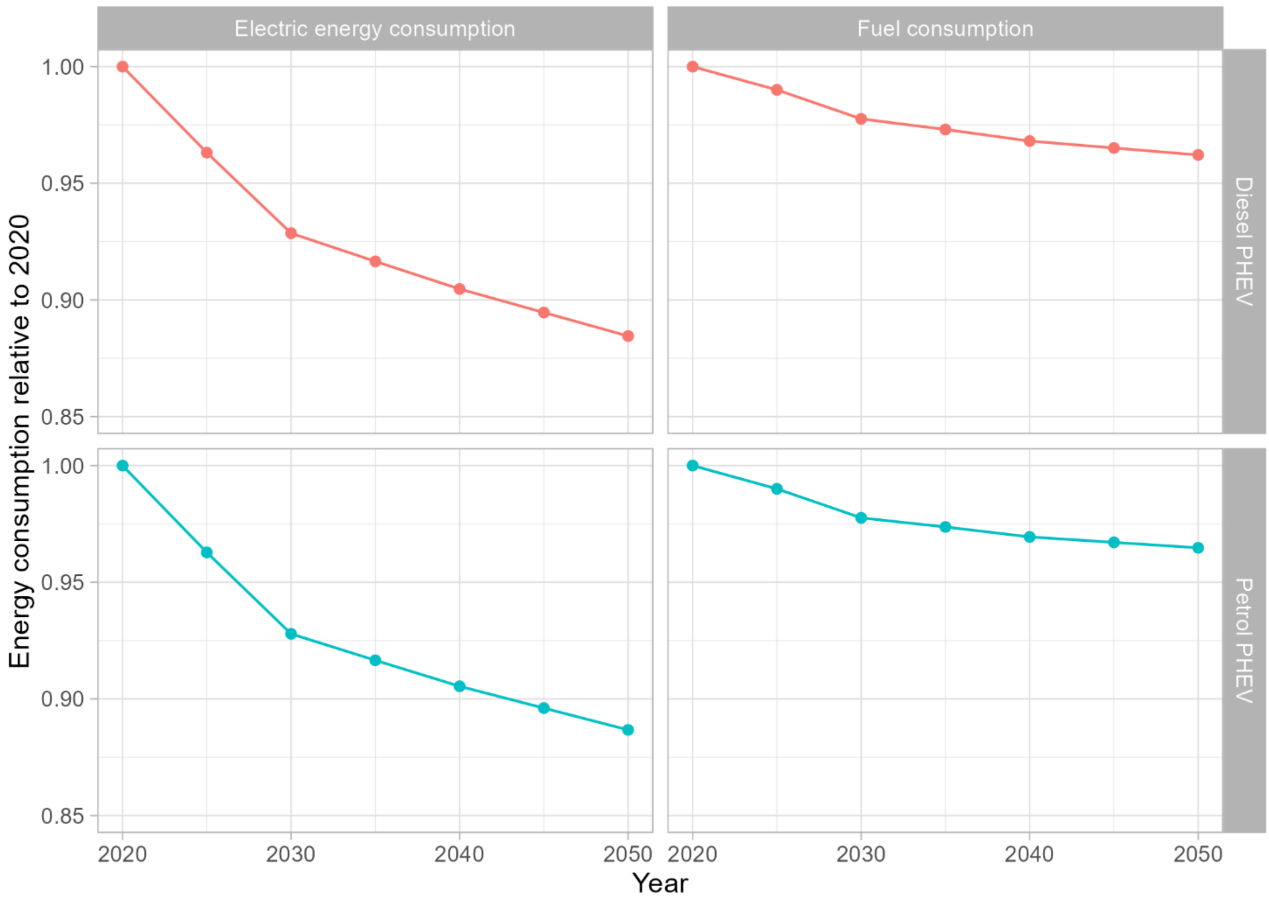


3.4 PLUG-IN HYBRID (PHEV) CARS

PHEVs can operate purely in electric mode and to charge their battery directly from the grid. As such, when driven only within their electric range they can operate like battery electric vehicles by depleting their battery. When driven beyond their battery range, or in charge sustaining mode, they will operate like HEVs. Therefore, the basic speed energy consumption for PHEV cars driven in a charge depleting mode is the same as the energy consumption curve for a BEV car. The basic speed emission and petrol or diesel fuel consumption curves for PHEV cars driven in a charge sustaining mode are the same as for the equivalent Euro standard petrol or diesel HEV car. The curves should be weighted according to the utility factor (see Section 2.2.4).

Future improvements in the energy and fuel consumption of PHEV cars were derived from the Ricardo's calculations based on anticipated mass reduction and other powertrain efficiency improvements. The energy consumption trends are presented relative to vehicles sold in 2020 are presented in Figure 15.

Figure 15 Future trends in energy consumption for diesel and petrol PHEV cars

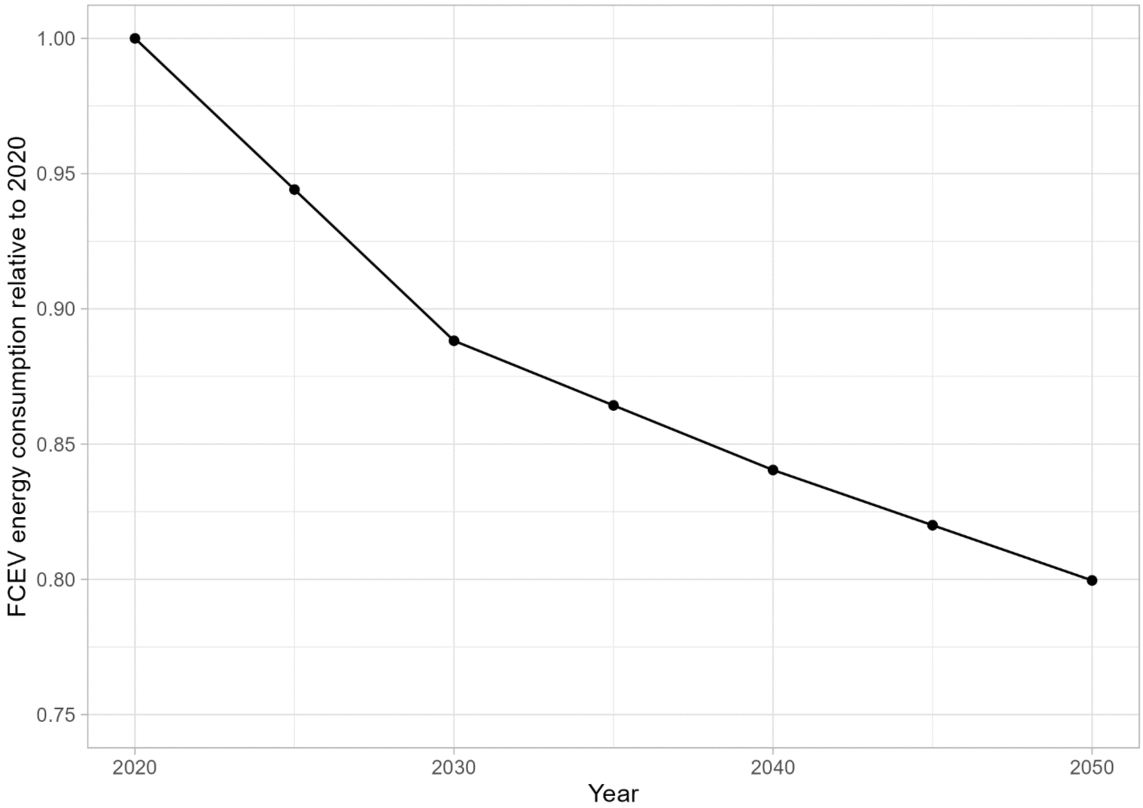


3.5 FUEL CELL (HFCV) CARS

Following the approach set out in Section 2.2.6, speed energy curves for HFCV cars were calculated by applying a factor of 1.84 to the speed energy curve for BEV cars.

Future improvements in the energy efficiency of HFCV cars were derived from Ricardo's previous calculations. The energy consumption trends relative to vehicles sold in 2020 are presented in Figure 16.

Figure 16 Future trends in energy consumption for HFCV cars



3.6 PETROL HEV VANS

The development of speed emission and fuel consumption curves for petrol HEV vans followed the same methodology as for petrol HEV cars. Curves were developed from PHEM simulations developed for HBEFA. As for HEV cars, the speed NOx and PM emission curves for HEV vans were assumed to be the same as for conventional petrol vans because there is currently insufficient evidence to develop separate emission factors for HEV vans. Figure 17 and Figure 18 present the speed emission curves for NOx and PM_{10} emissions from Euro 4 to Euro 6 petrol HEV vans. Curves were developed separately for three size classes of vans, class I, II and III.

Figure 18 shows that the PM emission factors for petrol HEV vans were significantly higher under high-speed motorway driving situations above ~120 kph than under lower speed driving conditions. The quality of the polynomial fit to the data was improved by (1) restricting the fits to exclude traffic situations with average speeds greater than 120 kph, and (2) reducing the order of the polynomial fit from 6th order to 4th order. These updates to the fitting procedure reduced the presence of unrealistic oscillatory behaviour in the fits. An increase in emissions at speeds less than ~10 kph remains. As a result of the assumptions made and the observed fits, it is recommended that the speed PM emission curves for petrol HEVs are assumed to be valid between 10 and 120 kph. The speed NOx emission curves are valid between 5 and 130 kph.

A speed related fuel consumption curve was developed for petrol HEV vans and is presented in Figure 19. The curve generated is representative of HEV vans currently available in the fleet. Evidence on the expected historic and future trends in fuel consumption was sought, however HEV vans were not covered in Ricardo's previous work on ULEV energy consumption. Therefore, in this study the speed fuel consumption curve for petrol HEV vans presented in the figure is assumed to be applicable for all generations (past, present and future) of petrol HEV vans. If data or assumptions about future trends in fuel consumption for petrol ICE vans are used by DfT in modelling, it is recommended that DfT assume the same trends for petrol HEV vans. The aggregation tool provided to DfT allows the user to update the trends in fuel consumption if information is available.

Figure 17 Speed NOx emission curves for petrol HEV vans

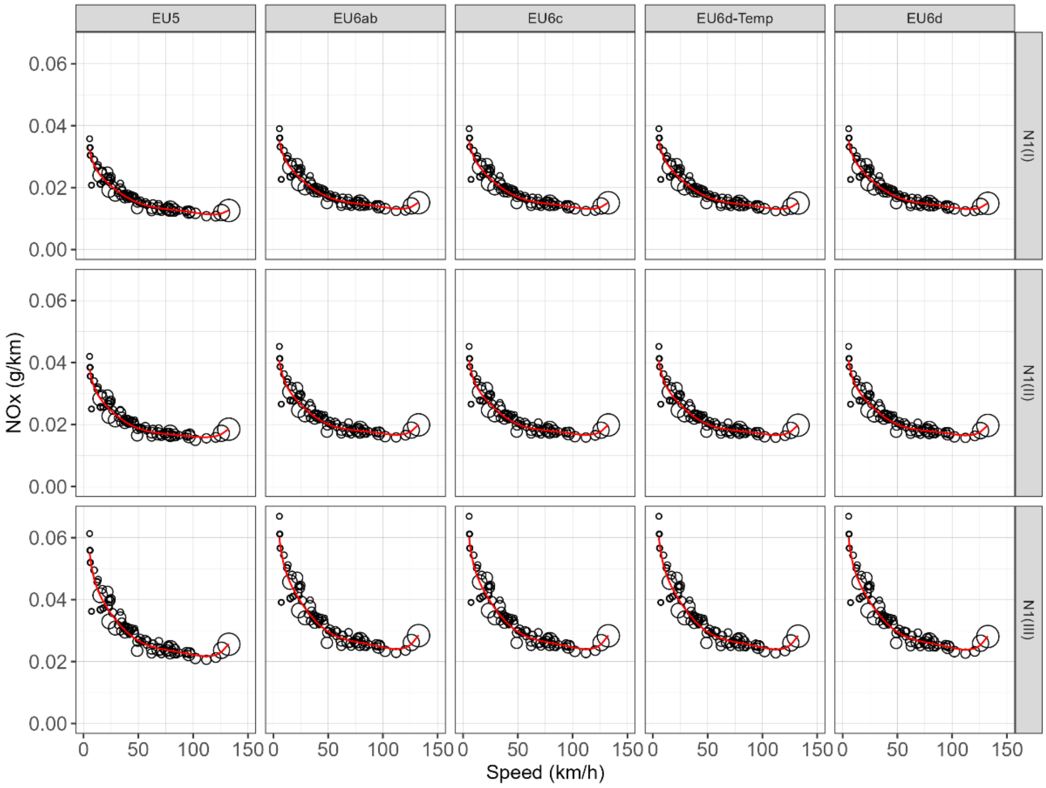


Figure 18 Speed PM emission curves for petrol HEV vans

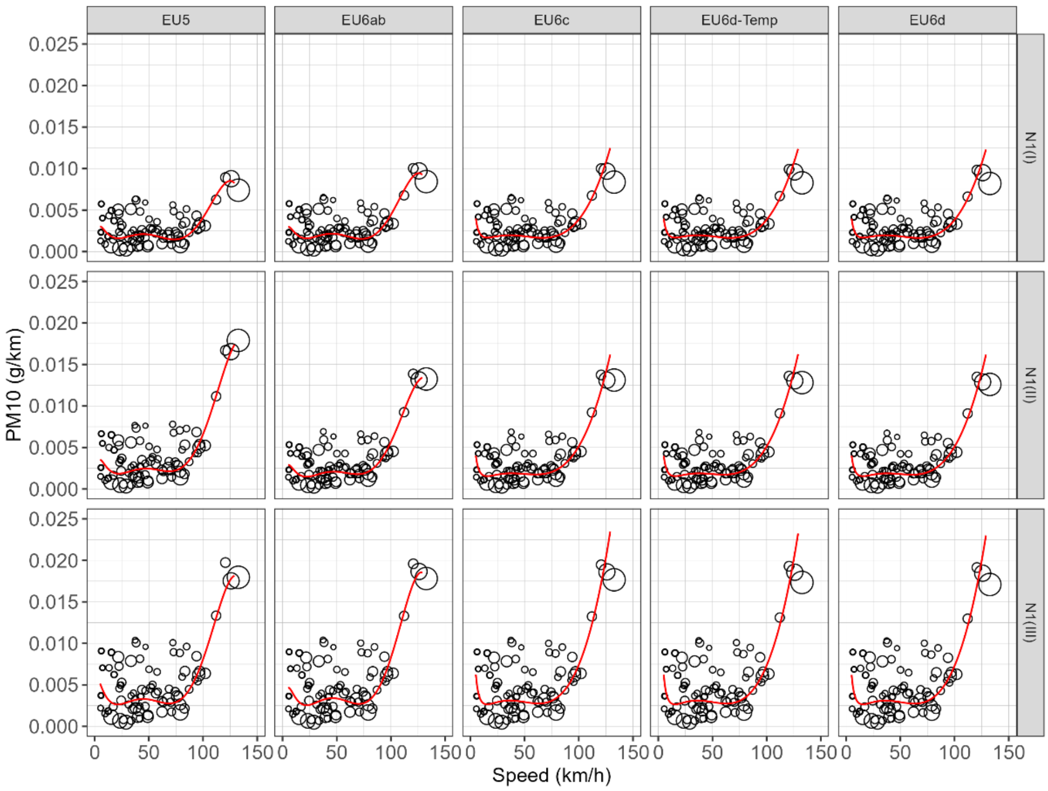
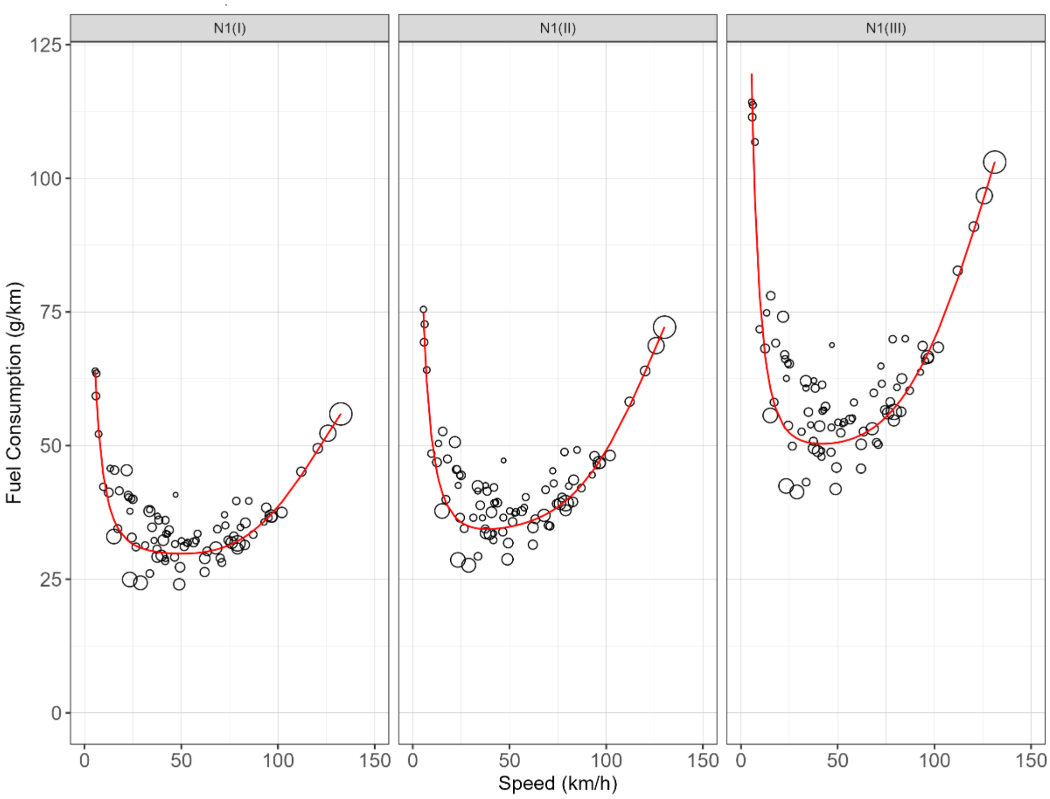


Figure 19 Speed fuel consumption curves for petrol HEV vans



3.7 DIESEL HEV VANS

Speed emission curves and fuel consumption curves were developed from PHEM simulations developed for HBEFA. As for petrol HEV vans, it is assumed that speed NOx and PM emission curves for diesel HEV vans are the same as the curves for conventional diesel vans. Figure 20 and Figure 21 present the speed emission curves for NO_x and PM_{10} emissions from Euro 5 and Euro 6 diesel HEV vans. Curves were developed separately for three size classes of vans, class I, II and III.

Figure 21 shows that the PM emission factors for diesel HEV vans were significantly higher under high-speed motorway driving situations above ~120 kph than under lower speed driving conditions. Under the highest speed driving condition PM emissions for Euro 6c, d-temp and d vehicles exceeded the maximum 0.05 g/km emission factor presented in the figure. The quality of the polynomial fit to the data was improved by (1) restricting the fits to exclude traffic situations with average speeds greater than 120 kph, and (2) reducing the order of the polynomial fit from 6th order to 4th order. These updates to the fitting procedure reduced the presence of unrealistic oscillatory behaviour in the fits. As a result of the assumptions made and the observed fits, it is recommended that the speed PM emission curves for diesel HEVs are assumed to be valid up to 120 kph. The speed NOx emission curves are valid up to 130 kph.

A speed related fuel consumption curve was developed for diesel HEV vans and is presented in Figure 22. The curve generated is representative of HEV vans currently available in the fleet. Evidence on the expected historic and future trends in fuel consumption was sought, however HEV vans were not covered in Ricardo's previous work on ULEV energy consumption. Therefore, in this study the speed fuel consumption curves for diesel HEV vans are assumed to be applicable for all generations (past, present and future) of diesel HEV vans. If data or assumptions about future trends in fuel consumption for diesel ICE vans are used by DfT in modelling, it is recommended that DfT assume the same trends for diesel HEV vans. The aggregation tool provided to DfT allows the user to update the trends in fuel consumption if information is available.

Figure 20 Speed NOx emission curves for diesel HEV vans

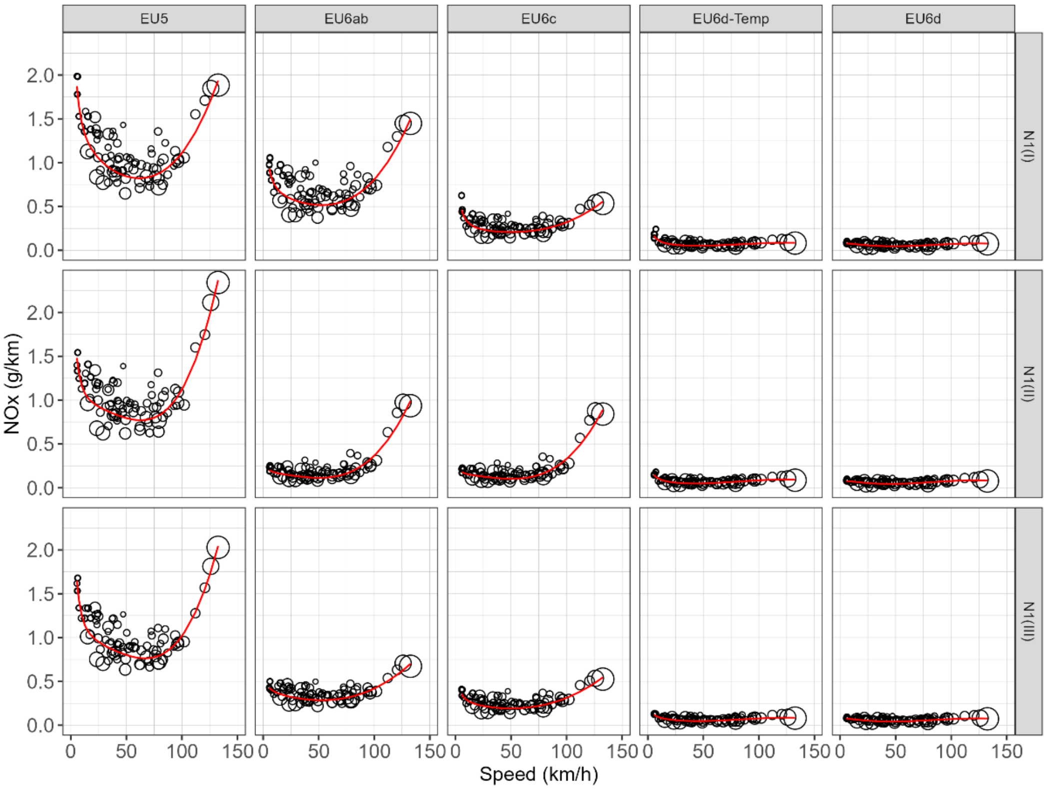


Figure 21 Speed PM emission curves for diesel HEV vans

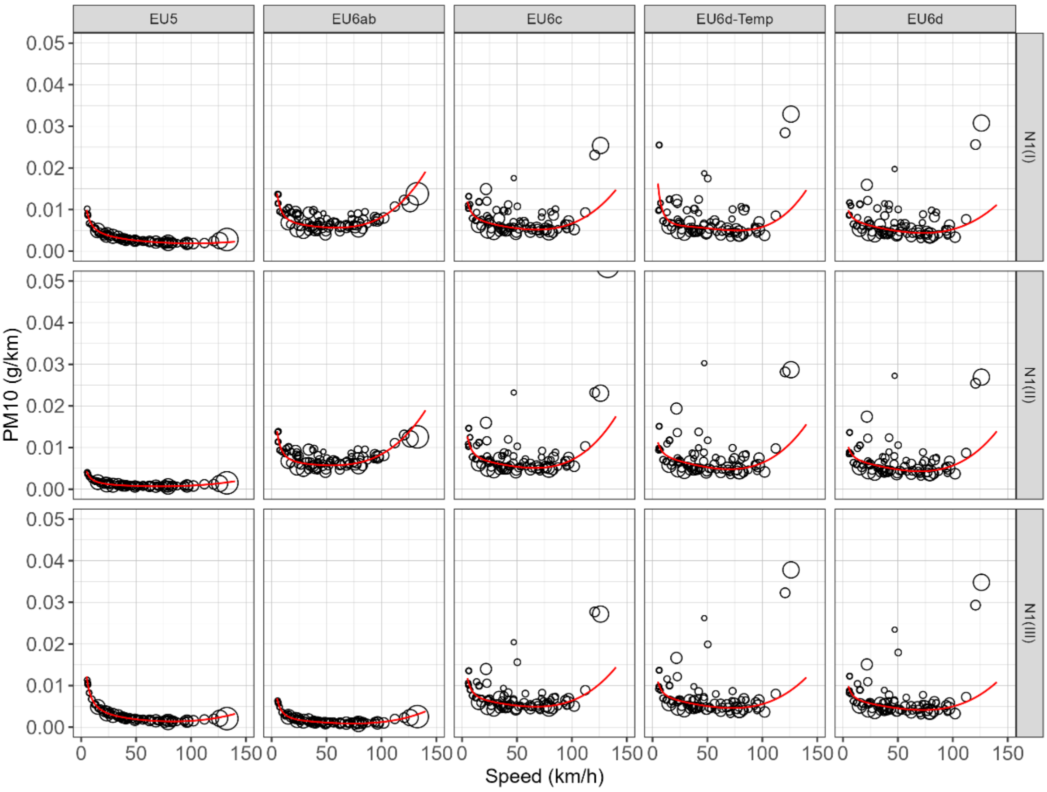
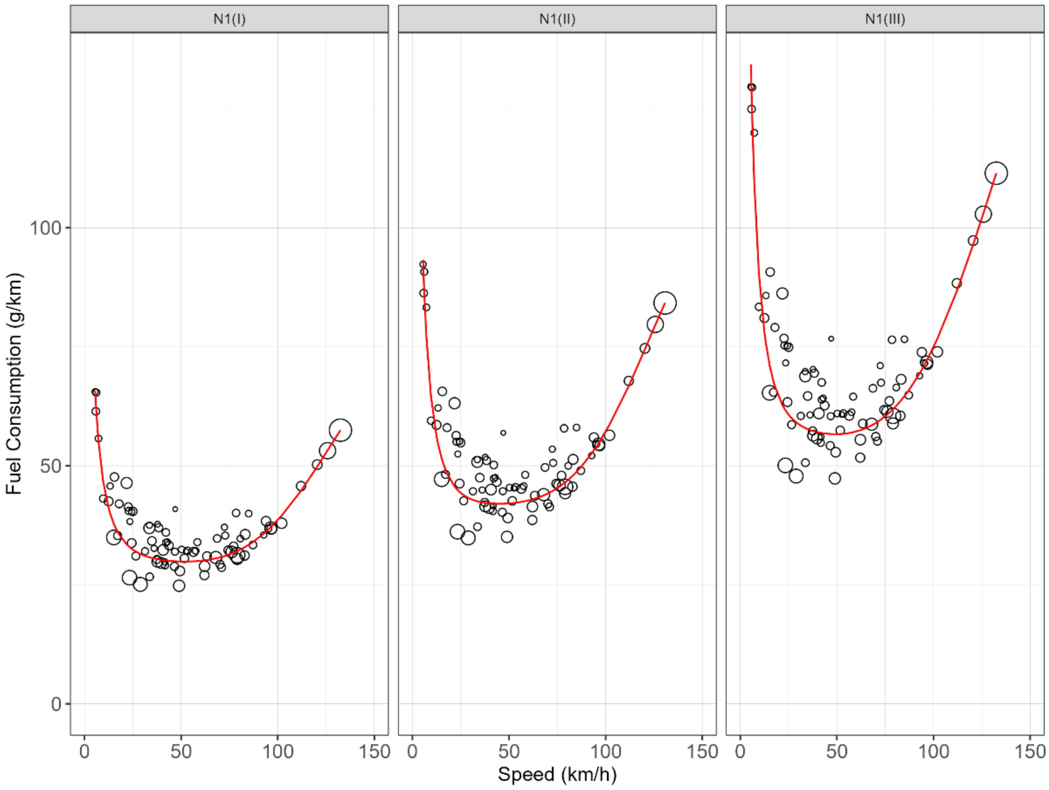


Figure 22 Speed fuel consumption curves for diesel HEV vans

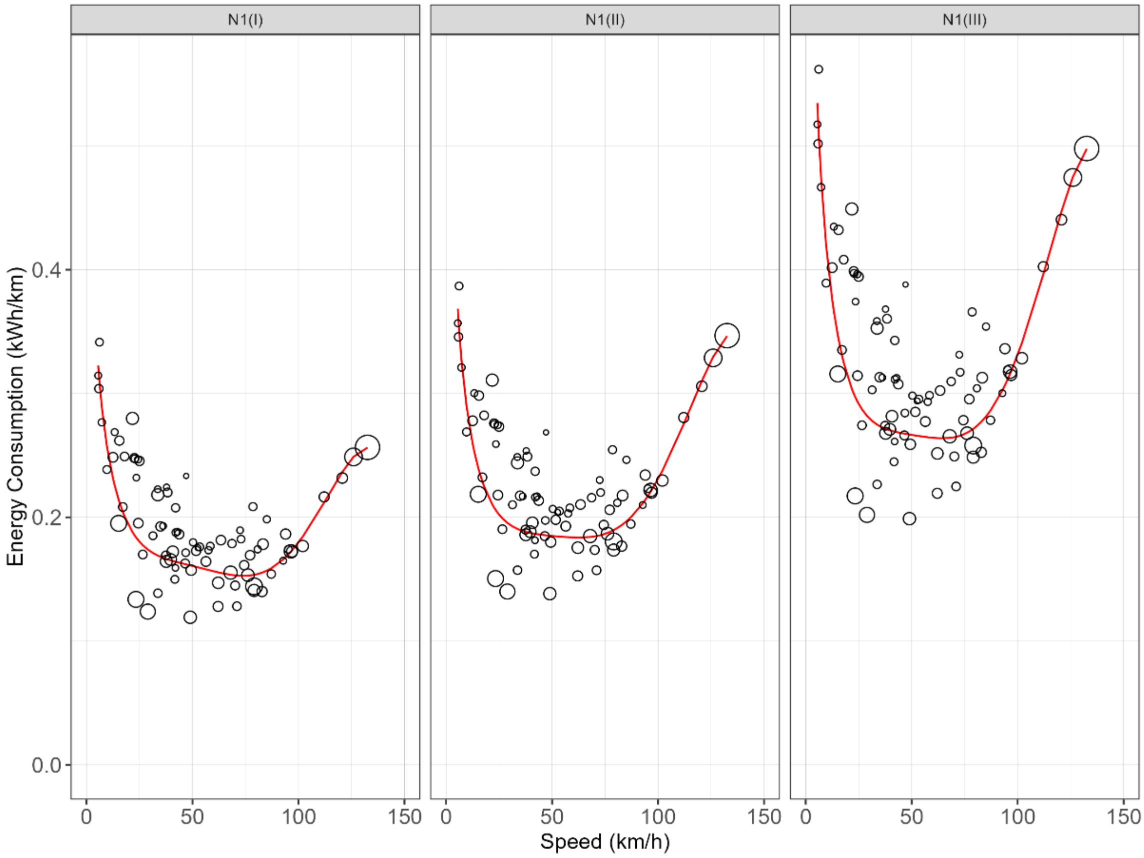


3.8 BATTERY ELECTRIC (BEV) VANS

The base data for the development of speed energy curves for BEV vans was derived from the updated PHEM model simulations that were undertaken by TU Graz for this project (see section 2.2.1). Figure 23 presents the speed energy curve developed for BEV vans. The base emissions data from the PHEM model simulations provide energy consumptions from battery to wheel. The curve in Figure 23 accounts for a grid to battery conversion efficiency and therefore provide energy use in terms of kWh/km at the power supply socket. A grid to battery conversion efficiency of 88.2% was assumed, consistent with the assumptions made in the Ricardo's previous work.

Future improvements in the energy efficiency of BEV vans were derived from the Ricardo's calculations. This data suggests that there will 10.6% reduction in electric energy consumption between 2020 and 2050.

Figure 23 Speed energy curves for BEV vans



3.9 PLUG-IN HYBRID (PHEV) VANS

PHEVs can operate purely in electric mode and to charge their battery directly from the grid. As such, when driven only within their electric range they can operate like battery electric vehicles by depleting their battery. When driven beyond their battery range, or in charge sustaining mode, they will operate like HEVs. Therefore, the basic speed energy consumption for PHEV vans driven in a charge depleting mode is the same as the energy consumption curve for a BEV van of the same size class. The basic speed emission and petrol or diesel fuel consumption curves for PHEV vans driven in a charge sustaining mode are the same as for the equivalent Euro standard and size class of petrol or diesel HEV van. The curves should be weighted according to the utility factor.

Future improvements in the energy and fuel consumption of PHEV vans were derived from the Ricardo's calculations based on anticipated mass reduction and other powertrain efficiency improvements. This analysis indicated that for diesel PHEV vans there will be a 2.4% reduction in fuel consumption by 2050 and an almost 10% reduction in electric energy consumption by 2050. The trends in fuel and electric energy consumption derived for petrol PHEV vans were similar, with a 2.1% reduction in fuel consumption calculated by 2050 and a 9.6% reduction in electric energy consumption.

3.10 FUEL CELL (HFCV) VANS

Following the approach set out in Section 2.2.6, speed energy curves for HFCV vans were calculated by applying a factor of 1.84 to the speed energy curve for BEV vans.

Future improvements in the energy efficiency of HFCV vans were derived from Ricardo's calculations and show that a 6% reduction in energy consumption is achieved between 2020 and 2030 and a further 4% reduction would be achieved between 2030 and 2050.

3.11 PRIMARY NO_2 EMISSIONS

NOx is emitted from vehicles both as NO and NO_2. The NOx emitted as NO will get converted to NO_2 in the atmosphere, but the time taken for that conversion depends on the local composition of the atmosphere, and in particular the local availability of ozone and that differs in urban and non-urban environments. The NO_2 emitted will contribute to roadside NO_2 concentrations without any influence of the local atmospheric composition. Overall, both the emitted NO_x and the fraction emitted as NO_2 will impact on the concentration of NO_2 in the urban atmosphere.

The NAEI provides recommended values for the fraction of NO_x emissions from road vehicle emitted directly as NO_2 (f-NO_2). Values of f-NO_2 were developed from recent real-world roadside vehicle emissions remote sensing measurements of NO_2/NO_x ratios compiled by Ricardo and the University of York. Factors were developed for different vehicle and fuel types and Euro standards. The f-NO_2 factors for cars and vans are provided in Table 5. The factors were developed for conventional petrol and diesel cars and vans and there is currently not sufficient evidence available from existing measurements to provide separate factors for hybrid vehicles. The conditions that lead to direct NO_2 emissions from the exhaust of an engine (as a fraction of total NO_x) are largely the same for an HEV and PHEV as for an ICE vehicle. Therefore, it is recommended that the f-NO_2 factors in Table 6 are adopted for HEV and PHEV cars and vans. Combining the f-NO_2 factors with NO_x emission factors will provide an indication of the impact of the fleet on NO_2 concentrations at the roadside, but the total NO_x is also important, and a more complex model is required to understand the full impact of NO_x emissions on NO_2 concentrations.

Table 5 Fraction of NO_x emitted by vehicles as NO_2 (by volume) for cars and vans

Vehicle and Fuel Type	Euro Standard	f-NO_2
Petrol cars	Euro 3	0.02
	Euro 4	0.05
	Euro 5	0.08
	Euro 6 abc	0.04
	Euro 6 d-temp	0.04
	Euro 6 d	0.04
Petrol vans	Euro 3	0.02
	Euro 4	0.05
	Euro 5	0.08
	Euro 6 abc	0.04
	Euro 6 d-temp	0.04
	Euro 6 d	0.04
Diesel Cars	Euro 4	0.21
	Euro 5	0.16
	Euro 6 abc	0.25
	Euro 6 d-temp	0.25
	Euro 6 d	0.25
Diesel vans	Euro 4	0.21
	Euro 5	0.10
	Euro 6 abc	0.25
	Euro 6 d-temp	0.25
	Euro 6 d	0.25

3.12 COMPARISON OF SPEED EMISSION/ENERGY CURVES DEVELOPED WITH ALTERNATIVE DATA

The latest version of the Guidebook (consistent with COPERT 5.6) provides emission factors for a subset of ULEV cars: petrol HEV, petrol PHEV and diesel PHEV cars. Speed emission and energy curves for other classes of ULEV cars and vans are not provided. The 2015 study to develop speed emission/energy curves for ULEVs also covered some of the vehicle classes included in this study. This section provides a summary of the similarities and differences between the speed emission/energy consumption curves developed in this study with curves available from these other sources.

As noted above, specific speed emission curves for NO_x were not available from the PHEM simulations. Instead, emission factors for HEVs were assumed to be the same as for ICE vehicles the equivalent size, fuel and Euro standard, consistent with the assumptions made in HBEFA. However, specific speed emission curves for petrol HEV cars are provided in COPERT and were developed in the 2015 study. These curves were also recommended for use for petrol PHEV cars operating in charge sustaining mode. Figure 24 provides a comparison between the NO_x emission curves for petrol HEV cars developed in this study with the corresponding curves from other sources. The blue solid lines in the Figure show the emission curves developed in this study from fits to PHEM simulations for petrol ICE cars that are also recommended for use for petrol HEV cars and petrol PHEV cars operating in charge sustaining mode. The red solid and dashed lines provide the speed emission curves from COPERT 5.6 for petrol ICE and petrol HEV/PHEV cars, and the green dashed lines show the curves developed for HEV cars in the 2015 study. Note that the COPERT curves and the curves from the 2015 study are the same for all Euro standards. The curves developed for petrol HEV cars in this study were derived from PHEM simulations for petrol ICE cars and the curves are similar to the COPERT curves for ICE vehicles. The COPERT curves for HEV cars show much lower emissions at low speeds than at high speeds, in contrast to the NO_x curves from other sources that tend to show higher emissions at low speeds. This discrepancy was raised with contacts at Emisia, who develop the COPERT emission factors. They reported that the curves for hybrids and plug-in hybrids in COPERT were developed several years ago based on actual vehicle measurements and would expect them to be representative of early hybrids. The team at Emisia plan to review the evidence on emissions from hybrids in a future release of COPERT. While the evidence on emissions from petrol HEV and PHEV cars continues to be assessed, it is considered that the more conservative approach of assuming that NO_x emissions are the same as from ICE petrol cars is reasonable and pragmatic. This is also consistent with the approach taken by COPERT and in the 2015 study for diesel HEV and PHEV cars, where recommended NOx emission factors were the same as for diesel ICE cars.

Figure 24 Comparison between speed NOx emission curves for petrol HEV cars developed in this study (DfT 2023, blue) with curves provided in COPERT 5.6 (red) and in the 2015 study (green).

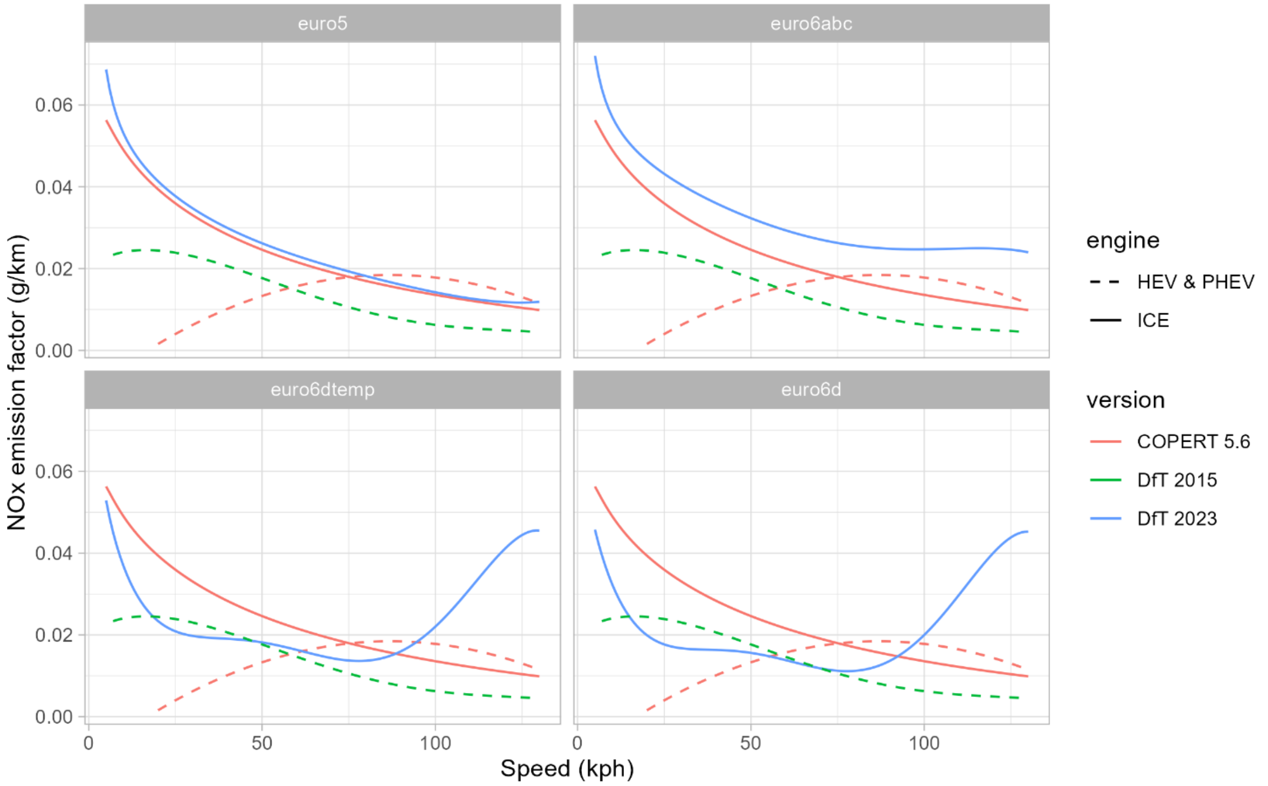


Figure 34 in Appendix A provides a comparison between the fuel consumption factors for petrol and diesel HEV cars at three speeds (15, 60 and 100 kph) with the factors from the 2015 study and from COPERT 5.6 (available only for HEV cars). In the 2015 study, fuel consumption curves for petrol HEV cars were developed based on simulated data from the PHEM model. The data used was for a single model of a medium car, the Volkswagen Jetta, and simulations were available for both HEV and ICE vehicles. The simulation data was not used directly, instead the ratio between HEV and ICE data was used to scale the CO_2 speed-emission curves for ICE petrol cars used in inventories to develop CO_2 and fuel consumption curves for petrol HEV cars. The figures show that the fuel consumption factors for petrol HEV cars and vans developed in this study are approximately 10% higher than the factors from COPERT. However, both the COPERT and the new fuel consumption factors are somewhat higher than the factors for petrol HEV factors from the 2015 study. The good agreement between COPERT and this study suggests that the petrol HEV fuel consumption factors may have been underestimated in the previous study. In the 2015 study, fuel consumption curves for diesel HEV cars were developed from PEMS measurement data for a single vehicle model. Figure 34 shows that the fuel consumption factors for diesel HEV cars developed in this study are ~10-30% higher than the factors from curves developed in the 2015 study, with the greatest difference seen at 100 kph.

Figure 35 provides comparisons between the fuel consumption factors for petrol and diesel HEV vans with the factors from the 2015 study. In 2015, no data was available for petrol hybrid vans and it was assumed that the energy curves were the same as for a medium HEV car. Similar to the observations for petrol cars, Figure 35 shows that the factors for petrol HEV vans developed in this study are significantly higher than the factors from the 2015 study. The 2015 study developed fuel consumption curves for diesel HEV vans based on data reported from two US studies looking at specific models of diesel hybrid truck. The reported speed dependent energy reduction compared to an ICE truck was used to develop fuel consumption curves for diesel hybrid vans. The figure shows that the fuel consumption factors for diesel HEV cars and LGVs developed in this study are generally similar to those developed in the 2015 study.

Figure 36 in Appendix A shows a similar comparison between the energy consumption of BEV cars developed in this study compared to those developed in the 2015 study. The 2015 curves were developed based primarily on an assessment of PHEM model simulations for two specific models of BEV car, the Nissan Leaf and the Peugeot Ion, and incorporated a real-world driving uplift of 20% based on data from a US study. In the 2015 study, curves were developed for three size classes of car, small, medium and large. In contrast, curves were developed for a single size class of car in this study which is designed to represent a fleet weighted average BEV car in Europe. The figure shows that the energy consumption of BEV cars in this study is ~8% lower than energy consumption from small BEV curves from the 2015 study at speeds of 25 and 60 kph and a greater difference is seen at higher speeds.

Figure 37 in Appendix A shows comparisons between the energy consumption of BEV vans from this study, compared with the factors from the 2015 study. In 2015, detailed data on the energy consumption of BEV vans was not available. The energy consumption curves developed were therefore based on the data available for BEV cars, uplifted to account for the additional weight of semi-laden vans. The plot show that the new energy consumption factors for BEV vans developed in this study are similar to the 2015 factors at speeds of 60 kph. However, the new factors developed in this study show less speed dependence and are lower than the 2015 factors at higher speeds, and higher than the 2015 factors at low speed.

The discussion above has highlighted some of the similarities and differences between the fuel and energy curves developed in this study compared to the previous study undertaken by Ricardo in 2015, and, where available, curves available from COPERT. The number of ULEV vehicles in the UK fleet today is significantly higher than in 2014/15 at the time of the previous study, and the evidence base on emissions, energy and fuel consumption from HEV and BEV cars and vans is significantly improved. In 2015, the curves were developed from a limited set of simulation and/or PEMS measurements for a small number of vehicles, further extrapolated based on additional evidence or reasonable assumptions to provide a set of speed emission and energy curves for ULEVs. In this study, fuel and energy curves are all derived from a single data source, PHEM simulations for HEVs and BEVs. The PHEM simulations undertaken by TU Graz are now underpinned by a larger pool of vehicle measurement data available from the European ERMES group. The PHEM data used in this study is therefore expected to provide more robust energy and fuel consumption curves for petrol and diesel HEV and BEV cars and vans with an established provenance. The curves developed in 2015 were subject to greater uncertainties due to the limited data available at the time. However, the curves developed in this study are representative of ULEV vehicles currently in the European fleet and there are many more models of HEV and BEV cars and vans in the fleet now than there were in 2015. There are also likely to have been some improvements in battery technology with potential impacts on vehicle weight, and improvements in vehicle aerodynamics which may be a factor when considering the differences between the curves developed in 2015 and the new curves developed in this study.

4. EMISSION CURVES FOR HEAVY DUTY VEHICLES

The detailed analysis and results for each of the HGV, bus and coach technologies is set out in the following sections. Sections 4.1 to 4.6 present the speed emission, fuel and energy curves for ULEV HGVs, buses and coaches and discusses the derivation of the curves from the PHEM simulation data for the core BEV and hybrid vehicle technologies. Section 4.7 provides recommended values for the fraction of NO_x emitted as primary NO_2 for relevant ULEV technologies.

4.1 BATTERY ELECTRIC (BEV) HGVS

PHEM simulations were available for five size classes of BEV HGVs: rigid HGV size classes <7.5t, 7.5-12t, 14-16t and 26-28t, and 34-40t articulated HGVs. Figure 25 shows the speed energy consumption curves developed from 6th order polynomial fits to the PHEM simulations.

Speed energy curves for other size classes of rigid and articulated HGVs were derived from the fuel consumption curves that were available for all size classes of conventional diesel HGVs. The first step in the calculation was to calculate the ratio between the energy consumption of BEV HGVs and the fuel consumption of ICE HGVs of the same size where data was available, i.e. rigid HGVs of weight <7.5t, 7.5-12t, 14-16t and 26-28t, and 34-40t articulated HGVs. The speed dependent ratios calculated for 14-16t rigid HGVs were then applied to the ICE fuel consumption curves available for all other size classes of rigid HGVs and the ratios for 34-40t articulated HGVs were applied to the ICE fuel consumption curves for all other size classes of articulated HGV. The resulting speed energy consumption curves for all size classes of HGVs are presented in Figure 26. The derived curves were validated by comparing the curves derived for <7.5t, 7.5-12t and 26-28t rigid HGVs with the curves developed from fits to the PHEM simulations. There was good agreement between the two methodologies.

The curves in Figure 25 and Figure 26 account for a grid to battery conversion efficiency and therefore provide energy use in terms of kWh/km at the power supply socket. A grid to battery charging efficiency of 88.2% was assumed for heavy duty vehicles, consistent with evidence from literature.

Future improvements in the energy efficiency of BEV HGVs were derived from Ricardo's calculations based on anticipated BEV mass reduction and other powertrain efficiency improvements. The energy consumption trends estimate a 10% reduction in energy consumption will be achieved by 2050.

Figure 25 Speed energy consumption curves for BEV HGVs derived from fits to PHEM simulations

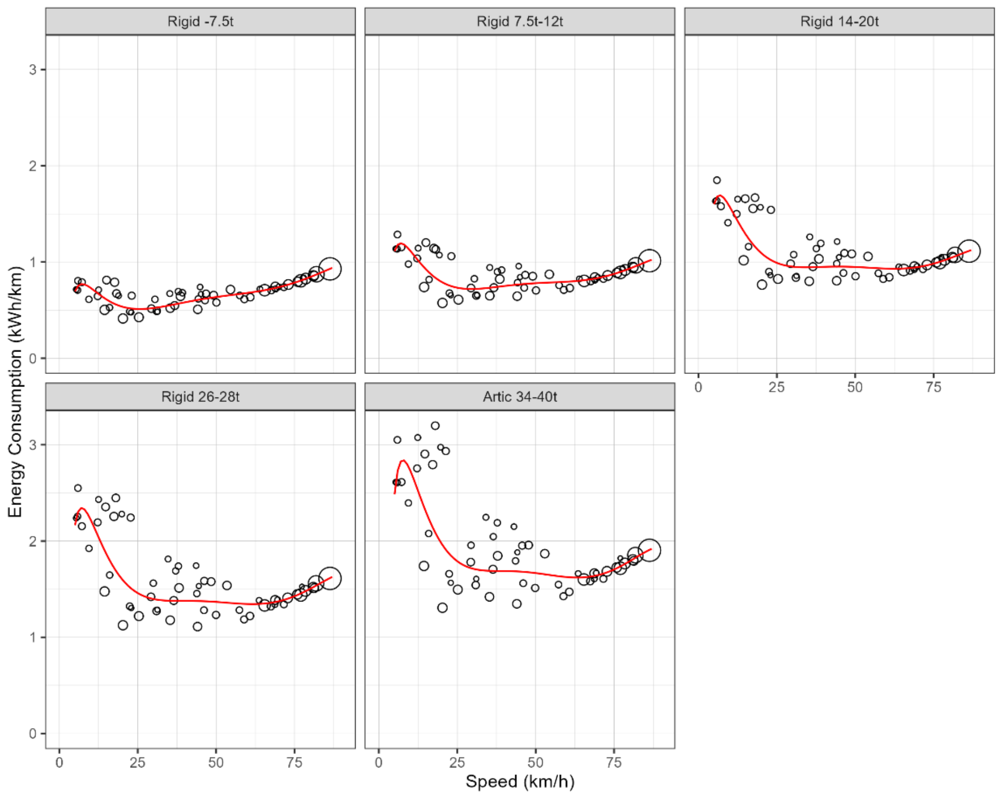
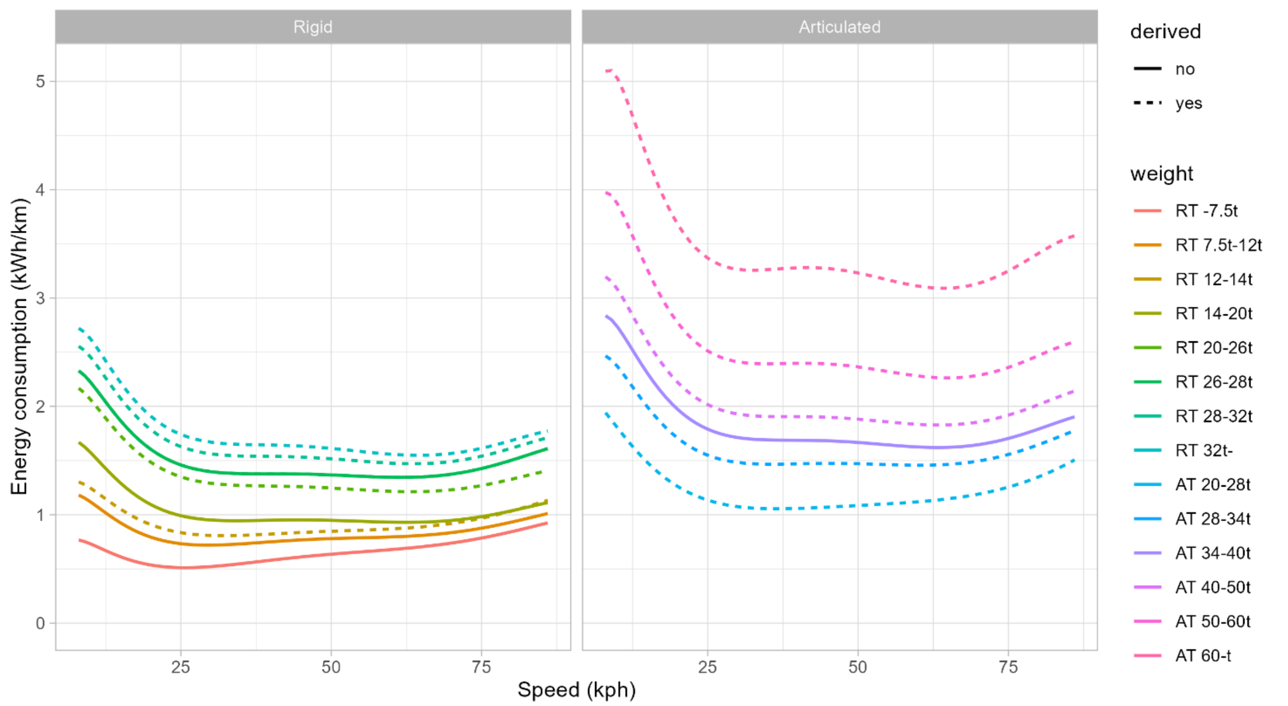


Figure 26 Speed energy consumption curves for all size classes of rigid (RT) and articulated (AT) BEV HGVs. Solid lines are used for curves developed from fits to PHEM simulations and dashed lines indicate fits were derived from fuel consumption curves for conventional diesel HGVs.



The 2015 study to develop speed emission/energy consumption curves for ULEVs provided speed energy curves for BEV rigid trucks of weight class <7.5 t and 7.5-12t. At the time of the 2015 study, an absence of speed related energy consumption meant that the curves for BEV trucks were extrapolated from larger N1(III) vans, scaled by the fuel consumption of ICE trucks of the same weight relative to the fuel consumption of N1(III) vans. Although BEV trucks remain quite new technology, more vehicle test data is now available to inform the PHEM model simulations. Figure 38 in Appendix A provides a comparison between the energy consumption factors developed for BEV trucks in this study with those from the 2015 study at two speeds, 25 and 60 kph. Overall, the factors are reasonably similar but the curves developed in this study show less dependence on speed.

4.2 PLUG-IN HYBRID (PHEV) HGVS

Speed emission curves for PHEV HGVs operating in a charge sustaining mode (i.e. using diesel fuel) were developed from fits to PHEM simulations. As for cars and vans, NO_x and PM_{10} emissions were assumed to be the same as emissions from conventional diesel HGVs because there is insufficient evidence available from vehicle measurements to develop separate emission curves for PHEV HGVs. Figure 27 and Figure 28 show the speed NO_x and PM emission curves developed for PHEV HGVs in charge sustaining mode. PHEV HGVs are a new and emerging technology, therefore the speed NO_x and PM_{10} emission curves developed for the latest Euro VI-D HGVs are expected to be most representative of emissions from PHEV HGVs.

Speed fuel consumption curves for PHEV HGVs operating in a charge sustaining mode were available from the PHEM simulations for four size classes of PHEV HGVs: rigid HGVs with weight class <7.5t, 7.5-12t and 14-20t, and 34-40t articulated HGVs. The PHEM simulations account for the improvements in energy consumption expected for PHEVs that can recoup energy through regenerative braking. The same approach that was taken to develop speed fuel consumption curves for BEV HGVs was used for speed energy consumption curves for PHEV HGVs. First fuel consumption curves were developed for the weight classes of PHEV HGVs available from the PHEM model. The ratio between the PHEV fuel consumption and conventional diesel vehicle fuel consumption curves for 26-28t rigid HGVs and 34-40t articulated HGVs was used to develop speed dependent factors to apply to the speed energy consumption curves for other size classes of rigid and articulated HGVs respectively. The resulting speed fuel consumption curves for all size classes of HGVs are presented in Figure 29.

Figure 27 Speed NO_x emission curves for Euro V and Euro VI articulated PHEV HGVs in charge sustaining mode by size class

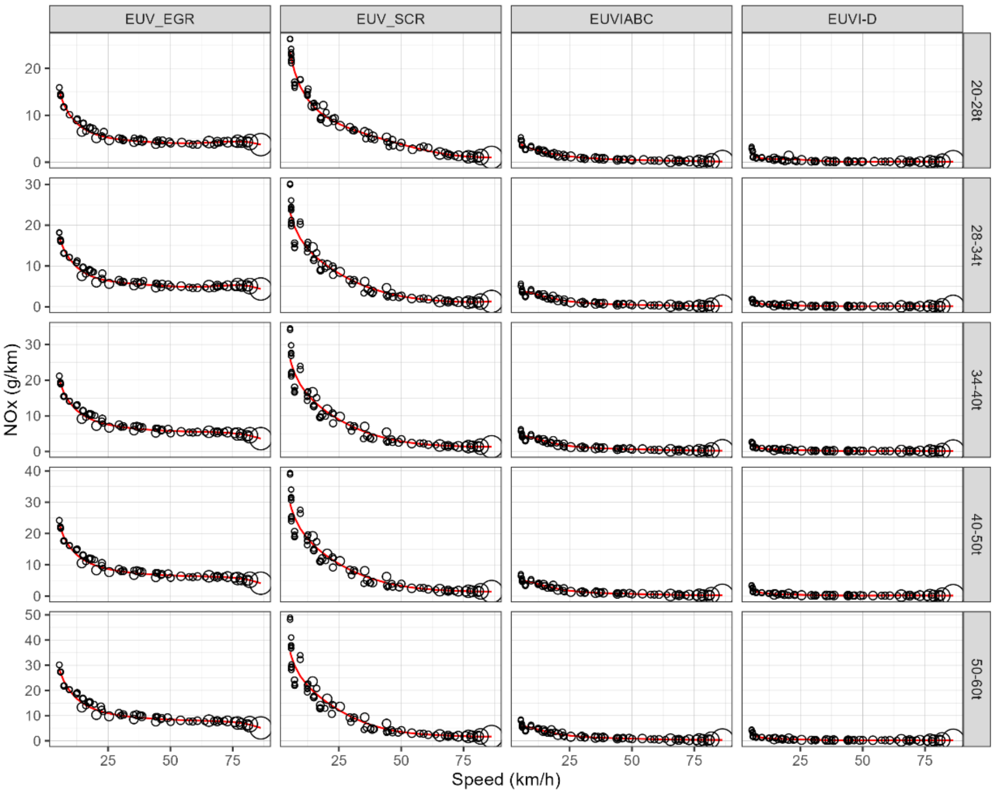


Figure 28 Speed PM10 emission curves for Euro V and Euro VI articulated PHEV HGVs in charge sustaining mode by size class

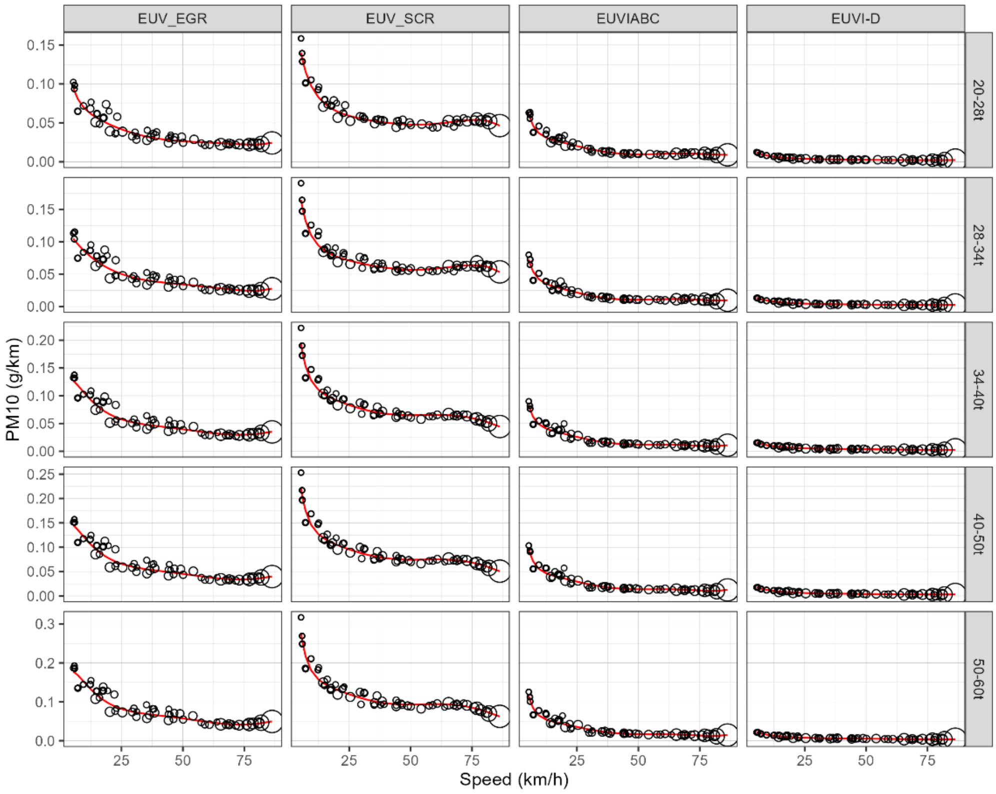
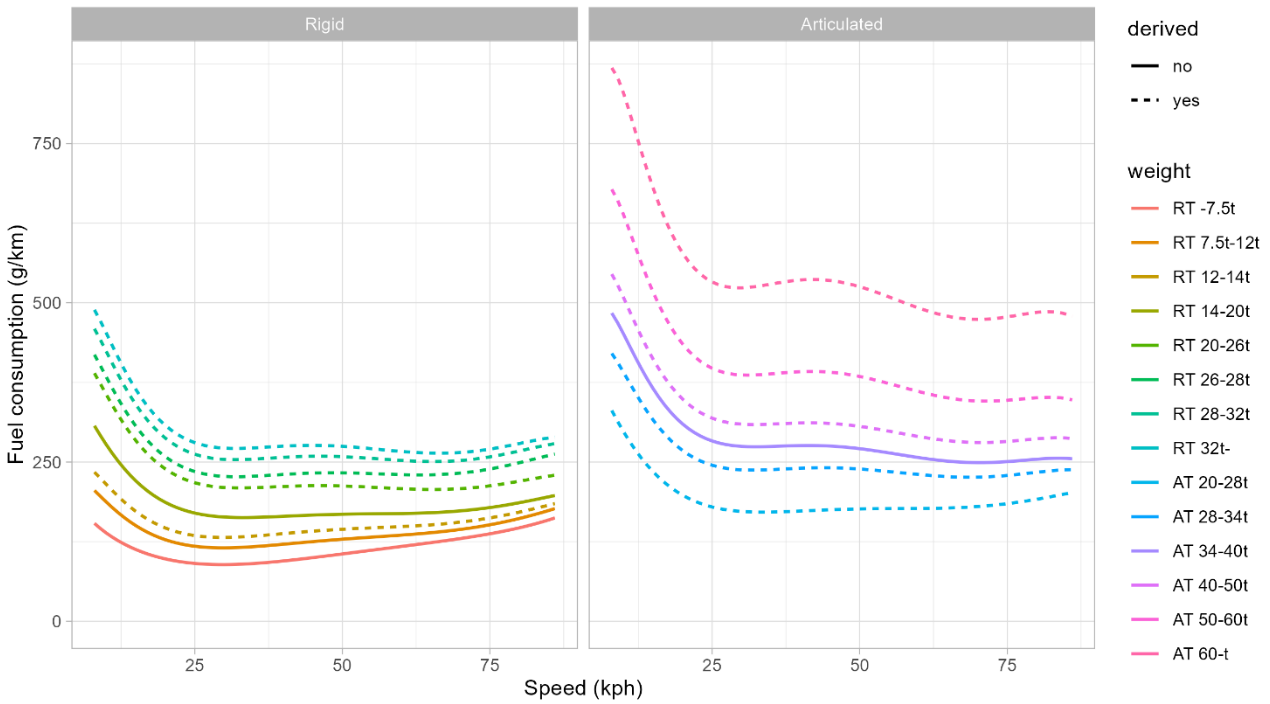


Figure 29 Speed fuel consumption curves for rigid (RT) and articulated (AT) PHEV HGVs in charge sustaining mode



Speed energy consumption curves for PHEV HGVs operating in a charge depleting mode (i.e. drawing energy from the battery) are assumed to be the same as the curves for BEV HGVs presented in section 4.1. The curves developed for PHEVs operating in charge sustaining and charge depleting mode should be weighted by the utility factor (Section 2.2.5).

Future improvements in the energy and fuel consumption of PHEV HGVs were derived from the Ricardo's calculations based on anticipated mass reduction and other powertrain efficiency improvements. This analysis indicated that for PHEV HGVs there will be a 2.2% reduction in fuel consumption by 2050 and an almost 10% reduction in electric energy consumption by 2050.

4.3 ELECTRIC (BEV) AND PLUG-IN (PHEV) CATENARY (ERS) HGVS

Electric and plug-in catenary HGVs can be powered by an external electric road system (ERS) that supplies electric power to the vehicle through overhead power lines on major motorways and trunk roads. BEV catenary HGVs can also operate off a battery with sufficient capacity for the vehicle to travel between a depot or a charging station and the ERS. BEV catenary HGVs are essentially the same as BEV HGVs, except that they can also be powered through the ERS. The approach taken therefore was to develop speed energy consumption curves for BEV catenary HGVs based on the curves for BEV HGVs. It was assumed that the energy requirements of the ERS system is equivalent to those of the battery for a BEV. A scaling factor is then required to account for the conversion efficiency of the ERS, the efficiency of charging the battery at the depot/ charging station, and the share of distance travelled when powered by the ERS. It was assumed that the efficiency of plug-in charging at the depot was 88.2%, consistent with the assumption made for BEV HGVs, and the efficiency of charging from the ERS was assumed to be 83.3%. The share of driving powered by the ERS is quite uncertain as currently there are not any ERS systems in use in the UK, and the share will be dependent on factors such as the length of ERS. An ERS share ratio of 40% for rigid HGVs and 50% for articulated HGVs is suggested based on evidence from previous calculations undertaken by Ricardo.

The same approach was taken for the development of speed energy curves for PHEV catenary HGVs. PHEV catenary HGVs can also be powered by a small diesel engine in a charge sustaining mode. The underlying speed emission and fuel consumption curves were assumed to be the same as for PHEV HGVs driven in charge sustaining mode. The final speed emission, fuel and energy curves require weighting functions that account for the share of driving undertaken by ERS, battery and diesel engine. Previous Ricardo work did not cover PHEV catenary vehicles and the share of driving undertaken with the diesel engine is unknown. In the absence of evidence, it was agreed with DfT to assume that split between electric and diesel driving by PHEV catenary HGVs would be consistent with the utility factors (i.e. share of electric driving) for conventional PHEV HGVs. The total share of electric driving was therefore assumed to be 50% and 20% for rigid and articulated PHEV HGVs, respectively, as presented in Table 3. The share of electric driving was further split between electricity consumption from the ERS and from the battery, assuming that the split between the two modes was consistent with the splits recommended for catenary BEV HGVs, i.e. 40% ERS share for rigid HGVs and 50% for articulated HGVs. These assumptions resulted in the following default driving shares:

- PHEV catenary rigid HGVs: 20% ERS, 30% battery electric and 50% diesel fuel
- PHEV catenary articulated HGVs: 10% ERS, 10% battery electric and 80% diesel fuel

However, the aggregation spreadsheet supplied with this report provides a mechanism to input alternative assumptions on share of driving and update the speed emission curves calculated when evidence is available to adjust the default assumptions made.

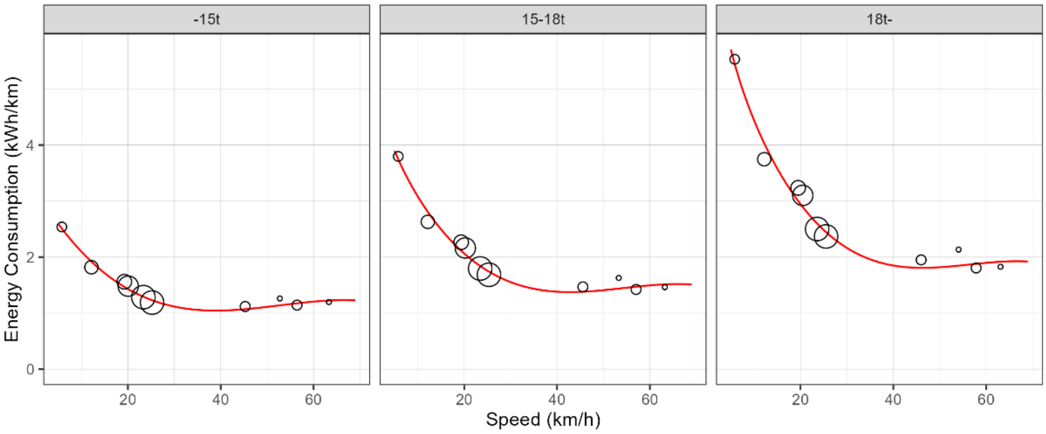
4.4 BATTERY ELECTRIC (BEV) BUSES AND COACHES

Speed energy consumption curves for BEV buses and coaches were developed from polynomial fits to PHEM simulations. Figure 30 shows the speed energy consumption curves developed. The curves account for a grid to battery conversion efficiency and therefore provide energy use in terms of kWh/km at the power supply socket. A grid to battery charging efficiency of 88.2% was assumed for heavy duty vehicles, consistent with evidence from literature.

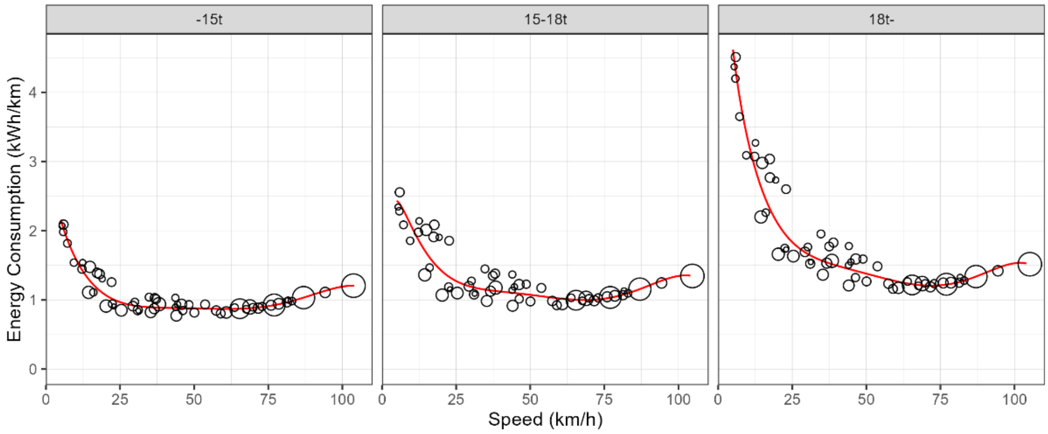
Future improvements in the energy consumption of BEV buses and coaches were derived from the Ricardo's calculations based on anticipated mass reduction and other powertrain efficiency improvements. This analysis indicated that for BEV buses and coaches there will be an 10% reduction in energy consumption by 2050.

Figure 30 Speed energy consumption curves for BEV buses and coaches

(A) Buses



(B) Coaches

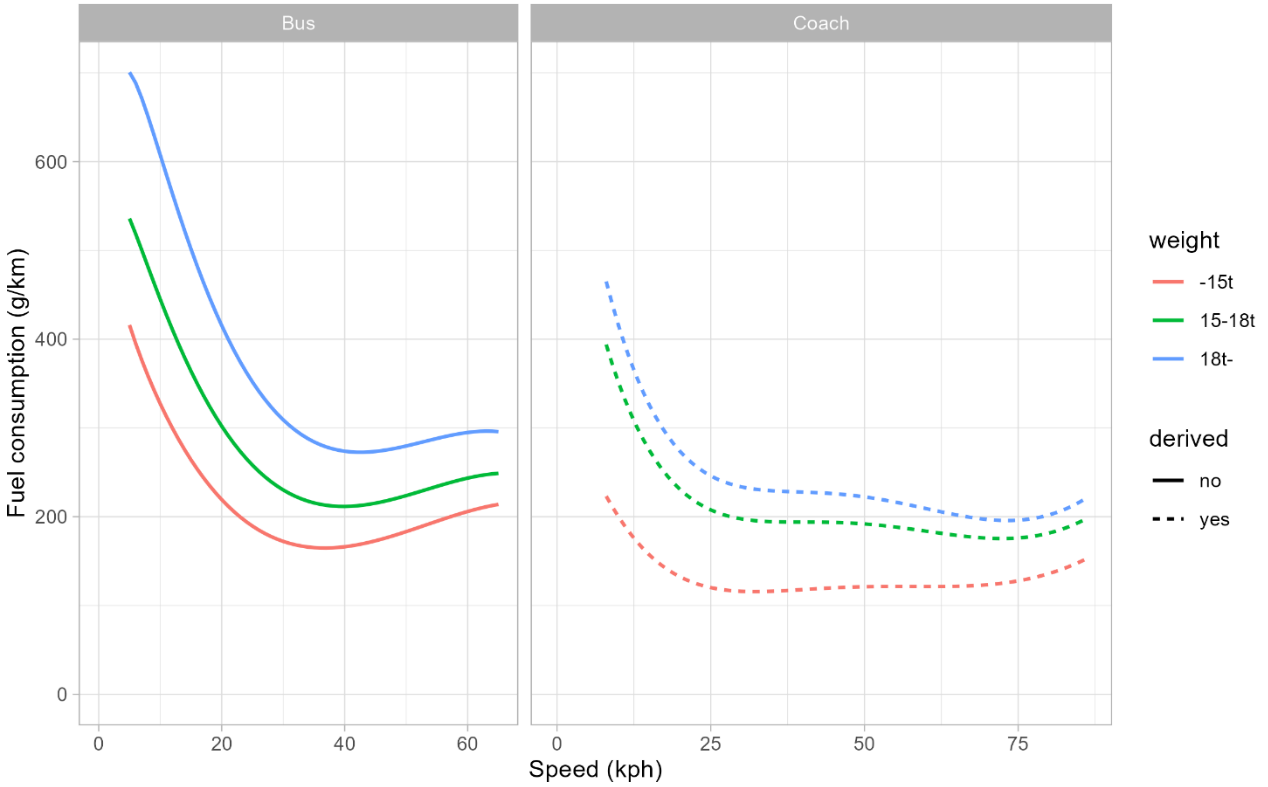


4.5 PLUG-IN HYBRID (PHEV) BUSES AND COACHES

Speed emission and fuel consumption curves for PHEV buses and coaches operating in a charge sustaining mode (i.e. using the diesel engine) were developed from fits to PHEM simulations. As for other PHEV vehicles, NO_x and PM_{10} emissions were assumed to be the same as emissions from conventional diesel vehicles because there is insufficient evidence available from vehicle measurements to develop separate emission curves for PHEV buses and coaches.

Speed fuel consumption curves for PHEV buses operating in a charge sustaining mode were available from the PHEM model for buses but not for coaches. As the operation of coaches is similar to rigid HGVs, fuel consumption curves for PHEV coaches were estimated based on the fuel consumption data available for rigid HGVs. The ratio between the PHEV fuel consumption and diesel fuel consumption curves for 14-16t rigid HGVs was used to develop speed dependent factors to apply to the speed fuel consumption curves for conventional diesel coaches to derive speed fuel consumption curves for PHEV coaches. The curves were validated by comparison to curves developed based on data for PHEV and conventional diesel buses which were in reasonable agreement but were limited to a maximum speed of 65 kph. The speed fuel consumption curves developed for PHEV buses and coaches in charge sustaining mode are presented in Figure 31.

Figure 31 Speed fuel consumption curves for PHEV buses and coaches in charge sustaining mode



Future improvements in the energy consumption of PHEV buses and coaches were derived from the Ricardo's calculations based on anticipated mass reduction and other powertrain efficiency improvements. This analysis indicated that for PHEV buses and coaches there will be a 10% reduction in electrical energy consumption and a 2% reduction in diesel fuel consumption by 2050.

4.6 FUEL CELL (HFCV) HGVS, BUSES AND COACHES

The approach taken was to derive speed energy and hydrogen fuel consumption curves for HFCV HGVs, buses and coaches from the speed energy curves for the corresponding BEVs (i.e. the same vehicle type and weight class). The basic methodology was the same as that described for HFCV cars and vans. Scaling factors were developed that account for the energy efficiency of fuel cells and should be applied to BEV curves to estimate energy consumption from HFCV HGVs, buses and coaches. The scaling factors are summarised in Section 2.2.6.

Future improvements in the energy consumption of HFCV HGVs, buses and coaches were derived from the Ricardo's calculations based on anticipated mass reduction and other powertrain efficiency improvements. This analysis indicated that for HFCV HGVs, buses and coaches, there will be an 18% reduction in energy consumption by 2050.

4.7 PRIMARY NO_2 EMISSIONS

The NAEI provides recommended values for the fraction of NOx emissions from road vehicle emitted directly as NO_2 (f-NO_2) (NAEI, 2023). Values of f-NO_2 were developed from recent real-world roadside vehicle emissions remote sensing measurements of NO_2/NO_x ratios compiled by Ricardo and the University of York. Factors were developed for different vehicle types and Euro standards, with the exception of buses. The f-NO_2 factors for buses were taken from the 2019 EMEP/EEA Emission Inventory Guidebook. The f-NO_2 factors for HGVs and buses are provided in Table 6. The factors were developed for conventional diesel vehicles and there is not sufficient evidence available from existing measurements to provide separate factors for hybrid vehicles. Therefore, it is recommended that the f-NO_2 factors in Table 6 are adopted for heavy duty hybrid vehicles. Separate f-NO_2 factors are not available for coaches and the values provided for buses should also be used for coaches.

Table 6 Fraction of NO_x emitted by vehicles as NO_2 (by volume) for Euro V and VI Rigid and Articulated (Artic) HGVs and buses

Vehicle and Fuel Type	Euro Standard	f-NO2
Rigid HGVs	Euro V	0.04
	Euro VI	0.14
Artic HGVs	Euro V	0.03
	Euro VI	0.15
Buses	Euro V	0.08
	Euro VI	0.05

5. NON-EXHAUST EMISSION FACTORS

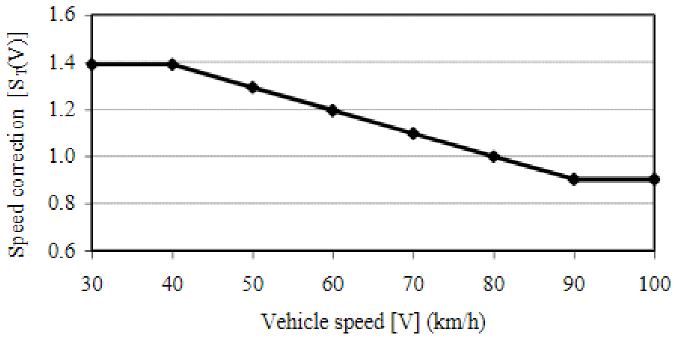
Non-exhaust sources of PM_{10} emissions to air arise from mechanical sources including brake wear, tyre wear and road surface abrasion. Non-exhaust emission factors for those sources were calculated based on the methods and emission factors provided in the EMEP/EEA Inventory Guidebook. The emission factors for non-exhaust sources of PM_{10} were updated in a recent revision to the Guidebook (published December 2022). This update introduced specific non-exhaust emission factors for HEV, PHEV and BEV cars that take account of the impact of regenerative braking on brake wear emissions, and the impact of different vehicle weights on non-exhaust emission from brake and tyre wear and road abrasion. Specific non-exhaust emission factors are not provided for other ULEVs and it is recommended to use the factors available for ICE vehicles where specific factors are not available for a ULEV.

Quantifying non-exhaust emissions is limited by a lack of available data and the emission factors are highly uncertain. The Guidebook provides speed dependent correction factors, shown in Figure 32, that should be applied to tyre and brake wear emission factors for all vehicle types based on mean trip speed. The correction factors reflect that tyre and brake wear tend to be higher under slower urban driving conditions because braking and cornering are more frequent than in motorway driving. Although there is a rough speed-dependence to brake and tyre wear emissions the high uncertainty in the data has meant that continuous speed-emission relationships have not been developed. Factors for tyre and brake wear emissions for typical traffic situations on urban, rural and motorway road conditions are shown in Table 7. Factors for road abrasion are not available for different speeds or road types, but average values for all road types are shown in Table 8. Unlike exhaust emission factors, non-exhaust emission of PM_{10} are not all emitted in the 2.5 µm particle size range, i.e. as $PM_{2.5}$. Table 9 provides the fraction of PM_{10} emitted as $PM_{2.5}$.

Research into real-world emissions from non-exhaust sources is ongoing, indeed the DfT's brake and tyre wear research project is underway, and it is recommended that the research continues to be reviewed to improve the estimate of non-exhaust emissions in inventories and models.

Figure 32 Speed correction factors for (a) tyre wear and (b) brake wear particle emissions provided in the EMEP/EEA Inventory Guidebook

(a) Tyre wear



(b) Brake wear

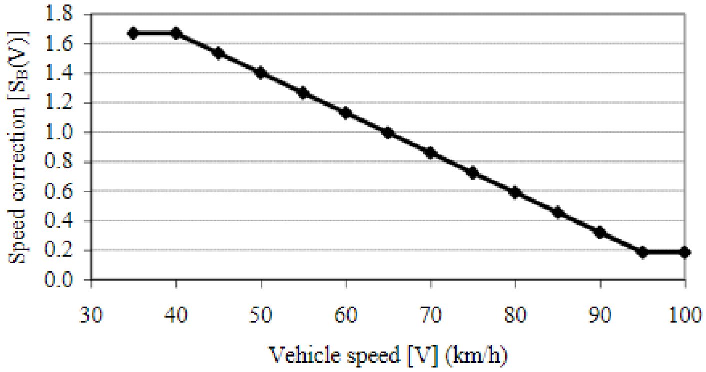


Table 7 Emission factors for PM_{10} from tyre and brake wear (in mg/km).

mg PM_{10} /km	Technology	Road class	Tyre	Brake
Cars	ICE	Urban	9.0	20.0
		Rural	7.3	11.5
		Motorway	5.8	4.0
	HEV	Urban	9.3	15.9
		Rural	7.6	9.1
		Motorway	6.0	3.2
	PHEV	Urban	9.4	10.8
		Rural	7.6	6.2
		Motorway	6.1	2.1
	BEV	Urban	9.7	5.6
		Rural	7.9	3.2
		Motorway	6.3	1.1
LGVs	All	Urban	14.1	27.8
		Rural	11.7	16.9
		Motorway	9.7	7.9
Rigid HGVs	All	Urban	21.2	54.5
		Rural	19.0	36.6
		Motorway	16.4	24.7
Artic HGVs	All	Urban	48.1	54.5
		Rural	41.7	36.6
		Motorway	37.0	24.7
Buses	All	Urban	34.9	54.5
		Rural	29.9	36.2
		Motorway	24.7	16.8

Table 8 Emission factors for PM_{10} from road abrasion (mg/km)[4]

mg PM10 /km	Technology	Road abrasion
Cars	ICE	7.50
Cars	Hybrid	7.95
Cars	PHEV	8.05
Cars	BEV	8.45
LGV	All	7.50
HGVs	All	38.00
Buses	All	38.00

Table 9 Fraction of PM_{10} emitted as $PM_{2.5}$ for non-exhaust emission sources

Source	$PM_{2.5}/PM_{10}$
Tyre wear	0.7
Brake wear	0.4
Road abrasion	0.54

[4] The emission factors for PM_{10} from road abrasion presented in Table 8 have been updated compared to the values in the Report Issue 05, published on 31 October 2024. The emission factors in Issue 06 were incorrectly presented for total suspended particles (TSP) and not PM_{10}. Since PM_{10} makes up 50% of TSP, the updated emission factors for PM_{10} in this report are 50% of the values presented in Issue 05.

6. VEHICLE FLEET AGGREGATION

The previous sections describe the development of detailed emission/energy curves for different ULEV categories. For use in the NTM it is necessary to aggregate the emission curves for variants within each ULEV category (as specified in Table 10), for example vehicles of different Euro classes, engine sizes or vehicle weights.

The weightings used in the development of emissions curves for the ULEV vehicles reflect the mix of vehicle kilometres done by vehicles meeting the different Euro classes and engine size or weight class in the fleet in a given year. These weightings were derived from the NAEI's fleet turnover model which took account of historic and future sales of new vehicles according to data provided by DfT in December 2021, vehicle survival rates and data on mileage as a function of vehicle age. Where NAEI does not account for the fleet composition of a specific ULEV category (e.g. diesel PHEV cars), simplified fleet assumptions were made. A spreadsheet tool has been provided to DfT to undertake the required aggregations, so all assumptions made in the spreadsheet could easily be changed by DfT once evidence becomes available.

The energy and fuel consumption curves developed for the relevant ULEV vehicles incorporate future improvements in energy and fuel efficiency that reflect evidence on technology improvements and is based on studies discussed in previous sections. For some ULEVs (e.g. catenary trucks), technology is still in its infancy and policy has not yet been developed so the evidence of emissions and fuel/energy consumption from these vehicles and the fleet weightings are likely to undergo major changes as uptake of certain vehicle technologies is incentivised.

The remainder of this section summarises the ULEV categories for which aggregate curves are output, the methodology for generating emission curves and the required classification of the weighting factors by main ULEV category.

6.1 ULEV CATEGORIES

DfT decided to include emission curves for twenty ULEV categories in this project. The ULEV categories are summarised in Table 10 which also indicates which pollutant or fuel consumption types apply to each ULEV category. These main ULEV types encompass the range of vehicles discussed in Sections 3 and 4.

As part of the NTM, DfT will further weight the curves for aggregated ULEV categories, plus curves for conventional vehicle types (e.g. petrol cars, diesel cars, buses etc.), by proportion of vehicle kilometres in a given year for the different vehicles by five area types (London, Conurbations, other urban, rural and motorways) to provide emissions for different road/area types in the particular year. This additional aggregation step is dependent on future ULEV uptake and is not performed as part of this project.

Table 10 Summary of ULEV category and pollutant/fuel/electricity consumption combinations for which aggregated speed emission/energy curves are provided

Vehicle	Aggregated vehicle type	NOx	PM	CO2 & FC	Electricity consumption	Hydrogen consumption
Car	Petrol HEV	✓	✓	✓	✗	✗
	Diesel HEV	✓	✓	✓	✗	✗
	Petrol PHEV	✓	✓	✓	✓	✗
	Diesel PHEV	✓	✓	✓	✓	✗
	BEV	✗	✗	✗	✓	✗
	HFCV	✗	✗	✗	✗	✓
LGV	Petrol HEV	✓	✓	✓	✗	✗
	Diesel HEV	✓	✓	✓	✗	✗
	Petrol PHEV	✓	✓	✓	✓	✗
	Diesel PHEV	✓	✓	✓	✓	✗

Vehicle	Aggregated vehicle type	NOx	PM	CO2 & FC	Electricity consumption	Hydrogen consumption
	BEV	×	×	×	✓	×
	HFCV	×	×	×	×	✓
Rigid/Artic HGV and OGV1/OGV2	BEV	×	×	×	✓	×
	PHEV	✓	✓	✓	✓	×
	BEV-ERS	×	×	×	✓	×
	PHEV-ERS	✓	✓	✓	✓	×
	HFCV	×	×	×	×	✓
Buses and coaches	BEV	×	×	×	✓	×
	PHEV	✓	✓	✓	✓	×
	HFCV	×	×	×	×	✓

6.2 FLEET WEIGHTING FACTORS BY MAIN ULEV CLASS

This section describes the weightings used to develop the speed curves relevant to each main ULEV category and pollutant/fuel/energy consumption combination. Where available, the Euro standards and vehicle size weighting factors of a given ULEV category came from the NAEI fleet projections. The generation weighting factors provide the composition of the fleet by sales year and were introduced to allow technology improvements taken from the European studies mentioned in Section 2 to be accounted for in the fleet-weighted emission factors. Year-dependent weighting factors are provided for each main ULEV category from 2015 to 2060 in a 5-years interval. As the NAEI fleet projections do not go beyond 2050, the fleet weighting factors in 2055 and 2060 were assumed to be the same as in 2050. The NAEI does not provide vehicle size weighting factors specifically for ULEVs, therefore the size weighting factors for ULEVs were assumed to be the same as for ICE vehicles of the same class.

Table 28, Table 29 and Table 30 in Appendix B summarise the Euro standards, generations and vehicle size categories for which weighting factors are split by within each ULEV category. Note that the introduction of Euro 7/VII was not included as these regulations are still under consideration by the European Commission and the UK Government. The aggregation spreadsheet tool compiles disaggregated emission factors but develops aggregated speed curves for different pollutant/fuel/energy consumption combinations. All weighting factors are setup to be easily changed by DfT but must sum to 1 for each ULEV category. Where data on Euro standard or Generation fleet weighting factors were not available from the NAEI, simple default factors are provided. These factors are not necessarily realistic, and it is recommended that they are updated. The values of the default fleet weighting factors for each ULEV category are provided and documented in the aggregation tool.

Many ULEV classes are new and emerging technologies and these vehicles are not yet considered in the NAEI fleet projections. Table 31 in Appendix B indicates which ULEV fleet weightings are coming from the NAEI fleet projections. For other ULEV classes, Euro standard, generation and vehicle size weighting factors were not available from the NAEI. The aggregation spreadsheet tool requires this information to be provided for each main ULEV class for the years 2015 – 2060 in 5 year intervals.

6.3 AGGREGATION TOOLS

A spreadsheet tool capable of performing the aggregation of the emission and energy curves for variants within each ULEV category has been developed and provided to DfT. The structure of the tool and the general approach is similar to the tools previously developed by Ricardo for emission curves for conventional petrol and diesel vehicle types provided to DfT for the NTM and for the previous emissions/energy curves for ULEVs provided to DfT for the NTM in 2015. If the emission curves for all the variants are described by the same mathematical functional form, then an aggregate emission curve can be developed by weightings applied to each of the coefficients in the equations. The weightings are based on the fractions of each variant in the particular ULEV fleet and are year dependent. Coefficients which define the shape and magnitude of emissions/energy curves for a given year are derived for each main vehicle type by summing the contributing weighted coefficients relevant to the year. The final result is a set of year-specific speed curves for each main class of ULEV and pollutant or fuel or energy consumption combination.

The aggregation spreadsheet tool provides flexibility to update curves as new information becomes available since fleet composition data and various scaling factors (as discussed above) are inputs to the tool. The tool calculates aggregated emission curves for three pollutants (CO_2, NO_x and PM), petrol and diesel fuel consumption, electricity and hydrogen consumption, as applicable to each ULEV category. Curves are output from 2015 to 2060 in 5-year intervals.

6.4 GENERATION OF EF CURVES

Emission factors for all the detailed vehicle categories were provided in the same mathematical functional form:

$$EF(v) = k\,(a + bv + cv^2 + dv^3 + ev^4 + fv^5 + gv^6) / v \qquad (1)$$

In equation (1), the coefficients a-g were derived from fits to the average speed and emissions data from the PHEM simulations. The coefficient k accounts for any scaling of the curves required to account for, depending on the ULEV vehicle class, battery charging efficiency, utility factors for PHEVs, efficiency of hydrogen fuel-cells, and future trends in fuel and energy consumption.

As all curves were provided in the same functional form, it was straightforward to develop a single curve in the same form representing the average emission factor for all vehicles in the main ULEV category in a given year by weighting all the common coefficients according to the composition of the vehicle fleet in that year.

The aggregation spreadsheet tool provides a means to calculate emission curves for the main vehicle types. In summary, the emission curves developed take the 6th order polynomial form:

$$EF_y(v) = (A_y + B_y v + C_y v^2 + D_y v^3 + E_y v^4 + F_y v^5 + G_y v^6) / v \qquad (2)$$

The seven coefficients A-G for the main vehicle types in each year are weightings of the individual coefficients for the different constituent Euro standards and vehicle or engine sizes which make up the fleet according to the fractions in the fleet in the year. This is expressed mathematically in Equation 3 which shows how the coefficient A is calculated for a particular main vehicle category in year y:

$$A_y = \sum_e \sum_w k_{ew} a_{ew} R_{ye} S_{yw} \qquad (3)$$

R_{ye} is the fraction of vkm by vehicles of Euro standard e in year y.

S_{yw} is the fraction of vkm by vehicles of size or weight class w in year y.

k_{ew} and a_{ew} are the speed emission factor coefficients for vehicle of Euro standard e and size w within a main vehicle category.

Similar expressions can be derived for the other coefficients B-G by replacing the coefficient a_{ew} with the appropriate coefficient.

6.5 EMISSION CURVES FOR TRUCKS

The emission curves for HGVs are provided separately for the rigid and articulated HGV categories and the OGV1 and OGV2 HGV categories. The OGV1 category refers to rigid HGVs < 26 t gross vehicle weight (GVW) and OGV2 refers to rigid and articulated HGVs > 26 t GVW. The NAEI provides separately the composition of the rigid and articulated vehicle fleet by weight class. The NAEI also provides the total annual vehicle kilometres (vkm) travelled by rigid and articulated vehicles in past, current and future years. The fleet composition of OGV1 and OGV2 HGVs by is derived from the weight class compositions of rigid and articulated HGVs and the relative vkm of rigid and articulated HGVs on roads. These OGV1 and OGV2 fleet compositions were used with the Euro standard or generation compositions to weight the individual HGV curves by weight class, euro standard and generation for rigid and articulated HGVs and develop fleet-weighted emission curves for OGV1 and OGV2 HGVs.

6.6 USE OF THE EMISSION CURVES

The aggregation spreadsheet tool provided to DfT contains the coefficients A-G in equation (2) for calculating emission factors for each main ULEV type for the years 2015-2060 in five year intervals. The calculation of the coefficients for the fleet in each year is shown in the spreadsheet. All of the fleet-weighted speed emission curves have a valid speed range outside of which the curves should not be used. The speed range is defined by the available emission data and through assessment of the valid speed ranges of the fits used to compile the emission factor curves described in detail in Sections 3 and 4. Table 32 in Appendix C summarises the valid speed ranges of the speed emission curves. For speeds above the valid speed range it is recommended that the emission factor calculated at the maximum allowed speed is used and for speeds below the valid speed range the emission factor calculated at the minimum allowed speed should be used.

As noted in Section 6.1, to use these emission curves in the NTM, requires further weighting of the curves for aggregated ULEV categories, by proportion of vehicle kilometers for the different vehicles for different road or area types (London, Conurbations, other urban, rural and motorways). This additional aggregation step is not performed as part of this work.

7. NON-FUEL VEHICLE OPERATING COSTS (NFVOC)

7.1 INTRODUCTION

Non-Fuel Vehicle Operating costs (NFVOCs) are costs incurred by vehicle owners after purchase in order to operate and maintain the vehicle during normal use. The NFVOCs used in DfT's Transport Analysis Guidance (TAG) were last derived in the 1990s, and since then much has changed in terms of the composition and activity of the fleet. New powertrains have entered the market with fundamentally different cost profiles, while costs for the petrol and diesel variants that are still on the market have adapted as the capital cost profile of vehicles change, and as the behaviours of drivers change to meet new private and commercial needs. DfT therefore requires an update and extension of the existing assumptions in TAG around the costs to operate vehicles, in order to better reflect the current costs of operating vehicles.

Ricardo's approach to update these NFVOC estimates for combustion vehicles and create new estimates for Ultra Low Emission Vehicles (ULEVs) has been to:

1. Identify a set of cost parameters that reflects the non-fuel costs incurred by the current fleet
2. Identify available and recent data that capture these costs in the UK
3. Cross-validate these data with other UK data and relevant data from close neighbours (the European Union)
4. Establish a robust methodology to convert these underlying data into the units required by TAG (p/km), estimate costs for new powertrain types (where these are not available) and project all these costs out into the future.

The following sections outline the data needs and sources that were used in the updating of NFVOCs, the methodology used to convert those data in useable outputs, and finally the presentation of the outputs themselves. Here, we comment on key differences with the original estimates made in the 1990s.

A summary of the QA performed on the calculation model developed to provide the results is provided in Appendix D of this report.

7.2 DATA

The following Table 11 below shows the types of data Ricardo collected as part of this study and how it is used within the context of the model. Since ULEVs have not been on UK roads for very long, there are limited public data available on the running costs of hybrid, electric and fuel cell electric powertrains. Therefore using robust data for ICE vehicles was favoured as the starting point to derive estimates for ULEVs.

Table 11 Types of data collected for the estimation of NFVOCs

Parameter	Data Type	Relevant cost component	Description of use
A1	ICE vehicle maintenance costs	Maintenance	Used to derive ICE and ULEV costs
A1	ICE insurance premium costs	Insurance	Used to derive ICE and ULEV costs
A1	ICE tyre replacement costs	Tyres	Used to derive ICE and ULEV costs
A1	ICE depreciation costs	Depreciation	Used to derive ICE and ULEV costs
A1	Vehicle kms travelled per year	All	Used to convert annual costs into costs per km
A1	Projected share of vehicle stock by mode and segment	Insurance, Depreciation	Used to create a weighted average of relevant parameters across vehicle segments
A1, B1	ICE capital costs (current)	Insurance, Depreciation	Used to scale ULEV cost parameters that can be linked to the capital cost of the vehicle.

Parameter	Data Type	Relevant cost component	Description of use
A1, B1	Vehicle capital cost projections	Insurance, Depreciation	Used to create future projections for cost parameters that can be linked to the projected capital cost of the vehicle.
A1, B1	Price indices	All	Used to deflate source data prices

The operation and maintenance cost data are first presented below (in Section 7.2.1) in more detail, and then following this, the vehicle capital costs contributing towards the estimation of operation and maintenance costs for ULEVs and the future projections of cost factors are presented (in Section 7.2.2).

7.2.1 Operation and maintenance data

For passenger cars, data on maintenance and tyre costs were taken from a survey run by the Office for National Statistics on the average weekly household expenditure on goods and services in the UK (ONS, 2019), of which spending on vehicles is a part (see Table 12). This was then combined with an independent assessment of average car insurance premium costs made by the Association of British Insurers (ABI, 2023), and Ricardo's own assessment of UK average car depreciation (see Section 7.3.1.1 for more details).

Table 12 UK data for the operation and maintenance of cars (ONS, 2019)

Item	Description	Average weekly expenditure all households (£)
7.2.1	Spares and accessories	2.40
7.2.2	Petrol, diesel and other motor oils	21.50
7.2.3	Repairs and servicing	6.50
7.2.4	Other motoring costs	3.10
	Total	**32.5**

Regarding operating cost data for vans and heavy-duty vehicles (HDVs), two different sources were identified which estimated costs for vehicles operating in the UK for a variety of segments – the "Manager's Guide to Logistics" published by Logistics UK, a business group whose members operate more than half the UK road fleet (Logistics UK, 2019), and cost tables published by Motor Transport, a news organisation focusing on logistics for fleet operators (Motor Transport, 2021). These sources presented vehicle costs, annual standing costs and running costs for a variety of vehicle segments.

After adjusting for prices and converting into common units[5], these data were also compared with another industry source published by (Lastauto Omnibus, 2018), which provides widely used estimated operating costs for vehicles based in the EU (see Table 13). This dataset is considered the industry standard for estimating NFVOCs in the EU and has also been used in Ricardo's work for the European Commission, supporting analysis of impacts for revisions to the HDV CO2 regulations (not yet published). It was concluded that the UK datasets presented slightly different estimates from the EU, indicating the presence of location-specific factors and justifying exclusion of the EU estimates from our assumptions. As such, Ricardo take the mean of the two UK data sources where available as our base assumption for ICE vans and HDVs – this mean is shown in the far-right column in the below table. The authors also estimate annual costs associated with vehicle depreciation expressed on a per mile basis, but these are not reported below as these estimates comprise both time- and mileage-related depreciation, making their inclusion with other distance-related parameters misleading.

[5] Where annual costs are reported, we used the author's assumptions on annual mileage to convert to a pence/km figure.

Table 13 Comparison of operation and maintenance costs between data sources (Units: 2022 pence/km)

Segment	Variable	Lastauto Omnibus*	Motor transport	Logistics UK	UK average
3.5t Van	Maintenance	2.5	3.2	5.3	4.2
	Insurance	4.4	3.5	2.3	2.9
	Tyres	N/A	0.9	0.9	0.9
18t Rigid Box Lorry	Maintenance	6.4	5.5	6.8	6.2
	Insurance	3.4	2.5	3.3	2.9
	Tyres	N/A	1.8	1.7	1.7
44t Articulated Lorry	Maintenance	11.6	8.5	10.4	9.4
	Insurance	4.2	3.2	3.0	3.1
	Tyres	N/A	3.6	2.6	3.1

In the absence of available UK-specific data for PSVs (Passenger Service Vehicles – i.e. Buses and Coaches), available EU data for the operating costs of these vehicles has been used (Lastauto Omnibus, 2018). These are reported in the table below, having already been converted into pence/km figures.

Table 14 Assumed operation and maintenance costs for diesel PSVs (Lastauto Omnibus, 2018) (Units: 2022 pence/km)

Segment	Insurance	Maintenance	Tyres
12m SD Bus	5.1	23.2	4.2
M2 Mini Bus	0.8	3.6	1.5
Midi SD Bus	1.2	4.1	2.8
26t GVW SD Bus	5.1	23.2	5.2
28t GVW Artic SD Bus	5.1	23.2	5.6
19t GVW SD Coach	3.8	13.3	2.9
26t GVW DD Coach	3.8	13.3	3.7

*Notes: *SD / DD – Single / Double Decker*

7.2.2 Vehicle capital cost data

Regarding vehicle capital costs, information on the most current average prices of ICE vehicles by manufacturer was collected from readily available sources. For heavy duty vehicles, the averages of estimates by vehicle segment provided by (Motor Transport, 2021) and (Logistics UK, 2019) were used as the primary data source. Where UK data was lacking for a vehicle segment, data from the EU was used, as published by (Lastauto Omnibus, 2018). These data and assumptions are reported in Table 15 below. Petrol capital costs were also estimated where applicable based on Ricardo's detailed proprietary modelling on the costs of different powertrain types (discussed further below), but only diesel variants are reported in the table for brevity.

The Lastauto Omnibus data was based on European vehicles and has therefore been adjusted in three ways to improve consistency with UK figures:

1. To convert from EUR costs to GBP costs.
2. To adjust for prices since 2018 using GDP deflators (HM Treasury, 2023).
3. To account approximately for locational factors by applying a 'UK markup'. This markup was defined to reflect the average difference in price between UK and EU estimates where data were available from a UK data source and Lastauto Omnibus for the same vehicle segment, as an approximation.

Table 15 Comparison of diesel HGV and PSV capital cost estimates and assumed costs (Units: 2022£)

Mode	Segment	EU	Logistics UK	Motor Transport (UK)	Assumed cost	Underlying Assumption
Van	N2 Heavy (>3.5t GVW)	29,150	NE	NE	38,197	EU adjusted
Rigid Lorry	7t GVW Box	36,439	47,544	52,004	49,774	UK average
Rigid Lorry	10t GVW Box	40,083	NE	NE	52,522	EU adjusted
Rigid Lorry	12t GVW Box	45,184	NE	60,331	60,331	Motor Transport
Rigid Lorry	16t GVW Box	51,014	79,217	NE	79,217	Logistics UK
Rigid Lorry	18t GVW Box	57,857	79,217	78,062	79,217	Logistics UK
Rigid Lorry	26t GVW Box	73,398	NE	85,897	85,897	Motor Transport
Rigid Lorry	26t GVW Tipper/Box	73,398	NE	NE	96,177	EU adjusted
Rigid Lorry	32t GVW Tipper	102,029	NE	NE	133,693	EU adjusted
Rigid Lorry	32t GVW Tipper (8x4)	NE	NE	132,174	132,174	Motor Transport
Artic Lorry	32t GVW Box (4x2)	NE	NE	107,067	107,067	Motor Transport
Artic Lorry	40t GVW Box (4x2)	101,300	NE	108,249	108,249	Motor Transport
Artic Lorry	40t GVW Tipper/Box	108,240	NE	NE	141,833	EU adjusted
Artic Lorry	44t GVW Tipper/Box	NE	144,262	121,064	132,663	UK average
Bus	M2 Mini	29,150	NE	NE	38,197	EU adjusted
Bus	Midi SD	36,439	NE	NE	47,747	EU adjusted
Bus	12m SD	189,482	NE	NE	248,288	EU adjusted
Bus	26t GVW SD	240,236	NE	NE	314,793	EU adjusted
Bus	28t GVW Artic SD	258,716	NE	NE	339,008	EU adjusted
Coach	19t GVW SD	237,581	NE	NE	311,314	EU adjusted
Coach	26t GVW DD	338,881	NE	NE	444,053	EU adjusted

Notes: NE – Not estimated

Table 16 below presents our capital cost assumptions for cars and LGVs. For passenger cars, an average vehicle price disaggregated by vehicle segment was available from the European Vehicle Market Statistics Pocketbook, published by the International Council on Clean Transportation's (ICCT, 2018). This presents an average price for EU vehicles, which we then converted into GBP and adjusted for the change in vehicle prices using the CPI index for New Cars (ONS, 2023). These reference figures were also utilised in recent work supporting proposed revisions to CO_2 regulations for cars and vans (Ricardo et. al, 2019). Data for vans were taken from the available UK data sources previously mentioned (Motor Transport, 2021) (Logistics UK, 2019).

Table 16 Comparison of Car and LGV capital cost estimates and presentation of assumed costs (Units: 2022£)

Mode	Segment	EU	UK (Logistics UK)	UK (Motor Transport)	Assumed cost, £	Notes
Car	Small	10,411	NE	NE	12,183	EU adjusted
Car	Lower Medium	16,535	NE	NE	19,350	EU adjusted
Car	Upper Medium	24,497	NE	NE	28,666	EU adjusted
Car	Large	36,745	NE	NE	43,000	EU adjusted
Van	N1 Small/Class I	12,827	NE	18,101	18,101	Motor Transport
Van	N1 Medium/Class II	17,054	NE	18,362	18,362	Motor Transport
Van	N1 Large/Class III	26,601	30,536	26,153	28,344	Average of Logistics UK and Motor Transport

Notes: Definitions for European LDV classes as defined in (Ricardo et. al, 2016): For passenger cars: Small = Segment A+B, Medium = Segment C, Upper Medium = Segment D, Large = other segments. For vans, Small = <1.8 GVW, Medium =1.8GVW - <2.5 GVW, Large = 2.5 GVW – 3.5 GVW.

The future costs of ULEV powertrains are uncertain, and the pace of technical and cost improvement in these has been rapid in recent years – particularly for battery technology (mainly in light-duty vehicle applications), but also for other xEV components. These technologies are not yet mature, and in some cases significant further improvements in performance and costs are still expected beyond 2030. Therefore, these merited also a more detailed and systematic approach compared to the other technical options already discussed.

Ricardo has previously developed a sophisticated and dynamically adjustable modular approach to characterise the baseline and future performance of different powertrain options for a vehicle life-cycle assessment (LCA) project for the European Commission's DG CLIMA (Ricardo et al., 2020), which was also used in similar recent work for DfT (Ricardo, 2022). This methodology calculates the size of the required vehicle components based on key reference vehicle powertrain parameters, including energy consumption per km, peak power, engine capacity, etc. This modelling framework has also recently been further updated and expanded by Ricardo to enable the calculation of the CAPEX costs for different vehicle and powertrain types for LDVs and HDVs. This work was completed during projects for DG CLIMA providing support to their impact assessment for proposed revisions to the post-2020 CO_2 regulations for cars and vans (Ricardo et al., 2021 forthcoming), and also in similar work to inform proposed amendments to the HDV CO_2 regulations (Ricardo et al., 2023 forthcoming). Outputs from Ricardo's proprietary modelling of the baseline costs and performance of different vehicle/powertrain combinations have been used in this study to calculate the likely variation in current and future insurance (see Section 7.3.1.1) and depreciation costs (see Section 7.3.1.3) for this study for different ULEV powertrain types vs conventional diesel/gasoline ICEV equivalents.

7.2.3 Vehicle activity data

Data on large van and HDV mileage is consistent with Ricardo's work for the European Commission, supporting analysis of impacts for revisions to the HDV CO_2 regulations (not yet published) (Ricardo et al., 2023 forthcoming). Implicitly, it is assumed that vehicle mileage for HDVs in the EU is similar to distances travelled by UK vehicles. Vehicle mileage for cars were derived from UK Vehicle Mileage and Occupancy data (Department for Transport, 2022)[6]. Table 17 below presents our assumptions on vehicle activity in the UK – these are used to convert cost estimates made by other authors (for example, annual expenditure) into a per kilometre cost estimate as required in the Transport Analysis Guidance model.

[6] Data was taken from 2019 as the last year for which the Coronavirus pandemic did not affect vehicle activity. Mileage for the years 2020-2022 appeared significantly lower than the previous trend.

Table 17: Assumed vehicle mileage (Units: kilometres)

Mode/Class	Annual mileage, km
Cars	17,000
Vans (Class 0 ML)	58,000
OGV1 (3.5 - 7.5 tons)	58,000
OGV1 (7.5 - 16 tons)	59,333
OGV2 (16-32 tons)	103,000
Class 4	98,000
Class 9	108,000
Class 11	108,000
Class 16	60,000
OGV2 (>32 tons)	111,500
Buses	60,000
Coaches	96,000

Within transport modes, the split of the UK fleet by vehicle segment was derived from NAEI fleet projections for conventional (petrol and diesel) powertrains, consistent with those used in Section 6.2 Fleet Weighting factors by main ULEV class. These projections were adapted to fit vehicle segments for which cost data was available, as displayed in Table 18 below. It is assumed that ULEV vehicles will conform to a similar split, and that this remains constant over time.

Table 18: Weighting factors used to group cost estimates into representative vehicle modes (Units: per cent)

Mode	Fuel Type	Segment	HD Vehicle Group***	Weighting, %
Car*	Diesel	Lower Medium	N/A	100%
Car*	Petrol	Lower Medium	N/A	100%
Van	Diesel	Small Van	N/A	6%
		Medium Van	N/A	26%
		Large Van	N/A	68%
Van	Petrol	Small Van	N/A	17%
		Medium Van	N/A	21%
		Large Van	N/A	62%
OGV1 Rigid Lorry	Diesel	7t GVW Box	Group 0 ML	55%
		10t GVW Box	Group 1	12%
		12t GVW Box	Group 2	5%
		16t GVW Box	Group 3	14%
		18t GVW Box	Group 4	14%
OGV2 Rigid Lorry	Diesel	26t GVW Box	Group 9	31%
		26t GVW Tipper/Box	Group 11	20%
		32t GVW Tipper	Group 16	49%
OGV2 Artic Lorry**	Diesel	40t GVW Box (4x2)	Group 5	33%
		40t GVW Box (6x2)	Group 10	33%
		40t GVW Tipper/Box	Group 12	33%
Bus	Diesel	12m SD	P31	23%
		M2 Mini	P0 LB	16%
		Midi SD	P0 MB	16%
		26t GVW SD	P33	23%
		28t GVW Artic SD	P35	23%
Coach**	Diesel	19t GVW SD	P32	50%

Mode	Fuel Type	Segment	HD Vehicle Group***	Weighting, %
		26t GVW DD	P34	50%

*Note: * cost estimates for lower medium cars are assumed representative of fleet average costs. ** where fleet projections were not available by segment, an even split was assumed between segments for which cost data was available. *** As defined in HDV certification regulations (European Union, 2023).*

7.3 METHODS

The overall structure of the estimation of NFVOCs has not changed to remain compatible with TAG and is combined in a formula of the form:

Equation 1: $$C = a1 + b1/V$$

Where:

- C = cost in pence per kilometre travelled,
- a1 is a parameter for distance related costs defined for each vehicle category, formerly comprising cost components like oil, tyres, maintenance, and depreciation (all assumed constant over time)
- b1 is a parameter for vehicle capital saving defined for each vehicle category (relevant only to working vehicles), and
- V = average link speed in kilometres per hour.

The following sections are separated into the a1 and b1 parameters, where we outline our methodology on how these were estimated.

7.3.1 Parameter a1: Distance-related costs

As agreed with DfT, Ricardo have developed a new set of 'cost components' that comprise the a1 parameter. The model below displays the cost components that have been estimated.

Equation 2: $$a1_{mpst} = Insurance_{mpst} + Maintenance_{mp} + Depreciation_{mpst} + Tyres_{mp} + BatteryFC_{mpst}$$

Where:

- *Insurance** = the annual premium paid to be covered by an insurer.
- *Maintenance* = the annual costs incurred to upkeep the vehicle, so that it continues running and passes MOTs (including AdBlue for HDVs).
- *Depreciation* = the fall in a vehicle's value after purchase as time passes and more distance is driven
- *Tyres* = the cost to replace a vehicle's tyres as they wear or pop.
- *BatteryFC** = the cost incurred to replace batteries and fuel cells in relevant vehicles (*if* anticipated to be needed in a typical vehicle lifetime, which is expected only for heavy duty vehicles).

*Notes: * new cost components additions since the original estimate was made.*

The subscripts denote that the relevant cost component varies between:

- *m* – Mode (Car, LGV, OGV1, PSV etc.).
- *p* – Powertrain (Diesel, PHEV, BEV etc.).
- *s* – Segment (size / tonnage).
- *t* – Time (i.e. the component is not assumed constant when projected into the future).

The assumptions underlying these subscripts are explored in the following subsections, where each component is addressed in turn. A notable omission from the above is a component addressing road Vehicle Excise Duty (VED) - it is understood that this is considered separately in TAG (i.e. VED is interpreted for appraisal purposes as relating to car ownership), and hence excluded from operating costs) and will be highly variable by vehicle, fuel and powertrain type.

7.3.1.1 Annual insurance costs

The updates and expansion of data for insurance costs was based on the following steps:

(1) Update insurance data for baseline conventional diesel vehicles *

(2) Interpolate/extrapolate diesel vehicle data to the other HDV categories (e.g. based on vehicle capital prices in Table 16). **

(3) Calculate equivalent maintenance & repair costs for other powertrain types* based on simplified assumptions for particular powertrain types **.
(4) Create a weighted average across segments using fleet projection data provided by DfT.

*Notes: * All data sources are listed in section 7.2.1 Operation and maintenance data; ** The method used to interpolate/extrapolate diesel insurance data to other diesel segments and to other powertrain types follows the logic outlined in Equation 3 below.*

It is difficult to make a reliable estimate of average insurance premia for ULEVs because the industry lacks claims data over a large number of years, contrary to ICE vehicles. However, a proportion of the premium can be linked to the capital cost of the vehicle (i.e. premia are higher for more expensive vehicles). Therefore, this was used to make estimates for these powertrains by using the difference in calculated capital costs between ULEV and conventional vehicles to derive ULEV insurance premia.

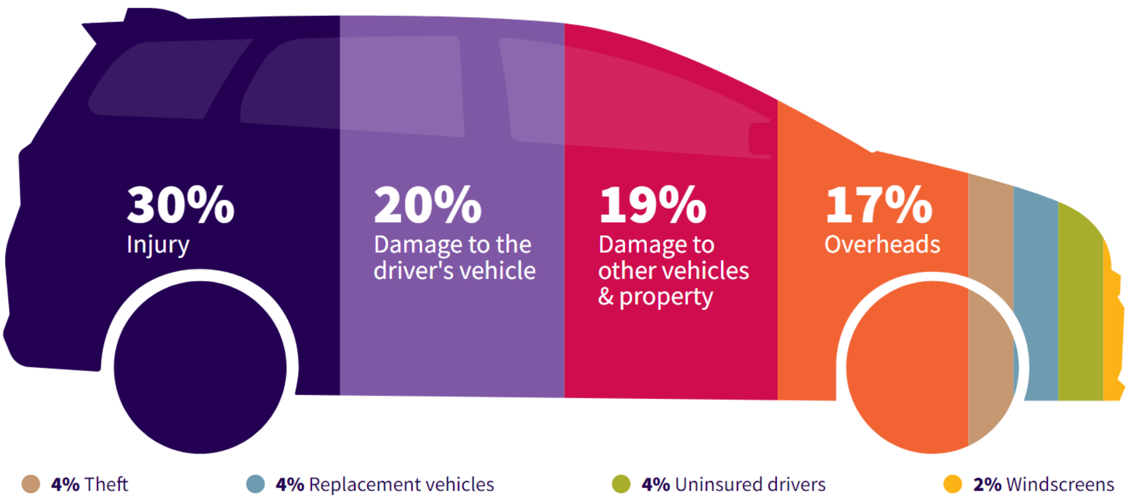
The methodology for estimating the insurance premium for ULEV variants is shown in the formula below. ICE insurance data is scaled by a ULEV markup, which is itself a multiple of two things: (1) the difference in the capital cost between the two vehicles, and (2) the share of the insurance premium that can be attributed to the capital cost of the vehicle (*CapitalShare)*. To calculate insurance premia in future years, $CapitalCost_{ULEV}$ is replaced by Ricardo's proprietary capital cost projections.

Equation 3: $Insurance_{ULEV} = Insurance_{ICE} * ULEVMarkup$, where:

$$ULEVMarkup = \frac{CapitalCost_{ULEV}}{CapitalCost_{ICE}} * CapitalShare$$

Figure 33 below shows the most recent publicly available breakdown of a car insurance premium for petrol and diesel cars provided by the Association of British Insurers for 2021 (ABI, 2021) [7]. Only the portion of the premium that can be linked to insurance claims is shown, but the authors also note that there is a 12% tax on the insurance premium, and a profit margin for the insurance companies in the 'single digits', varying by the provider. Aviva reported this margin to be around 8% of the total price paid by motorists in Britain in 2018 (Aviva, 2020), so this figure has been utilised as well in the absence other information. The cost of claims is therefore assumed to comprise 86% of the annual premium paid by British car motorists. Of this share, ~24% can be associated with the capital cost of the vehicle itself ('Damage to the driver's vehicle' + 'Theft'), implying that 21% of the total premium can be linked to the vehicle's own capital cost. In the absence of other sources, the same split is also assumed for drivers of LGVs.

Figure 33 Car insurance premium breakdown (ABI, 2021)



The capital share of premium was calculated in a similar way for lorries and buses based on an analysis of the liability and comprehensive insurance costs in (Lastauto Omnibus, 2018). Liability and comprehensive insurance were presented separately, where liability insurance covers the costs for repair/replacement of the

[7] The Association of British Insurers (ABI) is an organisation comprising over 200 member companies that include most household names and specialist providers in the UK.

first-party vehicle, whilst comprehensive insurance covers 3rd party costs. Similar to light duty vehicles, it is expected that therefore only the liability insurance component should change significantly for different vehicle types based on their relative cost. Table 19 below presents the assumptions used on the proportion of the annual insurance premium that can be linked to the capital cost of the first-party vehicle, which is based upon an analysis of data from (Lastauto Omnibus, 2018) on the liability and comprehensive insurance costs.

Table 19 Assumed share of insurance premium attributable to the capital cost of the vehicle

Mode	Value (%)
Car	19%
LGV	19%
OGV1/2, Rigid and Artic	30%
Bus and Coach	48%

7.3.1.2 *Annual maintenance costs*

The updates and expansion of data for maintenance costs was based on the following steps:

(1) Update of data for baseline conventional diesel vehicles*, for a range of different representative vehicle models **.

(2) Calculate the equivalent maintenance & repair costs for other powertrain types***, based upon simplified assumptions for particular powertrain types**.

Key assumptions are stated as follows:

* Baseline maintenance costs for diesel vehicles were updated using the data sources are listed in section 7.2.1 Operation and maintenance data. Since the estimate for cars relies on ONS survey data on typical household expenditure, we converted this into a pence/km figure by deriving an estimate for the average number of cars per household in the UK

** the representative vehicle models chosen for each mode of transport are shown in Table 20 below. All other segments in this mode were assumed to bear the same maintenance costs for ICE vehicles.

Table 20 Vehicle segments taken as representative of the mode for calculation of maintenance cost

Mode	Representative vehicle segment
Car	Lower Medium Car (i.e. UK market segment C)
LGV	N1 Large Van (i.e. Class III van, up to 3.5t GVW)
OGV1 Rigid	7t GVW
OGV2 Rigid	18t GVW
OGV2 Artic	40t GVW Tipper/Box
Bus	Estimated individually
Coach	19t GVW SD

*** Maintenance costs for ULEV powertrains are based on assumptions previously used by Ricardo to estimate costs in our work for the European Commission ((Ricardo et al., 2021 forthcoming), (Ricardo et al., 2023 forthcoming)) for the original maintenance datasets in (Lastauto Omnibus, 2018) – as summarised in Table 21 below. The assumptions for percentage reduction maintenance costs of BEV, FCEV and other ULEV powertrains (vs conventional diesel ICE) are also broadly in-line with the findings of (Kleiner, F. & Friedrich, H.E., 2017), which conducted a bottom-up analysis of the maintenance and repair cost components for different powertrain options for a number of different heavy truck categories.

Assumed proportionality of ULEV maintenance costs relative to conventional powertrains

Table 21 Assumed proportionality of ULEV maintenance costs relative to conventional powertrains

Mode	Value (%)
Conventional diesel, petrol and full hybrid vehicles	100%
Plug-in hybrid vehicles (including those with catenary systems)	90%
Fuel cell electric vehicles	80%
Battery electric vehicles (including those with catenary systems)	70%

7.3.1.3 Annual vehicle depreciation

The updates and expansion of data for vehicle depreciation costs that are purely attributable to distance was based on the following steps:

(1) Update data for baseline conventional diesel vehicles * for a range of different representative vehicle models. **

(2) Calculate proportionate depreciation costs for (a) other diesel-fuelled segments within the same mode of transport, and (b) other powertrain types using their relative capital cost. ***

Key assumptions are stated as follows:

* Baseline depreciation costs for diesel vehicles were updated to account for the change in vehicle capital costs since original estimation. For cars and vans, this was scaled in line with the CPI index for New Cars (ONS, 2023).[8] This methodology is consistent with the update for the b1 parameter (see Section 7.3.2), and therefore ensures the separability of mileage- and time-related depreciation. For HGVs and PSVs, these two components of depreciation were not considered separable in the original estimation, and depreciation was entirely accounted for in the b1 parameter. Ricardo adopt the same approach in this update.

** representative segments are consistent with those assumed in the estimation of maintenance costs, shown in Table 20.

*** scaling depreciation of segments for which we did not have data, including non-diesel powertrains, was done directly using a ratio of relative capital cost, calculated using a formula of the form:

Equation 4: $$Depreciation_{NonReference,t} = Depreciation_{Diesel,Reference,t} * \left(\frac{CapitalCost_{NonReference,t}}{CapitalCost_{Diesel,Reference,t}}\right)$$

Where *NonReference* refers to diesel segments where data is not available, or non-diesel powertrains, and *t* indicates that the capital ratio is taken using capital costs projected in the given year.

Despite the fact that a standard depreciation curve is steeper in the early years of a vehicle's life, with more of the vehicle's value lost over the first year as compared to a later year, mileage-related depreciation was assumed constant over time in this estimation for two reasons.

(1) Since there is no available data to indicate the contrary, it was assumed that the average age of the fleet remains constant in the time period considered. Adjusting for vehicle age would require making additional assumptions on the average age of the entire fleet.

(2) Fleet averages were taken for other cost parameters, meaning that this assumption maintains consistency across the entire NFVOC estimation (i.e. the UK fleet is comprised of vehicles across the entirety of the depreciation curve age profile).

7.3.1.4 Annual tyre replacement costs

As in previous sections, the updates and expansion of data for tyre costs was based on the following steps:

(1) Update data for baseline conventional diesel vehicles * for a range of different representative vehicle models. **

(2) Tyre replacement costs for other powertrain types are based on simplified assumptions for all powertrain types**.

Key assumptions are discussed below:

[8] The CPI Index for New Cars starts its time series in 1996, so we have spliced the index pre-1996 with the RPI index for Motoring Expenditure, which beings in 1987 (ONS, 2023)

* Baseline depreciation costs for diesel vehicles were updated using the data sources are listed in section 7.2.1 Operation and maintenance data

** representative segments are consistent with those assumed in the estimation of maintenance costs, shown in Table 20.

*** Tyre replacement costs are assumed constant over time for all vehicles.

In the absence of available data specifying a cost differential between ULEVs and conventional powertrains, Ricardo have opted to assume parity in annual tyre replacement costs across powertrains for vans, trucks and passenger vehicles. While there is an argument that tyre degradation should be higher for heavier vehicles and vehicles with higher torque (both characteristics of ULEV vehicles), leading to shorter-lasting tyres and increased tyre replacement cost over time, the increase in weight from the powertrain is low proportional to the vehicle's overall weight, implying a small impact on tyre degradation.

For cars, however, we use the PM_{10} emission factors reported in Table 7 to scale the replacement costs reported for conventional powertrains to ULEVs. Whilst airborne particles are a small proportion of overall tyre wear, and PM_{10} only a proportion of airborne particles, it was assessed that the difference in particulate emissions between powertrains should be broadly proportional to total tyre wear. The presence of this effect is confirmed through anecdotal evidence provided by the RAC that diesel taxis do tend to get an extra 5,000 to 10,000 miles of lifespan out of their front tyres relative to their EV counterpart (RAC, 2023), while rear tyres reportedly experience similar wear across electric and conventional powertrains.[9]

7.3.1.5 Battery or fuel cell replacement costs

For LDVS, fuel cell/battery costs are not included. It is generally accepted that with current technology, batteries and fuel cells are anticipated to last the lifetime of the vehicle for typical usage for LDVs (i.e. cars and vans up to 3.5t GVW). Therefore, these costs are assumed to be zero for relevant ULEV powertrain types. This assumption is also consistent with that made for Ricardo's prior work assessing the impacts of CO_2 regulations on cars and vans (Ricardo et. al, 2019), (Ricardo et al., 2021 forthcoming).

However, replacements costs are currently needed for HDVs (buses, coaches and lorries). HDVs operate over significantly higher lifetime distances, and so currently battery and fuel cell replacements (or refurbishments) are expected to be needed at least once in the vehicle lifetime in high-usage applications. However, in most applications only the original battery or fuel cell may be needed over the entire lifetime of the vehicle in future models (e.g. post-2030 or perhaps even earlier for some vehicle models/HDV types) depending on battery and FC technology improvements (i.e. in durability/lifetime) and larger battery capacities (i.e. requiring fewer cycles to power the vehicle the same distance).

The current and projected future costs of the batteries and/or fuel cells used for different HDV types/powertrains has been calculated as part of Ricardo's proprietary modelling of ULEV powertrain costs (briefly discussed in earlier Section 7.2.2). These costs have been used to calculate the typical (annualised) costs for a single replacement over the lifetime of the vehicle where relevant for different ULEVs.

7.3.2 Parameter b1: Vehicle capital saving

The b1 parameter essentially accounts for the rest of vehicle depreciation that is not directly attributable to mileage, i.e. time-related depreciation. This is therefore entirely separable from mileage-related depreciation as estimated in the a1 parameter. The 'vehicle capital saving' is named as such because it takes into account that working vehicles are not constantly in use during business hours. For example, cars can be left parked in the conduct of business and vehicles transporting goods can be idle while their contents are being loaded and unloaded from storage. This proportion of time spent idle was originally estimated as part of a review of vehicle operating costs in COBA (DETR, 1991). It was agreed with DfT that Ricardo would not derive a new methodology to estimate the vehicle capital saving, but rather adjust the figures used in TAG to account for the changing capital costs of UK vehicles as derived for the rest of the NFVOC estimation. Implicitly, this assumes that the proportion of vehicle working hours spent at rest remains the same as it was in 1991. A formula of the below form was used for this:

Equation 5: $$b1_{2022} = b1_{2010} * \left(\frac{GDPIndex_{1991}}{GDPIndex_{2010}}\right) * \left(\frac{CapitalPrice_{2022}}{CapitalPrice_{1991}}\right)$$

[9] The authors also note that EVs are often more expensive and come fitted with higher quality and longer lasting tyres at first purchase. This may offset some of the weight effect over the first years of the vehicle's lifetime.

Where:

- *GDPIndex* are GDP deflators (HM Treasury, 2023) used to put prices back to their original 1991 estimates, as it is our understanding that DfT have used the same index to inflate those estimates to the base year in TAG (2010 at time of writing).
- *CapitalPrice* is used to account for the increase in vehicle capital costs since 1991. Where possible, indices for new vehicle prices were used to make this adjustment – for cars and vans, the CPI index for New Cars was used (ONS, 2023). [10] For other modes of transport, vehicle price indices were not publicly available. Instead, an average vehicle capital price weighted across various segments was used. The capital costs used to derive the weighted average diesel vehicle costs are reported in Table 15 , and the methodology to derive ULEV capital prices is outlined in Section 7.2.2 for ULEV vehicles.

7.4 OUTPUTS

Table 22 presents the outputs of Ricardo's updates to the NFVOCs for vehicles operating in the UK, reporting both a1 and b1 parameters in the period 2022-2050. Prices are expressed in 2010 values to be consistent with the TAG model. General observable trends are discussed below, along with the causes of any disparities between these estimates and those currently used in the TAG model.

Table 22 Updated NFVOC parameter estimates

		a1, p/km, 2010 prices							b1, p/hr, 2010 prices
Mode	Powertrain	2022	2025	2030	2035	2040	2045	2050	2022
Car (Work)	Petrol	10.1	10.1	10.1	10.1	10.1	10.1	10.1	118.5
	Diesel	10.3	10.3	10.3	10.3	10.3	10.3	10.3	118.5
	BEV	11.9	11.2	10.9	10.7	10.6	10.6	10.6	163.8
	PHEV	11.5	11.1	11.0	10.9	10.8	10.8	10.8	147.2
	NPHEV	10.9	10.8	10.7	10.7	10.6	10.6	10.6	131.0
	FCEV	12.8	11.9	11.5	11.3	11.2	11.1	11.0	177.9
Car (Non-work)	Petrol	7.8	7.8	7.8	7.8	7.8	7.8	7.8	118.5
	Diesel	7.9	7.9	7.9	7.9	7.9	7.9	7.9	118.5
	BEV	8.6	8.2	8.0	7.9	7.9	7.9	7.8	163.8
	PHEV	8.5	8.3	8.2	8.2	8.1	8.1	8.1	147.2
	NPHEV	8.2	8.2	8.1	8.1	8.1	8.1	8.1	131.0
	FCEV	9.2	8.7	8.5	8.4	8.3	8.2	8.2	177.9
LGV	Petrol	6.7	6.7	6.7	6.7	6.7	6.7	6.7	41.1
	Diesel	6.8	6.8	6.8	6.8	6.8	6.8	6.8	41.1
	BEV	6.0	6.0	5.9	5.9	5.9	5.9	5.9	51.8
	PHEV	6.6	6.6	6.6	6.5	6.5	6.5	6.5	50.6
	FCEV	6.5	6.4	6.4	6.3	6.3	6.3	6.3	57.7
OGV1 Rigid	Diesel	8.0	8.0	8.0	8.0	8.0	8.0	8.0	371.7
	BEV	14.8	11.4	10.3	10.0	9.8	9.6	9.4	658.5
	PHEV	11.8	9.7	9.0	8.7	8.5	8.5	8.4	551.1
	FCEV	19.9	13.6	11.9	10.3	9.4	9.2	9.1	909.5
	BEV (catenary)	11.5	9.7	9.1	8.9	8.8	8.6	8.5	759.8
	PHEV (catenary)	12.4	10.6	10.0	9.8	9.7	9.6	9.4	759.8

[10] The CPI Index for New Cars starts its time series in 1996, so we have spliced the index pre-1996 with the RPI index for Motoring Expenditure, which beings in 1987 (ONS, 2023)

		a1, p/km, 2010 prices							b1, p/hr, 2010 prices
OGV2 Rigid	Diesel	8.6	8.6	8.6	8.6	8.6	8.6	8.6	712.1
	BEV	29.4	19.6	16.3	15.6	15.3	15.0	14.7	1626.9
	PHEV	14.8	11.6	10.5	10.1	9.8	9.7	9.6	1058.2
	FCEV	30.4	19.2	16.2	13.2	11.8	11.4	11.1	1889.8
	BEV (catenary)	11.5	9.7	9.2	8.9	8.9	8.7	8.6	843.9
	PHEV (catenary)	12.5	10.7	10.1	9.9	9.8	9.7	9.5	843.9
OGV2 Artic	Diesel	12.0	12.0	12.0	12.0	12.0	12.0	12.0	814.4
	BEV	35.3	25.9	22.9	20.9	19.9	19.2	18.5	2232.5
	PHEV	16.2	13.9	13.1	12.7	12.5	12.4	12.3	1179.0
	FCEV	25.4	18.1	16.1	14.3	13.3	13.1	12.9	2015.9
	BEV (catenary)	15.3	13.1	12.4	12.3	12.3	12.1	11.9	1177.4
	PHEV (catenary)	16.8	14.6	13.9	13.8	13.8	13.6	13.4	1177.4
Buses	Diesel	19.2	19.2	19.2	19.2	19.2	19.2	19.2	1356.5
	BEV	26.5	21.7	20.2	19.6	19.3	19.0	18.7	1812.7
	PHEV	25.3	22.8	22.0	21.2	20.7	20.5	20.3	1723.1
	FCEV	30.6	23.6	21.7	20.0	19.1	18.9	18.7	1978.4
Coaches	Diesel	15.7	15.7	15.7	15.7	15.7	15.7	15.7	2330.5
	BEV	26.8	20.5	18.4	17.9	17.7	17.5	17.3	3128.8
	PHEV	17.5	16.1	15.6	15.4	15.3	15.3	15.2	2555.7
	FCEV	29.9	21.8	19.6	17.4	16.4	16.1	15.9	3392.8

Regarding the a1 parameter, one can observe that variations in annual distance-related running costs can be significantly different between conventional ICE powertrains and ULEV powertrains in 2022. This due to three main reasons: the additional depreciation cost incurred due to the higher purchase price of the vehicles, the increased premium paid to insure the vehicle, and for relevant vehicle types, the additional cost incurred in any given year to replace the battery or fuel cell. Counteracting this effect are the assumptions that maintenance effects are lower for ULEVs, but this effect is smaller relative to those just mentioned.

The differential between conventional powertrains and ULEV powertrains is expected to fall over time as learning effects in vehicle production kick in and the cost to purchase ULEVs falls at a faster pace than conventional powertrains, also causing a reduction in fleet average depreciation costs and insurance premia. Tyre replacement costs and maintenance costs are assumed constant over time, meaning that they can help to explain the difference in running costs between modes of transport, but not the falling differential over time.

When we compare these estimates with those currently displayed in TAG (see Table 23 below), we can see that Ricardo's estimates are significantly higher than those previously estimated in 1991. For conventional powertrains, they are in the order 1.6 – 2.5 times higher per kilometre.

Table 23 TAG Table A 1.3.14: Non-Fuel Resource Vehicle Operating Costs (2010 prices and 2010 values)

Vehicle Category	Powertrain	Parameter Values	
		a1 p / km	b1 p / hr
Car	Work Petrol	4.966	135.946
	Work Diesel	4.966	135.946
	Work Electric	1.157	135.946
	Non-Work Petrol	3.846	0.000
	Non-Work Diesel	3.846	0.000
	Non-Work Electric	1.157	0.000

Vehicle Category	Powertrain	Parameter Values	
		a1 p / km	b1 p / hr
LGV	Work	7.213	47.113
	Work Electric	2.170	47.113
	Non-Work	7.213	0.000
	Non-Work Electric	2.170	0.000
OGV1	Work	6.714	263.817
OGV2	Work	13.061	508.525
PSV	Work	30.461	694.547

The primary reasons estimated to be the main causes for these differences are summarised as follows:

1. **Distance assumptions:** in 1991 it was assumed that an average passenger car travels 19,300 km per year for the first three years of its life, falling as the vehicle is owned longer. By contrast, data on vehicle mileage and occupancy collected via the UK National Travel survey indicates that the average lower medium segment car now travels only 11,900 km in a year[11] (Department for Transport, 2022). A large part of the variation in car distance-related operating costs can therefore be explained by changes in distance assumptions. Table 24 below shows that similarly, vehicle kilometre assumptions for light LGVs are at the extreme lower end of those assumed in 1991. By contrast, the assumptions for HGVs fall at the upper end of the 1991 range.

Table 24 Comparison of vehicle mileage assumptions between 1991 and this study

Mode	Assumed vehicle mileage per year (1991)	Assumed vehicle mileage per year (this study, 2022)
Car	19,300 km	11,900 km
LGV (light vans)	16,000 – 39,000 km	17,000 km
HGV (<24t GVW)	21,000 – 64,000 km	58,000 km
HGV (>24t GVW)	41,000 – 106,000 km	103,000 km

2. **Capital cost assumptions:** the capital cost data collected for conventional diesel vehicles during this study are greater than the capital costs assumed in the 1991 report when expressed in the same price levels. Table 25 below reports the data referenced in the 1991 report, converts them in the second column into 2022 prices using UK GDP deflators (HM Treasury, 2023), and then displays our assumed capital cost assumptions for the weighted average capital cost across the vehicle segments displayed in Table 20. This shows that for passenger cars, prices are not significantly different, whereas for heavy lorries and buses capital costs for vehicles have grown significantly higher than price levels from the initial 1991 assumptions. This would therefore reflect in the a1 parameter through higher depreciation costs and increased payments on insurance premia, and in the b1 parameter since these are adjusted directly via the relative capital price in 2022 versus the original estimation in 1988.

[11] This figure was taken from 2019 in order to avoid any confounding effects caused by the COVID pandemic, which reduced nationwide travel starting in 2020.

Table 25 Comparison of capital cost assumptions between 1991 and this study

Mode	Capital cost (1998 value, 1988 prices)	Capital cost (1998 value, 2022 prices)	Capital cost (2022 value, 2022 prices)
Car (Diesel)	£9,310	£23,682	£19,350
OGV1 Rigid	£16,460	£41,866	£58,986
OGV2 Rigid	£31,326	£79,679	£111,577

3. **Addition of insurance:** the original estimation of NFVOCs did not include a parameter to account for insurance, where our estimation does. These generally fall between 1-6 pence/km, rising with the capital cost of the vehicle (as explained in Section 7.3.1.1), and therefore represent an additive element, raising the NFVOC estimate for every road transport mode.

8. UNCERTAINTY ASSESSMENT OF ULEV EMISSION CURVES

The quantification of traffic emissions by the NTM and TAG using these speed-emission curves will have inherent uncertainties associated with them. Whilst it is not possible to quantify these, an understanding of the main uncertainties in the factors themselves and their limitations will help DfT understand the main factors contributing to these uncertainties in the NTM outputs. Our previous review of emission factors for ULEVs in 2015 explained that whilst there were uncertainties associated by fitting emission and energy factors to simple average speed-related polynomial equations, the largest source of uncertainties at the time were due to the paucity of 'real world' emission test data, partly a reflection of the fact that few examples of the different types of technologies were even available in the vehicle market. This meant that approximations and assumptions were widespread in our analysis to derive speed-related curves, with little hard evidence to back them up.

Since 2015, certain ULEV technologies have increased their market share, particularly in the case of HEV, PHEV and BEV types in the light duty fleet. This has meant that a larger amount of emissions and energy consumption test data now exists which has allowed more robust vehicle simulations over real-world test cycles in transient models such as PHEM. Data for heavy duty vehicles remain sparse by comparison, though more are available than in 2015, or at least a greater understanding of the factors that affect energy consumption to allow more robust relationships to be developed from physics and engineering considerations.

In our previous 2015 evaluation, the curves were developed from a number of sources including existing emission inventory guidebooks and models such as COPERT, data from manufacturers and literature and simulations using a limited set of PEMS data from vehicle tests in the UK. For this work, most of the data come from PHEM model simulations carried out by TU Graz from a more extensive set of vehicle test data on ULEVs available from sources in Europe. The PHEM model is used to derive the traffic-simulation based factors in the HBEFA model, which is widely used in Europe for road transport emissions inventories and models. The same pool of test data for conventional ICE vehicles is also the origin of the speed-related factors used in COPERT. The connection with these models and databases of emissions and energy consumption data therefore gives the polynomial equations developed here for the NTM and TAG a greater degree of provenance than our previous set of curves for ULEVs

There are several issues to consider on uncertainties of the ULEV speed curves which are of a general nature, while there are others that are specific to vehicle types and technologies, pollutant and emission sources. There are inherent uncertainties in the original test data which are unquantifiable and in the curve fitting process. There are also uncertainties associated with assumptions made, particularly for vehicle technologies that do not exist in the market other than perhaps as a prototype, but not yet in full production, and how emissions and efficiencies may improve for technologies in the future.

8.1 GENERAL OVERVIEW OF MAIN SOURCES OF UNCERTAINTIES

The following remarks are of a general nature and apply to all the speed curves developed:

- Where possible, the speed curves were developed from emission and energy consumption factors that originated from real-world measurements on in-service ULEVs, but still from a relatively small number of vehicles compared with the ICE vehicles. Since there can be differences in technological approaches between manufacturers within a ULEV class (e.g. for hybrid cars), the representativeness of the speed curves to the UK fleet can be questioned. However, we consider the situation to have improved since 2015 such that overall uncertainties for vehicles such as HEVs, PHEV and BEV light duty vehicles will have been much improved.

- Uncertainties in the PHEM simulations. The PHEM model is widely recognised in Europe as a mature, state-of-the-art vehicle simulation model, based on sound engineering and scientific principles, however any model is subject to uncertainties in its outputs.

- TU Graz provided data from PHEM for different traffic situations, as used in HBEFA and specific for this project the average speed of each traffic simulation so that speed curves could be developed. Different traffic situations may have the same average speed, but different emissions and energy consumption. TU Graz provided weighting factors that reflect the typical prevalence of a particular driving condition in Austria at a given average speed. It is not known how relevant to the UK such weightings will be. Further research will need to be carried out on UK traffic, although it is not felt that weightings are likely to be significantly different, hence are unlikely to be a major source of uncertainty.

- Average speed is a convenient, but fairly crude metric to represent the driving cycle of a vehicle and its effect on emissions. There are inherent uncertainties associated with relating an emission or energy consumption factor to average vehicle speed when a much wider set of conditions (acceleration, load etc) relating to driving style, road and traffic situation affect these. The variability in emissions and consumption at a given average speed will be reflected in the scatter of PHEM data used in the curve fitting. This factor is likely to be one of the largest sources of uncertainties

- There are uncertainties in forcing a statistical fit to a 6^{th} order polynomial equation.

- In general, the curves for NO_x and PM pollutant emissions will be much more uncertain than for energy consumption. This is the case for all vehicles, including ICE vehicles. Although recent European emission standards have set more stringent limits on emissions, pollutant emissions remain variable between model types, partly reflecting the range of technical solutions used by different manufacturers, but also their variability in performance and vehicle maintenance, particularly for vehicles fitted with exhaust aftertreatment systems in the case of HEVs and PHEVs. Energy consumption can be predicted with a greater amount of certainty due to engineering and physics principles.

- Assumptions in future performance. Existing ULEV technologies are expected to show improvements in future performance but it can be uncertain as to how significant these will be. For HEV and PHEV vehicles, future emission standards such as proposed Euro 7 regulations may affect NO_x and PM exhaust emissions, as well as non-exhaust sources of PM. There may also be improvements in battery efficiencies, range and durability that will affect the speed curves for future BEVs, FCEVs and PHEVs

- Vehicle turnover used to develop the fleet weightings. The NTM and TAG require individual curves for future years and each ULEV type that represent the vehicle fleets of the future. This needs to take into account the sale of new vehicles and fleet turnover to derive the proportions of vehicle kilometres done by each vehicle sub-category (e.g. Euro standard or generation). This has been done using Ricardo's fleet turnover model which was developed for use in the NAEI in combination with DfT's forecast in new vehicle sales for certain vehicle types. This was limited to HEVs, PHEVs and BEVs for light duty vehicles. For other vehicle types, default assumptions have been made which DfT can change in the spreadsheet provided to carry out the fleet weightings, e.g. on the uptake of new generation BEVs

8.2 ULEV SPECIFIC UNCERTAINTIES

8.2.1 Petrol and Diesel HEV Cars and LGVs

A major uncertainty for this ULEV type is with regards the factors developed for NO_x and PM exhaust emissions and whether or not they are lower than the corresponding factors for a petrol ICE car/LGV. To be consistent across all ULEV types based on the data received from TU Graz we have adopted the more conservative HBEFA approach recommended by TU Graz that assumes that pollutant emissions in g/km are the same as for an equivalent ICE vehicle. This is because TU Graz believes there is currently insufficient evidence to show that factors are lower for HEV cars. This is contrary to COPERT which provides separate speed-emission curves for NOx and PM that show a significant reduction in emission factors relative to an ICE vehicle, particularly at low speeds. We contacted Emisia, the developers of COPERT, who stated that the COPERT curves were developed several years ago, based on actual vehicle measurements, which means they represent the emission behaviour of early hybrid models. Emisia acknowledged that they are unsure how representative these curves are for modern hybrids.

Ricardo's own evidence from roadside remote sensing measurements suggests that there might be some reduction in petrol hybrid NO_x emissions relative to an ICE on a g/km basis, but not as large as implied by COPERT. Furthermore, the remote sensing technique does not directly yield factors in g/km but in g/kg fuel so a direct comparison with an ICE is more difficult.

This matter clearly needs further investigation through carrying out more tests. The emission factors can be readily updated in the emission curves spreadsheet provided for the NTM and TAG when further evidence is available or if an alternative assumption is made for sensitivity tests, e.g. by adopting the curve reductions implied by COPERT.

The fleet weightings for HEVs in future years reflect the split in Euro classes (each having different emission factors, in line with those for ICE vehicles) according to vehicle kilometres travelled. This is based on the NAEI fleet turnover model and DfT assumptions on future new vehicle sales provided in December 2021. The uncertainties in the curves for future years therefore reflect the uncertainties in new vehicle sales and fleet turnover.

8.2.2 Petrol and Diesel PHEV Cars and LGVs

The emission factors for these vehicles in battery sustaining (engine) mode are assumed to be the same as for HEVs (and hence ICEs) so the remarks given above for those vehicles apply to PHEVs. The effect that switching between charge depleting and charge sustaining mode may have on the temperature of catalysts and diesel particulate filters and the resulting impact on NOx and PM emissions is uncertain. In battery depleting mode the energy consumption is assumed to be the same as for a BEV.

The overall factor for a PHEV depends on the utility factor assumed. This was discussed in Section 2.2.4 and there is likely to be some variability in utility factor that reflects the battery range and type of trip the vehicle is used on, with potentially lower utility factors applied to longer distance, highway driving associated with higher speeds compared with urban driving which might be associated with higher utility factor and lower speeds. The possibility of providing speed dependency to the utility factors (as well as the emission and energy consumption factors) was discussed with DfT but for now has not been included. However, the spreadsheet provided does allow the utility factor to be varied.

8.2.3 Car and LGV BEVs

The energy consumption curves for current generation BEVs are considered fairly robust, based on recent data from PHEM model simulations. The main source of uncertainty for these vehicle types is how battery efficiencies improve in future years and what the uptake of future generations of BEVs is likely to be. This is reflected in the curves for future years by assumptions made in improvements in energy consumption for future generations. It is assumed that the shape of the speed curves is unchanged, so a scaling is applied that affects consumption to the same extent at all speeds. The scaling is applied to new vehicles in a stepwise fashion in 5 year intervals. The scalings and years of introduction of each generation of BEVs and their uptake rates are based on expert judgement that is subject to uncertainties.

There is some additional uncertainty associated with the real-world uplift to take account of auxiliary power requirements which may be climate and season dependent.

8.2.4 Fuel cell cars and LGVs

The energy consumption for a FCEV is assumed to be the same as a BEV. However, fuel cell efficiencies are taken into account to determine the hydrogen consumption requirements. Since there are few FCEVs on the road, there will be uncertainties into the efficiency assumptions and also how they will change in future.

8.2.5 Non-Exhaust Emissions

Emission factors for PM from non-exhaust source are highly uncertain even for ICE vehicles. This is because they are difficult to measure and there has been, until recently, little drive to do so. Emissions can be highly variable and dependent on many factors, not just average speed, including driving style (this also applies to exhaust emissions), vehicle weight, load and road gradient, tyre and brake materials and system design, as well as environmental conditions such as the road surface and weather conditions. It is expected that non-exhaust emissions for ULEVs will differ from equivalent ICE vehicles, with possible increases in emissions due to increased vehicle weight offset by reductions for vehicles using regenerative braking. These differences have not been well-quantified, but the latest version of COPERT 5.6 does now provide emission factors with speed corrections for ICE (light and heavy duty vehicles) and HEVs, PHEVs and BEVs (light duty only). These have been adopted for this work but should be regarded as highly uncertain still. Work is underway to improve the evidence base for this source of PM emissions, which now exceed exhaust emissions of PM, including a research programme commissioned by DfT. It is currently too early for any findings from that study to be used for the development of these emission curves.

Uncertainties in the non-exhaust emission factors for HGVs and buses will be more uncertain than for light duty vehicles and it is not possible to propose alternative factors for different types of ULEVs. Emissions for ULEV types of HDVs may differ from ICE equivalents less than for light duty vehicle because of potentially smaller changes in vehicle weight, but regenerative braking is likely to have a strong influence.

8.2.6 Non-Fuel Vehicle Operating Costs (NFVOC)

For NFVOCs, the main uncertainties relate to the quality of the available data sources, and the lack of real-world data on NFVOCs of ULEVs. For conventional powertrains, with the exception of passenger cars, there are no statistical datasets available for NFVOCs for other vehicle types, so datasets are based on industry estimates (although these are often widely used). NFVOCs for other powertrain types/ULEVs are based on a variety of methods (as documented), including Ricardo's own bottom-up calculations of powertrain costs for different vehicle types, and how these might be projected to change in the future. Other than for cars, tyre costs are assumed to be similar for all powertrain types, in the absence of clear data to suggest they might be significantly different for ULEVs vs conventional vehicles. For passenger cars, as an approximation it has been assumed that the wear rates vary proportionally with the defined tyre/brake wear rates reported in Table 7 of this report, with the significant uncertainties also still attached to these figures (as noted in the preceding sub-section).

9. SUMMARY AND CONCLUSIONS

9.1 SPEED EMISSION AND ENERGY CONSUMPTION CURVES FOR ULEVS

In 2015, Ricardo developed a set of speed emission/energy consumption curves for a range of ultra-low emission vehicle technologies for use in the NTM and TAG. Since this time the UK fleet has continued to evolve with new technologies entering the fleet and the evidence on emissions and energy consumption for ULEVs has further developed. In this study updated speed emission curves for ULEVs have been developed that reflect the latest evidence on ULEV technologies in or beginning to enter the UK fleet.

The main source of emissions data for this study was from detailed simulations from PHEM. PHEM simulations are designed to be representative of the European vehicle fleet and are underpinned by vehicle measurements. The model outputs provided average speed, tailpipe emission factors of NOx and PM and energy or fuel consumption for over 300 traffic situations for each vehicle type. Speed emission and energy curves were developed by polynomial fits to the data of the form required by the NTM and TAG. The PHEM simulations provided speed related energy consumption data for BEVs and NOx, PM and fuel consumption data for hybrid vehicles, though the NOx and PM factors for HEVs were assumed to be the same as for equivalent ICE vehicles provided from PHEM simulations. These were the core technologies that provided the basis of the curve fitting for all other ULEV technologies. Table 26 summarises the methodology to develop speed emission curves for the ULEV classes in this study.

Table 26 Summary of the methodologies to develop speed emission and energy curves for ULEVs.

Vehicle class	ULEV technology	Methodology
Car, van	Petrol HEV	Polynomial fit to PHEM simulations. NOx and PM curves were derived from PHEM simulations for ICE vehicles, while fuel consumption was derived for specific simulations for HEVs.
Car, van, bus	Diesel HEV	Polynomial fit to PHEM simulations. NOx and PM curves were derived from PHEM simulations for ICE vehicles, while fuel consumption was derived for specific simulations for HEVs.
Car, van, truck, bus, coach	BEV	Polynomial fit to PHEM simulations of battery to wheel EC for BEV, uplifted to account for grid to battery charging losses. Apply future trends in EC derived from previous Ricardo work.
Car, van	Petrol PHEV	NOx, PM and FC are based on curves for petrol HEVs (charge sustaining mode) and EC is derived from BEV EC curves (charge depleting mode). Curves for charge sustaining and charge depleting mode are weighted by utility factor. Apply future trends in EC and FC derived from previous Ricardo work
Car, van, truck, bus, coach	Diesel PHEV	NOx, PM and FC are based on curves for diesel HEVs (charge sustaining mode) and EC is derived from BEV EC curves (charge depleting mode). Curves for charge sustaining and charge depleting mode are weighted by utility factor. Apply future trends in EC and FC derived from previous Ricardo work
Car, van, truck, bus, coach	HFCV	Based on battery to wheel EC curve for BEV, uplifted to account for fuel-cell energy requirement and losses. Apply future trends in EC derived from previous Ricardo work
Truck	Catenary BEV	Based on battery to wheel EC curve for BEV. Uplift the EC to account for grid to battery charging losses when driving off the battery and in-motion energy losses when operating from the catenary system. Account for the relative share of driving between the external catenary system and battery.

Vehicle class	ULEV technology	Methodology
		Apply future trends in EC derived from previous Ricardo work
Truck	Catenary PHEV	NOx and PM emissions and diesel FC are based on curves for diesel hybrid trucks. Electric EC based on battery to wheel EC curve for BEV, uplift the EC to account for grid to battery charging losses when driving off the battery and in-motion energy losses when operating from the catenary system. Curves are weighted to account for the relative share of driving between the external catenary system, battery and diesel fuel. Apply future trends in EC derived from previous Ricardo work

A set of speed emission/energy curves were developed for each main ULEV category which when combined with year specific fleet compositional data on the mix of Euro standards, vehicle generations, and weight classes yield fleet-average exhaust emission or energy consumption factors for each ULEV type in-5 year intervals from 2015 to 2060.

The following key assumptions were made during the development of the speed emission/energy curves:

- NOx and PM speed emission curves for HEVs and PHEV operating in a charge sustaining (fuel) mode were assumed to be the same as for ICE vehicles, consistent with the approach taken in HBEFA
- Speed emission/energy curves for PHEVs were assumed to be a combination of speed NOx and PM emission and fuel consumption curves for HEVs when operating in charge sustaining (fuel use) mode, and electric energy consumption for BEVs when operating in a charge depleting.
- The recommended utility factors for PHEVs were assumed to show no speed dependence.
- PHEM simulations for BEV and PHEV HGVs were only available for a limited set of HGV size classes. Energy and fuel consumption curves for all other size classes of BEV and PHEV HGVs were developed on the assumption that the relationship between the energy and fuel consumption curves and HGV size class for BEV and PHEV HGVs was the same as for ICE HGVs.
- Fuel consumption curves for PHEV coaches operating in a charge sustaining mode were not available from the PHEM model. The operation of coaches was assumed to be similar to rigid HGVs, so fuel consumption curves for PHEV coaches were estimated based on the fuel consumption data available for rigid HGVs. The ratio between the PHEV fuel consumption and diesel fuel consumption curves for 14-16t rigid HGVs was applied to the fuel consumption curves for conventional diesel coaches to derive fuel consumption curves for PHEV coaches.
- Hydrogen fuel-cell vehicles were assumed to behave like a BEV (i.e. energy and hydrogen consumption shows the same speed dependence as a BEV). Account was taken of the additional energy losses associated with using a fuel cell to power a vehicle.
- Petrol and diesel HEV cars and vans were assumed to show no improvement in fuel consumption in future years. Future improvements in energy and fuel consumption of BEVs, PHEVs, HFCVs and catenary BEV HGVs were assumed and accounted for.
- Catenary BEV and PHEV trucks are not yet used in the UK and the vkm share assignment to each power mode (ERS/battery/fuel engine) is highly uncertain and dependent on the length of catenary system and usage patterns of the trucks. Default assumptions of the vkm shares are provided, but these should be updated once more evidence becomes available.
- When weighting the ULEV curves according to the fleet composition, the proportion of ULEVs by size class were assumed to be the same as the weight classes for ICE vehicles in the NAEI fleet projections.

Alongside this report, a spreadsheet aggregation tool has been provided to DfT to enable the calculation of fleet weighted emission and energy consumption curves for each of the main ULEV classes in each required year. The aggregation spreadsheet tool provides flexibility to update curves for different fleet assumptions and scenarios and as new information becomes available since fleet composition data and various scaling factors are inputs to the tool. The spreadsheet includes documentation to assist the user in updating the input data and details of QA/QC activities undertaken to check the quality and calculation of the fleet weighted emission/energy curves that are output by the tool.

Non-exhaust emission factors for PM emissions from brake and tyre wear and road abrasion have been provided that are consistent with the latest non-exhaust emission factors from the EMEP/EEA Inventory Guidebook. Non-exhaust emission factors are provided by vehicle class under urban, rural and motorway driving conditions.

In the 2015 study, limited data was available for most ULEV classes, and the curves were developed from a number of sources including existing emission inventory guidebooks, and models such as COPERT, data from manufacturers and literature and simulations using a limited set of PEMS data from vehicle tests in the UK. In this study, all of the curves developed were derived from PHEM simulations carried out by TU Graz that incorporate a more extensive set of vehicle test data on ULEVs available in Europe. The curves developed in this work therefore have a greater degree of provenance than the previous set of curves for ULEVs and should offer improved consistency between ULEV classes. None-the-less, the speed emission/energy curves developed have inherent uncertainties associated with them. The main factors contributing to the uncertainties are:

- Representativeness of vehicle test data used to calibrate the PHEM model - there are still relatively few ULEV vehicles compared to ICE vehicles which will contribute to uncertainties in the curves developed. The evidence is more robust and improved for HEV and BEV light duty vehicles which are more numerous in the fleet, but PHEV and BEV heavy duty vehicles are still emerging technologies and there is greater uncertainty in the curves developed for heavy duty vehicles.
- Uncertainties in fits to model – the PHEM simulations are for numerous traffic situations and fits are weighted by the prevalence of traffic situations. UK specific weightings were not available and instead fits are based on weightings provide by TU Graz for Austria. Forcing a statistical fit to a 6th order polynomial equation will also lead to uncertainties. It is not felt that either of these factors will be a major source of uncertainties.
- Use of average speed curves - average speed is a fairly crude metric to represent the driving cycle and its effect on emissions and this is likely to be one of the larges sources of uncertainty.
- Assumptions about future performance – there is uncertainty around how technologies will change. For HEV and PHEVs, future emission standards such as Euro 7/VII may affect NOx and PM exhaust emissions as well as non-exhaust sources of PM.
- Vehicle turnover used to develop fleet weightings - the NAEI fleet-turnover model provides fleet compositions by Euro standard/generation for HEV and PHEV light duty vehicles only. Fleet weightings were not available for other new and emerging ULEV classes. The aggregation tool provides default fleet figures, but with the capability to input fleet weightings once data becomes available.
- NOx and PM speed emission curves for HEV and PHEVs – in this study, NOx and PM exhaust emissions are assumed to be the same as for an ICE vehicle, consistent with the approach in HBEFA and recommendations by TU Graz. However, COPERT and the 2015 study provide separate speed emission curves for petrol HEV and PHEV light duty vehicles that show a reduction in emissions. This is a major source of uncertainty for these ULEV types.

Overall, the curves developed in this study incorporate the latest evidence on emissions and energy consumption from ULEVs. We recommend that all of the emission and energy curves developed are periodically revisited as more vehicles enter the UK fleet, more vehicle test data becomes available and improved real-world evidence of the impact of driver behaviour becomes available. Non-exhaust emissions are highly uncertain even for ICE vehicles and we recommend that evidence from the ongoing DfT brake and tyre wear project is reviewed as this project matures.

9.2 NON-FUEL VEHICLE OPERATING COSTS (NFVOC)

In the 1990s, a set of Non-Fuel Vehicle Operating costs (NFVOCs) were estimated for conventional petrol and diesel powertrains for use in Transport Analysis Guidance (TAG). Since then, much has changed in terms of the composition and activity of the fleet – new ULEV powertrains have entered the market with different cost profiles to conventional powertrains, and the behaviour of the fleet has changed, affecting also the cost profile of conventional powertrains. In this study, updated NFVOCs have been developed that reflect the latest evidence on costs for conventional powertrains, and a new set of NFVOCs have been developed to estimate the costs for ULEVs.

Ricardo identified a set of cost parameters that reflects the non-fuel costs incurred by the current fleet and used recent and available industry data sources to capture these costs in the UK. A robust methodology was developed to convert the author's units into the pence/kilometre format required in the TAG model, and costs for different vehicle segments were weighted into representative vehicle categories using NAEI fleet projections. These costs were also projected out to 2050, based on Ricardo's analysis of future cost reduction potential for ULEV powertrains. Table 27 summarises the methodology used to estimate the NFVOCs for each of the cost parameters.

Table 27: Summary of methodology used to update NFVOC estimates for the UK fleet

Cost factor	Methodology
Distance-related cost factors	
Insurance*	Conventional powertrains updated based on recent UK data. ULEV powertrains estimated by deriving a relationship between insurance premia and the capital cost differential between ULEVs and conventional powertrains.
Maintenance	Conventional powertrains updated based on recent UK data. ULEV powertrains estimated by scaling down conventional powertrain maintenance, due to the reduction in mechanical wear.
Tyre replacement	Conventional powertrains updated based on recent UK data. ULEV powertrains scaled from conventional powertrains based on typical relative tyre wear (assumed to correlate with the PM10 particulate emission factors for these).
Depreciation	Original distance-related depreciation estimates from 1990 scaled according to capital cost developments for all powertrains.
Battery or fuel cell replacement*	Estimated for certain ULEV powertrains and HDV types based on proprietary bottom-up capital cost estimations (no replacements are anticipated for LDVs in typical use).
Time-related cost factors	
Working vehicle capital saving	Original time-related depreciation estimates from 1990 scaled according to capital cost developments for all powertrains.

*Note: * new costs parameters added since original NFVOC estimation.*

This study has two main conclusions:

- **NFVOCs for conventional powertrains have risen substantially in the UK since their original estimation.** Analysis of the different assumptions used between the studies indicates that that there are three main reasons for this increase: differences in vehicle mileage assumptions, capital prices developing at a different rate to GDP deflators, and the addition of the insurance cost factor.
- **NFVOCs are higher for ULEVs compared to conventional powertrains**. This is primarily due to relative capital costs: distance-related depreciation and insurance costs are higher, outweighing the reduction in maintenance costs due to fewer moving mechanical parts. This difference is greater for HDVs, which are assumed to require battery or fuel cell replacement in their lifetime for relevant powertrains. The cost differential to conventional powertrains is, however, expected to fall over time as high initial ULEV purchase costs fall due to learning effects in the production.

In summary, this study uses the latest evidence to inform updates and new estimates of NFVOCs for ULEVS. There are inherent uncertainties in this estimation of NFVOCs, most notably a reliance on industry cost estimates for operating costs of conventional powertrains, and the lack of real-world data on operating costs for ULEVs. We recommend that these figures be updated as new evidence comes to light on the operational costs of ULEVs: in particular, the upcoming Zero Emission Road Freight Demonstrator (Innovate UK KTN, 2022) projects (announcements pending) should provide sound operational data for the largest heavy goods vehicles.

GLOSSARY

Term	Description
Artic Lorry	Lorry where tractor and trailer are distinct
BEV	Battery electric vehicle
Catenary	Vehicles equipped with a pantograph for connection with overhead wires supplying electricity
CO_2	Carbon dioxide
COBA	Cost-benefit analysis
DD	Double decker (bus/coach)
Drive cycle	A drive cycle represents a set vehicle speed points versus time and is used to provide a standardised assessment of fuel consumption
EC	Energy consumption (expressed in units of kWh/km)
ERS	Catenary HGVs can be powered by an external electric road system (ERS) that supplies electric power to the vehicle through overhead power lines
FC	Fuel consumption (expressed in units of g/km)
FCEV	Fuel cell electric vehicle
GVW	Gross vehicle weight (tonnage)
HDV	Heavy-duty vehicle
HGV	Heavy goods vehicle (collective term for freight vehicles, OGV1 and OGV2)
ICE	Internal combustion engine
LDV	Light-duty vehicle
LGV	Light goods vehicle (vehicles less than 3.5 tonnes GVW, typically vans)
NAEI	UK National Atmospheric Emissions Inventory
NFVOC	Non-fuel vehicle operating costs
NO_x	The sum of nitric oxide (NO) and nitrogen dioxide (NO_2), with the mass expressed based on the molecular weight of nitrogen dioxide
NPHEV or HEV	Non plug-in hybrid electric vehicle
NTM	DfT's National Transport Model
OGV1	Other goods vehicle (vehicles with 2-3 axles)
OGV2	Other goods vehicle (vehicles with 4 or more axles)
PHEM	The Passenger Car and Heavy Duty Emission Model, an instantaneous emission model developed by TU Graz
PHEV	Plug-in hybrid electric vehicle
PM	Particulate matter
PSV	Public service vehicle (buses and coaches)
Rigid Lorry	Lorry where tractor and trailer are fixed securely
SD	Single decker (bus/coach)
TAG	Transport analysis guidance

Term	Description
UF	Utility factor that defines the fraction of vehicle kilometres driven by PHEVs in electric (charge depleting) mode
ULEV	Ultra-low emission vehicle

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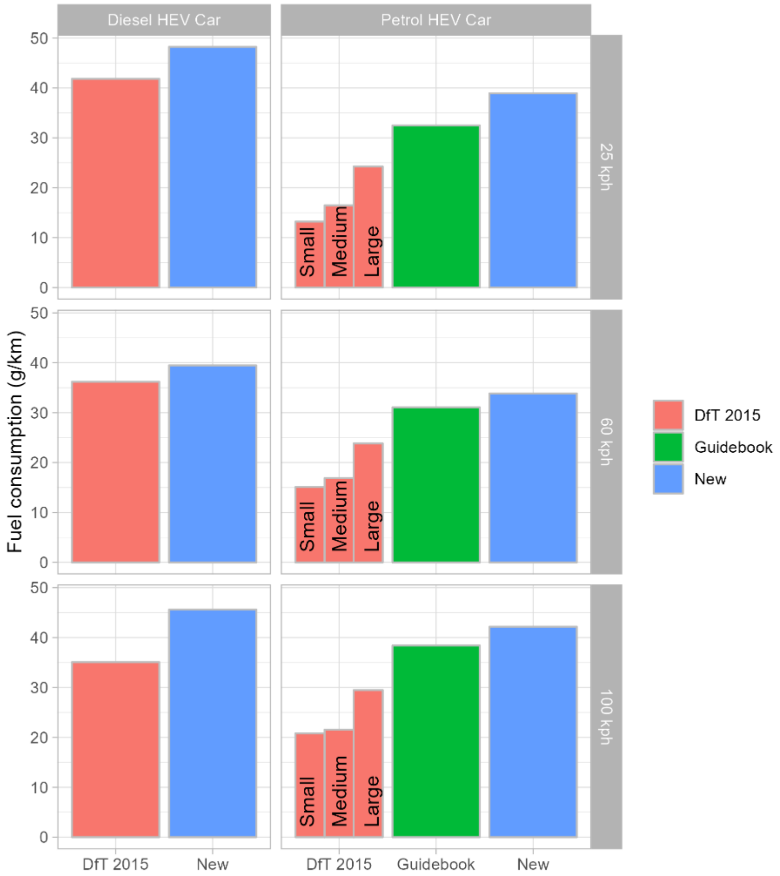
APPENDICES

APPENDIX A – PLOTS COMPARING SPEED FUEL/ENERGY CURVES DEVELOPED WITH ALTERNATIVE DATA

The data presented in the sections provides a comparison between the speed fuel/energy consumption curves developed in the work with other available sources of data. The two data sources reviewed were the EMEP/EEA Inventory Guidebook and the previous 2015 DfT study to develop speed emission/energy curves for ULEVs. The comparison focussed on petrol HEVs, diesel HEVs and BEVs, the core vehicle technologies that were the basis of curves for all other technologies. Of these technologies, the Guidebook provides data for petrol HEV cars only. The 2015 ULEV study provides data for petrol and diesel HEV cars and vans[12], and BEV cars, vans and small trucks (rigid trucks <7.5t and 7.5-12t).

Figure 34 Comparison between fuel consumption factors for diesel and petrol HEV cars from the 2015 study (DfT 2015), the Guidebook (consistent with COPERT 5.6) and from this study (New) at three speeds (25 kph, 60 kph and 100 kph).



[12] The fuel consumption factors for petrol and diesel HEVs from the 2015 ULEV study that are presented in the plots are for Euro 6 vehicles.

Figure 35 Comparison between fuel consumption factors for diesel and petrol HEV vans from the 2015 study (DfT 2015) and from this study (New) at three speeds (25 kph, 60 kph and 100 kph).

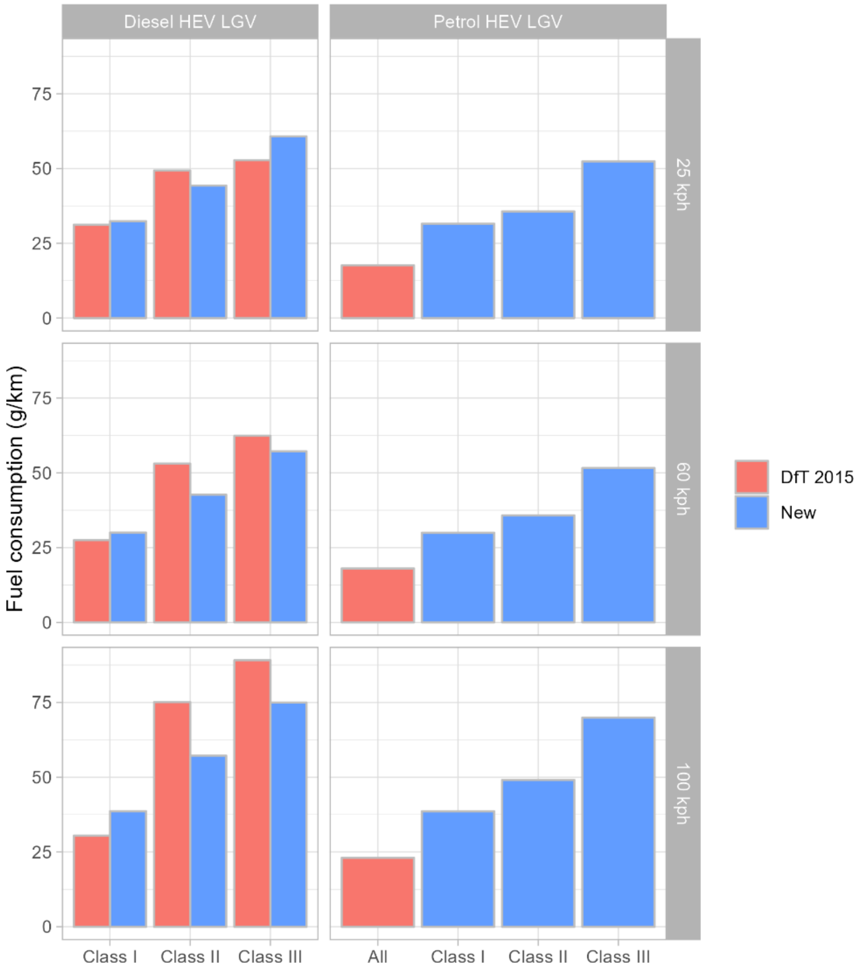


Figure 36 Comparison between energy consumption factors for BEV cars from the 2015 study (DfT 2015) and from this study (New) at three speeds (25 kph, 60 kph and 100 kph).

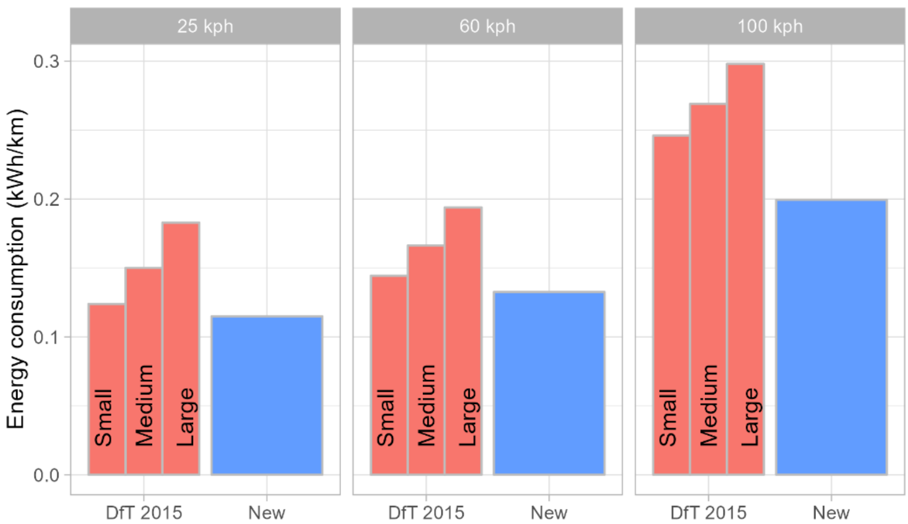


Figure 37 Comparison between energy consumption factors for BEV vans by size class from the 2015 study (DfT 2015) and from this study (New) at three speeds (25 kph, 60 kph and 100 kph).

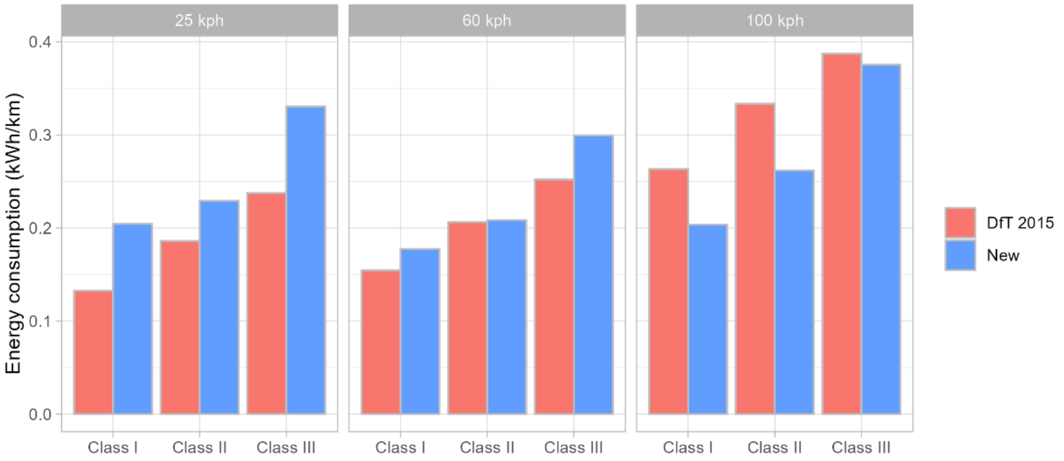
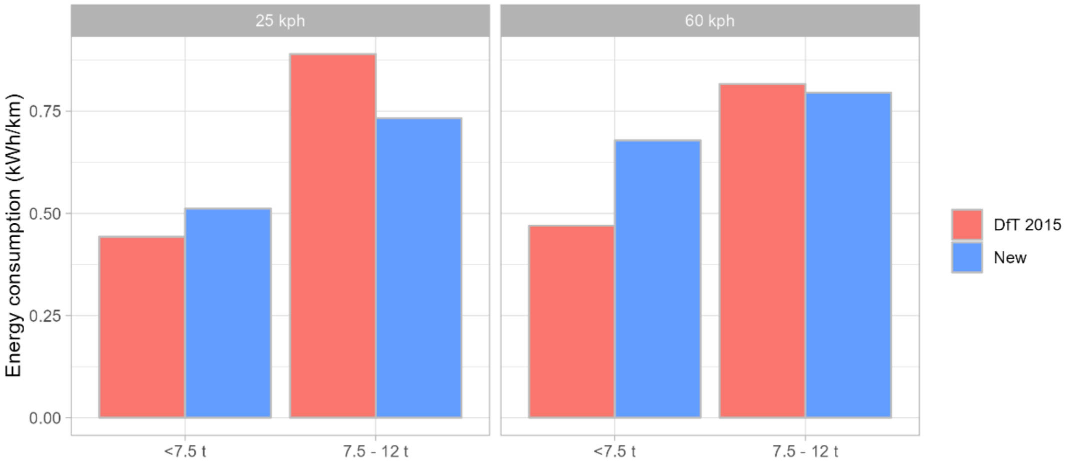


Figure 38 Comparison between energy consumption factors for BEV small trucks by size class from the 2015 study (DfT 2015) and from this study (New) at two speeds (25 kph and 60 kph).



APPENDIX B - FLEET WEIGHTING FACTORS

Table 28, Table 29 and Table 30 summarise the Euro standards, generations and vehicle size categories for which weighting factors are split by within each ULEV category.

Many ULEV classes are new and emerging technologies, and these vehicles are not yet considered in the NAEI fleet projections. Table 31 indicates which ULEV fleet weightings are coming from the NAEI fleet projections. For other ULEV vehicles, Euro standard, generation and vehicle size weighting factors were not available.

Default assumptions for the fleet weighting factors, in some cases coming from the NAEI fleet projections (Table 31), are provided in the aggregation tool provided to DfT. The vehicle fleet compositions for each ULEV class split by Euro standard and generation are provided in the 'Fleet mix' tab of the tool, and the proportion of vehicles by weight class for each ULEV are provided in the 'Size mix' tab. If alternative data becomes available, the assumptions can be updated in the spreadsheet. Where data on Euro standard or Generation fleet weighting factors were not available from the NAEI, simple default factors are provided, but these factors are not necessarily realistic and it is recommended that they are updated.

Table 28 Euro standard, generation and vehicle size categories for ULEV cars

<table>
<tr><th>ULEV category</th><th>Euro standard</th><th>Generation</th><th>Sizes</th></tr>
<tr><td>Petrol HEV</td><td>Euro 3 – 6d</td><td rowspan="6">GEN 2020
GEN 2025
GEN 2030
GEN 2035
GEN 2040
GEN 2045
GEN 2050</td><td rowspan="6">One size</td></tr>
<tr><td>Diesel HEV</td><td>Euro 3 – 6d</td></tr>
<tr><td>Petrol PHEV</td><td>Euro 3 – 6d</td></tr>
<tr><td>Diesel PHEV</td><td>Euro 3 – 6d</td></tr>
<tr><td>BEV</td><td>N/A</td></tr>
<tr><td>Hydrogen</td><td>N/A</td></tr>
</table>

Table 29 Euro standard, generation and vehicle size categories for ULEV LGVs

<table>
<tr><th>ULEV category</th><th>Euro standard</th><th>Generation</th><th>Sizes</th></tr>
<tr><td>Petrol HEV</td><td>Euro 3 – 6d</td><td rowspan="6">GEN 2020
GEN 2025
GEN 2030
GEN 2035
GEN 2040
GEN 2045
GEN 2050</td><td rowspan="6">Class I, II and III</td></tr>
<tr><td>Diesel HEV</td><td>Euro 3 – 6d</td></tr>
<tr><td>Petrol PHEV</td><td>Euro 3 – 6d</td></tr>
<tr><td>Diesel PHEV</td><td>Euro 3 – 6d</td></tr>
<tr><td>BEV</td><td>N/A</td></tr>
<tr><td>Hydrogen</td><td>N/A</td></tr>
</table>

Table 30 Euro standard, generation and vehicle size categories for ULEV HDVs

<table>
<tr><th>ULEV category</th><th>Euro standard</th><th>Generation</th><th>Sizes</th></tr>
<tr><td>Diesel HEV Buses</td><td>Euro V-EGR, SCR and Euro VI-ABC, D</td><td>GEN EUV
GEN 2020
GEN 2025
GEN 2030
GEN 2035
GEN 2040</td><td><15t
15-18t
>18t</td></tr>
</table>

ULEV category	Euro standard	Generation	Sizes
		GEN 2045 GEN 2050	
Diesel PHEV Buses	Euro V-EGR, SCR and Euro VI-ABC, D	GEN 2020 GEN 2025 GEN 2030 GEN 2035 GEN 2040 GEN 2045 GEN 2050	
BEV Buses	N/A		
HFCV Buses	N/A		
Diesel PHEV Coaches	Euro V-EGR, SCR and Euro VI-ABC, D	GEN 2020 GEN 2025 GEN 2030 GEN 2035 GEN 2040 GEN 2045 GEN 2050	15-18t <18t
BEV Coaches	N/A		
HFCV Coaches	N/A		
BEV Rigid Trucks	N/A	GEN 2020 GEN 2025 GEN 2030 GEN 2035 GEN 2040 GEN 2045 GEN 2050	3.5-7.5 t 7.5-12 t 12-14 t 14-20 t 20-26 t 26-28 t 28-32 t >32 t
Diesel PHEV Rigid Trucks	Euro V-EGR, SCR and Euro VI-ABC, D		
BEV Catenary Rigid Trucks	N/A		
Diesel PHEV Catenary Rigid Trucks	Euro V-EGR, SCR and Euro VI-ABC, D		
HFCV Rigid Trucks	N/A		
BEV Articulated Trucks	N/A	GEN 2020 GEN 2025 GEN 2030 GEN 2035 GEN 2040 GEN 2045 GEN 2050	14-20 t 20-28 t 28-34 t 34-40 t 40-50 t 50-60 t >60t
Diesel PHEV Articulated Trucks	Euro V-EGR, SCR and Euro VI-ABC, D		
BEV Catenary Articulated Trucks	N/A		
Diesel PHEV Catenary Articulated Trucks	Euro V-EGR, SCR and Euro VI-ABC, D		
HFCV Articulated Trucks	N/A		

Table 31 Summary of whether the ULEV fleet weightings are coming from the NAEI fleet projections or factors are not available

ULEV category	Included in NAEI fleet projections
Petrol HEV cars	✓
Diesel HEV cars	✓
Petrol PHEV cars	✓
Diesel PHEV cars	✗
BEV cars	✓
Hydrogen cars	✗
Petrol HEV LGVs	✗
Diesel HEV LGVs	✗
Petrol PHEV LGVs	✗
Diesel PHEV LGVs	✓
BEV LGVs	✓
Hydrogen LGVs	✗
Diesel HEV Buses(a)	✓
Diesel PHEV Buses	✗
BEV Buses	✗
HFCV Buses	✗
Diesel PHEV Coaches	✗
BEV Coaches	✗
HFCV Coaches	✗
BEV Rigid Trucks	✗
Diesel PHEV Rigid Trucks	✗
BEV Catenary Rigid Trucks	✗
Diesel PHEV Catenary Rigid Trucks	✗
HFCV Rigid Trucks	✗
BEV Articulated Trucks	✗
Diesel PHEV Articulated Trucks	✗
BEV Catenary Articulated Trucks	✗
Diesel PHEV Catenary Articulated Trucks	✗
HFCV Articulated Trucks	✗

(a) The HEV bus fleet composition provided in the accompanying spreadsheet was developed from the NAEI fleet data for diesel buses, but restricting the fleet to include buses that meet Euro V or Euro VI emission standards only. Thus, the fleet was developed assuming that the sales and turnover of HEV buses follow the same trends as for diesel buses. If specific data on the HEV bus fleet becomes available, it is recommended that the default fleet assumptions in the spreadsheet are updated.

APPENDIX C – VALID SPEED RANGES OF SPEED EMISSION CURVES

Table 32 summarises the valid speed ranges over which the speed emission, fuel and energy curves should be used.

Table 32 Valid speed ranges for speed emission, fuel and energy curves

Vehicle type	Valid speed range				
	FC/CO_2	NO_x	PM	Electricity	Hydrogen
Petrol HEV car	5-130	5-130	5-130		
Diesel HEV car	5-130	5-130	5-130		
Petrol PHEV car	5-130	5-130	5-130	5-130	
Diesel PHEV car	5-130	5-130	5-130	5-130	
BEV car				5-130	
HFCV car					5-130
Petrol HEV LGV	5-130	5-130	10-120		
Diesel HEV LGV	5-130	5-130	5-120		
Petrol PHEV LGV	5-130	5-130	10-120	5-130	
Diesel PHEV LGV	5-130	5-130	5-120	5-130	
BEV LGV				5-130	
HFCV LGV					5-130
PHEV truck	8-86	5-86	5-86	8-86	
BEV truck				8-86	
Catenary BEV truck				8-86	
Catenary PHEV truck	8-86	5-86	5-86	8-86	
HFCV truck					8-86
HEV bus	5-65	5-65	5-65		
PHEV bus	5-65	5-65	5-65	5-65	
BEV bus				5-65	
HFCV bus					5-65
PHEV coach	5-86	5-100	5-100	5-100	
BEV coach				5-100	
HFCV coach					5-100

APPENDIX D – MODEL QA FOR CALCULATION OF NFVOCS

This appendix provides an overview of the QA process applied for the calculation of NFVOCs for this project.

Ricardo's approach to performing model QA/QC checks has been shaped by our work for BEIS on models that inform the NAEI. The framework we have adopted is founded on five principles, and our audits involve inspecting models for how they perform against criteria related to these five following categories:

1. Documentation
2. Clarity and Structure
3. Verification
4. Validation
5. Data and Assumptions

Depending on the QA level defined for the model, shaped by the objectives and use-case for the model, a greater or lesser emphasis/expectation is set for a range of criteria under these categories. In this case the model was developed primarily to provide outputs (i.e. NFVOCs by vehicle category and powertrain type) for this project, and was not intended for reuse. Therefore, the QA review focused on ensuring the robustness of the data and assumptions, the calculation methodology employed and the correctness of the model formulae used to provide the outputs. Aside from clear model version control and simple explanatory comments within the Excel model itself, the documentation requirements were agreed internally to be minimal prior to the model development.

Ricardo's modelling template (used as a basis for the calculations for NFVOCs) provides the structure and formatting to facilitate model development to more easily and consistently meet targeted model QA requirements across these different categories. In addition, when conducting the QA/QC review, we have used Ricardo's bespoke QA toolbar to facilitate the review of the model particularly from the perspective of methodology and formula correctness, clarity and structure. The following sections provide a summary of the assessment conducted under each category. The model, the data, assumptions and methodology were all reviewed and agreed with Ricardo's Head of Vehicle Technology and Fuels, who has over 23 years in this topic area and has led the development and QA review of many complex models, including those produced for UK Government (e.g. by Ricardo under the NAEI contract, and also model's developed previously be DfT).

DOCUMENTATION

Good documentation allows the developer to keep track of the all the QA procedures that must be and have been carried out. It is also important to have documentation that enables the model to be transferred to another analyst, shared with external parties and/or audited.

The model developed to calculate updated NMVOCs was relatively simple, and was not designed to be re-used, only to provide outputs for the project task. Therefore, the documentation requirements were assessed to be minimal. Documentation for the model is therefore limited to model version control, with simple explanatory material on the content, basis and sources of data within the model, and some basic explanations for key data and calculations. No formal scope, specification or user guides have been produced for the model.

STRUCTURE AND CLARITY

Models should be built in a transparent and logical fashion, and inputs, calculations & outputs should be easily identifiable and correctly labelled with units. Calculations should follow a logical structured flow. The use of unnamed constants and variables should be avoided.

Following the initial QA review of the model, it was concluded that the overall layout of the model was reasonably clear, however a number of recommendations were made to improve the logical flow and better document the transfer of data between different tables and worksheets, also to improve audibility. In cases where unnamed constants and variables were used in calculations, these were in most cases removed and replaced with defined names and referenced cells for specific assumptions to improve clarity and reduce the likelihood of errors. The quality and quantity of documentation was deemed to be sufficient for this relatively simple model and for the defined use case.

VERIFICATION

All formulae should be reviewed to verify that the model has been correctly implemented, and that they are robust and work as intended. A good model should be free of formula errors and include automatic checks on data inputs & outputs to prevent inaccurate results.

As indicated earlier, Ricardo conducted a detailed review of the formulae and methodology in the model, facilitated by the use our bespoke QA toolbar. During the initial review of the model, it was concluded that some of the formulae were not robust, and we made some changes to address this. The model does not provide automatic checks on data inputs and outputs for out of range values, however these are not viewed to be important given the model is not intended to be reused, only to provide outputs for this project. These outputs have been carefully reviewed by our senior sustainable transport experts to ensure they are valid/correct based on the data and methodology developed. Additional (simpler) reviews/checks were also conducted following changes made to the model during the finalisation of the project (i.e. after the submission of the draft report and results, and the full model QA review).

VALIDATION

A model can implement equations perfectly with no errors, but if the underlying methodology is incorrect, then it is unlikely to be fit for purpose. Hence it is important to review the methodology, and validate its operation using sensitivity, extreme and/or reperformance testing, and historical data. Where no historical data are available to test the model, ideally its outputs should be triangulated (i.e. cross-checked) against the results from other comparable models, and opinion sought on its accuracy and relevance from several subject matter experts.

As part of this project, Ricardo's senior experts in this area reviewed the model's methodology and outputs and compared it with the previous TAG dataset, and also results of similar modelling exercises. The use of sensitivities and extreme value testing was not deemed to be necessary in this case.

DATA & ASSUMPTIONS

It is important to ensure that all data sets used are correctly sourced and assumptions are clearly stated and reviewed with stakeholders. It is also essential to check that there are no errors in importing or transforming data, and that data transformations are clearly documented.

A simple data log has been provided within the model itself, including information on public (and internal) data sources used in the calculations, which are also documented in this report. The data sources used and methodology was also discussed and agreed with Ricardo's technical leader in this area and with DfT during the course of the project. As part of this project, we have also identified some potential weaknesses and provided in the report some suggestions as to possible improvements in the future, should additional/more robust data become available. During the QA process our QA reviewer made appropriate checks to ensure input data/assumptions were correct/aligned with the original sources, and that the transformations (or aggregations) made were clear and documented where appropriate.

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