REVIEW OF $PM_{2.5}$ REDUCTION TECHNOLOGIES FOR ON ROAD TRANSPORT

Horizon Scanning Report

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EXECUTIVE SUMMARY

Road transport emissions of particulate matter comprise of exhaust and non-exhaust emissions (NEE). NEE include brake wear, tyre wear, road surface wear, and the re-suspension of road dust. The UK National Atmospheric Emissions Inventory (NAEI) estimated emissions for $PM_{2.5}$ (particles with a diameter of 2.5 micrometres or less) from road transport in 2021 were 10.7 kilo tonnes (kt) in 2021. This is a decrease of 64% since 1990, primarily due to reduction in $PM_{2.5}$ emissions from exhausts, as new euro limits were implemented and technologies introduced as standard, for example diesel particle filters (DPFs). However, over the same period $PM_{2.5}$ from brake and tyre wear has increased by 18% and road abrasion by 15%, due to the increase in traffic volumes and heavier vehicles on the road. $PM_{2.5}$ emissions are of particular concern as these fine particles can penetrate deep into the lungs, potentially causing health issues. As the proportion of electric vehicles in the UK fleet increases (with zero tailpipe emissions), the importance of NEE will also increase. In addition, even though exhaust emissions have decreased over the years, most vehicles on the road today are internal combustion engine (ICE) vehicles, therefore exhaust emissions still contribute to airborne $PM_{2.5}$.

For this study, a horizon scanning review of current and future technologies for mitigating $PM_{2.5}$ from road transport was undertaken. The review considered technologies that focused on preventative measures to reduce emissions of $PM_{2.5}$ and those that targeted active removal of $PM_{2.5}$ from the source. The outcomes from the review presented in this report are based on available literature, including peer-reviewed journal articles, theses, patents, reports, and manufacturer websites along with stakeholder interviews and in house knowledge.

From the horizon scanning review it was found that there are a number of manufacturers and companies that are developing technologies that have the potential to mitigate $PM_{2.5}$ emissions from road transport. The technologies broadly fitted into the following groups:

- Brakes, including brake design and materials, and the use of regenerative braking systems
- Tyre design and materials
- On-board particle capture devices
- Control of exhaust emissions, including engine design, fuels/lubricants and aftertreatment technologies
- Roadside technologies

The technologies considered in the report were assessed against the following criteria:

- Potential for mitigating $PM_{2.5}$
- Technology readiness level (TRL)
- Feasibility of implementation
- Maintenance requirements
- Cost of implementation

An overview of the findings for each of the technology groups is summarised below.

New materials for **brakes** are being tested and implemented to reduce wear and increase the lifespan of the components, with the benefit of a reduction in particle emissions. Emissions reductions are being driven by expected limits from Euro 7 [1]. Non-asbestos organic (NAO) pads have the potential to reduce $PM_{2.5}$ emissions (~20%-65%) compared to low/semi-metallic pads, but while widely used in America and Japan, these are not considered suitable for European applications as braking capability is also reduced. Manufacturers are therefore currently investigating hybrid NAO/low-metallic pads, combining reduced wear with good braking performance through new developments in friction materials. These may be matched to low-wear formulations of Grey Cast Iron (GCI) discs such as those developed by Brembo, together offering a moderate reduction in emissions suitable for current production vehicles (including retrofitting) for a relatively small cost increase over existing brake components, and available in the near future.

Brake disc coatings using ceramic-metallic compounds such as tungsten-carbide show potential for significantly reducing disc wear and achieving $PM_{2.5}$ emission reductions of up to 80%, depending on the drive cycle, paired with suitably matched pad materials. Laser cladding is a favoured coating technology although other developing technologies also show promise. Coated discs are fitted to some performance vehicles already although high costs may limit their adoption for smaller and cheaper vehicles.

Regenerative braking system (RBS) have been around for many years and although primarily fitted to electric vehicles as standard, they are also used in hybrid and fuel cell vehicles. Instead of using friction to brake, RBS use magnetic resistance in the electric motor, and the energy recovered from the braking can be stored in the onboard batteries. The benefit of RBS is that $PM_{2.5}$ emissions are also reduced. The amount of PM reduction depends on the drive cycle and how much regeneration is used. Studies have shown $PM_{2.5}$ reductions in the region of 50-80%, when compared to friction braking, however there are also studies that show the benefits are regenerative braking are outweighed by the total increase in NEE due to the increase in weight of electric vehicles. Therefore, a combination of low emission brakes, and tyres with RBS may be required to fully see the benefits.

Reducing PM emissions from **tyres** is challenging as the emissions are related to the wear rate, and reducing the wear rate can result in a negative impact on tyre performance (fuel efficiency and safety). There have been some developments in this area, however, with silica, nanoclay and butadiene rubber being potential materials that could be incorporated into the tyre manufacturer process to improve wear resistance. ENSO is one company who have developed a tyre that has a total mass emission reduction of > 30%. These tyres are currently in production for use by van fleets and London taxis.

On-board capture devices are systems that are installed on the vehicle and designed to capture and filter particles emitted from brakes and tyres at source, as the vehicle is moving. For brakes, both passive (filters around the brakes) and active (using suction to transport the particles to a collection area) particle capture systems are in development. Two such devices by MANN+HUMMEL and Tallano are currently in pilot/commercial deployment stages, with high potential for mitigating $PM_{2.5}$ (~60-80% reduction in brake wear emissions). Systems for capturing tyre particles are less developed, however one such system from The Tyre Collective is undergoing testing in pilot studies. The device uses electrostatic plates to attract particles as they are emitted from the tyre and has the potential of capturing 20-80% of tyre wear $PM_{2.5}$ emitted. All on-board capture systems will likely need to be retrofitted to vehicles, with costs in the region of a few hundred pounds. There is also maintenance required to change filters, which can vary from monthly to every 2 years depending on the device and levels of particles captured. Other on-board designs include filtering devices that fit onto the roof or front grill of vehicles (typically buses or commercial vehicles) which filter the particles within the ambient air, to offset emissions from the vehicle itself. The potential for $PM_{2.5}$ reduction in this case depends on ambient $PM_{2.5}$ concentrations.

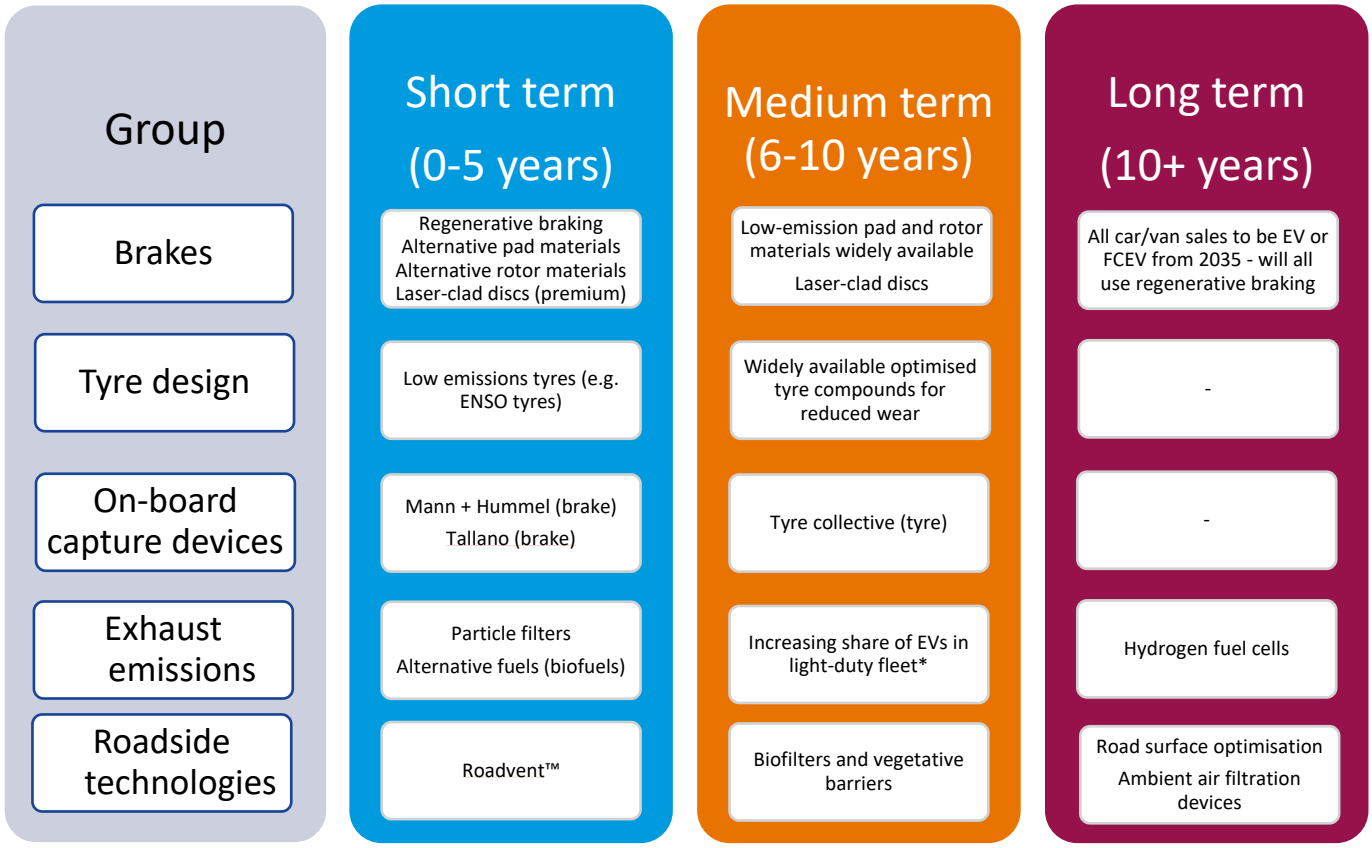
After treatment technologies for reducing particulate matter from **exhausts** are now fitted as standard to ICE vehicles. These include diesel oxidation catalyst (DOC) diesel particulate filter (DPF), and gasoline particulate filter (GPF). In addition, aftertreatment technology that focuses on removing gases (three-way catalyst, selective catalytic reduction, diesel oxidation catalyst, and lean NOx trap) can also help mitigate $PM_{2.5}$, through the reduction of PM precursors. To further reduce $PM_{2.5}$ emissions from exhausts alternative fuels may be used. Studies have shown that paraffinic diesel fuels and low carbon fuels can reduce PM emissions. Some fuels such as oxymethylene methyl ethers (OME) have the potential for even further reductions, but these are still in the development stage. To remove particles from exhausts completely, hydrogen fuel cells will completely remove PM emissions from the exhaust.

Roadside technologies focus on a general removal of PM from the roadside rather than the removal of particles from specific sources, such as brakes and tyres.

Active systems typically include high powered suction devices to pull in polluted ambient air and which then passes through a series of filtration devices before exhausting the clean air. Their potential for mitigating $PM_{2.5}$ from road transport depends highly on the filtration efficiency and the ambient levels. These devices may be situated on the pavement beside high traffic areas, or in the case of Roadvent™ by Pollution Solutions, embedded into the road surface. The costs of these systems can be in the region of £10,000s-£100,000, therefore are likely to only be implemented in on a small section of road areas where there are idling vehicles.

Non active devices such as vegetative barriers, and alternative road surfaces that can capture particles have also shown some potential for reducing $PM_{2.5}$, with studies showing removal efficiencies between of around 20%-80% for vegetative barriers (the higher end is for active biofilters) and 50% for a double layered porous asphalt road surface. Similarly to the active systems, due to the cost and effort in implementing these solutions, it is likely that only small sections of road will be targeted. Dust suppression via street cleaning, sweeping, washing or applying chemical suppressants to the roads have also been used to reduce resuspension of particles. However, these methods do not remove the particles completely.

The figure below summarises the different technologies and their potential for implementation in the short-, medium-, and long-term.



*UK Policy: New sales of light duty vehicles to be 100% zero-emission (ZE, EV or hydrogen FCEV) from 2035, 80% by 2030, according to "ZEV mandate".

Truck sales to be 100% ZE from 2035 (up to 26 tonne) or 2040, city buses possibly from around 2030

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GLOSSARY

Term	Meaning/expansion
µm	Micrometre (10^{-6}m)
6PPD	A chemical compound used for stabilising rubber in tyres
APS	Atmospheric plasma spray
ASC	Ammonia slip catalyst
BPWCS	Brake pad waste collection system
CFD	Computational fluid dynamics
CGDS	Cold gas dynamic spray
CGI	Grey cast iron
DEF	Diesel exhaust fluid
DfT	Department for Transport
DI	Direct Injection
DLPA	Double layered porous asphalt
DOC	Diesel oxidation catalyst
DPF	Diesel particulate filter
EGR	Exhaust gas recirculation
ESP	Electrostatic precipitator
EV	Electric vehicle
FAME	Fatty acid methyl ester
GPF	Gasoline particulate filter
GTL	Gas to liquids
HD	Highly dispersible
HDV	Heavy duty vehicles
HPCR	High pressure common rail
HVAF	High velocity air fuel
HVOF	High velocity oxy-fuel
ICE	Internal combustion engine
LDV	Light duty vehicles
LNT	Lean NOx trap
MVP	Minimal viable product
NAEI	National Atmospheric Emissions Inventory
NAO	Non-asbestos organic (brake pads)
NEDC	New European Drive Cycle
NEE	Non exhaust emissions
nm	Nanometre (10^{-9}m)

Term	Meaning/expansion
OBD	On-board diagnostics
OEM	Original equipment manufacturer
OME	Oxymethylene methyl ethers
PEO	Plasma electrolytic oxidation
PHEV	Plug-in hybrid electric vehicle
PM	Particulate mass or particulate matter
PM10	PM sampled with an inlet of 50% efficiency at 10µm
PM2.5	PM sampled with an inlet of 50% efficiency at 2.5µm
PMP	Particle measurement programme
PN	Particle number
PTA	Plasma transferred arc
RBS	Regenerative braking system
RDE	Real driving emissions
REA	Rapid evidence assessment
REE	Rare earth elements
SCR	Selective catalytic reduction
SMA	Stone mastic asphalt
SPS	Suspension plasma spray
TfL	Transport for London
TRWP	Tyre and road wear particles
TWC	Three-way catalyst
WAYU	Wind augmentation and purifying units
WLTC	World harmonised light-duty test cycle
WLTP	Worldwide harmonised light vehicle test procedure

1. INTRODUCTION

1.1 OBJECTIVES

Ricardo, supported by AECOM, undertook horizon scanning of technologies that have the potential for reducing $PM_{2.5}$ emissions from on-road transport, for the Department for Transport. This report provides the findings from the review of the technologies.

The systematic review of material focussed on the following areas:

- In-vehicle/on-vehicle technologies to reduce $PM_{2.5}$ non-exhaust emissions.
- Technologies to reduce $PM_{2.5}$ exhaust emissions.
- On-road/roadside technologies to remove $PM_{2.5}$.

Technologies to reduce $PM_{2.5}$ from brakes and tyres broadly fit into two categories: 1) preventative measures, which includes regenerative braking systems and low emission materials for tyres/brake pads/brake discs, 2) particle collection systems, which are designed to trap and/or remove particles that would otherwise be emitted. This review covers both of these categories.

The technologies considered in the report were assessed against the following criteria:

- Potential for mitigating $PM_{2.5}$
- Technology readiness level (TRL)
- Feasibility of implementation
- Maintenance schedule
- Cost of implementation

It should be noted that the technologies reviewed in this report do not necessarily target a reduction in $PM_{2.5}$ emissions, but a reduction in overall wear, or in particle emissions across a broader size range. In some cases manufacturers have undertaken studies to assess $PM_{2.5}$ reduction specifically and these are discussed in the review. In other cases the potential for $PM_{2.5}$ mitigation (%) is based on the efficiency of removal if PM or other pollutants. It should also be noted that as the PM arises from different sources with varying emissions, it is not possible to determine an absolute reduction in PM.

1.2 REVIEW METHODOLOGY

1.2.1 Rapid Evidence Assessment

A Rapid Evidence Assessment (REA) was undertaken using a three-step approach for this work.

Step 1: Key search terms which are relevant to the main scope of the review were used to identify material for review. The material included peer-reviewed journal articles, theses, patents, government and industry reports, outputs from projects, and manufacturer websites, in addition to Ricardo's "in house" knowledge. The focus was on material published within the last 5 years. For each successful search, the key words used, the search engine, and the number of records returned were recorded in a spreadsheet. The results from each search undertaken were saved as a list of references.

Step 2: An initial screening process was applied to the list of references using the titles to identify relevant material to be included in the review. The results from the initial screening were documented in a spreadsheet this included information about the source material (e.g. source type, authors, company etc), and information about the subject matter (e.g. location of study, type of technology). A second screening was then undertaken: abstracts for all screened material were downloaded and read and a ranking based on the relevance of the material to the scope was applied to each document: 1= "very low", 2= "low", 3= "moderate", 4= "high", 5= "very high".

Step 3: Evidence relevant to the focus areas was extracted from the material from those documents ranked as "moderate" to "very high". Information for each paper or document was noted down to summarise the main findings from the material. This information was then used to form the review presented here.

Further information on the search terms and number of documents retrieved is provided in Appendix 1.

To supplement the material and fill gaps where needed interviews were conducted with some manufacturers to discuss their mitigation technology in more detail. The table below provides an overview of the manufacturers interviewed and the focus of the mitigation technologies discussed.

Mitigation focus	Manufacturer
Tyre wear emissions	Tyre Collective ENSO tyres
Brake wear emissions	Tallano Brembo MANN+HUMMEL
Road/roadside	Roadvent

During the interviews Ricardo discussed the following topics:

1. The stage of development of the technology and readiness for market.
2. Suitability/adaptability of the system for different vehicles.
3. Effectiveness of the system for mitigating $PM_{2.5}$ emissions.

Information gathered from the interviews is presented alongside the data extracted from the review material. The review includes technologies at all stages of development, however, not all of these are assessed with respect to the criteria above as information is not always available, especially for those at a very early stage or have very low potential for mitigation of $PM_{2.5}$. Table 1 below provides information on the manufacturers and technologies that are included in the assessment. At the end of the report (see Table 5) a summary table comparing all technologies assessed is provided.

Table 1 Manufacturers/technologies assessed in the review.

Area	Company/Manufacturer	Technology
On-board capture devices (Brake)	Tallano	TAMIC® Active and passive brake wear capture devices
On-board capture devices (Brake)	MANN+HUMMEL	Passive brake wear capture device
On-board capture devices (Brake)	MANN+HUMMEL	Active brake wear capture device
On-board capture devices (Brake)	OGAB	Brake wear capture device
Brakes	Brake manufacturers	NAO brake pads
Brakes	Brembo, other brake manufacturers	New brake pad materials
Brakes	Brembo, other brake manufacturers	New low-emission brake pad materials
Brakes	Brembo, other brake manufacturers	Low wear cast iron disc and optimised pads (“Greenance” kits)
Brakes	Vehicle manufacturers, electric powertrain suppliers	Regenerative braking systems (RBS)
Tyres	All tyre manufacturers	Optimised tyre compounds for reduced wear

Area	Company/Manufacturer	Technology
Tyres	ENSO Tyres	Optimised bio-based materials and manufacturing
On-board capture devices (Tyre)	Tyre Collective	Tyre wear capture device
Exhaust emissions	Johnson Matthey BASF Umicore	Catalyst Chemistry
Exhaust emissions	Corning NGK Ibiden	Catalyst Substrate incl DPF
On-board capture devices (Ambient)	MANN+HUMMEL	“PureAir” roof box
On-board capture devices (Ambient)	MANN+HUMMEL	Integrated fine dust particle filter
Road/roadside	Pollution Solutions	Roadvent™
Road/roadside	National Environmental Engineering Research Institute (NEERI) and IIT Bombay	Wind Augmentation and Purification Units (WAYU)
Road/roadside	Road surface manufacturers	Double layered porous asphalt (DLPA)
Road/roadside	Biofilter manufacturers	Vegetative barriers and biofilters

2. LITERATURE REVIEW

2.1 NON EXHAUST EMISSIONS

Non-exhaust emissions (NEE) are the emissions of particulates from road vehicles that do not originate from the powertrain, and include particles emitted from brake wear, tyre wear, and the abrasion and resuspension of road dust as the vehicle is driven. Any vehicle regardless of powertrain will contribute to NEE, and these air pollutant emissions are not currently regulated. As the number of vehicles on the road has increased and the exhaust emissions have decreased over the years the relative contribution of brakes, tyres and abrasion to PM has increased. Road transport statistics published by the Department for Transport (DfT), based on data from the National Atmospheric Emissions Inventory (NAEI), show that in 2021 52% of $PM_{2.5}$ emissions from road transport came from tyre and brake wear, and a further 24% of emissions from road abrasion [2] . A report by the Air Quality Expert Group (AQEG) acknowledged that the most effective mitigation strategy for NEE is to reduce traffic volumes [3], as do other studies including Piscitello et al. [4].

Brake wear is increased by higher braking forces and higher temperatures, which depend on vehicle weight, initial vehicle speed, and deceleration rates, so limiting severe braking and high-speed braking can reduce wear and particulate emissions [5]. Similarly, tyre wear is influenced by aggressive accelerations, braking, and cornering since these increase the shear forces and temperatures within the tyre and the friction heat between the tyre and the road surface, while high speeds can also increase tyre temperature [4], [6].Therefore, NEE can be reduced through moderating driving style, and through road design that minimises the need for braking and cornering. Tyre wear can also be affected by the properties of the road surface, as noted in Section 2.3.4. Vehicle weight has a significant influence on NEE since the increased inertia of the vehicle increases both braking force and tyre shear force for similar manoeuvres. Since electric vehicles use heavy batteries, their total weight is likely to be 190 kg-430 kg (or 15-20%) greater than a diesel or petrol vehicle of similar size, and so unabated NEE could exceed the *total* PM emissions of diesel or petrol vehicles [7].

Mitigation technologies for NEE have been reviewed covering the brake friction materials (pads), the brake rotor (disc) (see Figure 1), the use of regenerative braking, the design and use of tyres, and finally the use of active particle capture systems on-board the vehicle.

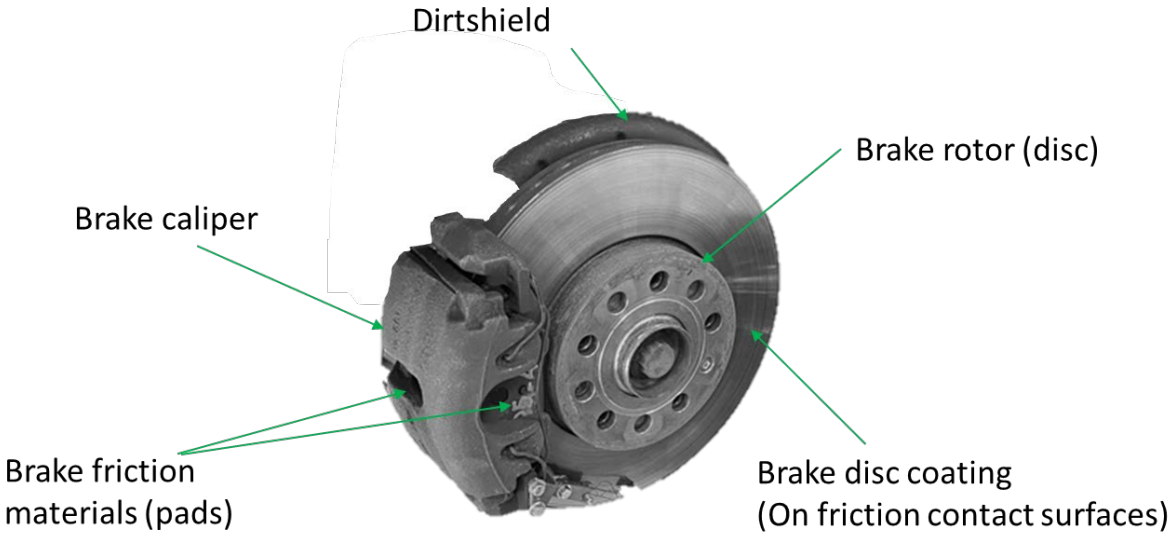

Figure 1 Components of a disc brake system. Source: Ricardo.

2.1.1 Brake design: Friction materials

Brake friction pads/linings typically consist of five primary components: binders, fibres, fillers, frictional additives or lubricants, and abrasives. The proportions of these components vary depending on the type of lining and the manufacturer. Three main types of brake linings are commonly found [8], [9]:

- **Low-metallic** (low steel) pads combine organic compounds with small amounts of metals (10-30% by mass), offering high friction and good braking capacity and fade resistance at high temperatures. A trade-off is increased rotor wear due to the abrasiveness of the pad material. This type of brake material is widely used in European to suit its dense traffic and high-speed motorways and meet the performance expectations of consumers.
- **Semi metallic** brake pads contain a higher metallic content (up to 65% by mass), providing durability and excellent heat transfer but potentially causing higher rotor wear and noise issues.
- **Non-asbestos organic (NAO),** non-steel. NAO pads are relatively soft and produce less brake noise and less dust with less disc wear but exhibit reduced braking capacity and fade resistance at high temperatures. NAO pads are common in the US and Japan but not widely used in Europe.

Notwithstanding the terminology used, *all* types of brake pads in the UK and Europe are asbestos-free due to health concerns arising from asbestos. In the UK, the use of asbestos in brake components in the UK has been banned since 1999. Concerns about copper poisoning of waterways from brake wear emissions has led to restrictions on the use of copper in brake pads in the USA, less than 5% is permitted from 2021 and less than 0.5% from 2025 [10]. The US Automotive Manufacturers Equipment Compliance Agency has established a “Better Brake” standard which also recognises brake pads without the use of cadmium, chromium, lead, and mercury [11]. These measures address the content of the brake friction materials due to their poisonous effects (to humans or nature), but do not address the emissions of particles generally.

Storch et al. undertook a comparison of NAO pads to European specification low-metallic pads for a small family car (C-segment vehicle) using a brake dyno and showed that they reduced $PM_{2.5}$ emissions by 21%

and PM_{10} emissions by 26% compared to low-metallic pads, while particle number (PN) was reduced by 58%. The wear rate by mass of the NAO pads was greater than the low-metallic pads but the wear of the discs was reduced, such that total wear rate was similar [12]. A third set of aftermarket pads was also tested which demonstrated even lower emissions, with $PM_{2.5}$ emissions reduced by 57% and PM_{10} reduced by 68% compared to low-metallic pads, although PN emissions increased slightly, total wear by mass was substantially reduced with four times less disc wear. The same study identified that particulate emissions from the front brakes of a C-segment vehicle were around three times higher than those of the rear brakes, and that around two thirds of brake wear by mass is from the discs with the remaining third split approximately equally between inner and outer pads, when using low-metallic pads and iron discs.

In a study using brake dyno tests to compare NAO pads with European specification semi-metallic pads over the Worldwide Harmonised Light Vehicle Test Procedure (WLTP) brake cycle, Kulkami and Kendrick observed that $PM_{2.5}$ emissions were reduced by 43% and PM_{10} reduced by 55% using the NAO pads [13]. Particle Number emissions were reduced by a similar magnitude (41% and 57% respectively), while weight and thickness loss of the pads was substantially reduced and wear of the (iron) discs reduced to negligible levels. The results also showed that for all pads most particles were in the PM_1 size range, with the least (10,000 times fewer) in the $PM_{2.5}$-PM_{10} size range. The same tests found a new formulation of NAO pads were able to further decrease emissions, by 60% ($PM_{2.5}$) and 49% (PM_{10}) compared to the standard European pads, again with a similar magnitude of PN reduction (65% and 43% respectively). The composition of the new NAO pads or how their performance attributes compared to the semi-metallic pads is not made clear, although they are reported as being designed as a replacement for the semi-metallic pads to minimise particle emissions.

A different study by Woo et al. saw brake $PM_{2.5}$ emissions reduce by 64% and PM_{10} by 80% for the same vehicle model using NAO pads compared to semi-metallic pads [14]. It was noted that the emissions factor for NAO pads was higher on urban and rural roads than motorways, whereas semi-metallic pads had the highest emissions on motorways due to high initial speeds and brake drag or resuspension. NAO pad emissions had a slightly smaller size mode at 2 µm compared to 3 µm for the semi-metallic pad emissions, although the distribution was broadly similar overall.

A comparison of different compositions of low-metallic pads by Kim et al. including the use of a graphite lubricator in the pad material showed that using zirconium silicate as the abrasive material resulted in lower PM_{10} emissions and wear rate than silicon carbide or aluminium oxide, or mixtures of all three, and that lower PM_{10} emissions and wear rate were observed with larger graphite particles (700 µm) than smaller graphite particles (100 µm) used as a lubricant [15].

Novel metal-free and bio-derived brake friction material compositions are being developed to address environmental concerns around the toxicity and ecological impacts of the brake particles or the sustainability of the materials used in and manufacture of the pads. Saha, Sharma and Satapathy report that these compositions face a challenge in matching the thermal stability and fade resistance of conventional materials and effective bonding of the friction material to the backing plate, although there is potential to maintain or reduce wear rate [9]. Experiments with introducing rice husk material into brake pads reported by Carlevaris et al. showed promise, but in most cases increasing the natural material content increased wear and PM_{10} emissions [16].

Brembo are currently developing low emission pad material formulations for both standard and modified Grey Cast Iron (GCI) discs for original equipment manufacturer (OEM) fitment. These represent advanced materials, able to couple the lower friction coefficient and wear typically exhibited by NAO friction materials with the superior braking performance characteristics of low metallic formulations. They are being developed to be used in brake devices compliant to the upcoming Euro 7 regulation and so are expected to be commercially available before the actual implementation of the regulation. Brembo have also developed low emission pad materials along with matched low wear discs that are already available for aftermarket fitment, and pad materials optimised for use with coated discs, as detailed below.

For these new brake pad materials the feasibility of implementation will be high, with similar or a small cost increase compared to current brake pads. Brake pads would be expected to have a similar lifetime to those already on the market, so there will not be any significant maintenance except for changing pads when they are worn.

2.1.2 Brake design: Rotors

Brake rotors (discs or drums) are most commonly made from GCI. It has excellent thermal characteristics and mechanical strength and is also cheap to manufacture, but is prone to corrosion and wear, with discs often expected to be replaced with every second set of pads. Friction brakes generate heat, which can increase wear rates and particle emissions and reduce brake effectiveness due to brake fade. Compared to drum brakes, brake discs have a greater opportunity to dissipate heat due to increased surface area and exposure to airflow allowing improved cooling hence reducing the risk of brake fade. Alternative materials including carbon composite and carbon ceramic may be used in some extreme performance applications, but due to performance characteristics or cost are not considered practical for general use. However, coatings or treatments for GCI rotors can improve their wear characteristics and reduce particle emissions. These technologies include [17]:

Non-thermal spray processes:

- **Hard Chrome Plating** has been shown to increase wear resistance of GCI rotors, although it also reduces the coefficient of friction and so braking force, and production involves the use of toxic hexavalent chromium.
- **Plasma Electrolytic Oxidation** (PEO) or micro-arc oxidation is an electromechanical surface treatment for aluminium, magnesium, and titanium alloys that results in a uniform thin layer of oxidation on the surface that resists wear and has a coefficient of friction only slightly reduced compared to GCI. It is also suitable for GCI rotors with a coating of such alloys.
- **Laser Cladding** enables the deposition of pore and crack free coatings containing cobalt, nickel, tungsten carbide, or other alloys or ceramics, with a strong metallurgical bond to the substrate and providing a corrosion and wear resistant surface. The technology can be limited by a risk of cracking caused by internal stresses and differing thermal expansion rates between coating and substrates.
- **Plasma Transferred Arc** (PTA) is a similar process to laser cladding with similar materials but using a higher temperature, with similar benefits to corrosion and wear resistance. There is a risk that dilution of the coating with the cast iron changes its properties.

Thermal spray processes:

These coating processes deposit metallic or ceramic layers by high-velocity high-temperature spraying of powdered material onto the substrate with force in a partially or fully molten form. The range of materials that can be used and applied to complex geometries offers a versatile solution. Materials include oxides of aluminium, titanium, and chromium, and in some processes, ceramics.

- **Atmospheric Plasma Spray (APS)** is already used for other automotive engine components. Powdered material is sprayed in a plasma jet. A range of materials can be used to optimise wear rate without reducing friction coefficient or increasing pad wear. There is a challenge to avoid damaging defects within the layer.
- **High Velocity Oxy-Fuel (HVOF)** uses a high temperature supersonic combustion gas stream to produce dense coatings for industrial applications. The braking and wear rate properties will depend on the materials used.
- **Cold Gas Dynamic Spray (CGDS)** uses a cold inert gas to spray heated particles at high speed onto the substrate, the particles adhering through deformation rather than melting. This avoids oxidation of the particles and resultant brittleness of the surface but is only suitable for ductile materials such as metals, and not for carbide-based hard coatings.
- **High Velocity Air Fuel (HVAF)** is a relatively new process that aims to combine the HVOF and CGDS approaches by using air instead of oxygen and a higher velocity compared to HVOF, but a higher temperature than CGDS. It shows promise for brake rotor applications.
- **Suspension Plasma Spray (SPS)** is another relatively new process which atomises very fine powders in a plasma jet that solidify onto the substrate, forming a more dense and stable coating than APS. Different solvents can be used to create different microstructures within the coating enabling its properties to be tuned.

An investigation of a nickel-based coating via **laser cladding** by Shi et al. showed wear resistance increased by 50% compared to the substrate [18]. Laser cladding with nickel-tungsten carbide has been shown by Dizdar et al. to reduce both wear (halved mass loss) and particle emissions (by 30%) without reducing wear of the friction material and increasing the coefficient of friction [19].

Federici et al. carried out comparisons of the properties of conventional and coated discs via the HVOF process using chromium carbide and tungsten carbide through tests carried out at room temperature and at 300°C. These showed negligible wear rate of the coated discs, said to be since the contact temperature is not sufficiently high to induce a softening or an oxidative damage of the coatings [20]. Bondorf et al. considered a coating of 20% tungsten carbide with 30% titanium carbide in a 50% ductile matrix of stainless steel, applied in a 2-stage process with HVOF. Fine/ultrafine (4 nm - 3 µm) particle emissions were reduced by 19-79% depending on drive cycle, with coarser (300 nm – 10 µm) particles reduced by 34-83% over the same tests, it was noted that cycles with more brake applications showed the greatest reduction in emissions with the coated disc [21].

Hesse et al. carried out tests comparing tungsten carbide coated discs and carbon ceramic discs to CGI discs in brake rig tests over the WLTP brake cycle, which demonstrated their potential to reduce particulate emissions, although the method of disc coating is not detailed [22]. $PM_{2.5}$ emissions were shown to reduce by 50% with the carbide coated discs and 63% with the carbon ceramic discs for similar size brakes for the same vehicle (55% and 70% reductions in PM_{10} respectively), although particle number remained similar. The reduction in wear is mostly attributed to the discs, which show negligible wear, although pad wear is also reduced slightly.

Storch et al. found a brake dyno test of a tungsten carbide-coated disc resulted in a 24 times wear rate of 0.5 mg/km compared to 12.1 mg/km for a GCI disc for the same vehicle. It was noted that for compatibility with the carbide-coated disc, brake pads with a 15% higher wear rate compared to the low-metallic pads used with the GCI disc. Overall, $PM_{2.5}$ was reduced 71% and PM_{10} reduced 79% with the tungsten carbide-coated disc, and PN reduced by 64%. The method used for coating the disc was not discussed [12].

Brembo see coated discs as one of the main technologies to achieve compliance to the upcoming Euro 7 limits when used in conjunction with appropriate pads as dedicated friction pairs developed together. Of the HVOF, CS, and laser cladding manufacturing methods, laser cladding is expected to provide the best total cost of ownership and have the widest application. The higher cost than a standard brake disc means the technology is expected to be applied to larger and premium cars rather than small budget cars, at least in the initial Euro 7 implementation, for which products are in the pre-production validation phase. Development is also looking at its adaptability to light commercial vehicles and Heavy Duty Vehicles (HDVs). Coated discs are significantly harder than conventional discs with different tribological characteristics so must be paired with specially developed low-metallic pads to maintain performance, comfort and noise, while minimising the emissions. The combination is found to assure reliable and reproducible reduction of emissions, which currently provides PM_{10} emission factors below the proposed initial Euro 7 level (7 mg/km per vehicle), although further development work is being developed to meet the second threshold level of Euro 7 limits (3 mg/km per vehicle).

Brembo have also developed a low wear cast iron brake disc with a formulation specifically designed to increase their hardness and reduce their wear, this offers a cheaper solution than coated discs and one which can be applied as an aftermarket fitment. As with coated discs, they are paired with pads optimised for the disc material. Demonstrations of this technology (including through the EU Horizon funded VERA project) show it is very effective in reducing significantly the PMs generated by brakes, especially when coupled with dedicated friction materials. It is suitable for a wide range of cars and light commercial vehicles, is already available for selected applications in the aftermarket as disc-pad kits (see Brembo's Greenance kit for more information) and is expected to become increasingly widely available and adopted. The disc-pad components are a straight swap, and it is expected that the disc replacement may be less frequent as wear is reduced. There is likely to be a small increase however in the costs of the discs.

2.1.3 Regenerative braking system (RBS)

There are alternatives to friction brakes which do not result in abrasion, including flywheels, magneto rheological fluids and eddy current machines, although these have limited practicality for vehicles. However, regenerative braking can be adopted for all vehicles with an electric motor in the drivetrain, such as an electric vehicle, but also in full hybrid and plug-in hybrid vehicles and fuel cell electric vehicles. A regenerative braking

system (RBS) utilises the magnetic resistance in the electric motor to generate the braking force allowing some of the excess energy to be recovered and stored in a high voltage battery. RBS therefore provides an efficiency advantage in that braking energy is not wasted as heat, but rather a significant proportion can be recovered, reducing overall energy use of the vehicle. A secondary benefit of regenerative braking is that as it does not rely on frictional wear of brake materials to slow the vehicle, the need to use conventional friction brake systems is greatly reduced and thus particulate emissions are reduced as well. Regenerative braking is limited by the power generation capacity of the electric motor(s), which axles are equipped with electric motors (most effective with motors on all axles and front more effective than rear) and the available battery capacity (total capacity and state of charge). Due to legislative and safety requirements, friction brakes are still required in vehicles and must be considered as the primary braking system even where regenerative braking is expected to be utilised for most deceleration events. Friction braking is also still required during rapid deceleration, during a quick change from acceleration to braking, at high speeds (where motor torque is limited and brake force requirements are high), and at very low speeds and when the vehicle is close to/at stationary as well as any time the battery is fully charged [23], [24], [25].

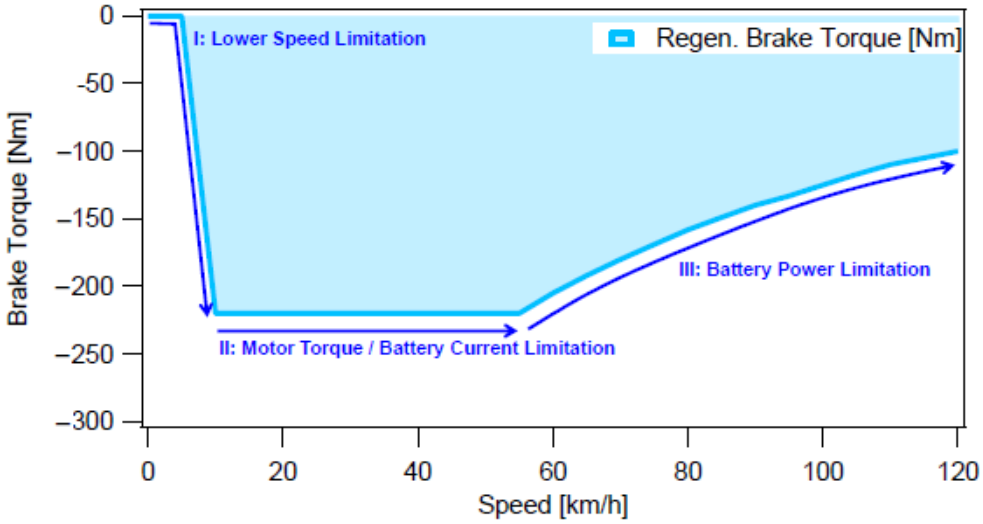

Figure 2 Example torque-speed limitation characteristics of regenerative braking. Source: [25] (licensed under CC BY 4.0).

An analysis of the impact of regenerative braking by Kulkami and Kendrick [13] found that initial braking may be provided by friction brakes for consistent feel and immediate response, with electrical recuperation taking over and providing up to 100% of the braking, until the vehicle speed slows to the point that the motor is inefficient at providing energy recuperation where the friction brake takes over. In this way most of the braking energy can be recuperated through the electric motor, reducing the use of the brakes and the average pressure applied, and reducing the average and maximum temperatures of the brakes. In brake dyno tests comparing the wear over the WLTP brake cycle for an ICE vehicle to that for an EV with regenerative braking (using European specification semi-metallic pads on CGI discs), $PM_{2.5}$ and PM_{10} emissions were reduced by half using regenerative braking, with both mass and thickness loss of the pads substantially reduced and no disc wear observed.

Storch et al. [12] used simulation of a C-segment plug-in hybrid electric vehicle (PHEV) assuming a motor power of 86kW to calculate a deceleration rate of 0.156 g (1.53 m/s^2) was possible using regenerative braking, while for a similar sized BEV, due to motor sizing and battery capacity, a regenerative deceleration rate of 0.29 g (2.84 m/s^2) was possible. Applying these regenerative braking assumptions over a WLTP brake cycle showed that the friction work demanded of the brakes reduced by 76% for the PHEV and 90% for the BEV. Testing the different brake use profiles determined on a brake dyno demonstrated $PM_{2.5}$ reductions of 57% for the PHEV and 71% for the BEV (with PM_{10} reduced by 62% and 79%, and PN reduced by 40% and 82% respectively), compared to the conventional powertrain and use of friction brakes only.

Simulation of the effects of different levels of regenerative braking capacity associated with different powertrains was carried out by Wicks, Green, and Beevers. They found that although the increased weight of hybrid and electric vehicle powertrains would increase their brake particulate emissions without the use of RBS, applying RBS reduced brake emissions depending on the nature of the drive cycle. Urban driving

enabled PM_{10} to be reduced by 65-87% for a small/compact car (B-segment vehicle) depending on the drive cycle (Transport for London (TfL) and WLTP cycles), and by 54-85% for an SUV type vehicle. The TfL cycle has lower speeds than the WLTP and so less regeneration was possible, and consequently emissions reductions were smaller. Urban and motorway driving may be able to use the friction brakes even less reducing PM_{10} emissions to negligible levels [24].

Other studies have reported similar findings. Hess & Augsburg studied three different types of regenerative braking observing a reduction in the particle number concentrations ranging from 66-99% [26]. Bondorf et al. found that driving with regenerative braking could lead to reduce particle number emission in the fine/ultrafine range (4 nm - 3 µm) by 65% over the WLTP cycle and 90% on a real driving cycle, while coarse particles (300 nm – 10 µm) were reduced by 68% and 35% respectively in the same tests [21]. Hagino found through brake dyno testing of brake profiles measured during vehicle tests over the WLTP-Brake cycle that using regenerative braking in a PHEV fitted with non-steel NAO pads reduced $PM_{2.5}$ by 78%, PM_{10} by 85%, and PN by 87% [25].

A different view is provided by Lui et al. (2021) who concluded that the benefit of regenerative braking might only compensate for the increase in total NEE due to the greater weight of EVs compared to conventional petrol and diesel vehicles, depending on vehicle size, driving type (urban, rural, or motorway), and the extent to which regenerative braking could be deployed [7]. In a comparison of NAO and semi-metallic brake pads on diesel, petrol, and electric powertrain versions of the same vehicle model [14], little change or even an increase in in total vehicle $PM_{2.5}$ is seen for EVs even with regenerative braking when using NAO pads, depending on the level of regeneration, since NAO pads have lower emissions anyway and the reduction in brake PM did not offset the increase in tyre and road wear and resuspended road dust. When using semi-metallic pads, total vehicle $PM_{2.5}$ reduced 5% for an EV at 50% regeneration and 22% at 90% regeneration compared to conventional vehicles. However, when secondary PM from NOx emissions is included, the total vehicle $PM_{2.5}$ of the EV reduced by 48-52% for NAO pads and 48-57% for semi-metallic pads depending on the level of regeneration.

The use of regenerative braking could have other consequences affecting friction brakes. The reduced dependence on friction brakes may enable the use of smaller brakes or even drum brakes, provided sufficient emergency braking power is available, such as on the rear axle of smaller vehicles; drum brakes tend to retain particle emissions within them although limited heat dissipation capability limits their use [23]. The reduced use of friction brakes can lead to corrosion of discs since corrosion is not removed by pad abrasion, when the brakes are used the corroded surface means the brakes may be slow to bed in, braking force may be reduced, and wear rate can be increased [27]. This can be mitigated by using coated discs (see 2.1.3) which are resistant to corrosion (Brembo confirmed this but noted the coating composition may be different to that used for conventional vehicles to optimise corrosion resistance), or through strategies that deploy the friction brakes regularly sufficient to remove abrasion [28]. As RBS systems are already installed as started in electric vehicles, the feasibility of implementation is high, and the costs is already incorporated into the cost of the vehicle. There is the potential for discs to become corroded if not used regularly, but if managed well, then disc replacement is likely to be reduced when compared to ICE vehicles.

2.1.4 Tyre design and use

The tyre forms the contact between a vehicle and the road and is critical to achieving traction to accelerate and decelerate the vehicle and grip during cornering, without the friction between the vehicle and road surface a vehicle would not be able to drive safely. However, this friction results in abrasion which releases particles from both tyre and road surface, known as tyre and road wear particles (TRWP). As well as the attributes of the tyre itself, factors that affect tyre and road abrasion rate and hence emissions include [29]:

- Vehicle weight and loading: heavier vehicles have increased abrasion.
- Vehicle speed: higher speeds increase tyre temperature and abrasion.
- Driving behaviour: higher acceleration, braking, and cornering rates increase sheer forces. Torque control and optimisation of traction control and anti-lock braking can help mitigate, while optimising road design/layout and traffic management may reduce the occurrences of acceleration and braking.
- Road surface: micro-roughness affects tyre abrasion while road surface durability impacts the road wear and dust release. There may be a trade-off between road wear and tyre abrasion properties, for example, concrete road surfaces may have much reduced wear rates compared to tarmac but increase tyre abrasion.

- Vehicle maintenance: incorrect tyre pressure and wheel misalignment can both increase tyre wear, while tread wear reduces with tread depth.

Regarding maintenance and the optimal use of tyres to minimise wear, tyre pressure monitoring systems have been mandatory in Europe since 2009 (according to EU Regulation No. 661/2009 of July 13, 2009), which reduces the dependency on drivers to check tyre pressures. The tread wear of a tyre reduces as the tread depth reduces since the tread blocks become thinner and more flexible, reducing hysteresis, therefore for optimal tyre particle emissions tyres should be used until their minimum (legal and safe) tread depth, but this requires regular checks by the driver, and many tyres may be replaced earlier at a service/inspection if they are considered likely to be illegal or unsafe before the next formal inspection. Wheel alignment is rarely checked (unless tyre wear is so bad as to indicate an issue) and is not part of periodic technical inspections (MoT tests). Doftek has developed both a technology to monitor wheel alignment on-board the vehicle and report issues, and a technology to actively control and correct wheel alignment (see Doftek's website for more information).

Tyre attributes affect durability, ride comfort, noise, rolling resistance (and so vehicle fuel/energy consumption), wear rate, as well as traction, cornering, and braking performance [30]. These attributes are shaped by tyre design features, construction methods, and materials, and are optimised through research and development by manufacturers according to their objectives. Which objectives are prioritised will depend on the tyre and vehicle manufacturers priorities and customer demand, and it is notable that three attributes are rated according to standards and displayed to the consumer on a tyre label at time of purchase: wet grip, noise, and rolling resistance (or efficiency) [31]. Tyre wear or abrasion rate is not currently subject to standard assessment in the UK (or Europe). However, there is a well-established "treadwear" rating in use in the USA which assesses the life of a tyre compared to a standard baseline (see National Highway Traffic Safety Administration for details), and a standardised measurement method for tyre abrasion performance has been established by the UN ECE [32], [33] which will be adopted within the Euro 7 emissions limits in Europe [1]. Of course, cost is also a significant driver for both vehicle manufacturer and consumer choice.

A 'magic triangle' of tyre property development (Figure 3) is widely referred to regarding the relationship between the three main tyre performance parameters: rolling resistance (fuel efficiency), wet grip (safety), and abrasion/wear resistance (tyre life and particle emissions), which are described as being connected so that improving one parameter will generally worsen at least one of the other two, leading to trade-offs of tyre design. Nonetheless, a range of tyre attributes are observed in their labelling (for wet grip, noise, and rolling resistance) and measurements (as shown by the ADAC study in the paragraph below) suggesting that some tyres achieve better optimisation of these conflicting attributes than others, managing to improve abrasion resistance and fuel efficiency without compromising wet grip. This challenge is also being addressed through the use of new materials, although novel tread designs can be used to optimise noise and wet grip characteristics and may have potential to compensate for improvements in abrasion. The challenge is complicated by the move towards more environmentally sustainable tyre materials to reduce the manufacturing impacts of tyres, with a lower reliance on fossil oil and natural rubber [29], [34], [35].

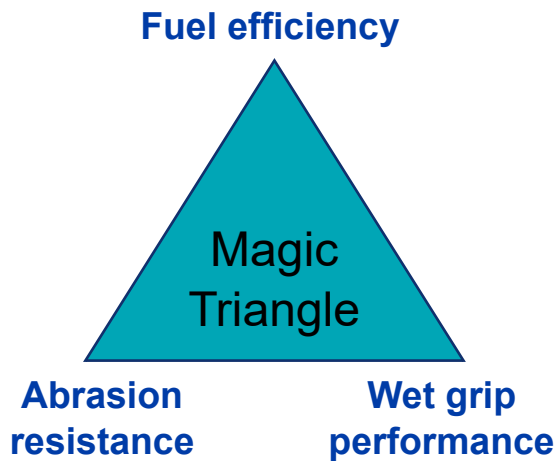

Figure 3 The magic triangle of tyre property development. Source: Ricardo.

A study by the German automobile association ADAC investigated the tyre abrasion and tyre performance of existing tyres on the market finding wear rates averaged around 118 mg/km but ranged from 59 mg/km at best

to 171 mg/km at worst [36]. For some tyres a lower abrasion rate was associated with reduced grip, although this was not universal, and Michelin (average 95 mg/km) and Goodyear (average 107 mg/km) were noted as having low wear without compromising safety (grip). Wear rates were generally greater for larger/wider tyre sizes which may be due to the characteristics of smaller vehicles as much as the tyre, but on average only slightly higher with winter tyres compared to summer tyres for a comparable size. This study indicates that there is scope to reduce the abrasion rates of many tyres as demonstrated by the best in class, but does not measure airborne PM. It also noted that some tyres are supplied with vent spews attached – small rubber hair-like threads on the treads of the tyres as a residue of manufacturer – which wear off quickly within the first few miles. Eliminating these would remove an unnecessary source of microplastic pollution, although they are unlikely to contribute to airborne particulate matter.

The use of nanomaterials such as silica (particularly Highly Dispersible (HD) silica) in place of carbon black as a filler and reinforcing agent provides the rubber with lower hysteresis at lower frequencies and higher hysteresis at higher frequencies, which leads to tyres that use this material having lower rolling resistance (by up to 25%) and higher traction while increasing wear resistance up to 20%. Another nanomaterial that has been shown to improve tyre performance is nanoclay, which can be dispersed in the rubber of the tyre's inner liner, improving rolling resistance and wear resistance by a small percentage [29], [37]. The addition of butadiene rubber into the tyre composition has also been shown to improve abrasion resistance [34]. However, these materials are already becoming established, and their potential to further reduce abrasion or emissions isn't clear. Furthermore, Gehrke et al. notes that tyres with higher abrasion rate generally produce larger particles, and so reducing abrasion rate could increase airborne PM [29].

ENSO is a UK-based tyre technology company offering tyres said to reduce tyre pollution and extend the range of electric vehicles through lower rolling resistance, while minimising the tyre's environmental impact (see ENSO's website for more information). Their objectives are to:

1) Reduce the total mass emissions from tyres, aiming to move from around 30 mg/km per tyre to 15 or even 10 mg/km (30-50% reduction) to reduce emissions of particles both to air and to soil and water (microplastics), while also reducing rolling resistance to maximise vehicle efficiency, and matching competitors for performance (grip, handling etc).
2) Change the raw materials used (and being emitted as particles) to reduce their toxicity, including 6PPD which is a chemical used as a stabiliser in tyres but known to be toxic to some fish, and to shift from virgin fossil materials to increasingly use bio-based, renewable, and recycled materials.
3) Introduce more biodegradable, renewable, recyclable, and low carbon raw materials into tyre production without compromising durability and useful life and to completely phase out all fossil fuel based materials from its products, by 2030.

ENSO's tyres are aimed at electric vehicles since their greater weight, high torque and predominantly urban-based driving cycle risks otherwise increasing overall tyre emissions, and the energy savings have proportionally greater benefit due to the greater vehicle efficiency, compared to internal combustion engine vehicles. In trials with Royal Mail and DPD in 2021 ENSO reported that their tyre showed up to 10% more range and improved durability (reduced wear) by up to 35% compared to branded tyres, demonstrating good progress with their first objective. While the way this is achieved is a trade secret, the use of novel materials and advanced manufacturing techniques are mentioned, as is the use of data from vehicles in use to continually optimise the design to suit each application and driving environment. ENSO say their tyres cost 10-20% less than the major brands due to direct selling (rather than through third party distribution) and offer much better value through reducing energy use and lasting longer. The ENSO tyre is currently available in limited sizes, and future expansion will target popular electric vehicle models the UK, Europe and the US.

Depending on the manufacturer there may be small to medium outgoing cost associated with the purchasing of tyres using optimised compounds compared to current tyres on the market. However with the potential for reduced wear, maintenance (tyre replacement) will also be reduced, which will result in an overall cost saving.

A disruptive technology for tyres may emerge with the use of airless (or non-pneumatic) tyres. These use a flexible sprung support structure of a spoked, matrix, honeycomb or sponge design in place of the air-filled part of a tyre, with a thin tread-bearing rim around the outside. Advantages include being impervious to puncture, potentially extending their useful life, plus reduced ground pressure and increased grip through a larger contact patch and a low rolling resistance from reduced hysteresis losses. However, while airless tyres have been developed by several manufacturers including Michelin [38] and Bridgestone [39], challenges remain around durability (particularly at high speeds) and the complexity of production, and to date airless tyres have only been used in specialist applications such as non-road machinery for construction and

agriculture. It is not yet clear whether airless tyres will have any impact on abrasion rates or PM emissions [40].

2.1.5 On-board capture devices

A number of established and startup companies are in the process of developing technologies to capture non-exhaust emission particles as they are emitted, to reduce the quantity of particles becoming airborne. The technologies reviewed here include both active and passive methods. Some are targeted to mitigating either brake wear or tyre wear alone, and some are system that collect particles from a combination of brake wear, tyre wear and resuspended dust/road wear.

2.1.5.1 Brake Wear Particles

For on-board capture devices focusing on remove brake particle emissions it is important to ensure that the brake system is not impacted in a way that could increase wear rates or cause a safety concern. In addition, if a device encloses the brake system temperatures may increase which could also lead to a greater quantity of particles being released. Therefore, some form of cooling may be required, either via injection or suction of air through the system.

MANN+HUMMEL, an automotive tier 1 supplier of air and fluid filter systems, have developed both active and passive brake dust particle filter systems [41], and both are said to be ready for volume production. The passive system fits around part of the disc adjacent to the existing brake calliper and consists of a folded filter medium to collect the brake wear particles within an enclosure. This fits within the wheel and can be retrofitted to most vehicles and easily adapted to different models. The design can cover part or all of the disc; 120°, 240°, or 360° of disc coverage has been tested although the more of the disc that is enclosed the greater the increase in disc temperature – by as much as 42°C peak for the 360° enclosure. MANN+HUMMEL report that particle reduction efficiency is around 15-40% with a new filter depending on the design (120° to 360° of the disc) and on the vehicle and its duty cycle, but this falls to 5-15% as the filter fills over the life of the pads. Filter changes aligned to routine vehicle servicing could maintain average efficiency in the 10-25% range. Due to the need for the device and its filter to withstand the high brake temperatures and corrosive atmosphere, costly materials (such as stainless steel) need to be used for the device and its filters, putting the system in the mid 3-digit euro price range.

The MANN+HUMMEL active brake filter system uses a small suction device fitted around the brake disc next to the calliper to transport the particles away from the brake to a filter housing via a flexible hose. The filter and suction pump unit can be fitted inside the engine bay, within the wing, or even within the wheel arch. A separate filter and pump unit can be provided for each wheel, or combined as a two-wheel system which may simplify servicing but require a larger filter housing. Brake temperatures are not affected. MANN+HUMMEL said that PM_{10} reduction efficiency is up to 80% with the pump running continuously, although an intelligent control system uses vehicle speed and other available sensors to enable the pump when braking is expected, which saves power but reduces particle reduction efficiency to around 60%. $PM_{2.5}$ reduction efficiency is similar. This efficiency is maintained over the life of the brake pads and so the filter could be serviced with brake pad changes (60,000 km) given sufficient space for the filter housing, or at vehicle service intervals if using a smaller housing accessible under the bonnet. The system draws 0.14-0.3 kWh (kilowatt hour)/100 km per brake. This system requires integration into the vehicle but can utilise lower cost components and filters than the passive system, so that it could achieve a similar or only slightly higher cost per axle (mid 3-digit euros), and service costs will be much lower – similar to air filter replacement. The control strategy could be developed with the OEM to suit the vehicle and its available sensors. Both MANN+HUMMEL brake dust particle filter systems can be fitted to existing brake components so feasibility of implementation is moderate-high. The filters can be changed during normal vehicle servicing, so no additional maintenance is required.

Fieldhouse and Gelb [42] have developed and tested a prototype Brake Pad Waste Collection System (BPWCS). This nearly full enclosure is made up of two parts, one either side of the brake system which includes a vented brake disc. With the two halves there is a gap between them which still allows for air flow for cooling through the disc. Within the enclosure are filters to capture the particles. Tests undertaken on the system showed >92% of brake dust was removed by the system. Further work to improve the system has been proposed, however as far as we are aware there has been no further publications on this system.

A research and development company, OGAB, have patented the Ogab® Sustainable Braking system that is designed to reduce the temperature of the brake discs when operating to increase its lifespan, whilst also capturing brake wear particles [43], [44]. Their design is an enclosure around the brake assembly, which has

active cooling for the disc via air injection, and a suction device to remove particles, which are then stored in a container. Their website states that their system *…"allows up to 100% of particulate matter caused by brake wear to be captured…".* The system has undergone testing but does not appear to be available on the market at this current time.

Tallano on the other hand have approached the removal of brake dust via the modification of the brake pad to direct particles to a vacuum device [45]. Tallano's TAMIC® collection system involves creating a groove in the brake pads which are then connected to a vacuum system and a filter device. The particles are transported across the face of the pad into the groove, where they are then sucked through channels in the brake caliper and into the filtration system. Particles down to 0.01µm can be collected with this device.

The system requires three vacuums, two at the front and one at the rear of the vehicle, which require power. The total energy consumption over a WLTP braking cycle (192 km) is 50Wh per system in sequence mode, although they are looking at ways to reduce energy use. As the system requires modifications to the brake pad and installation to the vehicle, the feasibility of implementation is moderate – high. The maintenance schedule requires a filter change every two years or 30,000 km, the filters have the capacity to collect > 200 g of material. The cost of the system is estimated to be around $400 per vehicle. The efficiency of particle collection of PM_{10} and $PM_{2.5}$ has been determined using a constant volume sampling (CVS) system to measure the particles emitted from the brakes when the TAMIC® system was operational. Up to 85% reduction in PM_{10} and 83% reduction in $PM_{2.5}$ was observed.

Woo et al. [46] have developed and tested two different methods of mitigating brake dust. One of the collectors uses an electrostatic precipitator (ESP) and the other an inertial separator. Each dust collector was tested separately in a brake dynamometer to determine the collection efficiency, and third test involved a hybrid version of the two collectors. As brake particles are already charged due to the friction from the brakes, the ESP can be used to filters the brake particles via deposition onto metal collection plates. The inertial separator removes the brake particles from the air flow which can then be collected. The collection efficiency of the ESP (for particles 520 nm to 5 µm) was up to 52% for low metallic pads and 64% for non-asbestos organic pads. For the inertial separator the collection efficiency was above 50% for particles above 2.2µm but dropped quickly at smaller sizes. As a hybrid system, the collection efficiencies improved with an efficiency up to 70% for PM above 3 µm diameter. The dust collectors are still in a very early stage of development therefore no further information on feasibility of implementation, maintenance schedule or costs can be determined at this point. The next phase is to create a design that can be installed on a vehicle.

The REA has also found several patents for brake wear particle collection devices. A summary of the information from the patents is given below. It should be noted however, that no further information could be obtained as to whether any of these designs have been manufactured, or how well they mitigate PM.

- Korea Institute of Ceramic Engineering have also patented a passive system for capturing brake wear (patent: KR102311867B1). The system partially encloses the brake disc with two collectors, the first collector goes around the outer surface of the brake discs, and the second collector goes round the inner surface. Inside the collectors are ceramic foam, used to filter the brake particles.
- Continental Automotive Romania SRL (Patent: GB2586609A) – This design uses a vacuum system to collect the brake wear particles with the brake pad partially enclosed.
- YOO HEONG JOO – (patent: KR20230010960A) – uses a deflector that is installed partially over the disc and brake pad to deflect particles emitted to from the brake system to a pipe and vacuum device.
- Federal-Mogul Motorparts LLC (Patent:CN114207307A) have patented a design that does not require any changes to the braking system, but instead uses strong magnets to collect brake wear. It is not clear however how the particles will be removed from the magnets afterwards.

2.1.5.2 Tyre Wear Particles

Capturing tyre wear particles is challenging as the tyre cannot be enclosed as for a brake system, therefore particles can become airborne immediately after emission. Technologies that have addressed this issue are using the fact that tyre wear particles can be electrically charged and attracted to oppositely charged surfaces.

An on-board tyre particle collection system for light goods vehicles has been developed by The Tyre Collective [47]. The system is designed to fit just behind the wheel of a vehicle, attached to the chassis, and captures tyre wear particles using electrostatically charged collector plates which attract the particles once they are emitted. The particles collected on the plates can then be removed, either by a suction device, or a brush. It is

proposed that a system could be mounted behind all four wheels. As the system uses passive airflow, no pump is required, and the power draw is only for the electrostatic plates which requires minimal power. The electrostatic plates can attract particles from 0.3 to 130µm in size, with 68% by number less than PM_{10}. The material has a high selectivity to NEEs, by weight 88% of the material collected is tyre and road wear particles. The company is currently working on a methodology to quantify the collection efficiency of $PM_{2.5}$ emitted from the tyre.

At present the company is targeting the system at commercial vehicle fleets, with the aim to expand to heavy goods vehicles, and buses in the future. In 2024 trials are being undertaken with fleets to create a minimal viable product (MVP) in 2025. Currently the system is designed as a retrofit option, therefore feasibility of implementation is moderate, but The Tyre Collective are actively working with vehicle manufacturers and tier 1 suppliers to investigate the potential for the system to be integrated into new vehicles.

Postech Academy-Industry Foundation (patent: US20200331005A1) and International Business Machines Corp (IBM) (patent: WO2023025481A1) have filed patents for tyre particle collection devices that also incorporate a charged surface to capture tyre wear particles. The Postech Academy-Industry Foundation device incorporates an air pipe mounted on the vehicle within two inlets into which the tyre particles are directed towards dust collection plates towards the rear of the pipe. IBM's device can be installed into the wheel arch and uses one or more triboelectric generators embedded into the tyre to generate an electric current from the frictional motion of the tyre, which can be used to electromagnetically charge a surface made of conductive metal, such as copper. Filters are connected to the surface to capture the tyre particles. In order to measure the build-up of particles on the filters IBM propose a photo detector to measure changes in light through the filters. Diagnostic information from the capture device and the light signal can then be used to adjust the power that goes to the capture device. It appears that these devices are currently at a very early stage of development, so no information on feasibility of implementation, maintenance, or costs can be determined.

Dong et al. used computational fluid dynamics (CFD) to model the airflow around a wheel in order to design tunnels that can capture tyre wear particles [48]. The capture tunnels were designed to have an opening of 100 mm high and 200 mm wide and located behind each wheel, into the body of the vehicle. The height of the opening above the floor of the vehicle and the depth of the opening were varied and 15 scenarios chosen for testing using simulations and a 3D printed $1/10^{th}$ scale model on a test rig. The capture ratios from the physical test were above 50% and that the rear tunnel capture rate can reach above 60% as it also captures some of the tyre wear particles (TWP) from the front wheel that bypass the front tunnel. For the simulation particles with a diameter <10um have a data capture above 34%. For larger particles the capture rate decreases. A similar study was performed by Xu et al, (2024) but using a different type of capture tunnel which had two openings (principal and auxiliary channels) for capturing TWP [49]. In this study 6 variations of the channels were tested. The capture rate was determined from the mass of the particles collected and the difference between the tyre mass at the start and end of each test. The tests show that up to 48.5% of the total tyre wear particles could be captured. These two studies show promising results; however, capture rates are determined from simulations and scaled models. Whether this would scale up to a full-size vehicle on-road has not been determined yet.

As brake wear can also become airborne, then these systems designed for tyre wear particle capture may also be capturing some brake wear. The Tyre Collective can confirm they are collecting metal particulates. Confirmation on if the source is brakes requires further investigation.

2.1.5.3 Combined Systems

In addition to their brake dust particle filter systems (see Section 2.1.5.1) MANN+HUMMEL have also developed vehicle-mounted systems which filter particulates out of the ambient air. Although these don't address the PM emissions of the vehicle's own brakes and tyres, by removing PM from the ambient at the same time they aim to achieve a net reduction in PM, or even negative PM emissions overall. The ambient PM collected may originate from brake and tyre wear of other vehicles, road wear/dust, and other sources. The "PureAir" system is packaged in a pod or roof box that can be mounted on top of the vehicle as a retrofit solution [50] and consists of a fan with an integrated 2-stage fine dust particle filter for removing dust whilst driving, or even while stationary if left operational. This system is unlikely to be attractive to private individuals but provides an opportunity for public service vehicles that have a high urban mileage to contribute to improving local air quality, for example buses, refuse collection vehicles, and even taxis, perhaps through a local authority incentive or requirement. Larger vehicles could have multiple units fitted. The devices have already been

demonstrated on recycling trucks in Singapore, Italy, and Brazil, although costs are relatively high being into 4-digit euro territory. Feasibility of implementation for public service vehicles such as trucks or buses is high, as there is plenty of room for fitment. This will be more challenging for passenger vehicles, but maintenance is low, with filter changes expected every 1-2 years.

MANN+HUMMEL's integrated fine dust particle filter takes the same concept as their "PureAir" device and integrates it into the vehicle itself during vehicle development [51]. The primary approach is to install a filter ahead of the vehicle cooling pack and behind the grille/bumper where it can work in existing airflow and with radiator fans, an alternative installation is under the floor of a larger van with airflow ducted up through filters and over the axle to exit under the rear of the vehicle. The particle collection effectiveness will depend on ambient concentrations and according to MANN+HUMMEL has been calculated to be 45% for PM_{10} and 48% for $PM_{2.5}$ assuming average Stuttgart ambient PM, and 271% for PM_{10} and 229% for $PM_{2.5}$ assuming average Beijing ambient PM, for a front-end filter in a passenger car over 22 km with filtration active for 8 hours when parked. Since particulate concentration is greatest closer to the road surface the lower mounting of the integrated filters maximises their potential effectiveness. System costs are said to be affordable compared to exhaust filtration systems, in the order of low 3-digit euro range, and servicing is simple (since the filter slots in place from above or below) and is expected every two years under typical European conditions. Design is reported to be a trade-off between the pressure loss or flow reduction, the filtration efficiency, and the filter lifetime or capacity between services. The addition of the filter ahead of the cooling pack is said to have minimal impact on cooling effectiveness, although there may be some limitation of maximum cooling (which could for example slightly increase the charging time of an EV if fast charging at high ambient temperatures and maximum cooling airflow), and if designed into the vehicle the vehicle design could compensate. Where active shutters are available, they could be open for urban operation and to maximise filtration and closed at higher speeds, which has been shown to minimise the effect on aerodynamic drag to insignificant levels. Feasibility of implementation is moderate to high depending on if it is integrated into the vehicle of retrofitted.

A vehicle-mounted particle filtration device, designed by Pall Aerospace, has been installed on the roof of buses in Southampton operated by the Go-Ahead Group. A pilot study where a filter system was installed on a Bluestar bus, was conducted in 2018 for 100 days and was shown to remove 65g of particulate matter from the air during the study [52]. The filtering system is stated as having a particle removal efficiency of 99.5%.The system has since been expanded to six buses in the Southampton area and further deployments for 6 other locations in the UK were announced in early 2020 [53]. No further information on the costs of deployment or their current operation could be determined by Ricardo.

HAHM DONG YOON has designed a system (patent: KR102136771B1) that aims to collect dust from the road surface as well as tyre wear and brake wear. The idea behind the design is to create static electricity via a Wimhurst machine which is powered by the rotation of the wheel of the vehicle. The static electricity then charges the brake, tyre and road dust which can then be collected and filtered. MTR Corporation Limited in Hong Kong has a design patented (patent: KR102339694B1) that uses the air from the exhaust to power a turbine. The turbine then creates a vacuum system which can extract non-exhaust emissions via a dust collecting module that is located behind the wheel then to a filter. Both of these designs appear to still be at a very early stage of development.

2.1.5.4 Impact of weather on operational capabilities

With on-board capture devices it is important to consider whether the weather can have an impact on the operation and/or capture efficiency of the system. Sensors and On-board Diagnostics (OBD) can be used to monitor the performance and if necessary, control the device. While the particle collection efficiency of devices may be affected by water, stakeholders observed that particle emissions are much reduced in wet weather.

Tyre Collective noted that water ingress is the main challenge, however, during a single test in wet weather they only saw only a minor drop in tyre wear samples collected (1-2%). Particles adhere securely to the collection plates even in wet weather. Their device has on-board sensors to detect moisture and humidity, which currently can be monitored and logged in real-time with and online platform. If the device is immersed in water (for example going through flood water) it can shut down and reset. Tallano have also tested their system in wet weather using the climatic wind tunnel at CSTB Nantes [44]. After 4 hours under rainy conditions, the test showed no water entered the filter system. Efficiency of particle collection has not been tested in rain or snow, but it is not expected to change as the particles are collected from inside the braking system.

The MANN+HUMMEL active brake filter system has been tested to demonstrate it is robust to water and snow, although they noted sensors could be used to shut-down the vacuum pump in excessive conditions such as

standing water or off-road driving. The same company's integrated particle filter is also designed to be robust to weather as well as stone chipping and high-pressure cleaning, and where present active shutters could be used to protect the filter in very wet conditions.

2.2 EXHAUST EMISSIONS

$PM_{2.5}$ particles issuing from the exhaust come from combustion (either directly as carbon, metals or metal oxides), or as emissions of chemicals which in the atmosphere are important precursors to the formation of particulates. In addition to these fine particles, there are also ultra-fine, or nanoparticles formed. These too are included in this review.

What is combusted is principally within the engine, and comprises fuel, but with a small amount of lube oil. The solid PM fraction is mostly formed in the engine combustion chamber, while the semi-volatile and volatile fractions are formed with cooling and dilution immediately after the exhaust gas is discharged into the atmosphere [54].

Several "exhaust emissions control technologies" may be positioned in the exhaust stream after the engine to significantly reduce the amount of engine pollutants that leave the exhaust pipe. Most of these are mature, established technologies that have been in use on vehicles for more than 5 years. The driver for the use of these technologies has been the introduction of increasingly stringent European regulations setting standards for exhaust emissions. These apply to vehicle manufacturers and are a pre-requisite to vehicles being able to be sold in the EU (and since "Brexit" in GB). Table 2 gives an indication as to how these emissions standards have evolved for Light Duty Vehicles (LDV) and HDVs since Euro 3 emission standards. LDV data in the table are for small vehicles (passenger cars up to 2,500 kg GVW, < 6 seats, and LCV Class 1). In this period, from January 2001 and until Euro 6, emissions were evaluated using the New European Drive Cycle (NEDC). During the Euro 6 period, the drive cycle changed to the World Harmonised Light-duty Test Cycle (WLTC) and Real Driving Emissions (RDE) requirements were introduced. For HDVs data are normalised to the Euro III standards for the European Transient Cycle (ETC) that applied to all vehicles sold in the EU from October 2001.

Table 2 Table of particulate matter (PM), nitrogen oxides (NOx), hydrocarbons (HC) and carbon monoxide (CO) exhaust emission standards for the EU. Emissions of LDV in mg/veh-km, and for HDV, mg/kWh.

	Pollutant	Euro3 (01/01/2001)	Euro 4 (01/01/2006)	Euro 5 (01/01/2009)	Euro 6b (01/09/2014)	Euro 6d (01/01/2020)
Petrol	**PM**	0	0	5	4.5	4.5
Petrol	**NOx**	150	80	60	60	60
Petrol	**HC**	200	100	100	100	100
Petrol	**CO**	2300	1000	1000	1000	1000
Diesel LDV	**PM**	50	25	5	4.5	4.5
Diesel LDV	**NOx**	560	250	180	80	80
Diesel LDV	**HC**	60	50	50	90	90
	Pollutant	**Euro III (01/10/2001)**	**Euro 4 (01/10/2006)**	**Euro 5 (01/10/2009)**	**Euro 6 (01/01/2014)**	
Diesel HDV	**PM**	160	30	30	10	
Diesel HDV	**NOx**	5000	3500	2000	460	
Diesel HDV	**HC**	780	550	550	160	

In meeting these standards, the following emission reduction technologies were widely adopted:

- LDV PI – Vehicles able to meet standards in place from 1/1/2001 (Euro 3) generally needed to have a three-way catalyst (TWC), with active lambda control, and all from Euro 4. Direct injection (DI) gasoline engines need a gasoline particulate filter (GPF) to meet PN standards at Euro 6.
- LDV CI – Vehicles meeting Euro 4 NOx standards in place from 1/1/2006 needed to be well calibrated with exhaust gas recirculation (EGR) widely used. To meet Euro 6 NOx standards from 1/9/2014 vehicles needed either selective catalytic reduction (SCR) or highly effective EGR. The introduction of RDE at Euro 6d made the use of SCR universal. Vehicles able to meet Euro 5b PM and PN standards in place from 1/1/2009 needed to have a diesel particulate filter (DPF).
- HDV CI – Vehicles able to meet PM standards in place from 1/10/2006 (Euro IV) needed a DPF, and to meet NOx standards in place from 1/1/2014 (Euro VI) needed SCR.

Technologies that have the potential for reducing $PM_{2.5}$ emissions from other IC Powertrains, e.g. methane PI fuelled lorries, are included in the three categories above.

For the European Commission Euro 7 emissions standards their main impact for particulate emissions is expected to be that the PN limit will apply to particles above 10 nm in size, rather than 23 nm as currently. Since this includes a greater proportion of the size distribution, even though the limits remain the same it could be seen as an increase in stringency. There may also be reductions in NOx limits for some vehicles, and early proposals included extending the valid testing conditions for real-world compliance (since watered down). However, the current Euro 7 proposals do not appear to require new PM reducing technologies, and it is expected the standards will be met through existing technologies with suitable optimisation.

Table 3 below gives a matrix of exhaust emission species and mitigation technologies. The final column gives an indication as to how many of these mitigation measures are relevant for the prior 5 years' time period stipulated by DfT. For mature technologies we provide insight from an organisational perspective rather than a fully referenced one. Novel technologies, those with "Y" in the final column are reviewed and referenced.

Table 3 References sources on exhaust emission species and mitigation technologies.

	Mitigation	Carbon	Urea	Ammonia	Oxides of nitrogen	Sulphur Dioxide	Metals	Metal Oxides	VOC	Past 5 years?
Engine	Base engine design						X	X		N
	Calibration	X	X	X	X				X	N
	Fuel ingection system	X			X				X	N
Fuels and Lubes	Standards - Base fuel					X				N
	Oil quality					X				N
	Carbon free fuels	X			X				X	Y
	Oxygen containing fuels	X							X	N
Engine Emissions Control	Particle filter	X	X				X	X		N(Y)
	Diesel oxidation catalyst	X							X	N
	Three-way catalyst				X				X	N
	LNT				X					N
	SCR (urea & H2 as reductant)			X	X					N
	Heated urea injector		X							Y
	ASC			X	X					N

It should be noted that engine and fuels and lubes emission mitigation measures are usually used in association with external emissions control measures and to account for trade-offs between emissions. Hence a diesel engine may be calibrated for optimum fuel efficiency and lower engine-out PM but accepting a higher level of NOx than could be achieved with a differently optimised calibration because it is fitted with a high efficiency SCR unit to address NOx at the tailpipe. Together, the engine's calibration and the SCR unit reduces the engine out NOx, enabling the vehicle's combined engine and external emissions control system to be optimal for both fuel efficiency and NOx emissions, and allowing the DPF to control the PM and PN.

The individual mitigation measures found from the literature survey will now be discussed individually.

2.2.1 Engine

2.2.1.1 Engine design

Base engine design, specifically ring pack optimisation of the piston, affects oil consumption thereby reducing the metal ions and metal oxides in engine out emissions.

A study optimised the ring pack with the introduction of a positive tilt to the top groove, reduced oil consumption from 0.75 g/kWh to 0.12 g/kWh during the first 4000 hours of operation [55]. If the lube oil contained 0.1% (w/w) metals, this would reduce the engine out emissions from 0.75 mg/kWh, by ~0.6 mg/kWh. Not insignificant relative to the Euro VI standard of 10 mg PM/kWh, but this is before the engine out exhaust passes through any external emission control measures, e.g. a DPF.

2.2.1.2 Calibration

NOx and soot formation vary with the temperature and the equivalence ratio (ϕ). The equivalence ratio is the air/fuel ratio relative to stoichiometric conditions. A value of ϕ = 1.0 means there is enough air for complete combustion of the available fuel. The NOx formation zone occurs at high temperatures (~2000-3000 Kelvin) and equivalence ratios close to 1. Whereas soot is formed at higher equivalence ratios and lower temperatures [56].

Base diesel engine calibration will target controlling both NOx and PM (and PN) emissions. Whilst diesel engines operate overall in with low equivalence ratio, locally in the cylinder, during fuel injection the equivalence ratio is within the soot formation zone. However, research indicates reductions in engine out PM has not been further vigorously pursued due to the effectiveness and maturity of DPFs. Because diesel engines operate at high air/fuel ratios, low equivalence ratios, they have naturally low engine out HCs and CO, hence the base engine calibration controls HC emissions. In addition, the diesel oxidation catalyst also plays a role in HC and CO control.

2.2.1.3 Fuel injection system

Modern diesel engines use high pressure common rail (HPCR) fuel injection systems, at pressures up to 2,000 bar. This increased pressure causes a correctly matched fuel injector to produce a finer, more penetrating fuel spray which promotes the premixing of air and fuel in the near nozzle region by increasing the fuel jet lift-off length. It also ensures that the fuel penetrates the entire chamber and fully utilizes the air charge. These factors are important to help limit PM emissions. Higher pressure injection affects ignition delay, peak pressures, and through these, overall engine efficiency and emissions. Su et al. [57] found that a higher injection pressure, lower emissions of PM were observed. A similar result was observed by Ezzi et al. [58], with smoke number (used as a proxy for PM formation) reduced when the injection pressure was increased from 800 to 1200 bar. This study also showed lower smoke formation with biofuel compared to ultra-low sulphur diesel. This is discussed further in the next section.

2.2.2 Fuels and Lubricants

2.2.2.1 The importance of fuel quality standards

The fuel entering the combustion chamber directly affects the engine emissions, and therefore fuel quality standards are an important aspect. Those currently relevant for pump diesel and petrol are EN 590 and EN 228, respectively.

A historic example of how changing fuel standards directly affecting PM exhaust emissions, is the banning of lead additives to petrol that occurred at the start of 2000.

Currently important is the concentration of sulphur. Sulphur in fuel is converted, almost quantitatively, into sulphur dioxide (SO_2), which when oxidised across a catalyst leads to the formation of the sulphate (SO_4^{2-}) fraction of PM and to the formation of nanoparticle PN. Permitted concentrations of sulphur in diesel reduced from 500 ppm to 10 ppm in 2005 to protect the exhaust emissions control catalysts (particularly SCR). There was a similar earlier reduction to 10 ppm in sulphur in petrol (to protect TWCs).

For a diesel engine consuming 200 g fuel per kWh engine power output, 10 ppm sulphur equates to 4 mg SO_2 being formed per kWh. Some of this gaseous compound will leave the vehicle (not comprising part of its primary PM emissions). This SO_2 released to the atmosphere can form the basis for making secondary atmospheric PM and PN.

The sulphur content of “red” diesel (used in non-road mobile machinery, inland waterway vessels etc) and of marine fuels has also been reducing and is now matched to road diesel.

2.2.2.2 Impact of increased hydrogen content in hydrocarbon based fuels

The engine exhaust particulate concentration is reduced as the fuel’s hydrogen content is increased. This can be fundamentally explained by the fact that the higher the hydrogen content is, the lower the number of carbon-carbon bonds present in the fuel. At its extreme, an internal combustion engine running on carbon free fuels (e.g. hydrogen) would eliminate fuel carbon (and VOC emissions) and NOx emissions would be significantly reduced. Some PM emissions derived from lubricant additives (emitted as ash), urea-derived solid particles and lube-based hydrocarbon volatiles and urea-derived products would still be emitted. However, these will be very much lower than the mass emissions concentrations from carbon-containing fuels [59].

Paraffinic diesel fuels, e.g. made by the gas to liquids (GTL) process, have been shown to lead to lower direct PM emissions [60]. Studies have shown how oxygen containing fuels, such as Fatty Acid Methyl Ester (FAME) biofuels, reduce engine out PM and HC [61], [62]. Figure 4 shows the impact on PM as a function of increasing biodiesel content. Currently, diesel fuel standard (EN 590) permits up to 7% FAME in pump diesel, although standards for B20 and B30 are in development. Higher levels of FAME are principally being considered as a route to reducing well-to-wheels GHG emissions through the displacement of fossil fuel with biogenically-derived fuel.

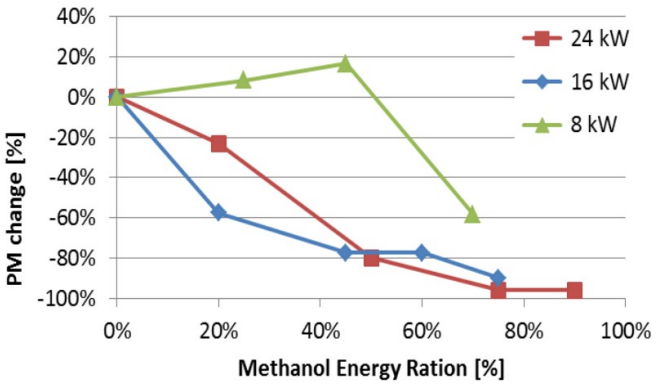

Figure 4 The impact of oxygen content on changing PM emissions. Source: [63] (licensed under CC BY 4.0).

The reduction in PM emissions from fuels with increasing biodiesel content holds true, in addition to FAME, for both di-methyl-ether and methanol fuels. These give very low engine out PM and HC as the fuels are partially oxidised, and these molecules have no carbon-carbon bonds within them which reduces the soot forming potential of the fuel. Fuels that are more diesel-like in their physical properties, such as the oxymethylene methyl ethers (OME), contain a much higher oxygen fraction than FAME containing fuels, even at B100. OME as a fuel for CI engines is at the development stage but also provides a potential route to lower engine-out PM. Also, the use of methane gas within the cylinder (both as a spark ignited pure methane fuel, and as methane/diesel duel fuel, compression ignition engine) reduces PM emissions.

2.2.3 Exhaust emissions control

2.2.3.1 Particulate filters (DPF and GPF)

Particle filters were first introduced at Euro 4 (January 2006) as options for diesel passenger cars, followed by the introduction for DI gasoline at Euro 6 (September 2014) and HD applications at Euro IV (October 2006). All diesel vehicles meeting Euro 6/VI are fitted with a filter. As a physical trap they can mitigate multiple sources of PM; carbon, urea, metal ions and metal oxides (ash), with a very high efficiency. Due to their substrate design, and to the assistance of higher levels of collected soot during engine operation, DPFs have higher filtration efficiencies than GPF.

DPFs typically comprise a ceramic honeycomb matrix where the ends of alternate channels are blocked (Figure 5). Therefore the exhaust gas enters the filter and flows through the gas-porous walls into an adjacent

channel before leaving the filter. The particles cannot transit the walls and accumulate in the blocked inlet channels.

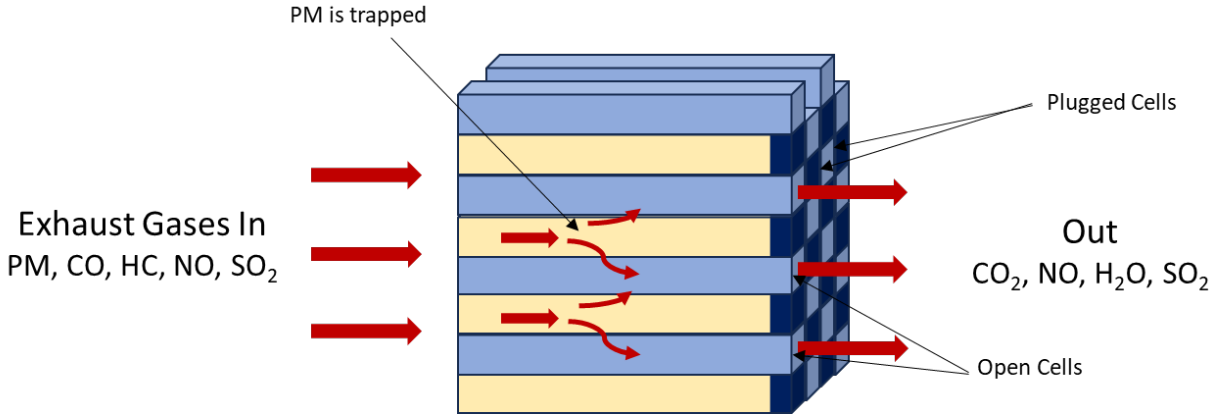

Figure 5 Schematic of a diesel particulate filter showing its honeycomb monolith with the ends of alternative channels blocked. Source: Ricardo

Particulate filters require no reagents, but do become clogged with usage, and therefore require regeneration. This is usually undertaken by injecting additional fuel into the exhaust post engine, to raise the filter's temperature sufficiently to burn off the deposited carbon (much of the caught material). Despite the pore size being much greater than 100 nm, DPFs are very effective at reducing PN emissions of a wide range of particle sizes (<10 nm to >1000 nm), through diffusion and impaction.

Whilst thermal regeneration is effective at removing the majority of carbonaceous material trapped on a filter, it does not remove "ash" particles of metal oxides formed from the combustion of lube oil. (This arises from the oxidation of additives, and is composed primarily of zinc, calcium, and magnesium in the form of sulphates, phosphates, and oxides). A small proportion of the ash (<10%) can escape during DPF regeneration but this is not a significant contribution to ambient PM. Higher proportions of ash may escape from GPFs (<50%) but these emissions are still very low (of the order 0.1 mg/km).

2.2.3.2 Diesel oxidation catalyst (DOC)

DOCs have been fitted to diesel passenger cars since pre Euro 4 and generally at Euro V for heavy-duty (HD) vehicles. (There may have been limit Euro IV HD vehicles fitted with a DOC). DOCs contain precious metals (Pt/Pd) supported on a ceramic monolith. The catalyst, using the excess oxygen in the exhaust gases, can have a significant impact on VOC reduction and a limited impact on carbon reduction. The carbon reducing impact of a DOC is significantly lower than a DPF, as the DOC is a flow through device and does not physically trap then oxidise soot. Soot particles that do impact the walls of the flow-through channels can be eliminated at higher temperatures. The DOC requires no added reagents and is normally fitted upstream of a DPF [64].

2.2.3.3 Three way catalyst (TWC)

TWC have been in production on gasoline engines since pre Euro 4 (January 2006). They contain precious metals such as platinum (Pt), palladium (Pd), and rhodium (Rh) supported on a matrix (often a ceramic monolith). TWCs both oxidise unburnt hydrocarbons and carbon monoxide (reducing HC (VOC) and CO emissions) and reduce NOx to nitrogen when the engine is operating under stoichiometric conditions, cycling between being very slightly fuel rich (λ < 1.0) and oxygen rich (λ >1.0). Figure 6 shows the relative concentrations of NOx, HCs and CO, as a function of the stoichiometric ratio (λ).

The annual roadworthiness emissions test checks both that the engine is running very close to stoichiometric (λ control) and the emitted CO concentration (effectiveness of the oxidation catalyst). Poor lambda control, or a failed catalyst seriously reduces the effectiveness of a TWC.

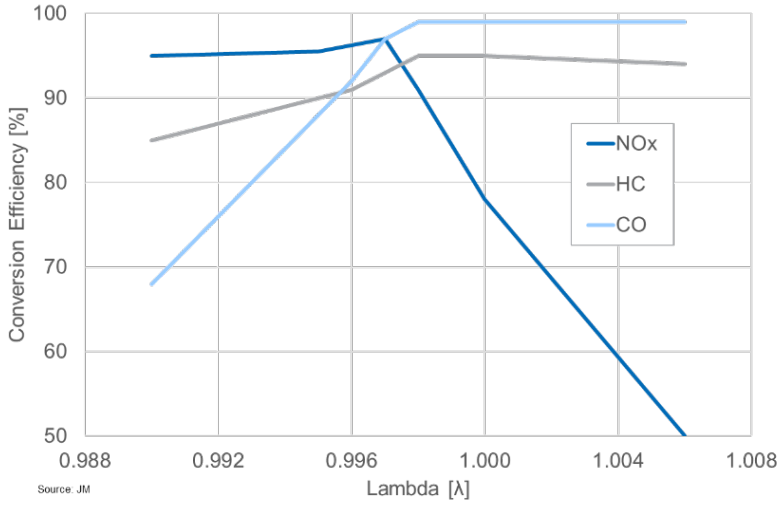

Figure 6 The relative concentration of NOx, HCs and CO, as a function of λ. Source: Ricardo.

2.2.3.4 Lean NOx trap (LNT)

LNT were used by a limited number of OEMs, mostly in the 2000s, on light duty lean burn petrol or diesel engined vehicles. They have been generally superseded by the use of SCR. LNTs operates by storing NOx during normal lean operation (when excess oxygen in the exhaust hinders the chemical reduction of NOx). The LNT must be regenerated periodically by a "rich spike" excursion, a brief event when the exhaust air/fuel ratio (AFR) is reduced providing excess fuel without oxygen present in the exhaust to achieve overall reducing conditions. LNTs NOx reduction potential is around 10 – 20% in passive systems but can be up to 50% in active systems. The NOx removal can potentially reduce the nitrate contribution to PM. However, during a rich event to control NOx emissions, ammonia can be formed by over reduction of NOx. This increases with increased frequency of the rich spikes. Also, as the LNT ages the rich spike selectivity to N_2 reduces and the selectivity to ammonia increases, hence potentially increasing ammonia contribution to PM.

2.2.3.5 Selective catalytic reduction (SCR)

SCR is highly efficient at NOx removal (> 90% at its normal operating temperature) and hence can potentially reduce the nitrate contribution to PM. Consequently it is the dominant technology for controlling NOx emissions from diesel engines (both light- and heavy-duty). An SCR uses a reagent which is added to the exhaust gas, post engine, and then flows over a heated catalyst. The reagent (known as "diesel exhaust fluid", DEF) is a non-toxic solution of aqueous urea. This is 32.5 % urea in purified water, sold under the brand name of AdBlue (registered to the German Association of the Automotive Industry).

However high NOx conversion efficiency requires high DEF injection rates which can lead to ammonia slip. Hence there is a trade-off between NOx and ammonia emissions. This is mitigated in some vehicles by NOx sensors before and after the SCR unit, providing feedback to the DEF injection rate (closed loop control). Generally, however, vehicles have an ammonia slip catalyst (ASC) fitted after the SCR unit. This oxidises the ammonia back to molecular nitrogen.

In addition to emissions of NOx, ammonia and urea, studies have shown an increase in PN emissions, especially PN 7-23 nm which was more significant than PN > 23 nm, attributed to urea. (Discerned from studying increases in PN emissions with increasing urea injection rate relative to injecting different rates of deionised water [65].

2.2.3.6 Heated urea injector

If the DEF used in SCR is injected at too low a temperature, there is the possibility of urea crystals forming and solid urea-based particles being emitted. This risk can be mitigated using heated urea injectors.

Research has shown increased NOx conversion efficiency for gaseous injection of the DEF compared to liquid phase injection [66]. However, this increased NOx efficiency, for gaseous injection, also leads to higher NH_3 emissions. Hence there is a trade-off between NOx efficiency and NH_3 slip leading to the requirement for an ASC (see explanation of this exhaust emission control technology in the following sub-section). Whilst the majority of vehicles using SCR to control NOx emissions use DEF as the reducing agent, researchers have

shown that hydrogen can be used. This can overcome some shortcomings of DEF, namely low activity at low temperatures, ammonia slip etc [67].

2.2.3.7 Ammonia Slip Catalyst (ASC)

Ammonia slip catalysis (ASC) are used to control ammonia slip post SCR catalyst. They are now fitted to many vehicles which are also fitted with SCR. The ASC is dual layer catalyst which mitigates both ammonia, by oxidation, and NOx, via reduction. The latter occurs via an SCR layer, whilst the former uses platinum (as in a DOC or TWC) as the catalyst for the oxidation step [68].

2.3 ROADSIDE AND OTHER MITIGATION TECHNOLOGIES

2.3.1 Vegetation

Vegetation can be used to remove gaseous pollutants from the roadside via stomatal uptake and via dry and wet deposition, deposition is particularly relevant to particulate matter. The use of roadside vegetation to remove particulate matter from urban air has been specifically studied in relation to non-exhaust emissions. The removal efficiency of PM of various sizes by different tree, shrub and vine species was investigated at a site in the south of Poland [69]. High removal efficiency was found in all vegetation types, and these vegetative barriers accumulated fine PM as well as coarser fractions, especially in waxes. The analysed PM contained high concentrations of heavy metals associated with vehicle tyre and brake wear and road abrasion, including iron, titanium, manganese, barium, zinc, chromium, lead, tin, nickel and rare earth elements (REE).

Other studies have investigated PM removal at the roadside via deposition to vegetation without focussing on NEE. Several of these studies consider the species-specific efficiency of PM removal via deposition on vegetation at the roadside [70], [71], [72], [73]. Characteristics of vegetation that can enhance PM capture include stomatal density, size, and the quality of surface waxes [74].

The location of the roads where vegetative barriers can be implemented is of interest. Generally, the focus is on urban areas however vegetative barriers for PM removal can have a high impact on highly polluted routes leading out of cities and industrial areas [71]. The placement of the vegetation in relation to the roadside is also important for PM removal, as is the ability of the plant community, as opposed to individual plants, to accumulate PM. Road-derived inorganic PM deposition within a roadside plant community, stretching from herbaceous roadside border to nearby urban forest, was found to decrease on herbaceous plants with distance from the emission source whilst increasing on the foliage inside the urban forest [71]. The structure of the vegetative barrier also impacts the effectiveness of PM removal. Trees planted in an avenue can cause air turbulence which increases the buildup of PM on their leaf surfaces [74]. Botanical filtration has been found to be effective at removing some roadside $PM_{2.5}$. A field assessment of three different botanical biofilter designs from roadside ambient air in Sydney, Australia found average single pass removal efficiencies of up to 22.1% for $PM_{2.5}$ [75].

As part of a recent EU Horizon 2020 research programme, the “Noise and Emissions MOnitoring and Radical Mitigation” (NEMO) project undertook testing of a multifunctional barrier, installed in Spain [76]. The barrier was designed to reduce noise and air pollution near the roadside, for pedestrians. The multifunctional barrier incorporated a biofilter system, with a fan to remove NOx and PM. Measurements made with air quality monitoring sensors either side of the barrier over four different tests showed a reduction in $PM_{2.5}$ between 30 and 81%.

The feasibility of implementation of vegetative barriers and biofilters is likely to be moderate to high, as planning permission will need to be sought. There is no detailed information on the cost of installing the barriers as these are still in a relatively early stage of development, but costs will include the vegetation itself and there is likely to be ongoing maintenance requirements, so would expect it to be moderate to high, depending on the length of the barrier. It is important for the physical design of the barrier and the vegetation type used to be considered, as these can have an impact on the effectiveness of the barrier [77].

2.3.2 Dust suppression

Resuspended particles comprise particles deposited onto the road surface from brake wear, tyre wear and road surface wear as well as deposited particles from other sources such as exhaust emissions, de-icing and gritting, wind-blown dust and biogenic sources. Dust suppression can reduce the road dust emissions from paved roads by removing or binding particles deposited on the road surface before they can be resuspended

by traffic-generated turbulence. Sweeping, water flushing, and use of chemical suppressants are common techniques.

The effectiveness of street cleaning by sweeping or washing to reduce particulate matter on road surfaces is difficult to quantify due to confounding factors such as rainfall or other meteorological effects. A small number of studies were able to identify improvements in PM_{10} of the order of 2-3 μm m^{-3} and a 6-30% reduction [78]. Combined sweeping and washing has been found to measurably reduce PM_{10} in contrast to sweeping only [3].

Chemical dust suppressants are often used on unpaved roads, especially in mining industries. Calcium magnesium acetate, magnesium chloride and calcium chloride are some of the most commonly used suppressants. Recent studies evaluate the effectiveness of chemical dust suppressants on reduction of PM containing heavy metals, and the associated economic and health impacts [79], [80]. It was found that suppression rates were limited [80], with a maximum rate of around 12% [79]. There is lack of available recent literature on the effect of chemical dust suppressants on paved roads.

2.3.3 Active particulate removal

Pollution Solution is a relatively new company (founded in 2014) that aims to address the issue of air pollution by having developed a solution that can capture, extract and filter pollution on the roads (Roadvent™). Roadvent™ consists of intake slots which sit at the road surface using re-engineered water slot drains, positioned directly adjacent to where brake and tyre dust is emitted. The technology employs a suction technique which is expected to remove particulate matter as well as NOx (independent testing has evidenced a NOx reduction at roadside of 91%). Underneath the intake slots is a pre-formed pipe which connects to a cabinet on the side of the road, eliminating the need for moving parts in or on the road. Power is provided to the roadside cabinet by an independent metered source, 3 phase supply to an inverter.

Air is pulled through the slots in the road and then passed through a series of heavy duty filters, including a mesh which stops larger items from entering along with a HEPA, ESP And Carbon. Future design upgrades may also include a microplastic filter to filter surface water at the front end as Roadvent™ also acts as a water drainage system. Firstly, air flow passes through an electrostatic precipitation (ESP) filter, to remove the majority of micro and submicron particles. Air flow is then directed through a high efficiency particulate air (HEPA) filter, which removes particles down to 0.2 - 0.3 μm. The final stage is an activated carbon filter, this is mainly to remove NOx and VOCs.

Maintenance is mostly automated as rainwater is flushed through, cleaning the Roadvent™ system. As the water enters apertures it gets pushed into the slots below which are drains. The drains are self-flushing and sump pumps can also be used if required when installed on an incline. The slot drains are serviced during normal highways maintenance via road sweeping. The slot drains also have a pre-installed rodding eye inspection chamber, for clearing blockages if they occur. There is also a diagnostic tool which can switch the system off, for example if there is a fuel spill. This is essentially a vapour detector. Maintenance engineers will clean meshes, clean filters, check fans and replace any filters which have reached end of life. HEPA filters are disposed of when they reach end of life. The HEPA filter is under a pressured system which can be used to monitor how blocked up it is and how freely air is flowing through. The activated carbon filters are removed and re-catalysed. For high polluting junctions filters require changing every 3 to 6 months, for lighter use this increases to 9 to 12 months (schedules are estimated and subject to pollution levels).

This technology is ready for market and due to be installed in a live environment at the time of writing. It is a universal system, optimised via CFD, modelling and a live test bed environment. The dual linear positioning of the slots ensures capture of emissions from all brake pads, tyres and exhaust pipe positioning i.e. left, right, side or centre, except for HGV's that have high level exhaust exits (above the cab).

Studies are underway into the effectiveness of the system for mitigating $PM_{2.5}$ emissions. Work is ongoing with Professor Paul Lewis at Swansea University to study the Roadvent™ installation and create a peer reviewed study paper. Based on results from a recent modelling study completed by Professor Paul Lewis on behalf of the Welsh Government, the use of Roadvent™ brought modelled emissions of NOx into compliance, on a previously non-compliant road. The study also found an improvement in health impacts for local residents. The company are also working with a Local Authority to install the technology and do further testing. Independent studies conducted by Cambustion [81] at the Millbrook Proving Ground in Bedfordshire, indicate that Roadvent™ is highly effective at capturing pollution (as it is positioned so closely to the source of emissions). The system can reduce pollution at the roadside by ~91% (based on measurements of NOx). It is expected that a similar reduction would be possible for $PM_{2.5}$ based on the analogy and understanding of PM being 'flow

followers'. The company are looking for an independent party that has the required equipment to test and verify this. As the system uses re-engineered water drains for the vents the feasibility for implementation is moderate to high, depending on the target area.

Other types of active particle removal include devices mounted on the roadside [82] or on vehicles [50], [51], [83]. Gulia et al. [82] undertook a study to assess the performance of roadside air purifiers in Delhi, India. “Wind Augmentation and purifYing Units” (WAYU), developed by the National Environmental Engineering Research Institute (NEERI) and IIT Bombay, were installed at five different traffic intersections in Delhi. As the units were stand-alone systems the feasibility of implementation is high. There is no information however on the maintenance schedule or cost for implementation. There are two designs of the WAYU. The S-shape WAYU has a flow rate of 1250 m^3/h or of 2500 m^3/h, and the Mushroom shape WAYU a flow rate of 2500 m^3/h. Each device contains Non-Woven Fabric filters for removing the particulates. The average efficiency of the air purifiers in removing $PM_{2.5}$ was determined to be 19–25%.

2.3.4 Road surface properties

Since tyre and road wear is dependent on the road surface properties, the emission of tyre and road wear particles can be addressed through changes in the road surface material. Solutions to reduce tyre and road wear particles focus on the improvement of rubber compounds and asphalts as these are the materials that generate the greatest quantity of wear particles. Increases to traffic speed and vehicle weight loads has reduced the lifespan of asphalt roads. To address shortened lifespans and to reduce particulate matter, various modifiers and additives have been tested. To support circular economy, rubber crumb (recycled from tyres) has been added to asphalt for road pavements [84]. These mixtures can have increased road durability compared to other mixtures [4], [85]. One study also showed that a rubber crumb asphalt mix reduced tyre wear emission rates by 1.4 to 2 times when compared to plain cement concrete (PCC) road surface [86].

A double layered porous asphalt (DLPA) features a smooth but hard-wearing top layer of fine aggregates with a lower layer of coarser aggregates, providing a high air void ratio [87]. Measurements performed close to the DLPA road indicated a 52% reduction in PM_{10} concentrations compared to conventional asphalt [88]. Atmospheric measurements of NOx and PM_{10} performed for 7 months along a road stretch containing two different surfaces, one DLPA and one stone mastic asphalt (SMA), found PM_{10} concentrations were significantly lower at the porous pavement during all meteorological conditions [89]. The authors of the study suggested that this is due to the removal of road dust from the surface into the pores of the pavement, the reduction of the air-pumping suspension forces of the tyres, and the prolonged drying of the surface as water is retained within the pores.

In environments with low road dust loads the emission reduction effect of the DLPA is likely to be lesser but more long-lasting than where road dust is abundant, as the porous surface becomes clogged and requires cleaning. Indeed clogging is the main issue with this abatement technique, as the ‘infiltration capacity’ of the mixtures decreases with use. The infiltration capacity of the porous surface of the DLPA has been found to partially recover after performing simple maintenance [90].

A recent review of the strategic road network in the UK notes that the most commonly used material within the network is thin surface asphalt as this is considered to provide a longer lifespan than porous asphalt [91]. TfL states that “The use of porous asphalts in the UK is rare with the exception of minor roads and car parks and there is currently no national guidance available to highway authorities” [92].

‘Environmentally-friendly’ photocatalytic roads which can trap and degrade pollutants emitted from car exhausts include materials such as anatase titanium dioxide, zinc oxide and graphite-phase carbon nitride [93]. The main issue with this technique is that the abrasion and peeling caused by vehicle traffic and environmental factors decreases the efficiency of the process. A recent study evaluated the long-term mechanical performance of the pollutant trapping and degradation capacity of innovative self-cleaning roads [94], [95]. Urban and peri-urban asphalt mixtures were designed and tested for their durability and performance in mitigating pollutants and microplastics. Tests on the collection of microplastics in the asphalt is currently ongoing.

With any change in road surfacing the feasibility of implementation and the costs are expected to be high, as the road surface will need to be relayed. The new road properties will also need to be durable to wear, to ensure that maintenance time and costs do not increase when compared to standard road surfaces.

3. SUMMARY

3.1 KEY FINDINGS

3.1.1 Non-exhaust emissions

NAO brake pad materials offer potential for reductions in $PM_{2.5}$ and PM_{10} of 20%-65% for European vehicles compared to low/semi-metallic pads, but with a reduction in braking capability, which limits feasibility for adoption. However, developments in new pad materials with a hybrid of NAO and low-metallic properties show potential to enable a reduction in PM emissions, while maintaining performance and safety, and may be possible to retro-fit.

Brake disc coatings using ceramic-metallic compounds such as tungsten-carbide show potential for significant reductions in disc wear and $PM_{2.5}/PM_{10}$ emissions of between 20% and 80%, although the impact is highly dependent on drive cycle. Laser cladding is a favoured technology although other developing technologies also show promise. Coated discs will require suitably matched pad materials, and discs and pads will need to develop together.

Regenerative braking will become widely adopted alongside vehicle electrification due to its efficiency benefits. It's effectiveness at reducing PM emissions will depend on the nature of the drive cycle, and the vehicle architecture, with the greatest benefit for all-wheel-drive vehicles with high motor power and good battery capacity. Brake $PM_{2.5}$ reductions of 50% to over 80% appear possible. However, the additional battery weight of electric vehicles increases overall weight by around 15-20% which increases the abrasion and emissions of brakes, tyres, and road, and in some cases (such as vehicles fitted with lower-emission NAO pads) regenerative braking may barely mitigate the total vehicle $PM_{2.5}$ emission increase. Nonetheless, when secondary exhaust PM is considered, EVs with regenerative braking can show significant (~50%) reductions in total $PM_{2.5}$ compared to diesel and petrol vehicles.

A range of both passive and active brake particle capture systems have been developed by different manufacturers that enclose or partially enclose the brake, suck particles into a cannister, or use a magnet. There is no universal and comparable measure of $PM_{2.5}$ reduction effectiveness, and claims vary in assumptions. Those that enclose the brake wholly or partially may risk increasing temperature and emissions if they don't also provide additional cooling. Those with active extraction of particles appear to show the most promise, and may have similar costs to exhaust filtration systems, although they also draw a little vehicle power and require a control strategy to balance energy use with effectiveness. The MANN+HUMMEL and Tallano systems are demonstrated and appear to be ready for pilot/commercial deployment.

Euro 7 brake emissions standards are likely to lead in the short term to the adoption of revised brake pad and disc compositions as a low-cost solution for lighter vehicles, and coated discs with matched pads on heavier and more expensive vehicles. The technology choice will depend on the current level of emissions and the reduction needed, which will depend on vehicle mass as well as brake design. Electrified vehicles will utilise regenerative braking, but electric vehicles have greater mass and lower brake emissions targets are expected at Euro 7, coated discs may be an attractive option for avoiding corrosion as well as reducing emissions. Active particulate reduction systems may be used where vehicles cannot meet the limits without them, to meet reduced emissions limits in the longer term, or if they prove cheaper to implement than coated discs when commercialised.

Current production tyres show a range of abrasion rates which suggests there is scope for some manufacturers to reduce wear rates, and so reduce the average wear rate. The established view is that there is limited scope for significant reductions in tyre wear without compromising safety, and only incremental improvements are feasible. However, ENSO claim to have demonstrated significant (~35%) reductions in abrasion combined with 10% lower rolling resistance while claiming similar grip performance to the tyres they replaced, as well as starting to reduce the use of toxic substances and increasing bio-based materials in the tyre. Airborne PM constitutes a small proportion of total tyre wear, and the relationship between abrasion rates and particulate emissions is not well understood but is thought to vary according to tyre compound, and so a reduction in abrasion rate may not always result in a reduction in $PM_{2.5}/PM_{10}$ emissions. It is expected that the greater weight of electrified vehicles will increase tyre abrasion due to the increased loads on tyres. The limits on tyre abrasion for the Euro 7 standards are not yet clear but are likely to promote best available tyre technology performance in the near term.

On-board collection of tyre particles is challenging since the tyre-road interface is an open system that cannot be enclosed and is in a turbulent airflow contaminated with other particles and sometimes water, and fewer systems are in development than for brakes. The use of the electrostatic properties of the tyre particles offers a promising pathway to their collection, and The Tyre Collective device has been demonstrated. An alternative approach using ducted airflow has been explored in laboratory conditions. However, measuring tyre particle emissions is even more challenging than for brakes making understanding and comparing the effectiveness of $PM_{2.5}$ reduction difficult. For this reason, it's unclear whether the use tyre particle collection devices will be incentivised by emissions standards.

Instead of mitigating brake and tyre wear directly, MANN+HUMMEL have an alternative approach in which ambient PM is collected via an external or integrated filter to offset that emitted by the vehicle. $PM_{2.5}$ collection (reduction) effectiveness will depend on ambient $PM_{2.5}$ concentration. The integrated solution may be being simpler to deploy into a vehicle than targeted collection devices. The external retrofittable device may be attractive to local authorities to adopt for public service vehicles (buses, taxis, refuse collection) to improve local air quality and as such could be considered a similar approach to deploying roadside filters.

3.1.2 Exhaust Emissions

Emissions of $PM_{2.5}$ from internal combustion engines result from the incomplete combustion of the fuel, impurities within the fuel, lubrication oil entering the combustion chamber, and secondary effects of NOx emissions in the atmosphere. Technology to mitigate PM from vehicle exhaust emissions has been developed over many years in response to increasingly stringent emissions standards and so can be considered mature. With little significant change for PM/PN standards likely from Euro 7 there is limited pressure to further develop or introduce new particulate mitigation technologies. From this review, fuel standards are also seen to be important in mitigating PM emissions.

While engine combustion systems are designed to ensure effective and efficient combustion which reduces PM and NOx formation, it is the exhaust aftertreatment technologies which have the largest impact on reducing $PM_{2.5}$ and other pollutants from the tailpipe. These include catalysts to reduce HC and NOx emissions (TWC for gasoline, DOC for diesel), catalysts to target NOx and ammonia (SCR, LNT, ASC) from diesel vehicles, as well as particulate filters to trap PM, then burning them off in regeneration (DPF for diesel, GPF for gasoline engines). These systems have a high effectiveness when operating correctly, however there is an importance of in-service roadworthiness testing to ensure these technologies are properly functioning in use.

Alternative fuels can lead to reduce PM emissions. Gaseous fuels such as methane result in less PM emissions than similar diesel engines, although there is a risk of methane slip (fugitive emissions). Biodiesel and synthetic diesels exhibit lower PM emissions than fossil diesel. Using hydrogen as a fuel in an internal combustion engine would eliminate PM emissions from the fuel completely, although low levels of NOx emissions would be expected along with traces of PM from lubrication oil and urea.

3.1.3 On-road/roadside

On-road and roadside technologies do not focus on one particular source of pollution but are designed to remove or filter particles that are present at the roadside environment. This includes, brake wear, tyre wear and exhaust emissions, but also road wear and resuspended dust. The benefit of these technologies is that modifications do not need to be undertaken on the vehicle itself. However, as the systems are not located directly at the source of the emissions, there will be a lot of dispersion before the capturing, meaning the impact on the local area may be minimal. In addition, the cost of running these devices tends to be much higher than low emission pads/tyres or on-board capture devices and so are not likely to be implemented widely in the near future. Pollution Solution already have a system in production and are targeting their Roadvent devices at locations such as air quality management areas, outside of hospitals, drive-thru restaurants, click-and-collect stations, outside schools, bus stops and traffic hotspots. These are areas where vehicles may be idling, and employees or members of the public are also located, so the impact is maximised while limiting the section of the road with the technology installed.

Pollution reduction techniques such as vegetative barriers can be less costly and targeted barrier systems have been shown to be very effective at reducing $PM_{2.5}$. Their effectiveness is dependent on location, structure and vegetation type. Street cleaning, sweeping and chemical dust suppressants can also be targeted to certain areas or roads to increase the efficiency of PM removal. However, this type of mitigation is not very efficient, and it requires ongoing resourcing, for example for frequent deployment of mechanical sweepers.

As PM is accumulated on the road surface before dispersion into the environment, an alternative to roadside capture is the use of the road surface itself as a trap for PM. A number of materials have performed well during testing, using coarser and more porous material to act as a sink to trap PM. The durability of the materials used is variable and modified road surfaces work best in non-urban areas where braking and acceleration is less frequent than in urban areas, causing less abrasion of the road surface. Implementation of this technology would be a long-term process, with considerable disruption caused by replacing current roads and a high associated cost.

3.2 OVERVIEW OF TECHNOLOGIES AVAILABLE

Table 5 below provides an overview of the main technologies reviewed. The Technology Readiness Levels (TRL) is a scale of 1-9 developed by NASA that describes how mature the product/technology is. A description of each TRL relevant to the technologies discussed here is given in Table 4.

Table 4 Technology Readiness Levels.

TRL	Description
9	System proven in operational environment and technology available to customers
8	System complete and qualified
7	Prototype system demonstrated in operational environment
6	Technology demonstrated in operational environment
5	Technology validated in operational environment
4	Testing of technology under laboratory conditions
3	Proof of concept established
2	Technology concept formulated
1	Basic principles observed and reported

Table 5 Summary table of technologies.

Area	Company	Technology	Potential for mitigating $PM_{2.5}$	Technology Readiness Level (TRL)	Feasibility of implementation	Maintenance schedule	Cost of implementation
Brakes	Brake manufacturers	NAO brake pads	Moderate-high: 20%-65%	TRL9; In production in some markets	Limited in Europe due to more demanding brake requirements	May be reduced compared to low metallic pads due to reduced disc wear	Negligible – similar cost to existing pads
Brakes	Brembo, other brake manufacturers	New brake pad materials	Unclear but likely low-moderate (less than NAO)	TRL5-8; some in pre-production validation	High: If costs, PM reduction, and performance can be balanced. Potential to retrofit	None/unclear	Small cost increase over existing pads likely
Brakes	Brembo, other brake manufacturers	New low-emission brake pad materials	Unclear but likely low-moderate (less than NAO), optimised to meet Euro 7 for vehicle	TRL5-7; some in pre-production validation	High: If costs, PM reduction, and performance can be balanced. Potential to retrofit	None/unclear	Small cost increase over existing pads likely
Brakes	Brembo, other brake manufacturers	Low wear cast iron disc and optimised pads ("Greenance" kits)	High: Website claims up to 80% but likely to be less than coated discs	TRL7-8; in validation and available for some applications	High: Straight component swap, suitable for retrofit ("Greenance" kits) or OEM fitment	Disc replacement less frequent vs conventional CGI	Unclear but small cost increase over existing disc likely – cheaper than coated discs.
Brakes	Vehicle manufacturers, electric powertrain suppliers	Regenerative braking systems (RBS)	Moderate-high: 50-80% Low-moderate: 0-50% vs total EV PM increase due to weight	TRL8-9 with electric and hybrid vehicles	Excellent with electric and hybrid vehicles Weight of battery increases brake emissions before	Fit and forget. May reduce frequency of brake replacement if	Negligible for electric powertrains, used for efficiency gains so overall

Area	Company	Technology	Potential for mitigating $PM_{2.5}$	Technology Readiness Level (TRL)	Feasibility of implementation	Maintenance schedule	Cost of implementation
					RBS and tyre abrasion	corrosion risk is managed	cost benefit is likely
Tyres	All tyre manufacturers	Optimised tyre compounds for reduced wear	Low: 10-20%	TRL6-9:	Incremental improvements especially for highest abrasion tyres, limited by performance trade-off	None, although reduced abrasion rates may reduce frequency of tyre replacement	Small-medium cost increase for lower price tyres
Tyres	ENSO Tyres	Optimised bio-based materials and manufacturing	Unclear for $PM_{2.5}$ but total mass emission reduction of >30%, aiming for 50%	TRL8-9: Used in some van fleets and London taxis	Medium-High: No clear reason why other tyres could not achieve similar improvements	None but tyre replacement frequency reduced	None – cost savings possible.
On-board capture devices (Brake)	Tallano	TAMIC® Active and passive brake wear capture devices	High: 83%	TRL7-8	Moderate-high: Requires modification of brake pad and installation of capture device. Potential for integration in the future	Low: Filter change every two years or 30,000 km	Moderate
On-board capture devices (Brake)	MANN+HUMMEL	Passive brake wear capture device	Low: 10-20%	TRL7-8	High: Can be designed to fit to existing calliper.	Filter change during vehicle service	Moderate
On-board capture devices (Brake)	MANN+HUMMEL	Active brake wear capture device	Moderate-high: 60% if energy saving, 80% if continual	TRL7-8, ready for integration into vehicle design	Moderate-high: Depends on if designed/integrated into vehicle	Filter change during brake service or vehicle service	Moderate

Area	Company	Technology	Potential for mitigating $PM_{2.5}$	Technology Readiness Level (TRL)	Feasibility of implementation	Maintenance schedule	Cost of implementation
On-board capture devices (Brake)	OGAB	Brake wear capture device	Moderate-very high: Potential of up to 100% of PM	TRL5-7	Moderate – high: Requires enclosure around brake system and vacuum system to be installed	Unknown	Unknown
On-board capture devices (Tyre)	Tyre Collective	Tyre wear capture device	Moderate-high: 20-80%	TRL5-6; some being tested in pilot studies	Moderate: Requires fixing to vehicle.	Monthly, to remove the collected particles. Currently working on an on-board cannister to remove particles via suction.	Moderate
Exhaust emissions	Johnson Matthey BASF Umicore	Catalyst Chemistry	Can reduce precursors to $PM_{2.5}$	TRL9: In production	In production	Fit and forget	As part of base engine cost
Exhaust emissions	Corning NGK Ibiden	Catalyst Substrate incl DPF	Best technologies can reduce $PM_{2.5}$ by >90%	TRL9: In production	In production	Passenger car DPFs are service free, HD applications require ash cleaning	As part of base engine cost
On-board capture devices (Ambient)	MANN+HUMMEL	“PureAir” roof box	Unclear, depends on ambient PM	TRL7-9: in use on refuse trucks in Singapore	Low for private vehicles, high for public service vehicles. External installation on roof.	Filter change every 1-2 years / 1,500 hours of operation	Moderate - High

Area	Company	Technology	Potential for mitigating $PM_{2.5}$	Technology Readiness Level (TRL)	Feasibility of implementation	Maintenance schedule	Cost of implementation
On-board capture devices (Ambient)	MANN+HUMMEL	Integrated fine dust particle filter	Moderate-very high: 45-200+%, depends on ambient PM	TRL6-7: prototype and concept design. Website states market ready	Moderate-high : Depends on if designed/integrated into vehicle	Filter change every 1-2 years (vehicle service)	Moderate
Road/roadside	Pollution Solutions	Roadvent™	Very high: ~91% based on NOx and assuming similar for PM	TRL9: In production	Moderate-high: Depends on target area. Uses re-engineered water drains for vents.	Filter changes every 3-6 months (high pollution areas), 9-12 months (lighter use)	Moderate-High
Road/roadside	National Environmental Engineering Research Institute (NEERI) and IIT Bombay	Wind Augmentation and Purification Units (WAYU)	Low: 19–25% efficiency in removing $PM_{2.5}$	TRL6-7: Demonstrated in Delhi.	Low-moderate: Unit can be installed at roadside.	Unknown	Unknown
Road/roadside	Road surface manufacturers	Double layered porous asphalt (DLPA)	Moderate – high: 52% reduction in PM_{10}, possibly similar for $PM_{2.5}$	TRL5-6; some being tested in pilot studies	High: Requires relaying of road surface.	Unknown	Unknown
Road/roadside	Biofilter manufacturers	Vegetative barriers and biofilters	Low-high: 20-80% depending on design	TRL5-6; some being tested in pilot studies	Moderate-high: Depends on target area.	Unknown	Unknown

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APPENDICES

APPENDIX 1 SEARCH TERMS AND RESULTS

Mitigation focus	Common Search Terms	Initial number of documents retrieved	After 1st Screening	After 2nd Screening
Tyre wear emissions	alternative, material, composition, tyre, tire, wheel size, dimension, thick, filter, collect, filtrate	583	119	39
Brake wear emissions	disc, brake, pad regen, recover, alternative, material, filter, collect, filtrate	456	183	49
Road/Roadside	surface wear, abrasion sweep, road dust, resuspension wash, suppress, bind, barrier, veg, green, botanic	73	30	16
Exhaust emissions	Particle Filter, Carbon free fuels (H_2 & NH_3), O_2 containing fuels, Calibration, Particle Filter, NH_3 Injection, Heated urea injectors, ASC, H_2 as reductant, SCR, LNT, TWC, ASC, Oil Quality, DOC	20	13	-

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