



ROAD WEAR AND DUST RESUSPENSION

Final Report

Report for: Department for Transport

Ref. T0414 TETI0037

Ricardo ref. ED14775

Issue: Issue 2

5 September 2025

Customer:

Department for Transport

Customer reference:

T0414a TETI0037

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EXECUTIVE SUMMARY

Fine particulate matter (PM) with a mean aerodynamic diameter of 2.5 micrometres (μm), also known as $\text{PM}_{2.5}$, is a serious concern in the atmosphere due to its adverse health impacts¹, and is the subject of recent UK Government target setting legislation² to reduce exposure and concentrations. Road transport is a significant source of PM in the UK, and with vehicle exhaust emissions being reduced through stringent emissions standards and increasing adoption of electrified vehicles, non-exhaust emissions (NEE) are now the primary source of both PM_{10} and $\text{PM}_{2.5}$ from the road transport sector, based on pollutant emissions estimated by the National Atmospheric Emissions Inventory (NAEI). In 2023, road transport emissions of $\text{PM}_{2.5}$ in the UK were estimated at 16% from exhaust, 59% from brake and tyre abrasion, and 23% from road abrasion³. PM from resuspended material already present on the road which is uplifted into the atmosphere by the tyres or the wake flow of the vehicle as it is moving can also contribute to NEE but are not included in the NAEI estimates. Much research is focusing on brake and tyre emissions including that supported by the Department for Transport (DfT) and National Highways in the UK, but for road wear and dust resuspension there are still many gaps in current knowledge.

The aim of this study is to identify the factors thought to affect the contribution of road wear and resuspension to $\text{PM}_{2.5}$, understand where knowledge gaps exist, explore measurement methodologies and abatement solutions for road wear and dust resuspension, and to make recommendations for further research to increase understanding and to improve current emissions factors. The study has relied on literature review with expert analysis for a rapid assessment.

The factors influencing road wear and dust resuspension can be categorised into four main areas:

- 1. Vehicles.** The size, weight, and tyre type can all affect road wear. However, while there is evidence to link vehicle weight and axle load to road degradation, there is little evidence for their impacts on $\text{PM}_{2.5}$ formation. Vehicle torque has been cited as a cause of greater tyre wear for electrified vehicles and may also affect road wear. Future Euro emission standards are expected to drive development of tyres with lower abrasion rates, but little is understood about how that might affect $\text{PM}_{2.5}$ from tyre and road wear.
- 2. Vehicle dynamics.** including driving style and road layout. Particle emissions measured from the road have been shown to increase with vehicle speed. However, most studies focussed only on PM_{10} and the relationship between speed and emissions varies between studies. PM emissions are also seen to increase where vehicles brake, accelerate, or corner (especially at higher speeds), and where traffic density is high. However, there is little information on the potential effect of road layouts and traffic management.
- 3. Road Characteristics.** Studies show that there are mainly three road related characteristics that can affect tyre road wear: road geometry, surface characteristics and materials. Although road geometry may influence tyre and road wear, due to the different speed levels and manoeuvres undertaken by vehicles at e.g. junctions, it is likely that this will be a less relevant factor in the UK as there are fewer opportunities to build entirely new roads versus maintenance and renewals⁴. In terms of surface characteristics, studies have shown how surface macro- and microtexture affect tyre wear, with older degraded surfaces that tend to generate higher emissions. Greater dust resuspension is also observed in countryside or industrial areas due to deposition from other sources. In terms of materials, studies have shown how concrete surfaces tend to generate higher PM emissions than asphalt, that harder quartzite aggregate can result in lower PM emissions and that porous surfaces can trap dust. A comparison of two quartzite aggregate sizes also showed that the smaller aggregates can reduce PM emissions. Although it is clear that road surfaces can affect PM emissions, as well as grip, noise, and rolling resistance, no studies have been found on the effect of road types and condition on road wear for UK roads.
- 4. Climate.** Road surfaces can be damaged by changes in temperature mixed with effects of precipitation and humidity, increasing wear as noted above, although there is limited evidence linking climate to road

¹ Chief Medical Officer's Annual Report 2022: Air Pollution (<https://www.gov.uk/government/publications/chief-medical-officers-annual-report-2022-air-pollution>)

² [The Environmental Targets \(Fine Particulate Matter\) \(England\) Regulations 2023](#)

³ NAEI, 'Air Pollutant Emissions Data | National Atmospheric Emissions Inventory', Air Pollutant Emissions Data. Accessed: Mar. 07, 2025

⁴ Shaping the future of England's strategic roads (<https://www.gov.uk/government/consultations/shaping-the-future-of-englands-strategic-roads/shaping-the-future-of-englands-strategic-roads>)

dust emission. Climate change, with more extreme temperatures and increased rainfall, may result in more roads being damaged and an increase in wear. Road dust emissions are suppressed (temporarily) by wet surfaces and have also been observed to be affected by wind speed.

The review has highlighted the limitations of the current emissions factors for road wear and dust resuspension in the UK. Currently, the Tier 1 and Tier 2 road wear emission factors in use come from the European Monitoring and Evaluation Programme/European Environment Agency (EMEP/EEA) guidebook. Many studies are based on, and decisions informed by these emission factors, yet these are derived from very limited measured data. The factors are only segregated into four different vehicle types (heavy duty vehicles (HDVs), light goods vehicles (LGVs), cars and two-wheelers), and do not consider variations in vehicle load, vehicle speed, road surfaces, or climate. For resuspended dust there are no emission factors within the Guidebook. Other countries have developed models and methods for estimating road dust emission factors; however, the results from these vary widely, and there is no standard methodology.

With improved emission factors, and a better understanding of the effect of the different variables on road wear and resuspended dust emissions, modelling studies can be undertaken which can inform future mitigation methods, such as reducing vehicle load, introducing speed limits, and other traffic or vehicle measures to promote smoother driving and reducing the number of vehicles on the road.

Non-vehicle-based mitigation methods to address PM_{2.5} emissions from road vehicles are limited. They include suppression through sweeping, street washing, or chemical suppressants, roadside vegetative barriers, and active particle removal systems to filter air close to the road. All are likely to be suited to limited areas only, where locally high PM is an issue, potentially where major roads are close to housing, schools or hospitals.

The main findings from the literature review and evidence gaps identified are summarised in the table.

Area	Current understanding	Evidence gaps
Road surface condition	- Older roads can result in higher dust loadings and increased resuspension - Older roads can emit finer material	- Variation in PM_{2.5} emissions due to pavement deterioration (e.g. aggregate shape, micro- and macrotexture over time) is unknown - No information on whether large cracks/potholes or pavement unevenness can increase wear - No published studies on UK roads
Road materials	- Combined tyre and road wear emissions shown higher for concrete than asphalt - Smaller aggregates (e.g. 11 mm) can result in lower emissions than larger (e.g. 16 mm) - Porous pavements can better trap particles	- PM_{2.5} emissions for aggregates used in the UK (and pavement macrotexture) are unknown - PM_{2.5} emissions for the different materials typically used in the UK (e.g. concrete vs asphalt, but also in between different types of concrete and asphalt mixes) are uncertain - Whether tyre-road wear can be reduced without affecting skidding resistance or other attributes
Effect of vehicle load	- Wear increases with vehicle mass/load/size - Mass increases acceleration and braking forces - Axle load is important	- Many studies rely on emission factors based on limited evidence - Link between road degradation wear and particle emissions is unclear - Large variability between studies for the weight-emissions relationship
Effect of vehicle speed	- Higher vehicle speeds typically result in higher resuspended PM₁₀ and PM_{2.5} emissions - Road dust loading higher at lower vehicle speeds	- No clear information on whether/how vehicle speed affects road wear - Large variability between studies for the speed-emissions relationship

Area	Current understanding	Evidence gaps
	Studded tyres have a larger impact on road dust emissions at higher speeds	
Effect of braking and acceleration	- Increase in particles smaller than 10 µm measured above the road during vehicle acceleration and deceleration - Harsher braking can result in higher PM₁₀ and particle number concentrations	- No studies solely on the effect of braking and acceleration on road wear - Measurements are influenced by brake particles during the braking events - Higher torque of electric vehicles is sometimes highlighted in literature, but no direct evidence of impact on road wear
Effect of road layout & traffic management	- Lower traffic volumes result in lower road dust due to less turbulence - PM₁₀ and PM_{2.5} increased when closer to braking zones due to more particles being deposited on the surface - Larger roundabouts have higher emissions due to faster cornering speeds	- No published studies that directly investigate road layout and traffic management effects on PM_{2.5} emissions from road wear and dust resuspension. - Limited evidence linking road wear rate to rate of braking/acceleration
Climate change and seasonal effects	- High humidity and precipitation can suppress road dust emissions - High winds can affect road dust loadings	No studies consider if temperature or precipitation changes may directly affect road wear emissions
Emission factors	- EMEP/EEA Guidebook provides road wear emissions factors for different vehicles - Range of different methods for calculating road dust resuspension emission factors	- No standardised method for determining emission factors - Independent of vehicle speed and weight, road type, precipitation - High uncertainty for road wear - No emission factors for road dust in EMEP/EEA guidebook

To address these evidence gaps, ideas for potential research campaigns have been developed using both laboratory and on-road testing approaches. These include:

- Evaluating road wear and emissions of different surfaces under controlled laboratory conditions.
- Evaluating tyre, road wear, and resuspension particle emissions from vehicle(s) in the real world in varied driving and across different road surface types and condition.
- Evaluating the particles found on road surfaces in the real world, across different road types and locations, and assess their likely sources and contribution to (resuspension) particulate emissions.
- Evaluating the potential for road surface materials to form particulate emissions as they wear.

These have been further developed into draft research programmes designed to close the gaps in the current understanding of the road wear and dust resuspension related challenges, with a focus on the UK road network. Depending on the outcome of the initial testing, further research could cover more conditions, road surfaces, and other factors, with the results that could feed into recommendations for updates to national road materials and pavement specifications.

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GLOSSARY

Term	Meaning/definition
Aggregate	Material that is formed from different elements that are used for pavements
Ambient	Defined here as outdoor air or atmosphere
BEV	Battery electric vehicle – vehicles powered fully by batteries
Binder	Material that is used to bind together the road aggregate
Emission Factors	A factor that describes the rate of emissions into the atmosphere
DMRB	Design Manual for Roads and Bridges
DfT	Department for Transport
HDV	Heavy duty vehicle – gross weight exceeding 3.5 tonnes
Hybrid vehicle	Vehicles that have a battery and a fuel tank. The battery is charged via regenerative braking alone
ICE	Internal combustion engine – vehicles that use fossil fuels
ISO	International Organisation for Standardization – The group develop and publish standards for goods, services and measurements
LGV	Light good vehicles – gross weight 3.5 tonnes or less
MCHW	Manual of Contract Documents for Highway Works
NAEI	National Atmospheric Emissions Inventory
NEE	Non exhaust emissions
Pavement	Paved surface e.g. road
PHEV	Plug-in hybrid electric vehicle – vehicles that have a battery and a fuel tank. The battery is charged via regenerative braking and a charging port
PM	Particulate mass or particulate matter
PM ₁₀	PM sampled with an inlet of 50% efficiency at 10µm
PM _{2.5}	PM sampled with an inlet of 50% efficiency at 2.5µm
Road simulator	A mechanical system that simulates wear and from tyres on a road surface
Tribology	The study of friction, lubrication and wear
TRWP	Tyre and road wear particles
Silt load	Amount of loose material present on the road surface
µm	Micrometres (10 ⁻⁶ m)

1. INTRODUCTION

1.1 BACKGROUND

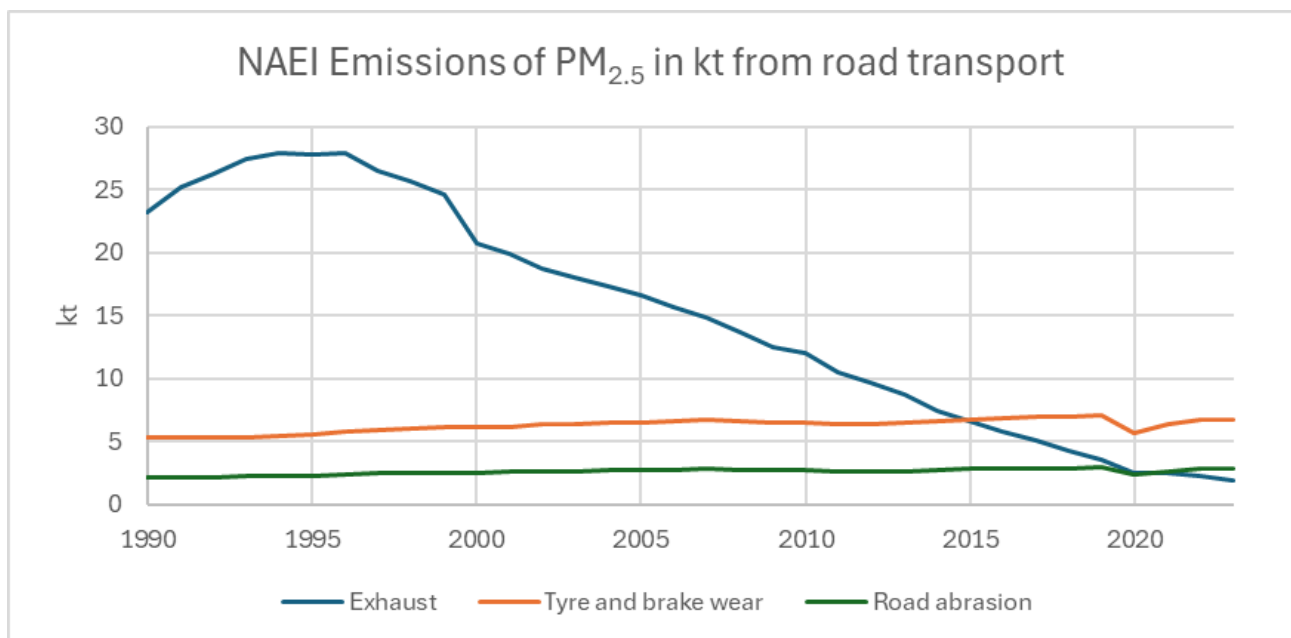
Particulate matter (PM) is comprised of many different species and can vary in size and shape. Sources of PM include emissions from combustion, transport, industry, and natural sources, such as dust and sea salt. PM can be emitted either directly (primary PM) or can form in the atmosphere via chemical reactions (secondary PM).

Fine particulate matter (PM sampled with an inlet of 50% efficiency at a diameter of 2.5 μm), also known as $\text{PM}_{2.5}$, is a serious health concern in the atmosphere. These small particles can travel deep into the lungs when breathed in, causing adverse health impacts[1]. Under the Environment Act 2021, targets (which are to be met by 2040) have been established by the Government for $\text{PM}_{2.5}$ in England⁵, which are:

- Annual mean concentrations of $\text{PM}_{2.5}$ to be 10 $\mu\text{g m}^{-3}$ or lower at all relevant locations.
- Population exposure to $\text{PM}_{2.5}$ to be reduced by 35% compared to 2018 levels.

Road transport is a large source of primary PM in the UK [2]. PM emissions from the road transport sector consist of both exhaust and non-exhaust emissions (NEE). NEE include brake wear, tyre wear, road wear and resuspension of road dust. As shown in Figure 1-1, exhaust emissions of $\text{PM}_{2.5}$ peaked in 1996 and have decreased since then, with 93% lower $\text{PM}_{2.5}$ emissions in 2023 compared to 1996. This decrease is the result of aftertreatment technologies (e.g. Diesel Particulate Filters) being implemented in order for vehicles to meet emissions standards. On the other hand, emissions of $\text{PM}_{2.5}$ from tyre and brake wear over the same period increased by 17.5 % and road wear/abrasion by 19.9 % , and NEE are now the primary source of both PM_{10} and $\text{PM}_{2.5}$ from the road transport sector. For 2023, the estimated contribution of exhaust, brake/tyre wear, and road abrasion to road transport emissions of $\text{PM}_{2.5}$ in the UK are, 16%, 59% and 23% respectively [3].

Figure 1-1 The UK National Atmospheric Emissions Inventory estimated emissions of $\text{PM}_{2.5}$ in kilotonnes (kt) from road transport in the UK from 1990 to 2023 (NAEI, 2025) [3]. © Crown 2024 copyright Defra & DESNZ via naei.energysecurity.gov.uk, licenced under the Open Government Licence (OGL).



1.2 STUDY OBJECTIVES

To develop policies to reduce concentrations of $\text{PM}_{2.5}$ in the atmosphere (ambient $\text{PM}_{2.5}$) it is important to understand the dominant sources. The Department for Transport (DfT) and National Highways are supporting

⁵ <https://www.legislation.gov.uk/ukxi/2023/96/note/made>

work to investigate tyre and brake wear[4], [5]. However, there have been limited studies on road wear and dust resuspension both in the UK and internationally.

Road wear occurs due to the friction between the tyres and surface of the road as vehicles are moving. Larger wear particles ($> 100 \mu\text{m}$ in diameter) typically remain on the road or get washed away; however, the smaller particles can become airborne. As the mechanisms for formation are the same, tyre wear and road wear emissions are often combined in studies as tyre and road wear particles (TRWP), although their chemical compositions are very different.

Resuspended dust consists of material that is already present on the road and is uplifted into the atmosphere by the tyres or the wake flow of the vehicle as it is moving. Resuspended dust can include both exhaust and non-exhaust emissions, as well as other sources of particles that have been deposited on the road (e.g. mineral dust from soil).

The purpose of this study is to:

- Identify factors/variables that influence road wear and dust resuspension.
- Identify future road surfaces which may reduce road wear.
- Recommend research programmes to fill in gaps in current knowledge on road wear and dust resuspension.
- Recommend studies that could be implemented to improve current emission factors.
- Identify abatement solutions that could be used to reduce road wear and dust resuspension.

This study assumes that all materials are produced and installed in accordance with the relevant standards; therefore, impacts of poor quality control either at production or installation stages are considered out of scope.

1.3 METHODOLOGY

A literature review was undertaken to assess current evidence relating to road wear and dust resuspension emissions, and to identify any research gaps. The primary focus of the literature review was on studies and reports that investigated various factors which could be influenced by the government and local authorities to reduce emissions, i.e. road surface materials and treatments, road surface condition, vehicle parameters, and traffic management. The review also covered external factors such as climatic effects (precipitation, temperature changes) as this information is important for road wear and dust resuspension and is key to inform the planning, design and development of climate resilient infrastructure.

Online resources such as Google Scholar, Science Direct and Research Gate were used to access peer-reviewed material for the literature review. Relevant grey literature (e.g. industry and project reports) was also identified and included in the literature search.

Section 2 of this report provides a summary of the main findings from the literature and highlights areas where there is limited information and potential research gaps. Section 3 discusses the different methodologies that are currently used to assess road wear and dust resuspension, and details of the current emission factors that have been developed and used in the UK and other countries. Section 4 summarises the evidence gaps that have been identified in the literature. Section 5 provides recommendations for future research programmes that could be implemented to improve understanding and fill in knowledge gaps. In Section 6 technologies that have been identified as possible candidates for mitigating road wear and dust resuspension are presented, and discussion on the feasibility of these approaches and potential for UK road networks is given. Finally, Section 7 provides a summary of the review and final conclusions.

2. LITERATURE REVIEW

This section includes findings from the literature review and highlights research/knowledge gaps.

2.1 EVIDENCE BASE FOR WEAR RATES

2.1.1 Mechanisms for road wear and dust resuspension

Tribology is the study of interacting surfaces in relative motion. For instance, as two surfaces such as those of a tyre and pavement interact under a certain load and environmental conditions these can wear, due to different mechanisms.

Understanding the fundamentals of tribology provides a foundation for exploring the complex mechanisms involved in tyre-road interaction. For example, tribology encompasses the study of wear, friction and lubrication, all of which can be considered critical factors influencing the performance and longevity of both tyres and road surfaces. In the context of tyre-road wear, different types of wear must be considered to fully capture the range of mechanical and environmental stresses that affect the contact interface, and these are[6]:

Adhesive wear: adhesion between a harder material and a weaker material causes fragments of the weaker material to detach. Wear mass in this case is proportional to the sliding distance travelled, applied load and inversely to the hardness of the less-hard material, as described by Archard's law[7]. Although modern vehicles are equipped with Anti-lock Braking Systems (ABS), which impedes tyres to continuously slide when braking, it is clear how this type of wear can affect the ability of vehicles to safely stop in emergency. Therefore, changes in specifications will have to make sure road materials provide adequate levels of skidding resistance.

Abrasive wear: cutting effort of hard surfaces acting on softer surfaces from the roughness of the contacting surfaces or of hard particles between them. As this type of wear is related to the shape and hardness of the aggregates used in road mixtures, this is definitely an area worth exploring, to understand how shape of aggregates and changes of that shape over time (under the effects of weather and traffic) affects wear.

Fatigue wear: repeated loading causing high contact stress, or thermal cycling, leads to degradation of the materials. Although weather related factors and traffic levels might be difficult to control, there are road related aspects that can be considered, such as the resistance of aggregates and road surface properties to wear under repeated thermal and heavy traffic loads.

Although other types of wear exist, such as corrosive wear, rubbing wear and erosion wear, it is highly unlikely that these can be relevant to road wear and affect the production of road PM₁₀ and PM_{2.5}. Although climate change may make the effects of weather elements more and more relevant to road wear, they cannot corrode or erode road materials as rapidly or intensely as traffic loading, which remains the primary cause of wear and thus the focus of this research.

The interaction between tyres and road surfaces is influenced by a complex set of variables related to both vehicles and the road pavements, as well as environmental factors. Understanding these factors is essential for accurately assessing tyre-road wear mechanisms and developing strategies to minimise their impact. For instance, vehicle-related variables, such as the type of manoeuvre, vehicle speed, tyre pressure, load, and alignment, directly affect the distribution of contact forces and the resulting wear patterns. On the other hand, road-related factors such as surface macrotexture, materials and their chemical composition, contribute to the frictional properties of the road and could be a factor in the generation of tyre-road wear particles, both from the qualitative and quantitative perspective.

Figure 2-1: Schematic of the complexities of pavement-vehicle interaction and variables in play.

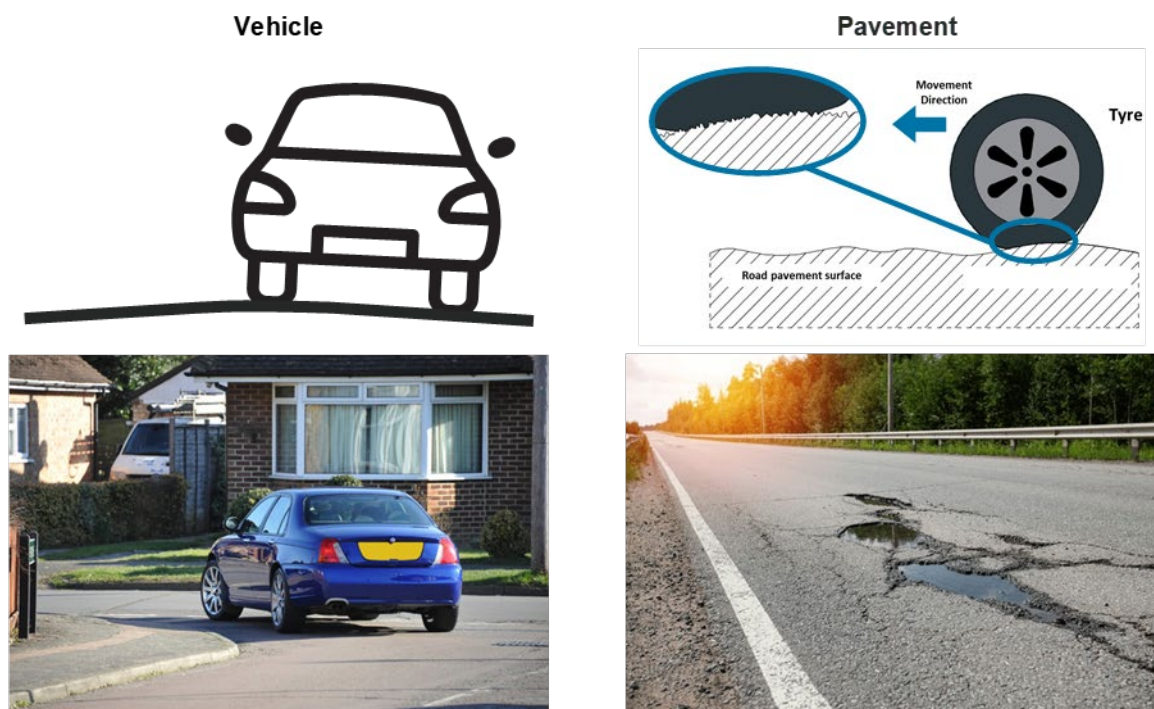


Table 2-1 provides a list of the key variables that can affect tyre and road wear. Clearly, there are some variables depending on vehicle technology and others to road pavement materials and characteristics.

Table 2-1 Key variables in play that can affect tyre and road wear.

Vehicle	Movement	Speed, acceleration and slip	Grip / Skidding Resistance (Safety)
	Loading	Load, contact area and pressure distribution	
	Tyre	Hardness, inflation pressure and tread pattern	
Pavement	Aggregate	Hardness, microtexture and sharpness	
	Surface characteristics	Roughness, macrotexture and their deterioration	
	Weather conditions	Temperature and wet / dry	

Although road geometry may also influence tyre and road wear, due to the different speed levels and manoeuvres undertaken by vehicles at e.g. junctions, the fact that majority of roads are already built, could make this less of a factor to consider in the UK and other developed countries.

The OECD (2020) report on “Non-exhaust Particulate Emissions from Road Transport”[8] summarised the findings on the variables that influence road wear and resuspension based on studies that were available at that time (Table 2-2). There are still many unknowns relating to the vehicle features, road surfaces, and vehicle driving, and many of the findings summarised are based on limited studies.

Table 2-2 Factors that can affect road wear and resuspension. *Adapted from OECD report (OECD, 2020)*[8]

Variable	Road wear	Resuspension
Vehicle features		
Vehicle size	↑	↑
Vehicle load	?	?
Studded tyres	↑	↑
Vehicle undercarriage		?
Road features		
Allowed max speed	↑	↑
Allowed max weight	↑	↑
Pavement age/state	↑	↑
Durable aggregate	↓	?
Nominal aggregate size	↓	↓
Asphalt porosity	?	↓
Rubberised asphalt	?	?
Cement concrete pavement	↑	?
Road dust loading	↑	↑
Road moisture	↓	↓
Side-slip angle	?	?
Driving features		
Aggressive driving style	↑	↑
Speed	↑	↑
Acceleration/Deceleration	?	?
Weather conditions		
Temperature	?	↑
Humidity	?	↓
Precipitation	?	↓
Wind speed		↑

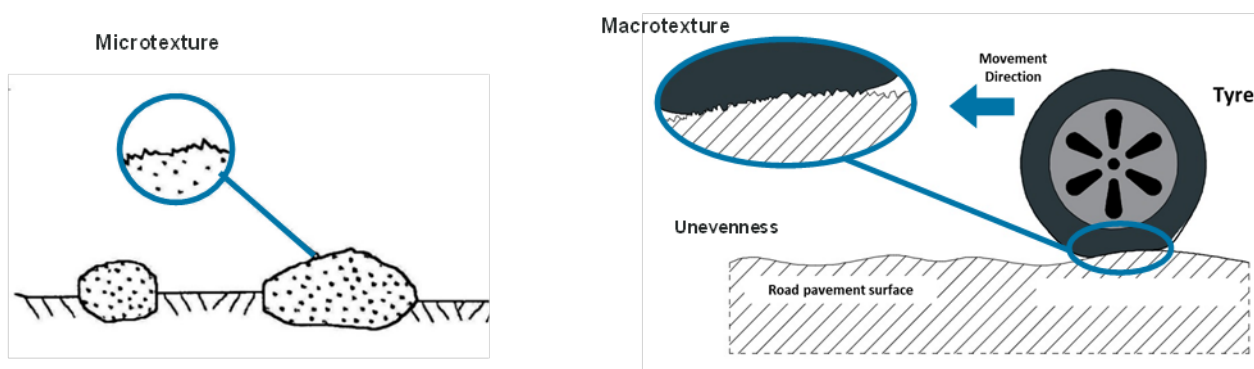
Red arrows indicated an increase in emissions; blue arrows indicate a decrease in emissions; “?” indicates a possible change in emissions unknown due to lack of evidence.

The road feature variables highlighted in Table 2-2 can be influenced by the DfT, National Highways and local highway authorities as these bodies specify and enforce compliance of road materials and construction. They also have some influence on the driving features, through setting speed limits and traffic management.

2.1.2 Effect of road surface condition on emissions

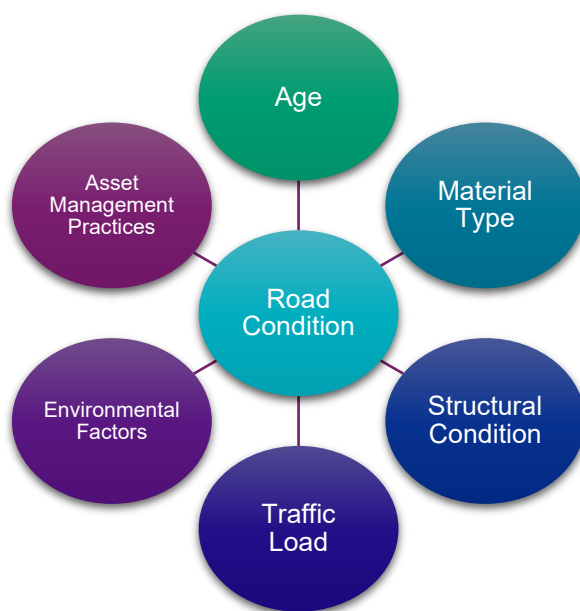
Road/pavement texture can be classified into three different groups based on the band of road profile they refer to (or wavelength) [9]. Micro-texture has a wavelength of less than 0.5 mm; macro-texture is between 0.5 and 50 mm; and mega-texture, are between 50 mm and 500 mm. Figure 2-2 illustrates the macro- and micro-texture of the road surface. Mega-texture features include large cracks, potholes and ruts in the road.

Figure 2-2 Road unevenness, macro- and micro-texture.



As illustrated in Figure 2-3, a number of factors can affect the condition of the road surface, including: the age of the road; the type of material used; the structure of the underlying layer; traffic load (e.g. vehicle passes and weight); environmental factors (e.g. cold, heat, rain); and how often the roads are maintained and repaired.

Figure 2-3 Factors affecting road surface conditions (Adapted from *Office of Rail and Road, Benchmarking National Highways, 2023* [10]).



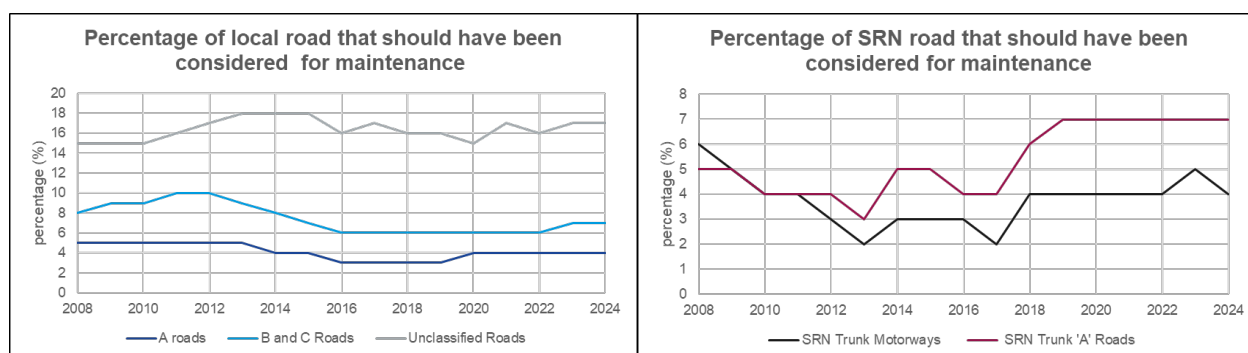
Studies have shown that road surface deterioration can affect the emissions of tyre and road wear particles. A field experiment in Spain found that old roads in a poor state of repair had high road dust loadings[11]. The average road dust loading on the urban roads studied were 1.9 mg m^{-2} and for older roads the loading was up to 10 mg m^{-2} . Pachon et al. (2021)[12] also found that measurements of road dust ($< 10 \text{ }\mu\text{m}$ diameter) in Bogotá, Columbia, on road conditions that were visually classified as bad (damaged road texture with cracking and indentations) were on average 9 mg/m^2 higher than those roads classified as good. In Paris dust emissions were measured from deposition flux measurements at the side of the road[13]. The results showed that older roads with considerable deterioration including visible cracks were found to have much higher PM_{10} loadings (2.4 mg m^{-2}) than nearby newer roads ($0.7\text{--}2.2 \text{ mg m}^{-2}$), although the authors of the study state that the findings may also be partly attributed to a higher share of heavy-duty vehicles (HDV) on the older roads. The size of the particles emitted may also depend on the road conditions. He and Jiang [14] found that the collected particles from newly constructed roads in Xi'an, which have an intact asphalt film on the surface, were coarser (average particle size $>300 \text{ }\mu\text{m}$), whilst older rural roads with exposed aggregates generate a higher quantity of smaller particles (average particle size $<300 \text{ }\mu\text{m}$). Gehrig et al. (2010)[15] used a Model Mobile Load Simulator (MMLS), to investigate PM_{10} emissions from abrasion and resuspension of dust on two different road

surfaces. The results showed that PM₁₀ emissions from asphalt concrete in poor condition were 8 mg/km/wheel compared to 0.7 mg/km/wheel for asphalt concrete in good condition.

In the UK, The Department for Transport publishes data on the road network conditions each year. Figure 2-4 shows the percentages of the total road network length that should be considered for maintenance from 2008-2024, for local roads and the strategic road network (SRN - maintained by National Highways) from the latest publication[16]. The roads are inspected using specialised equipment which take visual images and also measures the shape and condition of the road surface. Using the data collected, each road inspected is then assessed against various thresholds to determine whether the road may require maintenance. Further information on the methods of inspecting the roads and how the road condition is assessed is available on the UK government website[17].

For local roads: **4% of “A” roads, 7% of “B” and “C” roads, 17 % of “unclassified” roads** should have been considered for maintenance in 2024. For the SRN: **4% of “motorways” and 7% of “A” roads** should have been considered for maintenance in 2024. Although these sets of road maintenance statistics are indicative, they don't place any further duty on highways authorities to conduct maintenance of specific roads.

Figure 2-4 Percentages of the total road network length that should be considered for maintenance from 2008-2024, for local roads and the strategic road network (SRN - maintained by National Highways)[16].



As far as we are aware there have been no studies on the effect of road conditions on road wear and PM_{2.5} emissions on UK roads. Therefore, there is no evidence available to determine whether the roads that should be considered for maintenance in the UK will have an impact on road wear and PM_{2.5} emissions. A study, similar to that performed by Gehrig et al. (2010) or via on-road testing could be undertaken to assess the impact of road conditions on wear and emissions for road pavement aggregates used in the UK.

2.1.3 Resilience of road surface materials and compositions to abrasive wear

Differences in surface materials can influence both road wear and tyre wear. Although concrete is a harder material than asphalt, so has a longer lifetime, studies have shown that the abrasion rate is higher for concrete, which can result in higher pavement and tyre wear emissions. Bae et al. (2024)[18] studied tyre-road wear particles and road pavement particles using an abrasion simulator and found that at a speed of 60 km/h the abrasion rate for a concrete pavement (based on the measurement of both tyre and road wear particles) was up to 2.8 times higher than the rate for asphalt. A report by Arizona Department of Transportation compared tyre wear emissions on a road that was previously a plain cement concrete surface and was then relayed with Asphaltic Concrete Friction Course (ACFC). The results showed that at a speed of 96.5 km/h tyre wear emissions were 1.4 to 2 times higher on the concrete surface compared to ACFC[19].

A road simulator at the Swedish National Road and Transport Research Institute (VTI) was used to assesses wear and PM₁₀ emissions from three different road pavement materials. These included an asphalt concrete pavement and two quartzite stone pavements with different aggregate sizes (11 mm and 16 mm)[20]. The quartzite stone pavements produced markedly less particles than the asphalt concrete, and the smaller aggregate size of the quartzite stone also reduced PM₁₀ emissions.

The porosity of the pavement is also important to assess as pavements with porous asphalt surfacing can better trap road dust, reducing the potential for the particles to be emitted into the atmosphere[15], [21].

Therefore, while there are some studies available into the wear rate of different road surfaces internationally, there is a need to further investigate the wear of road surfaces in use in the UK. It should be noted that the safety aspects for driving are key. This is explored further in Sections 2.3 and 2.4.

2.1.4 Impact of vehicle load and vehicle size on road wear and dust resuspension

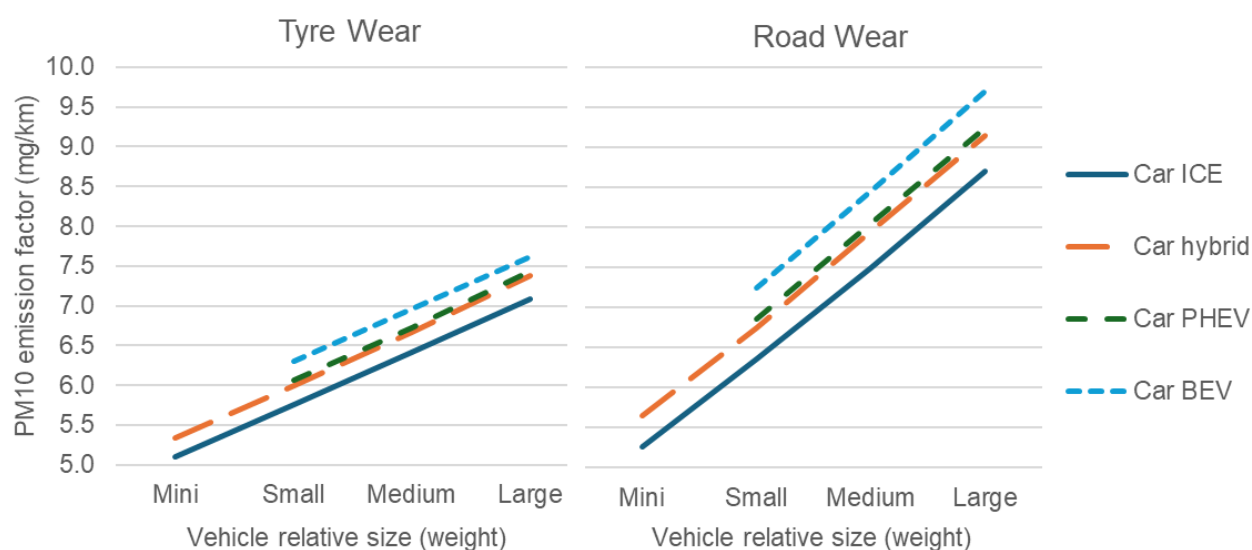
Emissions factors for road and tyre wear are provided in the EMEP/EEA air pollutant emission inventory guidebook 2023 [22] according to powertrain type and vehicle size for light duty vehicles. Although vehicle load is not directly considered (see Section 3.4), vehicle size may be considered analogous to vehicle load. The emissions factors for PM₁₀ as set out in the guidebook and plotted in Figure 2-5 imply the relationships set out in the bullet points below. However, it should be noted that there are limitations and uncertainties inherent in these emissions factors, which are discussed further in the section below.

- Both tyre and road wear increase with vehicle size (mass/weight).
- Both tyre and road wear increase with increased powertrain weight, as hybrids have higher emission factors than internal combustion engine (ICE) vehicles and have increased weight, while battery electric vehicle (BEV) emission factors are even higher and BEVs have the greatest weight. A BEV has 8-9% greater tyre wear and 11-14% greater road wear.
- For small vehicles, emission factors for tyres and roads are of similar magnitude.

For larger and heavier vehicles and heavier powertrains, road wear is increased more than tyre wear. The heaviest vehicles have road wear emissions over 60% greater than the lightest, but tyre wear emissions are increased only 40%.

Emission factors for light commercial vehicles and trucks also increase with vehicle size and mass/weight, and in the case of tyre wear, number of axles, although alternative powertrains are not considered.

Figure 2-5: Tyre and road surface wear PM₁₀ emission factors for ICE, hybrid, plug-in hybrid electric vehicle (PHEV) and BEV (data from EMEP/EEA 2023[22])



These EMEP/EEA provided Tier 2 tyre emission factors ([22] Table 3.6) are assigned a quality rating of B, C or D, on a scale of A to E where A has the lowest uncertainty; only medium passenger car data is rated B. The Tier 2 road wear emission factors ([22] Table 3.8) are assigned C-D or D. These are described as ([22] Section A5):

- **A:** An estimate based on a large number of measurements made at a large number of facilities or individual sources across a comprehensive range of operating conditions that fully represent the sector. Typical error range 10 to 30 %
- **B:** An estimate based on a large number of measurements made at a large number of facilities or individual sources across a range of operating conditions that represent a large part of the sector. Typical error range 20 to 60 %
- **C:** An estimate based on a number of measurements made at a small number of representative facilities or individual sources across a smaller range of operating conditions, or an engineering judgement based on a number of relevant facts. Or an estimate based on many measurements across a range of conditions for a source which is complex and/or variable. Typical error range 50 to 200 %.

- **D:** An estimate based on single measurements, or an engineering calculation derived from a number of relevant facts. Or an estimate based on many measurements across a range of conditions for a source which is particularly complex and/or variable. Typical error range 100 to 300 %

Tier 1 road wear emission factors (without speed dependency and with less vehicle disaggregation) date from the 2003 inventory guidebook (section B770)[23] which does not have a methodology provided because “the contribution to total national emissions is thought to be currently insignificant, i.e. less than 1% of national emissions of any pollutant”, although as explored in the introduction (section 1.1) this assumption may no longer be valid.

In other words, the current road wear emission factors are entirely dependent on extrapolation of very limited measured data or estimation from indirect data, as is the share of PM₁₀ or PM_{2.5} emitted, and may differ from reality by up to a factor of 3. Therefore, it is unclear to what degree the association between vehicle mass and tyre and brake wear seen in the emission factors is informed by data rather than extrapolation and assumption. Despite this limited evidence base, several papers use the EMEP/EEA to discuss the mass impact of vehicles on their NEE, such as Simons (2016)[24] who illustrate the linear relationship between vehicle size and their NEE PM emissions factors. On the other hand, Beddows and Harrison (2021)[25] calculated mass based emission factors for tyre wear, brake wear and road wear by assigning vehicle masses to the different vehicle types used in the EMEP/EEA Guidebook and applying a non-linear regression curve to the PM₁₀ and PM_{2.5} emission factors against vehicle mass. NEE emissions factors from various European and National emissions inventories are compared by Timmers and Achten (2016)[26] who noted that (at that time) only the UK included road wear, and highlighted: “There is very little other research that directly links non-exhaust PM emissions to vehicle load. Some authors have speculated about the possible influence of weight, but not directly measured it”.

There is a long-established relationship between vehicle load and the degradation in road serviceability through wear. This is said to originate in experimental work by the American Association of State Highway and Transportation Officials (AASHTO)[27] from which derives a “fourth power law”, that damage caused to road surfaces by vehicles is related to the 4th power of their axle weight. Re-analysis by the Transport Research Laboratory in the UK found that the relationship was more complex, since roads are exposed to wide variety of vehicle types and axle weights and vary according to the design strength of the pavement. The study found that the power law relationship actually ranged from around 3 to 6 [28]. However, the 4th power law relationship between vehicle axle weight and road degradation/wear is still used in the UK road design guidance[29].

Since road degradation wear increases with vehicle mass and axle load, it is reasonable to assume particulate emissions also increase with road wear and so vehicle mass, although the same relationship cannot be assumed. A strong linear relationship between road dust PM₁₀ emissions and vehicle load (and speed) based on measured data is reported by Gillies et al. (2005)[30], although this is for an unpaved road so it is not clear how applicable this result would be to a paved road. The US Environmental Protection Agency (EPA) AP42 Method[31] for estimation of road dust resuspension includes a factor based on vehicle load to the power 1.02, suggesting resuspension increases almost linearly with weight. The concentration of loose dust (silt) on the road surface and its particle size are also factors. A more simplistic approach was used when modelling particle emissions in the Netherlands, with a ratio of 9 used between PM₁₀ emission factors for resuspended dust from heavy and light duty vehicles[32], whereas for the relationship determined by Düring et al. the PM₁₀ resuspension emissions factors are proportional to the weight of the vehicle to the power of 2.14[33]. In their literature review of NEE, OECD (2020)[8] finds that road dust resuspension emission factors for HDVs are nine-to-ten times those of light duty vehicles, suggesting that both weight and aerodynamic attributes may be a factor, and the relationship between road wear and vehicle load has “hardly been studied in the literature”.

The road wear impact of different vehicles on UK (Scottish) roads is considered by Low et al. (2023)[29] including the effect of battery electric and hydrogen powertrains. The impact of vehicles under 7.5 tonnes was found to be negligible compared to HDVs which cause 99% of road wear, while additional axles reduce the impact of vehicles of similar weight – so the impact of 40-44 tonne trucks with 6 axles is less than 38-40 tonne trucks with 5 axles. The findings suggest that electric heavy-duty vehicles could increase road wear by 20%, and hydrogen fuel cell heavy-duty vehicles by around 6%, when compared to diesel vehicles, but these powertrains in light-duty vehicles are unlikely to have a significant impact. However, this study was focusing on road wear in the context of durability and repair costs (in Scotland) rather than particulate emissions, and notes that at a local level considering road conditions, the impacts of increasing weight of smaller vehicles may be more significant.

While research confirms a link between vehicle mass and road degradation and repair costs, there is little direct evidence linking road wear emissions to vehicle weight. Although road wear emission factors are

categorised by vehicle size, these are based on limited measurements and have high uncertainty. Nonetheless, a greater vehicle mass results in greater forces at the contact patch of tyre and road surface when a vehicle accelerates, brakes, or steers, and these dynamic effects are seen to increase particulate emissions (see 2.1.5 below), so an association between mass and road wear particulates would be expected. Further research could look at the effect of vehicle mass both on road wear and road dust resuspension, and aim to quantify emissions factor variation by vehicle load, but such research will need to overcome the challenges of identifying a repeatable and representative measurement method and discriminating between road, tyre, resuspension (and if relevant, brake) emissions.

2.1.5 Impact of vehicle speed, acceleration/deceleration on road wear and dust resuspension

Vehicle speed is currently not considered in emission factors for road wear in EMEP/EEA air pollutant emission inventory guidebook, or for resuspended dust using the EPA's AP42 Method. However, as the speed of a vehicle increases it is expected that the vehicle wake will result in a greater amount of uplift of particles on the road due to turbulence, and a number of studies have shown that emissions of particulates from the road can vary with vehicle speed. The methodology used in these studies can generally be divided into either flux experiments performed at the roadside, or on-road sampling using a mobile laboratory. A laboratory road simulator study and a study collecting PM mass on tape have also been undertaken. Table 2-3 provides an overview of the different studies looking at the effect of vehicle speed on particulate mass concentrations and emissions factors on paved and unpaved roads.

For flux experiments, particle measurements are obtained at different heights above the road surface. The gradient in the concentration with height is obtained and this information, along with data on the wind direction and wind speed, can be used to calculate an emissions flux of particles from the road surface as vehicles pass. The mobile laboratory studies measure emissions of particles from the road via sample points behind front or rear wheels on a moving vehicle. Further details on the mobile laboratory set ups and flux measurements can be found in Section 3.3.5.

Table 2-3 Summary of studies investigating the effect of vehicle speed on road emissions.

Reference	Methodology	Measurement parameters	Road type
Pachon et al. (2021)[12]	Deposition chamber	PM ₁₀ loadings	Paved and unpaved
Fitz et al. (2021)[34]	Mobile laboratory (SCAMPER, TRAKER) Flux measurements	PM ₁₀ emission factors	4 lane highway
Zhu et al. (2009)[35]	Mobile laboratory (TRAKER)	PM ₁₀ emission factors	Paved road
Hussein et al. (2008)[36]	Mobile laboratory (TRAKER)	Particle mass concentrations	Paved road
Pirjola et al. (2009)[37]	Mobile laboratory (SNIFFER, TRAKER)	PM ₁₀ concentrations	Paved road
Amato et al. (2017)[38]	Flux measurements	PM ₁₀ emission factors	Paved road
Woo et al. (2024)[39]	Mobile laboratory (TRAKER), Flux measurements	PM ₁₀ PM _{2.5} concentrations factors	Paved road
Sehmel (1973)[40]	Flux measurements (using a tracer species).	Fraction of resuspended material	Paved road
Gustafsson et al. (2009)[20]	Circular road simulator	PM ₁₀ concentrations	Quartzite
Edvardsson and Magnusson (2009) [41]	Mobile laboratory	PM ₁₀ concentrations	Unpaved road
Beji et al. (2021)[42]	Mobile laboratory	Rear of wheel particles (RoWP), Tyre and road wear particles (TRWP)	Test track – different materials Paved road
Gillies et al. (2005)[30]	Flux measurements	PM ₁₀ emission factors	Unpaved road
Etyemezian et al. (2003)[43]	Mobile laboratory (TRAKER)	PM ₁₀ concentrations and emission factors	Unpaved road

Reference	Methodology	Measurement parameters	Road type
Tsai and Chang (2002)[44]	Flux measurements	Total suspended particulate (TSP) emission factors	Unpaved road
Kavouras et al. (2016)[45]	Mobile laboratory (TRAKER)	PM ₁₀ emission factors	Unpaved road
Williams et al. (2008)[46]	PM collection on sticky tape at different heights	Particle mass concentrations	Unpaved road
Kuhns et al. (2010)[47]	Flux measurements	PM ₁₀ emission factors	Unpaved road

Real-world sampling of PM₁₀ was undertaken by Etyemezian et al. (2003)[43] and Zhu et al. (2009)[35] using a mobile laboratory known as a TRAKER (Testing Re-entrained Aerosol Kinetic Emissions from Roads), the methodology for which is detailed in Section 3.3.1. Samples are obtained behind the tyres, to measure resuspended dust, and a background measurement is taken from the front of the vehicle (below the bumper). The measured emissions from the TRAKER (mg/m³) followed an exponential relationship, with PM emissions increasing with vehicle speed to the power of ~3 (for particles below 4 µm). Fitz et al. (2021)[34] found a similar relationship with the PM₁₀ signal from the TRAKER following a relationship with the vehicle speed to the power of 3.1. Woo et al. (2024)[39] also used a TRAKER type system to determine that PM emissions factors of road dust increased exponentially with a power of 1.9 for PM₁₀ and 2.3 for PM_{2.5}.

Amato et al., (2017)[38] determined a lower exponent with a value of ~1.5 for the relationship between PM₁₀ emission factors and vehicle speed, from flux measurements along the side of the road in Milan, Italy. Also calculated from flux measurements, Gillies et al. (2005)[30] found that the emissions factors of PM₁₀ followed a linear relationship with vehicle speed.

Beji et al (2021)[42] investigated increases in tyre and road wear particles (TRWP) and particles measured at the rear of the wheel (RoWP) with vehicle speed and acceleration/deceleration. TRWP were determined as particles measured inside/alongside the wheel less the RoWP. The individual contributions from road wear, tyre wear, brakes and resuspended dust; however, are not differentiated. Particle number emissions (in units of particles/s) for particles < 10 µm were found to increase with vehicle speed, to the power of 1.22 for RoWP and 1.26 for TRWP.

In contrast to the above studies Pachon et al.(2021)[12] found that PM₁₀ road dust loading (measured in units of mg/m²) increased when vehicles were travelling at lower speeds. This was attributed to reduced turbulence when vehicles are travelling slower. The different result may be due to the methodology and metrics. In this study the particles were collected directly from the pavement and the vehicle speeds obtained from local data or via velocity measurements at the location. Whereas in the other studies described above, the measurements represented emissions of road dust that became airborne.

The type of tyres on the vehicle are also likely to have an impact on the resuspended dust. Hussein et al. (2008)[36] used a version of the TRAKER system to measure NEE particle mass concentrations under real world driving conditions on paved roads in Sweden. The results show that the particle mass concentrations (the size range of the particle mass is not provided) behind a studded tyre increased by 10 times from a speed of 20 km/h to 100 km/h. The authors stated this could be the result of greater road wear and resuspended dust. For non-studded and summer tyres no clear relationship was observed with vehicle speed. Pirjola et al. (2009)[37] however, observed an increase in mean PM₁₀ concentrations at 80 km/h compared to 40 km/h from measurements in Helsinki, Finland for summer, winter and studded tyres, using a similar on-road system, known as the SNIFFER. Gustafsson et al. (2009)[20] found that the vehicle speed and tyre type had a large impact on measured PM₁₀ concentrations during a study with a circular road simulator. Measurements were undertaken between speeds of 30-70 km/h and a linear relationship between PM₁₀ concentrations and speed was determined. The authors note that resuspended material will also have an effect on the measurements. Studded winter tyres were found to lead to 10 times more PM₁₀ than standard winter tyres.

Although there is some variability between studies, it is clear that vehicle speed does have an effect on the particles measured above the road surface. How much of an impact this has in terms of the air quality on and around roads cannot be determined without modelling studies with speed dependant emission factors. This is discussed further in Section 3.3.5.

A few studies have also shown that braking and accelerating can have some effect on particles emitted. Beji (2020)[48] sampled tyre-road contact particles (TRCP) with a size range of 0.35–10 µm during tests on a track under varying acceleration and deceleration conditions. They observed that the ratio of the TRCP to

background number concentrations increased with higher rates of acceleration and deceleration. The vehicles' speed before the decelerations also had an effect, with around three times as many TRCP emitted when braking from a speed of 110 km/h compared to braking from 50 km/h. In the study by Beji et al. (2021)[42], it was observed that acceleration and deceleration of the vehicle also coincided with increases in particle number from the RoWP sampling on the road, and found that even braking gently at high speeds can result more than double the amount of particles emitted than harsher braking at lower speeds. Woo et al. (2024) also observed higher PM₁₀ concentrations under harsh braking conditions. Etyemezian et al. (2003) also noted that PM concentrations increased when their TRAKER vehicle was braking hard or accelerating. To remove the influence of these high concentrations of PM in their assessments of road dust, a threshold of 0.5 m/s² was used for acceleration and deceleration in the study.

In all these studies it has been noted that some of the increase observed during braking events may be due to brake wear particles, either emitted during the decelerations or brake particles already on the road. One approach to remove the effect of directly emitted brake wear particles on the measurements is to enclose the brake system, similar to the approach used in the DfT brake and tyre wear study [4].

It should also be noted as far as we are aware there are no studies that have focussed solely on the effects of vehicle speed or acceleration/deceleration on road wear emissions of PM₁₀ or PM_{2.5}. This may be due to the challenge of separating the contributions of road wear from tyre wear and the resuspended dust under real world conditions. As noted above (section 2.1.4), the tyre-road contact patch forces associated with acceleration, deceleration, and cornering are amplified by vehicle mass, and so electric vehicles with a greater mass as well as their potentially higher torque could lead to increased forces at the road when accelerating, braking, and cornering. Comparison of tyre wear of taxis found greater wear on the driven axles of electrified (hybrid) vehicles which is attributed to their greater torque, as well as confirming a relationship between tyre wear and aggressive driving, these patterns could be reflected in road wear too[49]. Future research could focus on measurements under controlled laboratory conditions to address this gap (see Section 5).

2.1.6 Impact of road layout and traffic management measures

Traffic management strategies have been implemented in cities across the world with an aim of reducing traffic emissions and improving air quality. The focus for these strategies is typically on exhaust emissions, although they may also have some positive effect in reducing non-exhaust emissions. There is little information published relating the potential effect of road layouts and traffic management to road wear and dust resuspension. As discussed in Section 2.1.5 above, the speed of the vehicle and braking and accelerating can have an effect on the measured emissions from the road. A few studies have also investigated how particle emissions may vary with distance from junctions/braking zones and traffic intensity.

Beji et al. (2021)[42] found measured TRWP (below 10 µm diameter) to be high on tall bridges due to the inclines increasing tyre-road forces, and higher at junctions, wide corners and large roundabouts (where speeds are higher and steering angles lower) than at tight corners, small roundabouts and traffic lights, suggesting the cornering speed is more significant than radius. Padoan et al. (2018)[50] explored the relationship between the mobile fraction of road dust (MF10 - fraction that can be suspended with an airflow of 30 l/min with a diameter smaller than 10 µm) with different factors, including the pavement macrotexture, the traffic intensity and distance to braking zones. Results showed that the amount of MF10 sampled (mg/m²) decreased with traffic intensity and distance from the nearest braking zone. Pachon et al.(2021)[12] found a similar result from measurements in Bogotá, Columbia, with concentrations of PM₁₀ road dust loading increasing when nearer to the braking zone. More particles may be generated from wear of the road, tyres and brakes around braking zones, which are subsequently deposited on the road.

Although not related directly to traffic management, Beji et al. (2021) found TRWP particle number concentrations to be highest on motorways and lowest on urban and suburban roads, although it is noted that country roads and motorways were more prone to increased particulate deposition from adjacent industrial facilities or agricultural activities. This finding implies resuspended particles were seen to increase where there were higher local concentrations of particles from non-road sources. In contrast, Jeong et al. (2025)[51] found that resuspended PM_{2.5} (which was normalised to a vehicle speed of 30 km/h to account for variations in speed) was higher on local roads compared to major roads and highways. This was attributed to the lower volumes of traffic on these roads. With lower traffic volumes there is less turbulence, hence less dispersion, so road dust can build up.

It is clear that further research on how different road layouts and traffic management policies can effect PM_{2.5} and PM₁₀ emissions from road wear and dust resuspension is needed.

2.1.7 Impact of climate change and seasonal UK weather conditions on road wear emissions and abatement of PM_{2.5}.

Section 2.1.2 discusses how older roads that require repair can result in higher dust loadings. Changes in temperature, and precipitation can all damage road surfaces; therefore, future changes in climate, with more extreme temperatures and increased rainfall, may result in more roads being damaged and an increase in wear. On the other hand, high humidity and precipitation can suppress dust reducing the amount that becomes airborne[38],[39],[40],[41]. This is the reason why street washing and chemical suppressants have been used to reduce road dust emissions. Amato et al. (2012)[54] showed that mobile dust loads (g/m²) measured in both Barcelona and Utrecht drop to zero directly after a rain event but then become mobile again, reaching 90% of its maximum value 27 hours after the rain fall, in Barcelona. The USEPA include a precipitation correction term in their equation to calculate resuspended dust emissions. This is limited to a threshold of 0.254 mm/hour, as above this level of precipitation, resuspension is not expected to occur.

High winds will also have an impact on the road dust emissions[42],[43]. Thorpe et al. (2007)[55] investigated changes in resuspension emission factors with wind speed. The relationship depended on which background site (either London Bloomsbury or London Bexley) was chosen to calculate the roadside increments in PM_{2.5-10} (i.e. coarse particles) at Marylebone Road. Using London Bexley corrected background PM_{2.5-10}, the resuspension emissions factors initially decreased with wind speed, but then increased again after wind speeds of 4-5 m/s and up to 8 m/s. For London Bloomsbury corrected background PM_{2.5-10}, the resuspended emissions factor increased with wind speed, but the rate of increase got smaller.

2.2 PAVEMENT SPECIFICATIONS AND STANDARDS

In the United Kingdom, the Manual of Contract Documents for Highway Works (MCHW) and the Design Manual for Roads and Bridges (DMRB) serve as essential reference documents for road construction projects. The DMRB contains information about current design standards relating to the design, assessment and operation of motorway and all-purpose trunk roads; while the MCHW is a standard suite of specification documents which are included within a construction contract and the Contractor is required to comply with its contents (materials and installation requirements). Both documents belong to National Highways and are used for construction and maintenance of the Strategic Road Network (SRN).

There are some local authorities such as Cambridge and those represented by the Midlands Highway Alliance (MHA), who have developed ad-hoc documents that govern the way road construction projects are procured and managed in their areas. These set slightly different specifications to those at national level to be able to respond to specific supply chain and network requirements. However, the majority of local authorities refer to MCHW and DMRB requirements in their contracts. Regarding road wear, these two documents represent a starting point to understand the types of materials currently in use, quality assurance testing and safety requirements and road construction industry best practice.

In terms of openings and repairs, the Specification for the Reinstatement of Openings in Highways (SROH)[57] and Specification for the Reinstatement of Openings in Roads (SROR)[58] set the standard for the execution of the works at local level.

Complying with all clauses of MCHW, DMRB, SROH, SROR and ad-hoc local authority specifications regarding raw materials, design, construction and maintenance requirements, where applicable, enables raw materials and mixes to adequately contribute to the structural performance and durability of road surfaces. Nevertheless, it is believed that optimisation of some of these requirements to minimise road wear might be possible, without compromising their performance (including safety).

2.3 PAVEMENT MATERIALS AND SURFACE CHARACTERISTICS

Surfacing materials for road paving applications can be grouped into two categories: surface treatments and surface course materials. Whilst both categories might share a function to provide smooth running surface for the traffic, these surfaces have differences in their make-up, performance and durability as summarised in Table 2-4[59], [60], [61].

Table 2-4 Characteristics of surfacing materials.

Description	Surface Treatments	Surface Course Materials
Product Types	Surface dressing, HFS, CAUTS, slurry surfacing, microsurfacing	Asphalt concrete, HRA, SMA, porous asphalt, PQC
Installed thickness	Less than 15 mm	Between 20 mm and 60 mm
Service life	Mostly less than 10 years (typically 4 – 8 years)	Mostly greater than 10 years (typically 10 – 20 years)
Resistance against polishing or skidding (safety)	Better than surface course materials	Acceptable but not as good as surface treatments
Resistance against surface wear	Poorer than surface course materials	Better than surface treatments
Replacement cost	Less expensive (but more frequent) than surface course materials	More expensive (but less frequent) than surface treatments
Noise level	Mostly higher than surface course materials	Mostly lower than surface treatments, except HRA with chipping and PQC

Asphalt and concrete are the main two types of materials used to build and maintain roads in the UK. However, concrete only represents 4% of the SRN, making asphalt the main surfacing material.

Table 2-5 provides a list of surface materials and treatments allowed by the DMRB that represent the majority of existing road surfacings in the UK.

Table 2-5. Surface materials and treatments.

Type	Material/treatment
Surface treatments	High friction surfacing (HFS)
Surface treatments	Cold applied ultra-thin surfacing (CAUTS)
Surface treatments	Recipe / designed surface dressing**
Surface treatments	Slurry surfacing incorporating microsurfacing**
Surface course materials	Thin surface course systems (TSCS)
Surface course materials	Performance hot rolled asphalt surface course (HRA)
Surface course materials	Stone mastic asphalt surface course* (SMA)
Surface course materials	Recipe / designed hot rolled asphalt surface course**
Surface course materials	Asphalt concrete surface course**
Surface course materials	Porous asphalt**
Surface course materials	Pavement quality concrete

* England, Northern Ireland, Scotland and Wales have different requirements

** Only allowed by Local Authorities and in Devolved Administrations in the UK

To provide adequate comfort of driving and enable vehicles to safely brake in case of an emergency, the MCHW includes surface characteristics and validating methods related to unevenness, macrotexture and skidding resistance. Table 2-6 summarises these requirements and links them to the design, monitoring and maintenance assessment procedures included in the DMRB.

Table 2-6. Road surface properties and related national specifications.

Characteristics	Materials / Construction References	Design / Maintenance References
Unevenness	TRRL SR 290:1977 and BS EN 13036-5	Clause E/1.8, NI/1.13, W/1.16 and S/1.8 of DMRB CS 230
Macrotexture	BS EN 13036-1	Clause E/1.7, NI/1.12, W/1.15 and S/1.7 of DMRB CS 230
Skidding resistance	BS EN 13036-4	CS 228 of DMRB

Key differences between asphalt and concrete mixes constituents that may affect road wear and dust resuspension include:

Aggregates type: the geological nature of the aggregate – a limited range of types can be found locally.

Aggregate size: size of the aggregate used – usually a range sizes characterise a mix.

Aggregate shape: shape of the aggregates used – can be more or less angular.

Aggregate microtexture: texture of the aggregate – often characteristic of geology and crushing methods.

Binder type: typically, bitumen for asphalt (paving grade or polymer modified bitumens) and cement for concrete. Surface treatments normally use synthetic binders.

Binder content: typically, 5% - 8% for asphalt and 10% - 15% for concrete.

In addition, in-service variables can also affect road wear and dust resuspension, such as temperature, macrotexture (positive or negative texture, or texture depth), unevenness or water susceptibility. Longitudinal diamond grinding and fine milling of concrete pavement surfaces could also affect how road wears over time.

Based on MCHW specifications, in the UK, manufacturers of asphalt and concrete mixtures are required to undergo a series of production tests to demonstrate compliance with the Construction Products Regulation and meet CE marking requirements, in line with specific ISO EN / BS EN standards, or have a Product Acceptance Scheme Certificate. Although this ensures that materials enable constructions to achieve adequate levels of safety and structural performance, little is known in regard to the effects of current policy and standards on the generation of TRWP.

For instance, UK aggregates for asphalt and concrete mixes consist of limestone, igneous rock, sandstone, sand and gravel which, within certain limits (set in MCHW Series 900 and 1000), differ in size, shape and composition. In this regard, aggregates like sandstone and limestone can contain potentially harmful minerals like silica (SiO₂). However, it is currently unclear how these wear under the effect of traffic as well as in what quantity these are produced, or if there are situations or conditions where the wear produced can be harmful to human and environmental health. In addition, the increased adoption of recycled and secondary aggregates from industrial by-products and construction waste could introduce additional levels of uncertainty.

In consideration of the above, two questions arise in regard to the contribution of raw materials to the production of TRWP:

- 1) How do raw materials, such as aggregate types, shape and size, affect the production of tyre wear?
- 2) How does quality of raw materials affect road wear both qualitatively and quantitatively?

On the other hand, the problem becomes even more complex when different mixes are laid across the network, with different road surface characteristics that potentially evolve at different stages of the pavement lifecycle, depending on deterioration rates and external factors. In this regard, key variables to consider are:

Unevenness: road surface unevenness relates to surface regularity and as it impacts vehicle-pavement interaction it may also influence road wear to a certain extent.

Macro-texture: road macrotexture is the characteristic of a pavement that directly interacts with the tyre tread and thus the most likely to influence wear, both by the tyre and pavement itself.

Skidding resistance (friction): this characteristic of the road surface may not directly impact road wear but enables vehicles to safely brake on a road surface, and it depends on pavement macro- and micro-texture.

Taking into account the above, there are a few questions that currently remain unanswered:

- 1) Does pavement unevenness affect tyre-road wear?
- 2) How do different levels of macrotexture affect tyre-road wear?
- 3) Can tyre-road wear be minimised without affecting skidding resistance (safety performance)?

Special consideration is needed when assessing how high friction surfacing (HFS) wears and contributes to TRWP production. HFS is a specialist type of road coating with improved skidding resistance, thanks to the properties of its main component: calcine bauxite. HFS is commonly used in the UK at locations where significant risk of serious or fatal accidents exists - e.g. approaches to roundabouts or signalised intersections on motorways. Recent research has shown how, subject to road simulation testing, asphalt and concrete surfacing materials lost greater amounts of wet skid resistance, in comparison to the HFS coated materials, prior to reaching equilibrium. However, considering the higher percentages of silica and other metals that characterises calcine bauxite, it is recommended that some dedicated testing is performed on HFS coated surfaces, to better understand the qualitative and quantitative implications of using this product on UK roads.

In light of the above it is clear that any proposed changes to MCHW, DMRB and local authority specifications and clauses must be meticulously assessed, including supply chain implications from any adjustments that might disrupt delivery of highway projects. In assessing possible changes to specifications, it will of course remain a priority to maintain an appropriate level of grip, along with other such safety considerations, but an increased focus on the potential benefits to air quality and health would allow a 'healthy balance' between safety and environmental factors to be achieved.

2.4 NEW SURFACE DEVELOPMENTS

As delivering a reliable and safe to drive network remain paramount to road authorities, design, construction and maintenance specifications have always prioritised safety and structural performance above anything else. However, the growing urgency of global sustainability and climate resilience goals introduces a transformative perspective to current practices, with environmental impact and social value becoming also important. By integrating these priorities, infrastructure can evolve to meet the dual demands of performance and sustainability, aligning with the needs of a changing world.

In regard to road surfaces, recent research has shown that properties like unevenness, macro- and micro-texture or the type of mix used can affect environmental performance of road pavements, such as fuel consumption, noise and possibly tyre-road wear.

For example, the Danish Road Directorate (DRD) financed the COOEE project to develop Low Rolling Resistance Asphalt Mixtures (LRRAMs). These materials aimed to reduce RR while meeting national safety and durability standards. Tests using the trailer method demonstrated that specifically designed LRRAMs could achieve up to a 12% reduction in fuel consumption when compared to traditional materials. In addition, potential for reduction in road noise and tyre-wear particles were envisaged. For this though, the constructed pavement sections had an average International Roughness Index (IRI) of 0.9 m/km and a Mean Profile Depth (MPD) of approximately 0.6 mm, which contributed to low RR properties, but that current UK specifications do not allow. In addition, challenges to texture stability and durability were observed, which makes clear how further research and optimisation of these materials is still needed before they can be included in national specifications and widely used on public roads.

Also, rubberised asphalt is a technique where crumbed rubber - often from recycled tyres - is used in asphalt mixtures to partly substitute aggregates. Although this solution is often presented as a more sustainable approach to traditional mixtures, it is currently unclear what effects the use of rubberised asphalt in surface course systems could have in terms of tyre-road wear particles generation and composition. This together with other consideration on the use of recycled materials in pavements could be useful to add to a research programme on the impact that road surfaces have on the production of tyre-road wear.

More on the necessity to tackle dust resuspension, a technique that could work and bring other benefits to the table are porous asphalts (20%-30% mix void content in comparison to the usual 4% - 5%). In fact, although at the time of writing porous asphalts are not widely adopted in the UK, these have demonstrated to be a valuable solution in countries such as the Netherlands, Italy and others in Europe to tackle safety related challenges such as water stagnation at roadsides, water spray and road noise. Although further evidence might be needed to prove current hypotheses and considerations made about maintenance costs, research from Switzerland has shown that porous asphalts may induce a reduction in dust resuspension as well.

Considering the possible trade-offs that a revision of national and local specification current requirements could bring, it is crucial that a coordinated approach is taken to ensure environmental and social value considerations are included, without compromising safety. In this regard, achieving a 'healthy balance' between safety and environmental performance is essential, ensuring that new updates to reference documentation provides space for engineers to enhance the sustainability of road surfaces, and deliver improvements in terms of fuel consumption, noise, and tyre-road wear realised, without compromising the structural integrity and safety of the infrastructure. This balanced approach will not only contribute to environmental sustainability but also maintain the high safety standards that are vital for operating public roads.

3. CURRENT METHODOLOGIES FOR MEASURING/MODELLING ROAD WEAR AND DUST RESUSPENSION

This section includes details and discussion on the different methodologies that are currently used to assess road wear and dust resuspension.

3.1 STANDARDISED TEST METHODS

3.1.1 ISO 22638:2024 “Rubber: Generation and collection of tyre and road wear particles (TRWP) - Road simulator laboratory method”

ISO 22638:2024 outlines the standardised procedure to follow for generating and collecting tyre and road wear particles (TRWP) using a road simulator[62].

Key components of the “road simulator” include a 1) drum drive engine, operating at 200 kW and 200 r/min, 2) a clutch mechanism, to control the rotation of the drum, 3) a brake system, to secure the casket during testing, 4) bearings, to ensure smooth and stable operation, 5) the drum itself, usually characterised by a smooth and metallic inner surface, 6) free-wheeling hub with disc brake, to allow controlling the rotation of the tyre, 7) another tyre drive dedicated engine, with similar capabilities of that used for the drum, 8) a wheel slide mechanism, to simulate steering actions, 9) a tyre load application mechanism and 10) a tyre wheel, often also standardised.

Although this setup ensures the generation of TRWP under controlled, reproducible conditions, without interference from common road contaminants like brake dust, exhaust residues, or grease, the method substantially fails to account for the effects of road surface characteristics and materials on the production of TRWP as well as making unclear how the particles generated under real-driving conditions split in between tyre and road wear.

3.1.2 ISO/TS 20593:2017. Ambient air — Determination of the mass concentration of tire and road wear particles (TRWP) — Pyrolysis-GC-MS method

ISO/TS 20593:2017 describes the methodology for determining the concentration of tyre and road wear particles (TRWP) in filter samples of PM_{2.5} or PM₁₀[63].

Particulate matter is collected on filter samples, and following gravimetric analysis, the samples are then pyrolyzed and a gas chromatograph/mass spectrometer (GC-MS) is used to distinguish the pyrolysis products. Chemical markers for natural rubber (NR), butadiene rubber (BR), and styrene-butadiene rubber (SBR) are used to identify and quantify the amount of tyre polymer in the sample. The TRWP concentrations are then determined from the average market ratio of SBR to BR and the expected mineral content of TRWP.

3.1.3 PD CEN/TS 12697-50:2018 “Bituminous mixtures. Test methods - Resistance to scuffing”

PD CEN/TS 12697-50:2018 is the European standard that outlines the test method for assessing the resistance to scuffing (or fretting) of asphalt mixtures for road and airfield pavements[64]. These shear stresses typically occur in the contact area between tyres and pavement surfaces during vehicle manoeuvres like cornering, leading to material loss at the surface.

The procedure involves subjecting the asphalt specimen to controlled scuffing actions and simulate shear stresses, using a tyre in contact with the surface. The resistance to scuffing is then evaluated by measuring the material loss from the surface of the specimen after testing. This type of test is relevant to all kind of asphalt

materials but particularly for those with high air voids, such as porous asphalt mixtures. Test specimens can be produced in a laboratory or extracted directly from existing pavements.

Although the test has the benefit of involving both tyre and pavement, the type of load applied and testing manoeuvre makes this test less relevant to the production of fine particles, and in fact designed to test the ability of aggregates laying on the surface of a pavement to stick to the rest of the structure when subject to high levels of stress, i.e. at cornering.

3.1.4 BS EN 1097-2:2020 “Tests for mechanical and physical properties of aggregates - Methods for the determination of resistance to fragmentation”

Adapted from the American counterparts AASHTO T 96 and ASTM C 131, BS EN 1097-2:2020 describes the standardised method adopted to determine the resistance to fragmentation of road construction aggregates[65]. This basically subjects a sample of coarse aggregates – retained on a 1.7 mm sieve - to abrasion, by grinding the material in a rotating steel drum containing a specified number of steel spheres of known weight. After being into the rotating drum, the LA value is calculated as the percentage of weight aggregate that passes the 1.70 mm after the testing, to obtain a percentage. For instance, an LA loss value of 30 indicates that 30% of the original sample passed through the 1.7 mm sieve.

However, in this case the test is not designed to reproduce any sort of particles related to tyre-pavement interaction and so results may be hardly related to TRWP as intended in the present report. In fact, the test is designed to evaluate aggregate abrasion characteristics as constituents of bituminous and cementitious concrete mixtures, which must resist crushing, degradation and disintegration in order to produce a high-quality construction material.

3.2 LABORATORY MEASUREMENTS

3.2.1 Road Simulator

Accelerated Pavement Testing (APT) is a technique used in Pavement Engineering to assess the performance and durability of pavement materials and structures under controlled, simulated traffic conditions. By applying repetitive loading in a controlled environment, APT enables researchers and engineers to examine pavement behaviour, estimate lifespan, and identify potential failure mechanisms without waiting for long-term real-world traffic exposure. The approach allows for faster and more effective evaluation of new pavement designs, materials, and construction techniques in comparison to industry best practice.

APT road simulators typically consist of four or more mechanical arms equipped with wheels that apply repetitive loads over a test section, simulating real-world traffic stresses[20], [66]. By adjusting variables such as load intensity, speed, and environmental factors, researchers can accelerate the wear and aging processes of pavement materials, enabling the assessment of their long-term performance within a compressed timeframe.

Although employing APT road simulators in tyre wear studies could enable researchers to gain valuable insights into the wear mechanisms of both tyres and road surfaces, the high operating costs, the significant safety risks and difficulties in controlling key variables for the collection and separation of the particles deriving from the test section and testing equipment makes full scale test setups not viable overall.

3.2.2 MMLS

The Model Mobile Load Simulator (MMLS) is a one-third scale APT device capable of replicating realistic rolling wheel contact stresses under controlled conditions (Figure 3-1). It can simulate wandering traffic patterns, temperature variations, and wet trafficking scenarios, making it a valuable tool for assessing pavement performance.

For evaluating tyre-road wear, the MMLS provides a controlled testing environment where researchers can analyse the interaction between tyres and pavement surfaces. By adjusting load, speed, temperature, and moisture to desired levels, the MMLS enables detailed observation and measurement of wear patterns, material degradation, and performance indicators, and was in fact used already for this purpose in 2010. However, Gheirg et al. (2010) focussed their attention solely on PM₁₀ and further work is required to adapt the adopted methodology to evaluate the generation of particles in conditions typical of the UK.

Figure 3-1: Model Mobile Load Simulator (MMLS). Source: AECOM

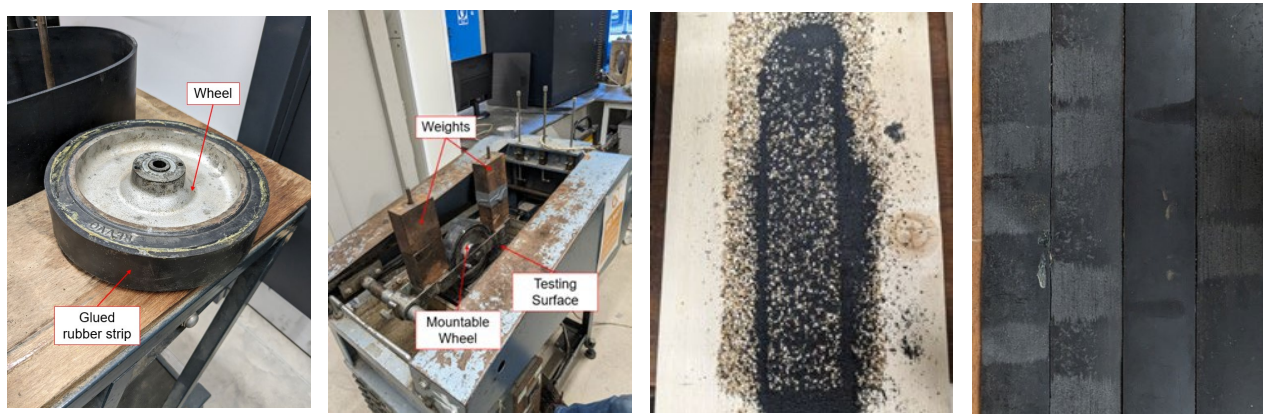


3.2.3 Modified Hamburg Wheel Tracking test

The Hamburg Wheel Tracking Test (BS EN 12697-22:2020) refers to a laboratory test that simulates the effects of traffic by repeatedly rolling a loaded wheel over a sample of asphalt pavement, measuring the depth of the resulting rut (depression) to assess the pavement's resistance to deformation and rutting (Figure 3-2). The test is often performed while submerged in water to evaluate moisture susceptibility as well.

Although this test is not designed to evaluate road wear of any type, recent research conducted at the Ulster University has shown how a slight modification to the testing equipment could enable the test to be used for wear investigation. In fact, having the wheel equipped with a rubber strip and dragged (instead of rolling) along the specimen could make the friction generate tyre and road particles, to be analysed per size, shape and composition. Specimens could be analysed after 30, 60 and 120 seconds at 9 position to produce complete data distributions. Ultimately, weighting or laser scanners could be then used to analyse results and calculate the portion of wear deriving from the tyre or road element of the specimen.

Figure 3-2: Modified Hamburg Wheel Tracking test. Source: Ulster University



3.3 REAL-WORLD MEASUREMENTS

3.3.1 TRAKER

The TRAKER (Testing Re-entrained Aerosol Kinetic Emissions from Roads) is a vehicle-mounted approach to measuring road dust, developed by the Desert Research Institute of Las Vegas [23],[33],[51],[52],[53].

Dust concentrations are measured in real time from in front of the vehicle, and from behind the wheels of the vehicle, to determine the increase in dust concentration (PM_{10}) due to the vehicle's motion. The front background sample point is on the bonnet/hood or front bumper of the vehicle. Measurement sample points are behind each of the front wheels aligned to the centre of the tyre width, 175-230mm from the road surface, 80-120mm from the tyre, and angled 40° down from horizontal and 40° outward from the vehicle centre line. Sample is drawn through the measurement points, flow measurement devices (pitot tube), and diluted in sampling plenums on-board the vehicle by a pump. Each sample plenum (one for each sample position) has a dedicated PM_{10} measurement device, TSI DustTrak optical sensors have been used. Additionally, particle sizing can be measured. The concurrent background concentration is subtracted from the concentrations measured behind the wheels, while GPS data is used to map results.

While the TRACKER has been used in several studies over two decades, tests have been carried out in desert conditions and focus on dust deposited on the road from the desert or construction vehicles. Nonetheless, findings may be applied in other contexts. Dust concentrations caused by the vehicle increased exponentially with speed, but were higher on lower-speed roads, perhaps as higher vehicle speeds prevent buildup of dust on the roads. The approach has been used to estimate emission factors. Some findings from studies using the TRACKER approach are discussed in Section 2.1.5 and Section 2.1.6.

Measurements may be affected by wind. Factors such as the type of vehicle and wheel size used, and the positioning of the vehicle on the road (relative to the tracks of other vehicles) can affect results. It's not clear how effective it would be at discerning a measurement when following another vehicle, such as in real-world traffic. The system as presented does not differentiate the source or composition of particles, nor are any sources isolated, so the particles measured are expected to contain brake and tyre particles as well as those from the road surface.

3.3.2 SCAMPER

The SCAMPER (System for the Continuous Aerosol Measurement of Particulate Emissions from Roads) is a vehicle-based road dust measurement approach developed by the University of California in Riverside [34], [69], [70], [71]. As with the TRACKER it compares dust concentrations in the wake of the vehicle to those of undisturbed air. The wake measurements are taken from on-board a trailer behind the vehicle, while the baseline is taken from the front or roof of the vehicle, or from a height well above the towing vehicle if on the trailer. The vehicle exhaust is ducted to outlet behind the trailer to isolate it from the wake measurements. The trailer has an extended drawbar to place the sample points between 2m and 6m behind the tow vehicle, with a frame on the trailer allowing sample points to be located at different horizontal and vertical positions. PM_{10} is measured at baseline and sample points simultaneously using TSI DustTrak optical instruments, and optionally with a TSI APS particle sizer for the wake sample. The concentration difference between the sample and baseline sensors is multiplied by vehicle's frontal area to calculate an emission factor in mg/m or g/vehicle-km.

Wake characterisation carried out using a tracer gas released and different points under the vehicle has been used to optimise sample positions, which may vary by vehicle. Particle concentrations are found to be greatest at lower heights, although large variations in concentration due to turbulence makes measurement higher from the road surface more repeatable. Sample positions at a height of 0.65m and symmetrical width placement at 0.85m either side of centreline were found to minimise turbulence affecting results, with the sample points 1.8m behind the tow vehicle.

Studies have sought to achieve isokinetic sampling or apply a correction of anisokinetic sampling, although it is noted that air velocities in the wake (within the envelope of the vehicle width and height) are much slower than the vehicle velocity and correction is only needed at velocities over 100kph. Emissions factors can be developed for the vehicle based on the measured samples and the dispersion of particles observed in the wake characterisation.

Studies using SCAMPER have reported estimates for non-exhaust particle emissions generated by the resuspension of road dust and the wear. Although originally developed in the USA, the system has been applied to European roads. For paved urban routes in Germany an emissions factor of 26 ± 19 mg per vehicle km were estimated, compared to 4.5mg/vkm for a Euro 5 vehicle. Emission factors generally increased with vehicle velocity but were lowest on motorways and highest on rural roads where dust deposits were found. High dust deposits led to increased emissions, but these fall and plateau as the dust is removed by passing vehicles. Emissions varied spatially, with hot spots where vehicles accelerate and brake. Some studies using the SCAMPER are highlighted in Section 2.1.5 and Section 2.1.6.

The SCAMPER approach may be less sensitive to vehicle wheel size and type than the TRAKER but may be affected by the vehicle size and the shape of its wake. As with the TRAKER, SCAMPER does not differentiate the source or composition of particles and no sources are isolated, so the particles measured are expected to contain brake and tyre particles as well as those from the road surface. The vehicle's position on the road, and wind (and rain) are likely to affect results. The following trailer will impact airflow behind the vehicle, although its low profile and the extended drawbar are intended to minimise its effect on measurements. It's also not clear how measurements might be affected when following another vehicle; although studies have looked at real-world emissions, they focused on quiet roads.

3.3.3 Other methods

There have been other groups that have also develop methods for measuring tyre and road wear particles under real-world driving conditions.

Université Gustave Eiffel equipped a Renault Clio 3 with sensors to record vehicle dynamics parameters at 0.1-second intervals and Electrical Low Pressure Impactors (ELPI Dekati™) and optical particle counter OPC Grimm™ EDM 1.108) for real-time monitoring of particles [31],[56].

Inlets are located behind the drivers front tyre and near the braking system. The inlet behind the tyre is used to sample rear of wheel particles and the one near the braking system is designed to sample particles emitted from braking system and any resuspended dust. Tyre and road wear particles are then determined from the difference between the measurements at the two locations.

A similar system was employed by Ricardo for DfT to measure tyre wear particles [4]. A sampling duct was fixed to the wheel hub carrier, which allowed the duct to move when steering, and a pump was used to draw samples from behind the tyre-road contact patch into the measurement system (see Figure 3-3). The particles collected when driving on the road include tyre, road wear and resuspended particulates. For this setup the brake system is enclosed, and air is pumped through the enclose and exhausted out the back. This removes any potential contamination by brake particles into the sample. Ambient samples were also taken from the front of the vehicle, although not concurrently with tyre particle sampling.

Figure 3-3: Location of sampling point behind the wheel in the Ricardo system[4].



3.3.4 Silt load collection

For calculation of emissions of road dust using the USEPA AP42 method, samples of road dust are required. There is currently no set standard on how to undertake the collection, with the following methods used in previous studies [73].

- Scoop
- Vacuum cleaner
- Vacuum sweeper
- Dustpan and brush
- Whisk broom
- Brush with swine bristles

- Road sweeper

Once collected the material is then filtered, as only the size fraction $< 75 \mu\text{m}$ diameter are classified as silt load according to the AP42 method.

The Swedish National Road and Transport Research Institute (VTI) use a slightly different method, called a wet dust sampler (WDS) that uses water to flush the samples into a sample bottle [74].

Although these methods provide a simple approach to sampling silt load, the measurements are very specific to the location where the samples were obtained. The manual collection of samples can also be time consuming.

3.3.5 Flux measurements for road dust resuspension

For flux measurements PM instruments and anemometers are installed at various heights on a tower beside the road. By obtaining measurements of PM at different heights above the road, a gradient of PM concentrations versus height can be determined. This gradient describes the deposition and resuspension of particulates above the road surface. From this data emission fluxes and emission factors can be calculated for each vehicle pass, with the assumption that equilibrium has been reached between resuspension and deposition of road dust [23],[58],[60].

The benefit of flux measurements is that emission factors can be calculated for different vehicle types and vehicle speeds. However, the measurement approach requires multiple instruments to measure PM and meteorological data, which also need to be calibrated and carefully synced to each other.

3.4 EMISSION FACTORS

Emission factors are used in inventories and models to assess how different activities can affect emissions of pollutants. They are usually determined from real-world studies that have been undertaken to calculate emission factors. For road wear and resuspended dust emissions there have only been limited studies worldwide to estimate road wear and resuspended dust emissions, which has resulted in limited emission factors for PM₁₀ and PM_{2.5} with high uncertainty. In addition, these emission factors are typically only applicable under certain conditions.

3.4.1 Road wear emission factors

The EMEP/EEA Guidebook 2023 chapter (update 2024) on non-exhaust road transport emissions provides emission factors and uncertainty values for road wear for PM₁₀ and PM_{2.5} for different vehicles, which European member states can use to support their national inventory submissions[22]. These factors are estimated based on data from a study published in 2002[76] but do not vary with changes in road conditions or vehicle speed.

Table 3-1 provides an overview of the EMEP/EEA Guidebook Tier 1 road surface wear emission factors for total suspended particulates (TSP), PM₁₀ and PM_{2.5} along with their 95% confidence intervals. Of the TSP emissions, 50% are assumed to be PM₁₀ and 27% are assumed to be PM_{2.5}.

Table 3-1 Tier 1 road surface wear emission factors (EMEP/EEA Guidebook) by vehicle type and pollutant.

Vehicle type	Pollutant	Value (gkm ⁻¹ vehicle ⁻¹)	95% confidence interval (lower, upper)
Two-wheelers	TSP	0.006	(0.0036, 0.0081)
Two-wheelers	PM ₁₀	0.003	(0.0018, 0.0041)
Two-wheelers	PM _{2.5}	0.0016	(0.0010, 0.0022)
Passenger cars	TSP	0.015	(0.0090, 0.0203)
Passenger cars	PM ₁₀	0.0075	(0.0045, 0.0101)
Passenger cars	PM _{2.5}	0.0041	(0.0024, 0.0055)

Vehicle type	Pollutant	Value (gkm ⁻¹ vehicle ⁻¹)	95% confidence interval (lower, upper)
Light goods vehicles (LGV)	TSP	0.021	(0.0090, 0.0253)
Light goods vehicles (LGV)	PM ₁₀	0.0105	(0.0045, 0.0123)
Light goods vehicles (LGV)	PM _{2.5}	0.0057	(0.0024, 0.0070)
Heavy duty vehicles (HDV)	TSP	0.076	(0.0456, 0.1026)
Heavy duty vehicles (HDV)	PM ₁₀	0.038	(0.0228, 0.0513)
Heavy duty vehicles (HDV)	PM _{2.5}	0.0205	(0.0123, 0.0277)

Higher Tier emission factors and uncertainty ranges are also provided in the Guidebook, which are disaggregated by vehicle size and technology type (e.g. ICE/hybrid/electric).

Mass dependant road wear emission factors have been calculated by Beddows and Harrison (2021)[25] using the EMEP/EEA Guidebook values and assigning different weights to the vehicle types and applying a regression. The Guidebook has highlighted the need for further experimental studies to improve the emission factors and reduce uncertainty as there are limitations around the variability of conditions and materials used and how these aren't accounted for. It notes that the emission factors provided were derived from studies on dry days and that a water layer on rainy days should result in a reduction in emission factors as the water may trap such particles.

Potential studies could focus on the following:

- Variability in surface material.
- Variability in road surface condition (wet and dry, cracks/potholes).
- Vehicle speed.
- Influence of studded tyres (although less important in the UK).

3.4.2 Resuspended dust emission factors

Resuspension of deposited dust is a complex process caused and greatly affected by the intensity of local traffic turbulence and speed of the circulating local traffic. The amount of resuspended dust depends on the local deposition and removal processes. Calculated emission factors contain large uncertainties and are applicable to certain conditions (i.e. loading rate, type of pavement, pavement condition & structure, driving speed, sampling season, vehicle fleet, etc.).

Raparathi and Phuleria (2022)[77] conducted roadway tunnel air pollutant measurements in India for the first time under real-world driving conditions. To identify potential sources and their contribution to total PM_{2.5} and PM₁₀ road traffic emissions, receptor modelling analysis was carried out. The variation in the distribution of emission sources is highly dependent on vehicle types, vehicle age and maintenance, driving behaviour and road conditions. Raparathi et al. (2021)[78] pointed out that the silt loading rate in India is 4 times higher than in European or American countries likely due to the tropical meteorological conditions and poor maintenance of roads which can lead to higher road dust PM emissions. It is observed that the share of resuspended road dust to PM₁₀ road traffic emissions found by Raparathi and Phuleria (2022)[77] in India was 63% (which is at the high end of similar analysis) whereas in the UK, Lawrence et al., (2016)[79] found the share to be 27% and Zhang et al. (2020)[80] 51-64% in China.

There are currently no emission factors for resuspended dust in the EMEP/EEA Guidebook. However, some modelling approaches have been developed to estimate resuspension emission factors. These are described in a review study by Galatioto et al. (2022)[81] and briefly discussed below.

USEPA AP42 method estimates resuspension emission factors for their inventory for paved roads, based on silt loading and vehicle mass[31].

$$EF = k(sL)^{0.91}W^{1.02}$$

where, EF is the emission factor (g/km/vehicle) for the average fleet on the road, k is the particle size multiplier for the size range of interest (PM_{10} or $PM_{2.5}$), sL is the road surface silt loading (g/m^2), for size range of material $\leq 75 \mu m$ in diameter, and W is the mean weight of the vehicles traveling the road (tons). A precipitation correction term can also be included in the equation, if applicable.

The HERMES v3 model estimates emission factors for resuspended dust for different road lengths and traffic flows, based on empirical emission factors for each vehicle type. Factors are then applied to account for precipitation, and the month, day and hour [82].

The NORTRIP model includes many parameters in the calculation of resuspended dust emissions, including vehicle speed, vehicle flow, and moisture [83].

The empirical model by Padoan is a multiple linear regression model that is used to estimate road dust emission factors using different variables, specific to the location of interest [50]. The general form of the equation is:

$$EF = a \times MF10^b$$

where, EF is the fleet averaged emission factor (mg/vehicle kilometre travelled), $MF10$ is the road dust suspensible fraction, and a and b are coefficients which are specific to the location.

Galatioto et al. (2022) acknowledged that there were advantages and disadvantages to all the different models and which one to use would depend on what information is available and availability of data.

To develop resuspended emission factors for UK roads, it is important to first undertake measurements to better understand the variability in resuspended dust, as levels can vary by location, traffic, vehicle load, vehicle speed, type of pavement, road gradient and prevailing weather conditions. This could be undertaken using a combination of silt-load measurements and roadside/on-road monitoring. These measurements can then be used to estimate emission factors for resuspended dust in the UK.

As discussed in Section 2.1.5, vehicle speed can have a large effect on resuspended dust emissions. Speed emission curves have previously been developed for different vehicle types in the UK, for NO_x and PM exhaust emission factors[84]. A similar approach could be applied to road dust emission factors.

4. SUMMARY OF EVIDENCE GAPS

The literature review has highlighted that despite studies going back decades, there are still many unknowns with regards to the variables that impact road wear and resuspended dust emissions Table 4-1 summarises the main findings from the literature review and evidence gaps identified.

Table 4-1 Summary of current understanding and identification of evidence gaps.

Area	Current understanding	Evidence gaps
Road surface condition	- Older roads can result in higher dust loadings and increased resuspension - Older roads can emit finer material	- Variation in $PM_{2.5}$ emissions due to pavement deterioration (e.g. aggregate shape, micro- and macrotexture over time) is unknown - No information on whether large cracks/potholes or pavement unevenness can increase wear - No published studies on UK roads
Road materials	Combined tyre and road wear emissions shown higher for concrete than asphalt	$PM_{2.5}$ emissions for aggregates used in the UK (and pavement macrotexture) are unknown $PM_{2.5}$ emissions for the different materials typically used in the UK (e.g. concrete vs

Area	Current understanding	Evidence gaps
	Smaller aggregates (e.g. 11 mm) can result in lower emissions than larger (e.g. 16 mm) Porous pavements can better trap particles	asphalt, but also in between different types of concrete and asphalt mixes) are uncertain Whether tyre-road wear can be reduced without affecting skidding resistance or other attributes
Effect of vehicle load	- Wear increases with vehicle mass/load/size - Mass increases acceleration and braking forces - Axle load is important	- Many studies rely on emission factors based on limited evidence - Link between road degradation wear and particle emissions is unclear - Large variability between studies for the weight-emissions relationship
Effect of vehicle speed	- Higher vehicle speeds typically result in higher resuspended PM₁₀ and PM_{2.5} emissions - Road dust loading higher at lower vehicle speeds - Studded tyres have a larger impact on road dust emissions at higher speeds	- No clear information on whether/how vehicle speed affects road wear - Large variability between studies for the speed-emissions relationship
Effect of braking and acceleration	- Increase in particles smaller than 10 µm measured above the road during vehicle acceleration and deceleration - Harsher braking can result in higher PM₁₀ and particle number concentrations	- No studies solely on the effect of braking and acceleration on road wear - Measurements are influenced by brake particles during the braking events - Higher torque of electric vehicles is sometimes highlighted in literature, but no direct evidence of impact on road wear
Effect of road layout and traffic management	- Lower traffic volumes result in lower road dust due to less turbulence - PM₁₀ and PM_{2.5} increased when closer to braking zones due to more particles being deposited on the surface - Large roundabouts can result in higher emissions due to faster cornering speeds (when compared to smaller roundabouts)	- No published studies that directly investigate road layout and traffic management effects on PM_{2.5} emissions from road wear and dust resuspension - Limited evidence linking road wear rate to rate of braking/acceleration (or to tyre-road shear force)
Impact of climate change and seasonal effects	- High humidity and precipitation can suppress road dust emissions - High winds can affect the road dust loadings	No studies available that detail whether changes in temperature or precipitation may directly affect road wear emissions
Emission factors	- EMEP/EEA Guidebook provides road wear emissions factors for different vehicles - Range of different methods for calculating road dust resuspension emission factors	- No standardised method for determining emission factors - Independent of vehicle speed and weight, road type, precipitation - High uncertainty in road wear emission factors - No emission factors for road dust in EMEP/EEA guidebook

Based on the gaps in the evidence we have proposed a number of research questions.

1. What is the composition of road wear particles emitted from UK roads?
2. Are there experiments that can be undertaken to quantify the effects of aggregate type on road wear and can tyre wear and road surface wear emissions be distinguished and quantified separately?
3. What tests can be undertaken to quantify the effects of surface characteristics on road wear?
4. What tests can be undertaken to quantify the effects of temperature, precipitation, wind on road wear and resuspended dust?
5. Are there any existing materials in UK that are less impactful in terms of TRWP?
6. Can new materials be designed and produced in the UK to minimise TRWP?
7. Can mathematical models be developed to estimate the impact of road characteristics on TRWP?
8. Can mathematical models or measurements be used to identify locations where any road works or mitigation measure can help minimising the production of TRWP generated in the area?
9. What are the trade-offs of minimising road wear, and can a “healthy balance” – to address related societal and environmental issues and keep roads safe (see sections 2.3 and 2.4) – be achieved?
10. How could materials, construction and maintenance specifications change to minimise TRWP?
11. What sort of updates would national specifications and industry practice require to minimise road wear and its effects on society and the environment?
12. What tests can be undertaken to develop new emission factors for road wear and resuspended dust, including effects of vehicle speed, mass, road type etc?

5. RESEARCH RECOMMENDATIONS

To address the evidence gaps and research questions identified in Section 4, ideas for potential research campaigns have been developed. These aim to build on the findings of previous literature and the test methodologies identified in Section 3, and consider the gaps in knowledge that are reported. Since road wear and resuspension are intrinsically linked to the tyres and vehicles that pass over the roads, it is impossible to separate them completely from the effects of tyre wear. However, the suggested approaches each aim to consider road wear and resuspension from a different angle. These include:

- Evaluating road wear and emissions of different surfaces under controlled laboratory conditions.
- Evaluating the particles found on road surfaces in the real world, and their likely contribution to particulate emissions.
- Evaluating the potential for road surface materials to form particulate emissions and its composition.
- Evaluating tyre, road wear, and resuspension particle emissions in the real world across different driving and road surface conditions.

The initial focus of the research projects over the first 1-2 years would therefore be to explore the potential and capabilities of these test approaches, to establish robust methodologies, and their initial application to address immediate questions as described. To give a sense of scale to the research, the potential scope for each project is outlined at a high level. The experimental methodologies could, once proven and refined, be then used to explore the knowledge gaps in more detail through testing a greater variety of surfaces and conditions.

Stakeholders for the initial research could include National Highways, local highway authorities and highways sector partners since research will consider the road surfaces used on UK roads and access to the road network may be needed for some of the tests proposed. The research can be expected to generate interest in relation to air quality, the road industry, tyre and vehicle manufacturers, and policy makers within the UK and Europe. Therefore, dissemination could include publishing papers or journal articles and presenting at relevant conferences.

In the longer term (3-5 years) with increasing detail available from the research, stakeholder engagement could be expanded to include members of the international community such as relevant European Asphalt Pavement Association (EAPA), Conference of European Directors of Roads (CEDR) and Transportation Research Board

(TRB) technical committees, to finalise programme and discuss routes to standardisation of the proposed methods. The research would be expanded to address other variables that may affect the road wear and dust resuspension (e.g. temperature, precipitation). Recommendations and support should also be provided to implement any changes to relevant DMRB and MCHW clauses.

5.1.1 Research programmes – Initial Testing

5.1.1.1 *Laboratory assessment of road wear particle emissions*

In the **short-term** the aim would be to understand if the different road surface materials and characteristics influence road wear and dust resuspension and how this can be assessed. For this, we recommend that future research should focus on establishing and comparing the performance of common surfacing materials in a laboratory setting. This will entail:

- Early stakeholder engagement (to ensure industry buy-in).
- Aggregates from 1 quarry (UK).
- Review of aggregate properties.
- 3 types of surfaces (HFS vs positive texture vs negative texture).
- 2 aggregate sizes for the asphalt mixtures.
- Design laboratory tests to compare road wear.
- Develop a simple mathematical model.
- Recommend further research (including stakeholder feedback).

This review has identified little evidence of past research into quantifying particle emissions from road surface wear, or the share of TRWP from roads and tyres. We recommend an approach that uses an MMLS (described in section 3.2.2) to create a test rig focused on measuring the particle emissions, with a focus on road materials and surface characteristics. The materials to be tested should be installed using realistic laying and compaction techniques, in a way that resembles the characteristics of actual UK roads but in a controlled environment. This approach will substantially enhance the comparability of the obtained results, making sure external factors do not hinder the evaluation of the performance of road materials and their texture.

Once construction is complete, the MMLS would be set up over each of the three types of road surface proposed above. Data would be collected at different intervals – e.g. 0, 50, 1000, 5000, 10,000 and 20,000 wheel passes of the MMLS – to evaluate the effect of changes in macro- and microtexture levels on the production of particles. Prior to any new testing, both the MMLS and road surface would be rigorously cleaned/swept/vacuumed to remove any debris and collect any particulates generated during the experiment.

An enclosure would be created around the MMLS. A measured volume of filtered air would be pumped into the enclosure (at the end where tyres contact the road surface) and pumped out a slightly lower flow rate at the rear, so that any excess air leaks out and no external aerosols leak in. The flow rate passing the tyre employed would be selected as having a sufficiently high velocity to transport PM₁₀/PM_{2.5} through the enclosure. It could be possible to relate this flow directly to the wake velocity likely for the given road speed experienced by the tyre (perhaps at 40-80% of the vehicle road speed), but this would add cost and complexity.

The exit of the enclosure would contain a particulate collection device, such as a bulk filter or bulk cyclone (or series of cyclones). Tests are expected to run for tens or even hundreds of hours to provide sufficient road (and tyre) wear to enable gravimetric analysis. These tests will focus only on the mass of particles generated (i.e. will contain road wear, tyre wear and resuspended dust) to assess whether they potentially have a significant contribution to airborne PM₁₀/PM_{2.5} mass concentrations and if differences can be observed between different pavement surfaces. The laboratory data will also be used to develop simple models that can be used to establish a network level baseline and evaluate performance.

In addition, it is suggested that additional tests are conducted combining the Road Simulator and Modified Hamburg Wheel Tracking tests (see sections 3.2.1 and 3.2.3). This would be used to validate the findings from the tests performed using the MMLS and test variation of performance over time. Similarly to the tests performed with MMLS, the testing performed would entail:

- 3 types of surfaces (HFS vs positive texture vs negative texture).
- 2 aggregate sizes for the asphalt mixtures.

Three slabs of each mix should be prepared to specification, to achieve macrotexture requirements. Then, the Modified Hamburg Wheel Track testing would be carried out on each slab after completing 0, 50, 500, 1000, 5000, 10,000 and 20,000 wheel passes of the Road Simulator. Variations in slab macrotexture would be measured using sand patch and lasers. Microparticles would be collected from the macrotexture of each slab after each stage of Road Simulator and Modified Hamburg Wheel Track testing is complete. Wear of the rubber test strip fitted to the Modified wheel track tester will be measured using lasers. Ultimately, results would be compared to those obtained from the MMLS, for validation.

5.1.1.2 Bulk analysis of road surface wear materials

The research proposed in Section 5.1.2.1 above focusses on the different road surface materials and whether particle emissions can be quantified. Further independent research programmes could also be undertaken to understand whether the material from road wear and dust resuspension has an impact on air quality. To achieve this, it is important to assess the size distribution of the particles and whether they contribute to PM₁₀ or PM_{2.5}. It is postulated that loose materials on the road surface interact with each other, the road surface, and the tyres in contact with the road, leading to changes in particle size distribution. Potentially the greatest factor in this evolution is the energy provided to the interaction of the particles by passing tyres, which will be related to both vehicle velocity and to vehicle mass. The proposed approach is to sample (large) quantities of particulate materials from different road types to determine whether different imposed energy leads to overall smaller particles and what those particle sizes might be. Table 5-1 presents road types that could potentially be studied.

Table 5-1: Suggested road types to sample.

Road type	Characteristics
Urban road	Low speed, high passenger car traffic density
Rural road	Moderate speed, moderate passenger car traffic density
Motorway inside lane	Moderate speed, high HGV traffic density
Motorway outside lane	High speed, high passenger car traffic density

The materials would be sampled from each road type by a high vacuum system, and the particulates then studied in terms of mass collected and particle size. Some physical and chemical/elemental classification of the particles would also be conducted, for example to eliminate any combustion generated particles. The primary objectives of the work would be to determine whether particles collected from the road surfaces tend towards smaller sizes when sampled from areas where the road surface experiences higher energy interfaces with tyres, and whether materials identified as deriving from the road surface are reduced in size to the extent that they become contributors to air-quality relevant metrics by entering the PM₁₀ or PM_{2.5} regimes.

Alongside the collection of material for bulk sampling, silt load measurements following the USEPA AP42 methodology can be taken to estimate the resuspended road dust emission factors.

5.1.1.3 Road wear particle size potential

If the findings from the bulk analysis of road surface wear materials show that the materials on the road surface do become part of the PM₁₀ or PM_{2.5} regimes, then further research could be carried out to explore the evolution of road wear particles over time.

A grinding rig experiment would be designed with the aim of, simulating the grinding and impact forces that occur between tyres, road wear particles, and road surfaces. In advance of the experiment, a suitable quantity of road wear particles would be harvested through a high flow vacuum attached to a vehicle driving on UK highways. The road wear particles, representing a mix of tyre and road surface materials, including hybrid particles, would be placed in a ball mill or rotating drum grinder with varying grinding media, pressure, and rotational speed. These parameters would be selected to replicate the forces experienced by particles in real-world driving conditions, where friction, shear, and impact lead to particle breakdown. During rig operation, samples of particles would be taken at intervals and the particles inspected using sieving, optical instrumentation and/or microscopy. The key objective would be to determine whether the particles continue to break down into smaller sizes over time and if a limiting particle size is reached, beyond which further wear

and/or fragmentation ceases. This experiment would provide insights into the behaviour of road wear particles, helping to understand their potential environmental impact and whether smaller, potentially more hazardous particles are produced as wear progresses. For example, if road wear particle size evolution reaches a limiting threshold above 10 µm, then this can be considered a minor impactor on air quality. The findings could also contribute to developing strategies to capture and mitigate the environmental effects of road wear debris.

5.1.2 Research programmes – Extended Testing

The initial research programmes are designed to assess road wear and dust resuspension particles from different road surface materials and to understand the size fractions of these particles. Depending on the outcomes of the initial testing, further assessment could be undertaken. Below are some examples of laboratory assessments and on-road testing that could be carried out, to address the sources of the particles and the different variables that can influence the emissions.

5.1.2.1 *Extended laboratory assessment of road wear particle emissions*

The tyre(s) would first be weighed to establish their baseline mass. Following testing, the tyres would be weighed and the MMLS enclosure vacuumed to collect all emitted material (using a cleaned cyclone-based vacuum cleaner). Emissions from both the bulk cyclone collector and the vacuum cleaner would be inspected and quantified gravimetrically. Emissions could then be portioned using sieving analysis to determine size distribution of particles >~50µm. Thermogravimetric analysis could be used to determine organic (dominated by tyre rubber) contributions to each size range. Potentially, a mass balance of losses from the tyre and recovered organic material could be achieved, leaving the remaining mass as mineral contributions from the road surface.

The air exiting the cyclone would be sub-sampled to allow measurement of very small particles, vapours and gases etc., although it should be noted the effective dilution of the emissions would be very high resulting in low concentrations of particles that may be challenging to measure accurately. Particle sampling at the air outlet may not be continuous, but at periodic intervals, potentially at decreasing intervals if emissions are found to stabilise. Repeat tests would be advised to accumulate material, to increase confidence in gravimetric results. Before, between, and after tests, a background measurement would be made in which the MMLS would be running but the tyres not contacting the road surface to provide a baseline of particles that may be entering or generated within the test rig (e.g. from the MMLS machinery).

On one or more tests, continuous measurements of PM₁₀/PM_{2.5} could be made with selected measurement equipment very close to the tyre/road contact patch, to study possible resuspension effects. However, the methodology aims to minimise resuspension of particles that did not originate from the road or tyres used.

This test approach aims to provide:

- An understanding of the size distribution and composition of particles generated by tyre-road abrasion.
- An understanding of PM₁₀ and PM_{2.5} emissions from the road-tyre interface.
- An indication of the mass split between tyre and road wear emissions.
- Potential insights into how particle resuspension emissions evolve from a “clean” road and tyre.
- For the different types of road surface tested, an understanding of how the quantity and size of particles emitted vary between road surfaces.

There are limitations to this approach. The MMLS represents vehicles rolling along a road at constant speed, and does not represent acceleration, braking, or cornering, which put greater strains on both tyres and road surface which are thought to lead to greater emissions as observed in literature at road junction “hot spots”. PM₁₀ and PM_{2.5} emissions are expected to be low in real-time, and high dilution ratios are likely to make accurate measurement challenging, while low mass emissions may lead to high uncertainty in mass comparisons. Nonetheless, the approach allows study of the emissions from tyre contact with a real road surface with a high degree of isolation from other factors.

Depending on the initial road surface research results and if there is potential for further research (i.e. the results show that the different surfaces provide different TWRP amounts, characteristics), further phases of research could:

- Expand on the limited number of materials tested initially to have better coverage of aggregates and mixtures typical of the UK, including concrete, and explore new road surface developments.

- Compare the wear and resuspension emissions of each, alongside key attributes such as grip, drainage, and durability.
- Perform independent tests on aggregate composition against CE mark and Declaration of Performance (DoP) and analyse the TWRP composition.
- Simulate different vehicle load configurations and explore how road wear is affected.
- Develop mathematical models and perform network level analysis to establish baseline of current network level performance and possible improvements.
- Provide recommendations for updates /changes to national specifications.

A further phase of the programme will expand the number of surfaces and treatments tested, using materials with recycled constituents and including a selection of under development materials (e.g. porous asphalt, low rolling resistance and biomaterials). Road wear particle size evaluation could also be undertaken.

5.1.2.2 *On-road measurements of tyre, road wear and resuspension particles*

To compliment the laboratory assessments, on-road testing could be undertaken to assess other variables such as vehicle speed, acceleration, braking, and cornering, in addition to different road surfaces. The on-road measurements would combine the approach used by Ricardo for DfT with the SCAMPER technique (described in section 3.3.2). This could comprise a sample point behind the tyre of a vehicle, with one or multiple point sample nozzles rather than the slot nozzle previously used to maximise flow velocity. Nozzle positioning may be optimised through experimentation or techniques such as computational fluid dynamics, which could also provide the likely distribution of particles behind the wheel. Enclosing the brake as carried out previously isolates measurement from the vehicle's own brake particle emissions, while measuring at a front wheel means emissions from other wheels and the exhaust are downstream as well as capturing the highest emissions levels (assuming front wheel drive and steering). Parallel measurement of background particle concentrations upstream of the vehicle would use a sample nozzle mounted on the front of the vehicle. Particle measurement devices along with sample pumps and battery supply would be installed on-board the vehicle.

Testing could take place on a variety of surfaces and with different vehicle loads. A test track provides an environment with minimal traffic adding to baseline emissions, and enable safe testing of high speeds, acceleration, brake, and cornering impacts. A swept road surface could minimise resuspension of existing particles on the road surface. Different real-world road surfaces in different environments could be explored, potentially covering different road surface construction, age, unevenness, state of degradation, etc. These tests could also be carried out on the same roads that are being proposed for the assessment of bulk analysis of road surface wear materials (Section 5.1.1.2) for example on key roads or emission hot-spots over a real-world route, and the data from the samples can then be compared to the measurements from obtained from the on-board measurements and those from literature.

This test approach aims to provide:

- How the passage of a vehicle (or a single wheel) affects particle concentrations in the air.

PM₁₀ and PM_{2.5} concentrations from tyre and road wear combined with resuspension.

Analysis of collected particles to identify the materials contained.

Particle size distribution may also be possible, but the higher power and air flow demand adds complexity and reduces scope for on-road testing.

- How the PM₁₀ and PM_{2.5} emissions vary with vehicle speed, acceleration, braking, and cornering.
- How the PM₁₀ and PM_{2.5} emissions vary across different road surfaces and environments.

Challenges are expected due to the low concentrations of tyre, road wear, and resuspension particles and the increase over background emissions may be small. Sample flowrates may need to be optimised to minimise sample dilution while ensuring adequate velocity for particle entry and transport. Test track environments minimise background PM from other vehicles and provide a baseline for on-road testing.

With a proven methodology, testing could be extended to explore how the emissions vary with vehicle load (by ballasting the vehicle, or using different vehicles), across a greater variety of surfaces and driving conditions, and in different ambient temperatures and surface wetness. Data from such testing can help inform emissions factors for different conditions and vehicle types.

5.1.3 **Expertise and facilities required**

The research activities proposed above would require a range of skills:

- Expertise in delivering practical research programmes
- An understanding of the factors affecting tyre and road wear and their interaction with vehicle operation
- A deep knowledge and understanding of the formation and emissions of particulates, especially from vehicle sources
- Expertise in measuring and analysing particles, including transport and sampling, and the use of different types of measurement instruments

Expertise in road surface construction, materials, their attributes, including chemistry, and the effects of wear and degradation

Equipment and facilities required would include:

- Particle PM₁₀ and PM_{2.5} real-time concentration measurement instruments
- Particle size measurement instruments

Particle mass measurement instruments and approaches

Particulate collection approaches, and the ability to physically partition particulate matter into different size ranges

- Airflow/sample flow measurement devices
- For laboratory assessment of road wear particle emissions:
 - A road surface-tyre wear test rig, such as a Model Mobile Load Simulator (MMLS) (see section 3.2.2)
 - Combination of Road Simulator and Modified Hamburg Wheel Tracking tests (see sections 3.2.1 and 3.2.3)
- For on-road measurement of tyre and road wear and resuspension:
 - Ability to install test equipment (including instruments and supporting systems) into a vehicle, and conduct road and track testing safely and accurately
- For road wear particle size potential evaluation:
 - Suitable grinding mill
- Fabrication and instrumentation capabilities for developing and adapting test facilities, installing and checking equipment and instruments, etc.
- Data collection and analysis systems, including data from lab/test rig and road/vehicle tests.

6. MITIGATION METHODS FOR ADDRESSING ROAD WEAR AND DUST RESUSPENSION

As highlighted in this study, it is important to fill the gaps in order to understand how much the road pavement surface can influence road wear and resuspension emissions and to improve emission factors. From the research programmes proposed in Section 5, knowledge can be gained on the different variables in play and to quantify these effects. The findings from the research can then be used to assess whether there are new or existing materials available for pavements that can reduce road wear and dust resuspension emissions of PM₁₀ and PM_{2.5}, and if changes in DMRB and MCHW specifications on materials should be proposed.

There are other mitigation measures that could be implemented to reduce particle emissions from the road surface, in addition to current and new technologies aimed at removing particles from on or above the road surface once emitted. These are discussed in more detail in the following sections.

6.1.1 Mitigation measures for reducing emissions of particles from the road

6.1.1.1 Vehicle load

Data has shown that the average weight of new vehicles has increased by nearly 400 kg from 2016 to 2023 [85]. The studies reviewed in this report show that heavier vehicles result in more degradation to the road surface although it is unclear if this results in an increase in road dust loading and road wear. Current road wear emissions factors imply an increase with vehicle size but are based on limited data and have high uncertainty. However, increased vehicle mass will mean greater forces at the tyre-road contact patch when

the vehicle accelerates, brakes, or corners, which are observed to increase road wear emissions, and so a relationship between vehicle mass and loading and the emissions from road wear might be expected. Since current understanding relies on limited direct measurement and many assumptions, there are still gaps in knowledge with regards to the exact relationship between weight and road wear and resuspension dust emissions.

Review studies focusing on mitigation methods have highlighted that reducing the weight of vehicles on the road, through newer lighter materials, smaller vehicles and/or smaller batteries, could result in lower non-exhaust emissions[86], [87]. Although this would require participation from vehicle manufacturers and incentives for consumers, as larger vehicle types are more gaining popularity, with SUV sales making up 60% of new car registrations in the UK in 2023[88].

Modelling studies focussing on transport emissions should be undertaken to evaluate how a shift to lower vehicle loads could reduce emissions from road wear and dust resuspension. However, these models require mass dependant emissions factors for road wear and dust resuspension, which are currently not considered in the EMEP/EEA Guidebook (see Section 3.4). Some studies have estimated mass based emission factors using the vehicle size as a proxy for vehicle load, but there are still large uncertainties. Improving this uncertainty through laboratory testing and/or on-road measurements under different vehicle loads/weights is necessary in order to evaluate emission through modelling.

6.1.1.2 Vehicle speed limits

The literature has shown that resuspended dust emissions of PM₁₀ and PM_{2.5} measured above the road can increase at higher vehicle speeds, therefore lowering the speed limit may reduce the amount of PM from the road that becomes airborne. However, at lower speeds and low traffic volumes some studies have also shown that the dust loading on the road may also increase, so this would need to be considered. Speed limit restrictions to reduce dust resuspension emissions may be better applied to high speeds roads with heavier traffic. It should be noted that the effect of vehicle speeds on the contribution of emissions from road wear itself to total TRWP has not been studied in great detail, therefore, further investigation into the effect of speed limits on road wear would be advisable before any potential traffic management strategies are implemented.

Sharp braking and accelerating can also result in higher emissions of road dust and TRWP, therefore, emissions could be higher at junctions and on roads where there are traffic calming measures such as speed bumps. A study for Transport of London investigated the effect of reducing speeds limits to 20 mph in London on emissions and health [89]. The focus of the study was on NO₂ emissions however the study noted that speed tables (which are raised sections on the road with ramps) could be considered instead of speed bumps as acceleration and braking are reduced. Other methods of reducing harsh braking and fast acceleration include 1) promotion of eco-driving, 2) promotion of vehicles with adaptive cruise control (ACC), and 3) smart traffic signalling. The promotion of eco-driving is theoretically the simplest method of improving smoother driving on the roads. However, research has shown that although immediate benefits after training on eco-driving is observed (measured by fuel consumption and/or emissions of CO₂), this can reduce over time as drivers fall back to old habits [89]. Vehicles with ACC and smart traffic signalling are long-term investments, either for the consumer (ACC) or for the government/local authorities (smart traffic signalling).

ACC is likely only to be used (and be beneficial for reducing braking severity and brake, tyre, and road wear) on motorways where vehicles are cruising. However, all vehicles sold in the UK and Europe since 2022 must have Autonomous Emergency Braking (AEB)[90], sometimes known as City Braking or Forward Collision Warning, which applies the brakes to avoid a collision based on radar and/or camera sensors. Since this only occurs in an emergency, AEB is unlikely to contribute to increased brake, tyre, or road wear. Regenerative brakes are another emerging brake technology used by electrified (electric and hybrid) vehicles, although they do not in themselves change the deceleration rate of the vehicle, they might encourage a driver to use more smooth, gradual braking to maximise vehicle efficiency and range,

All these approaches can aid in maintaining smooth vehicle flow on the roads, with the potential to reduce non-exhaust emissions. However, as highlighted by the evidence gaps in this review, there have been no published studies researching the impact of braking and acceleration on road wear alone, therefore it is not clear whether these approaches would directly reduce road wear emissions. Further research in this area is required to improve understanding of the direct effects of braking and acceleration on road wear.

6.1.1.3 Reducing the number of vehicles on the road

During the Covid-19 lockdowns traffic on the road decreased considerably. Two studies focussing on traffic emissions in on roads in and around London showed that non-exhaust emissions of PM₁₀ and PM_{2.5} (including

brake wear, tyre wear, road wear and resuspended dust) decreased overall as a result of changes in traffic flows[91], [92]. Policies promoting the use of public transport, car-sharing and active travel could reduce the number of vehicles on the road, therefore having a positive effect on mitigating road wear and resuspension of dust. NatCen Social Research undertook a rapid evidence assessment (REA) on behalf of DfT in 2021 to assess how effective different interventions were in encouraging a move from driving to other forms of travel[93]. They found that restrictions on vehicles entering city centres and a reduction in parking availability could be effective, but that other forms of transport such as public and active transport should be implemented initially. Initiatives and incentives to encourage people to switch can also improve the effectiveness.

It should be noted that the interventions described above to reduce traffic on the road focus on passenger cars and do not address commercial vehicles for transporting goods. These types of vehicles typically have higher loads resulting in higher tyre and road wear PM emissions factors (see Section 2.1.4).

6.1.2 Technologies for filtering or removing particles

There are also technologies that could be considered as part of a programme to in order to mitigate emissions of TRWP once emitted. In the 'Review of PM_{2.5} Reduction Technologies for On Road Transport' horizon scanning report a number of different technologies were highlighted as possible options for mitigating PM_{2.5} from road transport. In this section these technologies have been investigated further to assess whether further research should be undertaken any whether any of these technologies would be suitable and feasible for the UK road network.

6.1.2.1 Vegetative barriers

Vegetative barriers include naturally grown trees, hedges and shrubs beside the road, and the installation of living walls and green barriers. These barriers can reduce the PM concentrations near roads via deposition of PM to the vegetation. Studies have shown vegetative barriers can be effective at reducing PM₁₀ and PM_{2.5} behind the barrier.

Sillars-Powell et al (2020)[94] took samples of PM from leaves at different locations in Southampton (where the vegetation is located by the road). The authors found that the areas with the highest traffic density, had the higher amount of PM on their leaf surfaces - twice as much as the sites with less traffic. The analysis of the elements in the PM indicated that resuspended dust and vehicle emissions were the source of the particles.

The efficiency of removal is highly dependent on the design of the barrier, including the vegetation used. Abhijith and Kumar (2019)[95] undertook measurements at six different roadside locations in the UK to investigate the effectiveness of the reduction of PM due to vegetation. Different configurations of hedges, trees, and a mix of hedges and trees were targeted. They found that from these six locations the greatest reduction was observed when just hedges were present. A combination of trees with hedges also showed potential for reduction in PM but not trees on their own. Kumar et al. (2024)[96] and Tomson et al. (2021)[97] reviewed different infrastructures that were designed to mitigate air pollution. Street trees, hedges green roofs and green walls were included in the reviews, and there was a mixture of positive and negative effects on PM across the studies. Both studies highlighted the need for further field and modelling studies, to assess the potential effects of the different infrastructures reviewed.

The results from the limited studies in the UK looking at the effectiveness of green walls and barriers are promising, with decreases in PM₁₀ and PM_{2.5} observed, however it is clear that further investigations are required before this could be rolled out effectively. Widespread tree planting across urban areas would not necessarily be feasible in all areas as urban planning needs to be considered. However, vegetative barriers could be used to reduce PM in localised areas where members of the public may be regularly exposed. For example, Tremper et al. (2015)[98] installed an ivy screen in the playground of a school in the Royal Borough of Kensington and Chelsea to assess the potential impact in reducing NOx and PM₁₀. Results showed that once the ivy had matured PM₁₀ concentrations on the other side of the barrier were reduced by up to 38%.

A modelling study focussing on the West Midlands and Glasgow estimated that by planting additional trees in urban areas in these two regions primary ambient PM₁₀ concentrations could be reduced (the study did not look at PM_{2.5})[99]. For this study the focus was not on a vegetative barrier designed to remove PM at the roadside, rather the effectiveness of an increase in tree coverage to reduce primary PM₁₀ concentrations over the modelled area. The model results showed an increase from 3.7% to 16.5% tree coverage in the West Midlands (over a modelled area of 120 km x 80 km) reduced primary PM₁₀ by 10%. In Glasgow an increase in tree coverage from 3.6% to 8% (modelled area of 60 km x 50 km) reduced modelled primary PM₁₀ concentrations by 2%.

Future studies could focus on the following aspects:

- Effectiveness of vegetative barriers in different locations (street canyons, open roads etc).
- Long-term studies to investigate how the efficiency of particle capture may change across seasons and whether re-emission of particles can occur.
- Investigations into any negative effects of vegetative barriers (e.g. VOCs, increased pollen).

6.1.2.2 Dust suppression

Street sweeping and washing have been used on roads to reduce the amount of particles on the road becoming airborne. As part of their project the AIRUSE team developed a “Technical guide to reduce road dust emissions in Southern Europe”[100]. The guide provides important information on different approaches to reducing road dust emissions, including street sweeping, street washing and dust suppressants.

Street sweeping can be undertaken using vacuum sweepers, regenerative air sweepers or mechanical broom sweepers. The vacuum sweepers are the ones that are most effective at removing the smaller particle (e.g. PM_{2.5}). There are also water-assisted sweepers, which incorporate water sprays. These are used in more dusty locations to reduce the amount of dust that may become airborne when sweeping. A review study on street sweeping[101] found that sweeping was not that effective in reducing ambient PM concentrations. The addition of water did help in reducing PM, but it was not clear whether this was due to the water itself suppressing the dust, or the sweeping. The authors of the review study suggested that studies on wider areas, would be beneficial to assess the effectiveness of street sweeping. This type of study would require collaboration and interest from local authorities.

A news report highlighted two studies that were undertaken in London to investigate the effectiveness of regular road sweeping⁶. One study found a reduction in PM₁₀ levels of 10% and PM_{2.5} of 16%, the other a higher reduction of 33% in PM₁₀ and 29% in PM_{2.5}. The original source material is not stated in the article and could not be located, therefore these numbers cannot be confirmed here.

Street washing uses water to “stick” the particles to the road surface. Although effective at reducing the emissions from the road surface initially, the effectiveness decreases over time as the road surface dries out, resulting in a return of the road dust.

Chemical dust suppressants work in a similar way to washing, and incorporate reagents including calcium magnesium acetate, magnesium chloride and calcium chloride to reduce dust resuspension. Typically used on unpaved roads, or at construction sites to reduce workplace exposure. The majority of studies on dust suppressants on paved roads have focussed on PM₁₀ and have shown potential for reducing airborne particulates. However, the effectiveness is better when dust loads are high. A trial was previously undertaken by King’s College London for TfL to evaluate the effectiveness of dust suppressants to reduce PM₁₀ in London (“Evaluation of the impact of dust suppressant application on ambient PM₁₀ concentrations in London”, Kings College London, University of London, 2012). The report is not available, however in a response to questions posed to the Mayor of London in 2013⁷, the results suggested that it could be effective at industrialised sites in reducing PM₁₀, although only one roadside locations observed a significant reduction in PM₁₀. A dust suppression trial was also undertaken at HS2 construction sites in 2023. This was to evaluate whether dust suppressants additives were more effective than just water. The results suggest that the additives resulted in lower water usage for the same reduction in dust⁸.

The initial trials in London for street sweeping and chemical dust suppressants suggest that these approaches may be used to reduce road dust, however, as far as we are aware these trials have not been extended to other regions in the UK, nor have any programmes involving dust suppression on UK roads been implemented. It seems that there are still large uncertainties into the effectiveness of these methods, and there is likely to be large costs involved for staff and the purchasing the equipment. This type of approach would be more suited to local roads with potentially high dust loads.

⁶ <https://airqualitynews.com/features-opinion/road-sweeping-a-low-tech-efficient-and-affordable-solution-for-improving-uk-air-quality/>

⁷ <https://www.london.gov.uk/who-we-are/what-london-assembly-does/questions-mayor/find-an-answer/evaluation-dust-suppressants-programme>

⁸ <https://learninglegacy.hs2.org.uk/document/dust-suppression-trials-reduction-in-fugitive-dust-emission-from-construction-site-haul-roads-using-water-additives/#:~:text=Site%20trials%20were%20undertaken%20from,terms%20of%20reducing%20dust%20generation.>

6.1.2.3 Active particulate removal

Active particle removal refers to technologies that are designed to remove/filter particles from the road surface or air, reducing the PM concentrations in the immediate area.

A recent technology aimed at reducing pollution levels at the roadside is the Roadvent™ system by Pollution Solution (<https://www.roadvent.com/>). Slots in the road are used to pull in gases and particles emitted by road traffic, close to source. The air is then filtered, and clean air is released from a nearby roadside cabinet. The technology has been trialled and is available for installation. Due to the cost and logistics of installing the system, it would not be suitable for deploying on long lengths of paved roads but would be better suited to areas with high concentrations of PM_{2.5}, such as drive throughs and traffic hotspots.

Other types of active particle removal are roadside purifiers. These work by pulling in ambient air near to traffic hotspots. Roadside purifiers have been trialled in India (WAYU system) and have shown a reasonable efficiency for removing PM₁₀ (34–49%) and PM_{2.5} (19–25%) from the air at the inlet[102]. However, there is no information or data provided in the study on the effectiveness of the system in reducing ambient PM concentrations. Another roadside purifier that has been trialled in Italy is the APA (Air Pollution Abatement) ISCLEANAIR system[103]. A cluster of their filter-less and water-based purification systems were deployed in the city of l'Aquila. The study highlighted that the street canyon cleaning time is greatly reduced during APA operation. However, with these technologies there is no clear indication on how much impact they actually have on a wider area, and whether it can result in a discernible decrease in ambient PM_{2.5}. Further investigation into roadside purifiers, through long-term measurements at the roadside, would be beneficial in improving understanding on their effectiveness as a mitigation measure.

7. CONCLUSIONS

In this report we have reviewed the available literature and gathered evidence relating to road wear and resuspended dust emissions. The review has highlighted the need for further investigations as it is apparent there are still evidence gaps. Addressing these gaps is important so stakeholders have detailed information and recommendations to support any future policies aimed at mitigating particle emissions from the road transport sector.

The factors influencing road wear and dust resuspension can be categorised into four main areas:

1. Vehicles (size, weight/mass/loading, tyre type).
2. Driving style (speed, acceleration, braking, cornering).
3. Road (aggregate, surface (macro and micro-texture, condition, age).
4. Climate (temperature, humidity, precipitation, wind).

For the development of emission factors, it is important to understand all these factors. With improved emission factors, models can provide more robust estimates of the impact of non-exhaust emissions on air quality. The review has highlighted the need for improved emissions factors for road wear and dust resuspension in the UK. Currently, the Tier 1 road wear emission factors in use come from the EMEP/EEA guidebook and are based on limited studies and are only segregated into four different vehicle types (HDVs, LGVs, cars and two-wheelers). The factors do not consider variations in vehicle load, vehicle speed, road surfaces, or climate. For resuspended dust there are no emission factors within the Guidebook. Other countries have developed models and methods for estimating road dust emission factors, however, the results from these vary widely, and there is no standard methodology.

When considering future policies to mitigate emissions of particulate matter from road wear and dust resuspension, there are a number of different stakeholders. Vehicle and tyre manufacturers are undertaking their own research to reduce wear and emissions, for example through newer materials/compositions for tyres. However, this information is typically commercially sensitive and kept confidential. Governments and local authorities do have some indirect and direct influence on driving styles (via road layouts and traffic management), and the road materials and conditions. However, the evidence available in the literature is very limited and in order to make any changes, further research is still required to better understand how these factors can effect wear and dust resuspension.

To address these gaps, we have provided some recommendations for research programmes. The programmes include both laboratory and on-road testing and evaluation of emissions. The laboratory-based programmes are designed to investigate emissions under controlled conditions. This data can then be used to

assess whether any differences can be observed and quantified, with different pavement aggregates and surfaces, and also feed into emission factor estimates.

The on-road testing is designed to provide estimates for emissions under real-world driving conditions. Testing can take place on a wider range of surfaces than the laboratory measurements and allow for investigating the effect of different surface conditions (e.g. those with cracks/potholes) and the impact of braking and accelerating on particles generated by road wear and the resuspension of road dust.

The findings from these research programmes will aim to close the gaps in the current understanding, with a focus on the UK road network. Longer term, depending on the outcome of the initial testing, the results could be used to feed into recommendations for new road surfaces and materials.

The findings in this report have shown that vehicle load, vehicle speed and the volume of vehicles on the road can all have an effect on road wear and dust resuspension emission of PM_{2.5} and PM₁₀. Mitigation methods such as shifting the fleet to lighter vehicles, implementing speeds limits, promoting eco-driving and reducing the volume of traffic on the road may all have a positive effect on reducing emissions. Though, an improved understanding of road wear and resuspended dust emissions and reducing uncertainty in emission factors is essential in order to quantify the effectiveness of these mitigation methods and for the development of new methods in the future.

Beyond influencing the four core factors that affect road wear and dust resuspension, there are other mitigation measures which may benefit from further investigation, such as vegetative barriers, dust suppression, and active particle removal technologies. Some trials have taken place in the UK, however, results on their effectiveness are mixed, and none have yet been demonstrated to be effective at reducing ambient PM_{2.5} at the roadside although they may merit further investigation. It should also be noted that these solutions are not considered appropriate for the strategic road network and if employed should focus on local roads and for targeting areas of high dust load and where the public are likely to be exposed. Local authorities may also be interested in one or more of these technologies to address any Air Quality Management Areas (AQMA).

Due to the costs associated with implementing these technologies it would be important to first undertake further trials at targeted areas and monitoring any local changes in PM. However, further investigations into improving the understanding of road wear and resuspended dust and the variables that impact these, as discussed above, should be undertaken first before targeting other mitigation methods.

REFERENCES

- [1] CMO, 'Chief Medical Officer's annual report 2022: air pollution', Dec. 2022. Accessed: Apr. 07, 2025. [Online]. Available: <https://www.gov.uk/government/publications/chief-medical-officers-annual-report-2022-air-pollution>
- [2] Defra, 'Emissions of air pollutants in the UK – Particulate matter (PM10 and PM2.5)', GOV.UK. Accessed: May 15, 2025. [Online]. Available: <https://www.gov.uk/government/statistics/emissions-of-air-pollutants/emissions-of-air-pollutants-in-the-uk-particulate-matter-pm10-and-pm25>
- [3] NAEI, 'Air Pollutant Emissions Data | National Atmospheric Emissions Inventory', Air Pollutant Emissions Data. Accessed: Mar. 07, 2025. [Online]. Available: <http://naei.energysecurity.gov.uk/air-pollutants/air-pollutant-emissions-data>
- [4] Ricardo, 'Measurement of emissions from brake and tyre wear', Feb. 2023. Accessed: Mar. 26, 2025. [Online]. Available: <https://www.gov.uk/government/publications/measurement-of-emissions-from-brake-and-tyre-wear>
- [5] National Highways, 'Environmentally Optimal Tyres and Brakes Phase 1 Report for National Highways', 2024. [Online]. Available: <https://s3.eu-west-2.amazonaws.com/assets.nationalhighways.co.uk/Knowledge+Compendium/NH+T0462+Environmentally+Optimal+Tyres+and+Brakes+Draft+Final+Report+v1.0.pdf>
- [6] G. W. Stachowiak and A. W. Batchelor, Eds., *Engineering Tribology*. Boston: Butterworth-Heinemann, 2013. doi: 10.1016/B978-0-12-397047-3.00018-7.
- [7] E. Popova, V. L. Popov, and D.-E. Kim, '60 years of Rabinowicz' criterion for adhesive wear', *Friction*, vol. 6, no. 3, pp. 341–348, Sep. 2018, doi: 10.1007/s40544-018-0240-8.
- [8] OECD, 'Non-exhaust Particulate Emissions from Road Transport - An ignored environmental policy challenge', Dec. 2020. Accessed: Jan. 31, 2025. [Online]. Available: <https://doi.org/10.1787/4a4dc6ca-en>

- [9] PIARC, 'Report of the Committee on Surface Characteristics, XVIII World Road Congress, Brussels, Belgium.', 1987. [Online]. Available: https://www.piarc.org/ressources/virtlib_actes/18/1987_E_17.pdf
- [10] Office of Rail and Road, 'Benchmarking National Highways Road surface condition', Oct. 2023. Accessed: Mar. 18, 2025. [Online]. Available: https://www.orr.gov.uk/sites/default/files/2023-10/benchmarking-national-highways-road-surface-condition-2023_0.pdf
- [11] F. Amato *et al.*, 'Trends of road dust emissions contributions on ambient air particulate levels at rural, urban and industrial sites in southern Spain', *Atmospheric Chemistry and Physics*, vol. 14, no. 7, pp. 3533–3544, Apr. 2014, doi: 10.5194/acp-14-3533-2014.
- [12] J. E. Pachon *et al.*, 'Evaluation of factors influencing road dust loadings in a Latin American urban center', *J Air Waste Manag Assoc*, vol. 71, no. 2, pp. 268–280, Feb. 2021, doi: 10.1080/10962247.2020.1806946.
- [13] F. Amato *et al.*, 'Traffic induced particle resuspension in Paris: Emission factors and source contributions', *Atmospheric Environment*, vol. 129, pp. 114–124, Mar. 2016, doi: 10.1016/j.atmosenv.2016.01.022.
- [14] C. He and W. Jiang, 'Research on particle size distribution and composition of road deposit dust in Xi'an: From the perspective of non-exhaust emissions', *Journal of Cleaner Production*, vol. 470, p. 143269, Sep. 2024, doi: 10.1016/j.jclepro.2024.143269.
- [15] R. Gehrig *et al.*, 'Mobile load simulators – A tool to distinguish between the emissions due to abrasion and resuspension of PM10 from road surfaces', *Atmospheric Environment*, vol. 44, no. 38, pp. 4937–4943, Dec. 2010, doi: 10.1016/j.atmosenv.2010.08.020.
- [16] Department for Transport, 'Road conditions in England to March 2024', GOV.UK. Accessed: Feb. 04, 2025. [Online]. Available: <https://www.gov.uk/government/statistics/road-conditions-in-england-to-march-2024/road-conditions-in-england-to-march-2024>
- [17] DfT, 'Section 2: measuring surface condition using automated visual methods', GOV.UK. Accessed: May 16, 2025. [Online]. Available: <https://www.gov.uk/government/publications/road-condition-statistics-technical-note/section-2-measuring-surface-condition-using-automated-visual-methods>
- [18] S.-H. Bae, E. Chae, Y.-S. Park, S.-W. Lee, J.-H. Yun, and S.-S. Choi, 'Characteristics of tire-road wear particles (TRWPs) and road pavement wear particles (RPWPs) generated through a novel tire abrasion simulator based on real road pavement conditions', *Science of The Total Environment*, vol. 944, p. 173948, Sep. 2024, doi: 10.1016/j.scitotenv.2024.173948.
- [19] J. O. Allen, O. Alexandrova, K. E. Kaloush, and Arizona State University. Dept. of Civil and Environmental Engineering, 'Tire wear emissions for asphalt rubber and Portland cement concrete pavement surfaces.', Apr. 2006. Accessed: Mar. 18, 2025. [Online]. Available: <https://rosap.nrl.bts.gov/view/dot/20267>
- [20] M. Gustafsson, G. Blomqvist, A. Gudmundsson, A. Dahl, P. Jonsson, and E. Swietlicki, 'Factors influencing PM10 emissions from road pavement wear', *Atmospheric Environment*, vol. 43, no. 31, pp. 4699–4702, Oct. 2009, doi: 10.1016/j.atmosenv.2008.04.028.
- [21] N. Svensson, J. Lundberg, S. Janhäll, S. Kulovuori, and M. Gustafsson, 'Effects of a porous asphalt pavement on dust suspension and PM10 concentration', *Transportation Research Part D: Transport and Environment*, vol. 123, p. 103921, Oct. 2023, doi: 10.1016/j.trd.2023.103921.
- [22] EMEP/EEA, *EMEP/EEA air pollutant emission inventory guidebook 2023: Technical guidance to prepare national emission inventories*. LU: Publications Office of the European Union, 2023. Accessed: Dec. 07, 2023. [Online]. Available: <https://data.europa.eu/doi/10.2800/795737>
- [23] European Environment Agency, 'EMEP/CORINAIR Emission Inventory Guidebook - 3rd edition October 2002 UPDATE', Technical report 30/-1, Nov. 2002. Accessed: May 16, 2025. [Online]. Available: <https://www.eea.europa.eu/en/analysis/publications/emepcorinair3>
- [24] A. Simons, 'Road transport: new life cycle inventories for fossil-fuelled passenger cars and non-exhaust emissions in ecoinvent v3', *Int J Life Cycle Assess*, vol. 21, no. 9, pp. 1299–1313, Sep. 2016, doi: 10.1007/s11367-013-0642-9.
- [25] D. C. S. Beddows and R. M. Harrison, 'PM10 and PM2.5 emission factors for non-exhaust particles from road vehicles: Dependence upon vehicle mass and implications for battery electric vehicles', *Atmospheric Environment*, vol. 244, p. 117886, Jan. 2021, doi: 10.1016/j.atmosenv.2020.117886.
- [26] V. R. J. H. Timmers and P. A. J. Achten, 'Non-exhaust PM emissions from electric vehicles', *Atmospheric Environment*, vol. 134, pp. 10–17, Jun. 2016, doi: 10.1016/j.atmosenv.2016.03.017.
- [27] AASHO, 'The AASHO road test', Washington, D.C, Special Report 61G, 1962. [Online]. Available: <https://onlinepubs.trb.org/Onlinepubs/sr/sr61g/61g.pdf>
- [28] R. R. Addis and R. A. Whitmarsh, 'Relative damaging power of wheel loads in mixed traffic', *Publication of: Transport and Road Research Laboratory*, Art. no. TRRL LR 979 Monograph, 1981, Accessed: Mar. 19, 2025. [Online]. Available: <https://trid.trb.org/View/168067>
- [29] J. M. Low, R. S. Haszeldine, and G. P. Harrison, 'The hidden cost of road maintenance due to the increased weight of battery and hydrogen trucks and buses—a perspective', *Clean Techn Environ Policy*, vol. 25, no. 3, pp. 757–770, Apr. 2023, doi: 10.1007/s10098-022-02433-8.

- [30] J. A. Gillies, V. Etyemezian, H. Kuhns, D. Nikolic, and D. A. Gillette, 'Effect of vehicle characteristics on unpaved road dust emissions', *Atmospheric Environment*, vol. 39, no. 13, pp. 2341–2347, Apr. 2005, doi: 10.1016/j.atmosenv.2004.05.064.
- [31] U.S. Environmental Protection Agency, 'Emission Factor Documentation for AP-42 Section 13.2.1 Paved Roads', Jan. 2011. [Online]. Available: <https://www3.epa.gov/ttn/chief/ap42/ch13/bgdocs/b13s0201.pdf>
- [32] M. Schaap *et al.*, 'Regional modelling of particulate matter for the Netherlands | PBL Netherlands Environmental Assessment Agency', Jul. 2009. Accessed: Mar. 19, 2025. [Online]. Available: <https://www.pbl.nl/en/publications/regional-modelling-of-particulate-matter-for-the-netherlands>
- [33] I. Düring, J. Jacob, A. Lohmeyer, M. Lutz, and W. Reichen, 'Estimation of the "non exhaust pipe" PM10 emissions of streets for practical traffic air pollution modelling'.
- [34] D. R. Fitz *et al.*, 'Real-time PM10 emission rates from paved roads by measurement of concentrations in the vehicle's wake using on-board sensors Part 2. Comparison of SCAMPER, TRAKER™, flux measurements, and AP-42 silt sampling under controlled conditions', *Atmospheric Environment*, vol. 256, p. 118453, Jul. 2021, doi: 10.1016/j.atmosenv.2021.118453.
- [35] D. Zhu, H. D. Kuhns, S. Brown, J. A. Gillies, V. Etyemezian, and A. W. Gertler, 'Fugitive Dust Emissions from Paved Road Travel in the Lake Tahoe Basin', *Journal of the Air & Waste Management Association*, Oct. 2009, Accessed: Mar. 20, 2025. [Online]. Available: <https://www.tandfonline.com/doi/abs/10.3155/1047-3289.59.10.1219>
- [36] T. Hussein, C. Johansson, H. Karlsson, and H.-C. Hansson, 'Factors affecting non-tailpipe aerosol particle emissions from paved roads: On-road measurements in Stockholm, Sweden', *Atmospheric Environment*, vol. 42, no. 4, pp. 688–702, Feb. 2008, doi: 10.1016/j.atmosenv.2007.09.064.
- [37] L. Pirjola, K. J. Kupiainen, P. Perhoniemi, H. Tervahattu, and H. Vesala, 'Non-exhaust emission measurement system of the mobile laboratory SNIFFER', *Atmospheric Environment*, vol. 43, no. 31, pp. 4703–4713, Oct. 2009, doi: 10.1016/j.atmosenv.2008.08.024.
- [38] F. Amato, M. Bedogni, E. Padoan, X. Querol, M. Ealo, and I. Rivas, 'Characterization of Road Dust Emissions in Milan: Impact of Vehicle Fleet Speed', *Aerosol Air Qual. Res.*, vol. 17, no. 10, pp. 2438–2449, 2017, doi: 10.4209/aaqr.2017.01.0017.
- [39] S.-H. Woo, H. Jang, S.-B. Lee, J. Jeong, C. Lee, and S. Lee, 'Correction Method for Resuspended Road Dust Emission Factors according to Vehicle Speed Using a Mobile Monitoring Vehicle', *Aerosol Air Qual. Res.*, vol. 24, no. 9, p. 230322, Jul. 2024, doi: 10.4209/aaqr.230322.
- [40] G. A. Sehmel, 'Particle resuspension from an asphalt road caused by car and truck traffic', *Atmospheric Environment* (1967), vol. 7, no. 3, pp. 291–309, Mar. 1973, doi: 10.1016/0004-6981(73)90078-4.
- [41] K. Edvardsson and R. Magnusson, 'Monitoring of dust emission on gravel roads: Development of a mobile methodology and examination of horizontal diffusion', *Atmospheric Environment*, vol. 43, no. 4, pp. 889–896, Feb. 2009, doi: 10.1016/j.atmosenv.2008.10.052.
- [42] A. Beji, K. Deboudt, S. Khardi, B. Muresan, and L. Lumière, 'Determinants of rear-of-wheel and tire-road wear particle emissions by light-duty vehicles using on-road and test track experiments', *Atmospheric Pollution Research*, vol. 12, no. 3, pp. 278–291, Mar. 2021, doi: 10.1016/j.apr.2020.12.014.
- [43] V. Etyemezian, H. Kuhns, J. Gillies, M. Green, M. Pitchford, and J. Watson, 'Vehicle-based road dust emission measurement: I—methods and calibration', *Atmospheric Environment*, vol. 37, no. 32, pp. 4559–4571, Oct. 2003, doi: 10.1016/S1352-2310(03)00528-4.
- [44] C.-J. Tsai and C.-T. Chang, 'An investigation of dust emissions from unpaved surfaces in Taiwan', *Separation and Purification Technology*, vol. 29, no. 2, pp. 181–188, Nov. 2002, doi: 10.1016/S1383-5866(02)00074-6.
- [45] I. G. Kavouras, D. W. DuBois, G. Nikolich, A. Y. Corral Avittia, and V. Etyemezian, 'Particulate dust emission factors from unpaved roads in the U.S.–Mexico border semi-arid region', *Journal of Arid Environments*, vol. 124, pp. 189–192, Jan. 2016, doi: 10.1016/j.jaridenv.2015.07.015.
- [46] D. S. Williams, M. K. Shukla, and J. Ross, 'Particulate matter emission by a vehicle running on unpaved road', *Atmospheric Environment*, vol. 42, no. 16, pp. 3899–3905, May 2008, doi: 10.1016/j.atmosenv.2008.02.003.
- [47] H. Kuhns *et al.*, 'Effect of Soil Type and Momentum on Unpaved Road Particulate Matter Emissions from Wheeled and Tracked Vehicles', *Aerosol Science and Technology*, vol. 44, no. 3, pp. 187–196, Feb. 2010, doi: 10.1080/02786820903516844.
- [48] A. Beji *et al.*, 'Non-exhaust particle emissions under various driving conditions: Implications for sustainable mobility', *Transportation Research Part D: Transport and Environment*, vol. 81, p. 102290, Apr. 2020, doi: 10.1016/j.trd.2020.102290.
- [49] Y. Liu *et al.*, 'Impact of vehicle type, tyre feature and driving behaviour on tyre wear under real-world driving conditions', *Science of The Total Environment*, vol. 842, p. 156950, Oct. 2022, doi: 10.1016/j.scitotenv.2022.156950.
- [50] E. Padoan, F. Ajmone-Marsan, X. Querol, and F. Amato, 'An empirical model to predict road dust emissions based on pavement and traffic characteristics', *Environmental Pollution*, vol. 237, pp. 713–720, Jun. 2018, doi: 10.1016/j.envpol.2017.10.115.

- [51] C.-H. Jeong, C. Fang, and G. Evans, 'Spatial variation of resuspended particulate matter in urban environments and real-world assessment of street sweeping', *Environmental Pollution*, vol. 373, p. 126165, May 2025, doi: 10.1016/j.envpol.2025.126165.
- [52] R. Kantamaneni *et al.*, 'The measurement of roadway PM10 emission rates using atmospheric tracer ratio techniques', *Atmospheric Environment*, vol. 30, no. 24, pp. 4209–4223, Dec. 1996, doi: 10.1016/1352-2310(96)00131-8.
- [53] G. Omstedt, B. Bringfelt, and C. Johansson, 'A model for vehicle-induced non-tailpipe emissions of particles along Swedish roads', *Atmospheric Environment*, vol. 39, no. 33, pp. 6088–6097, Oct. 2005, doi: 10.1016/j.atmosenv.2005.06.037.
- [54] F. Amato *et al.*, 'Effect of rain events on the mobility of road dust load in two Dutch and Spanish roads', *Atmospheric Environment*, vol. 62, pp. 352–358, Dec. 2012, doi: 10.1016/j.atmosenv.2012.08.042.
- [55] A. J. Thorpe, R. M. Harrison, P. G. Boulter, and I. S. McCrae, 'Estimation of particle resuspension source strength on a major London Road', *Atmospheric Environment*, vol. 41, no. 37, pp. 8007–8020, Dec. 2007, doi: 10.1016/j.atmosenv.2007.07.006.
- [56] A. Charron and R. M. Harrison, 'Fine (PM2.5) and Coarse (PM2.5-10) Particulate Matter on A Heavily Trafficked London Highway: Sources and Processes', *Environ. Sci. Technol.*, vol. 39, no. 20, pp. 7768–7776, Oct. 2005, doi: 10.1021/es050462i.
- [57] DfT, 'Specification for the Reinstatement of Openings in Highways', Fourth Edition, May 2020. [Online]. Available: <https://assets.publishing.service.gov.uk/media/606f1ee2e90e076f56e46dfc/specification-for-the-reinstatement-of-openings-in-highways-fourth-edition.pdf>
- [58] Transport Scotland, 'Specification for the Reinstatement of Openings in Roads (4th Edition - 2019)', May 2019. Accessed: May 29, 2025. [Online]. Available: <https://www.transport.gov.scot/publication/specification-for-the-reinstatement-of-openings-in-roads-4th-edition-2019/>
- [59] 'Durability of thin asphalt surfacing systems: prepared for Safety Standards & Research (Highways Infrastructure) Pavement Engineering Team, Highways Agency. Pt. 4: Final report after nine years' monitoring / J.C. Nicholls', TRL, 2010.
- [60] EAPA, 'Long-Life Asphalt Pavements', Jun. 2007. Accessed: May 20, 2025. [Online]. Available: <https://eapa.org/download/15221/>
- [61] RSTA /ADEPT, 'The Service Life of Road Surface Treatments for Asset Management Purposes', May 2011. Accessed: May 20, 2025. [Online]. Available: <https://www.rsta-uk.org/document-gallery#category=99&txt=service+life>
- [62] International Organization for Standardization, *ISO 22638:2024 Rubber: Generation and collection of tyre and road wear particles (TRWP) - Road simulator laboratory method*, ISO 22638:2024, Jul. 2024. [Online]. Available: <https://www.iso.org/standard/84313.html>
- [63] International Organization for Standardization, *ISO/TS 20593:2017 Ambient air — Determination of the mass concentration of tire and road wear particles (TRWP) — Pyrolysis-GC-MS method*, ISO/TS 20593:2017, Jun. 2017. [Online]. Available: <https://www.iso.org/standard/68470.html>
- [64] BSI, *PD CEN/TS 12697-50:2018 - TC Bituminous mixtures. Test methods - Resistance to scuffing*, PD CEN/TS 12697-50:2018, May 31, 2018. [Online]. Available: <https://knowledge.bsigroup.com/products/bituminous-mixtures-test-methods-resistance-to-scuffing>
- [65] BSI, *BS EN 1097-2:2020 Tests for mechanical and physical properties of aggregates - Methods for the determination of resistance to fragmentation*, BS EN 1097-2:2020, Apr. 30, 2020. [Online]. Available: <https://knowledge.bsigroup.com/products/tests-for-mechanical-and-physical-properties-of-aggregates-methods-for-the-determination-of-resistance-to-fragmentation-1>
- [66] C. De La Roche, H. Odeon, J.-P. Simoncelli, and A. Spennol, 'Study of the fatigue of asphalt mixes using the circular test track of the laboratoire central des Ponts et Chaussées in Nantes, France', *Transportation research record*, vol. 1436, 1994.
- [67] H. Kuhns, V. Etyemezian, D. Landwehr, C. MacDougall, M. Pitchford, and M. Green, 'Testing Re-entrained Aerosol Kinetic Emissions from Roads: a new approach to infer silt loading on roadways', *Atmospheric Environment*, vol. 35, no. 16, pp. 2815–2825, Jun. 2001, doi: 10.1016/S1352-2310(01)00079-6.
- [68] V. Etyemezian, H. Kuhns, and G. Nikolich, 'Precision and repeatability of the TRAKER vehicle-based paved road dust emission measurement', *Atmospheric Environment*, vol. 40, no. 16, pp. 2953–2958, May 2006, doi: 10.1016/j.atmosenv.2005.12.042.
- [69] R. Langston *et al.*, 'The preferred alternative method for measuring paved road dust emissions for emissions inventories: "mobile technologies vs. The traditional ap-42 methodology"', 2007.
- [70] D. R. Fitz, K. Bumiller, C. Bufalino, and D. E. James, 'Real-time PM10 emission rates from paved roads by measurement of concentrations in the vehicle's wake using on-board sensors part 1. SCAMPER method characterization', *Atmospheric Environment*, vol. 230, p. 117483, Jun. 2020, doi: 10.1016/j.atmosenv.2020.117483.

- [71] M. Mathissen, V. Scheer, U. Kirchner, R. Vogt, and T. Benter, 'Non-exhaust PM emission measurements of a light duty vehicle with a mobile trailer', *Atmospheric Environment*, vol. 59, pp. 232–242, Nov. 2012, doi: 10.1016/j.atmosenv.2012.05.020.
- [72] A. Beji *et al.*, 'Physical and chemical characteristics of particles emitted by a passenger vehicle at the tire-road contact', *Chemosphere*, vol. 340, p. 139874, Nov. 2023, doi: 10.1016/j.chemosphere.2023.139874.
- [73] I. Casotti Rienda and C. A. Alves, 'Road dust resuspension: A review', *Atmospheric Research*, vol. 261, p. 105740, Oct. 2021, doi: 10.1016/j.atmosres.2021.105740.
- [74] J. Lundberg, G. Blomqvist, M. Gustafsson, S. Janhäll, and I. Järnskog, 'Wet Dust Sampler—a Sampling Method for Road Dust Quantification and Analyses', *Water Air Soil Pollut*, vol. 230, no. 8, p. 180, Jul. 2019, doi: 10.1007/s11270-019-4226-6.
- [75] A. Escrig *et al.*, 'Simple estimates of vehicle-induced resuspension rates', *Journal of Environmental Management*, vol. 92, no. 10, pp. 2855–2859, Oct. 2011, doi: 10.1016/j.jenvman.2011.06.042.
- [76] Z. Klimont, J. Cofala, I. Bertok, M. Amann, C. Heyes, and F. Gyarfas, 'Modeling Particulate Emissions in Europe. A Framework to Estimate Reduction Potential and Control Costs'. Accessed: Mar. 24, 2025. [Online]. Available: <https://pure.iiasa.ac.at/id/eprint/6712/>, <https://iiasa.dev.local/>
- [77] N. Raparathi and H. C. Phuleria, 'On-road vehicular emission characterization from the road-tunnel measurements in India: Morphology, emission factors, and sources', *Environmental Research*, vol. 215, p. 114295, Dec. 2022, doi: 10.1016/j.envres.2022.114295.
- [78] N. Raparathi, S. Debbarma, and H. C. Phuleria, 'Development of real-world emission factors for on-road vehicles from motorway tunnel measurements', *Atmospheric Environment: X*, vol. 10, p. 100113, Apr. 2021, doi: 10.1016/j.aeaoa.2021.100113.
- [79] S. Lawrence, R. Sokhi, and K. Ravindra, 'Quantification of vehicle fleet PM 10 particulate matter emission factors from exhaust and non-exhaust sources using tunnel measurement techniques', *Environmental Pollution*, vol. 210, pp. 419–428, Mar. 2016, doi: 10.1016/j.envpol.2016.01.011.
- [80] J. Zhang *et al.*, 'Vehicular non-exhaust particulate emissions in Chinese megacities: Source profiles, real-world emission factors, and inventories', *Environmental Pollution*, vol. 266, p. 115268, Nov. 2020, doi: 10.1016/j.envpol.2020.115268.
- [81] F. Galatioto, N. Masey, T. Murrells, S. Hamilton, and M. Pommier, 'Review of Road Dust Resuspension Modelling Approaches and Comparisons Analysis for a UK Case Study', *Atmosphere*, vol. 13, no. 9, Art. no. 9, Sep. 2022, doi: 10.3390/atmos13091403.
- [82] M. Guevara, C. Tena, M. Porquet, O. Jorba, and C. Pérez García-Pando, 'HERMESv3, a stand-alone multi-scale atmospheric emission modelling framework – Part 2: The bottom-up module', *Geoscientific Model Development*, vol. 13, no. 3, pp. 873–903, Mar. 2020, doi: 10.5194/gmd-13-873-2020.
- [83] B. R. Denby *et al.*, 'A coupled road dust and surface moisture model to predict non-exhaust road traffic induced particle emissions (NORTrip). Part 1: Road dust loading and suspension modelling', *Atmospheric Environment*, vol. 77, pp. 283–300, Oct. 2013, doi: 10.1016/j.atmosenv.2013.04.069.
- [84] Ricardo, 'Speed-emission/energy consumption curves for ultra-low emission vehicles and non-fuel operating costs for all vehicles', Jul. 2023. Accessed: Mar. 25, 2025. [Online]. Available: <https://assets.publishing.service.gov.uk/media/67166ff696def6d27a4c9b2f/dft-speed-emission-energy-consumption-curves-ultra-low-emission-vehicles-non-fuel-operating-costs-all-vehicles.pdf>
- [85] Autocar, 'Average weight of new cars rises by nearly 400kg in seven years'. Accessed: Apr. 09, 2025. [Online]. Available: <https://www.autocar.co.uk/car-news/new-cars/average-weight-new-cars-rises-nearly-400kg-seven-years>
- [86] J. C. Fussell *et al.*, 'A Review of Road Traffic-Derived Non-Exhaust Particles: Emissions, Physicochemical Characteristics, Health Risks, and Mitigation Measures', *Environ. Sci. Technol.*, vol. 56, no. 11, pp. 6813–6835, Jun. 2022, doi: 10.1021/acs.est.2c01072.
- [87] I. Gehrke, S. Schläfle, R. Bertling, M. Öz, and K. Gregory, 'Review: Mitigation measures to reduce tire and road wear particles', *Science of The Total Environment*, vol. 904, p. 166537, Dec. 2023, doi: 10.1016/j.scitotenv.2023.166537.
- [88] T&E, 'UK SUV sales have increased by more than a fifth in one year', T&E United Kingdom. Accessed: Apr. 09, 2025. [Online]. Available: <https://www.transportenvironment.org/te-united-kingdom/articles/uk-suv-sales-have-increased-by-more-than-a-fifth-in-one-year>
- [89] TfL, 'Speed, emissions & health: The impact of vehicle speed on emissions & health: an evidence summary', 2018. [Online]. Available: <https://content.tfl.gov.uk/speed-emissions-and-health.pdf>
- [90] RAC, 'Guide to Autonomous Emergency Braking | RAC Drive'. Accessed: May 29, 2025. [Online]. Available: <https://www.rac.co.uk/drive/advice/road-safety/autonomous-emergency-braking-what-you-need-to-know/>
- [91] S. Lin *et al.*, 'Impact of change in traffic flow on vehicle non-exhaust PM2.5 and PM10 emissions: A case study of the M25 motorway, UK', *Chemosphere*, vol. 303, p. 135069, Sep. 2022, doi: 10.1016/j.chemosphere.2022.135069.
- [92] W. Hicks *et al.*, 'Quantification of non-exhaust particulate matter traffic emissions and the impact of COVID-19 lockdown at London Marylebone road', *Atmosphere*, vol. 12, no. 2, p. 190, 2021.

- [93] NatGen Social Research, 'Switching to sustainable transport: a rapid evidence assessment', GOV.UK. Accessed: Apr. 09, 2025. [Online]. Available: <https://www.gov.uk/government/publications/switching-to-sustainable-transport-a-rapid-evidence-assessment>
- [94] L. Sillars-Powell, M. J. Tallis, and M. Fowler, 'Road Verge Vegetation and the Capture of Particulate Matter Air Pollution', *Environments*, vol. 7, no. 10, Art. no. 10, Oct. 2020, doi: 10.3390/environments7100093.
- [95] K. V. Abhijith and P. Kumar, 'Field investigations for evaluating green infrastructure effects on air quality in open-road conditions', *Atmospheric Environment*, vol. 201, pp. 132–147, Mar. 2019, doi: 10.1016/j.atmosenv.2018.12.036.
- [96] P. Kumar *et al.*, 'Air pollution abatement from Green-Blue-Grey infrastructure', *The Innovation Geoscience*, vol. 2, no. 4, Art. no. 4, Nov. 2024, doi: 10.59717/j.xinn-geo.2024.100100.
- [97] M. Tomson *et al.*, 'Green infrastructure for air quality improvement in street canyons', *Environment International*, vol. 146, p. 106288, Jan. 2021, doi: 10.1016/j.envint.2020.106288.
- [98] A. H. Tremper, D. C. Green, D. Chatter-Singh, and K. Eleftheriou-Vaus, 'Impact of green screens on concentrations of particulate matter and oxides of nitrogen in near road environmentse', 2015.
- [99] A. G. McDonald *et al.*, 'Quantifying the effect of urban tree planting on concentrations and depositions of PM10 in two UK conurbations', *Atmospheric Environment*, vol. 41, no. 38, pp. 8455–8467, Dec. 2007, doi: 10.1016/j.atmosenv.2007.07.025.
- [100] AIRUSE, CINEA, European Commission, 'Technical Guide to Reduce Road Dust Emissions in Southern Europe', Dec. 2016. [Online]. Available: <https://webgate.ec.europa.eu/life/publicWebsite/project/LIFE11-ENV-ES-000584/testing-and-development-of-air-quality-mitigation-measures-in-southern-europe>
- [101] F. Amato, X. Querol, C. Johansson, C. Nagl, and A. Alastuey, 'A review on the effectiveness of street sweeping, washing and dust suppressants as urban PM control methods', *The Science of the total environment*, vol. 408, pp. 3070–84, Jul. 2010, doi: 10.1016/j.scitotenv.2010.04.025.
- [102] S. Gulia *et al.*, 'Performance evaluation of air pollution control device at traffic intersections in Delhi', *Int. J. Environ. Sci. Technol.*, vol. 19, no. 2, pp. 785–796, Feb. 2022, doi: 10.1007/s13762-021-03641-3.
- [103] A. Avveduto, F. Ferella, M. De Giovanni, V. Innocenzi, L. Pace, and P. Tripodi, 'L'Aquila Smart Clean Air City: The Italian Pilot Project for Healthy Urban Air', *Environments*, vol. 4, no. 4, Art. no. 4, Dec. 2017, doi: 10.3390/environments4040078.



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