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Contents

1 Overview

This chapter covers the emissions of particulate matter (PM) including black carbon (BC) ([1]) which are due to road vehicle tyre and brake wear (NFR code 1.A.3.b.vi), and road surface wear (NFR code 1.A.3.b.vii). PM emissions from vehicle exhaust are not included. The focus is on primary particles — in other words, those particles emitted directly because of the wear of surfaces — and not those resulting from the resuspension of the previously deposited material.

It should be noted that the second level of the NFR code for these emission sources relates to 'combustion'. Clearly, tyre wear, brake wear and road surface wear are abrasion processes, not combustion processes. However, these chapters have been assigned their NFR codes as a matter of convenience, and to allow all emissions from road transport to be assessed together. For the present time, this anomaly must be accepted by inventory compilers.

PM emissions are considered in relation to the general vehicle classes identified in Chapter 1.A.3.b Road transport concerning exhaust emissions from road transport (NFR codes 1.A.3.b.i to b iv), these being passenger cars, light-duty trucks, heavy-duty vehicles and two-wheel vehicles.

2 Description of sources

2.1 Process description

Airborne particles are produced as a result of the interaction between a vehicle's tyres and the road surface, and also when the brakes are applied to decelerate the vehicle. In both cases, the generation of shear forces by the relative movement of surfaces is the main mechanism for particle production. A secondary mechanism involves the evaporation of material from surfaces at high temperatures developed during contact.

It should be noted that subsections 2.1.1 to 2.1.3 of the present chapter provide background information which relates to the total amount of material lost as a result of tyre wear, brake wear or road surface wear. This information is not to be used in the calculation of emissions, as not all of the worn material becomes airborne. The actual PM emission factors reported in the literature are reviewed in subsection 2.2 of the present chapter. The experimental methods used to determine wear factors and emission factors are described in Appendix A.

2.1.1 Tyre wear

A vehicle's tyres carry the vehicle and passenger load, offer traction and steering, and absorb variations in the road surface to improve ride quality. Tyre material is a complex rubber blend, although the exact composition of the tyres on the market is not usually published for commercial reasons. As a rule of thumb, Camatini et al. (2001) quote 75 % styrene butadiene rubber (SBR), 15 % natural rubber and 10 % polybutadiene for passenger car tyres. Metal and organic additives are also introduced to this blend to obtain the desired properties during the manufacturing process and to give the required road performance. Zinc oxide (ZnO), which acts as a vulcanising agent, is one of

[1] For the purposes of this guidance, BC emission factors are assumed to equal those for elemental carbon (EC). For further information please refer to Chapter 1.A.1 Energy Industries and Appendix B of this chapter.

the more significant additives. According to Smolders and Degryse (2002), the typical ZnO concentration in tyre tread is between 1.2 % (cars) and 2.1 % (trucks).

Tyre tread wear is a complex physio-chemical process which is driven by the frictional energy developed at the interface between the tread and the pavement. Tyre wear particles and road surface wear particles are therefore inextricably linked. However, for the purpose of determining emission factors, tyre wear and road surface wear must, at present, be treated as separate particle sources due to the lack of experimental data on the emission factors associated with different tyre-road surface combinations.

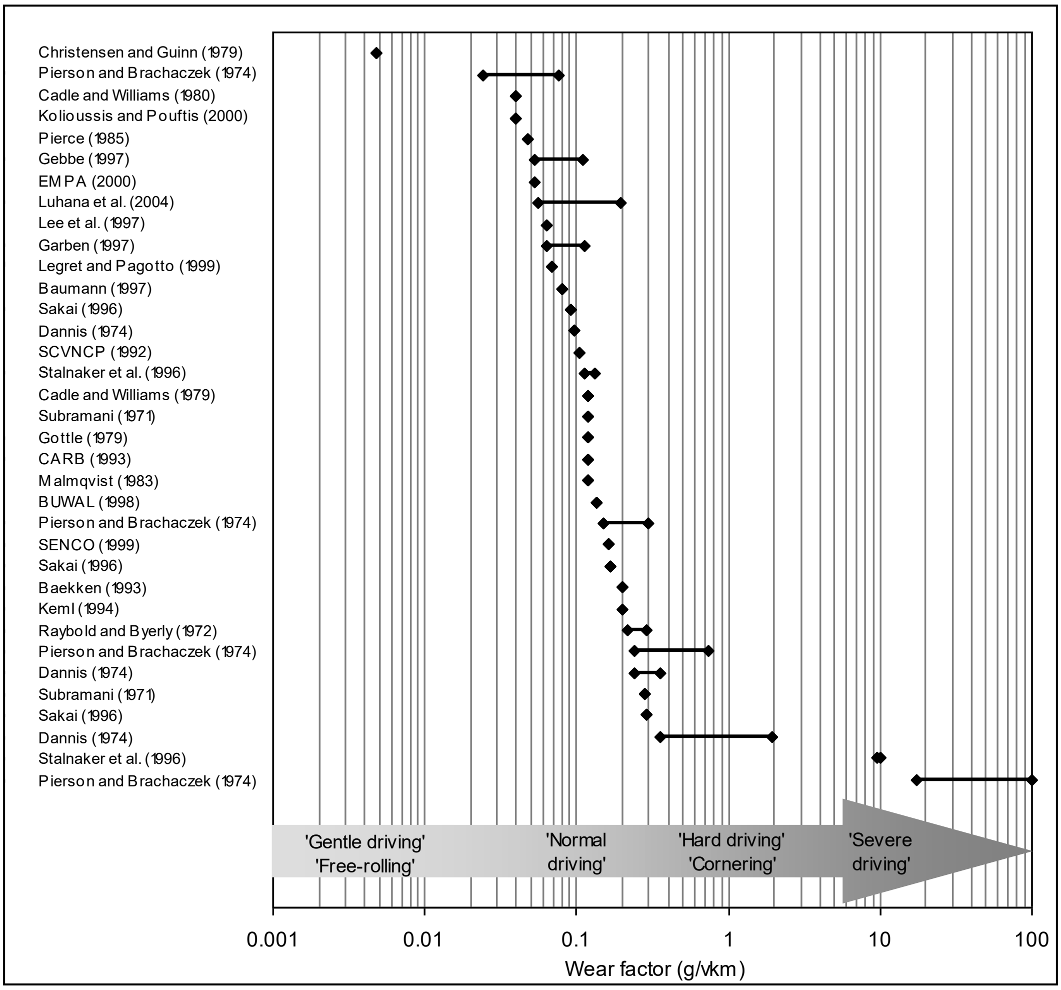
The actual rate of tyre wear depends on a large number of factors, including tyre characteristics (type, position, materials, condition and age of tyres), vehicle characteristics (weight, vehicle traction configuration, load), driving style (speed, acceleration/deceleration events, cornering), road surface material and condition, ambient conditions (temperature, humidity). For example, the driving pattern has a significant effect on the wear rate. Even when a vehicle is being driven at a constant speed, there is a continuous micro-sliding of the tyre on the road surface — an effect which is responsible for traction. When driving dynamics (cornering, braking, accelerating) increase, sliding develops in response to the larger forces generated at the road surface-tyre interface, and this can cause additional wear of both the tyre and the road surface. Therefore, 'smooth' driving extends the lifetime of a tyre and, conversely, tyre lifetime reduces as the amount of harsh or transient vehicle operation increases.

On a front-wheel drive (FWD) vehicle, the front wheels are used both for traction and steering, while the rear wheels are only responsible for rear axle control and load carriage. On a rear-wheel drive (RWD) vehicle, the front wheels serve primarily for steering, while traction is a rear-wheel responsibility. Due to these different roles, it is expected and experimentally verified, that front tyres show a higher wear rate on an FWD vehicle and rear tyres on an RWD one. For example, Luhana et al. (2004) reported that front tyres on an FWD vehicle accounted for 69–85 % of total vehicle tyre wear. High wear rates may also occur as a result of steering system misalignment and incorrect tyre pressure.

The physical characteristics of the tyre tread material have a prominent effect on the tyre wear rate. In general, high-performance tyres, such as those used in superbikes and sports cars, have the highest wear rates because of their large frictional coefficient and use under more severe operational conditions. The lifetime for such tyres may be as little as 10 000 km. On the other hand, a typical car tyre has a lifetime of 50 000–60 000 km, during which time it loses about 10 % of its total weight (UK Environment Agency, 1998, Kolioussis et al., 2000). The lifetime of truck tyres is estimated to be typically 100 000 km, depending on truck usage and load per tyre. Also, some tyres in this vehicle category are retreated, whereby a new tread is fixed onto a worn tyre. Retreading prolongs the lifetime of the tyre, but it has led to concerns about safety (Dunn, 1993). The total amount of material lost during a tyre's lifetime is different for each vehicle and may range from a few hundred grams for two-wheel vehicles to 1–1.5 kg for passenger cars, and up to 10 kg for a truck or bus.

Figure 2-1 shows that a wide range of wear factors have been reported for light-duty vehicle tyres based on old data. The figure incorporates most recent information provided by Councell et al. (2004), as well as other older values from the literature. These values have either been derived experimentally or have been estimated from average statistics such as those given above. The figure suggests that for 'normal' driving conditions an average wear factor for light-duty vehicles of around 100 mg per vehicle-km would probably be appropriate.

Figure 2-1 Wear factors for light-duty vehicle tyres (Boulter, 2005). 'vkm' = 'vehicle-km'



Much of the variability in these wear factors can probably be explained by differences in the factors mentioned above. For example, in the studies conducted during the early 1970s cross-ply tyres would have been used. Almost all modern cars are fitted with radial-ply tyres, which have greater rigidity for cornering, have better grip in the wet, and are much less susceptible to wear than the older cross-ply type. Driving behaviour and driving conditions are well-recognised determinants of tyre wear. An aggressive driving style will tend to result in more rapid and uneven tyre wear than a more restrained driving style. Where reported, the driving conditions in the studies cited in Figure 2-1 ranged from 'gentle' to 'severe' ([2]). Urban driving is associated with a high wear per unit distance. Most tyre rubber is lost during acceleration, braking, and cornering, and the amount of rubber lost will therefore tend to be greatest near busy junctions and on bends. Using a tyre-testing machine, Stalnaker et al. (1996) simulated the effects of 'city' and 'motorway' driving conditions on the wear of tyres. The city conditions included large numbers of turns. It was found that city driving accounted for 63 % of the tyre wear, even though it represented only 5 % of the distance driven. Luhana et al. (2004) weighed car tyres at two-month intervals and asked drivers to note the details of each trip undertaken. There was found to be a weak negative correlation between tyre wear and average trip

([2]) These subjective descriptions have been superimposed on Figure 2-1, although there is a considerable amount of variation in terms of how driving conditions have been defined in the literature.

speed, with the wear factor being around 50 % higher at an average speed of 40 km/h (dominated by urban driving) than at an average speed of 90 km/h (dominated by motorway driving).

Weather and road conditions may also affect the lifetime of a tyre. Wet conditions decrease friction, and hence should be expected to also decrease the wear rate. Similarly, new tarmac, although safer, is also harsher on the tyre than an older surface.

Vehicle weight is also an important parameter affecting non-exhaust emissions from all three main sources, including tyre wear emissions. Light-weighting efforts from manufacturers for improved fuel consumption are also contributing to reducing tyre wear emissions.

The battery of the electric vehicles increases the vehicle weight when compared to conventional Internal Combustion Engine (ICE) vehicles and this influences tyre wear among else. Timmers & Achten (2016) compared multiple combinations of electric vehicles and their equivalent non-electric version and indicated that electric vehicles are 280 kg or 24% heavier than their non-electric counterparts. This increase in vehicle weight leads to an increase in all non-exhaust emission sources in accordance with the estimation method developed by Simons (2013). A more recent study by Beddows & Harrison (2021) after comparing battery electric vehicles with their ICE counterparts based on the power output indicates an average mass increase of 258 kg and 314 kg for electric cars compared to petrol and diesel cars respectively, leading to 7-10 % increase of the tyre wear emissions for PM_{10} and $PM_{2.5}$. A similar increase in the study of Beddows & Harrison (2021) was reported in the study of Liu et al. (2021). The same study also indicates the differences between small, medium, and large ICE vehicles in terms of tyre wear. The reported differences are on average between 10-20% between the different segments. In addition, the study of S. Woo et al. (2022) concluded that an increase in vehicle weight by 20% leads to increased tyre wear emissions by around 15-20%. Emissions Analytics[3] has also tested many vehicles in real-world conditions and concluded that for every 500 kg extra vehicle weight, tyre wear emissions rise by 21%. Oroumiyeh and Zhu (2021) measured the tyre wear of small, medium, and large vehicles and concluded that the resulting tyre wear was proportional to the vehicle weight.

Tyre wear factors are substantially higher for HDVs than for LDVs but these are also based on old literature data. Legret and Pagotto (1999) assumed that the wear factor for heavy-duty vehicle tyres (at 136 mg/vkm) was double that of light-duty vehicle tyres. However, this appears to be an underestimate. Baumann and Ismeier (1997) give wear factors for ‘heavy-duty vehicles’, ‘articulated lorries’ and buses of 189 mg/vkm, 234 mg/vkm, and 192 mg/vkm respectively. Gebbe et al. (1997) report a tyre wear factor for heavy-duty vehicles of 539 mg/vkm. HDV wear factors closer to 800 mg/vkm have been reported by Garben et al. (1997) and EMPA (2000), and SENCO (1999) give a wear factor for HGVs of 1403 mg/vkm. The wear factor per vkm will be dependent on the vehicle configuration, such as the number of axles and the load, and so a wide range of values is to be expected.

2.1.2 Brake wear

Brake wear takes place during a braking event due to the mechanical abrasion and thermal fatigue of the braking system surfaces that are in direct contact, thus producing particulate matter, mainly in the PM_{10} (particles with aerodynamic diameter ≤10 μm) and $PM_{2.5}$ (≤2.5 μm) size ranges. Thermal decomposition of organic components at high temperatures can also produce ultrafine particles (≤0.1 μm), while tribochemical reactions at the friction interface contribute additional metal oxides and complex compounds. These diverse processes result to a broad particle size distribution thus producing particle emissions with potentially diverse environmental behaviour and health impact. Additionally, wheel turbulence and braking events can resuspend particles previously deposited on the brake system, further contributing to airborne PM levels. The most important factors affecting brake wear related emissions are the braking system configuration and vehicle characteristics (especially mass), the driving behaviour (e.g. frequency and intensity of braking events), environmental conditions (e.g. temperature and humidity) and the traffic flow.

There are two main brake system configurations currently in use: disc brakes, in which flat brake pads are forced against a rotating metal disc, and drum brakes, in which curved pads are forced against the inner surface of a rotating cylinder. Disc brakes are the most popular choice in Europe accounting for about 90% of the European brake market and are most commonly used on both front and rear wheels. In lower performance vehicles, drum brakes are often used on the rear wheels only.

In passenger cars and motorcycles, the braking force is mainly applied to the front wheels, whilst the rear brakes are mainly for maintaining vehicle stability. As a result, brake pads on the front axle are replaced more frequently than the rear axle. Manufacturers suggest changing brake pads every 40,000-50,000 km and discs every 90,000 km in a typical passenger car. Often, frequency of replacement is higher for components on the front axle than the rear one, but this depends on materials selection and maintenance schedule. With an average lifetime of a typical medium-sized car in Europe between 200,000 and 250,000 kilometres, brake discs may require 1-2 replacements and brake pads 3-5 replacements over vehicle's lifetime. For electrified vehicles, fewer replacements are foreseen since regenerative braking reduces the reliance on mechanical brakes, leading to less wear and therefore fewer replacements. With heavy trucks, the braking energy is more evenly distributed between the axles because of lower deceleration rates and the heavy load at the back of the vehicle. Wear rates also depend on brake actuation mechanism (pneumatic, electric), and hence it is more difficult to estimate the lifetime of linings. It is expected that for trucks and coaches, the lifetime of brake linings is in the order of 60 000 km.

Brake pads are usually categorised depending on the material of their friction layer. Brake linings generally consist of four main components — binders, fibres, fillers, and friction modifiers — which are stable at high temperatures. Various modified phenol-formaldehyde resins are used as binders. Fibres can be classified as metallic, mineral, ceramic, or aramide, and include steel, copper, brass, potassium titanate, glass, asbestos, organic material, and Kevlar. Fillers tend to be low-cost materials such as barium and antimony sulphate, kaolinite clays, magnesium and chromium oxides, and metal powders. Friction modifiers can be of inorganic, organic, or metallic composition. Graphite is a major modifier used to influence friction, but other modifiers include cashew dust, ground rubber, and carbon black. In the past, brake pads included asbestos fibres, though these have been totally removed from the European fleet since 1998 (European Commission, 1998).

Although the range of materials used for braking systems is wide, most European vehicles currently have a friction brake system with low-metallic (LM) or semi-metallic (SM) brake pads pressed against grey cast iron discs (GCI) (Giechaskiel 2024b). Outside Europe, ceramic pads or non-asbestos organic (NAO) pads are more common, with the latter exhibiting promising results in terms of reducing brake wear emissions.

Therefore, brake wear chemistry largely depends on the pad material and the application (car, truck, etc.). Commercial lining materials vary widely, but iron (Fe), copper (Cu), zinc (Zn), barium (Ba), and lead (Pb) are the most abundant metals in brake linings, along with compounds from organic material breakdown (Kukutschová et al., 2009; Grigoratos and Martini, 2015; Ciudin et al., 2014). Differences in the chemical composition of brake wear emissions are observed between heavy-duty and light-duty vehicles. For HDVs, copper dominates, followed by barium and iron, while for LDVs, barium dominates, followed by iron and zinc based on preliminary measurement results from ongoing research.

Although gaseous emissions do occur as a result of the mechanical abrasion of brake linings, they do not appear to be significant. During the tests conducted by Garg et al. (2000), no increases in the concentrations of CO, CO_2 and hydrocarbons above the background levels in the test chamber could be detected.

2.1.3 Road surface wear

A range of asphalt-based and concrete-based road surfaces are in use throughout Europe, with block paving being used in many urban areas. Concrete surfaces are composed of coarse aggregate, sand and cement. Asphalts are mixtures of mineral aggregate, sands, filler, and bitumen binder, although the composition can vary widely, both from country to country and within countries. Generally, the stone content is around 90–95 % and the bituminous binder around 5–10 %. The properties of asphalt can be modified by additives such as adhesives, polymers, and different types of filler.

Asphalt wear has been estimated by Muschack (1990) to be 3.8 mg/vkm. CBS (1998) reported wear factors for LDVs and HDVs of 7.9 and 38 mg/vkm respectively, although these values also included tyre and brake wear. For New Zealand, Kennedy et al. (2002) calculated a wear factor of 0.44 g/vkm for a road surface containing 50 % bitumen. In a situation where the bitumen comprises only 10 % of the worn surface, this figure would be reduced to 0.09 g/vkm.

Studded tyres are specialized winter tyres equipped with small metal studs embedded into the tread. These studs provide enhanced grip on icy and snow-packed roads, improving traction and braking performance. They are commonly used in Nordic countries during the winter season, reaching shares as high as 95% in northern regions (Gjerstad et al., 2024). The wear when non-studded tyres are used is insignificant compared to when studded tyres are used (Sörme and Lagerkvist, 2002). In Sweden, an average of 24 g/vkm of asphalt is worn off during winter (Lindgren, 1996), although it was estimated by Carlsson et al. (1995) that the introduction of softer studs and more durable asphalt would have reduced this to 11 g/vkm by 2000. The average wear factor of roads in Stockholm has been estimated to be 4–6 g/vkm (Jacobsson and Hornwall, 1999). Winter maintenance procedures in cold climates, such as traction sanding (the dispersion of sand aggregate on the road surface) and the use of studded tyres, have been associated with high airborne particle concentrations through a formation process known as the 'sandpaper effect' (Kupiainen et al., 2003).

The wear of the road surface increases with the moisture level and is 2 to 6 times larger for a wet road than for a dry one (Folkeson, 1992). It also increases after the salting of the road, since the surface remains wet for longer periods. Vehicle speed, tyre pressure and air temperature also affect road wear. As the temperature decreases the tyres become less elastic, with the result that the road surface wear rates increase (NTNU), 1997). Vehicle weight can also affect road wear emissions, leading to a 10-15% increase in PM_{10} and $PM_{2.5}$ emissions of electric vehicles compared to equivalent ICE vehicles based on the work of Beddows & Harrison (2021). The study by Liu et al (2021) analysed the impact of weight on non-exhaust emissions and concluded similar reductions. In addition, the study by Woo et al. (2022) indicated an increase of 15-20% in road wear from electric vehicles compared to ICE vehicles. However, further research is needed to quantify the impact of the weight of all vehicle categories.

2.2 PM emissions from tyre, brake and road surface wear

2.2.1 PM from tyre wear

Tyre wear material is emitted across the whole size range for airborne particles. Camatini et al. (2001) collected debris from the road of a tyre proving ground. They found tyre debris particles up to a few hundred micrometres in size. Such particles are not airborne and are of limited interest to air pollution, but they contribute the largest fraction by weight of total tyre wear. Although the samples were collected in the environment of a proving ground, where tyre wear may be extreme, similar observations were also made by Smolders and Degryse (2002), who found that roadside tyre debris < 100 μm had a mean diameter of 65 μm for cars and 80 μm for trucks.

Significant research in the area of airborne particle size definition was conducted in the 1970s. Cadle and Williams (1978) reported a tyre wear particle size distribution in the range of 0.01–30 μm. Other studies have indicated two separate size modes: one consisting of particles below 1 μm, and the other consisting of coarse particles above 7 μm (Cardina, 1974; Dannis, 1974; Pierson and Brachaczek, 1974; Cadle and Williams, 1978). This observation has also been confirmed by Fauser (1999). A plausible mechanism for the distinction is the volatilisation and subsequent condensation of material in the ultra-fine particle mode, and normal wear for larger sizes (Cadle et al. 1978). However, this is by no means verified as yet.

The observed mass-weighted size distribution has varied in different studies, and it is not straightforward to draw firm general conclusions. Early studies indicated a small mass fraction below around 3 μm (Pierson and Brachaczek, 1974; Cadle and Williams, 1978). Another study by TNO (1997) has suggested that PM_{10} is distributed as 70 % $PM_{2.5}$, 10 % PM_1 and 8 % $PM_{0.1}$. Rauterberg-Wulff (1999) noted that tyre wear particles were only found in the coarse mode (> 2.5 μm). On the other hand, Fauser (1999) reported size distributions with up to 90 % of mass below 1 μm. Additionally, Miguel et al. (1999) identified that 50–70 % of airborne road dust may be classified as PM_{10}. This provides an approximate estimate of the TSP/PM_{10} ratio for tyre wear.

Unsurprisingly, tyre wear particles mainly consist of the compounds used to formulate tyres. According to Hildemann et al. (1991), tyre particles contain 29 % elemental carbon and 58 % organic material, and zinc is the most abundant metal.

It is evident from the previous analysis that tyre wear PM emissions estimates rely on old data and recent measurements indicate that such older values tend to overestimate real-world PM emission rates (Saladin et al., 2024; Huber et al., 2024; Giechaskiel et al. 2024a). However, there are often large discrepancies in the literature varying across a range spanning five orders of magnitude. With this subject being an active field of research and new data being produced from experimental campaigns, a new set of emission factors is to be expected soon.

2.2.2 PM from brake wear

Similar to tyre wear, not all worn brake material becomes airborne PM; however a large fraction can be allocated to PM_{10} or even $PM_{2.5}$. The exact value of such fractions depends on the braking system, operating conditions, and could also be related to the measurement method used to characterise it.

On average, , less than half of the total brake wear mass becomes airborne as PM_{10}, of that, less than half is further classified as $PM_{2.5}$ (Giechaskiel et al., 2024b).

The Particle Measurement Program (PMP), an informal working group of the United Nations Working Party on Pollution and Energy (UNECE – GRPE), developed and standardized in 2023 a new braking cycle representative of real-world braking events and conditions for light-duty vehicles, the WLTP-Brake cycle (Mathissen et al., 2018), together with a PM sampling system. Having an agreed methodology is expected to lead to more precise and harmonized data for emission factors in the near future.

Giechaskiel et al. (2024b) gathered literature data from brake wear emission rates from over 60 studies conducted between 2019 and 2023 following the WLTP-Brake or comparable cycles. These studies emphasized the influence of the braking system, vehicle mass, and regenerative braking on brake emissions for LDVs, following the Global Technical Regulation No. 24 (GTR 24) methodology. Integrating this data with the European Union fleet statistics for brake systems, mass and powertrains, one can characterize the current state of brake wear emissions from light-duty vehicles and make estimations for their future evolution. The literature review estimated that the average PM_{10} emission rate for a conventional European passenger car equipped with low-steel (LS) brake pads and grey cast iron (GCI) brake discs is at 3.1 mg/km/brake/ton of vehicle mass. Based on an average mass of 1564 kg (including 37.5 kg from half passenger as defined in GTR 24) for conventional cars in 2022, this corresponds to a PM_{10} brake wear emission factor of approximately 13.7 mg/km. For light commercial vehicles (LCVs), which have an average mass of 2370 kg with a 28% payload (Karageorgiou et al., 2024), the corresponding emission factor rises to about 20.8 mg/km. These figures align with data published by the International Organization of Motor Vehicle Manufacturers (OICA, 2021). Additionally, the total number of emitted particles larger than 10 nm (PN_{10}) is estimated at around 9×10^9 particles/km for passenger cars and 14×10^9 particles/km for LCVs.

Brake wear particle emissions span over a broad size distribution, from coarse to ultrafine particles (PM_{10}, $PM_{2.5}$, $PM_{0.1}$). While the bulk of emissions are mass-dominated by PM_{10} and $PM_{2.5}$, ultrafine particles (<0.1 µm) are also generated through thermal and tribochemical mechanisms, especially under intense braking events.

As electrification advances and the use of regenerative braking becomes more widespread together with the newly introduced Euro 7 brake emission limits, total brake-related PM emissions are expected to decrease. Ongoing real-world testing and future updates to the WLTP-Brake methodology will be essential for accurately tracking future developments in this area.

2.2.3 PM from road surface wear

Emission factors for road surface wear particles are even more difficult to quantify than those for tyre and brake wear, partly because the chemical composition of bitumen is too complex for quantification with chemical mass balance and receptor modelling, and partly because primary wear particles mix with road dust and re-suspended material.

Few studies have provided emission factors for road surface wear according to PM_{10} or any other metric. According to Fauser (1999), around 70 % of the weight of airborne particles from bitumen ranges from 0.35 μm to 2.8 μm with a mean below 0.7 μm. Based on the chemical analysis of filters collected in the Hatfield tunnel, followed by principal component analysis, Luhana et al. (2004)

determined LDV and HDV emission factors for road surface wear of 3.1 mg/vkm and 29.0 mg/vkm respectively, but these values were considered to be highly uncertain.

The studded tyre share has been found to directly influence PM emissions in those regions (Kupiainen et al., 2017). Studded tyres cause significantly higher wear on road surfaces than non-studded reaching up to 40 times higher (Gjerstad, 2024), increasing non-exhaust PM_{10} emissions. Kupiainen et al. (2011) reported approximately 1.2-3.2 times higher PM_{10} emissions resulting from the use of studded tyres, compared to studless. Gustafsson et al. (2008) found that studded tyres result in 60-100 times higher particle concentration, compared to friction tyres. Kupiainen et al. (2005) tested the 'sandpaper effect' using an indoor road simulator. A range of non-studded (friction) and studded tyres were tested on a bituminous road surface with varying amounts of traction sand (two types of granite and one diabase). In the tests using non-studded tyres and no sand, PM_{10} emission factors at 15 km/h and 30 km/h were 11 mg/vkm and 9 mg/vkm respectively. Following the addition of between 865 and 1 046 g/m^2 of traction sand, the PM_{10} emission factor for non-studded tyres increased to between 36 and 108 mg/vkm. In the case of studded tyres, the emission factor without traction sand was 17 mg/vkm at 15 km/h and 40 mg/vkm at 30 km/h. Following the addition of traction sand (865 to 2 112 g/m^2), the emission factor increased to between 40 and 155 mg/vkm. The traction sand with the lowest resistance to fragmentation resulted in the highest airborne PM concentrations. Analysis of PM_{10} filters revealed that more than 90 % of the particles collected were aluminosilicates and therefore derived from the road surface and the traction sand. For non-studded tyres in the absence of traction sand, a maximum of 5 % of PM_{10} originated from the tyres. If it is assumed that, for non-studded tyres and no traction sand (i.e. conditions which might be more typical in Europe), 95 % of PM_{10} is due to road surface wear and 5 % due to tyre wear, this gives road surface and tyre wear emission factors of around 8.5 to 10.5 mg/vkm and around 0.5 to 0.6 mg/vkm respectively at low speeds. These findings contradict the view expressed by Kennedy et al. (2002) that in terms of the tyre/road surface wear interactions, any material loss is dominated by the wear material from the tyre treads.

The problem of quantifying particle emissions arising from road surface wear has been also tackled by Klimont et al. (2002), who proposed preliminary emission factors. These preliminary values have been adopted in this chapter.

2.3 Controls

In 1999, European Directive 98/12/EC enforced asbestos-free brake pads for all road vehicles. This does not necessarily affect the emission factor for brake wear, but it certainly has an impact on the chemical composition of the associated particles.

In response to the increasing concern over non-exhaust emissions, the adoption of the Euro 7 regulation by the European Parliament and Council marks a global milestone, as it introduces, for the first time PM_{10} emission limits for brake wear (European Parliament & Council, 2024). These limits apply to new light-duty vehicle types starting November 2026 and to all newly registered light-duty vehicles from November 2027 onward. Depending on vehicle category and fuel type, the PM_{10} limits range from 3 to 11 mg/km tested according to the conditions and protocol defined in the UN Global Technical Regulation No 24 on brake emissions. As discussed in section 2.2.2, current vehicles exceed these limits, regardless of vehicle mass, indicating that existing brake systems must be improved for vehicles to comply with Euro 7 standards. Limits for heavy-duty vehicles are expected once a harmonized methodology is defined.

There are several strategies available to reduce brake emissions, including the use of improved pad and disc materials, vehicle weight reduction, particle collection devices integrated into the braking system (such as drum brakes or passive/active filters), minimizing the use of friction braking through technologies like regenerative or predictive braking, and increased aerodynamic resistance for deceleration (Storch et al., 2023).

Non-Asbestos Organic (NAO) braking pads offer promising potential, reducing brake emissions by 60% compared to the currently used LS pads, a sufficient reduction for all Euro 7 LDVs based on agreed limits (Giechaskiel et al., 2024b). This is supported by recent (WLTP-Brake cycle compliant) measurements by Mamakos et al, (2019), Hagino et al. (2019), Hesse et al. (2021) which indicated 12 mg/km PM_{10} brake wear emissions for Low Steel (LS) pads while NAO pads lead to significantly lower brake PM_{10} emissions of about 3 mg/km.

Brake wear is also emitted by braking discs and therefore, brake emission reductions can also be achieved by modifying disc composition. Enhancing corrosion resistance (e.g., via hard-metal coatings) or replacing grey cast iron (GCI) with alternative materials like steel, aluminium alloys, or carbon-ceramic composites can reduce PM_{10} emissions by 57–81% (Giechaskiel et al., 2024b).

Another potential solution is the use of drum brakes, which, due to their enclosed design, emit approximately 23% less particulate matter than disc brakes, as a significant portion of the particles is contained within the braking system (Giechaskiel et al., 2024b; Grigoratos et al., 2023).

There are also a few market-ready brake filtration solutions which have been tested in both laboratory and real-world settings, claiming efficiencies of as high as 85%. The most recent on-going research that included both on-road and laboratory measurements showed that the average efficiency of brake filters is about 79% for PM_{10}, and 72% for $PM_{2.5}$ which means that brake filtration devices can be relevant in achieving Euro 7 brake emission limits.

Vehicle lightweighting also reduces brake wear emissions. There is evidence that the increased vehicle weight of electric vehicles affects all sources of non-exhaust emissions leading to a 10-15 % increase in brake wear (Beddows & Harrison, 2021). Similar conclusions about the impact of weight have been derived from the study of S. Woo et al. (2022) in which the increase of the vehicle weight by 20% increased brake wear emissions by around 15%-20%. The study of Liu et al. (2021) also evaluated the vehicle weights of small, medium and large ICE cars and their equivalent EVs in urban, rural and motorway environments. The impact of the increased weight of BEV to PM_{10} and $PM_{2.5}$ emission factors from brakes was found around 9-17%. Therefore, decreasing vehicle weight is expected to also decrease PM emissions.

When it comes to electrified vehicles, these can take advantage of regenerative braking, where part of the kinetic energy is recovered and stored as electricity, therefore reducing the need for friction braking. The PM reduction potential of such systems is under evaluation (Liu et al., 2021) but measurements by Hagino et al. (2019), Stanard et al. (2020) and Koupal et al. (2021) indicated measurable reductions. GTR24 is currently being reviewed with suggestions[4] to decrease PM emissions by 10-48% for hybrid vehicles (distinction on friction share coefficients between mild and full hybrid vehicles), 66% for PHEVs and 83% for pure electric vehicles, due to regenerative braking.

Finally, it is worth noting that the Euro 7 regulation includes a placeholder for tyre abrasion limits, although no official limits have been announced yet. A standardized testing methodology is still

[4] (PMP) Proposal to amend ECE/TRANS/WP.29/GRPE/2024/4 | UNECE

under development, covering both laboratory (drum method) and on-road (convoy method) methods.

2.4 Contribution of tyre, brake and road wear to total emissions

Historically, road transport was a major contributor to ambient PM pollution, with its share exceeding 20% in past decades. The introduction of emission control technologies—particularly Diesel Particulate Filters (DPFs) mandated under Euro 5b from 2011—has led to a significant reduction in exhaust-related PM emissions. As a result, road transport's contribution to ambient PM has declined to around 10% (Karageorgiou et al., 2024). However, this positive trend in exhaust emissions has been counterbalanced by the rise in non-exhaust emissions, including those from brake, tyre, and road surface wear.

Non-exhaust PM emissions have gradually increased and are now emerging as the dominant source of PM from road transport. Recent EU vehicle emission inventories, alongside projections from the Euro 7 Impact Assessment[5], show a marked shift: non-exhaust sources accounted for 30–45% of road transport PM in 2010, rising to 54–69% by 2020. Without intervention, this share is expected to surpass 90% by 2040 (Giechaskiel et al., 2024b). Brake wear alone is estimated to contribute approximately 30% of $PM_{2.5}$ and 40% of PM_{10} emissions within the non-exhaust category.

Despite the increasing market share of battery electric vehicles, the issue of brake wear remains largely unmitigated. While BEVs reduce fleet-average exhaust emissions, their higher weight and reliance on mechanical braking in certain conditions can still lead to significant particulate output — especially if regenerative braking is not optimally deployed. Importantly, current national and international emission inventories distinguish primary PM emissions from tyres, brakes, and road abrasion, while resuspended material is excluded to avoid double-counting.

In response to the growing prominence of non-exhaust sources, the European Commission has proposed the inclusion of brake and tyre wear limits under the Euro 7 regulation framework. This is part of a broader legislative push to align with the EU's zero-pollution ambition for 2050, which includes newly revised air quality standards[6] for 2030. These standards set stricter annual average limits for $PM_{2.5}$ (10 $\mu g/m^3$) and PM_{10} (20 $\mu g/m^3$), moving significantly closer to WHO recommendations[7].

Resuspended particulate matter also contributes to the PM concentrations recorded by ambient air PM samplers, though re-suspension is not generally considered to be a primary particle emission source. On the other hand, the USEPA AP-42 model considers road slit loading as the predominant source for non-exhaust particle emissions and assumes that most vehicle-related non-exhaust PM_{10} arises from re-suspension. However, this modelling approach has been criticised within the US (Venkatram, 2000). Due to the open discussion with regard to the definition of resuspension as a primary source, and the uncertainty in the methods used for the estimation of its effect, no methodology to estimate PM concentrations from resuspension is provided in this chapter.

[5] Euro 7 impact assessment study - Publications Office of the EU
[6] https://data.consilium.europa.eu/doc/document/PE-88-2024-INIT/en/pdf
[7] https://www.who.int/news-room/questions-and-answers/item/who-global-air-quality-guidelines

2.5 Derivation of calculation methods

In this chapter, a methodology is proposed which provides a common basis for calculating and comparing non-exhaust particle emissions in different countries.

The emission factors and calculation methods for the two NFR codes covered in the chapter were derived using the information available in the literature. A major update of emission factors will be performed once more data is available.

3 Calculation methods

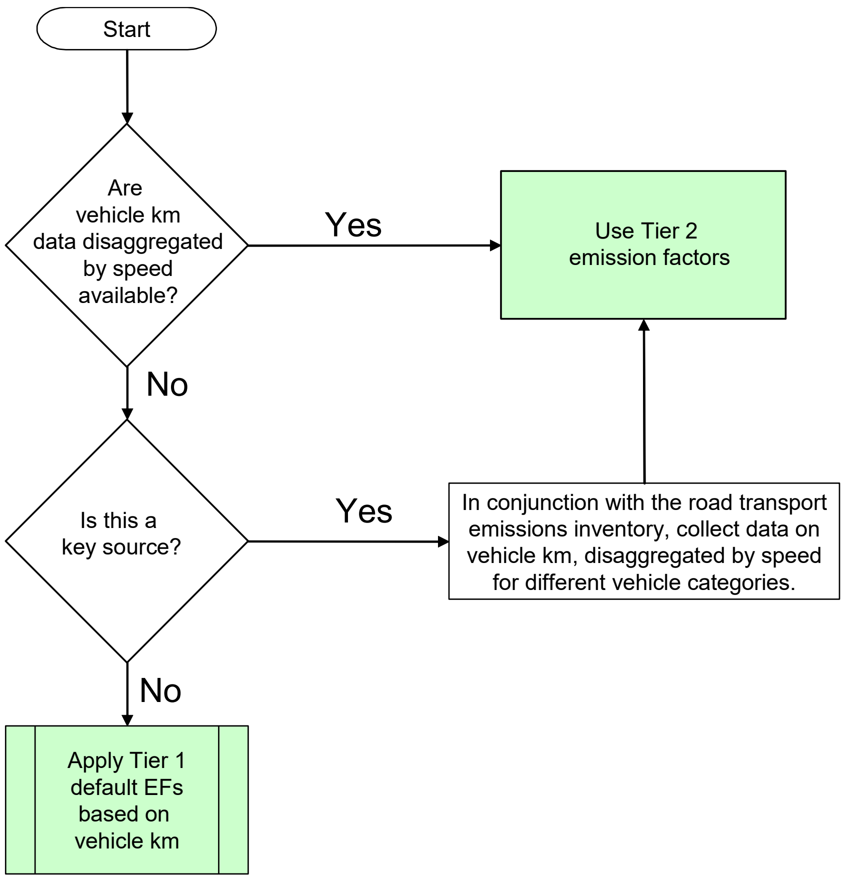
3.1 Choice of method

In Figure 3-1, a two-Tier procedure is presented to enable an appropriate method to be selected for estimating emissions from road vehicle tyre wear, brake wear and road surface wear.

If these source categories (when combined) represent a key source or disaggregated activity data are available, then the Tier 2 method must be used for estimating emissions, otherwise, the Tier 1 method can be used. No Tier 3 method has yet been developed.

However, for many national inventories, probably, tyre, brake and road surface wear are not a key source, but that road transport combustion (NFR codes 1.A.3.b.i-v) *is* a key source. In these circumstances, the important activity data (vehicle-km for different vehicle categories disaggregated by speed) are required to calculate exhaust emissions. These are the same activity data as those required for the Tier 2 methodology presented here. Consequently, it is anticipated that no new activity data would be required for the estimation of emissions due to tyre wear, brake wear and road surface wear.

Figure 3-1 Decision tree for vehicle tyre and brake wear and road surface wear



3.2 Tier 1 methodology

3.2.1 Algorithm

In order to calculate emissions of TSP, PM_{10} or $PM_{2.5}$ from (i) brake and tyre wear combined, and (ii) road surface wear, equation (1) can be used. This equation can be used to estimate emissions for a defined spatial and temporal resolution by selecting appropriate values for the fleet size and the activity (mileage). Emission factors are given as a function of vehicle category alone. Total traffic-generated emissions for each of the NFR codes can be estimated by summating the emissions from individual vehicle categories.

$$TE = \sum_{j} N_j \times M_j \times EF_{i,j} \qquad (1)$$

Where:

TE = total emissions of TSP, PM_{10} or $PM_{2.5}$ for the defined time period and spatial boundary [g],

N_j = number of vehicles in category *j* within the defined spatial boundary,

M_j = average mileage driven per vehicle in category *j* during the defined time period [km],

$EF_{i,j}$ = mass emission factor for pollutant *i* and vehicle category *j* [g/km].

The indices are:

i = TSP, PM_{10}, $PM_{2.5}$

j = vehicle category (two-wheel vehicle, passenger car, light-duty truck, heavy-duty vehicle).

Two-wheel vehicles correspond to mopeds and motorcycles. Passenger cars are small or larger family cars used mainly for the carriage of people. Light-duty trucks include vans for the carriage of people or goods. Heavy-duty vehicles correspond to trucks, urban buses and coaches. More details on the vehicle classification and selection criteria can be found in Chapter 1.A.3.b Road transport.

3.2.2 Emission factors

Table 3-1 and Table 3-2 provide the emission factors for TSP, PM_{10} and $PM_{2.5}$ and the two NFR source categories (i.e. tyre and brake wear combined, and road surface wear). The Tier 1 emission factors have been estimated using the Tier 2 method and assuming some default emission values for vehicle characteristics.

Table 3-1 Tier 1 emission factors for source category 1.A.3.b.vi, road vehicle tyre and brake wear combined

Tier 1 emission factors						
		Code	Name			
NFR Source Category		1.A.3.b.vi	Road vehicle tyre and brake wear			
Fuel		N/A				
Not estimated		PAHs, POPs, HCB, PCBs, dioxins and furans				
Pollutant	Vehicle type	Value	Unit	95% confidence interval		Reference
				Lower	Upper	
TSP	Two-wheelers	0.0083	g km^{-1} vehicle^{-1}	0.0064	0.0103	EMEP-Corinair B770 v1.0
PM10		0.0064	g km^{-1} vehicle^{-1}	0.0047	0.0081	EMEP-Corinair B770 v1.0
PM2.5		0.0034	g km^{-1} vehicle^{-1}	0.0026	0.0042	EMEP-Corinair B770 v1.0
TSP	Passenger cars	0.0229	g km^{-1} vehicle^{-1}	0.0083	0.0369	EMEP-Corinair B770 v1.0
PM10		0.0184	g km^{-1} vehicle^{-1}	0.0067	0.0297	EMEP-Corinair B770 v1.0
PM2.5		0.0093	g km^{-1} vehicle^{-1}	0.0034	0.0150	EMEP-Corinair B770 v1.0
TSP	Light duty trucks	0.03427	g km^{-1} vehicle^{-1}	0.0190	0.0450	EMEP-Corinair B770 v1.0
PM10		0.0271	g km^{-1} vehicle^{-1}	0.0148	0.0351	EMEP-Corinair B770 v1.0
PM2.5		0.0139	g km^{-1} vehicle^{-1}	0.0076	0.0180	EMEP-Corinair B770 v1.0
TSP	Heavy duty trucks	0.0777	g km^{-1} vehicle^{-1}	0.0462	0.1318	EMEP-Corinair B770 v1.0
PM10		0.0590	g km^{-1} vehicle^{-1}	0.0500	0.0950	EMEP-Corinair B770 v1.0
PM2.5		0.0316	g km^{-1} vehicle^{-1}	0.0281	0.0541	EMEP-Corinair B770 v1.0

Note: due to the relatively low chlorine content of tyres and brakes (chlorine is a constituent of POPs, PCBs and HCB), and the fact that abrasion is a relatively low-temperature process which does not promote the formation of PAHs, no significant emissions of any of these species is expected. Therefore, no emission factors are proposed for Tier 1. The Tier 2 method suggests typical profiles for PAHs in tyre and brake wear.

Table 3-2 Tier 1 emission factors for source category 1.A.3.b.vii, road surface wear

Tier 1 emission factors						
		Code	Name			
NFR Source Category		1.A.3.b.vii	Road surface wear			
Fuel		N/A				
Not estimated		PAHs, POPs, HCB, PCBs, dioxins and furans				
Pollutant	Vehicle type	Value	Unit	95% confidence interval		Reference
				Lower	Upper	
TSP	Two-wheelers	0.0060	g km^{-1} $vehicle^{-1}$	0.0036	0.0081	EMEP-Corinair B770 v1.0
PM10		0.0030	g km^{-1} $vehicle^{-1}$	0.0018	0.0041	EMEP-Corinair B770 v1.0
PM2.5		0.0016	g km^{-1} $vehicle^{-1}$	0.0010	0.0022	EMEP-Corinair B770 v1.0
TSP	Passenger cars	0.0150	g km^{-1} $vehicle^{-1}$	0.0090	0.0203	EMEP-Corinair B770 v1.0
PM10		0.0075	g km^{-1} $vehicle^{-1}$	0.0045	0.0101	EMEP-Corinair B770 v1.0
PM2.5		0.0041	g km^{-1} $vehicle^{-1}$	0.0024	0.0055	EMEP-Corinair B770 v1.0
TSP	Light duty trucks	0.0210	g km^{-1} $vehicle^{-1}$	0.0090	0.0253	EMEP-Corinair B770 v1.0
PM10		0.0105	g km^{-1} $vehicle^{-1}$	0.0045	0.0123	EMEP-Corinair B770 v1.0
PM2.5		0.0057	g km^{-1} $vehicle^{-1}$	0.0024	0.0070	EMEP-Corinair B770 v1.0
TSP	Heavy duty trucks	0.0760	g km^{-1} $vehicle^{-1}$	0.0456	0.1026	EMEP-Corinair B770 v1.0
PM10		0.0380	g km^{-1} $vehicle^{-1}$	0.0228	0.0513	EMEP-Corinair B770 v1.0
PM2.5		0.0205	g km^{-1} $vehicle^{-1}$	0.0123	0.0277	EMEP-Corinair B770 v1.0

Note: due to the relatively low chlorine content of tyres and brakes (chlorine is a constituent of POPs, PCBs and HCB), and the fact that abrasion is a relatively low-temperature process which does not promote the formation of PAHs, no significant emissions of any of these species is expected. Therefore, no emission factors are proposed for Tier 1.

Fractions of BC of wear PM are provided in the Danish inventory based on COPERT calculations and are shown in Table 3-3.

Table 3-3 Tier 1 BC fractions

Vehicle category	f-BC Brake/Tyre wear	f-BC road abrasion
Two-wheelers	0.12	-
Passenger cars	0.10	-
Light-Commercial Vehicles	0.10	-
Heavy duty vehicles	0.10	-

3.2.3 Activity data

The relevant activity statistics for Tier 1 are the number of vehicles in each defined category, and the average mileage is driven per vehicle in each defined category (or their product, i.e. the total vehicle-km for each defined category).

3.3 Tier 2 methodology

3.3.1 Algorithm for tyre and brake wear

The Tier 2 methodology expands upon the Tier 1 methodology to take account of the speed-dependency of tyre and brake wear and is based on the 'Detailed Methodology' in the previous version of the Guidebook. Emissions for additional particle size metrics (PM_1 and $PM_{0.1}$) can also be calculated with this method.

The following general equation is used to estimate emissions from tyre wear and brake wear separately:

$$TE = \sum_{j} N_j \times M_j \times EF_{TSP,s,j} \times f_{s,i} \times S_s(V) \qquad (2)$$

Where:

TE	=	total emission for the defined time period and spatial boundary [g],
N_j	=	number of vehicles in category *j* within the defined spatial boundary,
M_j	=	mileage [km] driven by each vehicle in category *j* during the defined time period,
$EF_{TSP,s,j}$	=	TSP mass emission factor for vehicles in category *j* [g/km],
$F_{s,i}$	=	mass fraction of TSP that can be attributed to particle size class *i,*
$S_s(V)$	=	correction factor for a mean vehicle travelling speed *V.*

The index *j* relates to the vehicle category (similar to eq.1). The index *s* refers to the source of PM, i.e. tyre (*T*) or brake (*B*) wear. The particle size classes *i* are TSP, PM_{10}, $PM_{2.5}$, PM_1 and $PM_{0.1}$.

3.3.2 Emission factors for tyre and brake wear

Emission factors for tyre wear

TSP emission factors for different vehicle classes are given in Table 3-4. The emission factors are based on available experimental data. It should be noted that the TSP emission factors do not assume that all tyre wear material is transformed into suspended particulate, as a large fraction of tyre rubber may be produced as dust fall particles or larger shreds (e.g., under heavy braking). A differentiation of emission factors among different segments of passenger cars has been performed based on recent literature.

Recent measurements demonstrated that the existing PM_{10} and $PM_{2.5}$ in this table are overestimated since the actual ratio of PM_{10} to total tyre wear is more recently found to be well below 3% (Saladin et al., 2024; Huber et al., 2024; Giechaskiel et al. 2024a). Therefore, the large majority of tyre wear is deposited on the ground and does not become airborne. Current evidence does not allow a revision of the values in Table 3-4. The ranges will be reconsidered once sufficient experimental evidence has become available. .

Table 3-4 TSP emission factors for source category 1.A.3.b.vi, road vehicle tyre wear

Vehicle class (j)	TSP emission factor (g/km)	Uncertainty range (g/km)	Quality code
Two-wheel vehicles	0.0046	0.0042–0.0053	B
Passenger cars – ICE – Mini	0.0085	0.0053–0.0128	D
Passenger cars – ICE – Small	0.0096	0.0060–0.0145	C
Passenger cars – ICE – Medium	0.0107	0.0067–0.0162	B
Passenger cars – ICE – Large	0.0118	0.0074–0.0179	C
Passenger cars – Hybrid – Mini	0.0089	0.0056–0.0134	D

Passenger cars – Hybrid – Small	0.0100	0.0063–0.0151	D
Passenger Cars – Hybrid – Medium	0.0111	0.0070 - 0.0168	D
Passenger Cars – Hybrid – Large	0.0123	0.0077 - 0.0186	D
Passenger Cars – PHEV – Small	0.0101	0.0064–0.0153	D
Passenger Cars – PHEV – Medium	0.0112	0.0071 - 0.0170	D
Passenger Cars – PHEV – Large	0.0124	0.0078 - 0.0188	D
Passenger Cars – BEV – Small	0.0105	0.0066 – 0.0161	C
Passenger Cars – BEV - Medium	0.0116	0.0072 – 0.0178	C
Passenger Cars – BEV – Large	0.0127	0.0079 – 0.0195	C
Light-Commercial Vehicles (N1 – I)	0.0107	0.0067–0.0162	B
Light-Commercial Vehicles (N1 – II, III)	0.0169	0.0088–0.0217	B
Heavy-Duty vehicles	Equation 3	0.0227–0.0898	B–C

Note:
B: Emission factors are non-statistically significant based on a small set of measured re-evaluated data.
C: Emission factors estimated based on available literature.
D: emission factors estimated by applying similarity considerations and/or extrapolation.
For BC emission factor estimation it is proposed to use a BC fraction of TSP of 0.153, c.f. Appendix B.

For heavy-duty vehicles, the emission factor needs to take vehicle size (by the number of axles) and load into account. These are introduced by the equation:

$$EF_{TSP,T,HDV} = \frac{N_{axle}}{2} \cdot LCF_T \cdot EF_{TSP,T,PC} \quad (3)$$

Where,

$EF_{TSP,T,HDV}$ = the TSP emission factor [g/km] for tyre wear from heavy-duty vehicles,

N_{axle} = number of truck axles,

LCF_T = a load correction factor for tyre wear,

$EF_{TSP,T,PC}$ = the TSP emission factor for tyre wear from passenger cars - ICE,

and

$$LCF_T = 1.41 + (1.38 \times LF) \quad (4)$$

LF is the load factor, ranging from 0 for an empty truck to 1 for a fully laden one. The same equations can be used for trucks, urban buses and coaches.

The load correction factor — which accounts for the load carried by truck or bus — has been derived by linear regression on experimental data.

A typical size profile for the TSP emitted by tyre wear has been obtained by combining information from the literature, as discussed in subsection 2.2.1. Based on this information, the mass fraction of TSP in the different particle size classes is shown in Table 3-5. A value of 0.6 has been selected as the PM_{10}/TSP ratio for tyre wear in order to derive TSP values where only PM_{10} emission factors are available in the literature.

Table 3-5 Size distribution of tyre wear particles

Particle size class (*i*)	Mass fraction ($f_{T,i}$) of TSP
TSP	1.000
PM_{10}	0.600
$PM_{2.5}$	0.420
PM_1	0.060
$PM_{0.1}$	0.048

A speed correction is required to account for the different wear factors of the tyre depending on the vehicle's speed. Figure 3–2 shows the speed correction, based on the findings of Luhana et al. (2002). It should be noted that, as in the case of exhaust emission factors, vehicle speed corresponds to mean trip speed and not constant travelling speed. Tyre wear decreases as mean trip speed increases, probably because braking and cornering are more frequent in urban driving than in motorway driving.

The mathematical expression of Figure 3–2 is:

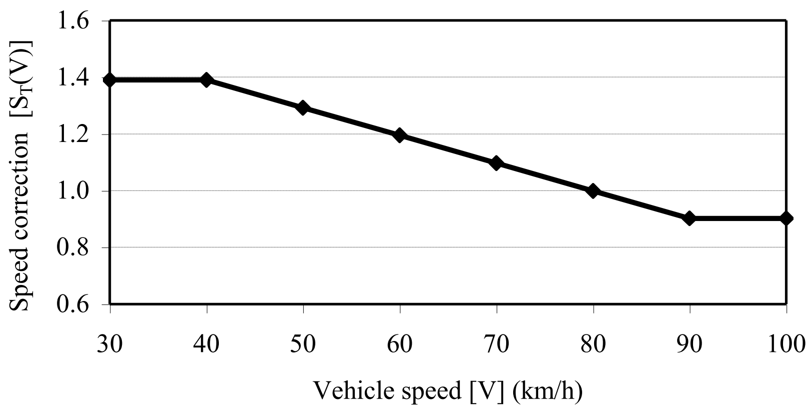
$V < 40$ km/h: $S_T(V) = 1.39$

$40 \text{ km/h} \leq V \leq 90$ km/h: $S_T(V) = -0.00974 \cdot V + 1.78$ (5)

$V > 90$ km/h: $S_T(V) = 0.902$

Note that $S_T(V) = 1$ when the mean trip speed is 80 km/h, and stabilises below 40 km/h and above 90 km/h due to the absence of any experimental data. Also, although the proposed equation has been obtained from measurements on passenger cars, it is to be used for all vehicle categories.

Figure 3–2 Speed correction factor for tyre wear particle emissions



Emission factors for brake wear

The TSP emission factors for brake wear particles are given in Table 3-6, together with the range and a quality code for the emission factor. Like tyre wear, not all brake wear becomes airborne. A differentiation of emission factors among different segments of passenger cars has been performed based on the findings of the literature study of Giechaskiel et al. (2024b) and the measurement data gathered from over 60 studies following the WLTP-Brake cycle. The average

PM_{10} brake wear emission rate of a typical conventional vehicle (using low metallic pads with gray cast iron discs) is estimated at 3.1 mg/km/brake per ton of vehicle mass. Combining this with the friction brake coefficients for electrified vehicles provided by the Particle Measurement Program (PMP) (i.e. 0.17 for electric, 0.34 for PHEV, 0.71 on average for hybrid vehicles) and the average WLTP vehicle mass per segment[8, 9, 10] , a differentiation among powertrains and car segments can be done. PN_{10} emission rates (number of particles down to 10 nm) are also obtained with the same approach. Considering that average mass of vehicle fleets varies among countries, these values may be selected to within their range, depending the fleet characteristics.

Table 3-6 TSP emission factors for source category 1.A.3.b.vi, road vehicle brake wear

Vehicle category (j)	TSP emission factor (g/km)	Range (g/km)	PN_{10} $\times 10^9$ (#/km)	Quality code
Two-wheel vehicles	0.0037	0.0022 – 0.0050	2.3	D
Passenger cars – ICE – Mini	0.0098	0.0060 - 0.0120	6.6	D
Passenger cars – ICE – Small	0.0118	0.008 - 0.015	7.9	B
Passenger cars – ICE – Medium	0.0142	0.01 - 0.018	9.5	B
Passenger cars – ICE – Large	0.0176	0.012 - 0.02	11.7	B
Passenger cars – Hybrid – Mini	0.007	0.0040 - 0.0090	5	C
Passenger cars – Hybrid – Small	0.0086	0.005 - 0.0110	5.8	C
Passenger Cars – Hybrid – Medium	0.0104	0.006 - 0.013	6.9	C
Passenger Cars – Hybrid – Large	0.0125	0.007 - 0.015	8.4	C
Passenger Cars – PHEV – Small	0.0059	0.004 - 0.008	3.9	C
Passenger Cars – PHEV – Medium	0.0059	0.004 - 0.008	3.9	C
Passenger Cars – PHEV – Large	0.0072	0.004 - 0.01	4.8	C
Passenger Cars – BEV – Small	0.0027	0.002 - 0.004	1.8	C
Passenger Cars – BEV - Medium	0.0030	0.002 - 0.004	2	C
Passenger Cars – BEV – Large	0.0033	0.002 - 0.004	2.2	C
Light-Commercial Vehicles (N1 – I)	0.0117	0.008 - 0.015	7.8	B
Light-Commercial Vehicles (N1 – II)	0.0155	0.01-0.02	10.3	B
Light-Commercial Vehicles (N1 – III)	0.0211	0.016 - 0.025	14.1	B
Heavy-Duty vehicles	Equation 6	0.0235 – 0.06	10-40	C

Note
Quality codes:
- B: emission factors non statistically significant based on a small set of measured re-evaluated data;
- C: emission factors estimated on the basis of available literature;
- D: emission factors estimated by applying similarity considerations and/or extrapolation.

For BC emission factor estimation it is proposed to use a BC fraction of TSP of 0.0261, c.f. Appendix B.

8 Pocketbook_202324_Web.pdf
9 Monitoring of CO2 emissions from passenger cars Regulation (EU) 2019/631
10 Data

The heavy-duty vehicle emission factor is calculated by adjusting the passenger cars' ICE medium emission factor to fit heavy-duty vehicle experimental data:

$$EF_{TSP,B,HDV} = 1.956 \cdot LCF_B \cdot EF_{TSP,B,PC} \quad (6)$$

In equation 6, 3.13 is an empirical factor derived from experimental data and LCF_B is defined in a similar way to LCF_T and can be determined again by linear regression on experimental data by the equation:

$$LCF_B = 1 + 0.79 \times LF \quad (7)$$

LF again has the value of 0 for an empty vehicle and 1 for a fully laden one. Equations 6 and 7 are used for trucks, urban buses and coaches.

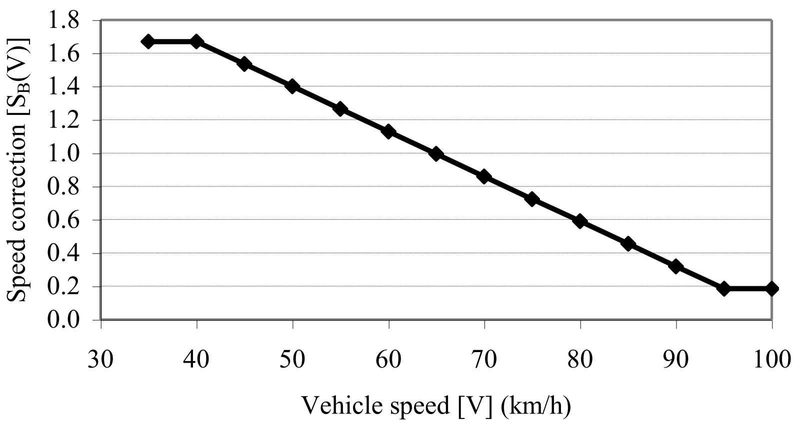
The mass fraction of TSP in the different particle size classes is shown in Table 3-7.

Table 3-7 Size distribution of brake wear particles

Particle size class (*i*)	**Mass fraction ($f_{B,i}$) of TSP**
TSP	1.000
PM_{10}	0.980
$PM_{2.5}$	0.390
PM_1	0.100
$PM_{0.1}$	0.080

The speed correction factor for the case of brake wear is given in Figure 3–3, and the mathematical expression of $S_B(V)$ is given in equation 8.

Figure 3–3 Speed correction factor for brake wear particle emissions



V < 40 km/h: $S_B(V) = 1.67$

40 km/h ≤ V ≤ 95 km/h: $S_B(V) = -0.0270 \cdot V + 2.75$ (8)

V > 95 km/h: $S_B(V) = 0.185$

In this case, the speed correction is normalised for a speed of 65 km/h, and the slope is generally larger than for tyre wear because brake wear is negligible at high motorway speeds when limited braking occurs. Again, although the proposed equation has been obtained from measurements on passenger cars, it is to be used for all vehicle categories.

3.3.3 Algorithm and emission factors for road surface wear

There is very little information on airborne particle emissions from road surface wear. Emissions are calculated according to the equation:

$$TE_{R;\,i} = \sum_{j} N_j \times M_j \times EF_{R;\,j} \times f_{R;\,i} \qquad (9)$$

where:

$TE_{R;\,i}$ = total emission of pollutant *i* from road surface wear for the defined time period and spatial boundary [g],

N_j = number of vehicles in category *j* within the defined spatial boundary,

M_j = mileage driven by vehicles in category *j* during the defined time period [km],

$EF_{R;\,j}$ = TSP mass emission factor from road wear for vehicles in category *j* [g/km],

$f_{R;\,i}$ = mass fraction of TSP from road surface wear that can be attributed to particle size class *i.*

The detailed methodology only provides a mass-weighted size classification of road surface wear particles and is independent of speed. Preliminary TSP emission factors for road surface wear are shown in Table 3-8. These TSP values should correspond to primary particles from road surface wear, but they are based on limited information and are highly uncertain. The mass fraction of TSP in the different particle size classes is shown in Table 3-9.

Table 3-8 TSP emission factors from road surface wear

Vehicle category (*j*)	Emission factor (g/km)	Quality code
Two-wheel vehicles	0.0060	C–D
Passenger cars – ICE – Mini	0.0105	D
Passenger cars – ICE – Small	0.0127	C-D
Passenger cars – ICE – Medium	0.0150	C–D
Passenger cars – ICE – Large	0.0174	C-D
Passenger cars – Hybrid – Mini	0.0113	D
Passenger cars – Hybrid – Small	0.0135	D
Passenger Cars – Hybrid – Medium	0.0159	C-D
Passenger Cars – Hybrid – Large	0.0183	D
Passenger Cars – PHEV – Small	0.0137	D
Passenger Cars – PHEV – Medium	0.0161	C-D

Passenger Cars – PHEV – Large	0.0185	D
Passenger Cars – BEV – Small	0.0145	C-D
Passenger Cars – BEV - Medium	0.0169	C-D
Passenger Cars – BEV – Large	0.0194	C-D
Light-Commercial Vehicles (N1 – I)	0.0150	C–D
Light-Commercial Vehicles (N1 – II, III)	0.0210	C–D
Heavy-Duty vehicles	0.0760	C–D

Note:
Quality codes:
- C: emission factors estimated on the basis of available literature;

D: emission factors estimated by applying similarity considerations and/or extrapolation.

Table 3-9 Size distribution of road surface wear particles

Particle size class (i)	**Mass fraction ($f_{R,i}$) of TSP**
TSP	1.00
PM_{10}	0.50
$PM_{2.5}$	0.27

Studded tyres are commonly used in Nordic countries during the winter season and are increasing the PM_{10} emissions from road wear between 1.2 and 3.2 times on average (Kupiainen, 2011).

3.3.4 Abatement

The technology abatement approach is not relevant to this methodology.

3.3.5 Activity data

Information on activity statistics relevant to tyre, brake and road surface wear may be found in Chapter 1.A.3.b Road transport concerning exhaust emissions from road transport.

3.4 Species profiles

For a detailed list of organic compounds and PAHs, the reader should refer to the work of Rogge et al. (1993) which is, however, based on a single-tyre type and a single brake pad. Instead of quoting the very extensive list of compounds, we focus on the four PAHs relevant to the United Nations Economic Commission for Europe Persistent Organic Pollutants' (UNECE POPs) protocol (B[b]F, B[k]F, B[a]P, I[1,2,3-cd]P) (Table 3-10).

Table 3-10 Brake and tyre debris-bound PAHs

Compound	Tyre wear (ppm wt.)	Brake wear (ppm wt.)
Benzo(a)pyrene	3.9	0.74
Benzo(b)fluoranthene	0	0.42
Benzo(k)fluoranthene	0	0.62
Indeno(1,2,3-cd)pyrene	-	-

Table 3-10 provides the speciation of tyre and brake wear into different elements, ions, elemental carbon and organic carbon. Several sources have been used to provide this speciation, and for this reason, a mean value and the minimum and maximum values are shown. In several instances, a large range is reported. This is obviously due to the variety of materials and sources used to manufacture tyre tread and brake linings, and a larger sample of materials needs to be studied. At present, due to the absence of such information, the 'mean' value is a non-weighted average of values given in old reports. Sources for the ranges of Table 3-10 include Brewer (1997), Hewitt and Rashed (1990), Hildemann et al. (1991), Hillenbrand et al. (2004), Hjortenkrans et al. (2007), Legret and Pagotto (1999), Malmqvist (1983), von Uexküll et al. (2005), VROM (1997), and Westerlund (2001). In the Guidebook 2008 version of the chapter, the content of tyre and brake in As, Cd, Cr, Ni, and Pb was revised with information that came by revisiting the Espreme emission factors (Kummer, U., 2008).

In terms of BC, and the absence of better information, EC values quoted in Table 3-12 can be used as proxies for BC as well. For road abrasion, the values of Table 3-11, originating from Kupiainen and Klimont (2004) can be used.

Table 3-11 BC and OC ratios to be used for road abrasion.

Category	f-BC	f-OC	+/- uncertainty (%)
Road abrasion	0.0106	0.135	50

Table 3-12 Composition of tyre and brake wear in terms of various metals, ions, and elemental and organic carbon (in ppm wt.)

Element	Elemental Speciation					
	Tyre			Break		
	Mean	Min	Max	Mean	Min	Max
Ag	0.1	0.1	0.1			
Al	324	81.0	470	2050	330	3770
As	3.8	1.6	6.0	67.5	10.0	130.0
Ba	125.0	0.9	370	38520	2640	74400
Br	20.0			40.0		
Ca	892	113.0	2000	7700	1100	14300
Cd	4.7	1.4	9.0	22.4	1.5	57.0
Cl	520			1500		
Cl-	600			1500		
Co	12.8	0.9	24.8	6.4		
Cr	23.8	2.0	61.0	2311	115	8050
Cu	174	1.8	490	51112	370	142000
EC	153000			26100		
Fe	1712	2.1	4600	209667	115000	399000
K	280	180.0	380	523.5	190	857
Li	1.3	0.2	2.3	55.6		
Mg2+	166	32.0	360	44570	6140	83000
Mn	51	2.0	100	2460	1700	3220
Mo	2.8			10000		
Na+	645	610.0	680	7740	80.0	15400
NH4+	190			30.0		
Ni	29.9	2.4	63	327	80	60
NO3-	1500			1600		
OC	360000			107000		
P						
Pb	176	6.3	670	6072	120	20000
Rb				50.0		
S	1100			12800		
Sb	2.0			10000		
Se	20.0			20.0		
Si	1800			67900		
SO4--	2500			33400		
Sn				7000		
Sr	14.4	0.2	40.0	520	81.4	740
Ti	378			3600		
V	1.0			660		
Zn	7434	430	13494	8676	270	21800

Note:

EC = elemental carbon, EC is assumed equivalent to BC. OC = organic carbon. Blank 'Mean' cells denote that no information is available, while blank 'Min' and 'Max' cells mean that only one source is available (i.e. no range can be given).

4 Data quality

4.1 Verification

The approaches which could be used to verify the emission factors and methodology in this chapter are essentially those which have been used to determine the primary information. These include tunnel studies, receptor modelling, and direct laboratory-based measurement. There is currently a lack of on-road measurement data (i.e. using instrumented vehicles), especially for tyre and road wear, under real-world driving conditions, and the collection of such data would also aid verification.

One simple verification approach would be to compare the results obtained using this method with those obtained in other inventories and to determine whether the proportion of non-exhaust particles is consistent.

4.2 Temporal disaggregation criteria

Since the emission factors presented in this chapter are global and differentiated only in terms of speed (and load for heavy-duty vehicles), temporal disaggregation mainly refers to activity data. A discussion on this topic is included in Chapter 1.A.3.b Road transport, concerning exhaust emissions from road transport. However, one needs to take into account that, as temporal resolution increases, the effects of wet weather need to be taken into account using some reasonable indicator.

4.3 Uncertainty assessment

4.3.1 Emission factor uncertainties

The emission factors provided in this chapter have been developed based on information collected by the literature review of experimental studies employing various measurement techniques. These include on-road vehicle tests, roadside receptor modelling at urban hot-spots or tunnels, laboratory-based wear simulations, and the application of particle size distributions to known wear rates to estimate the airborne fraction. Each method introduces its own level of uncertainty, particularly due to the variability in test conditions, chemical profiles, and potential interference from particle resuspension. For instance, reported PM emission factors for tyre and brake wear in heavy-duty vehicles vary widely—from no detectable tyre PM emissions in Abu-Allaban et al. (2002) to as much as 160 mg/km of brake wear particles. Discrepancies are also seen in particle size measurements, with Fauser (1999) reporting over 90% of tyre wear PM below 1 μm, while Rauterberg-Wulff (1999) found particles predominantly above 2.5 μm.

More recent efforts to harmonize testing procedures have led to the development of standardized methodologies such as the Global Technical Regulation No. 24 (GTR 24) for brake emissions from light-duty vehicles. Measurements can now be conducted either in laboratories using equipment like Pin-on-Disc (PoD) or brake dynamometers, or directly on vehicles via chassis dynamometers or on-road setups. These tests employ a variety of instruments—ranging from gravimetric filters to optical and electrical particle counters—and are run under different conditions and driving cycles, including the WLTP-Brake (WLTP-B) test designed specifically for non-exhaust emissions. The Euro 7 regulation has adopted the WLTP-B methodology, developed by the UNECE's GRPE working group, as the basis for establishing PM10 brake wear limits.

Given the diversity in test setups and environmental variables, an uncertainty margin of ±50% is generally assumed for most emission factor estimates except for brake emission factors of LDVs for which the uncertainty margin is much lower ±20%. Nevertheless, the use of well-established wear rates, combined with representative size profiles and cross-validation with inventory data and source apportionment studies, lends credibility to the proposed values.

4.3.2 Activity data uncertainties

See Chapter 1.A.3.b Road transport, concerning exhaust emissions from road transport, for comments on uncertainties in vehicle-km data.

4.4 Inventory quality assurance/quality control QA/QC

No specific issues.

4.5 Gridding

Since the emission factors presented in this chapter are global and differentiated only for speed (and load for heavy-duty vehicles), spatial disaggregation mainly refers to activity data. Such discussion is included in the road transport chapter.

4.6 Reporting and documentation

No specific issues.

4.7 Weakest aspects/priority areas for improvement in the current methodology

The following have been identified as weak aspects of the current methodology and, therefore, areas for improvement.

Tyre wear — effects of different tyre and road surface combinations

a) The current methodology is based on experimental data based on a variety of tyre and road surface types. More detailed information is required on the relative effects of different tyre and road surface combinations, including unpaved roads. There are often large discrepancies in the literature varying across a range spanning five orders of magnitude. As soon as more data is available soon extracted with the same harmonized methodology (drum or convoy method), a major update on PM and PN emission factors for tyre wear will be performed.

Road surface wear — conventional tyres

b) The preliminary emission factor values for asphalt wear are highly uncertain. Again, additional experimental information is necessary to establish more precise values.

Road surface wear — studded tyres

c) In some countries, the use of studded tyres results in a high rate of road surface wear, though the effects on airborne particle emissions are not well documented. The literature data indicates high variability in tyre emission factors from studded tyres.

Re-suspended particles

d) A significant weak area is a contribution from the re-suspension of road dust. In ambient and tunnel experiments, it is not possible to distinguish freshly emitted tyre and brake wear aerosol from re-suspended material from the same sources. Inherently, a part of re-suspension is included in the proposed emission factors.

Weather conditions

e) The methodology and the emission factors provided in this chapter have been derived from studies conducted on dry days with dry road conditions. It is obvious that a water layer on the road and a rainy day will result in a significant reduction of airborne particle emissions, especially from brake and road surface wear, because such particles may be trapped by the water.

5 Glossary

Accumulation mode	Particle size ranges from 0.050 to 1 μm which also forms a distinct lognormal distribution. Such particles are usually solids which originate from combustion or very fine abrasion.
Coarse mode	Particle size ranges above 2.5 μm. Such particles may form from mechanical processes (abrasion, grinding, milling, etc.).
Fine particles	Particles in the size range < 2.5 μm ($PM_{2.5}$).
Nuclei mode (also Aitken mode)	Particles in the size range 0.003–0.050 μm forms a distinct log–normal distribution. This mode usually forms by nucleation of condensable species.
Ultra-fine particles	Particles in the size range < 0.1 μm ($PM_{0.1}$).

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7 Point of enquiry

Enquiries concerning this chapter should be directed to the relevant leader(s) of the Task Force on Emission Inventories and Projection's expert panel on Transport. Please refer to the TFEIP website (www.tfeip-secretariat.org) for the contact details of the current expert panel leaders.

Appendix A Techniques used to determine particle emission rates associated with tyre wear, brake wear and road-surface wear

This Appendix describes the techniques used to determine particle emission rates associated with tyre wear, brake wear and road surface wear. A discussion of the various techniques is important in order to explain the wide range of emission rates reported and to aid the understanding of the uncertainties and difficulties associated with estimating PM contributions from non-exhaust sources.

Three main approaches have been used for estimating emission rates:

- the determination of particle emissions by direct measurement using a simulated wheel or brake operation in the laboratory;
- the sampling and analysis of particulate matter in ambient air followed by the application of source apportionment methods (receptor modelling);
- the combination of a size distribution profile with a measured wear rate to estimate emissions of given size ranges.

Currently, no standardized methodology exists for measuring tyre wear, resulting in significant variability and uncertainty in reported data. Tyre wear particle identification has largely relied on controlled laboratory experiments—such as the drum test or chassis dynamometer—and on-road measurement techniques like the convoy method. However, substantial discrepancies exist between these approaches. Laboratory tests often fail to accurately simulate the real-world mechanical stresses at the tyre-road interface, whereas on-road measurements are subject to external influences, including particle resuspension from surrounding traffic, weather conditions, and differences in road texture. As a result, findings across studies often diverge widely, with reported values differing by up to five orders of magnitude, as also confirmed in the literature review conducted for this study.

In the past, receptor modelling was a widely-used technique for determining particle emission rates for different vehicle-related sources, including tyre wear. With this technique, ambient aerosol samples are collected in specific locations (tunnels, street canyons, street junctions, etc.) and are apportioned to different sources using tracer species for identification. Traces used for tyre wear have included zinc or SBR (Fauser, 1999) or a typical tyre material profile (Rauterberg-Wulff, 1999; Abu-Allaban et al., 2003). This method is also termed chemical mass balance (CMB). Following well-structured statistical analyses (e.g. principal components analysis), the contribution from each primary source may be determined by comparing bulk material profiles with relevant contributions of the tracer species to the sample.

The third method is to record wear rates of particles by periodic weighing of tyres, and then to deduce an emission factor by assuming that a fraction of this wear is airborne (*e.g*. Luhana et al.

2002). Ranges for airborne fractions are mostly engineering judgements based on typical emission size profiles derived for tyre debris.

The Particle Measurement Program (PMP), an informal working group of the United Nations Working Party on Pollution and Energy (UNECE – GRPE), developed and standardized a new braking cycle representative of real-world braking events and conditions for light-duty vehicles, the WLTP-Brake cycle (Mathissen et al., 2018). This methodology was standardized in 2023 and is expected to lead to more precise and harmonized emission factor data in the near future.

There are inherent limitations to any of the techniques employed. Receptor modelling should generate accurate emission factors because samples are collected close to roadways. However, the samples obtained are a bulk average from different sources and different vehicles and largely depend on environmental conditions (e.g. wind direction). Another significant problem with this method is that re-suspended particles arising from vehicle-generated turbulence may be included as primary emissions during sampling. On the other hand, laboratory experiments may not fully reproduce real-world vehicle (i.e. tyre or brake) operation, and can only concentrate on a small sample of brake pads or tyre types. Also, the airborne fraction produced depends on the geometry of the dynamometer facility and the sampling conditions utilised.

Differences between these measurement techniques have contributed to the large ranges of particle emission rates reported in the literature.