Category		Title
NFR:	**1.A.3.b.vi** **1.A.3.b.vii**	**Road vehicle tyre and brake wear** **Road surface wear**
SNAP:	**070700** **070800**	**Road vehicle tyre and brake wear** **Road surface wear**
ISIC:		
Version	**Guidebook 2013**	

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Contents

1 Overview

This chapter covers the emissions of particulate matter (PM) 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 as a result of the wear of surfaces — and not those resulting from the resuspension of 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 has to 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 the 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 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 driving style, tyre position, vehicle traction configuration, tyre material properties, tyre and road condition, tyre age, road surface age, and the weather. 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 is experimentally verified, that front tyres show the higher wear rate on a FWD vehicle, and rear tyres on a RWD one. For example, Luhana et al. (2004) reported that front tyres on a 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 retreaded, 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). Obviously, the total amount of material lost during a tyre's lifetime is different for each individual 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. The figure incorporates information provided by Councell et al. (2004), as well as other values from the literature. These values have either been derived experimentally, or have been estimated from average statistics such as those given above. Thefigure 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.

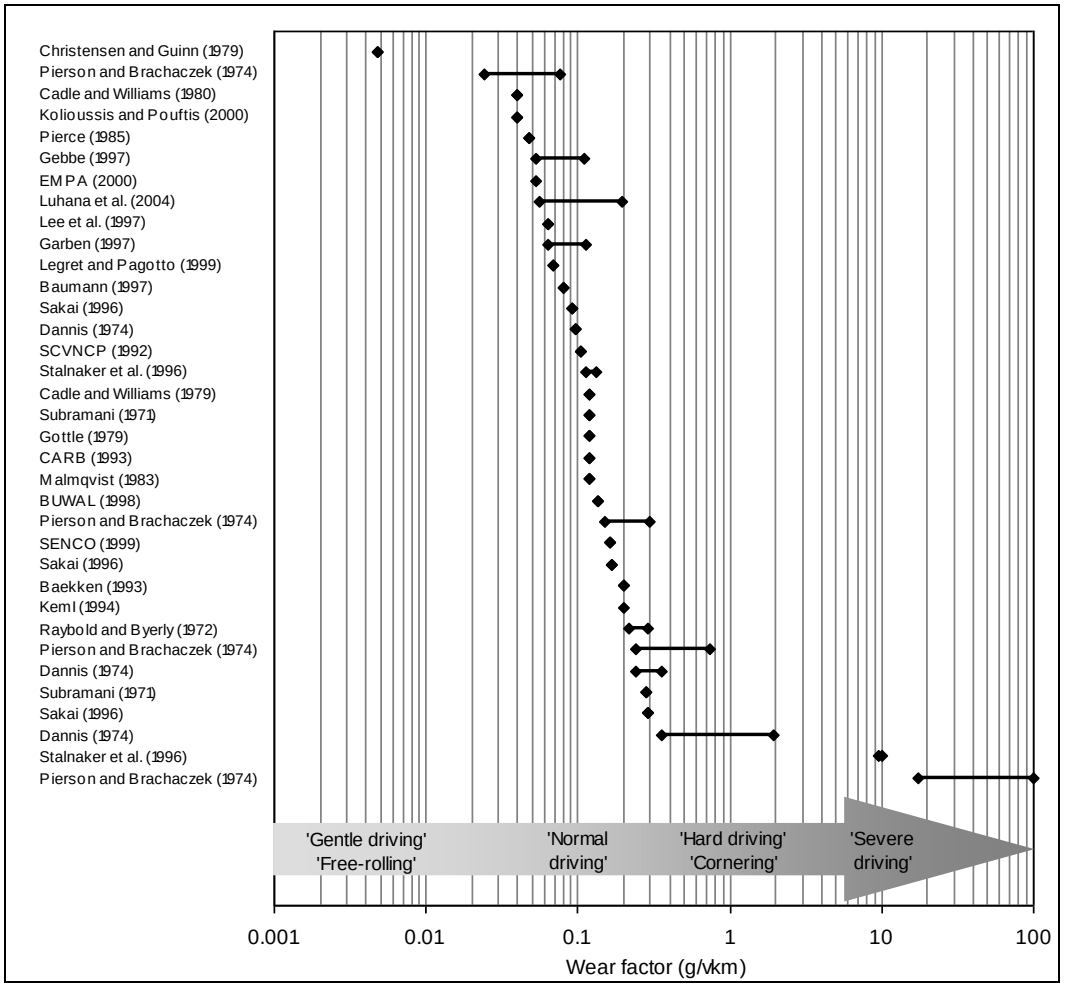

Figure 2-1 Wear factors for light-duty vehicle tyres (Boulter, 2005). 'vkm' = 'vehicle-km'

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' ([1]). Urban driving has been found to be 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 the 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 speed, with the wear

([1]) 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.

factor being around 50 % higher at an average speed of 40 km/h (dominated by urban driving) than at 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

Tyre wear factors are substantially higher for HDVs than for LDVs. 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) reports 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

There are two main brake system configurations in current 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 tend to be used in smaller vehicles (passenger cars and motorcycles) and on the front wheels of light-duty trucks. Traditionally, drum brakes tend to be used in heavier vehicles, although disc brakes are increasingly used in newer heavy-duty vehicles.

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 now been totally removed from the European fleet.

The effect on wear rate of the relative position of brakes on a vehicle is even more important than it is for tyres. 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, the brake pads on the front axle are replaced more frequently (~30 000 km) than the pads on the rear axle (~50 000 km) (Kolioussis and Pouftis, 2000). 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 lifetime of linings. It is expected that for trucks and coaches, the lifetime of brake linings is of the order of 60 000 km.

Garg et al. (2000) estimated that total wear amounts to 11–18 mg/vkm for cars, and for a large pick-up truck it would be 29 mg/vkm. Based on component size, density, and lifetime, Legret and

Pagotto (1999) calculated brake lining ([2]) wear factors of 20 mg/vkm for cars, 29 mg/vkm for light goods vehicles, and 47 mg/vkm for HGVs. In Stockholm, Westerlund (2001) estimated the amount of material lost from cars, HGVs and buses to be 17 mg/vkm, 84 mg/vkm and 110 mg/vkm respectively. For cars, Luhana et al. (2004) determined an average brake lining wear factor of 8.8 mg/vkm, and observed a negative linear dependence of the wear factor on average trip speed. In addition, Luhana et al. (2004) noted that a small number of severe braking events appeared to have a large impact on the amount of material lost. When such events were excluded from the analysis, the typical wear factor was around 10 mg/vkm at 40 km/h, and around 2 mg/vkm at 90 km/h. For HGV tractor units in New Zealand, Kennedy et al. (2002) calculated a wear factor for brake lining material of around 54 mg/vkm.

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.

However, in areas where there is extensive use of studded tyres during the winter, the wear of the road surface, and the resulting PM concentrations due to resuspension, are considerably higher. Indeed, 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 moisture level, and is 2 to 6 times larger for a wet road than for a dry one (Folkeson, 1992). It also increases after salting of the road, since the surface remains wet for longer periods. Vehicle speed,

([2]) It should be noted that the relative wear factors for brake linings and brake rotors are not well documented. In the literature, material loss rates tend to relate to linings.

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).

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 micrometers 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 0.01–30 μm. Other studies have indicated two separate size modes: one consisting of particles below 1 μm, 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.

2.2.2 PM from brake wear

As with tyre wear, not all of the worn brake material will be emitted as airborne PM, although proportionally more it seems in the case of brakes, and a significant proportion as $PM_{2.5}$. However, there is still a large amount of variation in the fraction of total wear mass that can be assumed to be airborne.

Garg et al. (2000) found that, on average, around 35 % of brake wear mass is released as airborne PM. However, this does not take into account sampling losses, and if these were to be included in the study by Garg et al. (2000) the airborne fraction would increase to around 64 % (Sanders et al., 2003). Sanders et al. (2003) conducted detailed laboratory tests using state-of-the-art equipment, and observed that, depending on the severity of the braking, between 50 % and 90 % of the total

wear material was in the form of airborne particles. The collection efficiency for wear debris was between 90 % and 100 % of the wear mass.

Whilst the majority of the fine particulate brake dust from disc brakes is released to the environment, small amounts of brake dust can be retained on the vehicle. According to Lohrer and Mierheim (1983), 10 % of brake dust is retained in the drum brake enclosure. This value appears to be slightly low compared with the observations made by Sanders et al. (2003), whose test track and wind tunnel measurements revealed that typically 50 % of the brake wear debris escapes the vehicle and enters the atmosphere. It was also found that 3–30 % of brake debris falls on the road, 16–22 % is retained on the wheel, and 8–25 % is retained on the brake and steering/suspension equipment, but the exact proportions will vary from vehicle to vehicle depending on the design and operating conditions. When low-metallic brake linings were used, 60 % of the wear debris was found to originate from the disc and 40 % from the linings, a result which could have implications concerning the interpretation of the results of studies which have only considered the brake linings.

Under controlled laboratory conditions, Cha et al. (1983) found that the diameters of airborne particles and deposited dust were generally similar, with a peak in the particle size distribution at 2.1-3.3 μm and around 10 % of particles in the sub-micron size range. The percentage of airborne particles was found to increase with vehicle speed. Data from the US Environmental Protection Agency (USEPA,1995) and Berdowski et al. (1997) indicated that 98 % (by mass) of airborne brake wear particles can be classified as PM_{10}, whilst around 40 % of the PM_{10} is $PM_{2.5}$, 10 % is PM_1, and 8 % is $PM_{0.1}$. Garg et al. (2000) recorded airborne brake wear particle mass fractions smaller than 10 μm, 2.5 μm, and 0.1 μm of 88 %, 63 % and 33 % respectively. Sanders et al. (2003) gave PM_{10} and PM_1 proportions of 80 % and 2 %. Different size distributions have been obtained elsewhere. Receptor modelling work by Abu-Allaban et al. (2003), using PM_{10} and $PM_{2.5}$ measurements, showed that the brake wear contribution was observed mainly in the PM_{10} fraction, and that the $PM_{2.5}$ share of PM_{10} was only 5-17 %. In any case, it appears that under normal driving conditions most airborne brake wear particles can be classified as PM_{10}, and a substantial proportion as $PM_{2.5}$. The mass mean diameter of brake wear debris reported by Garg et al. (2000) varied between 0.7 and 2.5 μm. It is possible that the high temperatures generated during braking can vaporise some of the brake pad material, and Garg et al. (2000) suggested that the volatile material may condense during measurement and contribute to the fine particle fraction. For three different types of brake lining, Sanders et al. (2003) observed a consistent mass-weighted size mean diameter over an urban driving cycle of around 5–6 μm. Under harsh braking conditions, the mass mean diameter was closer to 10 μm, and it was considered possible than a significant proportion of the wear debris could have been larger than 20 μm in diameter.

With regard to its chemical composition, brake wear material largely depends on the manufacturer, the application (car, truck, etc.) and the desired properties of the brake pads. Pads are expected to consist mainly of metals bound together with Si-based materials. Analyses by Legret and Pagotto (1999) and Hildemann et al. (1991) have shown a Fe contribution up to 46 %, Cu content of up to 14 %, organic material in the order of 13 %, and then several other metals, including Pb (~4 %), Zn (~2 %), Ca, Ba.

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 % by weight of airborne particles from bitumen range 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.

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

From 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. There is no other legislation which deals specifically with PM emissions from tyres and brakes. Currently, efforts are focussing on the development of low-friction tyres for fuel consumption and CO_2 benefits. Such tyres might also result in lower emissions of particles.

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

It was estimated by CEPMEIP (2003) that tyre wear, brake wear and road surface wear contributed 24.7 % of TSP for the EU-15. However, the particle size distribution for each of these sources was assumed to be dominated by coarse particles, in contrast with vehicle exhaust emissions, such that this sector contributed substantially less to PM_{10} and $PM_{2.5}$ (3.1 % and 1.7 % respectively). In addition, the Coordinated European Particulate Matter Emission Inventory Program (CEPMEIP) assumed that all tyre wear material became airborne PM.

However, this relatively small contribution from non-exhaust sources to PM_{10} emissions has not been observed universally. For example, according to Rauterberg-Wulff (1999) tyre wear was responsible for an annual PM_{10} emission in Germany of 56–98 kt, whereas diesel exhaust emissions were responsible for around 76 kt of PM_{10}. This would suggest that non-exhaust sources may be as significant as exhaust sources. Such variation in estimated annual emissions is likely to be due to the use of different methodological approaches, emission factors, and assumptions.

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 US (Venkatram, 2000). Moreover, the UK Airborne Particle Expert Group (APEG, 1999) considers the model unsuitable for UK conditions and, to enable the model to be used in Berlin, Düring et al. (2002) had to fully recalibrate it on the basis of local experimental data. 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.

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 by the chapter were derived using the information available in the literature and a number of assumptions. More information can be found at the following web site: http://vergina.eng.auth.gr/mech0/lat/PM10/.

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 it is probable that 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.

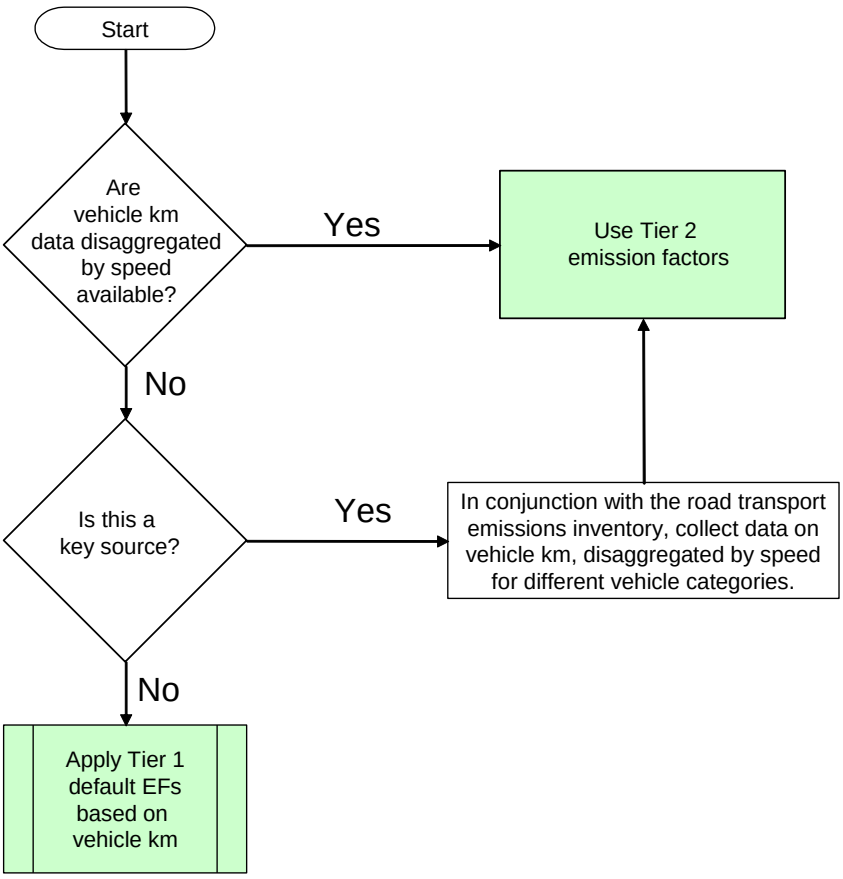

Figure 3-1 Decision tree for vehicle tyre and brake wear and road surface wear

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.

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

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 Note: **BC**: For two-wheelers, passenger cars, light duty trucks and heavy duty vehicles, the following BC fractions of PM (f-BC) are proposed: 0.12, 0.10, 0.10 and 0.10, c.f. Appendix B.

Table 3-2 provide the emission factors for TSP, PM_{10} and $PM_{2.5}$ and for 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				
				95% confidence interval		
Pollutant	**Vehicle type**	**Value**	**Unit**	**Lower**	**Upper**	**Reference**
TSP	Two-wheelers	0.0083	g km^{-1} $vehicle^{-1}$	0.0064	0.0103	EMEP-Corinair B770 v1.0
PM_{10}	Two-wheelers	0.0064	g km^{-1} $vehicle^{-1}$	0.0047	0.0081	EMEP-Corinair B770 v1.0
$PM_{2.5}$	Two-wheelers	0.0034	g km^{-1} $vehicle^{-1}$	0.0026	0.0042	EMEP-Corinair B770 v1.0
TSP	Passenger cars	0.0182	g km^{-1} $vehicle^{-1}$	0.0111	0.0262	EMEP-Corinair B770 v1.0
PM_{10}	Passenger cars	0.0138	g km^{-1} $vehicle^{-1}$	0.0083	0.0195	EMEP-Corinair B770 v1.0
$PM_{2.5}$	Passenger cars	0.0074	g km^{-1} $vehicle^{-1}$	0.0045	0.0107	EMEP-Corinair B770 v1.0
TSP	Light duty trucks	0.0286	g km^{-1} $vehicle^{-1}$	0.0176	0.0362	EMEP-Corinair B770 v1.0
PM_{10}	Light duty trucks	0.0216	g km^{-1} $vehicle^{-1}$	0.0139	0.0272	EMEP-Corinair B770 v1.0
$PM_{2.5}$	Light duty trucks	0.0117	g km^{-1} $vehicle^{-1}$	0.0071	0.0148	EMEP-Corinair B770 v1.0
TSP	Heavy duty vehicles	0.0777	g km^{-1} $vehicle^{-1}$	0.0462	0.1318	EMEP-Corinair B770 v1.0
PM_{10}	Heavy duty vehicles	0.0590	g km^{-1} $vehicle^{-1}$	0.0500	0.0950	EMEP-Corinair B770 v1.0
$PM_{2.5}$	Heavy duty vehicles	0.0316	g km^{-1} $vehicle^{-1}$	0.0281	0.0541	EMEP-Corinair B770 v1.0
Not estimated: PAHs, POPs, HCB, PCBs, dioxins and furans. 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 emission 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.						

Note: **BC**: For two-wheelers, passenger cars, light duty trucks and heavy duty vehicles, the following BC fractions of PM (f-BC) are proposed: 0.12, 0.10, 0.10 and 0.10, c.f. Appendix B.

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				
				95% confidence interval		
Pollutant	**Vehicle type**	**Value**	**Unit**	**Lower**	**Upper**	**Reference**
TSP	Two-wheelers	0.0060	g km^{-1} $vehicle^{-1}$	0.0036	0.0081	EMEP-Corinair B770 v1.0
PM_{10}	Two-wheelers	0.0030	g km^{-1} $vehicle^{-1}$	0.0018	0.0041	EMEP-Corinair B770 v1.0
$PM_{2.5}$	Two-wheelers	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
PM_{10}	Passenger cars	0.0075	g km^{-1} $vehicle^{-1}$	0.0045	0.0101	EMEP-Corinair B770 v1.0
$PM_{2.5}$	Passenger cars	0.0041	g km^{-1} $vehicle^{-1}$	0.0024	0.0055	EMEP-Corinair B770 v1.0
TSP	Light duty trucks	0.0150	g km^{-1} $vehicle^{-1}$	0.0090	0.0203	EMEP-Corinair B770 v1.0
PM_{10}	Light duty trucks	0.0075	g km^{-1} $vehicle^{-1}$	0.0045	0.0101	EMEP-Corinair B770 v1.0
$PM_{2.5}$	Light duty trucks	0.0041	g km^{-1} $vehicle^{-1}$	0.0024	0.0055	EMEP-Corinair B770 v1.0
TSP	Heavy duty vehicles	0.0760	g km^{-1} $vehicle^{-1}$	0.0456	0.1026	EMEP-Corinair B770 v1.0
PM_{10}	Heavy duty vehicles	0.0380	g km^{-1} $vehicle^{-1}$	0.0228	0.0513	EMEP-Corinair B770 v1.0
$PM_{2.5}$	Heavy duty vehicles	0.0205	g km^{-1} $vehicle^{-1}$	0.0123	0.0277	EMEP-Corinair B770 v1.0
Not estimated: PAHs, POPs, HCB, PCBs, dioxins and furans. Due to the relatively low chlorine content of asphalt (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 emission of any of these species is expected. Therefore, no emission factors are proposed for Tier 1.						

For comparative purposes, it is worth noting that the exhaust PM emission factors are generally considerably higher (typically 0.060 g/km for two-wheel, two-stroke vehicles, 0.040 g/km for diesel passenger cars, 0.080 g/km for diesel light-duty trucks and 0.30 g/km for diesel heavy vehicles).

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 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:

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

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

3.3.2.1 Emission factors for tyre wear

TSP emission factors for different vehicle classes are given in Table 3–3. 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).

Table 3-3 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	0.0107	0.0067–0.0162	B
Light-duty trucks	0.0169	0.0088–0.0217	B
Heavy-duty vehicles	Equation 3	0.0227–0.0898	B–C

Note:
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.
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,

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 the 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 3–4. 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 3-4 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 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:

$$\begin{aligned} &V < 40 \text{ km/h:} && S_T(V) = 1.39 \\ &40 \text{ km/h} \le V \le 90 \text{ km/h:} && S_T(V) = -0.00974 \cdot V + 1.78 \\ &V > 90 \text{ km/h:} && S_T(V) = 0.902 \end{aligned} \quad (5)$$

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.

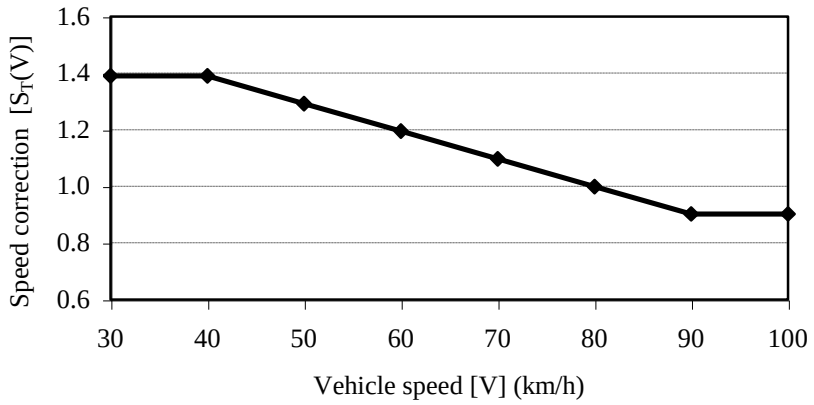

Figure 3–-2 Speed correction factor for tyre wear particle emissions

3.3.2.2 Emission factors for brake wear

The TSP emission factors for brake wear particles are given in Table 3–5, together with the range and a quality code for the emission factor.

Table 3-5 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)	Quality code
Two-wheel vehicles	0.0037	0.0022 – 0.0050	D
Passenger cars	0.0075	0.0044 – 0.0100	B
Light-duty trucks	0.0117	0.0088 – 0.0145	B
Heavy-duty vehicles	Equation 6	0.0235 – 0.0420	B–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 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.

The heavy-duty vehicle emission factor is calculated by adjusting the passenger car emission factor to fit heavy-duty vehicle experimental data:

$$EF_{TSP,B,HDV} = 3.13 \cdot LCF_B \cdot EF_{TSP,B,PC} \quad (6)$$

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 3–6.

Table 3-6 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.

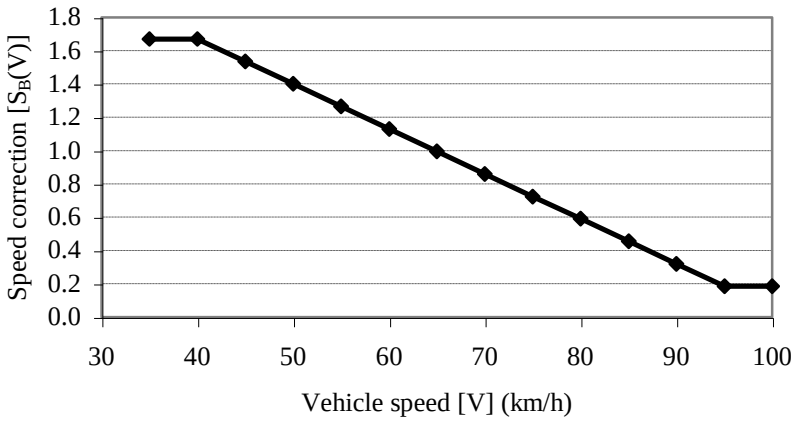

Figure 3–3 Speed correction factor for brake wear particle emissions

$$\begin{aligned} &V < 40 \text{ km/h:} && S_B(V) = 1.67 \\ &40 \text{ km/h} \le V \le 95 \text{ km/h:} && S_B(V) = -0.0270 \cdot V + 2.75 \\ &V > 95 \text{ km/h:} && S_B(V) = 0.185 \end{aligned} \quad (8)$$

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:

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

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 based on the work of Klimont et al. (2002). Preliminary TSP emission factors for road surface wear are shown in Table 3–7. 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 3–8.

Table 3-7 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	0.0150	C–D
Light-duty trucks	0.0150	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 applying similarity considerations and/or extrapolation.

Table 3-8 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

Due to the lack of appropriate experimental data, no emission factors are included for road surface wear associated with the use of studded tyres, although it is recognised that in some countries this may be an important particle source.

3.3.4 Abatement

Technology abatement approach not relevant for 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 for 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 3–9).

Table 3-9 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 different 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 break in As, Cd, Cr, Ni, and Pb was revised with information that came by revisiting the Espreme emission factors (Kummer, U., 2008).

Table 3-10 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) 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, 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 needs 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 on the basis of information collected by literature review. The experimental data were generally obtained using three different methods:

- by roadside receptor modelling at urban pollution hot-spots or in road tunnels;
- by airborne particle and wear factor determination in laboratory experiments;
- by applying a size distribution to wear factors in order to derive the airborne fraction..

Obviously, there is a significant uncertainty associated with each of these methods. In the case of receptor modelling, the chemical profile used is of large importance, and artefacts from re-suspension may significantly modify the emission factors. For example, Abu-Allaban et al. (2002) identified no airborne particles from tyre wear, and up to 160 mg/km particulate mass from brake wear for heavy-duty vehicles. On the other hand, Rauterberg-Wulff (1999) determined up to 32 mg/km tyre wear particles from heavy-duty vehicles. The uncertainties are similar for the other methods. For example, Fauser (1999) reported that more than 90 % of airborne tyre wear is less than 1 μm in diameter. In contrast, Rauterberg-Wulff (1999) found airborne tyre particles only above 2.5 μm diameter. Several such diverse effects apply also to chemical speciation (Tables 3–9 and 3–10). Of course, these are extreme examples, but they do provide a frame of reference for the uncertainty associated with the proposed methodology.

The emission factors used here are typical of the values in the available literature, and an uncertainty range is given next to each emission factor value in the relevant tables.

A solid point for cross-checking of the methodology is the wear factors for tyres and brakes, which are rather well established values. Therefore, the application of typical size profiles to these wear factors (method 3 in the list above) may also provide a reasonable emission factor value for comparison. The emission factor values proposed in this chapter have also been cross-checked with inventory activities (e.g. Flugsrud et al., 2000) and source apportionment investigations (e.g. Schauer et al., 2002). As a rule of thumb, an uncertainty in the order of ± 50 % is expected.

4.3.2 Activity data uncertainties

See the 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, 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 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

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.

Road surface wear — conventional tyres

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

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. Due to the lack of appropriate experimental data, no emission factors have been included for studded tyres, although it is recognised that this may be an important particle source.

Re-suspended particles

A significant weak area is the 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

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 range 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 range 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 which form 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.

The real-world performance of a tyre is difficult to simulate in the laboratory and, therefore, direct measurement of particle emissions is problematic. Early studies (Cardina, 1974; Dannis, 1974; Cadle and Williams, 1978) used laboratory-based techniques to identify particle characteristics, such as size distributions. More recently, Camatini et al. (2001) used a rotating drum method to simulate tyre wear in order to study the morphology and speciation of emitted particles.

Receptor modelling is a more 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.

In principle, the same techniques are also used to determine emission factors for brake and road surface wear. In the case of brake particles, the simulation of brake operation in the laboratory is more straightforward, and brake-wear emission factors have been directly determined this way. For example, Garg et al. (2000) and Sanders et al. (2002) have utilised closed-chamber dynamometers to collect dustfall particles, with airborne particles being sampled using filters, impactors and aerosol analysis instrumentation.

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.

Appendix B BC fractions of PM emissions for road transport tyre and brake wear and road abrasion

In the guidebook chapter for tyre and brake wear and road abrasion, data for BC fractions of PM emissions (f-BC) for the wear related emissions from tyres and brakes is included where relevant. The f-BC data are identical to the data proposed by Kupiainen and Klimont (2004), based on reported data from Hildemann et al. (1991), Garg et al. (2000), Chow et al. (1994) and Kupiainen et al. (2002). Tables also present data for OC identical to those from Kupiainen and Klimont (2004), which can be used as input for the further assessment of OC fractions of PM (f-OC). For road asphalt wear no data is available from the literature.

Table B.1 Proposed f-BC fractions for wear related emissions from road transport

Category	f-BC	+/- uncertainty (%)
Brake wear	0.0261	50
Tyre wear	0.153	50
Road abrasion	n.d.	-

Tier 1
Table 3-1 in the guidebook chapter for tyre and brake wear and road abrasion contains Tier 1 PM emission factors aggregated for tyre and brake wear. Tier 1 PM emission factors for road abrasion are given in Table 3-2. The PM size fractions TSP, PM_{10} and $PM_{2.5}$ (Tables 3-4, 3-6 and 3-8) are considered, and separate PM factors are given for two-wheelers, passenger cars, light duty vehicles and heavy duty vehicles.

To be consistent with this level of wear related PM emission factors, the Tier 1 f-BC fractions shown in Table 2 were derived from COPERT calculations made for the Danish fleet in 1995 (Winther, 2012). The Tier 1 f-BC fractions of PM can be used in combination with the PM emission factors irrespective of PM size range.

Table B.2: Tier 1 f-BC fractions of PM for non exhaust

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

Tier 2
For Tier 2 the proposed f-BC fractions from Table 1 can be used in connection with the TSP emission factors shown in the Tables 3-3, 3-5 and 3-7 for tyre wear, brake wear and road abrasion, respectively, in order to estimate the total BC emissions.

Further, the proposed f-BC values presented in Table 1 are used for all particulate size fractions; TSP, PM_{10} and $PM_{2.5}$, in order to estimate the BC emissions relating to the different particulate size fractions.

Appendix B References

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