SNAP CODE: **070700**
070800

SOURCE ACTIVITY TITLE: **ROAD VEHICLE TYRE & BRAKE WEAR**
ROAD SURFACE WEAR

NOSE CODE: **201.07**
201.08

NFR CODE: **1 A 3 b vi**
1 A 3 b vii

1 ACTIVITIES INCLUDED

This Chapter covers the emissions of airborne particulate matter (PM) from road transport which are due to vehicle tyre and brake wear (SNAP code 070700) and road surface wear (SNAP code 070800). PM emissions from vehicle exhaust are not included. The focus is on primary non-exhaust 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. The sources of such PM emissions are considered in relation to the general vehicle classes identified in the Road Transport Chapter of the Guidebook (SNAPS 0701-0705), these being passenger cars, light-duty trucks, heavy-duty vehicles and two-wheelers.

2 CONTRIBUTIONS TO TOTAL EMISSIONS

Table 1 presents total emissions of particulate matter (PM_{10}, $PM_{2.5}$ and TSP) in European Union countries (CEPMEIP, 2003). According to CEPMEIP, non-exhaust sources contribute 3.1% and 1.7% of total PM_{10} and $PM_{2.5}$ respectively at the EU15 level. The contribution of non-exhaust sources to TSP is much larger than the contributions to the finer particle fractions because CEPMEIP assumes that all tyre wear material becomes airborne PM. The validity of this assumption is examined later in this Chapter.

The estimation of the non-exhaust contribution to total PM emissions depends upon the emission factors selected for tyre wear, brake wear and road surface wear. However, the emission factors for these sources are rather uncertain, and the following brief discussion has been included here to justify *a priori* the large variability which has been reported for the contribution of non-exhaust sources to total PM in urban and national inventories.

In 1999 more than 54 million passenger car tyres were used in the UK, equating to a total weight of more than 430,000 tonnes (Used Tyre Working Group, 2000). A new passenger car tyre weighs around 8 kg, and loses roughly 1-1.5kg in weight during its service lifetime, which is typically around 3 years. Thus, between around 10% and 20% of the rubber which goes into a tyre will disappear before the tyre is ready to scrap (Environment Agency, 1998). Based on the upper estimate for rubber loss of 20%, a simple calculation reveals that around 90 kilotonnes (kt) of tyre material could have been lost to the UK environment during 1999, mainly as a result of in-service wear. The value can be compared with the estimated annual release of tyre debris in the US during the 1970s of 500 kt, and the 40 kt released in Italy in 1991 (Camatini *et al*., 2001).

Table 1: Total airborne particle emissions from CEPMEIP for EU15 Member States and grand average. Row ‘Tyre & Brake & Road’ corresponds to the non-exhaust particles sources covered in this Chapter, ‘Road Transport’ relates to both exhaust and non-exhaust emissions, and ‘National Total’ relates to all national sources, not covering international aviation and bunkers. Percentages are given as a fraction of the National Total.

Country	Source	PM10 [kt]	PM2.5 [kt]	TSP [kt]	%PM10	%PM2.5	%TSP
Austria	Tyre & Brake & Road	1.6	0.6	22.1	3.5	1.8	26.7
	Road Transport	7.5	6.5	28.0	16.3	19.5	33.8
	National Total	46.2	33.5	82.7			
Belgium	Tyre & Brake & Road	2.3	0.9	31.1	2.7	1.5	21.8
	Road Transport	12.6	11.2	41.4	14.9	19.5	29.0
	National Total	84.1	57.1	142.7			
Denmark	Tyre & Brake & Road	1.1	0.4	14.7	3.2	1.7	24.0
	Road Transport	5.4	4.7	19.0	16.2	20.1	31.0
	National Total	33.0	23.3	61.2			
Finland	Tyre & Brake & Road	0.7	0.3	10.3	2.5	1.3	20.5
	Road Transport	4.4	3.5	23.4	14.6	15.8	46.8
	National Total	30.0	22.0	50.0			
France	Tyre & Brake & Road	10.1	3.8	138.3	2.2	1.1	20.0
	Road Transport	60.9	54.6	189.1	13.5	15.6	27.3
	National Total	449.7	350.6	693.3			
Germany	Tyre & Brake & Road	14.7	5.6	202.3	4.4	2.6	29.5
	Road Transport	69.0	59.9	256.6	20.6	27.6	37.4
	National Total	335.3	217.1	685.8			
Greece	Tyre & Brake & Road	1.5	0.6	20.9	2.4	1.4	21.5
	Road Transport	9.2	8.2	28.6	14.7	19.6	29.4
	National Total	62.4	41.9	97.2			
Ireland	Tyre & Brake & Road	0.6	0.2	7.7	2.5	1.7	16.6
	Road Transport	2.5	2.2	9.7	11.2	17.1	20.8
	National Total	22.7	12.8	46.5			
Italy	Tyre & Brake & Road	10.1	3.8	139.4	3.2	1.7	26.9
	Road Transport	57.2	50.9	186.4	17.9	21.9	36.0
	National Total	319.3	232.3	518.3			
Luxembourg	Tyre & Brake & Road	0.1	0.0	1.6	2.3	1.6	18.3
	Road Transport	0.6	0.5	2.1	11.1	17.9	23.4
	National Total	5.2	2.8	9.0			
Netherlands	Tyre & Brake & Road	2.4	0.9	32.5	3.7	2.1	25.5
	Road Transport	11.9	10.4	42.1	18.5	25.2	33.0
	National Total	64.4	41.4	127.3			
Portugal	Tyre & Brake & Road	1.4	0.5	19.4	2.7	1.4	23.9
	Road	7.9	7.1	25.9	15.5	19.1	32.0
	National Total	51.0	37.0	81.0			
Spain	Tyre & Brake & Road	6.2	2.3	85.6	2.8	1.5	23.3
	Road	42.8	38.9	122.1	19.0	24.5	33.3
	National Total	225.6	158.5	366.5			
Sweden	Tyre & Brake & Road	1.6	0.6	22.0	3.8	2.0	28.6
	Road	7.5	6.5	27.9	17.8	21.9	36.2
	National Total	42.1	29.7	77.1			
UK	Tyre & Brake & Road	8.7	3.3	118.5	3.3	2.0	25.0
	Road	38.7	33.3	148.6	14.9	20.3	31.4
	All	259.6	164.4	473.4			
EU15	Tyre & Brake & Road	63.1	23.9	866.5	3.1	1.7	24.7
	Road Transport	338.1	298.4	1150.9	16.6	20.9	32.8
	Int. Total	2030.6	1424.4	3512.0			

It should be noted that these values relate to total dustfall debris, and not just respirable PM. In the UK National Atmospheric Emissions Inventory, it is estimated that over 80% of respirable PM in cities comes from road transport (Goodwin *et al*., 2002), although non-exhaust sources (tyre and brake wear) were responsible for the emission of just 5 kt of PM_{10} in UK in 2000, compared with the 26 kt from exhaust emissions, and represent just 3% of total PM_{10}. 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 is responsible for annual PM_{10} emissions in Germany of 56-98 kt, whereas diesel exhaust emissions are 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. In this Chapter, a methodology is proposed which provides a common basis for calculating and comparing non-exhaust particle emissions in different countries.

Resuspended particulate matter also contributes to the PM concentrations recorded by ambient air samplers, though resuspension 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.

3 SOURCE DESCRIPTION AND DEFINITION

Airborne particles are produced as a result of the interaction between a vehicle's tyre 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.

3.1 Tyre and road surface 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 aggregate particles.

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 appropriate experimental data on the emission rates associated with different tyre-road surface combinations.

The actual rate of tyre wear rate depends on a large number of factors, including driving style, tyre position, vehicle traction configuration, bulk surface material properties, tyre and road condition, tyre age, road surface age, and the weather.

For example, driving pattern has a significant effect on 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. Urban driving has been found to be associated with a high wear rate per unit distance. For example, Stalnaker *et al*. (1996) compared urban driving with Motorway driving, and found out that the wear rate associated with the former may be as much as 30 times greater than the wear rate associated with the latter.

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. Warner *et al*. (2002) report that front tyres on a FWD vehicle accounted for 69-85% of total vehicle tyre wear while on a RWD vehicle there was an equal contribution from each axle. High wear rates may also occur due to steering system misalignment. The most common effect is high peripheral wear of low pressure tyres, and unbalanced wear caused by improper steering system setting (wheel toe-in, camber and caster).

The physical characteristics of the tyre tread material have a prominent effect on tyre wear rate. In general, high performance tyres, such as those used in superbikes and sports passenger 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 – 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 hundreds of grams for two wheelers to 1-1.5 kg for passenger cars and up to 10 kg for a truck or bus. Table 2 provides a list of wear rates collected from the literature.

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

Table 2: Tyre wear rates found in the literature

Remarks	**Value / Range(1)**	**Source**
Average tyre wear rate for FWD car (meas.)	79 mg/vkm	Warner *et al.* (2002)
Average tyre wear rate for RWD car (meas.)	193 mg/vkm	
Average tyre wear for a vehicle (meas.)	97 mg/vkm	
Front tyre for FWD vehicle (meas.)	28 mg/tyre/km	
Rear tyre for FWD vehicle (meas.)	8 mg/tyre/km	
Front tyre for RWD vehicle (meas.)	50 mg/tyre/km	
Rear tyre for RWD vehicle (meas.)	47 mg/tyre/km	
Tyre wear rate (est.)	30 mg/tyre/km	Gottle (1979)
Tyre wear rate (est.)	30 mg/tyre/km	Malmqvist (1983)
Tyre wear rate (est.)	60-90 mg/tyre/km	Dannis (1974)
Tyre wear rate (est.)	50 mg/tyre/km	Baekken (1993)
Tyre wear rate (est.)	16 mg/tyre/km	Lee *et al*. (1997)
Tyre wear rate for light vehicles (est.)	17 mg/tyre/km	Legret and Pagotto (1999)
Tyre wear rate for heavy vehicles (>3.5t) (est.)	34 mg/tyre/km	
Tyre wear rate	53 mg/vkm	Gebbe (1997)
Passenger car tyre wear rate	120 mg/vkm	CARB (1993)
Tyre wear for car <1400cc (meas.)	36 mg/vkm	Kolioussis and Pouftis (2000)
Tyre wear for car 1400-2000cc (meas.)	40 mg/vkm	
Tyre wear for car >2000cc (meas.)	46 mg/vkm	
Average estimated tyre wear (meas.)	40 mg/vkm	

(1) Note that ranges are stated either in mg/ vehicle-km or mg/ tyre-km. "Meas." is a direct measurement by weighing of tyres while "Est." is an estimation based on statistical data and manufacturer information.

As a vehicle moves, the road surface is also being worn at the tyre-road interface, and this wear material contributes to total particle emissions from road transport. A range of asphalt-based and concrete-based road surfacings are in use throughout Europe, with block paving being used in many urban areas. Concrete surfacings are composed of coarse aggregate, sand and cement. Asphalts are mixtures of mineral aggregate, sands, filler, and bitumen binder, though 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.

In areas where there is extensive use of studded tyres during winter, the wear of the road surface increases considerably. In Norway, the use of studded tyres is thought to be responsible for the wear of around 250,000 tonnes of asphalt per year (NILU, 1996).

3.2 Brake wear

Brakes are used to decelerate a vehicle. 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 in the front wheels of light-duty trucks, whereas drum brakes tend to be used in heavier vehicles.

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 the 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 developed in the front wheels, whilst braking in the rear axle is applied only for 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 to different 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 pad lifetime. It is expected that for trucks and coaches, pad lifetime is of the order of 60,000 km. Table 3 provides a summary of brake wear rates found in the literature.

Table 3: Brake wear rates found in the literature

Remarks	Value	Method	Source
Brake wear of brake linings for passenger cars	20 mg/vkm	Estimation of wear for typical brake linings using manufacturer information	Legret and Pagotto (1999)
Brake wear of brake linings for light goods vehicles	29 mg/vkm		
Brake wear of brake linings for heavy lorries	47 mg/vkm		
Total brake wear for a small car	11 mg/vkm	Estimation of brake wear using the following data: (1) Average weight of brake's friction material, (2) lifetime of front and rear brakes under normal usage in km, (3) average percentage of mass loss, which is 80%.	Garg *et al.* (2000)
Total brake wear for a large car	17 mg/vkm		
Total brake wear for a pick-up truck	29 mg/vkm		
Average amount of brake material lost	8.8 mg/vkm	Gravimetric measurement of brake wear (brakes of 5 test vehicles -passenger cars- were weighed and mass loss was calculated)	Warner *et al.* (2002)
Material lost for passenger cars	17 mg/vkm	-	Westerlund, K-G (2001)
Material lost for heavy goods vehicles	84 mg/vkm		

3.3 Definitions

The following definitions are used in this Chapter in relation to airborne particulate matter:

- PM_x: Particulate matter which is collected by ambient samplers with a retention efficiency of 50% for particles of x µm aerodynamic diameter. For example, PM_{10} corresponds to all particles collected in an ambient sampler with a 50% cut-off at 10 µm. Particles smaller than PM_{10} comprise the "respirable" fraction which penetrates the nasal region.

- TSP: Total Suspended Particles. The definition of TSP is rather equivocal, since the residence time of particles in the atmosphere is a function of their size. Practically, particles larger than 50-100 µm have residence times of only seconds to minutes (depending on turbulence), and are generally considered as dustfall. Hence, only sizes up to 100 µm may generally be considered as TSP.

- Fine particles: Particles in the size range <2.5 µm ($PM_{2.5}$).

- Ultrafine particles: Particles in the size range <0.1 µm ($PM_{0.1}$).

- 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.

- 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.).

3.4 Techniques

This Section 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) have 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, 2002). 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 resuspended 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.

3.5 Emissions

3.5.1 Particles 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 agglomerated to particle sizes up to a few hundred micrometers. 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 (1979) 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 in a more recent study (Fauser, 1999). A plausible mechanism for the distinction is the volatilisation and subsequent condensation of material in the ultrafine 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). More recently, a 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, information from Miguel *et al*. (1999) may be used to estimate a TSP contribution from tyre wear. This investigation identified that 50-70 % of the airborne-sized road dust may be classified as PM_{10}. By extrapolation, this value may also be used to estimate an approximate TSP/PM_{10} ratio for tyre wear. A summary of the size-related studies is provided in Table 4.

Table 4: Summary of particle size information from tyre wear

Value / Range	Source
0.01µm to 30µm	Cadle and Williams (1979)
Smaller than 1µm or larger than ~7µm	Cardina (1974); Dannis (1974); Pierson and Brachaczek (1974); Cadle and Williams (1978); Fauser (1999)
Only 10% by mass of tyre wear particles are smaller than 3µm	Pierson and Brachaczek (1974)
Larger sizes of PM_{10} dominate the total mass	Cadle and Williams (1979)
90% by mass of tyre wear particles are PM_1	Fauser (1999)
Tyre wear particles were only found in the coarse mode fraction (2,5µm to 10µm)	Rauterberg-Wulff (1999)
70% by mass of tyre wear PM_{10} are $PM_{2.5}$, 10% are PM_1 and 8% are $PM_{0.1}$	USEPA (1995); TNO (1997)
50-70% of total airborne-sized road dust may be classified as PM_{10}	Miguel *et al.* (1999)

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

3.5.2 Particles from brake wear

The ability to measure particle emission rates from brake wear in the laboratory has also provided valuable information on the characteristics of such particles. However, there is still a large amount of variation in the fraction of total wear mass that can be assumed to be airborne. USEPA (1995) and TNO (1997) indicate that 98% by mass of wear particles can be classified as PM_{10}. On the other extent, Garg *et al*. (2000) performed laboratory tests with a number of pad types and brake systems, and found out that the airborne fraction corresponds to 16-35% of total wear, with the percentage increasing as temperature decreases. Even more recently, Sanders *et al*. (2002) conducted detailed laboratory tests, and observed that 55-70% of the total wear material was in the form of airborne particles. In this study the collection efficiency for wear debris was 90-100% of the wear mass, and the investigators used a state-of-art experimental setup. The same study identified 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 and suspension equipment.

The size distribution of airborne brake wear particles is also rather uncertain. Sanders *et al*. (2002) quote earlier studies in which the average size of wear debris was in the 1-3 μm region. USEPA (1995) and TNO (1997) indicate that PM_{10} can be classified as 40% $PM_{2.5}$, 10% PM_1 and 8% $PM_{0.1}$. Garg *et al*. (2000) found a much higher fraction attributable to the ultrafine range, and noted that 88% of TSP can be classified as PM_{10}, 63% as $PM_{1.5}$ and 33% as $PM_{0.1}$. By sampling at the roadside and using chemical mass balance for receptor modelling, Abu-Allaban (2002) estimated that $PM_{2.5}$ share is only 5-17% of the total PM_{10} brake wear. The ranges reported also reveal the uncertainties of the different methods.

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.

3.5.3 Particles from road surface wear

The wear rate of asphalt, at least in terms of airborne wear particles, is even more difficult to quantify than tyre and brake wear, partly because the chemical composition of bitumen is too complex for quantification with CMB, and partly because primary wear particles mix with road dust and resuspended material. Therefore, wear rates and particle emission rates for road surfaces are highly uncertain. Muschack (1990) reports an asphalt wear rate of 3.8 mg/km per vehicle kilometre. Work in Scandinavia suggests that studded winter tyres result in a much higher wear rate, producing 11-24 g/km of asphalt wear per vehicle in dry weather (Lindgren, 1996). 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.

The problem of quantifying particle emissions arising from road surface wear has been also tackled by Lükewille *et al.* (2002), who propose preliminary emission factor values. These preliminary values have been adopted in this Chapter.

3.6 Controls

From 1999, European Directive 98/12/EC enforced asbestos-free brake pads for all road vehicles. This has had no direct effect on the emission rate of brake debris, only on the chemical composition of the associated particles. There is no other control legislation or method for tyre and brake wear. Currently, efforts are focussing on the development of low-friction tyres for fuel consumption and CO_2 benefits. Such tyres might also result to lower emissions of particles.

4 SIMPLE METHODOLOGY

In order to calculate PM_{10} emissions from brake and tyre wear and 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 rate (mileage). Emission factors are then a function of vehicle class alone. Total traffic-generated emissions can be estimated by summating the emissions from individual vehicle classes.

$$TE_{s,j} = N_j \times M_j \times EF_{s,j} \qquad (1)$$

Where,

TE... Total PM_{10} Emissions for the defined time period and spatial boundary[g]
N… Number of vehicles in defined class within the defined spatial boundary
M… Average mileage driven per vehicle in defined class during the defined time period [km]
EF… Mass emission factor [g/km]

while indices correspond to:

s… non exhaust source of particles (s = tyre, brake, road),
j… vehicle class (j = two-wheeler, passenger car, light-duty truck, heavy-duty vehicle).

Therefore, the user of this simple methodology need only determine activity rates in the form of the vehicle population (by class) and mileage driven per vehicle (by class) for the requested temporal and spatial resolution.

Relevant emission factors for use in equation (1) are given in section 8.1. For selection of the appropriate vehicle class it is considered that two wheelers correspond to mopeds and motorcycles which are more common in cities. Passenger cars are small or larger family cars mainly for the carriage of people. Light-duty trucks also 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 Chapters 070100-070500 of this Guidebook.

5 DETAILED METHODOLOGY

5.1 Tyre wear particle emissions

In order to estimate particle emissions from tyre wear, equation 2 can be used. This equation refers to a single vehicle category for a defined temporal and spatial resolution. Also, different particle size classes are considered (TSP, PM_{10}, $PM_{2.5}$, PM_1, $PM_{0.1}$).

$$TE_{Ti,j} = N_j \cdot M_j \cdot (EF_T)_j \cdot f_{Ti} \cdot S_T(V) \qquad (2)$$

Where,

TE... Total Emissions for the defined time period and spatial boundary [g]
N… Number of vehicles in the defined class within the defined spatial boundary
M… Mileage driven by vehicles in the defined class during the defined time period [km]
EF_T… TSP mass emission factor from tyre wear [g/km]
f_{Ti}… Mass fraction of tyre-wear TSP that can be attributed to particle size class i
$S_T(V)$… Tyre-wear correction factor for a mean vehicle traveling speed V

and indices,
T… tyre
i… TSP, PM_{10}, $PM_{2.5}$, PM_1 and $PM_{0.1}$ size classes,
j… Vehicle class similar to eq.1.

The TSP emission factors for tyre wear are presented in Section 8.2.1.

Typical size profiles for TSP emitted by tyre wear have been obtained by combining information from the literature, as discussed in section 3.5.1. Based on this information, the mass fraction of TSP in the different particle size classes is shown in Table 5.

Table 5: Size distribution of tyre wear emitted particles

Particle size class (i)	Mass fraction (f_T) 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 rate of the tyre depending on the vehicle speed. Figure 1 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 traveling speed. There is a decreasing pattern of emissions with increasing speed. This is in contrast to the usual perception that airborne particles increase in the wake of a vehicle as speed increases, because Figure 1 corresponds to primary particle emissions from the tyre and not resuspended dust. Tyre wear decreases as mean trip speed increases, because braking and cornering are more frequent in urban driving than in motorway driving.

The mathematical expression of Figure 1 is:

$V < 40$km/h:	$S_T(V) = 1.39$	
40km/h $\leq V \leq$ 90km/h:	$S_T(V) = -0.00974 \cdot V + 1.78$	(3)
$V > 90$km/h:	$S_T(V) = 0.902$	

Note that $S_T(V) = 1$ when the mean trip speed is 80 km/h, and stabilizes 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.

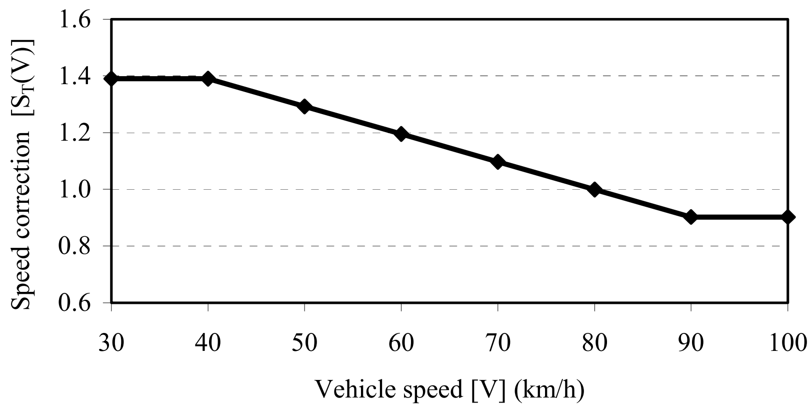

Figure 1: Speed correction factor for tyre wear particle emissions

5.2 Brake wear particle emissions

Similarly to tyre wear, brake wear emissions can be calculated by:

$$TE_{Bi,j} = N_j \cdot M_j \cdot (EF_B)_j \cdot f_{Bi} \cdot S_B(V) \qquad (4)$$

Where the nomenclature is similar to equation 2, but "B" corresponds to brake wear rather than tyre wear. The TSP emission factors for break wear are presented in Section 8.2.2.

The mass fraction of TSP in the different particle size classes is shown in Table 6.

Table 6: Size distribution of brake wear emitted particles

Particle size class (i)	Mass fraction (f_B) 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 2, and the mathematical expression of $S_B(V)$ is given in equation 5.

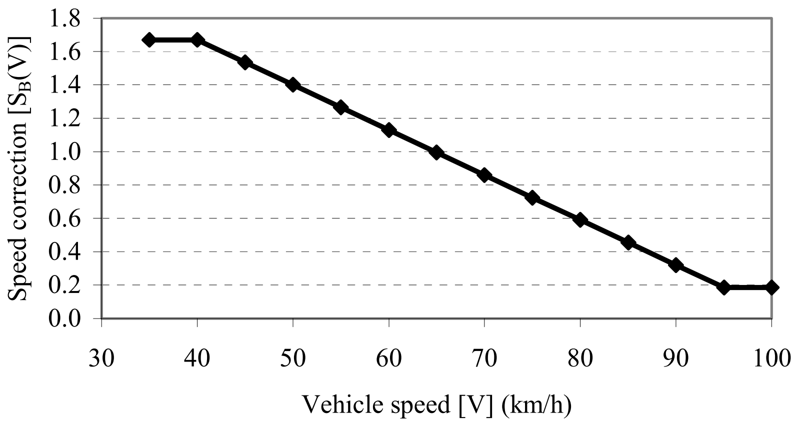

Figure 2: Speed correction factor for brake wear particle emissions

$$
\begin{array}{ll}
V < 40\text{km/h}: & S_B(V) = 1.67 \\
40\text{km/h} \leq V \leq 95\text{km/h}: & S_B(V) = -0.0270 \cdot V + 2.75 \\
V > 95\text{km/h}: & S_B(V) = 0.185
\end{array}
\qquad (5)
$$

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.

5.3 Road surface wear emissions

There is very little information on airborne emission rates from asphalt wear (Section 3.4.3), and therefore the quality of the detailed methodology does not differ from the quality of the simple one. The detailed methodology only provides a mass-weighted size classification of road surface wear particles based on the work of Lükewille *et al.* (2002), according to the equation:

$$TE_{Ri,j} = N_j \cdot M_j \cdot (EF_R)_j \cdot f_{Ri} \qquad (6)$$

Where the nomenclature is similar to Equation 2, but "R" corresponds to road surface wear. The TSP emission factors for particles of road surface wear are presented in Section 8.2.3. The mass fraction of TSP in the different particle size classes is shown in Table 7.

Table 7: Size distribution of road surface wear emitted particles

Particle size class (i)	Mass fraction (f_R) 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.

6 RELEVANT ACTIVITY STATISTICS

Information on activity statistics relevant to tyre, brake and road surface wear may be found in the Road Transport Chapter (SNAP Codes 070100 – 070500).

7 POINT SOURCE CRITERIA

There are no relevant point sources which fall under the source activities dealt within this Chapter.

8 EMISSION FACTORS, QUALITY CODES AND REFERENCES

8.1 Emission Factors for simple methodology

The emission factors quoted in Table 8 are only approximate estimates based on the wear rates and emission factors reported in the literature. The exhaust emission rates correspond to fleet average values in Europe for a typical year of the period 2000-2002, and are only quoted for comparison with non-exhaust sources. Application of the non-exhaust emission factors is only meant for calculation of indicative emission levels to the atmosphere. Based on the information used to derive these values, an expected range of -50% to +100% may be relevant, or even higher if individual vehicles and not traffic average emissions need to be studied.

Table 8: Non-exhaust PM_{10} emission factors to be used with the simple methodology and comparison with aggregated exhaust emission factors

Vehicle class (j)	Particle source(s)			
	Tyre wear (g/km)	**Brake Wear (g/km)**	**Road surface wear (g/km)**	**Exhaust emission rate (g/km)***
Two-wheelers	0.0028	0.0037	0.0030	0.060 (two-stroke)
Passenger cars	0.0064	0.0073	0.0075	0.060 (diesel)
Light duty trucks	0.0101	0.0115	0.0075	0.080 (diesel)
Heavy vehicles	0.0270	0.0320	0.0380	0.400

*For comparative purposes only.

8.2 Emission Factors of detailed methodology

8.2.1 Tyre wear

TSP Emission factors for different vehicle classes are given in Table 9. All emission factors are based on available experimental data. It should be noted that the TSP emission rates do not assume that all tyre wear material is transformed into suspended particulate, as a large fraction of tyre rubber may be produced as dustfall particles or larger shreds (e.g. under heavy braking). 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 rates are available in the literature.

Table 9: TSP emission factors from tyre wear

Vehicle Class (j)	Emission Factor (g/km)	Range (g/km)	Quality Code
Two-wheelers	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 trucks	Eq.7	0.0227 – 0.0898	B-C

Quality codes:

A: Statistically significant emission factors based on sufficiently large set of measured and evaluated data.
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 the heavy-duty truck case, emission factor needs to take vehicle size into account. This is introduced by the equation:

$$\left(EF_T\right)_{HDV} = \frac{N_{axle}}{2} \cdot LCF_T \cdot \left(EF_T\right)_{PC} \qquad (7)$$

Where,

N_{axle}… number of truck axles,
LCF_T… a load correction factor,
$(EF_T)_{PC}$… the passenger car relevant TSP emission factor.

For heavy-duty trucks, the number of axles is a parameter which can be used to differentiate truck size. An additional parameter is a load correction factor, which accounts for the load carried by the truck or bus. The load correction factor can be estimated on the basis of equation 8 which has been derived by linear regression on experimental data:

$$LCF_T = 1.41 + 1.38 \cdot LF \qquad (8)$$

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

8.2.2 Brake wear

TSP emission factors for brake wear particles are given in Table 10, together with the range and a quality code for the emission factor.

Table 10: TSP emission factors from brake wear. Emission factors coding as in Table 9.

Vehicle Class (j)	Emission Factor (g/km)	Range (g/km)	Quality Code
Two-wheelers	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 Trucks	Eq.9	0.0235 – 0.0420	B-C

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

$$\left(EF_B\right)_{HDV} = 3.13 \cdot LCF_B \cdot \left(EF_B\right)_{PC} \qquad (9)$$

In equation 9, 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:

$$LCF_B = 1 + 0.79 \cdot LF \qquad (10)$$

LF again receives the value of 0 for an empty truck and 1 for a fully laden one. Equations 9 and 10 are also proposed for urban busses and coaches.

8.2.3 Road surface wear

Preliminary values for road surface wear TSP emissions are shown in Table 11. These TSP values should correspond to primary particles from road surface wear but they are based on limited information and are highly uncertain.

Table 11: TSP emission factors from road surface wear. Emission factors coding as in Table 9.

Vehicle Class (j)	Emission Factor (g/km)	Quality Code
Two-wheelers	0.0060	C-D
Passenger Cars	0.0150	C-D
Light Duty Trucks	0.0150	C-D
Heavy Duty Trucks	0.0760	C-D

9 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 six protocol PAHs (Table 12).

Table 12: Brake and tyre debris-bound PAHs

Compound	Tyre Wear (ppm wt.)	Brake Wear (ppm wt.)
Fluoranthene	11.1	0.69
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	-	-
Benzo(ghi)perylene	0	2.6

Table 13 provides the speciation of tyre and brake wear into different elements. 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 13 include Malmqvist, 1983; Hewitt and Rashed, 1990; Brewer, 1997; VROM, 1997; Legret and Pagotto, 1999; Westerlund, 2001 and Hildemann *et al*., 1991.

Table 13: Elemental speciation of tyre and brake wear (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	0.8			10.0		
Ba	125.0	0.9	370.0	38520	2640	74400
Br	20.0			40.0		
Ca	892	113.0	2000	7700	1100	14300
Cd	2.6	0.3	5.0	13.2	2.7	29.9
Cl	520			1500		
Cl-	600			1500		
Co	12.8	0.9	24.8	6.4		
Cr	12.4	0.4	30.0	669	115	1200
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	33.6	0.9	50	463	133	850
NO3-	1500			1600		
OC	360000			107000		
P						
Pb	107	1.0	160	3126	50.0	6594
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

NB. EC = Elemental Carbon, OC = Organic Carbon.

10 UNCERTAINTY ESTIMATES

The emission factors provided in this Chapter have been developed on the basis of information collected by literature review, and on wear rate experiments. The experimental information required was obtained by three different methods:

1. By roadside receptor modelling at urban pollution hot-spots or in road-tunnels,
2. By airborne particle and wear rate determination in laboratory experiments,
3. By applying a size distribution to wear rates 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 profile used is of large importance, and artefacts from resuspension may significantly modify 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 that 1 μm. In contrast, Rauterberg-Wulff (1999) found airborne tyre particles only above 2.5 μm. Several such diverse effects apply also to chemical speciation (Table 13). 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 uncertainty range is given next to each emission factor value (Tables 9-11). A solid point for cross-checking of the methodology is the wear rates for tyres and brakes which are rather well established values. Therefore, application of typical size profiles on these wear rate values (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.

11 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.

- *Resuspended particles*
  A significant weak area is the contribution from the resuspension of road dust. In ambient and tunnel experiments it is not possible to distinguish freshly emitted tyre and brake wear aerosol from resuspended material from the same sources. Inherently, a part of resuspension 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 to significant reduction of airborne particle emissions, especially from brake and road surface wear, because such particles may be trapped by the water.

12 SPATIAL DISAGGREGATION CRITERIA FOR AREA SOURCES

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 (SNAPs 070100–070500).

13 TEMPORAL DISAGGREGATION CRITERIA

The same comment for spatial disaggregation criteria also applies here. 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.

14 ADDITIONAL COMMENTS

15 SUPPLEMENTARY DOCUMENTS

16 VERIFICATION PROCEDURES

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.

On 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.

17 REFERENCES

Abu-Allaban, M.; Gillies, J.A.; Gertler, A.W.; Clayton, R.; Proffit, D. 2002. Determination of on-road PM_{10} and $PM_{2,5}$ emission rates using roadside measurements. 11th International Conference "Transport and Air Pollution", June 2002, Graz, Austria.

APEG 1999. Source apportionment of airborne particulate matter in the United Kingdom. Airborne Particles Expert Group, DETR, London, UK.

Baekken, T. 1993. Environmental effects of asphalt and tyre wear by road traffic. Nordic seminar og Arbejdsrapporter 1992:628, Copenhagen, Denmark.

Brewer, P. 1997. M.Sc. Thesis: Vehicles as a source of Heavy Metal Contamination in the Environment. University of Reading, Berkshire, UK.

Cadle, S.H.; Williams, R.L. 1978. Gas and particle emissions from automobile tyres in laboratory and field studies. Rubber Chemistry and Technology, Vol. 52, pp. 146-158.

Camatini, M.; Crosta, G.F.; Dolukhanyan, T.; Sung, Ch.; Giuliani, G.; Corbetta, G.M.; Cencetti, S.; Regazzoni, C. 2001. Microcharacterization and identification of tyre debris in heterogeneous laboratory and environmental specimens. Materials Characterization, Vol. 46, pp. 271-283.

CARB 1993, referenced in Rauterberg-Wulff (1999).

Cardina, J.A. 1974. Rubber Chemistry and Technology, Vol. 46, p.232.

CEPMEIP, 2003. Co-ordinated European Programme on Particulate Matter Emission Inventories, Projections and Guidance, http://www.air.sk/tno/cepmeip/.

Dannis, M.L. 1974. Rubber dust from the normal wear of tyres. Rubber Chemistry and Technology, Vol. 47, pp. 1011-1037.

Dunn, J. 1993. Recycling/reuse of elastomers- an overview. Rubber Division, American Chemical Society, Orlando, Florida.

Düring, I.,; Jacob, J.; Lohmeyer, A.; Lutz, M.; Reichenbächer, W. 2002. Estimation of the "non exhaust pipe" PM_{10} emissions of streets for practical traffic air pollution modelling. 11th International Conference "Transport and Air Pollution", June 2002, Graz, Austria.

Fauser, P. 1999. Particulate air pollution with emphasis on Traffic Generated Aerosols. Risø National Laboratory, Roskilde, Denmark.

Flugsrud, K.; Gjerald, E.; Haakonsen, G.; Holtskog, S.; Høie, H.; Rypdal, K.; Tornsjø, B.; Weidemann, F. 2000. The Norwegian Emission Inventory, Norwegian Pollution Control Authority, Statistics Norway, Report 2000/1, Oslo, Norway.

Fwa, T. F.; Ang, B.W. 1991. J. Transp. Eng., 117, 298-310

Garg, B.D.; Cadle, S.H.; Mulawa, P.A.; Groblicki, P.J; Laroo, Ch.; Parr, G.A. 2000. Brake Wear Particulate Matter Emissions, Environmental Science and Technology, Vol. 34, pp.4463-4469.

Gottle A (1979). Ursachen und Mechanismen der Regenwasserverschmutzung - Ein Beitrag zur Modellierung der Abflussbeschaffenheit in stadt. Gebieten. Berichte aus Wassergutewirtschaft und Gesundheitsingenieurwesen, TU Munchen H. 23.

Gebbe *et al.* (1997) Quantifizierung des Reifenabriebs von Kraftfahrzeugen in Berlin, ISSFahrzeugtechnik, TU Berlin, i.A. der Senatsverwaltung für Stadtentwicklung, Umweltschutz und Technologie, Berlin.

Goodwin, J.W.L., Salway, A.G.; Dore, C.J., Murrells, T.P., Passant, N.R., King, K.R. Coleman, P.J., Hobson, M.M, Pye, S.T., Watterson, J.D., Haigh, K.E, and Conolly, C.M. 2002. National Atmospheric Emissions Inventory (NAEI). UK Emissions of Air Pollutants 1970-2000. National Environmental Technology Centre (NETCEN), Culham, Abingdon, Oxfordshire, OX14 3DB.

Hildemann, L.M.; Markowski, G.R.; Cass, G.R. 1991. Chemical Composition of Emissions from Urban Sources of Fine Organic Aerosol, Environmental Science and Technology, Vol. 25, pp. 744-759.

Kolioussis, M.; Pouftis, Ch. 2000. Calculation of Tyre Mass Loss and Total Waste Material from Road Transport, Diploma Thesis, Laboratory of Applied Thermodynamics, Report No. 0010, Thessaloniki, Greece.

Lee, Y.K., Kim, M.G. 1989. J. Analyt. Appl. Pyrolysis, Vol. 16, 49-55.

Legret, M.; Pagotto, C. 1999. Evaluation of pollutant loadings in the runoff waters from a major rural highway. The Science of the Total Environment, Vol. 235, pp. 143-150.

Luhana, L.; Sokhi, R.; Warner, L.; Mao, H.; Boulter, P.; McCrae, I.; Wright, J.; Reeves, N.; Osborn, D. 2002. Non-exhaust particulate measurements: results. Deliverable 8 of the PARTICULATES project, still in draft version.

Lindgren, A. 1996. Asphalt Wear and Pollution Transport. The Science of the Total Environment, Vol. 189/190, pp. 281-286.

Malmqvist, P.-A. 1983. Urban storm water pollutant sources. Chalmers University, Gothenburg, Sweden.

Miguel, A.G.; Cass, G.R.; Glovsky, M.M.; Weiss, J. 1999. Allergens in Paved Road Dust and Airborne Particles, Environmental Science and Technology, Vol. 33, pp. 4159–4168.

Moosmüller, H.; Gillies, J.A.; Rogers, C.F.; DuBois, D.W.; Chow, J.C.; Watson, J.G.; Langston, R.J. 1998. Particulate emission rates for unpaved shoulders along a paved road. J. of Air and Waste Manage. Assoc. Vol., pp. 398.

Muschack, W. 1990. Pollution of Street Run-Off by Traffic and Local Conditions. The Science of the Total Environment, Vol. 93, pp. 419-431.

NILU (1996). Norwegian Institute for Air Research Annual Report 1996. Available at Nilu.co.no

Pierson, W.R.; Brachaczek, W.W.; 1974. Airborne particulate debris from rubber tyres. Rubber Chemistry and Technology, Vol. 47, pp. 1275-1299.

Rauterberg-Wulff, A. 1999. Determination of Emission Factors for Tire Wear Particles by Tunnel Measurements. 8th International Symposium "Transport and Air Pollution", June 2002, Graz, Austria.

Rogge, W.; Hildemann, L.M.; Mazurek, M.A.; Cass, G.R. 1993. Sources of Fine Organic Aerosol. 3. Road Dust, Tire Debris, and Organometallic Brake Lining Dust: Roads as Sources and Sinks. Environmental Science and Technology, Vol. 27, pp. 1892 – 1904.

Sanders, P.G.; Dalka, T.M.; Xu, N.; Maricq, M.M.; Basch, R.H. 2002. Brake dynamometer measurement of airborne brake wear debris. SAE Technology Papers No. 2002-01-1280.

Schauer, J.J.; Fraser, M.P.; Cass, G.R.; Simoneit, B.R.T. 2002. Source Reconciliation of Atmoshperic Gas-Phase and Particle-Phase Pollutants during a Severe Photochemical Episode, Environmental Science and Technology, Vol. 36, pp. 3806-3814.

Smolders, E.; Degryse, F.; 2002. Fate and Effect of Zinc from Tire Debris in Soil. Environmental Science and Technology, Vol. 36, pp. 3706-3710.

Stalnaker, D.; Turner, J.; Parekh, D.; Whittle, B.; Norton, R. 1996. Indoor simulation of tyre wear: some case studies. Tyre Science and Technology, Vol. 24, pp. 94-118.

TNO, 1997. Particulate Matter Emissions (PM_{10}, $PM_{2,5}$, $PM_{0,1}$) in Europe in 1990 and 1993. TNO Institute of Environmental Sciences, Energy Research and Process Innovation, Apeldoorn, the Netherlands.

UK Environment Agency, 1998. Tyres in the Environment. Environment Agency, Rio House, Waterside Drive Aztec West, Almondsbury, Bristol, BS32 4UD. 1998. ISBM 1-873-16075-5.

Used Tyre Working Group (2000). http://www.tyredisposal.co.uk.

USEPA, 1995. Compilation of Air Pollutant Emission Factors, USEPA Report AP-42, Volume I, 5th Edition.

Venkatram, A. 2000. A critique of empirical emission factor models: a case study of the AP-42 model for estimating PM_{10} emissions from paved roads. Atmospheric Environment, Vol. 32, pp.1-11.

VROM, 1997. Emissies van Metalen en PAK door wegverkeer. Ministrie van VROM, Directie Stoffen, Veiligheid, Straling, p.6.

Warner, L.R.; Sokhi, R.S.; Luhana, L.; Boulter, P.G.; McCrae, I.; 2002. Non-Exhaust Particle Emissions from Road Transport, 11th International Symposium Transport and Air Pollution, June 2002, Graz, Austria.

Westerlund, K.-G. 2001. Metal emissions from Stockholm traffic – wear of brake linings. The Stockholm Environment and Health Protection Administration, 10064, Stockholm, Sweden.

18 BIBLIOGRAPHY

Compilation of Air Pollutant Emission Factors, AP-42, Fifth Edition, Volume I: Stationary Point and Area Sources, US Environmental Protection Agency, http://www.epa.gov/ttn/chief/ap42/.

Luhana L., Sokhi R., Warner L., Mao H., Boulter P., McCrae I., Wright J., Reeves N., Osborn D. 2002. Non-exhaust particulate measurements: results, Deliverable 8 of the PARTICULATES project, http://vergina.eng.auth.gr/particulates/.

19 RELEASE VERSION, DATE AND SOURCE

Version: 1.0

Date: August 2003

Original authors: Leonidas Ntziachristos
Aristotle University / Lab of Applied Thermodynamics
Thessaloniki, Greece

Reviewed August 2003

Paul Boulter
TRL Ltd.
Crowthorne, UK

20 POINT OF ENQUIRY

Any comments on this chapter or enquiries should be directed to:

Leonidas Ntziachristos

Aristotle University Thessaloniki
Lab of Applied Thermodynamics
PO Box 458 GR 541 24 Thessaloniki
GREECE

Tel. +30 23 10 99 62 02
Fax: + 30 23 10 99 60 19
Email: leon@eng.auth.gr