

Review of Tire Wear Emissions

A Review of Tire Emission Measurement Studies: Identification of Gaps and Future Needs

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1. INTRODUCTION

As tire tread wears from the use of the tires on a vehicle, particles are formed as a result of the tread abrasion caused by the road surface. Tire wear itself is a complex physicochemical process, which is driven by the frictional energy developed at the interface between the tread and the road pavement (Veith, 1995). The amount of wear that occurs during a tire's lifetime varies greatly depending on its type and how it is used. The factors affecting tire wear include:

- *Tire characteristics*
 - Size (radius/width/depth)
 - Tread depth

- Construction
- Tire pressure and temperature
- Contact patch area
- Chemical composition
- Accumulated mileage
- Alignment
- *Road surface characteristics*
 - Material: bitumen/concrete
 - Texture pattern
 - Texture wavelength—micro/macro/mega
 - Porosity
 - Condition, including rutting camber
 - Road surface wetness
 - Silt loading of road surface
 - Surface dressing
- *Vehicle operation*
 - Speed
 - Linear acceleration
 - Radial acceleration
 - Frequency and extent of braking and cornering
- *Vehicle characteristics*
 - Vehicle weight and distribution of load
 - Location of driving wheels
 - Engine power
 - Power/unassisted steering
 - Electronic braking systems
 - Suspension type and condition

The particles formed from the pavement interaction, known as tire wear particles, are elongated, with a “sausage-like” shape (Adachi & Tainosho, 2004; Cadle & Williams, 1979; Dannis, 1974; Kreider, Panko, McAtee, Sweet, & Finley, 2010; Padovan, Prasad, Gerrard, Park, & Lindsley, 1999; Williams & Cadle, 1978), and consist of a complex mixture of tread rubber and pavement. Tire wear particles are released directly into the environment both on the road surface and suspended in the air. These particles are included in the category of non-exhaust vehicle particulate emissions along with other vehicle-related wear particles, such as brake and clutch wear as well as pavement wear and road dust suspension. Subsequent to release, the tire wear particles can be transported to the soil and surface water via roadway runoff and air deposition. The ultimate fate of the particles in the environment is governed by their physical and chemical characteristics.

2. CHARACTERISTICS OF TIRE WEAR PARTICLES

The manufacturing of a tire is a complex process, requiring the use of a wide variety of chemicals, fillers, and polymers. Although the specific recipes used in tire manufacturing are dependent on the desired characteristics of the tire, the primary components of tire tread

remain consistent. Both unreactive (polymers, fillers, oils, waxes, resins, processing aids, and antioxidants) and reactive chemicals (sulfur compounds, accelerators and retarders, adhesives, and activators) are used in the compounding of tire tread. Most reactive chemicals are consumed during tire manufacturing, primarily in the vulcanization and curing process (Lawrence Livermore National Laboratory, 1996; U.S. EPA, 1997, p. 70). The physical and chemical characteristics of tire wear particles are distinct from tread rubber and are related to the wear processes exerted on the tread during driving.

2.1 Tire Wear Particle Morphology and Composition

As a tire is used, interaction with the road is thought to alter the chemical composition and characteristics of the particles generated during contact with paved surfaces when compared with original tread through both heat and friction or via incorporation of material from the road surface (Adachi & Tainosho, 2004; Williams & Cadle, 1978). Several studies have characterized particles from tires using rolling resistance machines or other methods (Cadle & Williams, 1979; Camatini et al., 2001; Davis, Shokouhian, & Ni, 2001; Ozaki, Watanabe, & Kuno, 2004; Rogge, Hildemann, Mazurek, Cass, & Simoneit, 1993; Sadiq, Alam, El-Mubarek, & Al-Mohdhar, 1989; Williams & Cadle, 1978). However, in an on-road scenario, as the tire passes over the road, particles from the tread combine with existing road dust and minerals from the pavement to produce a unique entity. Adachi and Tainosho (2004) demonstrated that rubber-containing particles in road dust are incorporated with metals from alternative contributing traffic-related sources (i.e., paint and brake dust).

Tire wear particles created using a laboratory road simulator utilizing actual pavement surfaces have been analyzed and confirm the differences in morphology and chemical composition of tire wear particles versus tread particles (Kreider et al., 2010). Fig. 7.1 shows pictures of roadway particles (including tire wear particles) and tire wear particles (generated using a road simulator). From the images it is clear that tire wear particles contain encrustations of minerals from the pavement. This observation was also confirmed in studies using aerosol time-of-flight mass spectrometer where incorporation of the pavement into tire wear particles as they exist in the environment was observed from the test results (Dall'Osto et al., 2014).

Chemical characterizations of tread particles have primarily addressed the metallic content, although studies of tire particle toxicity in aquatic species and human cell lines have alluded to organic constituents of tires (Adachi & Tainosho, 2004; Davis et al., 2001; Gualtieri, Andrioletti, Mantecca, Vismara, & Camatini, 2005; Ozaki et al., 2004; Rogge et al., 1993; Sadiq et al., 1989; Wik, 2007; Zheng, Cass, Schauer, & Edgerton, 2002). In addition, the contribution of tires to polycyclic aromatic hydrocarbons (PAHs) in road dust has also been discussed in the literature, with contrasting results (KEMI, 2003; Macias-Zamora, Mendoza-Vega, & Villaescusa-Celaya, 2002; Rogge et al., 1993; Takada, Onda, & Ogura, 1990; Zakaria et al., 2002).

The study by Kreider et al. (2010) provides a compositional analysis of tire wear particles, and a comparison of their chemical composition with that of tread particles derived from the tires used in the study is provided in Table 7.1. Significant differences between tire wear particles and tread particles were confirmed, in particular with respect to the mineral components. This supports the microscopic evaluations regarding encrustation of pavement wear into the tread particles. The mass concentration of Zn in tire wear particles is significantly less than that in tread particles because of dilution from the pavement. Additionally,

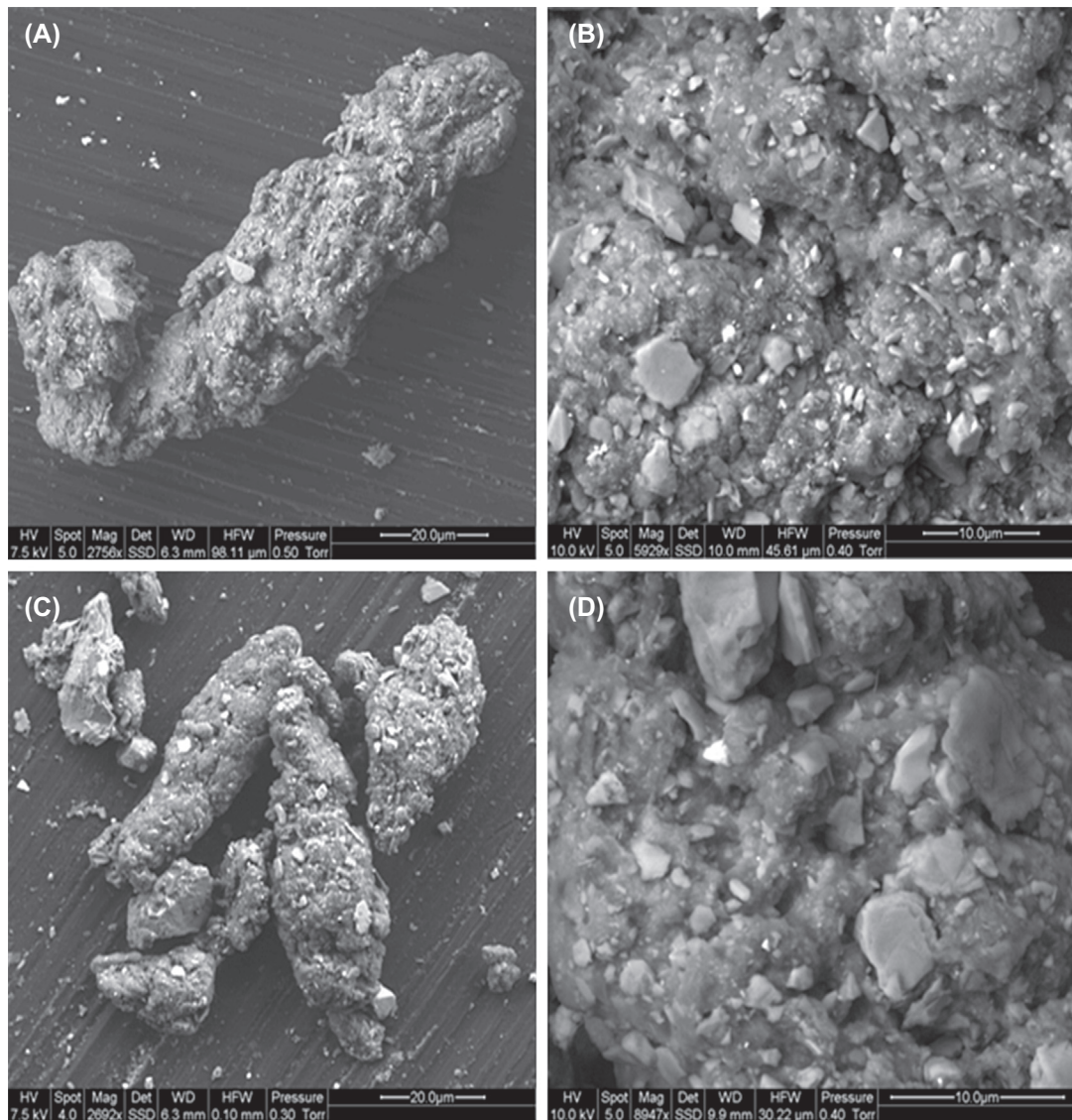


FIGURE 7.1 Pictures of tire wear particles (TWP). Scanning electron images of roadway particles (A, B) and TWP (C, D). Scales are located below the photographs. Mineral incrustations are evident in the photographs of greater magnification (B, D). From Kreider *et al.* (2010).

differences in some of the other metals detected show a clear contribution from pavement including Al, Ca, Cu, Fe, Mg, Mn, K, Ni, Na, Ti, and V. Differences in PAH concentrations were also observed where five substances, including phenanthrene, pyrene, benzo(a)pyrene, benzo(g,h,i)perylene, and indeno-1,2,3(c,d)pyrene, were detected at higher concentrations in the tire wear particles than in the tread, indicating pavement as a contributor.

TABLE 7.1 Chemical Constituents of Tire Wear Particles and Tread Particles (TPs)

Chemical Family (%w/w)	Tire Wear Particles	Tread Particles
Plasticizers and oils	10	19
Polymers	16	46
Carbon blacks	13	19
Minerals	61	16
Metals (ppm)	Tire Wear Particles	Tread Particles
Aluminum	28,200	470
Antimony	130	76.5
Arsenic	N.D.	N.D.
Beryllium	N.D.	N.D.
Bismuth	N.D.	86.8
Boron	N.D.	N.D.
Cadmium	N.D.	N.D.
Calcium	65,300	1010
Chromium	N.D.	N.D.
Cobalt	N.D.	N.D.
Copper	634	21.5
Iron	27,700	224
Lead	N.D.	N.D.
Magnesium	14,500	65.8
Manganese	607	N.D.
Nickel	52.6	N.D.
Potassium	5810	242
Selenium	N.D.	N.D.
Silicon	87,000	54,000
Silver	N.D.	N.D.
Sodium	4750	N.D.
Sulfur	5000	12,000
Titanium	1390	29.9

(Continued)

TABLE 7.1 Chemical Constituents of Tire Wear Particles and Tread Particles (TPs)—cont'd

Metals (ppm)	Tire Wear Particles	Tread Particles
Vanadium	49.6	N.D.
Zinc	3000	9000
PAHs (ppm)	Tire Wear Particles	Tread Particles
Acenaphthene	0.04	0.13
Naphthalene	0.2	1.18
Phenanthrene	1.66	1.21
Pyrene	4.77	0.06
Acenaphthalene	0.15	1.24
Anthracene	0.1	0.11
Benzo(a)anthracene	0.18	2.87
Benzo(a)pyrene	0.28	N.D.
Benzo(b)fluoranthene	0.37	0.92
Benzo(g,h,i)perylene	3.22	1.77
Benzo(k)fluoranthene	0.02	0.92
Chrysene	0.36	2.95
Dibenzo(a,h)anthracene	0.1	0.87
Fluoranthene	0.98	1.62
Fluorene	0.07	0.25
Indeno-1,2,3(c,d)pyrene	0.21	N.D.
Total	12.71	16.1

2.2 Volume Size Distribution

Historically, researchers who have studied tire wear and tread loss have reported wide size distributions in the particles ranging from 5 to more than 300 μm (Cadle & Williams, 1979; Dannis, 1974). More recently, Kreider et al. (2010) reported a wide unimodal size distribution, as measured by laser diffraction, from 5 to 220 μm , with a mode centered at ~ 75 μm . Additional measurements of the distribution using transmission optical microscopy were similar to the laser diffraction method and ranged from 4 to 350 μm , with a mode at 100 μm . Regardless of the method, Kreider et al. (2010) reported less than 1% by volume of the particles were less than 10 μm .

In addition to the overall size distribution of the bulk tire wear particles, studies have been conducted to understand the size distribution of the airborne fraction of tire wear particles, and

the results indicate that these distributions vary with the tire type (nonstudded or studded) and pavement type (Gustafsson et al., 2008). Unpublished research wherein PM₁₀ samples were collected while running passenger car tires on a roadway simulator showed that more than 60% of tire wear particles (by mass) were generally present in the coarse fraction (i.e., 2.5–10 μm) (Panko et al., 2009). In this study, the generation of PM₁₀ was quantified with an aerodynamic particle sizer (APS; 0.5 and 10 μm) and the nano-sized fraction was evaluated using a scanning mobility particle sizer (SMPS; 8–311 nm). Elemental analysis (particle induced X-ray emission, PIXE) and particle morphology (scanning electron microscopy) were also examined to apportion the particles between pavement and tires. APS and SMPS data show that the concentration of particles generated was low, seldom greater than 10–20 μg/m³. APS data indicated a bimodal distribution of the mass of particles, with peaks around 1 μm and between 5 and 8 μm. The SMPS data identified a peak in the number of particles generated between 10 and 100 nm, but the overall concentration was similar to that of background nanoparticles in the laboratory. In other studies, the use of studded tires has been demonstrated to produce particles in the nanometer range; however, the sources of these particles are the stud and pavement, not the tread rubber (Gustafsson et al., 2009). When non-studded tires are used, nanoparticle concentrations do not exceed background (VTI 2009).

3. TIRE WEAR STUDIES

A variety of studies have been conducted to understand the contribution of tire wear to airborne particulate, especially PM₁₀. The studies can be grouped into two categories: air concentration measurements and emission rate estimates.

3.1 Tire Wear Particle Air Concentrations

Very few reliable estimates of tire wear particles in the ambient air are available, primarily because of limitations in the chemical markers used to quantify this type of PM. Furthermore, many measurements of tire wear have been conducted at locations where higher than average levels would be expected, such as near or in tunnels, and thus are not representative of typical human exposures (Almeida-Silva, Canha, Freitas, Dung, & Dionísio, 2011; Fauser, Tjell, Mosbaek, & Pilegaard, 1999; Gualtieri et al., 2005; Hüglin & Gehrig, 2000, p. 14; Salma & Maenhaut, 2006; Schauer, Fraser, Cass, & Simoneit, 2002).

Because tire wear particles are not a single substance, a chemical marker is necessary to detect and quantify them in the environment. Historically, most researchers had relied on Zn as an indicator of tire wear particles. After Pierson and Brachaczek (1974) established a correlation between traffic activity and elemental Zn concentrations in airborne PM as well as in roadside soil samples, Zn was proposed as a marker for tire wear. However, other confounding sources of Zn from exhaust and non-exhaust emissions such as corrosion of crash barriers and brake wear were not considered in the studies. Because the use of elemental Zn lacks specificity to tire wear particles, Fauser et al. (1999) proposed to use extractable organic zinc (zinc-mercaptopbenzothiazole) as a marker because tires are, with the exception of engine oil, the only significant contributors to extractable organic zinc in airborne particulates. Nevertheless, given the interference from additives used in engine oils (zinc-dithiophosphates), which were widely

used in Europe, significant uncertainties remained for determinations of tire wear particles. Building off of initial research by Harada, Shbata, Panko, and Unice (2009) and Kitamura, Kuroiwa, Harada, and Kato (2007), Unice, Kreider, and Panko (2012) published a marker for tire wear that uses a pyrolysis GC/MS method wherein the presence of the particles are qualitatively confirmed using butadiene, isoprene, and styrene and quantified using the dimeric markers vinylcyclohexene and dipentene, which have good specificity for tread rubber polymer with no other appreciable environmental sources.

Panko, Chu, Kreider, and Unice (2013) presented the results of ambient air sampling conducted at roadside locations throughout parts of France, the United States, and Japan, wherein tire wear particles were quantified using the pyrolysis marker. The results indicated that the tire wear particle concentrations in the PM_{10} fraction were low with averages ranging from 0.05 to 0.70 $\mu\text{g}/\text{m}^3$, representing an average contribution to total PM_{10} of 0.84%. When concentrations are converted to a tread basis (i.e., divide the mass of tire wear particles by 2 to account for an approximate twofold difference between polymer content in tread [$\sim 50\%$] and tire wear particles [$\sim 25\%$]), the results from this study are consistent with the low end of the range of historically reported values (Table 7.2). The difference between results reported by Panko et al. (2013) and the upper portion of the range of historical estimates of tread concentration in PM_{10} could be a result of differences in collection or chemical markers, which have included benzothiazole compounds, metal concentration, and the analysis of pyrolysis products with a nonspecific flame ionization or flame photometric detectors (Kumata et al., 2011; Miguel, Cass, Weiss, & Glovsky, 1996; Sakamoto, Hirota, Nezu, & Okuyama, 1999; Toyosawa, Umezawa, Ikoma, & Kameyama, 1977). Kumata et al. (2011) reported that tread contributed 0.68% of the total PM_{10} in roadside samples collected in Japan based on the analysis of dihydroresin acid markers (Kumata et al., 2011). This estimate is also in close proximity to, albeit higher than, the percent contribution of tread to PM_{10} (0.42%) predicted for all samples collected in Japan by Panko et al. (2013). Additional factors that may affect the contribution of tire wear to total PM_{10} include differences in road types and vehicles, local driving behavior, background concentrations and wind (direction and strength) between the sampling locations, type of sampling site (background, urban, etc.) and distance of sampling sites from the road, and meteorological conditions and climate season.

3.2 Tire Wear Emission Rates

Over time, many estimates of emission rates for airborne tire wear particles have been made and were recently summarized by Grigoratos & Martini (2014, p. 53). For PM_{10} the most recent emission rate estimates range from 2.4 to 13 mg/vkm with an average of 6.3 mg/vkm (Table 7.3). The differences in the reported rates are likely explained by the varied methods used to calculate the emission rates such as derivation from emission inventories, receptor modeling, and statistical models using source profiles, as well as direct measurements in road simulator laboratory experiments and during roadside air sampling campaigns. Furthermore, although the PM_{10} emission rates listed in Table 7.3 are the most recent available, many originate from studies conducted 10–20 years ago and should be used with caution, as tire wear rates have improved with advanced tire technologies. Emission rates for tire wear particles in the $PM_{2.5}$ fraction are sparse and generally estimated as a percent of PM_{10} ; their reliability is uncertain.

TABLE 7.2 Historical Estimates of Tread Contribution to Airborne Particulate Matter (PM) (%)

Location	TSP	SPM	PM ₁₀	PM _{2.5}	Reference
United States	1.5–9.2		–	–	Cardina (1974), Cardina (1973)
	1–4		–	–	Pierson and Brachaczek (1974)
	1.6–2.4		–	–	Cadle and Williams (1979)
	1.6–3.5		–	–	Rogge et al. (1993)
	–		–	1	Fishman and Turner (1999)
	–		–	1.3, 3	Schauer et al. (2002)
	–	–	0.44	–	Panko et al. (2013)
Japan		5.2 ± 0.4	–	–	Toyosawa et al. (1977)
		1.3–3	–	–	Kima, Yagawaa, Inoue, Lee, and Shirai (1990)
		0.5–5.6	–	–	Yamaguchi, Yamazaki, Yamauchi, and Kakiuchi (1995)
		4.3	–	–	Sakamoto et al. (1999)
		3.6 ± 4.7			Kumata, Takada, and Ogura (1997)
		3	–	–	Miguel et al. (1996), Doki, Kunimi, and Takahasi (2002)
		3–4	2.3	1.3	JATMA (2001)
Europe			0.68		Kumata et al. (2011)
	–	–	0.2	–	Panko et al. (2013)
	–		5	–	Annema, Booij, Hesse, and van derMeulenSlooff (1996, p. 102)
	16		10	–	Israël, Pesch, and Schlums (1994)
	–		8.6	–	Rauterberg-Wulff (1998)
	–		5	–	Fausser et al. (1999)
	–		1–7.5	–	Hüglin and Gehrig (2000, p. 14)
	5		–	–	Fausser, Tjell, Mosbaek, and Pilegaard (2002)
	–		3–7	–	Gualtieri et al. (2005)
	–		6	3	BLIC (2005)
			0.1–3.9		Sjödín et al. (2010, p. 100)
			3–4	4–7	Kwak, Kim, Lee, and Lee (2013)
	–		0.62	–	Panko et al. (2013)

PM₁₀, particulate matter with aerodynamic diameter <10 µm; PM_{2.5}, particulate matter with aerodynamic diameter <2.5 µm; SPM, suspended particulate matter; TSP, total suspended particulate.

TABLE 7.3 Summary of PM₁₀ Emission Factors for Tire Wear

Reference	PM ₁₀ Emission Factor (mg/vkm)	EF Method
U.S. EPA (1995)	5	Emission Inventory
Keuken, Denier van der Gon, and van der Valk (2010)	5	Emission Inventory
Rauterberg-Wulff (1998)	6.1	Receptor Modeling
Hüglin and Gehrig (2000)	13	Receptor Modeling
Luekewille et al. (2001)	6.5	Receptor Modeling
CEPMEIP (2002)	4.5	Emissions Inventory
Luhana, Sokhi, Warner, Mao, and Boulter (2004)	7.4	Receptor Modeling
Kupiainen et al. (2005)	9	Road Simulation Study
Ten Broeke, Hulskotte, and Denier van der Gon (2008)	8	Emissions Inventory
Sjödin et al. (2010)	3.8	Road Simulation Study
CEPMEIP (2012)	3.5–4.5	Emissions Inventory
NAEI (2012)	7	Emissions Inventory
Panko et al. (2013) (central tendency)	2.4	Roadside Study
Panko et al. (2013) (95th percentile)	7	Roadside Study

PM₁₀, particulate matter with aerodynamic diameter <10 µm.

4. DATA GAPS AND NEEDS

As many researchers have noted, the percent contribution of non-exhaust vehicle emissions to traffic-related PM levels will continue to increase as exhaust emissions decrease. As such, an accurate picture of the sources in the non-exhaust vehicle emission category is important for making appropriate risk management decisions. Much of the existing data for tire-associated emissions are confounded by the lack of a consistent marker for measuring tire wear particles. Recently, the pyrolysis GC/MS method proposed by [Unice et al. \(2012\)](#) was accepted as an ISO Technical Specification (TS-20593). Use of this marker in conducting more measurements of tire wear particles in the ambient air would significantly strengthen the aging data set with more modern values. Additionally, very few data are available to characterize tire wear particle contributions to PM_{2.5}; therefore measurements in this fraction would help complete the tire wear emission profile and provide more reliable emission factors for tire wear particles in the PM_{2.5} fraction.

5. CONCLUSIONS

Emphasis on minimizing human exposures to respirable particulate in the ambient air is a global effort. Regulations governing the allowable PM in the air have been established

TABLE 7.4 International Standards for PM_{2.5} and PM₁₀

Pollutants	Australia	Canada	China	South Korea	EU	United States	India	WHO Guidelines
PM _{2.5} annual (µg/m ³)	8	10	15	25	25	12	40	10
PM _{2.5} for 24-h (µg/m ³)	25	28	35	50	—	35	60	25
PM ₁₀ annual (µg/m ³)	—	—	40	50	40	—	60	20
PM ₁₀ for 24-h (µg/m ³)	50	—	50	100	50	150	100	50

internationally, and programs are in place to measure progress toward achieving the PM goals (Table 7.4). Data obtained from established monitoring networks have indeed shown a measurable decline. For example, in the United States, from 2000 to 2016, the average nationwide levels of PM₁₀ and PM_{2.5} have decreased 40% and 42%, respectively, with the vast majority of the measurements below the national standards (U.S. EPA, 2017). Similarly, in Europe significant decreasing trends in the PM₁₀ annual mean were observed between 2000 and 2014, and for PM_{2.5} concentrations, a decreasing trend was observed between 2006 and 2014 (EEA, 2016). Nevertheless, some regional PM air concentrations, particularly in urban environments, still exceed air quality standards and are often attributable to vehicle traffic.

Available data indicate that the contribution of tire wear particles to the non-exhaust emission category is important, although the contribution of tire wear particles to the total ambient PM₁₀ and PM_{2.5} is low. Nevertheless, as vehicle exhaust emissions are curbed through various control measures, the contribution of tire wear particles may increase. To date, there are no known regulations that specifically govern tire wear particle emissions and no single approach or technology to control the emissions. Given the variety of factors that influence the generation of tire wear particles, any future efforts at reducing this source would need to consider not only the characteristics of the tire, but also the vehicle to which it is mounted, the pavement on which the vehicle is driven, and the design of roadway systems that affect the manner in which the vehicle is operated.

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