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Particulate Matter from Non-exhaust Sources

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Abstract. Air pollution is an important issue worldwide. Solid components in air (particulate matter, PM) originate from a variety of natural or anthropogenic sources and have different morphological, physical, and chemical properties. Their presence in the air also depends on meteorological conditions, such as humidity, rainfall, and wind speed. PM pollution has adverse effects on environment and human health. Therefore, it is very important to address sources and processes involved in PM generation. Among the existing sources, a special attention must be paid to PM emissions from road traffic, i.e., exhaust sources (e.g., fuel combustion) and non-exhaust sources (e.g., road, tyre, brakes). These traffic-related sources contribute to PM concentrations in cities, and this calls for research into new possible systems and/or mitigation measures. In light of the facts above, the objectives of this study are 1) To evaluate the contribution to PM emission from traffic-related sources. 2) To evaluate existing mitigation measures and to identify new ones to reduce PM production. First results show that: 1) Non-exhaust sources have a different role in PM generation and they differently affect PM_{10}, $PM_{2.5}$, and $PM_{0.1}$. 2) Even if emissions-related regulations have led to reductions in exhaust emissions from road traffic, other mitigation measures could reduce the non-exhaust part of emissions (e.g., brakes wear, road wear, and tyre wear). 3) New technologies could be developed to reduce PM from non-exhaust sources.

Keywords: particulate matter, non-exhaust sources, tyre wear, road wear, brake wear, mitigation measures.

Introduction

Based on pollution source, particulate matter (PM) is made up of very heterogeneous compounds in terms of chemical composition, solid or liquid state, and size. PM classification is usually based on the aerodynamic diameter (the one that appears as a subscript). This latter is the diameter of a spherical particle with a density of 1 g/cm^3 with the same settling velocity: 1) Total Suspended Particles (TSP) including all particles, of whatever size lower than 35 µm (Heinrich & Slama, 2007); 2) PM_{10} (less than 10 µm). 3) $PM_{2.5}$ (<2.5 µm in diameter). 4) $PM_{1.0}$ (<1 µm in diameter). 5) Coarse particles (particles which are from 2.5 to 10). 6) Fine particles (particles less than 2.5 in diameter), that include $PM_{0.1}$. 7) Ultra-fine particles (<0.1 µm, i.e., $PM_{0.1}$). Furthermore, PM can be classified as primary or secondary particles: 1) Primary particles (i.e., fine, $PM_{2.5}$ and ultrafine particles, $PM_{0.1}$) are directly released into the atmosphere by a large number of human or natural sources (e.g., combustion processes) (Reddington et al., 2011). 2) Secondary particles (including coarse particles with diameters greater than 2.5 µm, PM_{10} and TSP) are generated by mechanical or chemical reactions during the atmospheric oxidation of emitted precursor gases (e.g., sulfur dioxide, nitrogen oxides, ammonia, and volatile organic compounds). In this process, the saturation vapor pressure of the organic and inorganic gases becomes lower thus allowing them to transfer into particle phase by condensation and nucleation (Alanen et al., 2017; Reddington et al., 2011). Table 1 below shows a schematic PM classification.

Table 1. Particulate Matter Classification

Category	PM Fraction	Particle Size	Acronym	Source
Primary particles	Ultra-fine	<0.1 µm	$PM_{0.1}$	Volcanoes, forest fires, sea spray, and windborne dust, and anthropogenic sources (vehicles, engines or power plants, and biogenic sources) (Reddington et al., 2011)
	Fine	<2.5 µm	$PM_{2.5}$	
Secondary particles	Coarse	<10 µm	PM_{10}	Homogeneous nucleation (gas-to-particle conversion) and condensation of both natural and anthropogenic gaseous precursors. Also traffic and other anthropogenic sources are contributors to secondary aerosol formation. (Alanen et al., 2017; Reddington et al., 2011)
		>2.5 µm & <10 µm	$PM_{2.5-10}$	
	Total suspended	<35 µm	TSP	

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Note that anthropogenic activities have a negative impact on PM pollution. Importantly, in addition to industrial processes, farming, building operations, combustion of fossil fuels, also road traffic significantly contributes. Based on the above, the objectives of the study presented in this paper are to 1) Analyze the emissions of particulate matter (i.e. PM_{10}, $PM_{2.5}$, and $PM_{0.1}$) from traffic-related sources. 2) Evaluate existing mitigation measures and their effectiveness. 3) Provide a basis for a better understanding of traffic-related emissions in order to guide future research into new effective technologies and measures. The remaining part of this paper is organised as follows. Next section deals with the analysis of traffic-related PMs. Afterwards mitigations measures are discussed. Finally, Conclusions are drawn and references are listed.

1. Analysis of traffic-related PMs

In terms of PM thresholds and limits, note that the EU Directive 2008/50/EC (European Parliament, 2008), as well as the guidelines of the World Health Organization (WHO, 2006) set PM concentration thresholds (cf. Table 2). According to the EU Directive 2008/50/EC, the 24-hour average PM_{10} should not exceed 35 $\mu g/m^3$ more than 35 times in a calendar year. WHO guideline values are generally stricter than the EU standards. In the U.S.A., the National Ambient Air Quality Standards (NAAQS) (Buchoolz, 2014) serves as a national public health and environment protection program. NAAQS refers to several contaminants (e.g., carbon monoxide CO, nitrogen oxides NO_2, ozone O_3, sulfur dioxide SO_2 and lead Pb). For $PM_{2.5}$, NAAQS provides a "primary standard" (for the protection of public health) and a "secondary standard" (for the protection of public welfare). $PM_{2.5}$ limits are 12 and 15 $\mu g/m^3$, respectively.

Table 2. Different sources contribution to $PM_{2.5}$ and PM_{10}

Country	Target Limit				Reference
	PM_{10} ($\mu g/m^3$)		$PM_{2.5}$ ($\mu g/m^3$)		
	24-H	ANNUAL	24-H	ANNUAL	
EU	50	40	/	25	Directive 2008/50/EC
EU	50	20	25	10	WHO Air-Quality Guidelines
Norway	30	20	15	8	National Air-Quality Guidelines
USA	150	/	35	12–15	NAAQS
Canada			30		Canadian Council of ministries of Environment
Australia	50		25	8	Australia Government
Japan	100		35	15	Government of Japan

Traffic-related PMs can be distinguished into 1) Exhaust traffic-related particles, ES, which are emitted as a result of incomplete fuel combustion and lubricant volatilization during the combustion procedure. 2) Non-exhaust traffic-related particles, NES, which are either generated from non-exhaust traffic related sources such as brake, tyre, clutch and road surface wear or already exist in the environment as deposited material and become resuspended due to traffic induced turbulence (Grigoratos & Martini, 2014).

Based on the studies conducted in 51 countries around the world, Karagulian et al. (2015) assessed how the different sources identified contribute to air pollution (cf. Table 3). Note that, in decreasing order: 1) Unspecific anthropogenic sources are approximately 28–36%. 2) The contribution of natural dust and sea salt is about 23–26%. 3) Traffic (from exhaust, ES, and non-exhaust sources, NES) is a major contributor (about 23–25%). 4) Domestic fuel burning (e.g., wood, coal and gas fuel for cooking / heating) accounts for about 20–24%. 5) The share from industrial activities is about 17–19%. For traffic, note that in several contexts it may result as the main source of PM (Karagulian et al., 2015). This is particularly evident in urban areas where vehicle emissions (e.g. carbon dioxide (CO_2), hydrocarbons (HCs), nitrogen oxides (NOx) and PM) are constantly increasing.

Table 3. Different sources contribution to $PM_{2.5}$ and PM_{10}

Sources	Traffic				Industry	Domestic Fuel Burning	Natural Sources	Unspecified Sources (of Human Origin)
	ES	NES						
		RW	BW	TW				
PM_{10} (%)	8–38				6–29	3–45	3–44	12–44
$PM_{2.5}$ (%)	12–37				4–34	6–34	5–52	9–62

Note: ES = Exhaust Sources; NES = Non Exhaust Sources; RW = Road Wear; BW = Brake Wear; TW = Tyre Wear.

Based on literature results (Amato et al., 2014a; Denby et al., 2013; Hedberg et al., 2006; Kim & Lee, 2018; Kwak et al., 2013; Panko et al., 2019, 2013; Schauer et al., 2002; Sjödin et al., 2010; Srimuruganandam & Shiva Nagendra, 2012a, 2012b; Wåhlin et al., 2006; Weinbruch et al., 2014). Table 4 reports Contributions to Particulate Matter (PM_{10} and $PM_{2.5}$) from exhaust and non-exhaust sources.

Table 4. Results for Exhaust and Non-Exhaust (traffic related) Contributions to Particulate Matter (PM_{10} and $PM_{2.5}$)

Source Category	Source	PM concentration		PM size range	Reference
		(μg/m³)	%		
ES/NES	ES	2.4–4.4	10.3–19.2	$PM_{2.5}$	(Sjödin et al., 2010)
	RW	11.1–13	48.8–57		
	BW	5.8	25.5		
	ES	3.8–25.1	13.1–43.6	PM_{10}	
	RW	4–42.8	7–80.4		
	BW	0.02–42	0.1–7.2		
	TW	0.02–5.6	0.06–10.2		
ES/NES	ES	4.3	55	$PM_{2.5}$	(Wåhlin et al., 2006)
	RW	2.2	28.4		
	BW	0.72	9.3		
	ES	1.6	13.35	PM_{10}	
	RW	5.8	48.3		
	BW	0.1	0.8		
ES/NES	ES	2.4–3.3	10–20.1	PM_{10}	(Denby et al., 2013)
	RW	7.8–23.8	56.2–78		
	BW	0.9–1.7	5.5–5.9		
	TW	0.8–1.9	5.5–9.3		
ES/NES	ES	2.76	27	PM_{10}	(Weinbruch et al., 2014)
	BW+TW	1.6	15		
ES/NES	ES	3.8	6	$PM_{2.5}$	(Srimuruganandam & Shiva Nagendra, 2012a)
	BW+TW	3.4	5.4		
	ES	13.1	15.8	PM_{10}	
	BW+TW	3.4	4.1		
ES/NES	ES	23.5	57.7	$PM_{2.5}$	(Srimuruganandam & Shiva Nagendra, 2012b)
	BW	0.09	0.14		
	ES	31.9	58.5	PM_{10}	
	BW	3.4	8		
ES/NES	ES	6.5	18	$PM_{2.5}$	(Amato et al., 2014a)
	TW	6.6	18		
	ES	8.8	20	PM_{10}	
	TW	3.4	8		
NES	BW	0.6	14	$PM_{2.5}$	(Hedberg et al., 2006)
ES/NES	ES	11.9–25.9	30.1–37.4	$PM_{2.5}$	(Schauer et al., 2002)
	TW	0.4–2	1–3.3		
NES	TW+RW	0.004–0.29	0.1–0.68	$PM_{2.5}$	(Panko et al., 2019, 2013)
	TW+RW	0.05–1.34	0.14–2.8	PM_{10}	
NES	TW	13.8–28.7	4–7	$PM_{2.5}$	(Kwak et al., 2013)
	TW	20.8–37.1	3–4	PM_{10}	
NES	TW	2–7	0.04–0.12	$PM_{2.5}$	(Kim & Lee, 2018)
	TW	13–22.2	0.12–0.40	PM_{10}	

Note: ES = Exhaust Source; NES = Non Exhaust Source; RW = Road Wear; BW = Brake Wear; TW = Tire Wear.

On average, for exhaust sources (ES), PM_{10} accounts for about 10 µg/m^3, while for non-exhaust sources (NES), PM_{10} accounts for about 12 µg/m^3. Furthermore, on average, for ES, $PM_{2.5}$ accounts for about 11 µg/m^3, while, for NES, $PM_{2.5}$ accounts for about 19 µg/m^3. Note that, in Table 4, when $PM_{2.5}$>PM_{10} data are not consistent and refer to different authors/studies. Figure 1 shows 1) How $PM_{2.5}$ and PM_{10} relate. 2) Typical relationships among NES components (Sjödin et al., 2010).

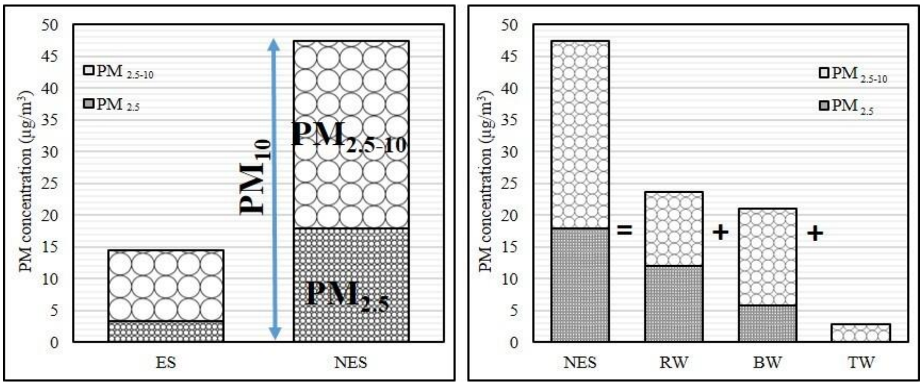

Figure 1. $PM_{2.5}$ and PM_{10} for ES and NES

The contact between tyre and road surface causes shear and heat in the tyre (Jan Kole et al., 2017), with generation of wear particles. The interaction of tyres and pavement alters both the chemical composition and characteristics of the particles generated compared to the original tyre tread due to heat and friction, as well as the incorporation of material from the road surface (Grigoratos & Martini, 2014; Panko et al., 2013). The amount and size of the particles released depends on climate (temperature), composition and structure of the tyre, road surface, driving speed and style, and the nature of the contact (e.g., rolling versus slipping). Kole et al. (2017) studied the tear and wear process and they summarised the amount released into the environment in different countries. Generally, two different approaches are used to estimate the amount of wear and tear from tyres: the first one uses emission factors per vehicle-km multiplied by the total mileage, and the second one uses the number of tyres multiplied by the weight loss of these tyres during use. Data collected have been grouped into 4 categories and reported in Table 5.

Table 5. The amount of car tyres wear and tear for different States (Jan Kole et al., 2017)

Nation	Wear and Tear in (mg/Km)				Total Wear and Tear emissions (Tonnes/years)	Total emissions *per* Capita/year (kg)
	Category 1	Category 2	Category 3	Category 44		
The Netherlands	9–60	85–132	102–159	267–850	8834	0.52
Norway	/	100–132	/	712	7884	1.5
Sweden	/	50	/	700	13238	1.3
Denmark	/	100–132	204	712	6721	1.2
Germany	22.5–45	80–90	180	700–1200	92594	1.1
United Kingdom	/	/	/	/	63000	0.98
Italy	/	/	/	/	50000	0.81
Japan	1136(2)*	1780(4)*	2880(4)*	5484(10)–5973(14)*	239762	1.9
China	7	132	204	1068	756240	0.55
India	7	132	204	1068	292674	0.23
Australia	/	/	/	/	20000	0.87
USA	7	132	204	1068	1524740	4.7
Brasil	7	132	204	1068	294011	1.4

Note: Category 1 – Moped, Motorcycle, and Motorised 2 – and 3 – wheelers; Category 2 – passenger car, light vehicle; Category 3 – van, special vehicle light, commercial car, lorry<7.5 t, light vehicle, and normal vehicle; Category 4 – articulated-lorry, lorry, truck, bus, special vehicle heavy, heavy transport, lorry>7.5 t, trailer, and heavy lorry; *data refer to wear and tear are reported in cm^3/tyre.

It is possible to observe as the amount of tyre wear and tear ranges from 9 mg/km, for two-wheel vehicles like motorcycles, to 1200 mg/km for the heaviest vehicles (i.e., lorries). Moreover, the estimated *per* capita emission ranges from 0.23 to 4.7 kg/year, with a global average of 0.81 kg/year. In particular, India has the lowest wear and tear estimate, i.e., 0.23 kg/capita/year, while the USA has the highest, i.e., 4.7 kg/capita/year. This difference can be explained by the fact that the USA has 0.82 cars per capita, while in India there are 0.13 cars per capita. The wear factor (defined as the total amount of material lost per kilometer) depends on several parameters such as: a) tyre characteristics; b) vehicle characteristics; c) road surface characteristics; d) vehicle operation. Many studies have been carried out to determine the amount of Particulate Matter (PM) emitted by non-exhaust source (e.g., tyres, brakes, and resuspension). Table 6 shows the PM_{10} and $PM_{2.5}$ emissions caused by tyre wear process.

Table 6. PM_{10} and $PM_{2.5}$ emission factor and concentration related to tyre wear

References	PM concentration (μg/m³)		References	PM emission factor (mg/vkm)	
	PM_{10}	$PM_{2.5}$		PM_{10}	$PM_{2.5}$
(Sjödin et al., 2010)	0.017–0.799	/	(Sjödin et al., 2010)	0.002–0.044	/
(Panko et al., 2019)	0.04–2.24	0.002–15	(Simons, 2013)	0.004	0.003
(Panko et al., 2013)	0.08–0.67	/	(ten Broeke et al., 2008)	1.2–30	0.25–6
(Kwak et al., 2013)	20.1–62.5	17.2–52.6	(EPA Environmental Protection Agency, 2014)	0.44–3.23	3.04–21.69
(Gustafsson & Eriksson, 2015)	0.004–0.011	0.0036–0.012	(EMP/EEA, 2016)	6.4–59	3.4–16
(Kupiainen et al., 2005)	750	80	(Timmers & Achten, 2016)	6.1–7.2	2.9–3.7

Note: mg/vkm = mg·Km^{-1}·$vehicle^{-1}$.

Brake linings consist of five different materials (Grigoratos & Martini, 2014, 2015): 20–40% (by mass) of binders (e.g., modified phenol-formaldehyde resins), 6–35% of fibres (metallic, mineral, ceramic or organic), 15–70% of fillers (e.g. inorganic compounds as barite ($BaSO_4$) or calcite ($CaCO_3$), silicates, and metal powders, 5–29% of frictional additives or lubricants (e.g., graphite, metallic particles, carbon black, and antimony trisulphide) and 10% of abrasives (e.g. aluminium oxide, iron oxides, quartz and zircon). Brake lining materials have a chemical composition with a high content of metals such as Fe (up to 60% by weight), Cu, Zn, K, Ti and Pb (up to 12% by weight) and other metals such as Ba, Mg, Mn, Ni, Sn, Cd, Cr at concentrations below 0.1% (Penkała et al., 2018; Thorpe & Harrison, 2008). 35–50% of the brake wear debris becomes airborne particulate matter (PM) while the remaining particles are deposited on road surfaces or are attracted to other parts of the vehicle (Grigoratos et al., 2018; Hagino et al., 2016). The chemical and physical composition of the brake wear particles is affected by vehicle speed, driving behaviour, vehicle maintenance, ambient conditions and brake characteristics (Kwak et al., 2013). On-road measurements and laboratory measurements (e.g., brake dynamometer test) can be used to characterize emissions from brake wear. Based on a literary survey, Grigoratos and Martini (Grigoratos & Martini, 2015) reported the following emission factors (EFs) for brake wear: 1) 2–8.8 mg $km^{-1}veh^{-1}$ for PM_{10}. 2) 0–15 mg $km^{-1}veh^{-1}$ for $PM_{2.5}$. 3) 1.2–3.1 mg $km^{-1}veh^{-1}$ for $PM_{0.1}$, where mg stands for milligrams. Road asphalt consists of a mixture of various elements (Gustafsson, 2018) 1) Mineral aggregates containing elements such as Si, Ca, K, Fe, and Al. 2) Bitumen with many compounds such as aliphatic and aromatic hydrocarbons. 3) Modifiers such as glass fillers, coal fly ash, and rubber tyres. The wearing of road surfaces depends on properties of asphalt, type of vehicle, and road surface conditions (Denier van der Gon et al., 2013). This affects the life and cycle costs of pavement and tire (Praticò et al., 2010), pavement properties, and acoustic performance. (Praticò, 2001, 2014). Different tracers such as asphaltenes and maltenes, metals (including vanadium, Ni, Fe, Mg and Ca) or polycyclic aromatic hydrocarbons (PAHs) can be used for road surface wear, but it is difficult to distinguish the specific contribution of road wear and road dust (Thorpe & Harrison, 2008). Apart from increasing with speed (Kwak et al., 2013), the increase in road wear particles depends on the type of tyre. To this end, it has been estimated that PM_{10} is 100 times higher for studded tyres than for standard tyres (Sjödin et al., 2010).

2. Measures for PM mitigation

Figure 2 and Table 7 show the main existing mitigation measures.

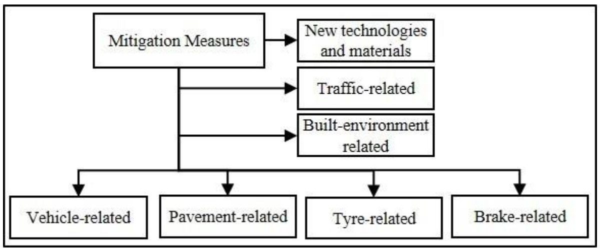

Figure 2. Mitigation measures

Table 7. Mitigation measures

Source	Mitigation Measures
Pavement	**Improvement of materials and maintenance of road surfaces.** Mineralogical nature of aggregates and bitumen. Type of pavement (e.g., porous asphalt concretes). Improving wear properties of materials. TiO_2-like treatments.
	Road cleaning/Road maintenance. Flushing and washing. Vacuum sweeping (Monks et al., 2013). Binding dust to road surface (dust binding, moistening) (Amato et al., 2014a, 2014b). Removing/immobilizing dust from road surface (Amato et al., 2014a, 2014b). Removing resuspended PM using dust suppressants (Monks et al., 2013). Storage and handling of dusty materials (AIRUSE Project, 2016).
Vehicle	**Reducing emission at the vehicle level** (Gwilliam et al., 2004)**.** Inspection and maintenance. Fuel quality; Alternative fuels. Vehicle technology. Making technical instruments effective (successful introduction of new vehicles, fuels, and emission control technologies). Retrofit (Yan et al., 2014) (e.g., Diesel particle filters (DPF) and diesel oxidation catalysts (DOC) are two examples of retrofit technologies).Scrappage (Yan et al., 2014) (refers to the replacement of old or high-emitting vehicles with newer ones that emit less pollution, before their owners would otherwise retire them from use).
Brake	**Reducing the formation of brake-source particles.** Improving/optimising brake-pad friction material (e.g., Non-Asbestos Organic (NAO) pad material (Perricone et al., 2018)).Using carbon ceramic disc to replace cast iron disc (Wakeling et al., 2017). Regenerative brakes and brake-by-wire (Wakeling et al., 2017).Thermal disc treatment (Perricone et al., 2018).
	Trapping particles. Using a capture technique. Vacuum cleaner type device (Chłopek et al., 2013). Brake Pad Waste Collection System (BPWCS) (Fieldhouse & Gelb, 2016).
Tyre	**Improvement of the composition and structure of the tyres** (Verschoor et al., 2016)**.** Wear-resistant tyres through changed composition and construction methods (Tyres with silica used as filler are, for example, less susceptible to wear than tyres with black carbon). Production of more resistant tyres to degradation (aging) from UV, moisture and oxygen.
	Potential measures against emissions and dispersion of tyre abrasion (Verschoor & de Valk, 2018)**.** Legal threshold value for tyre abrasion. Tyre label with tyre abrasion indicator. Prohibiting the use of winter tyres in summer. Tyre Pressure Monitoring System in cars. Including wheel alignment in periodic vehicle inspections. Kilometre price (Introduction of a kilometre tax).
Traffic	**Transport system improvement** (Gwilliam et al., 2004)**. Modal-based strategies/Influencing modal choice.** Improving public transportation. Cycling and pedestrian lanes. Car-sharing. Electric, Hybrids and Gas Vehicles.
	Traffic management. Traffic management. Lowering number of cars in the urban areas. Lowering traffic speed. Low emission zones (LEZ). Urban road tolls (Guevara, 2016). Key Access Regulation Schemes (Key-ARS) (Guevara, 2016).
	Fiscal policies. Polluting vehicle and fuel taxation.
Built-environment	Offices, Farms, industries, and plants.
Other	SUNSPACE (SUstaiNable materials Synthesized from by-Products and Alginates for Clean air and better Environment) (Zanoletti et al., 2018). Pollution Absorptive Billboard (Lima, Perù). Smog Free Tower in Beijing, China (ionisation technology) (Khodadad & Sanei, 2017). Air cleaning buildings (using TiO2).

Conclusions

Traffic-related sources account for 8–38% of PM_{10}. On average, for exhaust sources (ES), PM_{10} accounts for about 10 $\mu g/m^3$ and $PM_{2.5}$ accounts for about 11 $\mu g/m^3$. In addition, for non-exhaust sources (NES), PM_{10} accounts for about 12 $\mu g/m^3$, and $PM_{2.5}$ accounts for about 19 $\mu g/m^3$. Furthermore, ES are often lower than NES but the opposite may happen. Even if more studies and measurements are needed, road wear usually outranks brake wear and tyre wear, with PM concentrations up to 13 $\mu g/m^3$ and 42.8 $\mu g/m^3$ for $PM_{2.5}$ and PM_{10}, respectively. Many mitigation measures can be adopted to reduce PM emissions and they can refer to vehicles, pavements, and other emission sources. A holistic approach to the design of pavements is required, by considering not only NES but also other properties (e.g., skid resistance and drainability). This study interacts with the project LIFE18 ENV/IT/000201 (LIFE E-VIA), where tyre-pavement interaction for non-exhaust sources emerges as a key factor.

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Authors declare that they have not any competing financial, professional, or personal interests from other parties.

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