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Gap analysis and future needs of tire wear particles

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Abstract

Non-exhaust and exhaust particles from traffic were evaluated to account for nearly equal proportions in traffic-related emissions. Among non-exhaust emissions, tire wear has been a crucial contributor to Particulate matter (PM), with its mass contribution as high as 30% to non-exhaust emissions from traffic. As exhaust emissions control regulation becomes stricter, which leads to a substantial reduction in exhaust emissions from road traffic, currently relative contributions of non-exhaust particles generated from tire wear to PM is becoming more important. Accordingly, possible regulatory requirement and effectively control strategy of tire wear particles needs to be developed. This review paper covers the physical properties, chemical composition, emission rates, and mathematic model development of tire wear particles. Three main methods, including the road simulation in the laboratory, the source analysis, and the on-road direct measurement under real driving conditions, were used to analyse the tire wear particles in the existing literature. The particle number concentration presented primarily a unimodal distribution, while there was no consensus regarding the peak position of the distribution. The most important chemical components of tire wear were within coarse and fine particles.

Introduction

Exhaust and non-exhaust particles from traffic are evaluated to account for nearly equal proportions in traffic-related emissions [1,2]. Exhaust particles are generated due to incomplete combustion of fuel and volatilisation of lubricant, and non-exhaust particles are either produced from tire wear, brake wear and road surface wear or the deposited particles that already exist in the environment become resuspended owing to vehicle induced turbulence [1]. As exhaust emissions control regulation becomes stricter, developed technologies have led to a substantial reduction in exhaust emissions from road traffic.[3,4,5]. However, the formation process of non-exhaust particles has not yet been fully understood. Physical characteristics, chemical composition, emission rates, and emission model development of tire wear particles remain unclear [1-3,6].

Among non-exhaust emissions, tire wear particles have been a crucial contributor to PM, contributing to non-exhaust particle emissions by mass from traffic between 5-30% [2,7]. Tire wear particles are mainly generated in two ways: (1) shear forces between the tire tread and road mechanically wear and generates primarily coarse size particles [8]; (2) volatilisation of some tire content due to a thermal process in which local hot spots on the tire tread reach high temperatures leads to the generation of fine size particles [9,10]. The heat and friction under the interaction between tire tread and pavement not only give rise to the change in chemical composition and physical feature of tire wear particles but also incorporate substance from the road surface into these tire wear particles [11]. Moreover, Although it is difficult to measure and characterise tire wear particles, more and more researchers have discussed the necessity of possible regulatory requirement and effectively control strategy of non-exhaust emissions including tire wear particles [2,3,8]. So far, physicochemical properties of tire wear particles have not been clarified because all tire wear particles are a mixture of material coming from the tires, the material deposited on the tires, and the road [8].

The purpose of this literature review is to present the latest development in different aspects regarding tire wear particles and provide all the necessary information in terms of influence factors of tire wear, physical properties, chemical composition, emission rates and model development of tire wear particles. Moreover, this study gathers together technical evidence to assess major gaps regarding the above-mentioned aspects for current regulation of vehicles and identify further the research areas for reducing tire wear particles.

Tire wear particles

Influential factors of tire wear particles

The generation of tire wear particles is extremely complex physical and chemical process, which is dependent upon the friction energy generated at the interface between the tire tread and road surface. The amount of tire wear particles during its lifetime is closely related to the following factors: 1) tire feature, such as tire size and width, composition and cumulative mileage, 2) vehicle feature, like vehicle weight, maintenance status and engine power, 3) road surface features, such as texture pattern, road material and temperature, and 4) vehicle operating manoeuvres, such as driving speed, degree of deceleration and acceleration, degree of vehicle cornering and braking. Table 1 summarises these factors affecting the generation of tire wear particles and relative importance. Factors with a high and very high influence have a significant impact on the generation of tire wear particles. Therefore, the effective control of these significantly influencing factors provides the potential to decrease remarkably the tire wear rates per vehicle and kilometre. It is obvious in Table 1 that the generation of tire wear particles are closely associated with all stakeholders and thus reducing the tire wear particles requires the joint efforts of all the stakeholder.

Driving conditions and driving behaviour are well-recognised determinants of tire wear. Most tire rubber was lost during acceleration, braking, and cornering. Stalnaker et al. [12] tested the impact of city and motorway driving conditions on the tire wear particles using a tire-test machine. It was found that the city driving accounted for only 5% of the distance, while the tire wear was up to 63%. Luhana et al. [13] pointed out a limited negative relationship between tire wear and average trip speed. They found about 50% higher at urban driving of a mean speed of 40 km/h than at motorway driving of a mean speed of 90 km/h. Beddows et al. [14] reported that the wear particles for heavy-duty vehicle tires were several times higher for light-duty vehicle tires.

Table 1 Summary of the factors affecting the generation of tire wear particles and relative importance [3,15,16].

Influencing factors	Effect on the tire wear generated by	Effect level on the tire wear	Stakeholder category
Tire characteristics	Tire type, tire tread and chemical composition	Very high	Tire makers
	Tire radius and tire tread breadth	High	
	Tire tread temperature and tire pressure	Medium	
	Accumulated mileage and age	Medium	
Road surface characteristics	Road surface	Very high	Road makers
	Wetness and season's effect	Medium	
	Road and tire interaction	High	
Vehicle characteristics	Vehicle weight and load distribution	High	Vehicle makers
	Suspension type and condition	High	
	Location of driving wheels	Low	
	Electronic braking systems	Medium	
Driving behaviour characteristics	Speed	Medium	Drivers
	Frequency and extent of acceleration and deceleration	Very high	
	Frequency and extent of braking and cornering	Very high	

Physical properties of tire wear particles

When the vehicles extremely corner or fully brake, the tire tread temperature is generally over 180°C, which results in the thermal degradation of tire tread polymer and the volatilisation of thickener oil in the tire. These processes would generate the three modes of tire wear particles, including coarse mode, fine mode and even ultrafine mode [10,17]. Generally, there are three kinds of studies related to the characterisation of tire wear particles in the literature: (1) tire wear particles were measured directly in the laboratory using simulated wheels [8,11,18,19]; (2) PM in the ambient air was sampled and analysed by means of either the source analysis method [20] or special tire wear tracer [7,11]; (3) the wear particles of the tire under real driving conditions were performed using mobile unit [10,21]. The purpose of tire simulation laboratory studies is to obtain the contribution of tire and road wear under controlled single laboratory conditions [22]. All the studies have shown that these tire wear emissions are dependent upon various parameters including road feature, the tire characteristics and the nature of vehicle tested. In receptor modelling, it is difficult to consider all the changes of the above parameters, and thus the results from this model are likely to be only for the special region [24].

Table 2 summaries the mass size and number distribution of tire wear particles in the most important literature. In the study of Gustafsson et al. [24], they conducted the simulated investigations in the lab regarding studded and friction tires against various roughness of asphalt by means of the aerodynamic particle sizer and discovered that studded tires showed a unimodal distribution peaked at 5–6 μm. However, the size of friction tires distributed bimodal peaks at about 2–3 μm and 8–9 μm. Bimodal size distribution was found by Kreider et al. [25] for the tires on an asphalt pavement in summer and winter. Additionally, Kreider et al.[8] pointed out the mass size distribution for tire wear particles generated from friction tires against asphalt pavement was in the range of 5.0-220 μm, corresponding to the unimodal peak centre at 75 μm using a simulation method. In the study of Kaul et al. [23], the test system of the entirely enclosed tire was developed, and friction analysis of tires of two-, three- and four-wheeler vehicles against concrete asphalt roads were carried out. The final results indicated tire wear particles exhibited a bimodal distribution at the peak positions of 0.3–0.4 μm and 4–5 μm, respectively. Sjödin et al. [26] studied the various types of tires against asphalt pavements and observed a unimodal distribution in the range of 2-4 μm. In sum, the peak of tire wear particle in winter are in the range of 2–4 μm, while the peak of tire wear particles in summer centred at around 2 μm and more fine particles in summer would be generated relative to the winter. Moreover, the wear particles of studded tires distributed at the peak of 3–4 μm, generating more serious tire wear particles. In terms of the particle number (PN) distributions, Dahl et al. [19] investigated the PN distributions of the tire wear particle generated from the studded and friction tires against different kinds of asphalts using a road simulation in a lab. An ultrafine mode with a peak between 15-50 nm was observed, which was dependent upon the type of tire and pavement. Compared to the studded tire, the particle size distribution generated from the friction tires shifted to smaller diameters. Gustafsson et al. [24] found the ultra-fine particles formed by tire pavement interaction peaked in the number distribution at around 40 nm using a road simulation in a lab. Reduced speed of the road simulator gave rise to lower number concentration, while the peak position was at the same 40 nm. Sjödin et al. [26] measured various types of tires on stone mastic asphalt. There was no ultrafine particle generation for summer and winter tires. A peak at 30 nm in the PN distribution was measured for only studded tires. In addition, Kaul et al. [23] tested the tire wear particles generated from the friction tires against concrete asphalt pavement and revealed that the PN concentration exhibited a bimodal distribution with the peaks at 0.3 and 1.7 µm. Beji et al. [27] measured the PN distributions from tire and road wear and exhibited a bimodal distribution with peaks within 7-30 nm and within 50- 300 nm.

Table 2 Summary of mass and number distributions of tire wear particles

Study method	Mass size distribution	Particle number distribution	Reference
Simulation in lab	Bimodal with peaks at about 1.0 µm and 10 µm	--	[18]
Simulation in lab	--	Unimodal with a peak within 15-50 nm	[19]
Simulation in lab	Bimodal with peaks at 2.5 µm and 8-9 µm	Unimodal with a peak within 15-50 nm	[24]
Simulation in lab	Bimodal with peaks at 0.3 µm and 4-5 µm	Bimodal with peaks at about 0.3 µm and 1.7 µm	[23]
Simulation in lab	Bimodal with peaks at around 1.0 µm and 5-8 µm	--	[25]
Simulation in lab	Unimodal with a peak within 3-4 µm	Unimodal with a peak at 3 µm	[28]
Simulation in lab	--	Unimodal with a peak at 2 µm	[29]
Simulation in lab	Unimodal with a peak within 2-4 µm	Unimodal for a studded tire with a peak at 30 nm	[26]
Direct measurement on the road	Unimodal with a peak within 70-80 µm	Unimodal with a peak at around 25 µm	[8]
Direct measurement on the road	Bimodal (2.5 µm & 10 µm)	--	[7]
Direct measurement on the road	Unimodal (2-3 µm)	--	[22]
Direct measurement on the road	Bimodal with a peak within 0.1-0.6 µm and 1.0-15 µm	Bimodal with a peak within 7-30 nm and within 50- 300 nm	[27]

Chemical composition of tire wear particles

Chemical compounds for tires are significantly different due to the various types of vehicles and their required performance standards. Consequently, particles generated from tire wear possess significantly different chemical compositions. In addition, fine and coarse particles generated from tire wear exhibited various chemical compositions. There were higher concentrations of Fe, Ca, and Ti, for fine tire wear particles compared to the Ba and Sb concentrations [9,30]. In the coarse tire wear particles, the contents of Zn, Fe and Ca were dominant, followed by the contents of Ti and Sb [9,30]. In addition, Al and Si were observed to be the high concentration for the tire wear airborne particles with smaller sizes [18,24]. Gustafsson et al. [24] and Panko et al.[31] also reported that sulfur for particles from friction tire tested was enriched.

The content of tire wear particles was mainly organic matter accounting for 88%, followed by carbonate carbon with 8% and element carbon with 4% [9]. There were significant differences in the composition of PAHs and the content of individual PAHs for tire wear particles [32]. Furthermore, the main contributions for PAHs included internal combustion engine exhaust, production generated from fuel combustion and asphalt wear [8,22]. Thermal degradation of the tires would raise with increasing tire mileage, which resulted in an increase in the PAH content in tire wear particles [32,33]. Another substance named benzothiazoles was usually found in tire wear particles. Other organic substances, including natural resins, n-alkanoic acids and alkanes were found in the tire wear particles [34].

Emission factors of tire wear particles

Table 3 presents a summary of the most recent PM_{10} emission factors for tire wear of light-duty vehicles and passenger cars. It is obvious that the emission factors ranged widely from 2.4 to 13 mg km^{-1} $vehicle^{-1}$ with an average of 5.44 mg km^{-1} $vehicle^{-1}$. Such the different results might be ascribed to that the different methods, including emission inventory, simulation measurement in lab's road simulator and direct measurement on roadside, were used to calculate these emission factors. Moreover, it is worth mentioning that some data in Table 3 originated from the studies carried out 10 to 20 years ago, as tire wear has improved with advanced tire technologies [3]. Recently, Timmers et al. [35] reported that the PM_{10} emission factor was 2.9 for internal combustion engine passenger cars and 3.7 for the corresponding electrical vehicles using statistic analysis. Similarly, Beddows et al. [14] figured out that the PM_{10} emission factor was 6.6, 5.1 and 4.3 for conventional petrol passenger cars as well as 7.0, 5.4 and 4.6 for conventional diesel passenger cars on urban, rural and motorway roads, respectively. Additionally, it is found that, from the present literature, few data for $PM_{2.5}$ and ultrafine particles from tire wear particles were reported compared to PM_{10} from tire wear particles. Thus, in order to better understand the contribution for an airborne PM from tire wear particles and present more accurate evaluation, more measurements and simulations regarding $PM_{2.5}$ and ultrafine particles generated from tire wear particles need to be carried out.

Table 3 Summary of PM10 emission factors generated from tire wear particles

Reference	Emission factor for PM_{10} (mg km^{-1} vehicle^{-1})	Study .method
[36]	5.0	Emission Inventory
[34]	8.0	Emission Inventory
[37]	3.1	Emission Inventory
[38]	13.0	Simulation in lab
[39]	6.5	Simulation in lab
[40]	7.4	Simulation in lab
[18]	9.0	Simulation in lab
[26]	3.8	Simulation in lab
[11]	2.4	Direct measurement on a roadside
[35]	2.9 for internal combustion engine passenger cars 3.7 for corresponding electrical vehicles	Statistic analysis
[14]	6.6, 5.1 and 4.3 for conventional petrol passenger cars on urban, rural and motorway roads 7.0, 5.4 and 4.6 for conventional diesel passenger cars on urban, rural and motorway roads	Statistic analysis

Emission models of tire wear particles

So far, only some emission models for tire wear particles are available. EEA [41] presented a detailed methodology for estimating emission factors of tire wear particles, as shown in the following equation (1). This equation considered the emission factors for different particle size classes of various vehicle categories.

$$E_{tyre,i,j} = N_i \times M_i \times EF_{tyre,TSP,i} \times f_{tyre,j} \times S_{T(v)} \qquad (1)$$

Where $E_{\text{tire},i,j}$ is total emissions of tire wear particles of vehicles (g), N_i is the number of *i* type of vehicles, M_i is driving mileage of *i* type of vehicles (km), $EF_{\text{tire,TSP,i}}$ is emission factor of total suspended particle (TSP) mass generated from *i* type of vehicle tire wear (g/km). $f_{\text{tire,i}}$ is mass fraction of *j* particle size class of vehicle tire wear TSP, $S_{T(v)}$ is the correction coefficient of tire wear of vehicle driving speed.

The emission factors of tire wear TSP for motorcycles, cars and light goods vehicle categories could be obtained from the literature. The corresponding values are $EF_{TSP,T}$ = 4.6, 10.7, 16.7 mg/km, respectively. However, the emission factor for heavy goods vehicles is obtained based on equation (2) as a function of the passenger car emission factor $EF_{TSP,T,PC}$, axle number N_{axle} and a load factor LCF_T that is calculated according to equation (3).

$$EF_{TSP,T,HGV} = \frac{N_{axle}}{2} \times LCF_T \times EF_{TSP,T,PC}. \qquad (2)$$

$$LCF_T = 1.41 + (1.38 \times LF) \qquad (3)$$

The value of *LF* has a value between 0 (empty) and 1 (full) and represents the typical fraction of the maximum load-carrying capacity of the vehicle.

Table 4 lists the various particle size classes and the corresponding mass fraction of TSP according to the combined information in the literature. In addition, varying vehicle speed leads to various tire wear factor. Accordingly, the correction of vehicle speed is needed, and the $S_{T(v)}$ is obtained based on the following equation (4)

Table 4 Mass fraction of tire wear TSP with various particle size class [15]

Particle size class (j)	Mass fraction (*ftire*) of TSP
TSP	1.000
PM_{10}	0.600
$PM_{2.5}$	0.420
PM_1	0.060
$PM_{0.1}$	0.048

$$S_T = \begin{cases} 1.39 & v < 40\ kph \\ -0.00974 \cdot v + 1.78 & 40 \le v \le 90\ kph \\ 0.902 & v > 90\ kph \end{cases} \qquad (4)$$

Winther et al. [42] applied this detailed method to calculate tire wear particles in Denmark. The comparative analysis between calculated emission factor using this method and direct measurement on a roadside was carried out. The results showed that the PM_{10} emission factor derived from road measurement is higher than the predicted value of this model, while the $PM_{2.5}$ emission factors derived from both two methods exhibited good consistency. The underestimation of PM_{10} emission factor using the model method was due to the fact that the coarse mode tire wear particles derived from road measurement contributed larger than that from model prediction.

Recently, Beddows et al. [14] obtained the relationships between tire emissions factors and the weight (W) of passenger cars on urban, rural, and motorway roads through a non-linear least-squares fit method. The emissions factors can be obtained based on the following equation.

$$EF = b \cdot W_{ref}^{\frac{1}{c}} \tag{5}$$

where $W_{ref} = W/1000$, b and c refer to parameters of fitting the equation, as shown in Table 5.

Table 5 Parameters of fitting the equation

Road type		$PM_{2.5}$	PM_{10}
Urban roads	b	5.8 ± 0.5	8.2 ± 0.6
	c	2.3 ± 0.4	8.2 ± 0.6
Rural roads	b	8.2 ± 0.6	6.4 ± 0.5
	c	2.3 ± 0.4	2.3 ± 0.4
Motorway roads	b	3.8 ± 0.3	5.5 ± 0.4
	c	2.3 ± 0.4	2.3 ± 0.4

Gap analysis and future research needs

The physical feature of tire wear particles in the existing literature shows that most of the research is based on road simulation study in a lab, which cannot perfectly simulate physical nature of tire wear particles generated from real road driving situations. On-road direct measurement was only carried out over a short period of time, a short distance or local road conditions. The presence of interfering particles, such as brake wear particles, resuspension of road dust, and other source particles, might be crucial factors affecting the accuracy of on-road direct measurement. The particle number concentration, especially for ultrafine particle number concentration, should be addressed. The ultrafine particles could penetrate into the lungs and pose hazards related to oxidative stress and inflammation due to their higher reactivity of the free radicals and increased surface area. As for the chemical composition of tire wear particles, the different sampling method and measurement techniques were used, resulting in incomparable results. Therefore, a consistent measurement method should be developed to better understand the generation mechanism of tire wear particles. Volatile compounds on tire particles should be paid more attention because they would significantly affect secondary particle formation in the air. More literature concentrated on the tire wear particle contributions to PM_{10}. However, the $PM_{2.5}$, especially for the ultrafine particles, generated from tire wear particle, has not yet been well investigated. Accordingly, more measurements regarding these particles are needed, which provides more accurate evaluation for tire wear particle contribution to $PM_{2.5}$ and ultrafine particles. Moreover, the emission models of tire wear particles did not consider vehicle operating conditions, such as driving speed, frequency and extent of acceleration, deceleration, braking and cornering manoeuvres. Consequently, it is necessary to measure the tire wear particle data under different driving conditions, then collate and summarise it to provide general suggestions for the development of the tire wear model. Finally, the generation mechanism of tire wear particles should be developed to evaluate better the possibility of reducing tire wear particles.

Conclusions

The main conclusions drawn from the current literature research can be summarised below:

- Considering that a number of factors affecting the generation of tire wear particles, reducing these particles would need to consider not only the characteristics of the tire, but also the vehicle types and operating manners that tire mounted as well as the driven pavement feature.
- A consistent sampling and analysis methodologies need to be developed in order to avoid incomparable results.
- More measurements regarding $PM_{2.5}$ are needed, providing a more accurate evaluation for tire wear particle contribution to $PM_{2.5}$.
- The mainly chemical components of tire wear distributed in coarse and fine particle ranges. Although some studies have been carried out on the organic composition of these wear particles, the data on the organic composition of tire wear particles is quite limited.
- It is necessary to measure the tire wear particles under real driving conditions, and then collate and summarise it to provide general suggestions for the development of the tire wear model.

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