

Non-exhaust particulate matter emission from vehicles: A review

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Abstract. According to the source, particulate matter produced during vehicle driving can be divided into exhaust emission and non-exhaust emission. Exhaust emission includes exhaust pipe emission and crankcase emission, while non-exhaust emission includes brake wear, tire wear, road wear and road dust. For a long time, it has been considered that the particulate matter pollution of motor vehicles mainly comes from exhaust emissions, and the control of particulate matter pollution in various countries is mainly concentrated in the tail gas. However, with the continuous tightening of emission standards, the emission of particulate matter has been reduced, but also makes the environmental pollution of non-exhaust particulate matter increasingly prominent. This paper summarizes the research on vehicle non-exhaust particulate matter emissions, aiming to emphasize the importance of non-exhaust particulate matter emissions and the necessity of legislation, so as to reduce their contribution to environmental particulate matter concentration.

1 Introduction

According to the EDP source, the particulate matter produced by motor vehicle can be divided into exhaust emission source and non-exhaust emission source. The emission source of vehicle non-exhaust particulate matter includes brake wear, tire wear, road wear and road dust, among which road dust is an indirect source. It is estimated that the contribution of exhaust emission sources and non-exhaust emission sources to total PM₁₀ emissions related to traffic is almost equal [1-4]. The research of Barlow et al. [5] showed that, the non-exhaust particulate matter emission of China 6 gasoline vehicle was about seven times of that of exhaust particulate matter emission, and because the particulate matter of China 6 diesel vehicle equipped with DPF was very low, non-exhaust particulate matter emission has become the main source of particulate matter emission of China 6 diesel vehicle. With the increasingly stringent vehicle emission standards, the contribution of non-exhaust particulate matter emissions to the total PM₁₀ emissions related to traffic will be further highlighted [6-8].

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In addition, the impact of non-exhaust particulates on human health can not be ignored. Brake wear particles contain barium, copper, antimony, iron, etc., while tire wear particles contain zinc. These heavy metals not only cause respiratory diseases, but also have cancer risk to exposed people [9, 10]. Therefore, the emission of non-exhaust particulates has become the regulatory direction of emission standards in the next stage. As early as 2014, the Economic Commission for Europe (ECE) started the Legislative Study on the emission of particulate matter from brake wear, and planned to issue the official standard in 2022. However, the research on non-exhaust particulate matter emission in China is still relatively small. This paper reviews the literature research on vehicle non-exhaust particulate matter emission at home and abroad, and introduces the research status of non-exhaust particulate matter emission based on brake pad, tire and vehicle.

2 Experimental study on non-exhaust particulate matter emission

2.1 Experimental study in laboratory

1.1.1 Research on vehicle non-exhaust particulate matter emission test based on operating loss enclosure

Except for the California Air Resources Board (CARB), there are few reports on the indoor research of non-exhaust particulate matter emissions based on vehicle. CARB has carried out an experimental study on non-exhaust particulate matter emissions based on the whole vehicle in the operating loss chamber of chassis dynamometer [11]. During the test, the researchers kept the temperature and total volume of the chamber unchanged. The ambient air was delivered to the engine inlet through a long flexible hose, and then the vehicle exhaust was led out of the enclosure with a pipe. At the same time, the CO₂ level was monitored during the test to ensure that the exhaust gas did not leak into the chamber. Through these measures to isolate the intake and exhaust, there is no exhaust tailpipe emissions in the airtight chamber. The only emissions in the airtight chamber are tire wear, brake wear, resuspended dust and evaporative emissions. The particulate matter sampler with five PM₁₀ filters and six PM_{2.5} filters is used for particulate mass and chemical analysis.

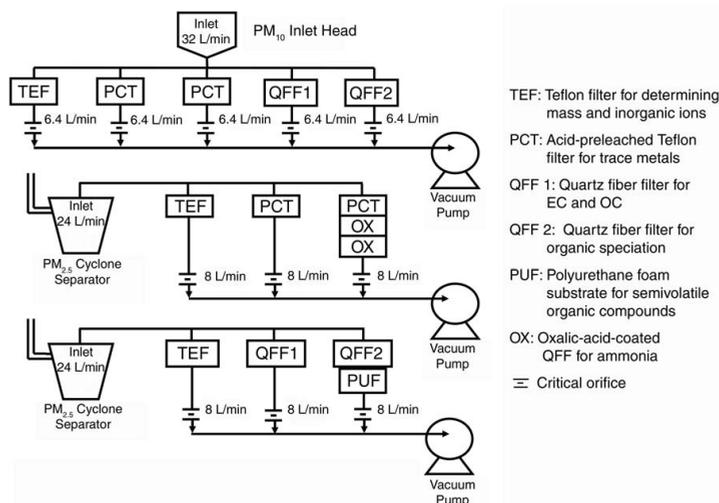


Fig. 1. Particulate matter sampling system [11].

1.1.2 Research on brake wear particle emission test based on brake dynamometer

1.1.2.1 Study on mass distribution of particulate matter

Although brake wear particles are mainly generated by mechanical processes, and coarse-grained particles are expected to be generated, many studies have shown that the concentration of fine-grained and ultra-fine-grained particles is also high^[12-14]. Garg et al.^[15] carried out particle emission tests on different brake pad wear on a brake dynamometer. It was found that 86% and 63% of the particulate matter mass in PM₁₀ and PM_{2.5} came from brake pad wear; 33% (by mass) of air brake wear particles distributed in the area with diameter less than 0.1 μm. Sanders et al.^[16] conducted a brake wear particle emission test on a brake pad dynamometer, and found that PM₁₀ accounted for 80% of the total brake wear particle mass. Iijima et al.^[17] carried out wear test research on three different kinds of asbestos free organic brake pads, and found that PM_{2.5} accounted for 56%-70% of the total brake wear particles; SEM images showed that ultra-fine particles and some fine particles looked smoother (some of which were close to spherical) and had less sharp edges than rough particles. Therefore, these fine particles are produced by thermomechanical or thermochemical processes^[18]. This may be due to that the brake wear process can cause the temperature of the brake/rotor interface to be too high, thus decomposing many brake lining materials. Therefore, some materials are likely to volatilize during braking and condense in the air flow, resulting in small particles.

1.1.2.2 Study on the quantity distribution of particulate matter

In order to understand and characterize the particles produced by brake wear, it is necessary to study their quantity size distribution. Garg et al.^[15] carried out wear particle emission test on different brake pads on a brake dynamometer, and concluded that the maximum number of particles emitted was located in the area with a diameter less than 30 nm, which was the minimum threshold value for particle size detection by ELPI. Kukutschová et al.^[14] studied the particle size distribution of brake pad wear particles in dynamometer test of low metal brake system. Using both SMPS and APS analyzers, they found that although the small particle size (< 500 nm) produced at low rotor temperature was negligible, the concentration of nanoparticles less than 100 nm increased significantly with the increase of brake disc temperature (up to 340 °C). Based on the shape of particle size distribution and its change with time, they concluded that submicron particles (100 nm-1 μm) were formed by the aggregation of primary nanoparticles through evaporation / condensation process, rather than by brake pad wear.

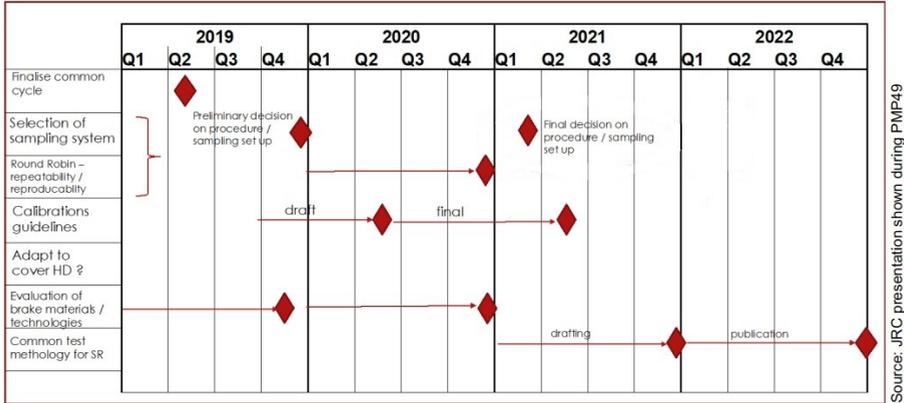
Not all studies have reported that the peak value of the number size distribution of brake wear particles occurs at the ultrafine particle size. Several studies have found that the number of brake wear particles has a peak at about 350 nm. Wahlström et al.^[18] tested the low metal brake pad and non asbestos organic brake pad in clean air environment, and detected it by Grimm aerosol spectrometer. It was found that the number of brake wear particles was bimodal, with the peak values of 280 nm and 350 nm. Mosleh et al.^[19] carried out wear particle emission test on semi metal brake pads of commercial trucks on brake dynamometer, and found that no matter what test parameters (sliding speed and nominal contact pressure) are, the number of brake wear particles presents a bimodal distribution, the first peak is about 350 nm, and the second peak appears at the higher particle size (~2.0 μm) depending on the nominal particle size and the applied pressure.

1.1.2.3 Research on ECE legislation of brake wear particles

The PMP, which is subordinate to the ECE Working Group on pollution and energy (GRPE), established two task groups in 2014 to carry out the research on brake pad wear particle emission braking cycle and brake particle emission measurement and characterization method based on brake dynamometer. At present, the PMP working group has determined the test cycle (WLTC Novel cycle) and particulate matter sampling system,

and completed the repeatability test of particulate matter sampling system. ECE plans to complete the draft standard in 2021 and issue a formal standard in 2022. As shown in Table 1, it is the potential schedule of ECE brake PN emission legislation.

Table 1. Potential timetable for ECE brake PN emission legislation.



ECE released the braking test cycle (WLTC Novel cycle) in July 2018, aiming to establish a generally accepted sampling and measurement method for brake wear particles [20]. The cycle is based on the WLTP reference database, which includes in use driving data from five different world regions (EU, USA, India, Korea and Japan) with a total mileage of 740000 km. The WLTC Novel cycle consists of 10 stages, 303 braking times, the emission test duration lasts for 4 hours and 24 minutes, and the total test mileage is 192 km.

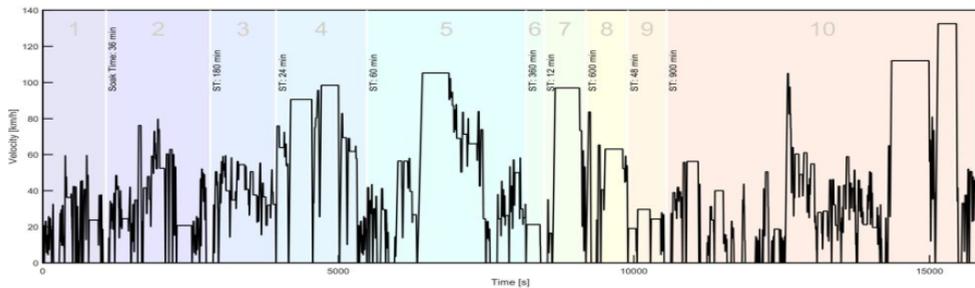


Fig. 2. Brake test cycle (WLTC-novel).

1.1.3 Research on tire wear particle emission test based on wheel road simulator

1.1.3.1 Study on mass distribution of particulate matter

The mechanical process involved in tire tread wear can lead to large particles (particle size greater than 20 μm) and coarse particles (PM_{2.5-10}). The thermal mechanical and thermochemical processes (thermal degradation of tire polymer, volatilization of filling oil and subsequent condensation of ultrafine particle mode materials) will also occur when the tire temperature exceeds 180 °C (extreme cornering, unusual handling and complete braking stop), which will lead to the production of fine particles and some small particles such as ultra-fine particles [21-23]. Studies have shown that less than 10% (by mass) of tire wear particles are airborne [23, 24].

Kreider et al. [25] tested the summer tires and friction tires on the asphalt pavement on the wheel pavement simulator, and found that the particle size distribution of the collected tire wear particles ranged from 5.0 μm to 220 μm, with a clear peak at 70-80 μm. Under the normal driving conditions (steady driving, acceleration/deceleration < 2), the particle size

distribution of the collected tire-road wear particles has a peak at 50 μm . It should be noted that in these two experimental studies, due to the limitation of instruments, the particle size measured is less than 0.3 μm . Smolders et al. [26] also conducted a similar study. They found that the average diameter of roadside tire debris was 65 μm (passenger car) and 80 μm (truck), which indicated that most of the substances emitted during tire wear would not stay in the air for a long time. On the other hand, tire wear particles in the air could be divided into fine particles and coarse particles according to their size.

Gustafsson et al. [27] carried out road simulation research on friction tire and stud tire with different asphalt materials, and detected the mass size distribution of tire wear PM_{10} by aerodynamic particle size analyzer. The results show that the mass distribution of PM_{10} in friction tire is bimodal, the peak value is about 2-3 μm and 8-9 μm , while the mass distribution of PM_{10} in stud tire is single peak with peak value of 5-6 μm . On the other hand, the concentration of PM_{10} in friction tire is significantly lower than that in stud tire. It is also found that the velocity has little effect on the shape of particle size distribution, but the total mass concentration of particles increases with the increase of velocity.

On the other hand, Kupiainen et al. [28] carried out wear emission test of friction tire and stud tire on Asphalt Concrete Pavement on wheel pavement simulator, and found that PM_{10} mass size distribution was different under different tire types and speeds. Low speed (15 km/h) is associated with bimodal mass size distribution, at least for studded tires with bimodal peak particle size of about 1.0 μm and 10 μm , while high speed (30 km/h) is related to unimodal distribution, with peak particle size ranging from 9 to 10 μm .

1.1.3.2 Study on the quantity distribution of particulate matter

In order to understand and characterize the particles produced by tire wear, it is necessary to study the particle number distribution. Dahl et al. [29] carried out road simulation research on different types of asphalt pavements with studs and friction tires. Although the particle size detection limit of the detector is 15 nm, they found an obvious ultrafine particle mode, with the peak particle size between 15 and 50 nm, and the peak particle size depends on the type of tire and pavement tested. They also found that the higher the vehicle speed, the more particles were produced, and the particle size distribution of friction tire moved toward the direction of smaller particle size (the peak particle size of friction tire was less than 20 nm, and the maximum peak particle size of stud tire was 40 nm).

Kreider et al. [25] tested summer tires and friction tires on Asphalt Pavement in the road and laboratory, but no ultrafine particles were found under laboratory conditions. Their research includes larger wear particles. The number concentration distribution of road collected particles is single peak, and the peak particle size is about 25 μm , while the number concentration distribution of laboratory generated particles is bimodal, with the first peak size of 5 μm and the second peak particle size of 25 μm . Sjödín et al. [30] carried out wear test research on all types of tires on asphalt mastic macadam pavement. The research results show that the wear test of winter tire and summer tire does not produce ultrafine particles, only the number of wear particles of stud tire has a peak at 30 nm.

2.2 Experimental study outside the laboratory

1.2.1 Tunnel test

The function of highway tunnel is similar to that of large-scale laboratory, and its known boundary conditions provide a good environment for researchers to quantify atmospheric particulate matter emission factors of tail gas and non tail gas sources. Since the concentration of non-exhaust emission tracers is low, and the meteorological impact in the tunnel is small, tunnel sampling has the advantage of maximizing the collection of particulate matter by selecting a shorter sampling period [31]. At present, the domestic tunnel test research mainly

focuses on the calculation of vehicle emission factors, particle size distribution and component characteristics, while there is less research on non-exhaust particulate matter emission which has been paid more attention in recent years^[32].

Lawrence et al.^[31, 33] calculated the particulate matter emission factors of vehicle exhaust and non-exhaust by combining highway tunnel (Hartfield tunnel) sampling and source apportionment model calculation. The results show that $PM_{2.5}$ accounts for 66% of PM_{10} , which is greatly affected by traffic (turbulence) and meteorological conditions; iron, copper, manganese, nickel, lead, antimony and traffic volume have good correlation; based on the source analysis model, PM_{10} emission factors from different sources are as following, brake wear (3.8-4.4 mg/ (km·vehicle)) and gasoline vehicle exhaust (3.9-4.5 mg/(km·vehicle)), diesel vehicle exhaust (7.2-8.3 mg/ (km·vehicle)), resuspended dust (9-10.4 mg/ (km·vehicle)), road wear (3.9-4.5 mg/ (km·vehicle)) and unexplained emission (7.2 mg/ (km·vehicle)). In the tunnel test, the non-exhaust PM_{10} emission factor (16.7-19.3 mg/ (km·vehicle)) is higher than that of the vehicle fleet (11.1-12.8 mg/ (km·vehicle)) in tunnel test. Therefore, the author emphasizes the necessity of legislation and emission reduction measures for non-exhaust particulate matter.

Hung-Lung et al.^[34] carried out a study on the particle composition characteristics of Taiwan tunnel, and found that iron, aluminum, calcium, sodium and potassium are the main elements of particulate matter, and barium is in the range of $PM_{2.5-10}$. It is concluded that $PM_{2.5-10}$ may be derived from road resuspension dust, brake wear and other mechanical friction particles, while $PM_{2.5-10}$ mainly comes from exhaust emissions during fuel combustion and friction and wear of parts and engines.

1.2.2 Research on real road emission test

1.2.2.1 Tire-road wear particle emission test

The purpose of the wheel pavement simulation laboratory study is to study the contribution of tire pavement wear particles in the isolated environment under controlled laboratory conditions. However, the contribution of resuspended dust under environmental conditions is usually additionally measured in tire pavement wear particle test of actual road using mobile device^[35]. Since the particles generated by the interaction between tire and road surface include tire rubber and pavement materials, the effect of tire wear on particulate matter concentration in the air may be underestimated by measuring the composition of tire rubber alone^[36]. Therefore, in order to evaluate the particulate matter emission of tire wear during actual operation of vehicles, so as to better analyze urban aerosol source and evaluate $PM_{2.5}$ exposure, many scholars have carried out research on tire pavement wear particulate matter emission on actual roads^[37-42]. The results show that there is a positive correlation between tire-road wear particle emissions and vehicle speed, and the use of stud tires will lead to more tire-road wear particles emissions.

Pirjola et al.^[37, 38, 40] developed a set of collection and detection device for tire pavement wear particles and road resuspension dust for actual road vehicles. Road dust samples were collected from the rear of the left tire through a conical inlet with a surface area of 0.20 m × 0.22 m and collected into a vertical tube with a diameter of 0.1 m. The researchers conducted five tests in Helsinki, Finland, on dry days, on a specially designed 20 km route. The test results show that $PM_{2.5}$ produced by tire-road wear is positively correlated with PM_{10} , and PM level increases with the increase of vehicle speed; background $PM_{2.5}$ is only about 6% of $PM_{2.5}$ behind the tire^[38].

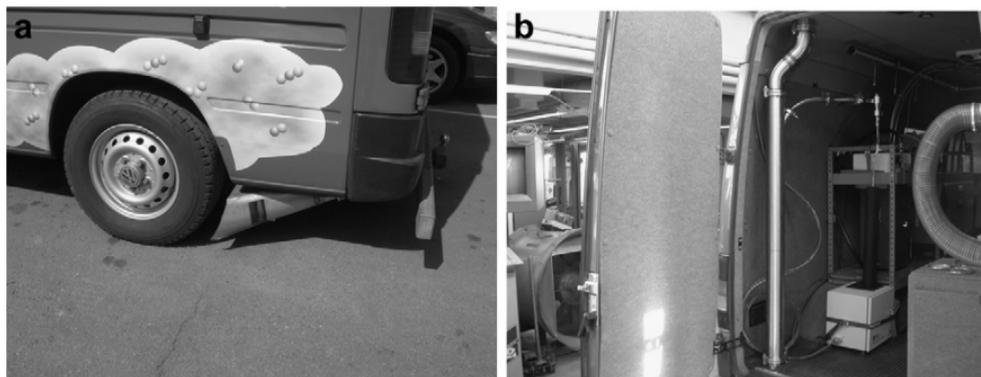


Fig. 3. Tire-road wear particulate matter emission sampling and detection device diagram [37].

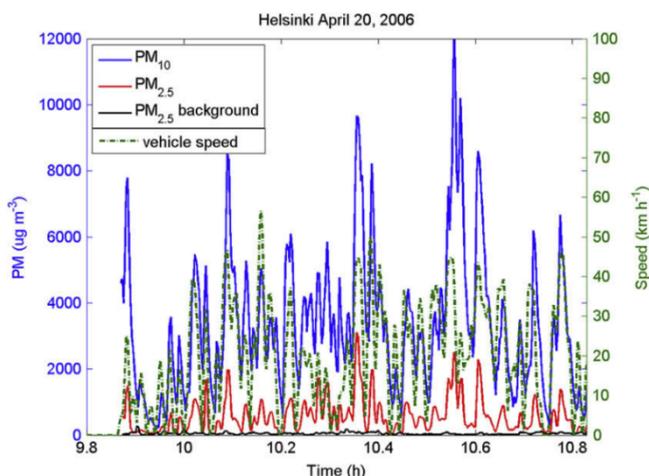


Fig. 4. Tire-road wear particle emission of test vehicle [38].

Lee et al. [39] developed a set of tire-road wear particle emission measurement system, which can also measure brake wear particulate matter emission. The PM concentration was measured by TSI Dusttrak-DRX aerosol monitor, and the mass and size distribution of fine and ultrafine particles were measured by FMPs and APS. The researchers used the system to carry out the actual road research on tire pavement wear particulate matter emissions of test vehicles, and found that a large number of tire pavement wear particles emissions will be generated when the vehicle decelerates rapidly; because the wear of vehicle tires on asphalt pavement is higher than that on concrete pavement, the PM₁₀ concentration and particle number generated by friction are relatively high.

Hussein et al. [41] quantitatively analyzed the relative importance of road surface direct wear, tire type (stud tire, friction tire, summer tire), road surface type and vehicle speed on road dust emission and resuspended dust by using mobile measurement system. The results show that the tire-road wear particle emission of the vehicle with stud tire is always the highest, while the summer tire is the lowest; In May, the tire road wear particle emission of the test vehicle with stud tire at 100 km/h was ten times higher than that at 20 km/h. However, in September, the dependence of tire-road wear particle emissions on vehicle speed is not so obvious, which may be due to less dust deposition on the road.

1.2.2.2 Brake wear particle emission test

Farwick et al.^[43] studied the brake wear particle emission of medium-sized passenger cars when driving on a closed test track through a self-designed brake wear particle inhalation monitoring system (as shown in Figure 5). It is found that for different brake materials, the emission coefficient of PM₁₀ is between 1.4 mg/(km·brake) and 2.1 mg/(km·brake), and the emission rate of one material is reduced by 18%. Because the semi closed particulate sampler limits the cooling of the brake pad, the high temperature of the brake disc even exceeds 170 °C, which will lead to the generation of ultra-fine particles, resulting in a large number of particulate emissions. In the same test, the braking temperature of the vehicle in normal driving process will not exceed 153 °C. Therefore, ultrafine brake particle emission is not expected to occur in normal driving process. Since it is not possible to collect all the wear particles by this method, the PM₁₀ emission results detected by this method are smaller than those obtained by the brake dynamometer^[15, 16, 44, 45], but the magnitude of PM₁₀ is similar.

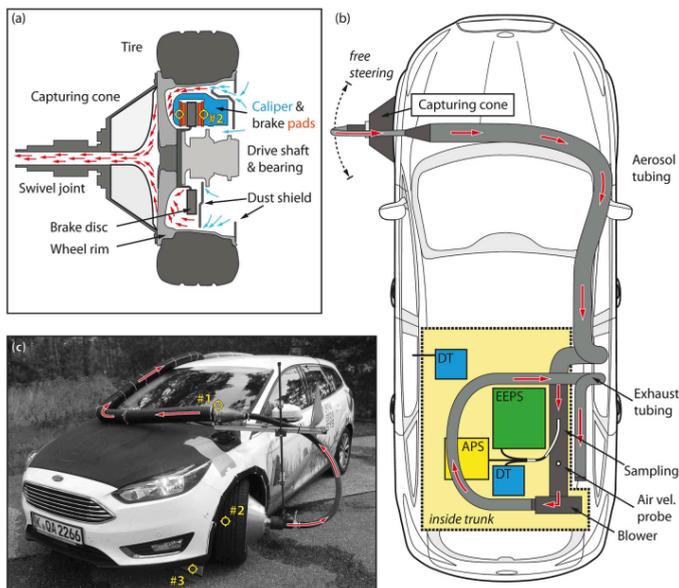


Fig. 5. Brake wear particle inhalation monitoring system ^[43].

1.2.3 Study on roadside air detection

By determining the characteristic elements or element combination of specific non-exhaust traffic related sources, researchers can estimate the contribution of traffic non-exhaust particulate matter emissions to particulate matters in the air, and analyze the air detection at different roadside stations, which may lead to different contribution rates. Thorpe et al. ^[46] analyzed the roadside air quality of a canyon road with heavy traffic in London. The results showed that the particulate matter (PM_{2.5-10}) generated by various wear accounted for 44%-57% of the total particulate matter emissions, of which brake wear accounted for 55%, tire wear accounted for 27%, and road wear accounted for 18%, the suspended road dust accounts for 20%-22% of the total PM₁₀ emission. The other 19% can be attributed to coarse-grained wear source emission, while the remaining 60% comes from vehicle exhaust and fine-grained wear emission.

Iron, barium, antimony, copper and other elements are widely associated with brake wear. According to the study of Geitl et al. ^[47], the roadside concentrations of barium, iron, copper and antimony in the urban background in London, UK, are greatly increased, and the particle

size distribution of these pollutants in the roadside air is very similar. Barium is used as a marker element of brake dust particles, which accounts for 1.1% of brake dust emission; iron is only caused by brake wear, accounting for 75% of brake dust emission. Bukowiecki et al.^[48] identified antimony as an element related to brake wear, and their research results showed that antimony emissions along urban street canyons were significantly lower than those measured along urban street canyons.

3 Study on emission factors and emission inventory

3.1 Non-exhaust particulate matter emission factor

2.1.1 Emission factor of brake wear particles

Emission Factors (EFs) are used by researchers and regulators as a tool to quantify specific pollutants emitted by a single vehicle or fleet. They can be used to predict the amount of pollutants emitted by a vehicle or a fleet of vehicles for each distance traveled, consumed a certain amount of energy or used a certain amount of fuel. EFs is usually derived for vehicle type and depends on vehicle characteristics, vehicle emission control technology, type and quality of fuel used, operating environment and operating conditions and other parameters^[49]. In order to determine EFs from non-exhaust sources and their contribution to atmospheric particulate concentration, EFs can be determined either by direct measurement (including real-world test conditions and / or laboratory measurements) or by constructing receptor models^[50]. Although EFs of relatively few vehicles are provided by direct measurement, they have the advantage of being carried out under very good control conditions. However, for brake wear, it is difficult to simulate the actual braking conditions under controlled test. On the other hand, receptor modeling requires an accurate understanding of the source components and assumes that the designated source contributes to the species measured in the receptor model^[24]. Table 2 lists the key tracers used by researchers to identify brake wear^[51].

Table 2. The most commonly used key tracer for brake wear particles^[51].

Literature	Tracer	Literature	Tracer
Adachi et al. ^[52] , 2004	Fe, Ba, Cu, Sb, Zr	Bukowiecki et al. ^[3] , 2009	Fe, Cu, Zn, Zr, Mo, Sn, Sb
Schauer et al. ^[53] , 2006	Fe, Ba, Cu	Amato et al. ^[4] , 2011	Fe, Cu, Zn, Cr, Sn, Sb
Tanner et al. ^[54] , 2008	Cu, Cd	Apeageyi et al. ^[55] , 2011	Fe, Ti, Cu, Ba
Harrison ^[56] , 2009	Ba, Cu	Duong et al. ^[57] , 2011	Ni, Cu
Dongarra ^[58] , 2009	Cu, Mo, Sb	Song et al. ^[59] , 2011	Sb, Cu, Fe, Pb
Keuken ^[60] , 2010	Cu	Harrison et al. ^[61] , 2012	Ba, Cu, Fe, Sb

Garg et al.^[15] conducted an emission test of particulates from commercial brake pads of light vehicles on a brake dynamometer. The results showed that the EFs of PM₁₀, PM_{2.5} and PM_{0.1} were 2.9-7.5 mg/ (km·vehicle), 2.1-5.5 mg/ (km·vehicle) and 1.2-3.1 mg/ (km·vehicle) respectively. The upper limit of the range of PM₁₀ EFs is very close to the EPA's 7.9 mg/ (km·vehicle), which is mainly calculated for light gasoline vehicles equipped with asbestos brakes^[22]. Sanders et al.^[16] carried out tests using low metal, semi metal and non asbestos organic brake pads show that the PM₁₀ EF of brake wear is relatively high (Table 3). The PM₁₀ EFs reported by Lükewille et al.^[62] are 1.8-4.9 mg / (km·vehicle) for light-duty vehicles and 3.5 mg/ (km·vehicle) for heavy-duty vehicles respectively, while Iijima et al.^[17] calculated that PM₁₀ EFs was 5.8 mg/ (km·vehicle) and PM_{2.5} EFs was 3.9 mg/(km·vehicle).

In general, the brake wear EFs of light vehicles measured directly are in the range of 2.0-8.0 mg/(km·vehicle) (PM₁₀) and 2.1-5.5 mg/ (km·vehicle) (PM_{2.5}).

Table 3. PM₁₀ emission factor of light vehicle braking wear in literature (mg / km·vehicle).

Literature	Research type	PM ₁₀ Emission factor
U.S. EPA ^[22] , 1995	Emission inventory	7.9
Garg et al. ^[15] , 2000	Experimental study on brake dynamometer	2.9~7.5
Lükewille et al. ^[62] , 2001	Emission inventory	1.8~4.9
Sanders et al. ^[16] , 2003	Experimental study on brake dynamometer	8.1
Luhana et al. ^[63] , 2004	Receptor model	8.8
Barlow et al. ^[24] , 2007	Emission inventory	4.0~8.0
Iijima et al. ^[17] , 2008	Experimental study on brake dynamometer	5.8
Bukowiecki et al. ^[3] , 2009	Receptor model	8.0
NAEI ^[64] , 2012	Emission inventory	7.0
Average value		6.7

Abu-Allaban et al.^[65] used chemical mass balance receptor model and scanning electron microscopy technology to determine the brake wear EFs of light and heavy vehicles on the roadside in the United States. They found that the PM₁₀ EFs of light vehicles was 0-80 mg/(km·vehicle), that of heavy vehicles was 0-610 mg/(km·vehicle), and the corresponding PM_{2.5} EFs were 0-5 and 0-15 mg/(km·vehicle), respectively. Generally speaking, higher EFs of brake wear particles are observed at the exit of expressway, while the emission of brake wear particles in expressway and tunnel can be ignored. According to Rauterberg-Wulff^[66], the EFs of PM₁₀ in tunnel is very low, with EF of 1.0 mg/ (km·vehicle) for light vehicle and 24.5 mg/ (km·vehicle) for heavy vehicle. In order to identify the wear sources in the experimental data obtained from two different locations in Switzerland, the apart project uses positive matrix factorization (PMF) in the research process, and the results calculated by this method are more consistent with the direct measurement results.

2.1.2 Particulate matter emission factor of tire wear

The tire can wear out 10% of its mass during its service life^[67], while under "normal" driving conditions, 10% of the tire wear material is expected to be emitted in the form of PM₁₀^[22]. Speed, tire type, road surface type and driving conditions have been reported as the influencing parameters of tire wear emissions^[27, 42, 51]. In order to determine tire wear PM EFs, the methods used include direct measurement (i.e. road sampling, road simulation study) and modeling.

Kupiainen et al.^[28] reported that PM₁₀ EF of friction tire was 9.0 mg/ (km·vehicle), Sjödin et al.^[30] reported that PM₁₀ EF of summer tire was 3.8 mg/(km·vehicle), and PM₁₀ emission rate in road research conducted by Panko et al.^[68] was 7.0 mg/km, which was close to PM₁₀ EF (5.0 mg/ (km·vehicle)) of light vehicles reported by EPA in the early stage, and 6.0-9.0 mg/(km·vehicle) in the research by Rogge et al.^[69]. On the other hand, the study of Sjödin et al.^[30] shows that the PM₁₀ EF of stud tire is 350 mg/(km·vehicle), and its EFs is significantly higher than that of other types of tires; the conclusion of this study is that the PM₁₀ EFs of light vehicle friction tire measured directly is in the range of 3.8-9.0 mg/(km·vehicle).

Table 4. PM₁₀ emission factor of light vehicle braking wear in literature (mg/ km·vehicle).

Literature	Research type	PM ₁₀ Emission factor
U.S. EPA ^[22] , 1995	Emission inventory	5.0
Keuken et al. ^[70] , 1999	Emission inventory	5.0

Rauterberg-Wulff ^[66] , 1999	Receptor model	6.1
Hüeglin et al. ^[71] , 2000	Receptor model	13
Lukewille et al. ^[62] , 2001	Receptor model	6.5
CEPMEIP, 2002	Emission inventory	4.5
Luhana et al. ^[63] , 2004	Receptor model	7.4
Kupiainen et al. ^[28] , 2005	Road simulation experiment	9.0
Ten Broeke et al. ^[72] , 2008	Emission inventory	8.0
Sjödin et al. ^[30] , 2010	Road simulation experiment	3.8
CEPMEIP ^[73] , 2012	Emission inventory	4.5
NAEI ^[64] , 2012	Emission inventory	7.0
Panko et al. ^[68] , 2013	Real road test	2.4
Average value		6.3

3.2 Emission inventory study

Timmers et al.^[74] studied the non-exhaust particulate matter emissions of different vehicle models through the existing literature, and found that there is a positive correlation between vehicle mass and non-exhaust particulate matter emission factors; the average weight of electric vehicles is 24% higher than that of the same internal combustion engine vehicles. According to Simons et al.^[75] on the impact of vehicle mass on non-exhaust particulate matter emissions and the emission factors of exhaust and non-exhaust particulates in various emission inventories, the author calculated the exhaust and non-exhaust PM₁₀ and PM_{2.5} emissions of light electric vehicles, light gasoline vehicles and light diesel vehicles, as shown in table 5. The analysis shows that the increasing popularity of electric vehicles may not have a great impact on PM emission level, the non-exhaust particulate matter emission accounts for 85% - 90% of the total particulate matter emission.

Table 5. Comparison of PM₁₀ and PM_{2.5} emissions of light electric vehicles, gasoline vehicles and diesel vehicles ^[74]

PM	Vehicle technology	Exhaust emission	Non-exhaust emission				Total emissions
			Tire wear	Brake wear	Road wear	Resuspended dust	
Unit: mg/(km·vehicle)							
PM ₁₀	Electric vehicles	0	7.2	0	8.9	49.6	65.7
	Gasoline vehicles	3.1	6.1	9.3	7.5	40	66.0
	Diesel vehicles	2.4	6.1	9.3	7.5	40	65.3
PM _{2.5}	Electric vehicles	0	3.7	0	3.8	14.9	22.4
	Gasoline vehicles	3.0	2.9	2.2	3.1	12.0	23.2
	Diesel vehicles	2.4	2.9	2.2	3.1	12.0	22.6

Hao et al.^[76] used the measured data to locally modify the moves model, and calculated the emission source, particle size and composition characteristics of light vehicle particles. The analysis results show that the non-exhaust emission accounts for 72.70% of the PM₁₀

emission of light-duty gasoline vehicles, and the non-exhaust emission proportion of light diesel vehicles is reduced, but it also accounts for more than 40%; the PM₁₀ and PM_{2.5} emissions of light-duty gasoline vehicles are 1/4 of that of light diesel vehicles, PM₁₀ and PM_{2.5} emissions from non-exhaust gas are the same as those of light diesel vehicles; for exhaust emissions, the particle size is mainly concentrated in 0-2.5 μm, and PM_{2.5} produced by exhaust gas of light gasoline vehicles and light diesel vehicles accounts for more than 90%.

4 Conclusions

Based on the investigation of non-exhaust particulate matter emission at home and abroad, the following conclusions can be drawn:

1) contribution of exhaust source and non-exhaust source to traffic related PM₁₀ is almost equal. Brake, tire and road wear and road dust resuspension have been identified as the most important non-exhaust emission related sources. The impact of brake wear on traffic related PM₁₀ is much lower due to the significant reduction of braking times, while the contribution of tire wear is much higher in areas where studded tires are used. Due to more stringent emission control, the relative contribution of non-emission sources to traffic related emissions (PM₁₀ and PM_{2.5}) will increase in the next few years.

2) is estimated that about 50% of total brake wear and 0.1%-10% of tire wear will emit air PM₁₀. The rest may accumulate on or near the road or be attracted by vehicles.

3) PM₁₀ of brake wear usually presents a single peak mass particle size distribution, and the peak value is between 2-6 μm. For tire wear, some researchers have found unimodal distribution and other bimodal distribution, with one peak in the fine particles and the other between the coarse particles. In any case, a large portion of PM₁₀ emissions from tire and brake wear are in the fine particulate fraction.

4) emission factors for braking and tire wear of light vehicles have been reported, ranging from 1.0-9.0 mg/(km·vehicle) and 4.0-13 mg/(km·vehicle), respectively. Most studies have found that the PM₁₀ EFs of these two sources is about 6.0-7.0 mg/(km·vehicle), which is very close to the Euro 5/6 diesel vehicle emission standard. The brake and tire wear of HDV PM₁₀ EFs is about one order of magnitude higher than LDV. In addition, it is reported that the emission coefficient of PM₁₀ is much higher when using studded tires. In the receptor model study, the most commonly used key tracers of brake wear are copper and antimony.

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