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On-Road Vehicle Measurement of Tire Wear Particle Emissions and Approach for Emission Prediction

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ABSTRACT: Airborne particulate matter has long been associated with negative environmental and health impacts. Tire wear, in the form of particulate matter and microplastics, also poses a potential hazard to human health and the ecosystem. In order to develop measures minimizing tire related pollution, it is necessary to identify and classify all relevant influencing parameters. Within the scope of this study, a measurement vehicle is presented enabling sampling and measurement of tire-induced particles under varying operating conditions. The measurement setup ensures the separation of brake and tire wear and includes particle measurement devices as well as numerous vehicle motion sensors. Based on on-road tests, correlations between driving dynamic parameters and particle emission were analyzed. Furthermore, a first approach for tire-induced particle emission prediction is presented.

KEY WORDS: tire wear, particle emissions, microplastics, road dust, environmental pollution

Motivation

The mileage of a typical light duty vehicle (LDV) tire is 40–50 tkm. During this distance, up to 30% of the tire tread mass is emitted into the environment in form of wear particles. The wear rate depends on tire type (compound, dimension), vehicle configuration (weight, engine power), and driving dynamic properties (speed, longitudinal, and lateral acceleration) [1]. Since wear occurs not only on the side of the tire, but also on the side of the road, tire and road wear particles (TRWP) must be considered as combined pollutant. Therefore, road properties such as texture, roughness, and friction level play an important role. Additionally, tire-induced resuspension of road dust (RD) has a significant influence [2]. TRWP, together with RD resuspension and brake wear particles (BWP), are the three main contributors to nonexhaust emissions (NEE). Nowadays, exhaust and nonexhaust sources already contribute to the same extent to vehicle-related PM_{10} (particle matter 10–particle mass concentration of particles smaller than 10 μm sampled with a specific sampling inlet). The

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contribution of TRWP emissions is estimated to be 5–30%, with up to 10% of tire wear mass falling into the <10 μm size fraction of airborne particles. Corresponding PM_{10}-emission factors of 3.5–9.0 mg/km are reported. The remaining wear mass is deposited on or next to the road [1]. The environmental challenges associated with tire wear therefore relate to PM_{10} on the one hand, and microplastics on the other. Epidemiological studies prove the connection between fine dust pollution and negative health effects. As a result, the recommendations of the World Health Organization have been translated into concentration limitations (PM_{10} and $PM_{2,5}$) for the ambient air [3]. Considering current trends towards more electric powered vehicles, TRWP emissions are becoming increasingly relevant. As a result, exhaust emissions are eliminated, and brake wear emissions can be effectively prevented as a result of brake blending and regeneration reducing fictional braking action to a minimum [4]. At the same time, higher vehicle masses of electric vehicles favor the generation of TRWP emissions [5], especially in the case of vehicles equipped with in-wheel motors. There is also consensus that tire wear is one of the largest contributors of anthropogenic microplastics. Regulations and standards to limit tire abrasion do not exist up to this time point. However, it is likely that this issue will also become the subject of governmental regulations in the future [6]. At present, there are few reliable findings regarding the hazardous potential of microplastics. However, many studies have already demonstrated the accumulation potential of synthetic polymers over several trophic levels [7]. The number of studies on measurement of TRWP is limited. There are several publications dealing with the topic; however, they differ strongly in the applied particle sampling strategy as well as the general objective of the study. The studies of [8], [9], and [10] were mainly concerned with the effects of tire-induced resuspension and particle loading of the road surface. The work of [11], [12], and [13] demonstrated the relationship between vehicle dynamic properties and the generation of TRWP emission for specific driving maneuvers. In [13], the influence of the air flow around wheel and on the sampling of TRWP emission were also described. Initial approaches to predict NEE are already known from [14], which were also rudimentarily applied to TRWP emissions in [15]. Furthermore, there are first measurement approaches based on testing facilities (corner module test rig) [16].

According to previous publications, the regulation of TRWP emission under real driving emissions (RDE) conditions will not be possible in the near future due to the enormous number of influencing variables. Instead, the measurement of tire-induced emissions shown in this study aims to investigate the underlying formation mechanisms. Based on the results, a first prediction approach for TRWP will be derived depending on the vehicle dynamic state.

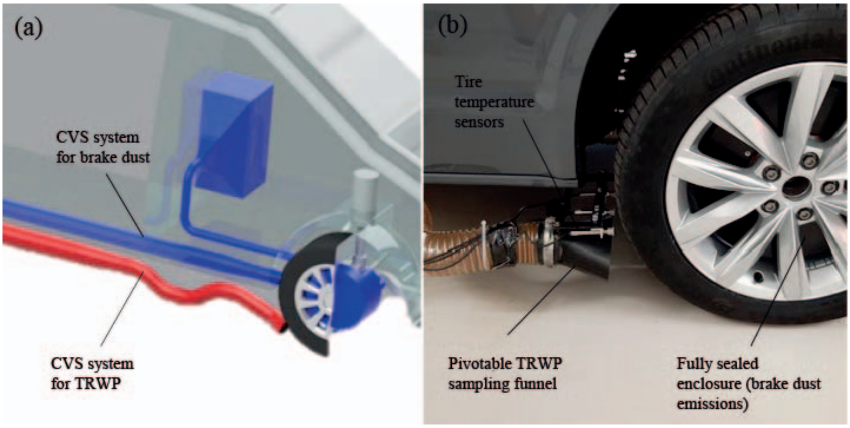

FIG. 1 — *(a) CVS systems for BWP (blue) and TRWP (red) implemented into a measurement vehicle (b) pivotable TRWP inlet funnel behind the right front tire.*

Vehicle-Based TRWP Measurement Setup

A front-wheel drive LDV with a vehicle weight of 2119 kg, a maximum engine power of 75 kW and summer tires was used for the road tests. TRWP emissions are sampled by a constant volume sampling system (CVS) on the run-out side, behind the right front tire (Fig. 1a red sampling line). The measurement setup allows parallel measurement of brake- and tire-emissions. For this purpose, the brake system was detached from the ambient air by a sealed enclosure. An electric blower evacuates brake wear particles into a sampling tunnel (Fig. 1a blue sampling line). This measure is necessary to exclude the influence of brake dust on the TRWP measurement as well. The TRWP sampling funnel was developed based on CFD simulations in order to ensure a maximum sampling and transport efficiency. Therefore, sampling losses can be described as a function of aerodynamic particle diameter and vehicle speed [13].

The TRWP inlet is mounted to the knuckle and is pivoted in lateral direction during cornering in order to ensure measurement orthogonal to the tire surface. This measure is necessary to avoid sampling losses during high steering angel maneuvers, such as in-city turning. An electric blower (volume flow 118 m^3/h) is used to drag the particles into a measurement tunnel (100 mm diameter). Inside the tunnel, samples are fed into different particle measurement systems by means of isokinetic partial volume flow sampling. Even though the system enables highly efficient sampling of TRWP particles, influences by other ambient sources such as road dust cannot be excluded or separated.

The focus of this study is on particle diameters below 10 μm. Therefore, a DustTrak II Aerosol Monitor 8530 (TSI Inc., Shoreview, Minnesota) with a <10 μm preseparator is applied (referred to as PM <10 μm). The TSI DustTrak

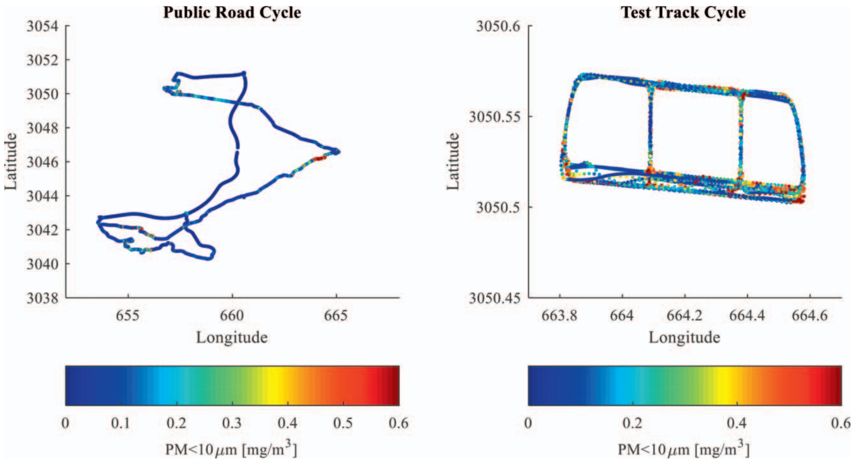

FIG. 2 — *Test environments for TRWP measurement (left) public road cycle (right) test track cycle.*

allows the measurement of particle mass concentration with a maximum sampling rate of 1 Hz. The time-resolved data is necessary to draw connections between the driving dynamic properties and particle formation process. In addition, the vehicle is equipped with a VBOX (RACELOGIC GmbH, Wetzlar, Germany), and an inertial measurement unit (IMU04; RACELOGIC GmbH, Wetzlar, Germany) to record vehicle position, speed, longitudinal, and lateral acceleration as well as additional parameters. Further analog sensors were integrated into the measurement setup. These include pyrometers (CS LT15; Optris GmbH, Berlin, Germany) for the measurement of tire temperatures and a lateral tension potentiometer (WPS-1000-MK46-CR-P25; MICRO-EPSILON GmbH & Co. KG, Ortenburg, Germany) for the determination of suspension travel of the front right wheel.

The goal is to characterize the formation of TRWP emissions under RDE conditions. For this purpose, a drive cycle in public road traffic (Fig. 2, left) is analyzed, which is based on the requirements of the regulation (EU 2018/1832). The cycle has a length of 87 km and is composed of urban ($<$60 km/h), rural (60–90 km/h), and highway segments (90–145 km/h) of $\sim$33% distance each. Due to the open configuration of the sampling system, background influences from other vehicles have to be avoided as good as possible. Therefore, the test drives were carried out at night (10:00 p.m.–12:00 a.m.) in order to ensure the lowest traffic possible. Nevertheless, the number of influencing parameters, such as local road surface pollution and continuously changing road surfaces in general, remains very high. Therefore, it makes sense to reduce the number of possible influences by carrying out tests on a closed test track at first. For this purpose, a test track

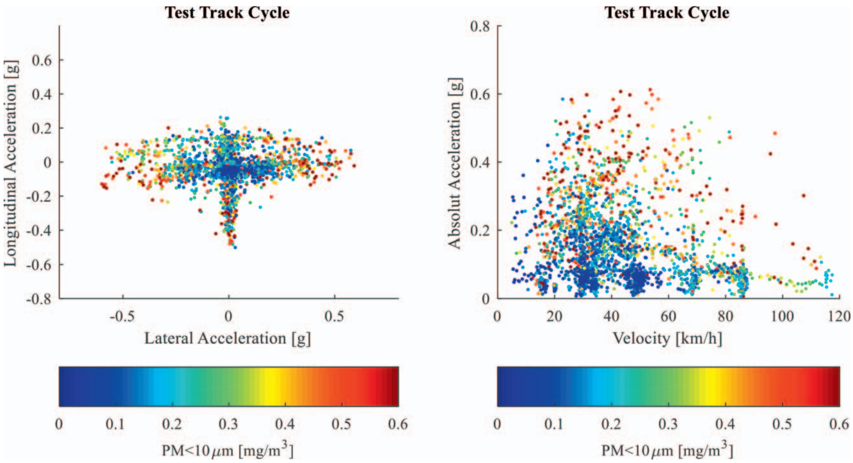

FIG. 3 — *Correlation between vehicle dynamics properties and TRWP emission based on a test track cycle: influence of longitudinal/lateral acceleration and vehicle velocity.*

cycle (Fig. 2, left) was developed by reproducing the maneuvers of the public road cycle in the same sequence on a closed testing facility.

Correlation between Vehicle Dynamic State and TRWP Emissions (Test Track)

Figure 3 illustrates the relationship between vehicle dynamic parameters and the generation of TRWP emissions. A dynamic driving style (accelerations up to 0.6 g) was applied in order to study the emissions process for a wide variety of load conditions. Vehicle speed, as well as longitudinal and lateral acceleration, characterize the vehicle dynamics state. In particular, high acceleration values are linked with increased emissions. Most high acceleration maneuvers (>0.3 g) occur at a vehicle speed below 60 km/h and are correlated with high particle concentration levels. However, the emissions potential increases with higher vehicle speeds also for significantly lower acceleration values.

The frictional power P_{friction} transmitted between the tire and the road surface is transformed into thermal energy (increased tire temperature) and mechanical energy (wear generation). The wear generation process includes the formation of particles with diameters below 10 μm. Therefore, a proportionality between the TRWP emission factor EF_{TRWP} and frictional power P_{friction} is assumed and will be further investigated within this work.

$$P_{\text{friction}} = P_{\text{therm}} + P_{\text{wear}} \rightarrow EF_{TRWP} \sim P_{\text{friction}}. \tag{1}$$

Figure 4 shows the relationship between the tire temperature and TRWP concentration. Both temperature and particle emissions peaks are caused by

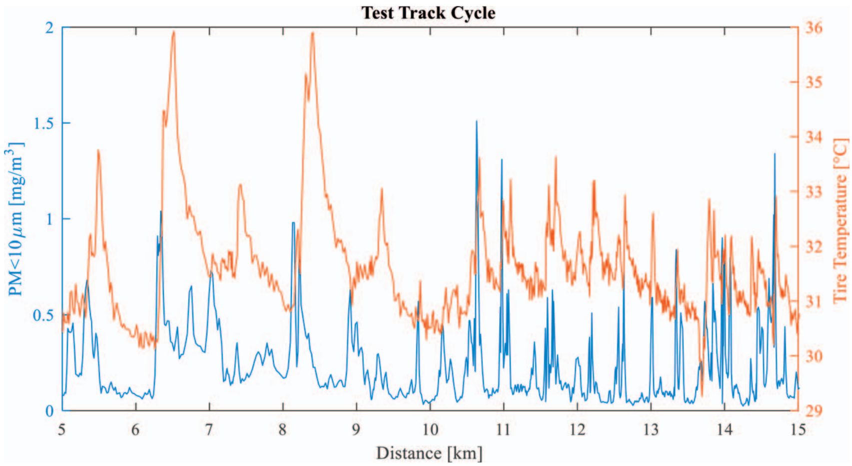

FIG. 4 — *Correlation of tire temperature and particle concentration.*

frictional processes. However, the tire temperature is subject to effects not directly related to friction. These include the influence of the road temperature, heating due to hysteresis losses, and air-cooling as a function of vehicle speed. Particle emissions, on the other hand, are subject to sampling and transport losses (CVS system) as a function of vehicle speed and particle size.

In the first step, the frictional power is calculated in a very simplified manner based on the slip velocity v_{slip} between the tire and the road surface and the sum of forces acting on the vehicle. These include the rolling resistance, air resistance and acceleration resistance.

$$P_{\text{friction}} = v_{\text{slip}}\left[(f_r m_{\text{veh}} g) + \left(\frac{v_{\text{veh}}^2}{2}\rho_{\text{air}} c_w A_{\text{veh}}\right) + m_{\text{veh}}\sqrt{a_x^2 + a_y^2}\right]. \qquad (2)$$

$$P_{\text{tire\_}f_r} = \frac{m_{\text{stat}}}{m_{\text{veh}}}\left[\frac{m_{\text{stat}} g}{m_{\text{stat}} \times g + (s_{\text{spring}} c_{\text{spring}})}\right] P_{\text{friction}}.(3)$$

TABLE 1 — *Vehicle parameters.*

Parameter	Value
f_r	0.014
ρ_{air}	1.23 kg/m^3
c_w	0.35
A_{veh}	3.3 m^2
m_{veh}	2119 kg
m_{stat}	622.5 kg
c_{spring}	400 N/cm

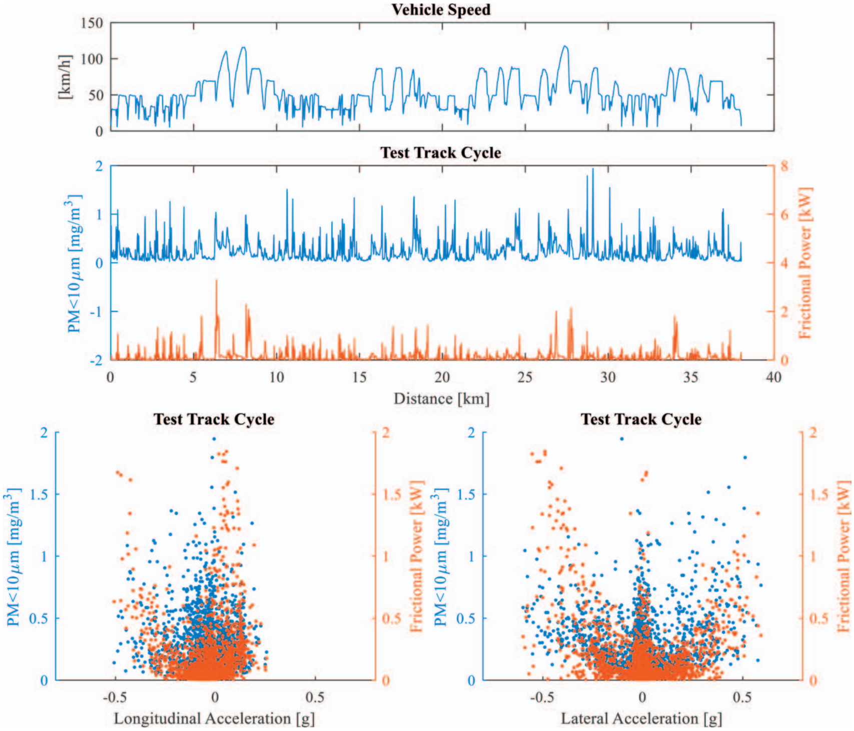

FIG. 5 — *Comparison of particle concentration and frictional power as a function of longitudinal and lateral acceleration (test track cycle).*

The power transmission is assumed proportional to the wheel load on each tire. For this purpose, a static wheel load factor is introduced relating the static wheel load m_{stat} and the vehicle weight m_{veh}. In addition, the dynamic tire load change is calculated by the deflection of the potentiometer s_{spring} and the spring constant c_{spring} for the right front tire.

Based on Eqs. (2) and (3) and the model parameters shown in Table 1, the frictional power transmitted on the right front tire was calculated and compared to the corresponding PM $<$10 μm-emission values. As shown in Fig. 5, the methodology is well suited to describe the measured emission events qualitatively. If the longitudinal acceleration is considered, a relevant increase in frictional power is found especially for braking maneuvers since the acceleration potential of the specific test vehicle is limited.

The high frictional power and emissions values at low longitudinal acceleration values are caused by cornering maneuvers. Regarding lateral acceleration, an asymmetry between left-hand ($a_y > 0$ g) and right-hand ($a_y < 0$ g) corner is apparent (note: measurement is conducted on the right front wheel). While the frictional power is higher in right-hand corners due to the higher

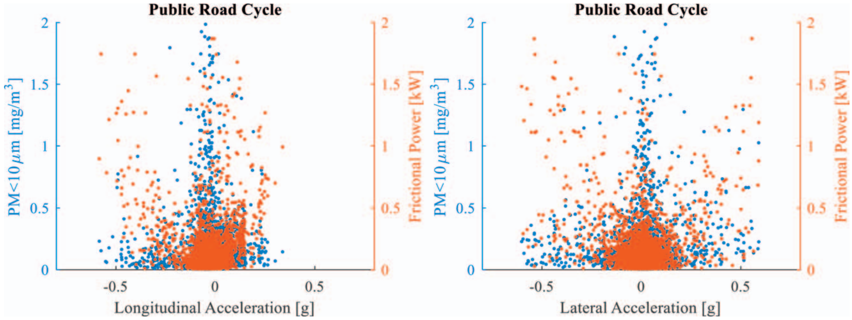

FIG. 6 — *Comparison of particle concentration and frictional power as a function of longitudinal and lateral acceleration (public road cycle).*

wheel slip (lower wheel load), the opposite effect can be seen for emissions. Consequently, an additional influence of the wheel load on the formation of PM <10 µm particles can be derived.

TRWP Measurement Based on a Public Road Cycle

In the next step, the methodology is transferred to the public road cycle (Fig. 6). As expected, besides driving dynamics parameters also other effects play a role. An increase of frictional power does not necessarily lead to higher emission values. Some effects are comparable to those, found on the test track, such as the higher emission values in left-hand ($a_y > 0$ g) opposed to right-hand ($a_y < 0$ g) corners.

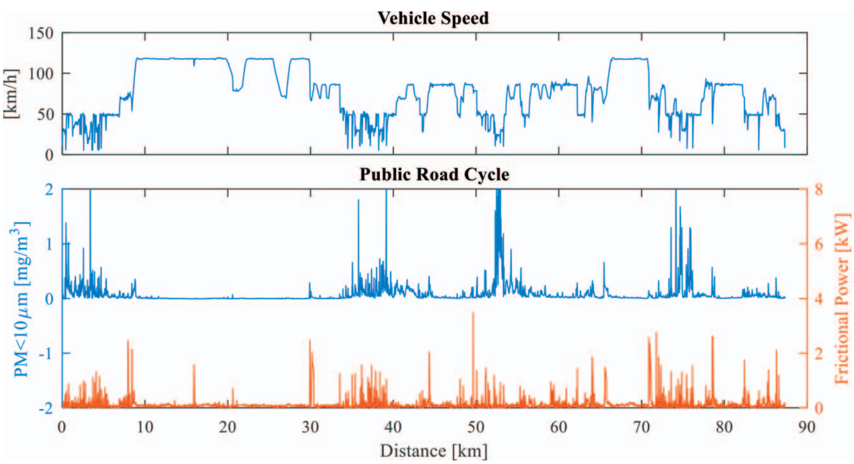

FIG. 7 — *Vehicle speed, emissions values and frictional power along the public road cycle.*

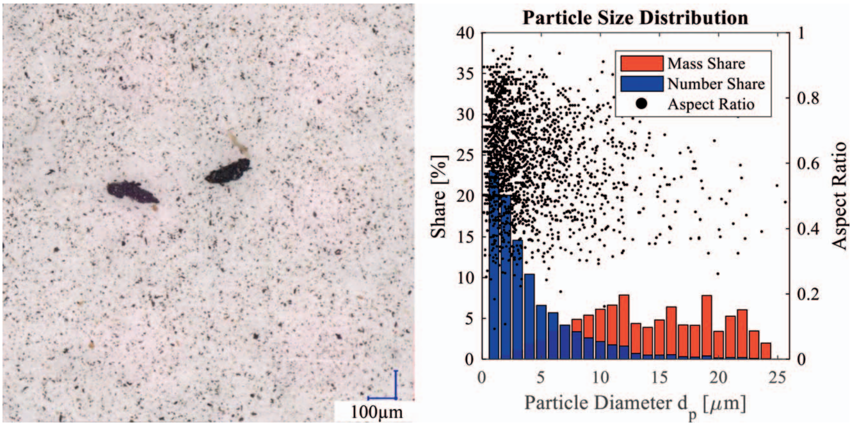

FIG. 8 — *Microscopic image of TRWP sample (left) mass/number share and aspect ratio based on image processing software (right).*

However, on average the TRWP emission response to the frictional power is significantly lower. This indicates a dependence from the road surface. More importantly, the highest particle concentrations are measured while the frictional power is low ($a_x/a_y \approx 0$ g). This effect has to be attributed to local road dust contamination and tire-induced resuspension.

Figure 7 shows the vehicle speed, frictional power, and emission level along the course of the public road cycle. Areas with increased frictional power are associated with increased TRWP concentrations. The urban segments, which are characterized by a lower vehicle speed (<60 km/h) but have a high maneuver density, especially contribute significantly to tire-related PM <10 µm emissions. In addition, resuspension may play a role since particles accumulate on the road surface inside the street canyons. Significantly lower emission levels are recorded on the rural segments. The highway segments, which are characterized by long straight stretches, show only few relevant emission peaks except for the acceleration and deceleration events at the beginning and the end of the segment. In addition, the dependency of sampling efficiency from vehicle speed has to be considered. According to a simulation-based estimation by [13], a reasonable percentage of particles (40%) can be collected at low vehicle speeds (≤30 km/h). However, the sampling efficiency decreases well below 10% for higher vehicle velocities (>60 km/h).

Analysis of TRWP Size Distribution (Public Road)

In the next step, the particle size distribution (PSD) was analyzed. Therefore, a Dekati eFilter (Kangasala, Finland)and a TSI Optical Particle Sizer

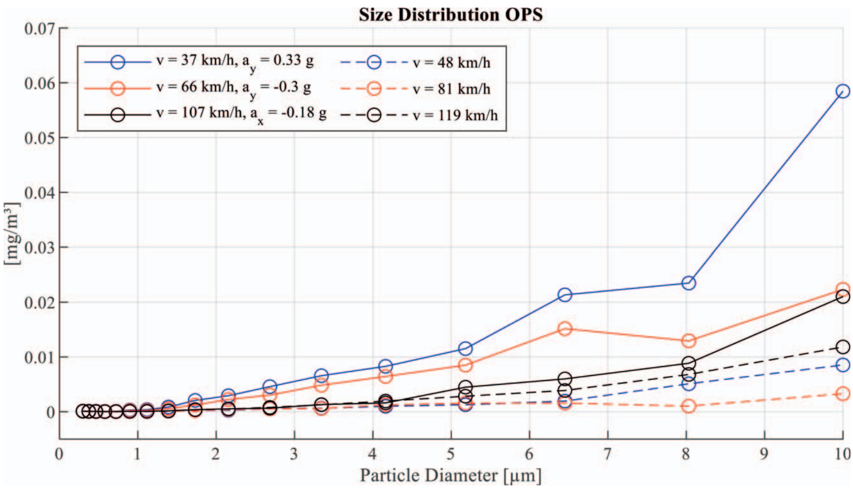

FIG. 9 — *Mass-related PSD for different driving maneuvers (public road cycle) 22.*

3330 (CleanAir Engineering, Palatine, Illinois) were integrated into the measurement setup. The Dekati eFilter was used for particle sampling on a filter for a complete public road cycle. The filter was analyzed using an optical microscope (VHX 7000, Keyence, Itasca, Illinois) and evaluated by image processing software. Figure 8 shows the dust sample and the corresponding evaluation. In order to analyze the PSD, particles were divided into discrete size fractions of 1 µm each from 0–25 µm and their share relative to the total particle number was determined.

The number-related PSD is dominated by small particles with a maximum for particle diameters below 1 µm (Fig. 8, right). It should be noted that these cannot be linked directly to TRWP due to sampling from the ambient air. However, the mass-related PSD reveals that the measurement of PM <10 µm emissions is mainly determined by more coarse particles, since particles <1 µm do not contribute significantly to particle mass. In addition, the particle shapes were analyzed. An aspect ratio = 1 corresponds to an ideal sphere. TRWP particles show a tendency to deviate from an ideal sphere with increasing diameter and show more elongated shapes.

Figure 9 shows the mass-related PSD evaluated by the TSI OPS 3330, which allows a time-resolved measurement of discrete particle sizes from 0.3 to 10 µm. For this purpose, different sections on the road cycle were averaged over a duration of 10 seconds. At first, sections with constant speed on city, rural, and highway segments were analyzed to determine the size distribution under low driving dynamic load.

Afterwards, the same procedure was applied for characteristic driving maneuvers. As a result of increased acceleration, emission values of the coarse particle fractions >1 μm rise considerably. The highest mass increase was recorded in the urban segment. This is consistent with the previous finding of high emission levels in the urban segments.

Approach for TRWP Emission Prediction

Tire-induced emissions represent a complex mixture of particles varying in formation mechanisms, characteristic size distribution, material composition, and morphology. At first, emission-factors due to particle resuspension $\mathrm{EF}_{\mathrm{Res}}$ and friction-induced particle generation $\mathrm{EF}_{\mathrm{TRWP}}$ have to be distinguished

$$\mathrm{EF}_{\mathrm{tire}} = \mathrm{EF}_{\mathrm{TRWP}} + \mathrm{EF}_{\mathrm{Res}}. \tag{4}$$

As shown for the public road cycle, road dust resuspension plays a major role and may overshadow friction-induced emissions in many cases. Road dust particles are either carried upwards along the wheel rotation or are resuspended by flow-induced forces (Saffmann force) in the wake of the tire

$$\mathrm{EF}_{\mathrm{Res}} = f_{\mathrm{Res}}(d_p, \rho_p, A_p, \ldots n) \times v_{\mathrm{veh}}. \tag{5}$$

In addition to the particle loading of the road surface, further parameters must be taken into account. These include the particle properties (diameter d_p and density ρ_p), the molecular adhesion to the road surface (Hamaker constant A_p), the porosity of the road surface, and the tire dimensions as well as tread pattern. Consequently, the emission factor $\mathrm{EF}_{\mathrm{Res}}$ can be specified as a function of the vehicle speed v_{veh} and a dynamic proportionality factor f_{Res}.

TRWP emission occurs as result of friction between the tire and the road surface. The particle size, shape, and material composition depends on the particular wear mechanism (tribochemical reactions, abrasion, and cyclical stress). In addition, tire type (rubber compound, tread structure, age) and pavement parameters (asphalt type, porosity, and condition) play a decisive role. Further influence variables are the wheel load F_N and tire surface temperature T_{tire}. The friction-related emission factor $\mathrm{EF}_{\mathrm{TRWP}}$ can therefore be determined as a function of the frictional power P_{friction} and a dynamic proportionality factor f_{TRWP}

$$\mathrm{EF}_{\mathrm{TRWP}} = f_{\mathrm{TRWP}}(F_N, T_{\mathrm{tire}}, \ldots n) \times P_{\mathrm{friction}}. \tag{6}$$

The prediction of tire-induced emissions is therefore a highly complex challenge. For a meaningful prediction, the individual influencing variables must be investigated in detail. Further investigations should be carried out under laboratory conditions (e.g., on a chassis dynamometer) in order to reduce noise and sampling losses. Nevertheless, this work provides important insights into the tire emission process under real operating conditions.

Conclusion

TRWP represent the future main source of vehicle-related PM_{10}. At the same time, tire abrasion is already classified as one of the largest sources of microplastics. However, knowledge of TRWP formation and measurement is limited. Within the scope of this study, a vehicle-based measurement method was presented.

Based on a test track cycle, the causal relationship between the TRWP formation and driving dynamics stress (frictional power) was shown. Under public road conditions, the correlation between TRWP emission and frictional power is much weaker and overshadowed by a large number of disturbance variables (e.g., road dust resuspension). Over the course of the public road cycle, the highest emission values were found within the urban segments, which can be explained by the high maneuver density. However, sampling losses at higher vehicle speeds have to be considered. Analyzing the size distribution of TRWP, the formation of particles >1 µm was directly linked to the driving dynamic stress (accelerated maneuvers).

Furthermore, a first framework for the prediction of tire-induced particle emissions was presented. Therefore, the frictional power provides a suitable basis. However, further influencing variables need to be identified and implemented into a model. For example, there appears to be a relationship between PM <10 µm emissions and tire load. In addition, a strong influence of the asphalt type is indicated, which should be addressed in further studies.

The goal of this study was to characterize the emissions behavior of TRWP under real operating conditions. Based on this methodology, more detailed studies can be derived in the future (e.g., influence of tire compound, road compound).

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