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Study of brake wear particle emissions of a minivan on a chassis dynamometer

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Abstract

Car brakes appears to be a significant atmospheric pollutant source, with a contribution to total non-exhaust traffic related PM_{10} emissions being estimated at approximately 55% in big cities and urban environments (Bukowiecki et al., 2009). Brake wear particle emissions of a minivan running on a chassis dynamometer were measured using a custom sampling system, positioned close to the braking system, under different initial speeds (30km/h and 50km/h), deceleration rates (0.5m/s^2 , 1.5m/s^2, 2.5m/s^2) and ambient temperature (0°C, 15°C and 25°C). Braking from 50km/h to full stop, results in 40-100% more particles compared to 30km/h, depending on the deceleration rate. It was also found that only 9-50% of the total particles emitted, are released during the braking phase and therefore the most significant amount is released on the acceleration phase following. High brake pad temperatures, result in a bimodal distribution with the first peak being at 1μm and the second falling at the nanometer scale at 200 nm. The ambient temperature appears to have a negligible effect on the particle generation.

Nomenclature

a	Time at 10th braking
APTL	Aerosol and Particle Technology Laboratory
b	Time at 20th braking
BM	Braking Metric (bar · s)
CPC	Condensation Particle Counter
ELPI	Electrical Low Pressure Impactor
HBP	Hydraulic Brake Pressure
MOBILAB	Mobile Laboratory
OBD	On Board Diagnostics
PM	Particulate Matter
PN	Particulate Number
PN¬background	Minimun of PN curve from a to b time
PNCPC	CPC concentration
PNsampled	Total particle number collected
Qanalyzer	Flow rate of CPC (25 cm3/s)
WLTP	Worldwide harmonized Light vehicles Test Procedure
Δx	Analyzer measurement interval (1s)

1. Introduction

There are several studies reporting that the contribution of exhaust and non-exhaust traffic related sources to total traffic related PM10 emissions is almost equal (Querol et al. 2004; Amato et al. 2011; Denier Van der Gon et al. 2012; Denier Van der Gon et al. 2013). Furthermore, there is a general consensus that the relative contribution of non-exhaust traffic related sources will increase in the forthcoming years due to the more stricter regulations already introduced for exhaust emissions control (Denier Van der Gon et al. 2013; Pant and Harrison, 2013; Amato et al. 2014; Grigoratos and Martini, 2015). Among the non-exhaust traffic related sources, brakes appears to be one of the most significant with their contribution to total non-exhaust traffic related PM10 emissions being estimated at approximately 55% in big cities and urban environments (Bukowiecki et al., 2009). However, not all brake wear particles become airborne. It is estimated that approximately 50% of brake wear is emitted as PM10 (Garg et al., 2000; Sanders et al., 2003; Kukutschová et al., 2011; Harrison et al., 2012), while the rest may deposit on the road with its fate remaining unknown (Wik and Dave, 2009). It is deduced that higher concentrations of brake wear particles are found near busy junctions, traffic lights, pedestrian crossings, and corners. However, particles may also be released from the brake mechanism or wheel housing sometime after the primary event.

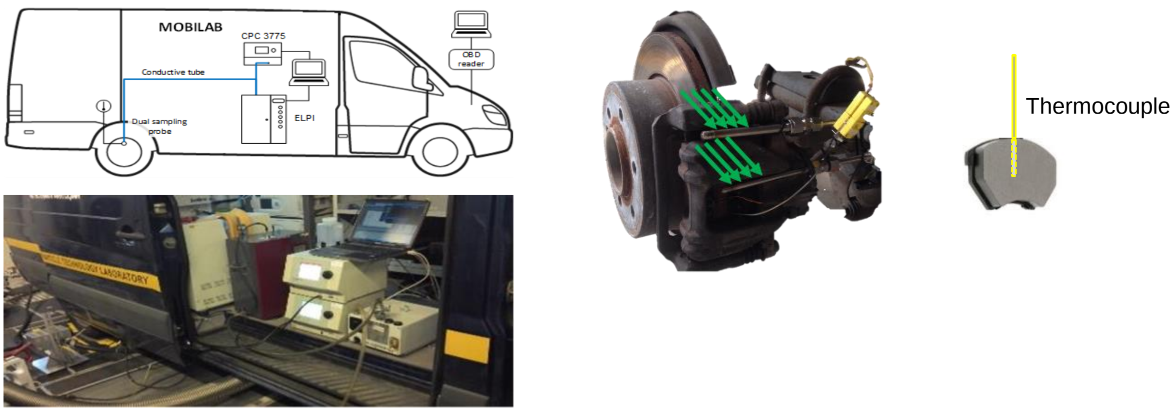
Driving parameters such as initial and final speed of the vehicle during the braking event, deceleration rate, duration and severity of the braking event as well as the frequency of brake use appear to have a large influence on the generation mechanism and the properties of emitted wear particles. From the available literature studies it is seen that different applied driving conditions often result in different - or sometimes - contradictory results. For instance, initial speeds of 7-100 km h^{-1} and decelerations of 0.1-7.9 m s^{-2} have been applied for normal and full stop braking applications. As a consequence, different results regarding brake wear PM and PN distributions, emission factors and chemical composition have been reported (Garg et al., 2000; Sanders et al., 2003; Mosleh et al. 2004; Von Uexküll et al. 2005; Iijima et al. 2007; Wahlstrom et al. 2010; Mathissen et al., 2011). This needs to be taken into account when comparing experimental data with those available in the literature. Furthermore, existing test cycles (i.e. Mojacar, Los Angeles City Traffic, SAE J2707) have been designed for industrial applications such as study of brakes' durability, and therefore they are not appropriate for assessing real world brake wear emissions (Grigoratos and Martini, 2015; Perricone et al. 2015). A common definition of "normal" driving conditions as well as of "severe", "extreme" or "infrequent" conditions would be extremely useful as it would narrow down the range to be taken into consideration, at least when discussing about real world brake wear emissions.

The aim of the present study is to investigate brake wear particles generated on a chassis dynamometer under carefully selected driving conditions in terms of their physicochemical characteristics. More specifically, the number concentration and distribution of brake wear particles generated under different initial speeds and deceleration rates are being investigated. To our knowledge this is the first published study including brake wear particles' generation and sampling on a chassis dyno level and aims also into comparing the results with those found from other studies conducted in a brake dynamometer level.

2. Experimental setup

2.1. Sampling System

Brake wear particle measurements were performed with APTL's MOBILAB vehicle (Mercedes Benz Sprinter 315) running on a climatic chassis dynamometer (VELA 2 – Joint Research Center, Ispra). The test cell VELA 2 has the capacity of measuring pollutant emissions from light duty vehicles at varying test temperatures (from -10°C to +35°C) in order to investigate the temperature effect on emissions. The sampling system was installed in one of the rear wheels due to lab space constrictions and the particle measurement equipment and data acquisition system in the loading compartment of the van as shown in Fig. 1. The dynamometer roller driving the rear wheel axle, was set to simulate 70% of the inertia mass of the vehicle to match the weight distribution of the vehicle and therefore simulate real world braking of the front wheels, where due to the higher braking forces more particle emissions are expected.



a

b

Fig. 1 a) Experimental apparatus arrangement, b) sampling probes and brake pad thermocouple

The sampling probes were positioned close to the brake disc/pad in order to sample the naturally (not forced) airborne particles and to ensure high sampling efficiency. Furthermore, the length and the bends of the tubing were kept to the least possible in order to minimize particle losses. Finally, the selection of the position was based on the need to minimize the possible effect of the wear of the tyres. Assuming that the rotation of the wheel forces generated tyre wear particles to move towards the back of the wheel, only a small portion of tyre wear particles would be sampled with the selected configuration. Furthermore, the selected driving conditions (i.e. application of certain initial speeds and braking decelerations) have not been correlated to the generation of fine and ultrafine tyre wear particles (Grigoratos and Martini, 2014), therefore it is expected that the contribution of the tyres – at least at the current campaign – would be negligible for the aforementioned sizes and minimized for coarse wear particles.

The custom sampling probes consisted of 2 x ¼ in. SS pipes connected to a single conductive silicon tube towards the particle measurement instrumentation. Each probe tube had 4 holes of 2mm diameter across the length and facing towards the direction of the brake pad/disc system through the brake calliper slots (fig 1b). The dual probe concept was applied in order to spatially cover a larger area of sampling. The particle losses due to the non-isokinetic sampling (probe flow vs. local flow field) is expected to be approximately 25% at particle diameters of 5 μm and decrease with decreasing diameter (Sanders et al. 2003).

The Brake pad temperature was measured via a thermocouple installed within the brake pad material. The thermocouple was positioned in the centre of all axis of the pad. The vehicle speed and the hydraulic brake pressure were acquired from the OBD port of the vehicle. Particle number concentration and size distributions were measured with a TSI CPC 3775 (0.003 – 3.0 μm) and an ELPI (0.033 - 10 μm), respectively.

2.2. Driving conditions - braking parameters

Several different tests were performed in order to study the generation of wear particles under different braking conditions. Since no particular driving cycle for studying brake wear particles exists, the idea involved the braking of the vehicle under constant conditions by employing different initial speeds and different deceleration rates. Initial speeds of 30 and 50 km/h as well as deceleration rates of 0.5, 1.5 and 2.5 m s^{-2} were selected. As shown in Table 2, six different tests were performed with each test comprising of 20 repetitions of each braking event. Harder braking tests (i.e. initial speed of 50 km h^{-1} and deceleration rate of 2.5 m s^{-2}) were also performed under different environmental temperatures (i.e. 0, 15, and 25°C) in order to study the possible effect of this parameter to the particles' emissions.

Table 1. Driving and environmental parameters selected for the braking campaign

Test cycle (#)	Start of braking speed (km/h)	Deceleration (m/s^2)	Ambient Temperature (°C)
1	50	0.5	25
2	30	0.5	25
3	50	1.5	25
4	30	1.5	25
5	50	2.5	25, 15, 0
6	30	2.5	25 ,15, 0

The selection of the initial speeds and decelerations was based on the need to better represent driving conditions met in urban environments. The reason for studying urban braking behaviour has to do with the fact that the contribution of brake wear is reported to be significant in big cities and urban environments (up to 55%), while due to the limited number of braking events it has been found to be negligible (~3%) in highways (Bukowiecki et al., 2009). As seen from an extended analysis of the WLTP database performed by the PMP informal working group (PMP, 2015), average speeds of 30 km h^{-1} or less represent approximately 55-60% of the trips performed in urban areas worldwide (with initial speed of 30 km h^{-1} being the 50th percentile), while speeds of 50 km h^{-1} or less cover approximately 90% of the cases. From the same analysis it comes out that in European urban areas only 5% of average speeds are higher than 60 km h^{-1} and therefore they can be considered as "extreme" or "threshold". Regarding the selection of the deceleration rates, 90% of braking events analyzed from the urban part of the WLTP database occur with an average deceleration rate lower than 1.25 m s^{-2} with the most frequent values being around 0.4 m s^{-2}. Based on the analysis conducted it was decided to select the deceleration rate of 0.5 m s^{-2} in order to represent a rather typical urban braking mode, a rate of 1.5 m s^{-2} as a more aggressive and "threshold" braking mode and a rate of 2.5 m s^{-2} as an extreme and closer to the industrial standards braking mode (PMP, 2016). Due to a technical problem at the dynamometer the experiment of 1.5 m s^{-2} was interrupted and therefore the results will not be presented here.

3. Results and discussion

3.1. Braking vs. Acceleration

Fig. 3 shows Particle Number concentration, brake pressure and wheel speed over time of the different testing cycles zoomed at a section between 10-15th braking out of 20 of each cycle. It can be seen from the PN concentration curves how brake wear particles are released at different braking patterns and wheel accelerations.

For example, at softer braking (0.5 m s^{-2}), both at 50 km h^{-1} and 30 km h^{-1} initial speed, a single brake event reveals a clear twin peak PN concentration curve, the first at acceleration phase and the other during brake application. At 30 km h^{-1} and 2.5 m s^{-2} a single sharp curve can be seen at brake application, while at 50 km h^{-1} and 2.5 m s^{-2} a more spread curve without distinct peaks is obtained.

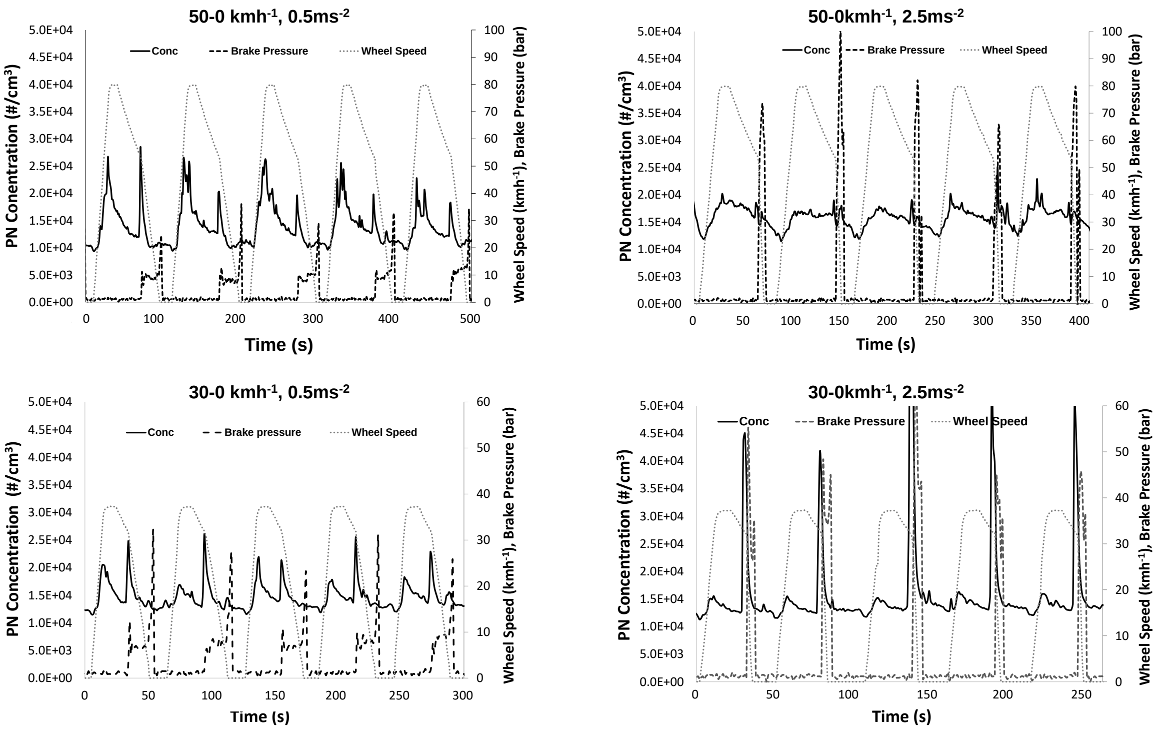


Fig. 2 PN concentration, Wheel Speed and Brake Pressure over time for the four different braking cycles. The graphs show 5 (out of 20) braking events

In order to make comparisons of the four different braking patterns and also evaluations within each cycle e.g. acceleration phase particles versus braking phase particles, a metric called Particle Number Sampled was calculated from Equation 1.

$$\boldsymbol{PN_{sampled}} = [\sum_{a}^{b}(\boldsymbol{PN_{CPC}} - \boldsymbol{PN_{background}})\boldsymbol{\Delta x}] \cdot \boldsymbol{Q_{analyzer}} \qquad (1)$$

The duration of the sum for the calculations is set to the last 10 braking events, from 10th - 20th, to ensure that particles possibly attached from the history of the brake pad/disc system have been released at the previous wheel acceleration phases of the cycle. Furthermore, with this approach a minimum disc temperature threshold is reached assuring thus a better representativeness of the braking events tested with those of real driving conditions.

In Fig. 4 results of the Braking versus Acceleration Phase Particles are shown. Acceleration Phase Particles are defined as those that are released during the wheel acceleration and coastdown part of the cycle. Of course someone could easily assume that part of these particles come from other sources rather than brakes with the most prominent being tyre wear. However, as explained previously the selection of the position was based on the need to minimize the effect of the wear of the tyres. For that reason the expected contribution of the tyres is negligible for the ultrafine and fine particles and minimum for coarse wear particles.

As it can be seen from Fig. 4 the particles emitted at each braking event are comparable for all different braking patterns. However, at the lower initial braking speed of 30 km h^{-1} the percentage over total particles is higher. This maybe an indication that a higher number of smaller particles of magnetic content (i.e. Fe oxides) is emitted when

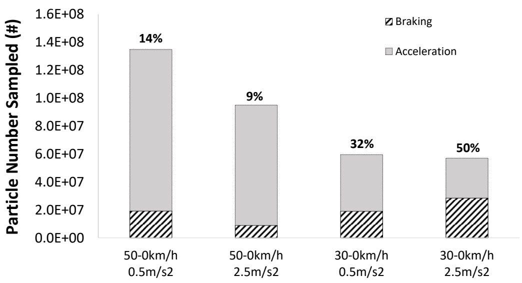


Fig. 4 Braking Particles partition over total PN sampled

higher initial braking speed is applied. These particles are most probably attracted to the brake mechanism or the rim and released at a later stage when the wheel is accelerating (Boutler, 2006). On the other hand, at higher initial speed only up to 15% of the total particles is emitted at the braking event. This can be attributed to the lower resuspension at lower wheel acceleration due to the lower swirling air flow and lower vibrations. Similar two peaked shapes have been also reported in brake studies conducted at brake dynamometers with however quite different proportions (Nosco et al. 2015; Perricone et al. 2015).

3.2. Particle Number Distributions vs. Brake Pad Temperature

The ELPI system was used for the measurements of the PN distributions because it can provide fast and second by second measurements. Therefore, a single braking event that lasts even for few seconds can be studied and characterized.

Particle number distributions of the braking cycles are shown in Fig 5. These represent the peak values obtained at braking application duration. For each cycle, the low temperature distribution corresponds to the first braking of the cycle (20 brakings) and the higher temperature to the last.

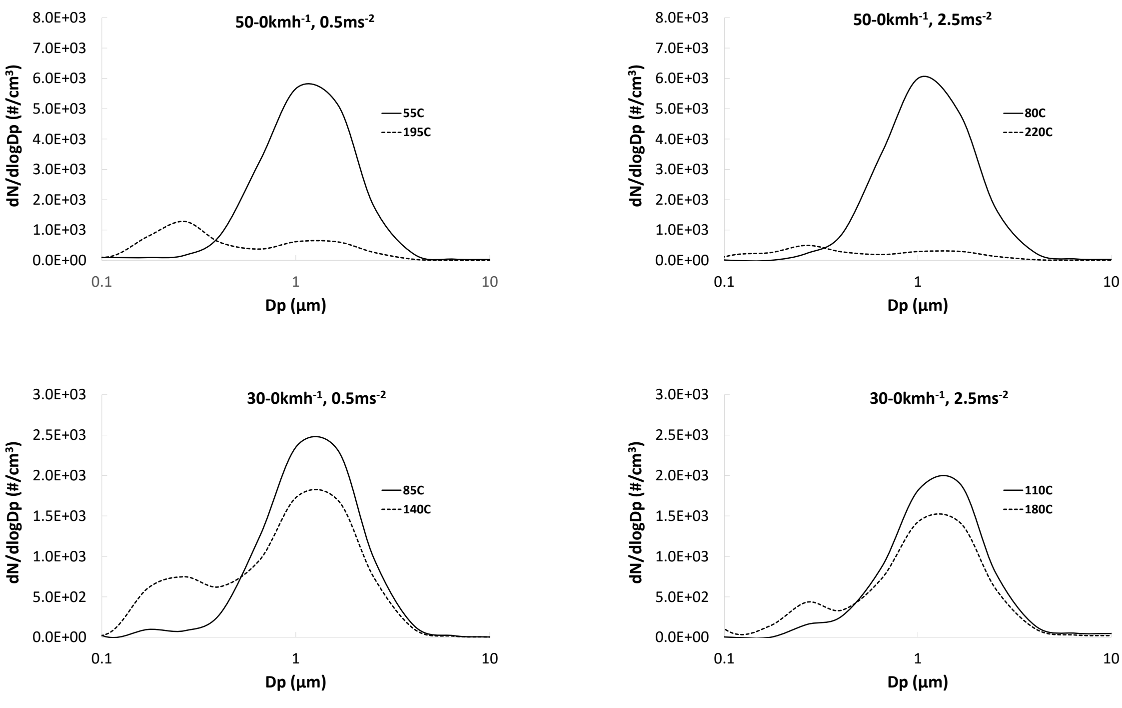


Fig. 5 Particle Number distributions for braking cycles at low and higher brake pad temperature

At lower brake pad temperatures <100°C, mean aerodynamic diameter of approximately 1.5 μm was observed. At higher temperatures, a bi-modal distribution is observed with a second peak at the nanometer scale, at approximately 200 nm. High nanoparticles production has been linked with temperatures of the disc higher than 180°C (Nosco et al. 2015). The current study shows that even in temperatures of the pad higher than 140°C a clear second peak at the nanoparticle size range appears.

Higher brake pad temperatures activate the thermo-oxidation mechanism of the organic content of the pad resulting ultrafine particles. Also higher pad temperatures are followed by higher disc temperatures that produce more nanoparticles according to the "third layer" mechanism described by several researchers (Österle et al. 2006). On the other hand, larger diameter particles can be attributed to the mechanical wear mechanism.

3.3. Particle Number Concentration vs. Ambient Temperature

The climatic dynamometer gave the opportunity to test the harder braking cycles (50-0 km h^{-1}, 2.5 m s^{-2} and 30-0 km h^{-1}, 2.5 m s^{-2}) at ambient temperatures of 25°C and 0°C to see whether the brake wear PN emissions are affected. Prior to the start of the tests the brake pads were preheated in order to have the same initial temperature at the start of the test. Results are shown in Fig. 6 and 7. Slightly lower PN at lower temperature can be attributed to the slightly lower temperature of the pads (Fig 6) and the disc that affect wear particles production.

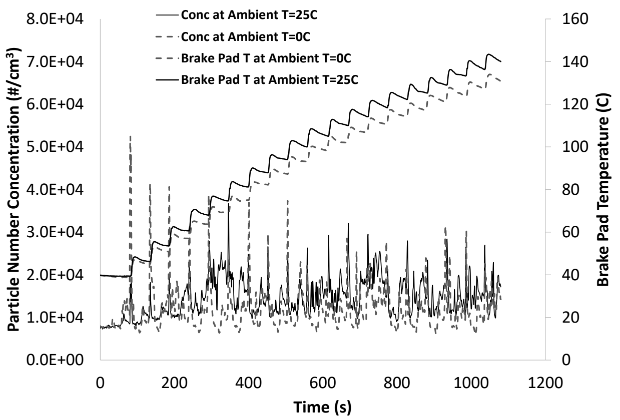


Fig. 6 Braking test cycle (30 – 0 km h^{-1}, 2.5 m s^{-2}) performed at 0 and 25°C

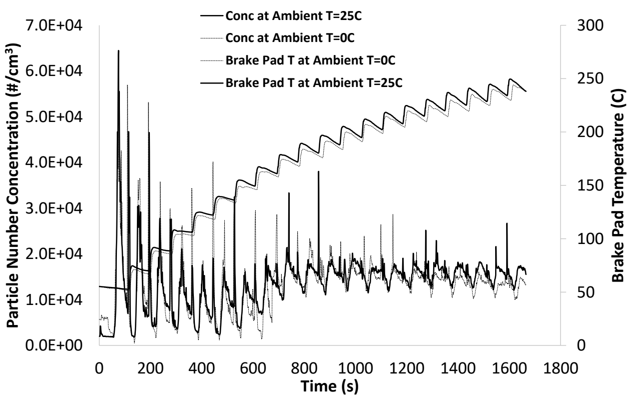


Fig. 7 Braking test cycle (50 – 0 km h^{-1}, 2.5 m s^{-2}) performed at 0 and 25°C Ambient Temperature

Furthermore, a cycle derived from real-world driving and braking data (PMP IWG unpublished data) that simulates average urban driving behaviour was repeated at the dynamometer at ambient temperatures of 0, 15 and 25°C. Again the brakes were preheated to have the same initial temperatures in all tests. As it can be seen from Fig. 8, the brake pad temperature is marginally affected by the ambient temperature.

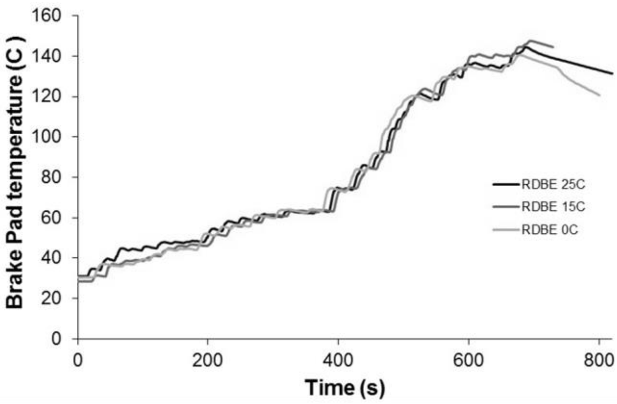


Fig. 8 Brake Pad Temperature over Time for a braking cycle representing real world urban driving performed at 0, 15 and 25ºC

Generally, lower emissions at lower ambient temperatures can be explained with the thermophoresis phenomenon. A larger temperature gradient of the emissions surfaces (pad/disc) and the surrounding air and surfaces (calliper, wheel, etc.) can result larger forces to airborne particles towards the colder surfaces. Therefore, less particles can travel beyond the vehicles wheel and be released to the environment.

4. Conclusions

The current study aimed at investigating the physical characteristics of brake wear particles generated by a whole vehicle on a chassis dynamometer under different initial speeds, deceleration rates and ambient temperatures. The selection of driving conditions was made in such way to better represent driving conditions met in urban environments due to the fact that the contribution of brake wear is more significant in big cities and urban sites.

Braking from 50km/h to full stop, results in 40-100% more particles compared to 30km/h, depending on the deceleration rate. Lower deceleration rate results more particles released due to the higher contact time of the disc/pad. This fact could be useful for future speed limit legislation within urban areas.

Regarding the PN distribution, higher temperatures of the pad result in a bimodal distribution with the first peak being at approximately 1 μm and the second falling at the nanometer scale at approximately 200 nm. Even if high nanoparticles production has been linked with temperatures of the brake system higher than 180°C, the current study demonstrates that also in temperatures of the pad higher than 140°C a clear second peak at the nanoparticle size range appears. Although it is not common to heat the brake pad material at these high temperatures under normal urban driving, aggressive driving or driving in hilly areas may do. Several toxicological studies have shown that particles in the nanometer scale are particularly dangerous as they can enter the blood stream through the lungs (Oberdörster 2005, Oostingh 2013). Furthermore, metallic brake wear particles damage tight junctions within the mechanisms that involve oxidative stress (Gasser et al., 2009; Zhao et al., 2015); therefore, the important point is not only the particle mass, but also the particle quality (e.g. chemical composition and biological effect).

Regardless the driving conditions, a single brake event reveals a clear two peak PN concentration curve, the first at acceleration phase and the second during brake application. The total particles emitted during the braking phase account 9-50% and therefore the most significant amount is released on the acceleration phase following. These are most probably particles that have been deposited in the brake system from past braking and are released due to the high velocity flow resulting from the wheel acceleration.

The ambient temperature appears to have a negligible effect on the particle generation. Slightly lower PN concentration at lower temperatures can be attributed to the lower temperature of the pads and the disc that affect wear particles production.

5. Licensing

Acknowledgements

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