Faculty of Engineering
University of Kragujevac

Ministry of Science, Technological
Development and Innovation

10th International Congress
Motor Vehicles & Motors 2024

ECOLOGY - VEHICLE AND ROAD SAFETY - EFFICIENCY

Proceedings

University of Kragujevac

Department for Motor Vehicles
and Motors

International Journal for Vehicle
Mechanics, Engines and
Transportation Systems

October 10th - 11th, 2024
Kragujevac, Serbia

10th International Congress
Motor Vehicles & Motors 2024

ECOLOGY -
VEHICLE AND ROAD SAFETY
- EFFICIENCY

Proceedings

October 10th - 11th, 2024
Kragujevac, Serbia

Publisher:	Faculty of Engineering, University of Kragujevac Sestre Janjić 6, 34000 Kragujevac, Serbia
For Publisher:	Prof. Slobodan Savić, Ph.D. Dean of the Faculty of Engineering
Editors:	Prof. Jasna Glišović, Ph.D. Asst. prof. Ivan Grujić, Ph.D.
Technical preparation:	Asst. prof. Nadica Stojanović, Ph.D. Asst. prof. Ivan Grujić, Ph.D.
Cover:	Nemanja Lazarević
USB printing:	Faculty of Engineering, University of Kragujevac, Kragujevac
ISBN:	978-86-6335-120-2
Year of publication:	2024.
Number of copies printed:	100

CIP - Каталогизација у публикацији
Народна библиотека Србије, Београд

CIP - Каталогизација у публикацији Народна библиотека Србије, Београд

629.3(082)(0.034.2)
621.43(082)(0.034.2)

INTERNATIONAL Congress Motor Vehicles and Motors (10 ; 2024 ; Kragujevac) Ecology - Vehicle and Road Safety - Efficiency [Elektronski izvor] : proceedings / [10th] international congress Motor vehicles & motors 2024, October 10th - 11th, 2024 Kragujevac, Serbia ; [editors Jasna Glišović, Ivan Grujić]. - Kragujevac : University, Faculty of Engineering, 2024 (Kragujevac : University, Faculty of Engineering). - 1 USB fleš memorija ; 1 x 1 x 6 cm

Sistemski zahtevi: Nisu navedeni. - Nasl. sa nasl. strane dokumenta. - Tiraž 100. -
Bibliografija uz svaki rad.

ISBN 978-86-6335-120-2

a) Моторна возила -- Зборници b) Мотори са унутрашњим сагоревањем -- Зборници

COBISS.SR-ID 153339657

Publishing of this USB Book of proceedings was supported by
Ministry of Science, Technological Development and Innovation of the Republic of Serbia

SCIENTIFIC BOARD

President: Prof. dr Jasna Glišović, UniKg, FE, Serbia

Secretary: Assoc. Prof. dr Aleksandar Jovanović, UniKg, FE, Serbia

Members:
Prof. dr Giovanni Belingardi, Politecnico di Torino, Italy
Prof. dr Ivan Blagojević, University of Belgrade, FME, Serbia
Prof. dr Murat Ciniviz, Selcuk University, Turkey
Prof. dr Adrian Clenci, University of Pitesti, Romania
Assoc. Prof. dr Aleksandar Davinić, University of Kragujevac, FE, Serbia
Prof. dr Miroslav Demić, University of Kragujevac, FE, Serbia
Prof. dr Jovan Dorić University of Novi Sad, FTS, Serbia
Assoc. Prof. dr Boris Stojić, University of Novi Sad, FTS, Serbia
Prof. dr Jovanka Lukić, University of Kragujevac, FE, Serbia
Prof. dr Valentina Golubović Bugarski University of Banja Luka, FME, Republic of Srpska, Bosnia and Herzegovina
Prof. dr Aleksandra Janković, University of Kragujevac, FE, Serbia
Assoc. Prof. dr Aleksandar Jovanović, University of Kragujevac, FE, Serbia
Prof. dr Emrullah Hakan Kaleli, YTU, Istanbul, Turkey
Prof. dr Dimitrios Koulocheris, NTUA, Athens, Greece
Prof. dr Božidar Krstić, University of Kragujevac, FE, Serbia
Prof. dr Danijela Miloradović, University of Kragujevac, FE, Serbia
Prof. dr Alexander Novikov, OSUni, Orel, Russia
Prof. dr ing Oday Abdulah, TU Ham, Germany
Prof. dr Radivoje Pešić, University of Kragujevac, FE, Serbia
Prof. dr Snežana Petković, University of Banja Luka, FME, Republic of Srpska, Bosnia and Herzegovina
Prof. dr Ralph Puetz, Landshut University UAS, Germany
Prof. dr Dragan Ružić, University of Novi Sad, FTS, Serbia
Assoc. Prof. dr Aleksandar Stevanović, UniPitt, USA
Assist. Prof. dr Slobodan Mišanović, Project Manager GSP Beograd, Serbia
Prof. dr Zoran Lulić, University of Zagreb, FSB, Croatia
Prof. dr Igor Gjurkov, FME, Skopje, Republic of North Macedonia
Prof. dr Sunny Narayan, Instituto Tecnológico y de Estudios Superiores de Monterrey, Mexico
Prof. dr Zbigniew Lozia, WUT, Warsaw, Poland
Prof. dr Breda Kegl, University in Maribor, FME, Slovenia

ORGANIZATIONAL BOARD

President:	Asst. prof. dr Ivan Grujić, UniKg, FE, Serbia
Secretaries:	Asst. prof. Nadica Stojanović, Ph.D., UniKg, FE, Serbia Assist. Slavica Mačužić Saveljić, M.Sc., UniKg, FE, Serbia

CONGRESS ORGANIZERS

University of Kragujevac
Faculty of Engineering of the University of Kragujevac
Department for Motor Vehicles and Motors, FE Kragujevac
International Journal “Mobility & Vehicle Mechanics”

CONGRESS PATRONS

Ministry of Science, Technological Development and Innovation
City Council of Kragujevac

PREDGOVOR

U oktobru se na Fakultetu inženjerskih nauka Univerziteta u Kragujevcu tradicionalno održava skup istraživača i naučnika koji se bave proučavanjem motornih vozila, motora i drumskog saobraćaja. Od 1979. do 2004. godine održano je trinaest bienalnih MVM simpozijuma koji su 2006. prerasli u Međunarodni kongres MVM. Od tada je održano devet MVM kongresa, a oktobra 2024. godine Fakultet inženjerskih nauka je organizovao deseti međunarodni kongres MVM od 10. do 11. oktobra 2024. godine.

Na deseti kongres Motorna vozila i motori, MVM2024 dostavljen je veliki broj naučnih radova iz Srbije i inostranstva. Kongres tradicionalno podržavaju Ministarstvo za nauku, tehnološki razvoj i inovacije Republike Srbije, Univerzitet u Kragujevcu, Fakultet inženjerskih nauka i međunarodni časopis „Mobility and Vehicle Mechanics“.

Tema Kongresa MVM 2024 bila je „Ekologija – Bezbednost vozila i na putevima – Efikasnost“. Tokom ovog istraživačkog putovanja, učesnici su puno naučili kroz rad na različitim sekcijama, koje su pokrivale širok spektar tema u vezi sa inženjerstvom u automobilskoj industirji, od fundamentalnih istraživanja do industrijskih primena, naglašavaju interakciju između vozača, vozila i životne sredine i stimulišući naučnu interakcije i saradnju.

Međunarodni naučni odbor u saradnji sa organizacionim odborom izradio je podsticajan naučni program. Program je ponudio preko 54 prezentacije radova, uključujući predavanja po pozivu i radove u sekcijama. Prezentacije na ovom kongresu obuhvatile su aktuelna istraživanja u oblasti motornih vozila i motora sprovedena u 12 zemalja iz celog sveta.

Zadovoljstvo nam je bilo što su nam uvodničari bili profesor Emrulah Hakan Kaleli (sa Tehničkog univerziteta Yıldız, Turska), profesor Ralph Putz (sa Univerziteta Landshut UAS, Nemačka) i profesori Nenad Miljić i Slobodan Popović (sa Univerziteta u Beogradu, Srbija). Izazovi i rešenja u korišćenju vodonika kao goriva za motore sa unutrašnjim sagorevanjem, korišćenje aditiva nanoborne kiseline dodatog u motorno ulje, kao i evropska politika o budućoj mobilnosti na putevima su bile teme uvodnih predavanja.

Sigurni smo da je ovaj program pokrenuo živu diskusiju i podstakao istraživače na nova dostignuća.

10. Kongres MVM 2024. finansijski je podržalo Ministarstvo za nauku, tehnološki razvoj i inovacije Republike Srbije.

Zahvaljujemo se iskusnim i mladim istraživačima koji su prisustvovali i prezentovali svoju stručnost i inovativne ideje na našem kongresu.

Posebnu zahvalnost dugujemo članovima međunarodnog naučnog odbora i svim recenzentima za njihov značajan doprinos visokom nivou kongresa.

Naučni i organizacioni komitet Kongresa MVM2024

FOREWARD

In October, the Faculty of Engineering University of Kragujevac traditionally holds gatherings of researchers and academics who study motor vehicles, engines and road traffic. From 1979 to 2004, thirteen, biennal MVM Symposiums have been held and they grew into an International Congress MVM in 2006. Since then, ninth MVM Congresses have been held, and in October 2024, the Faculty of Engineering organized the tenth International Congress MVM from 10th to 11th October 2024.

A large number of scientific papers from the Serbia and abroad were submitted to the tenth Congress “MVM2024”. Congress is traditionally supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia, University of Kragujevac, Faculty of Engineering and the International Journal “Mobility and Vehicle Mechanics”.

The theme of the Congress MVM 2024 was "Ecology - Vehicle and Road Safety - Efficiency". Along this journey we learned from the various sessions, which broadly cover a wide range of topics related to automotive engineering from fundamental research to industrial applications, highlight the interaction between the driver, vehicle and environment and stimulate scientific interactions and collaborations.

The International Scientific Committee in collaboration with the Organising Committee built up a stimulating scientific program. The program offered over 54 presentations, including key-note speakers and paper sessions. The presentations to this conference covered current research in motor vehicle and motors conducted in 12 countries from all over the world.

We were pleased to have professor Emrullah Hakan Kaleli (from Yıldız Technical University, Türkiye), professor Ralph Pütz (from Landshut University UAS, Germany) and professors Nenad Miljić and Slobodan Popović (from University of Belgrade, Serbia) as the keynote speakers, addressing Challenges and solutions in using hydrogen as a fuel for internal combustion engines, using nanoboric acid (nBA) additive added in engine oil, as well as European policy on future road mobility.

We are sure this program will trigger lively discussion and will project researchers to new developments.

The 10th Congress MVM 2024 was financially supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia.

We would like to thank experienced and young researchers, for attending and bringing their expertise and innovative ideas to our conference.

Special thanks are due to the International Scientific Board Members and all reviewers for their significant contribution in the high level of the conference.

Scientific and Organizational committee of Congress MVM2024

CONTENT

INTRODUCTORY LECTURES

SECTION A
Power Train Technology

SECTION B
Vehicle Design and Manufacturing

SECTION C
Vehicle Dynamics and Intelligent Control Systems

SECTION D
Driver/Vehicle Interface, Information and Assistance Systems

SECTION E
Transport Challenges in Emerging Economies

International Congress
Motor Vehicles & Motors 2024
Kragujevac, Serbia
October 10th - 11th, 2024

Motor Vehicles & Motors

MVM2024-051

Jasna Glišović[1]
Saša Vasiljević[2]
Jovanka Lukić[3]
Danijela Miloradović[4]

SUBSYSTEM AND SYSTEM ANALYSIS OF BRAKE WEAR PARTICLES FOR PREDICTION AND CONTROL OF THE TRAFFIC NON-EXHAUST EMISSION

ABSTRACT: Previous studies of brake wear emission have primarily performed as laboratory testing, i.e. on the brake dynamometer, which may not accurately reflect real-world driving conditions, especially vehicle’s dynamics. Different experimental designs have been developed to avoid that brake wear particles could be mixed with other non-exhaust emission sources, including tire particles and road resuspension particles. The subsystem level results (research object is brake), can provide useful data to increase the certainty of the system-level results (vehicle in the laboratory or on the road). The inclusion of real-world conditions can be enhanced by implementing a different Real-Driving Emission (RDE) solutions which does not affect the normal cooling of the vehicle's brakes and complements the test bench research to validate its results. Once the predictions for brake emissions produced by vehicles are improved, this may become a key component of a traffic-based model that combines data on different vehicles with different driving styles and environmental conditions, providing the possibility of better understanding the relevant sources of non-exhaust emission involved at the environmental level. Another possible methodology would determine the vehicle’s behaviour in the traffic environment using simulations, considering the vehicle dynamics at the system level makes the estimations much closer to reality. This research would open an innovative way for traffic engineers and environmental scientists to study the real brake emissions besides exhaust emissions in various traffic conditions. This paper aims to develop the most optimal methodology for prediction and control of brake emission released by either motor vehicles or electric cars day-to-day in order to reduce air pollution and improve the air quality in urban areas.

KEYWORDS: brake, wear, particle emission, modelling, traffic

INTRODUCTION

Brake wear particles are considered as one of the major contributions to road traffic-related emissions and have long exceeded the regulated exhaust particulate emissions. Perricone et al. reported that 35–58.5% of the particles resulting from wear emitted by elements of the brake system, discs, and pads became airborne [1]. Furthermore, Sanders et al. stated that the wear particles generated by a vehicle’s brakes are 50–70% airborne, whereas 15–25% of them remain on the wheel [2]. UNECE's Particle Measurement Program (PMP) have elaborated and proposed a standardized measurement methodology and regulation of brake dust was adopted in 2023, with contributions from

---

[1] Jasna Glišović, Ph. D., Full professor, University of Kragujevac Faculty of Engineering, Sestre Janjić 6, 34000 Kragujevac, Serbia, jaca@kg.ac.rs
[2] Saša Vasiljević, Ph. D., Teaching assistant, Academy of Professional Studies Šumadija, Department in Kragujevac, Kosovska 8, 34000 Kragujevac, Serbia, vasiljevic.sasa036@gmail.com , svasiljevic@asss.edu.rs .
[3] Jovanka Lukić, Ph. D., Full professor, University of Kragujevac Faculty of Engineering, Sestre Janjić 6, 34000 Kragujevac, Serbia, lukicj@kg.ac.rs
[4] Danijela Miloradović, Ph. D., Full professor, University of Kragujevac Faculty of Engineering, Sestre Janjić 6, 34000 Kragujevac, Serbia, neja@kg.ac.rs

institutes and industries across the globe. A fully encapsulated brake-dyno with supplied filtered cooling air, precise control of the ambient conditions, and an already defined real-world braking cycle (WLTP) have been selected for the brake wear testing procedure. This approach alleviates many of the complexities of the brake wear particle measurement, offering the best possible repeatability and reproducibility [3].

In braking situations, the particulate matter (PM) concentrations of brake wear particles (BWPs), sampled near the brake pad/disc contact, increased significantly and were much higher than the concentration of road wear particles (RWPs) during deceleration, indicating that BWPs are one of the main sources of non-exhaust emissions. There weren't many attempts to simultaneously characterize tire wear and brake wear particles in both on-road and laboratory measurements [8].

However, the reality of non-exhaust emissions is much more complex [4, 22]. Despite the advantages of the subsystem level research, like dynamometers or pin-on disc tests, for reviewing brake wear emissions, they cannot present a more realistic perspective of the parameters influencing the amount of generated brake wear. To increase the realism of the results, in addition to the speed, temperature, acceleration, and the other parameters of the subsystem level, some other key factors can be included. The vehicle dynamics, the geometry of the road, the effects of the weather, and driving styles can be cited as some well-known instances relating to this issue. In comparison to laboratory tests, on-road driving tests are more expensive and complicated. At the system level, the ability to characterize the emissions of vehicles in real driving conditions has some limits, such as lower repeatability and certainty. Due to this, there are few studies related to on-road driving tests in the literature. At the environmental level, the final effect of all the sources is detected, as the result of complex mechanisms involving resuspension, atmospheric phenomena, and so on [5].

The relationship between the environment and the real non-exhaust emission has not yet been adequately investigated and depends on various influences such as environmental conditions, driving characteristics, vehicle dynamics, recuperation, or locally varying geographical aspects. Real driving emissions (RDE) measurement of brake wear particles can be used to fill the gaps in the understanding of brake wear emissions, validate the test bench results, and to examine the relationship between temperature and emissions. Similarly to the exhaust regulation, it is expected that a robust on-board methodology can serve as a supplement to the brake-dyno test procedure to ensure an improved correlation with the real world. Currently, there are no specifications for the RDE measurement of brake emissions and maybe, future RDE tests could be designed based on current specifications for the RDE measurement of exhaust emissions of the EU Regulation 2018/1832 [3, 23].

The problem of source identification for non-exhaust traffic particles is complicated by interaction of sources. Different experimental designs have been developed to avoid that brake wear particles could be mixed with other emission sources including tire and resuspended particles [6]. For example, brake wear particles may deposit on the road surface and be resuspended, as can the tyre wear dust. Both particle types deposit into roadside soils, causing the trace metal enrichments which complicate the identification of the soil-derived component of resuspended dust. Road surface materials may have much in common compositionally with local crustal materials. Only through carefully controlled field experiments are these complexities likely to be disentangled, and even then, and the results may depend to a large extent on the specific site [7].

Generally, the generation of brake wear particles can be investigated at three levels: first, subsystem level, which deals with the wear of the braking system components (Figure 1). Second, system level, which is related to the investigation of wear released by a real vehicle in laboratory or road conditions, and third, suprasystem level that mainly focuses on on-road measurements. Considering the complexity of wear emission monitoring at the system level, the majority of research in the literature have been carried out at the subsystem level. Although previous models showed reasonably reliable results, the broad influential impacts of the real vehicle characteristics on the rate of emitted particles while driving in a real traffic conditions have been neglected. In contrast to exhaust emissions, non-exhaust emission estimation cannot be done without considering the effects of vehicle dynamics on the rate of brake wear generation. These impacts are not negligible because vehicle design features like mass, length, height, and distance of front and rear axles can significantly influence brake wear release rate during vehicle activities. Electric and hybrid vehicles, which recharge batteries during deceleration, reduce the use of brakes (which remain only for emergency brakes) and, hence, can significantly reduce wear particles emissions [9, 24].

To make the brake wear assessment more accurate, there is a tendency to integrate different levels of research. Due to the complexity of such models, no significant effort has been put into developing these models in emission estimation so far. The disadvantages of relying on laboratory tests to simulate real driving conditions have been previously shown, as they are largely simplified in terms of considering the substantial elements. These elements may include road geometry, traffic conditions, and driving styles. With traditional statistical modelling techniques, it is not possible to analyse and understand the non-linear dependencies corresponding to brake wear generation and this needs complex AI (Artificial Intelligence)-based models.

We can close the knowledge gaps in the correlation between brake-dyno and on-road testing with the vehicle fully equipped for on-board brake emission measurement. In conjunction with the recorded GPS data, we can identify emission hotspots that vary depending on the geographic location. This allows us to create city emission maps, including random and worst-case scenarios [10].

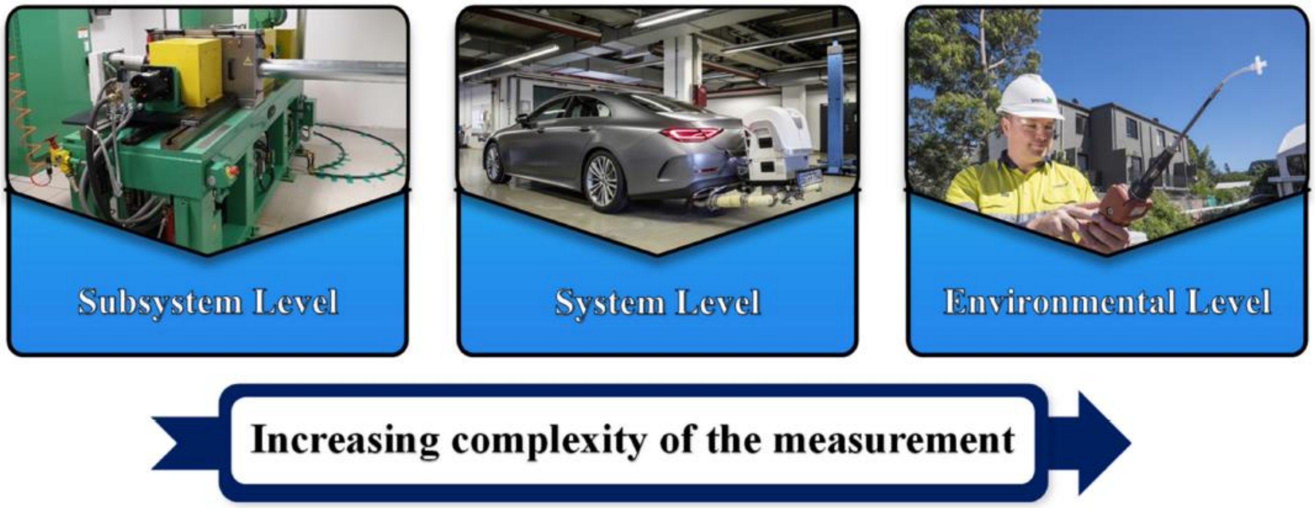

Figure 1 Hierarchical levels of investigation [9]

Studies reviewed by Grigoratos et al. [21] report that around urban environments, brake wear particles contribute to non-exhaust traffic related PM_{10} between 16 to 55 % by mass, while near highways that percentage is around 3% by mass. There are only a few studies on the brake wear investigations in on-road driving experiments. Sanders et al. [2] measured brake emissions by sampling in close vicinity to the brake with small probes. Kwak et al. [8] and Wahlström and Olofsson [11] sampled directly at the friction interface of the brake and showed the correlation between braking and emissions. A few studies have been carried out on brake and tire wear emissions using on-road sampling [12,13,8,2]. While these previous studies have discovered valuable information on the brake and tire wear particles, each study only focused on one vehicle, thus could not address the differences of brake and tire wear emissions across different vehicles. To address this issue, on-road experiments in which particles are measured during actual travel using sampling devices mounted on a vehicle have been performed.

This study aims to develop a methodology for braking system emission prediction by integrating research at the subsystem, system and suprasystem level.

ON-ROAD TESTING OF BRAKE WEAR EMISSION

In developing the effective system and methodology for measuring and characterising particles emitted from brake wear under real driving conditions, there was a need to consider:

- A common sampling system and measurement equipment which can be used for brake and tyre wear.
- Representative sample collection of particles.
- Repeatable and reproducible measurements.
- Careful consideration of background particles (i.e., resuspension of road dust, exhaust emissions).
- Power and spatial demands of the system [14].

Sanders et al. [2] investigated on-road emissions by using sampling tubes installed in the vehicle's wheels to minimize sampling losses from a series of driving conditions shown in Figure 2. As the authors state, this method has some disadvantages because of the losses in particle collection due to the bending angle of the tubes and due to non-isokinetic (constant) sampling. They calculated the on-road emissions both in traffic and using a high-speed test track and reported the correlations between them, and they also used dynamometer tests in a wind dilution tunnel. The results of this study showed that half of the wear debris obtained by vehicle tests became airborne. In addition, similar elements, such as Fe, Cu, and Ba, were observed in both the dynamometer and on-road samples.

Figure 2 Image of test vehicle showing location of sampling tubes [2]

To compare between wear debris recorded using the dynamometer to the airborne debris measured behind a vehicle, a series of tests at 1.8 m/s^2 stops from 96 km/h were performed in a wind tunnel. To collect particle samples, a hood was placed around the brake assembly along with a blower at constant flow of ~3.6 m^3/min. Particle size distributions were measured using micro-orifice uniform deposit impactor (MOUDI) and an electrical lowpressure impactor (ELPI). Using average wear densities of 5, 4, and 3 g/cm^3 for low metallic, semi-metallic, and NAO (Non-Asbestos Organic) linings respectively, the number weighted distributions of the brake wear particles under urban driving conditions peaked in the range of 0.5-2 µm. The mass mean diameter brake wear debris for the urban driving condition was reported to be about 6 µm for all three brake material types. Although the size distributions were the similar for the three brakes, the low metallic linings generated 2-3 times the number of wear particles than the semi-metallic and NAO linings. This study also suggests that particle size is not only a function of material type, but temperature as well. Under the harsh braking conditions, the number-weighted size distributions were dominated by particles less than 0.3 µm in diameter which likely occurs due to chemical processes occurring while the brakes reach 500 - 600°C. In addition, the mass-weighted average of particles at the harsh braking conditions occurred at 10 µm.

A similar approach was carried out by Kwak et al. [8] to investigate the physical and chemical characteristics (like the mass distribution) of ultrafine particles generated from non-exhaust sources such as brakes, tires, and road dust on-road and in the laboratory by using a mobile instrumented sampling vehicle and an isokinetic sampling design under different driving conditions. In this research, the authors installed sampling inlets in front of the vehicle, close to the tire and brake pads, to collect the on-road data and compare them with the data obtained from the laboratory tests. Four vehicle speeds were used at 50, 80, 110, and 140 km/h for the constant speed driving test. On the other hand, “braking” conditions were set up for the vehicle to gradually accelerate from 0 to 150 km/h at a rate of 0.71 m/s^2 and stopped with a deceleration rate of 3.02 m/s^2. “Normal cornering” was conducted on a round track with a diameter of 50 m at a constant velocity of 30 km/h, while “extreme cornering” was performed at 50 km/h. Two Dust Traks were simultaneously used to measure PM concentrations of the background and at the tire/road interface or brake pad. It was found that under braking conditions, the PM concentrations coming from road wear particles and tire wear particles were significantly less than those of brake wear particles. The brake wear particles had a broad size range from 1 µm to 10 µm, and there were no particles larger than 10 µm recorded during braking.

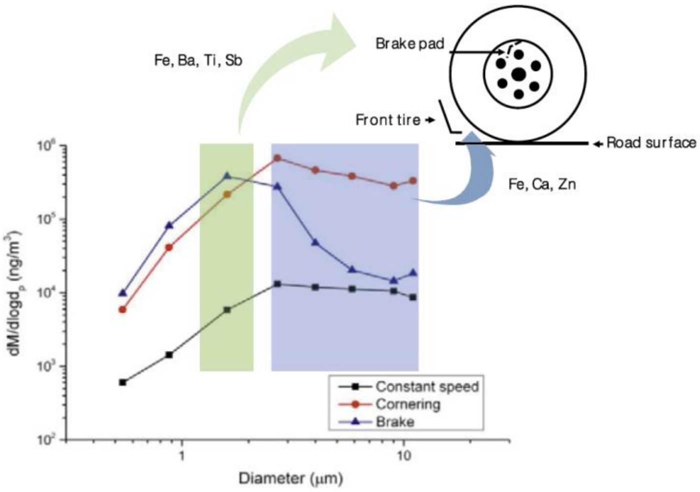

Figure 3 The dependence of particle mass and number on vehicle speeds and braking [8]

In 2015, Wahlström et al. presented field study measurements of brake wear by collecting data in the outer areas of Stockholm, Sweden [11]. They mounted two sampling tubes close to brake pads and also installed two tubes in front of an instrumented car. By mounting pressure and speed sensors in the sampling vehicle, simultaneous measurements of the vehicle's speed and brake pressure were provided. The results of this study showed a reliable correlation between brake operations and increased particle concentrations. Despite the remarkable results of sensor installation in the braking system, such sensors can only partially sample the brake dust. The vehicle field test shown in Figure 4 were performed on a test track in Stockholm, Sweden to simulate country roads at speeds of 30 km/h. To reduce the influence of resuspended traffic-generated particles, the vehicle tests were conducted on days when it rained. The car was fitted with two Grimm and two Dust Trak instruments to measure number and mass concentrations. An additional test was performed in heavy traffic to represent data from long tunnels, urban traffic and expressways. Results of this study showed that all test methods had peaks in number concentration of about 0.41 μm and volume-weighted mean diameters of 3, 2, and 1.7 μm for the brake, pin, and field tests respectively. As stated by the authors, regardless of the difference in load, load distribution, sliding velocity, and pad temperature, all three test methods showed similar number distributions [11,15].

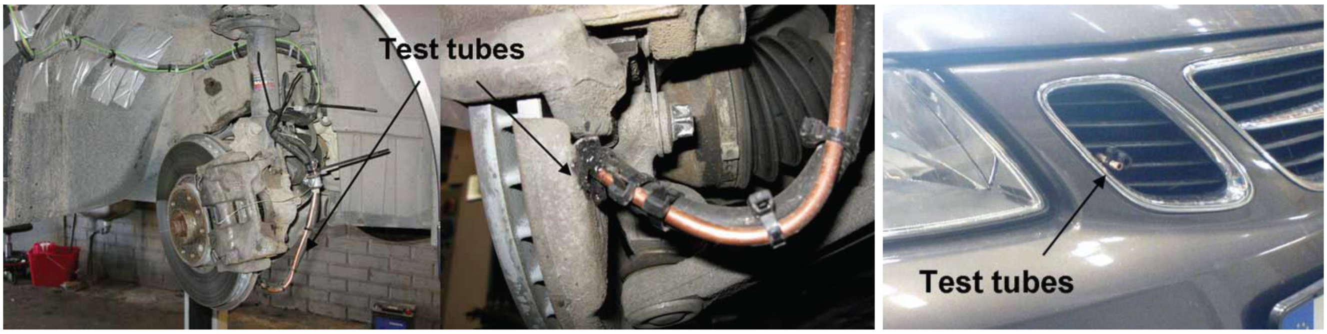

Figure 4 Test vehicle with sampling test tubes. Photo of the test tubes for particle measurements mounted directly behind the brake pad on the piston side (left), and test tubes mounted in front of the test car for measurement of background particle concentration (right) [15].

Farwick zum Hagen et al. [12,13] introduced an innovative sampling approach collected entire sets of brake wear emissions using a semi-closed vehicle setup, integrated into a midsize passenger vehicle, and tested on road. This setup helped them collect the entire set of brake aerosols. They compared the obtained results for conventional and novel materials for the pads with different coatings. They concluded that the novel composition presented almost 18% lower PM_{10} particles. Conserving the natural air flow at the brake, the brake wear was collected at the outside of the wheel rim (Figure 5). A semi-closed housing of the brake aimed the collection of the entire brake aerosol, which was transported to the measurement devices located in the trunk of the car. By means of tracer gas experiments, the aspiration efficiency was characterized as velocity dependent with decreasing aspiration at vehicle speeds above 50 km/h. Similarly, the setup air flow depended on the vehicle velocity. For increasing vehicle velocities, the air flow decreased and led to a decreased brake cooling.

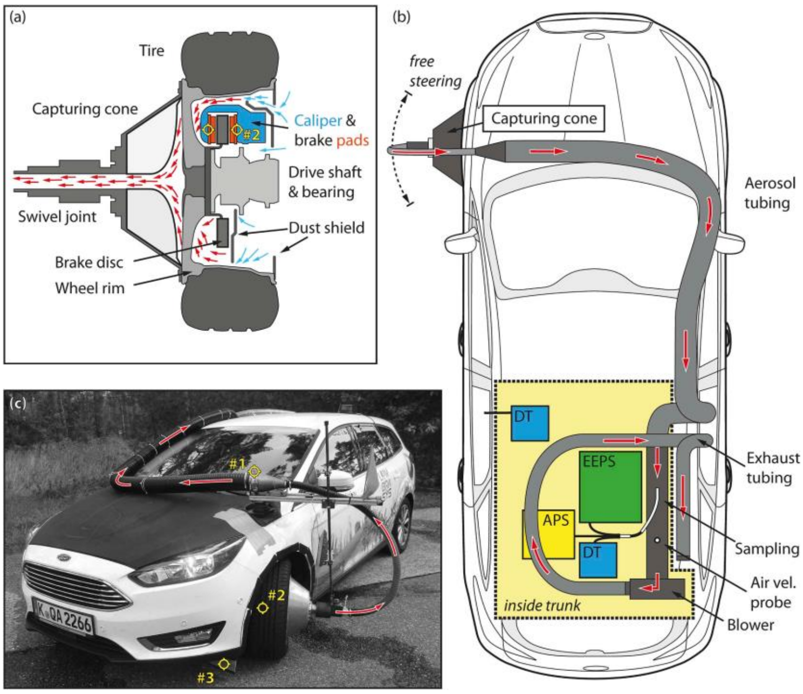

Figure 5 (a) Dust capturing cone at left front wheel (top view). (b) Test car with measuring setup. (c) Image of the test car [12,13]

Yellow background area shows components that are located inside the car. The brake particles are routed from the left front wheel to the trunk (red arrows), where the measuring equipment is located. A fraction of the total aerosol is analysed by the TSI EEPS, TSI Dusttrak, and TSI APS. The air flow is monitored by a TSI air velocity transducer. The ambient air is monitored by a second TSI Dusttrak. The ultra-fine particle formation was favoured, due to higher brake temperatures compared to the reference brake originating from the manipulated brake cooling through the setup. Additionally, the varying setup flow complicated the data analysis. A more realistic brake cooling and a stable setup flow could have been achieved only by a more powerful blower. On the other hand, this would have led to power supply problems on the vehicle. As recommendation, brake wear particle investigations should be carried out at dynamometer benches because of less technical restrictions, higher test-to-test reproducibility and robustness, and better cost efficiency, but attention should be paid to perform tests with realistic operational parameters, which – in particular the brake temperature – should be continuously verified through on-road investigations [12,13].

In 2020, Perricone et al. conducted a field road test by using an LDV (Light-duty Vehicle) equipped with temperature and pressure sensors on the brake system [1]. By calculating the emission factors, they showed that the brake system temperature during urban driving varied in the range of 100–170 °C. In addition, they compared the brake number and mass emissions factors and the Euro 6 and 4 regulations. As shown in this study, having a cycle that can act as a representative of the real world is crucial to obtain accurate results.

Feißel et al. used the test vehicle equipped with two separate constant volume sampling systems (CVS) for brake dust particles (blue) and tire related particles (red), both of which mounted to the right front wheel (Figure 6). The CVS for brake dust includes a full encapsulation of the brake system. The inlet air is filtered by a filter (class H13), in order to exclude background influences. An evacuation volume flow is generated by an electric fan in order to transport the brake dust aerosol into a measuring tunnel mounted to the vehicle underbody [16].

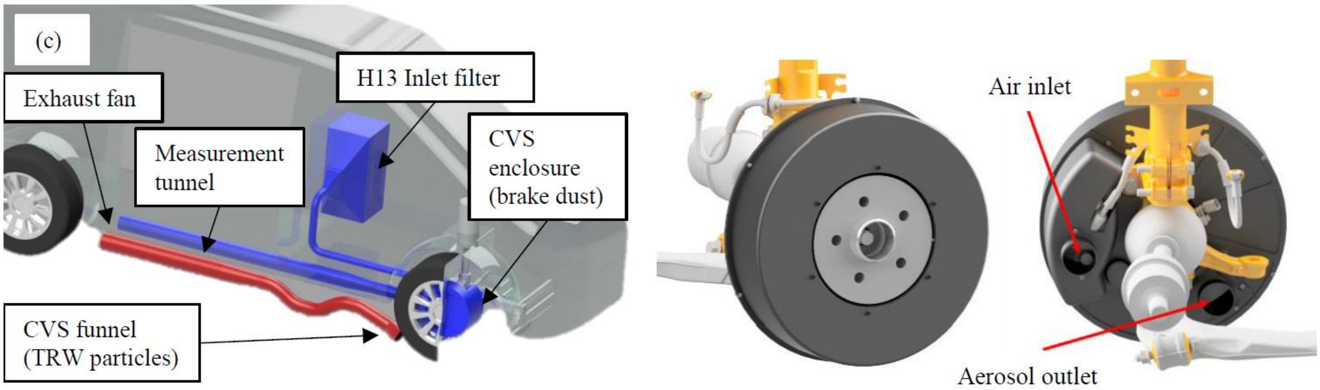

Figure 6 CVS systems for brake dust (blue) and tire related particle emissions (red) [16]

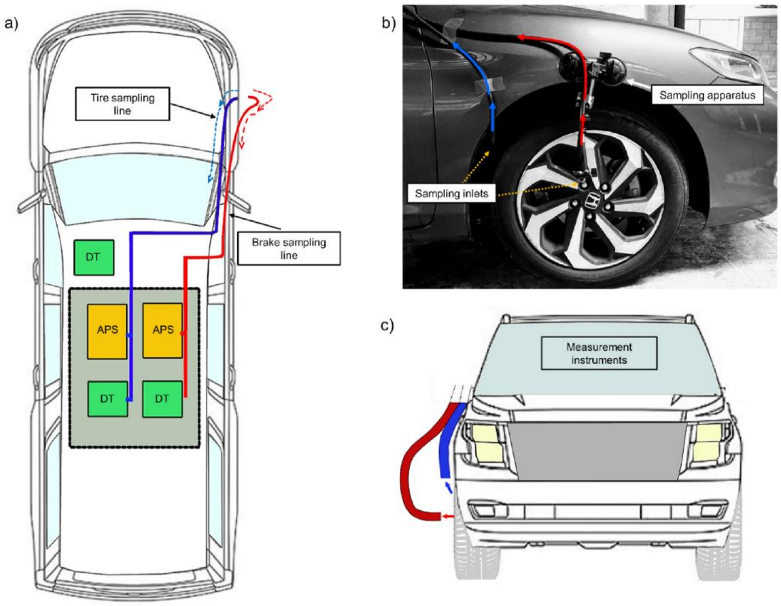

Figure 7 Schematic diagrams for the test vehicle with the sampling configuration. (a) Top view. Illustration of the sampling instruments installed inside the vehicle (b) The test vehicle and sampling apparatus. Arrows show the direction of the sampling flow from the brake and tire. (c) Front view. The tire particles are measured from the rear side of the right front wheel. The brake particles are measured at the centre of the right front wheel [17]

In study [17], Oroumiyeh et al. measured the brake and tire dust mass concentrations and size distributions from three test vehicles under real-world driving and braking conditions and investigated the effects of the vehicle mass and braking intensity on the brake and tire particles. This is probably the first study to investigate the effect of these factors on brake and tire particles using on-road measurements [17].

The main design target of Huber et al. [10] was to have as low influence on the actual brake temperature as possible. Instead of actively controlling the convective cooling by means of supplying cooling air to the brakes, the system was designed to minimize interference with the brake system, considering the on-board limitations. The small fingerprint of the system allows for an installation to different types of vehicles with simple adjustments and, more importantly, no changes on the vehicle. The system is based on the principle of extracting the brake wear particles at their origin at the brakes by applying negative pressure at the elbow located at the outside of the rim. Covering only a part of the brake disc is intended to prevent the brake disc from overheating. At the inner side of the brake disc, the standard brake dust shield is replaced by the mounting structure for the grommet, the rest remains unchanged. At the outside, the grommet covers about a quarter of the brake disc to have sufficiently uncovered disc surface for cooling through thermal radiation and convection. An additional important advantage of sampling on just one side of the disc is that the inner ventilation of the brake disc is not covered and therefore sufficient cooling can be obtained. RDE measurements are intended to represent the operation of a vehicle under normal driving conditions and normal load [10].

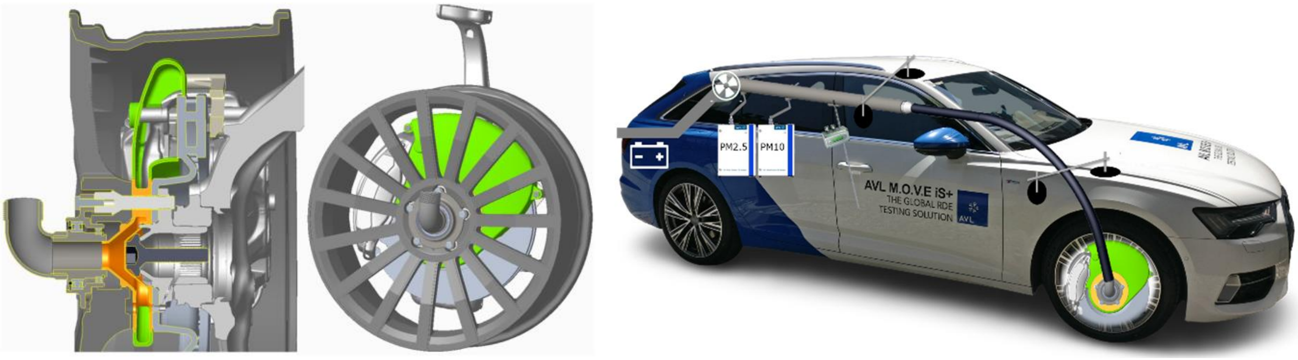

Figure 8 CAD model of prototype A. Particles are extracted from the guidance device (grommet – green), through the rotating hollow disc (spacer – orange), to the elbow at the outside of the rim (left), RDE System setup: sampling prototype at the wheel (right) [10]

Ricardo are supporting the Department for Transport in the UK to develop an effective system and methodology for measuring and characterising particles emitted from brake and tyre wear under real driving conditions. The entire system was installed to a small light duty van and measurements undertaken from the front wheel (Figures 9 and 10) [14].

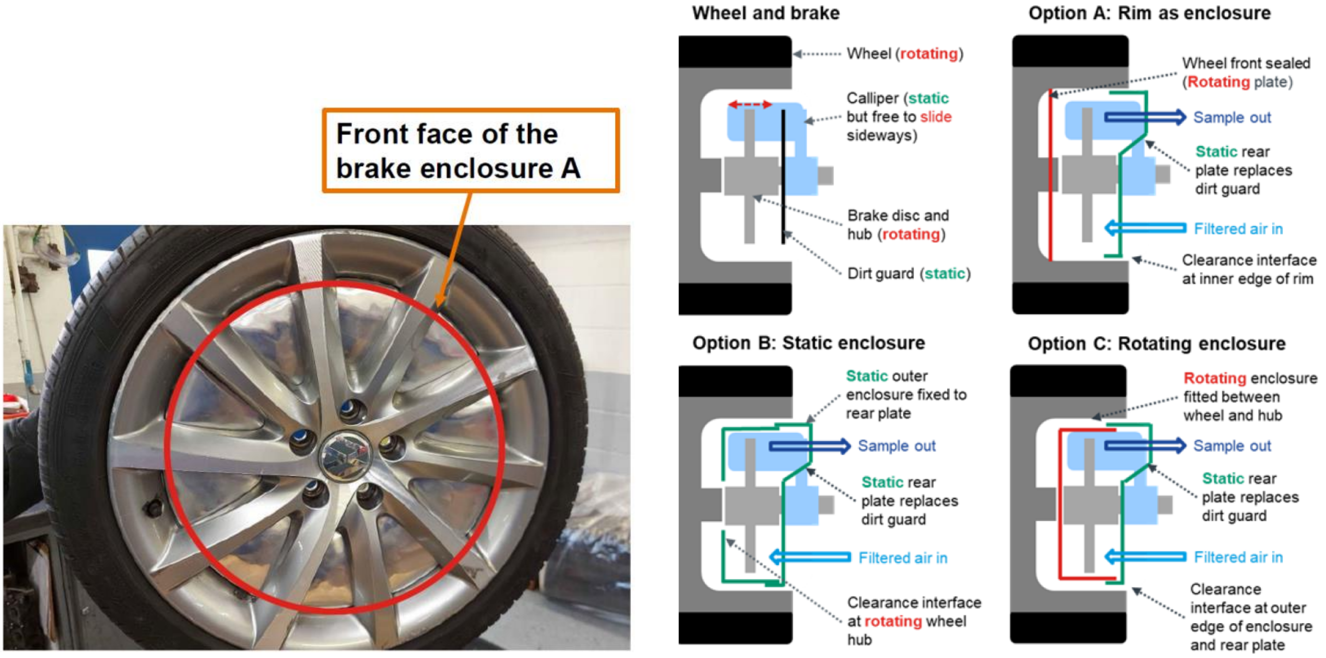

Figure 9 3 enclosure approaches used –to explore application to different braking system types [14].

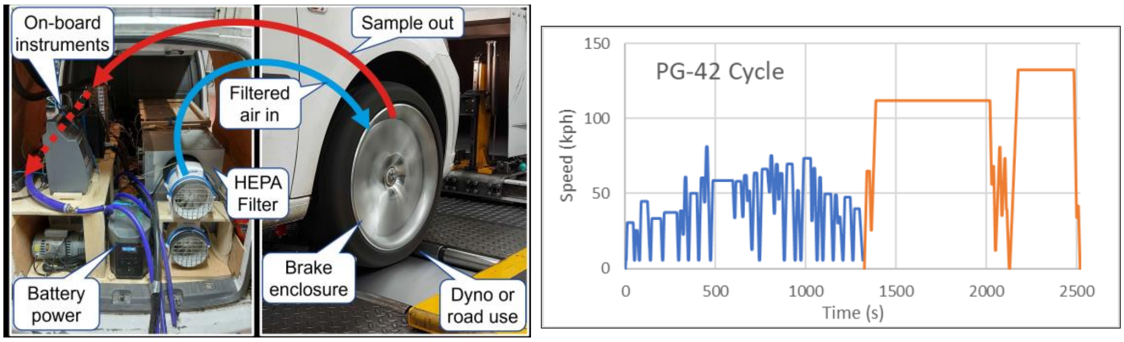

Figure 10 PG-42:42 minutes cycle based on high particle emitting sections of two well-known braking cycles: Worldwide Harmonized Light Vehicles Test Procedure (WLTP) and Los Angeles City Traffic (LACT) cycle [14].

CHEMICAL COMPOSITION OF BRAKE PAD MATTER

Ambient airborne particulate matter is a complex mixture of particles from a wide range of sources. Identifying the different sources and assessing the contribution of each source to the total atmospheric particulate loading is problematic. However, the chemical composition of ambient particulate matter samples can be useful in addressing these difficulties [7].

As reported by Grigoratos et al. [21], the trace elements for brake dust most widely used in the past by other researches contain Ba, Cu, Fe, Zn, and Sb. For example, Sanders et al. [2] reported that Fe, Cu, Si, Ba, K and Ti were highest in concentrations from low-metallic, semi-metallic, and non-asbestos organic brake pads. Thorpe and Harrison [7] reviewed sources and properties of non-exhaust PM and suggested Cu/Sb ratio may be used as reliable tracers of the presence of brake wear particles in the urban environment. A number of authors have concluded a diagnostic Cu:Sb concentration ratio of around 5:1 to be reflective of brake-related particles; this ratio is markedly different from the typical crustal ratio of around 125:1 and that associated with metallurgical processes, which is typically in excess of 10:1. The element Ti could also be an important tracer for brake wear particles of NAO brake pads as they are descendant of asbestos formulations but substituted with potassium titanate fibers. The magnitude of concentrations that contribute to wear debris from highest to lowest is Fe, Ba, Ti, and Sb. Numerous studies have shown that Fe and Cu together can also be used as a tracer of brake wear because both elements periodically showed up in higher concentrations as two peaks in the data during traffic rush hours. Their findings also showed that Fe and Cu are primarily emitted into the atmosphere and not resuspended particles from the road [18,25].

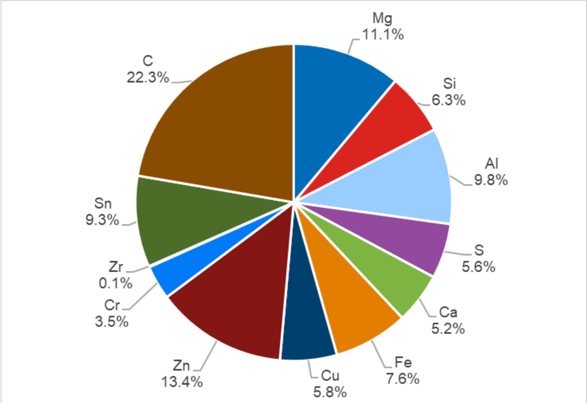

Figure 11 Chemical composition of key brake pad [19,20]

MODELS FOR EVALUATION OF TRAFFIC NON-EXHAUST EMISSION

The recently adopted UN GTR on brakes provides a worldwide methodology for the measurement of brake wear particle matter and particle number emissions. It aims to harmonize test procedures for emissions from light-duty vehicles. This harmonization facilitates the evaluation of emissions from different brake systems and supports the development of strategies aimed at reducing brake-related emissions.

Methodology based on brake-dyno measurement

Numerous studies in the literature have used traffic microsimulation models to estimate exhaust emissions. Nevertheless, none of them has tried investigating the possibility of non-exhaust emission estimation using traffic simulation-based models.

The number of particles and their masses generated by the braking system of targeted vehicles in different urban routes in a real case study could be estimated. One possible approach to research consists of combining three phases of brake wear investigation: suprasystem, system and subsystem levels. At the subsystem level, first, numerous (thousands) of tribological tests are conducted using the minidyno machine [5]. These tests are carried out considering initial speed, torque, pressure, and other operation parameters to measure the concentration of airborne brake wear particles generated for every brake operation and serve for training a neural network emission model. Second, the most useful variables (initial speeds, final speeds, and brake torques) are selected as independent variables to predict the brake emissions using the approximant artificial neural network model.

At the suprasystem level, first, real traffic data would be collected in a highcongested area in the target city in peak hours to identify field specifications. For instance, traffic-related data such as input volume, route choices, pedestrian volumes, modal splits, number of parking lots, traffic light green and red timings are identified. Additional non-traffic data are also acquired, such as road geometry, field scope, land use, and weather conditions. In the next step, all the obtained data are inserted into the traffic microsimulation software for monitoring the vehicles' trajectories and finding the route choice decisions. To ensure the accuracy of data collection, every single traffic element is modelled in the traffic microsimulation software. Vehicle records including vehicle coordination, speed, acceleration, number, length, height, mass, width, and positions in the networks, are accurately extracted from the microsimulation model.

A vehicle longitudinal dynamics model is developed, in order to provide its inverse dynamic, i.e. convert its kinematic behaviour into the brake activation quantities. Real vehicle information, such as wheels radius, drag coefficient, centre of mass height, wheel moment of inertia, coefficient of friction and other related information released by the vehicle manufacturer and published material must be acquired. The vehicle inverse dynamics model calculates the vehicle's front/rear wheels' brake torques and angular velocities starting from the vehicle speed time-series previously obtained by the traffic microsimulation model. Next, selected vehicle data (brake torques, initial and final speeds for every brake event) obtained by the combination of the microsimulation and vehicle inverse dynamics models are fed to the subsystem level ANN (Artificial Neural Network)-based model to estimate the brake emission in every event. In the final step, the obtained results are comprehensively analysed in the frame of the traffic environment and concluded. The findings of this research open an innovative and efficacious way for traffic engineers and environmental scientists to study the real brake emissions besides exhaust emissions in various traffic conditions [5].

Results may indicate deviations in the generation of total brake PNs (particles number) and masses in terms of route decisions. The routes and trajectories chosen by drivers can have remarkable differences in the number of particles they produce and brake particle mass in the travel distance. These route decisions can affect the number of braking events, especially in business areas of the city where there are many commuters and the number of signalized intersections is relatively high.

For future work, this approach for the brake emission modelling (PM estimations) can be improved by using data from an actual full-scale dynamometer setup that complies with current global technical regulation (GTR) on brake wear particle emission. Moreover, evaluating the whole particle range including ultrafine particles and considering brake temperatures can further develop the brake emission model. By following the proposed method for such congested areas, where a high number of brake events may happen, the environmental engineers and decision makers can prevent the adverse impacts of brake wear particles on the susceptible groups of commuters, tourists, residents, and citizens living or commuting around the location.

Methodology based on road measurement

Although the vehicle's measurement setup revealed limitations regarding sampling efficiency, particle transport efficiency, and brake cooling, this on-road measurements served well for validating the results obtained on the dynamometer. Both normal braking and emergency braking styles can be considered. These data were used to study the repeatability of emissions between nominally identical braking events, the impact of increasing brake disc and pad temperatures on particle emissions and to enable the consideration of other factors such as the relationship between initial braking velocity and particle emissions [6]. While there is a good agreement of PM emissions between on-road and laboratory tests, assessing PN emissions on public roads proved challenging. Especially high particle number concentrations from engine exhaust emissions present in the urban ambient air lead to significant noise signals. In rural areas and on highways with lower background pollution, the detection of individual heavier brakings proved viable. Future research will focus on minimizing the issue of PN background emissions to enable a more reliable PN measurement, even in urban environments [3].

CONCLUSIONS

The state-of-the-art of the research on non-exhaust emission indicates that the braking system is a source of emissions that produces airborne particles through complex events, which involve phenomena at different levels. For instance, the wear rate may be depending on the different materials of the brake system components, such as the brake pads and disc, and the driving conditions, like the pressure on the pads and the rotational speed of the disc. However, the pressure on the pads depends on the intensity of the braking action commanded by the driver, which is affected by the vehicle weight, road characteristics and last but not least, the driving style.

We try to close the knowledge gaps in the correlation between laboratory brake-dyno and on-road testing with the vehicle fully equipped for brake emission measurement. If the emission measurement is performed simultaneously with the tracking of the GPS position of the vehicle, we can identify emission hotspots that vary depending on the geographic location. This allows us to create city non-emission maps for a specific urban environment, including random and worst-case scenarios.

The paper presents two possible approaches to develop the traffic regulation models in order to reduce non-exhaust emissions. One method is the on-road measurement of brake emissions using an enclosure that would partially cover the brake calliper and pads, but not the disc, in order to reduce the impact on contact temperature, which has been proven to affect the value of the brake emission, i.e. on the accuracy of the measurement. Another possible approach is to estimate the level of non-exhaust emissions at a suprasystem level based on data on the number and category of vehicles, as well as the speeds of braking on a certain section of the city. By numerous measurements on brake-dyno of different pads, at different pressures and speeds at the start of braking process and using ANN, real road emissions can be estimated based on laboratory measurements.

ACKNOWLEDGMENTS

Paper is financially supported by The Ministry of Science, Technological Development and Innovation of the Republic of Serbia, Contract No. 451-03-65/2024-03/200107.

REFERENCES

[1] Perricone, G., Matějka, V., Alemani, M., Valota, G., Bonfanti, A., Ciotti, A., Olofsson, U., Söderberg, A., Wahlström, J., Nosko, O. et al.: “A concept for reducing PM10 emissions for car brakes by 50%”, Wear 2018, Vol. 396–397, pages 135–145. http://doi.org/10.1016/j.wear.2017.06.018

[2] Sanders, P.G., et al: “Airborne brake wear debris: size distributions, composition, and a comparison of dynamometer and vehicle tests”, Environmental science & technology, Vol. 37, No. 18, 2003, pages 4060-4069.

[3] Huber, M. P., Mamakos, A., Hofbauer, M., Fischer, P., Klug, A., & Steiner, G.: “Real Driving Emissions Sampling System for Brake Wear Particle Measurement”, Paper presented at EuroBrake 2022, 2022, Virtuell, United Kingdom.

[4] Zhang, Q., Fang, T., Men, Z., Wei, N., Peng, J., Du, T., Zhang, X., Ma,Y., Wu, L., Mao, H.: “Direct measurement of brake and tire wear particles based on real-world driving conditions”, Science of The Total Environment, Vol. 906, 2024, pages 167764, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2023.167764.

[5] Rahimi, M., Candeo, S., Da Lio, M., Biral, F., Wahlström, J., Bortoluzzi, D.: “A novel approach for brake emission estimation based on traffic microsimulation, vehicle system dynamics, and machine learning modelling”, Atmospheric Pollution Research, Vol. 14, No. 10, 2023, 101872, ISSN 1309-1042, https://doi.org/10.1016/j.apr.2023.101872.

[6] Feo, M.L., Torre, M., Tratzi, P. et al.: “Laboratory and on-road testing for brake wear particle emissions: a review”. Environ Sci Pollut Res 30, 2023, pages 100282–100300, https://doi.org/10.1007/s11356-023-29229-7

[7] Thorpe, A., Harrison, R.M.: “Sources and properties of non-exhaust particulate matter from road traffic: A review”, Science of The Total Environment, Vol. 400, No. 1–3, 2008, pages 270-282, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2008.06.007.

[8] Kwak, J., Kim, H., Lee, J., Lee, S.: “Characterization of non-exhaust coarse and fine particles from on-road driving and laboratory measurements”, Science of The Total Environment, Vol. 458–460, 2013, pages 273-282, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2013.04.040.

[9] Rahimi, M., Bortoluzzi, D., Wahlström, J.: “Input Parameters for Airborne Brake Wear Emission Simulations: A Comprehensive Review”, Atmosphere, Vol. 12, 2021, 871. https://doi.org/10.3390/atmos12070871

[10] Huber, M. P., Fischer, P., Huemer-Kals, S., Weidinger, C., Wanek-Rüdiger, C., Steiner, G., & Murg, J.: “Assessing a Vehicle’s Real World Brake Wear Particle Emissions on Public Roads”. Paper presented at Eurobrake 2023, 2023, Barcelona, Spain.

[11] Wahlström J, Olofsson U.: “A field study of airborne particle emissions from automotive disc brakes”, Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering. Vol. 229, No. 6, 2015. pages 747-757. doi:10.1177/0954407014550053
[12] Farwick zum Hagen, F. H.: “Investigation of brake wear particle emissions on the dynamometer and the vehicle under real-driving simulation”, Bergische Universität Wuppertal, Fakultat fur Mathematik und Naturwissenschaften, Dissertation (PhD), 2019
[13] Farwick zum Hagen, F.H., Mathissen, M., Grabiec, T., Hennicke, T., Rettig, M., Grochowicz, J., Vogt,R., Benter, T.: “On-road vehicle measurements of brake wear particle emissions”, Atmospheric Environment, Vol. 217, 2019, pages 116943, ISSN 1352-2310, https://doi.org/10.1016/j.atmosenv.2019.116943.
[14] Kramer, L., Andersson, J., Campbell, M., Marshall, I., Norris, J., de Vries, S., Waite, G., Southgate, J. and Norris, J.: “Development of a system to measure real world particle emissions from brake wear”, Onboard Sensing, Analysis, and Reporting (OSAR) 2024 Conference, March 14th & 15th, 2024, in Riverside, California
[15] Wahlström, J., Söderberg, A., Olander, L., Olofsson, U. and Jansson, A.: “Airborne wear particles from passenger car disc brakes: a comparison of measurements from field tests, a disc brake assembly test stand, and a pin-on-disc machine”. Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, Vol. 224, No. 2, 2010, pages 179-188. doi:10.1243/13506501JET633
[16] Feißel, T., Hesse, D., Augsburg, K., Gramstat, S.: “Measurement of Vehicle Related Non Exhaust Particle Emissions under Real Driving Conditions”, Paper presented at EuroBrake 2020, 2020, https://doi.org/10.46720/EB2020-STP-039
[17] Oroumiyeh, F., Zhu, Y.: “Brake and tire particles measured from on-road vehicles: Effects of vehicle mass and braking intensity”, Atmospheric Environment: X, Vol. 12, 2021, pages 100121, ISSN 2590-1621, https://doi.org/10.1016/j.aeaoa.2021.100121.
[18] Jung, H., Wu, G., Chen, L.-W. A., Wang, X., Zhang, K.M., Lopez, B.: “Real-world tire and brake wear emissions”, Final Report, Center for Environmental Research and Technology, University in Riverside, California, 2020
[19] Andersson, J., Campbell, M., Marshall, I., Kramer, L., Norris, J.: “Measurement of emissions from brake and tyre wear”, Final Report—Phase 1; Ricardo: Shoreham-by-Sea, UK, 2022.
[20] Andersson, J., Kramer, L.J., Campbell, M., Marshall, I., Norris, J., Southgate, J., de Vries, S., Waite, G. A: “A Practical Approach for On-Road Measurements of Brake Wear Particles from a Light-Duty Vehicle”, Atmosphere, Vol.15, No. 224, 2024, https://doi.org/10.3390/atmos15020224
[21] Grigoratos T. and Martini, G.: “Brake wear particle emissions: a review”, Environ Sci Pollut Res 22, 2015, pages 2491–2504, https://doi.org/10.1007/s11356-014-3696-8
[22] Guo, D. Wei, H., Guo, Y., Wang, C. and Yin, Z. : “Non-exhaust particulate matter emission from vehicles: A review”, 6th International Symposium on Vehicle Emission Supervision and Environment Protection (VESEP2020), E3S Web Conf. Vol. 268, 2021, pages 01015, eISSN: 2267-1242, https://doi.org/10.1051/e3sconf/202126801015
[23] Wei, H., Wu, C., Jing, X., Wang, X., Bai, F., Wang, S., Wang, W., Li, J. and Wang, C.: “Test method for particulate matter emissions from brake wear of light-duty vehicles: A review”, 9th International Symposium on Vehicle Emission Supervision and Environment Protection (VESEP2023), E3S Web of Conferences 522, 01001, 2024, eISSN: 2267-1242, https://doi.org/10.1051/e3sconf/202452201001
[24] Hesse, D. and Augsburg, K.: "Real Driving Emissions Measurement of Brake Dust Particles", 2019. Brake Colloquium & Exhibition - 37th Annual, Ed., doi:10.4271/2019-01-2138.
[25] Ayyagari, P.: “Variance in nanoparticle emissions over WLTP Brake wear testing procedure”, Master’s thesis, Czech technical university in Prague, Faculty of Mechanical Engineering, 2022

ISBN 978-86-6335-120-2

9 788663 351202