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IMPACT OF NON–EXHAUST PARTICLE EMISSIONS FROM MOTOR VEHICLES ON HUMAN HEALTH

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Abstract: According to the World Health Organization (WHO), PM2.5 and PM10 are a leading cause of air pollution and have been identified as having detrimental effects on human health even at low concentrations. By reducing exposure to these particles, countries can significantly decrease the incidence of both short– and long–term illnesses, as well as the overall burden of disease. This paper discusses the impact of the size and concentration of particles from braking systems, tires, and road on the respiratory, cardiovascular, and nervous systems of humans. The paper also presents methods for detecting and measuring non–exhaust emissions from motor vehicles, as well as United Nations Economic Commission for Europe (UNECE) regulations for defining standardised laboratory procedures for testing particle emissions resulting from the wear of brakes in light vehicles with a maximum permissible weight of up to 3500 kg. Based on the reviewed literature, possible mitigation measures to reduce fine particulate emissions are presented. In particular, an adaptation of an adequate braking process can significantly mitigate emissions and subsequently reduce harmful effects on human health and the environment.
Keywords: non–exhaust emissions, particulate matter (PM), human health

INTRODUCTION

Despite all the conducted research, some factors that contribute to the production of non–exhaust emissions have been partially neglected, and their contribution to the overall level of pollutants generated by traffic is decreasing to a much lesser extent compared to exhaust emissions.

Studies have found that the brake system, tire wear, and road surface are the most significant sources of non–exhaust particles (particulate matters), and they can have a substantial impact on human health [1–3]. These PMs are small enough to penetrate deep into the lungs, where they can cause inflammation [4] and damage to lung tissue. This can lead to a variety of respiratory problems, such as asthma and chronic obstructive pulmonary disease [5]. Moreover, exposure to PM from motor vehicle emissions has also been linked to an increased risk of cardiovascular disease [6,7], and some neurodegenerative phenomena and cognitive disorders [8,9]. Therefore, it is essential to take measures to reduce the emission of particulate matter from motor vehicles and limit our exposure to these harmful pollutants.

This paper provides an overview of previous studies examining non–exhaust emissions and their impact on human health, as well as a review of methods for measuring non–exhaust emissions generated by the brake system (brake discs and pads). A brief overview of the brake testing requirements prescribed by The United Nations Global Technical Regulation (UN GTR) will also be provided.

THE IMPACT OF NON–EXHAUST EMISSIONS ON HUMAN HEALTH

The proliferation of road traffic has resulted in significant repercussions, not limited to direct transportation safety concerns, but also with regards to the visible impact of vehicle emissions on the environment and human health, which has been the focus of research over the past two decades in urban areas worldwide [10], due to the increasing presence of motor vehicles and their emissions as a noteworthy source of particulate matter (PM) in the atmosphere, which can severely affect the respiratory system of humans.

According to the European Environment Agency's reports in 2014 and 2016, between 64% and 92% of the EU urban population is exposed to high concentrations of PM10 and PM2.5 particles [11][12], and air pollution is considered the largest environmental risk factor responsible for premature deaths worldwide. The World Health Organization's studies have shown that Europeans' life expectancy can be reduced by an average of about 8.6 months [13][14], or even up to 22 months in the most polluted cities, due to exposure to these particles [14].

Animal studies have demonstrated that exposure to highly polluted ambient air affects lung function and leads to premature death, and the same has been observed in humans, with air pollution contributing to as many as 4.2 million premature deaths globally in 2016 [15][16].

A study conducted in Taipei, Taiwan, investigated the exposure of PM2.5 on human health, specifically on the cardiovascular system [17][18]. The study concluded that commuters [18] and cyclists [17] are more exposed to PM on routes with heavy traffic compared to those with less traffic. Moreover, the study revealed that pedestrians [17] walking on sidewalks were more exposed to PM than people travelling in cars for the same purpose.

Particle size plays an important role in determining the impact of particles on human health, depending on how deep they can travel into respiratory structures. The authors from the University of Trento, Italy, have presented a classification overview of particles found in urban environments [19] based on their size and mass characteristics. The particles were divided into three groups: coarse, fine, and ultrafine particles, each with their unique characteristics.

Coarse particles (aerodynamic diameter of 2–20µm) [19] are characterised by a larger size and lower numerical representation, but they are considered primary emissions. Fine particles (aerodynamic diameter of 0.1–2µm) [19] are more prevalent and have a smaller mass and volumetric range, while ultrafine particles (aerodynamic diameter of 0.01–0.1µm) [19] have an even smaller mass and volumetric range and higher numerical representation. Ultrafine particles can be further divided into two groups based on their aerodynamic diameter, smaller than 0.01µm (nanoparticles) and those with an aerodynamic diameter between 0.01 and 1µm (Aitken mode). Hence, small particles, with a size of 2.5 µm or less, can penetrate the finest respiratory pathways, while particles of 1 µm can reach the terminal alveolar structures where oxygen and carbon dioxide exchange occur. Nanoparticles of 0.1 µm can directly penetrate into the bloodstream [20][21].

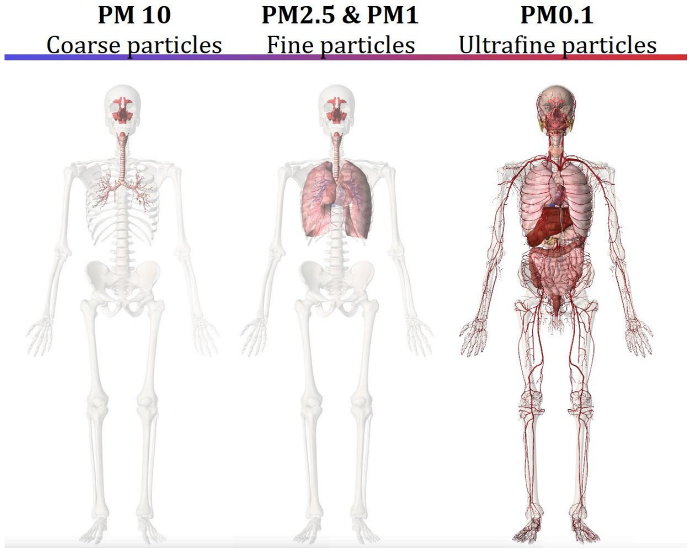

Figure 1. Representation of particles penetration into the human body depending on the size of their aerodynamic diameter. (Modified from [22])

Given the evident impact of particles on human health, viewed from various aspects, it represents an additional threat for chronically ill individuals and those susceptible to rapid changes in health status. In a study conducted by Gonet and Maher (2019) [23], which examines the impact of particles generated by car operation, it was noted that the concentration and size of particles can be strongly linked not only to respiratory and cardiovascular damage but also to neurodevelopment and cognitive functions. As such, the following sections present research on the impact of particles generated by road vehicles on the respiratory, cardiovascular, and nervous systems in humans.

Impact on the respiratory system

The investigation of ambient air pollutants has led to the suspicion that exposure to particles (PM), especially those in the fine (<2.5 mm aerodynamic diameter) and ultrafine range (<0.1 mm;), is considered a key risk factor for many harmful health effects [16][21]. Based on this assumption, it has been concluded that the particular effect of the presence of particles in ambient air is reflected in acute or chronic respiratory problems, which are caused by direct damage to the respiratory organs when inhaling air pollutants. Chronic exposure is associated with cough, sputum production, and reduced lung function [24]. In addition to symptoms, exposure studies in healthy individuals have documented numerous deep inflammatory changes in the respiratory tract, particularly before changes in lung function can be detected [16].

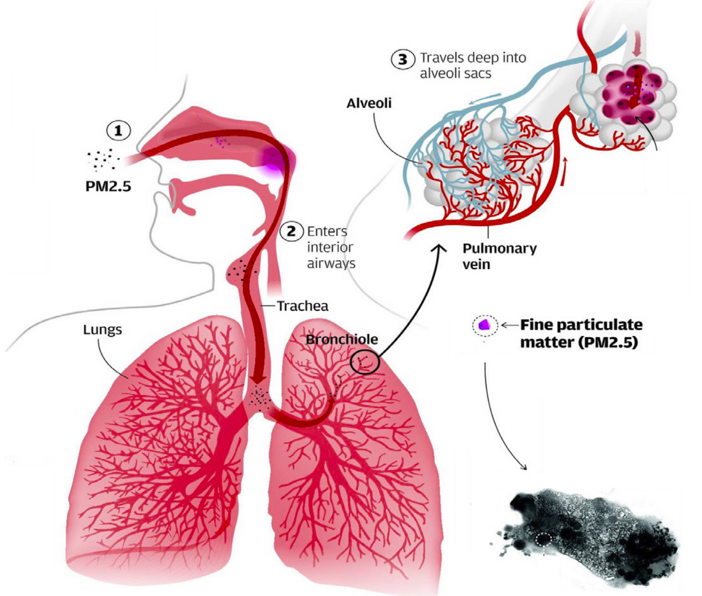

Figure 2. PM particle (specifically PM2.5) and how it can be synthesised into the bloodstream through the respiratory system. (Modified from [21])

A brief review of the literature by Italian researcher Luigi Vimercati (2011) highlighted that emissions from traffic processes, i.e. braking and tire wear, can play a key role in causing allergic conditions [5]. It was also noted that several pollutants (NO2, O3, and PM) are associated with worsening asthma and can significantly contribute to its pathogenesis. Therefore, based on the collected data, it can be concluded that in most industrialised countries, people living in urban areas tend to be more affected by allergic respiratory diseases than those in rural areas [5].

On another note, one experimental indirect study was conducted to investigate the effect of air pollution on changes in Sprague–Dawley rat lung tissue under whole–body exposure to PM1 (particles <1 mm in aerodynamic diameter) pollutants at the National Laboratory Animal Center (Taipei, Taiwan) [16]. It was found that the presence of PM1 particles enhances oxidative stress and inflammatory reactions under subchronic exposure to PM1, resulting from car work, while suppressing glucose metabolism and actin cytoskeleton signalling. These factors can lead to impaired lung function after chronic exposure to PM1 associated with traffic [16].

The study made a significant contribution to the investigation of several potential molecular characteristics associated with early lung damage in response to air pollution associated with traffic processes. These results would further contribute significantly to the screening process of individuals who are more significantly exposed to polluted ambient air, primarily supplied with particles resulting from car work and traffic processes.

Impact on the cardiovascular system

A study by a group of authors from the University of South China [17] examined the impact of PM2.5 particles on human health and provided an overview of previous conclusions on this topic. Long–term exposure to PM2.5 may not only affect the respiratory system but also cause significant structural changes in the heart muscle, such as myocardial hypertrophy (with increased hypertrophic markers) and harmful ventricular remodelling (changes in the size, shape, structure, and function of the heart muscle) [17, 25, 26].

Previous studies have also discussed how PM2.5 can disrupt a significant number of functions in the cardiac autonomic nervous system (ANS) and lead to reduced heart rate variability, which is considered an independent risk factor for cardiovascular morbidity and mortality [6,7,25]. The study also discussed changes in the endocrine system and the function of the hypothalamus and its hormone secretion, conditioned by changes in the heart muscle, but this association has not been sufficiently investigated.

To the extent of the relevance of the examined data, a connection was found between the increased concentration of PM2.5 particles and a range of pathophysiological responses that increase blood pressure and lead to the development of hypertension [17,25,27].

A study conducted in Taiwan examined the effects of PM2.5 exposure on the cardiovascular system of healthy travellers using different modes of transportation. The study involved 120 participants who were classified according to their transportation type, including electric subway trains, gasoline–powered buses, cars, scooters, and pedestrians with and without face masks. Measurements of various parameters were taken during six iterations. Results showed that exposure to PM2.5 is linked to increased systolic blood pressure and heart rate during walking and riding a gasoline–powered scooter. PM2.5 concentration was highest during scooter use and lowest during electric subway train use. The study did not find a significant correlation between PM2.5 and the systolic and diastolic blood pressure or heart rate while walking with a face mask. Overall, the study concluded that PM2.5 has a visible effect on the cardiovascular system. [17]

Impact on the nervous system

Previously, we described the relation of particles with changes in the respiratory and cardiovascular systems, while on the other hand, researchers have also investigated the impact of particles on other organs and systems within the human body. The effects of non–exhaust emissions of nanoparticles produced by vehicular processes have also been examined and linked to neurodevelopment and cognitive impairments.

Researchers von Mikecz, A. and Schikowski, T. (2020) from the Leibniz Research Institute for Environmental Medicine studied the effects of nanoparticles in the air on the nervous system through the aggregation of amyloid proteins, neurodegeneration, and neurodegenerative diseases such as Alzheimer's and Parkinson's disease [28]. Also, a study by a group of researchers from the US, Brazil, Germany, and the UK on various forms of cardiovascular and cerebrovascular diseases indicates their harmful effects on the brain and cognitive processes through vascular and inflammatory mechanisms [28, 29].

Besides age, the environment in which a person lives can also play a role in the development of Alzheimer's and Parkinson's disease. Exposure to certain pollutants in the environment may contribute to an increased risk of developing these diseases. This hypothesis has been confirmed by several studies, which have emphasised that Alzheimer's disease positively correlates with the level of air pollution in urban environments, most significantly with PM [28,30].

Schikowski, T. and Altuğ H.'s (2020) study on the role of air pollution in cognitive decline and impairment [31] confirmed the association between these two components. The collected data is quite heterogeneous, and additional analyses and research are needed to give more importance to this association and explore its relevance in detail [28].

What is also important to emphasise is that the accumulation of amyloid protein within the cells of the central nervous system is a common feature of neuropathology in Alzheimer's and Parkinson's disease and is closely associated with the appearance of amyloid–beta peptides, tau proteins, and alpha–synuclein [28]. In support of this, the study by Gonet and Maher (2019) [23] on urban air and its contribution to the development of dementia and Alzheimer's disease showed typical features of the pathogenesis of Alzheimer's disease, namely aberrant deposition of amyloid–beta peptides and tau proteins in post–mortem brain samples of clinically healthy people and dogs exposed to lifelong air pollution by living in the researched urban areas of Mexico City or Manchester (UK) [30].

Research has shown that nanoparticles generated from traffic processes, specifically from the wear and tear of brakes and tires in automobiles, have the ability to induce amyloid formation in nano–silicon dioxide. Furthermore, a significant amount of these nanoparticles has been detected in postmortem brains of animals and humans with chronic exposure to air pollution in highly urbanised environments. Epidemiological data has also indicated that living near traffic routes is a risk factor for the development of neurodegenerative diseases, such as Alzheimer's disease [8, 23].

Additionally, a study conducted in China [32] to investigate the effects of air pollution on unborn children (during prenatal development) and the development of ADHD in early childhood yielded significant results. It is particularly noteworthy that with an increase in the presence of PM10, PM2.5, and NO_2 during the period considered most sensitive to the development of degenerative behaviours (end of pregnancy and first four months of life), the possibility of hyperactivity in children increases significantly, with a statistically significant association. This conclusion supports the idea that exposure to particles during pregnancy can lead to the development of hyperactive behavior (or ADHD) in early childhood [32].

METHODS FOR DETECTING AND MEASURING NON–EXHAUST EMISSIONS FROM BRAKES

It is crucial to bear in mind that particle emissions related to traffic have been proven to have negative health effects. However, despite the scientific community's increasing interest in studying brake emissions, the vast majority of research findings are inconsistent and vary widely. This introduces a significant degree of uncertainty when attempting to assess the contribution of brake wear emissions to ambient PM levels, as brake wear emission factors are dependent on various parameters such as the type of friction material, brake assembly, and driving conditions [33].

One of the primary reasons for the lack of consistency in measuring particulate matter size and number emission factors, so far, is the absence of standardised methodologies for sampling and measuring brake wear particle emissions [34]. As such, researchers have employed different sampling and measurement techniques and devices, leading to variations in reported results. So, brake wear particles can be detected and measured under controlled laboratory conditions or in uncontrolled real–world settings on the road.

In the context of laboratory methods and devices, the most frequently used ones are pin–on–disc tribometers and inertial brake dynamometers [34]. On the other hand, measurements taken on the road [34] are conducted in uncontrolled, real–world conditions, and the methodology used differs significantly from laboratory methods.

Testing with a brake dynamometer

A brake dynamometer is a testing device or method that is used to simulate the conditions of a vehicle braking system in a laboratory environment. It works by applying a load to the brake system under test and measuring the force generated by the brake during operation. This allows for precise control and evaluation of the brake system's performance under different conditions, such as varying speeds and loads.

To use a brake dynamometer for testing brakes and generating brake PMs, the brake system to be tested is installed onto the dynamometer and connected to its load cell or torque transducer. The brake is then applied under various conditions, such as different speeds and loads, and its performance is evaluated. This evaluation can include measuring the stopping distance, fade resistance, and other characteristics of the brake system.

During testing, brake PMs are generated due to the friction generated between the brake pads and the rotor. These PMs can be collected using appropriate collection methods, such as filters or electrostatic precipitation, and then analysed using techniques such as microscopy or spectroscopy to determine their size, shape, composition, and other properties. [35–38].

Testing with a pin–on–disc tribometer

One method/device for measuring the wear and friction characteristics of brake pads or other brake components, under different conditions, is through testing with a pin–on–disc tribometer. The device consists of a rotating disc and a stationary pin that is pressed against the disc. The frictional force between the pin and disc is measured using a load cell or torque sensor, while the wear of the materials is measured using a profilometer or other measuring devices.

To use a pin–on–disc tribometer, the disc and pin are installed onto the device and brought into contact with each other. The load is then applied to the system, and the disc is rotated at a specified speed. The pin is pressed against the disc with a specified force, and the frictional force between the two materials is measured using the load cell or torque sensor. The test can be run for a specified duration or until a specified amount of wear has occurred.

These wear debris particles can be in the form of particulate matter (PM), which may contain harmful substances such as metals or other toxins.

To measure the PMs generated during testing, appropriate collection methods can be employed, such as using filters or electrostatic precipitation. These methods allow for the collection of wear debris particles in a controlled manner, which can then be analysed using techniques such as microscopy or spectroscopy. These analyses can provide valuable information on the size, shape, composition, and other properties of the wear debris particles [35][37].

On–road testing and measurement

In order to measure emissions under real conditions, it is necessary to conduct on–road testing. This method involves driving a vehicle on a designated test route that is designed to represent typical driving conditions. The route includes various driving conditions, including city, suburban, and highway driving, as well as different braking regimes and speeds. During testing, various instruments are used to measure the emissions produced by the vehicle, including sensors and specialised instruments for measuring particulate matter (PM) [39].

On–road testing is also a method used to evaluate brake performance under real driving conditions. It is important to note that on–road testing has some limitations due to the difficulty in controlling all the variables that can affect brake performance, such as road surface, weather conditions, and traffic flows. On–road testing is usually used in combination with other testing methods, as well as with different measuring instruments [35][40].

REGULATION AND PROPOSED STANDARDISED MEASUREMENT PROCESSES

Since the 1990s, regulations have limited PM emissions from vehicles by collecting PM from exhaust gases and measuring their concentration. The PN method was introduced in Europe in 2011 to improve testing methodology. While stricter regulations on exhaust emissions have reduced particle emissions, non–exhaust PM, from the wear of brakes and tires, has become a new concern. It accounts for nearly half of all PM generated from road transport processes [41]. Despite efforts to develop electrification strategies for road transport, even a fully electric vehicles still emit non–exhaust particles in significant quantities [42].

The above–mentioned scenario has required the development of a set of regulations and legal acts that will address this issue over the past decade. In this regard, the United Nations Economic Commission for Europe (UNECE) has developed a proposal for a new United Nations Global Technical Regulation (UN GTR) [43] based on the Worldwide Harmonized Light Vehicle Test Procedures (WLTP), which represents a regulation for defining harmonised laboratory procedures for testing particle emissions resulting from brake wear in light vehicles, with a maximum allowed mass of up to 3500 kg. The aim of the UN GTR is to improve understanding of different brake systems, reduce inconsistencies, and emissions through a harmonised approach to measuring brake particle emissions.

The regulation resulted from the Non–Road Transport PMP Informal Working Group, which was hired by UNECE VP.29 to study non–exhaust particles from road transport, focusing on brakes and tires as the most relevant sources. The group developed new testing cycles to simulate real–world conditions and established guidelines for reporting brake wear particles. UN GTR provides a globally harmonised methodology for measuring brake wear particles in light–duty vehicles in laboratory conditions, but it doesn't cover other vehicle categories (such as off–road vehicles, special purpose vehicles, etc.).

Test execution

Testing brake emissions consists of three segments, each requiring one or more cycles (trips) under certain conditions. The test itself is performed during the deceleration or stopping process, as this is the way to activate the brake system and, thus the precondition for the formation of particles. The mentioned three segments are:

- Brake cooling adjustment [43] – is process used to standardise and uniform the conditions for testing brakes in different locations and under different real conditions involves adjusting the level of airflow and its velocity, taking into account the design and size of the brake housing and the arrangement and geometry of the air duct system. This process is essential to ensure consistent and comparable results under all testing conditions. This section uses Trip #10 of the WLTP Brake cycle.
- Brake bedding [43] – is necessary to pre–test the brake pair under appropriate conditions and stabilise its response before measuring emissions. This procedure should be carried out either with the same brake pairs used during the brake cooling adjustment segment or with completely new brakes, evaluated after cooling adjustment. This procedure must be carried out for all brake pairs on the front and rear. This section uses five repetitions of the WLTP–Brake cycle.
- Brake emissions measurement [43] – defines the conditions for measuring particle emissions (PM) during brake testing, which the measuring system must meet. The sampling system determines the amount of PM produced by the brakes during the test itself. PM emissions and testing parameters should be presented as particle mass per distance travelled, for the brake pair being tested. It is necessary to assess emissions for both PM_{10} and $PM_{2.5}$ during testing, using separate sampling systems for each threshold (2.5 µm

and 10 μm). This section includes one performance of the WLTP–Brake cycle.

Each of the parameters, requirements of the system, procedures, and trips that further define the aforementioned segments are described in detail in the regulation itself and the WLTP procedure on which the regulation is based.

Minimum requirements for test equipment and automation

It is important to note the minimum testing system requirements (dynamometer and automation) prescribed by the regulation. The diagram illustrating the principle of the brake dynamometer testing system, as shown below, indicates the interactions with the essential subsystems needed to conduct brake emission tests according to UN GTR.

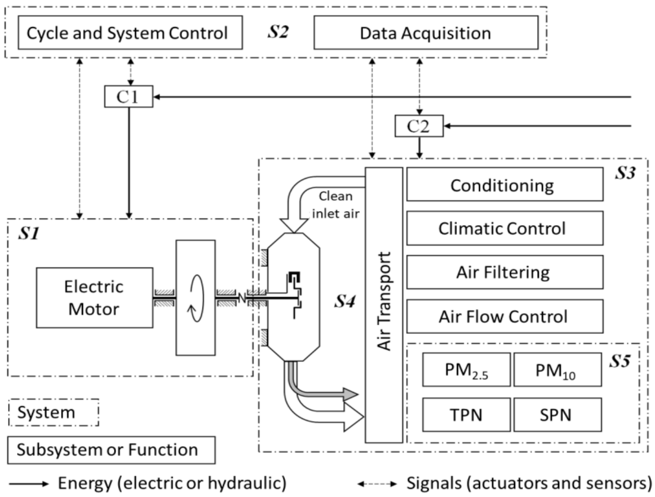

Figure 3. Layout of the test system with the brake dynamometer, where S1: Brake dynamometer, S2: Automation, control, and data acquisition system, S3: Climatic conditioning unit, S4: Brake enclosure and sampling plane, S5: Emissions measurement system. C1 and C2: Testing facility energy controls and monitoring system. The grey arrow represents the aerosol sample from the brake under testing [43].

The brake dynamometer must comprise the following components at a minimum [43]:

- An electric motor that can vary the rotational speed or maintain it at a constant rate. This motor is also responsible for adjusting the test inertia to simulate actual driving conditions and non–friction braking.
- A servo controller, either hydraulic or electric, that activates the brake being tested.
- A mechanical assembly that facilitates the mounting of the brake being tested, permits the disc or drum to rotate freely, and absorbs the reaction forces produced by braking.
- A robust framework that houses all the mandatory subsystems. The framework must have the capacity to withstand the forces and torque generated by the brake under testing.
- Sensors and devices that gather data and supervise the operation of the testing system.

The automation system performs crucial functions for the brake emissions test. It should accelerate and maintain constant speed during acceleration and cruise events, respectively, while reducing the kinetic energy of rotating masses by modulating the frictional torque during deceleration events. Besides, the system should provide an interface to the operator, stores test data, and manages communication with other testing facility systems.

During deceleration events, the automation system uses active torque control to increase or decrease the total effective test inertia. The electric motor can absorb some kinetic energy equivalent to the road loads and non–friction braking from the vehicle's powertrain.

Also, the test system software must have the following functions: automatically execute the driving cycle and closed–loop processes (primarily for brake controls, cooling air handling, and emissions measurements); continuously record data from all relevant sensors to produce specified outputs; and monitor signals, messages, alarms, and emergency stops from the operator and [43].

CONCLUSIONS

Non–exhaust emissions from motor vehicles, such as those generated by the brake system, tire wear, and road surface, contribute significantly to the overall level of pollutants generated by traffic, and have been found to have a substantial impact on human health. Exposure to PM from motor vehicle emissions has been linked to respiratory problems, cardiovascular disease, neurodegenerative phenomena, and cognitive disorders.

It is clear that the impact of PMs on human health represents an additional threat for chronically ill individuals and those susceptible to rapid changes in health status. The study provides a detailed overview of previous research that examined non–exhaust emissions and their impact on human health, as well as a review of methods for measuring non–exhaust emissions generated by the brake system.

The research concludes that while the scientific community's interest in studying brake emissions is increasing, the vast majority of research findings are inconsistent and vary widely, introducing a significant degree of uncertainty when attempting to assess the contribution of brake emissions to overall particulate matter emissions.

However, with the release of the proposal for a new United Nations Global Technical Regulation (UN GTR) it will now be easier to obtain more reliable data through standardised methods for brake lab testing. This is a significant development as it will lead to more accurate information on the contribution of brake emissions to overall PM emissions and will help policymakers take more effective measures to limit exposure to these harmful pollutants. Precise measurements can inform the development of new regulations on the amount of particles that brakes can produce, conditional on the use of suitable materials and technologies in the production process. In addition, standardised data on the level of PM can significantly influence the recommendation and development of EURO7 norms [44], which will entail restrictions in the domain of non–exhaust emissions in general.

On another note, by adopting and implementing an effective braking process that is tailored to specific conditions, harmful emissions could significantly be reduce, thus improving human health and the environment, which may require additional research.

It is important to continue to monitor research and develop new methodologies to improve our understanding of the impact of non–exhaust emissions on human health, and to implement measures to reduce these emissions in the future.

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