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Review

Input Parameters for Airborne Brake Wear Emission Simulations: A Comprehensive Review

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Abstract: Non-exhaust emissions, generated by the wear of brake systems, tires, roads, clutches, and road resuspension, are responsible for a large part of airborne pollutants in urban areas. Brake wear accounts for 55% of non-exhaust emissions and significantly contributes to urban health diseases related to air pollution. A major part of the studies reported in the scientific literature are focused on experimental methods to sample and characterize brake wear particles in a reliable, representative, and repeatable way. In this framework, simulation is an important tool, which makes it possible to give interpretations of the experimental results, formulate new testing approaches, and predict the emission produced by brakes. The present comprehensive literature review aims to introduce the state of the art of the research on the different aspects of airborne wear debris resulting from brake systems which can be used as inputs in future simulation models. In this review, previous studies focusing on airborne emissions produced by brake systems are investigated in three main categories: the subsystem level, system level, and environmental level. As well as all the information provided in the literature, the simulation methodologies are also investigated at all levels. It can be concluded from the present review study that various factors, such as the uncertainty and repeatability of the brake wear experiments, distinguish the results of the subsystem and system levels. This gap should be taken into account in the development of future experimental and simulation methods for the investigation of airborne brake wear emissions.

Keywords: brake wear; non-exhaust emission; airborne particles; emission factor; simulation

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1. Introduction

Transportation-related emissions, which are among the most influential phenomena affecting people's health in many large cities, can be categorized into various classes according to their sources. Emission originating from the incomplete combustion of fuel in a vehicle's engine, and, accordingly, emitted from the vehicle's tailpipe, is called "exhaust emission" or "tailpipe emission". On the other hand, "non-exhaust emission" includes particles generated during the operation of a vehicle's brake system and the particles generated by the wear of the tire and road contact surfaces due to slip, road dust resuspension, and dry clutches. The features of these four types of non-exhaust emissions have been discussed in general overviews and comprehensively compared in previous studies [1,2].

Many studies have emphasized the harmful effects of non-exhaust emissions on human health [3–7]. Scholars have exerted a lot of effort to find a way to reduce the diseases caused by coarse and fine particulate matter, ozone, and other toxic pollutants, to which traffic contributes significantly [8,9]. Similar attempts have been undertaken by governments (especially in developed countries) to improve the air quality of cities, regardless of the emissions' origins. Introducing new fuels with eco-friendly qualities, setting standard restrictive rules, forcing automobile manufacturers to use prevention filters, and encouraging people to use the public transportation fleets instead of private cars can be cited as some of these endeavors. Table 1 presents all abbreviations used in this research.

Table 1. Abbreviations used in the research.

Abbreviations					
AI	Artificial intelligence	EF	Emission factor	NAO	Non-asbestos organic pads
ANN	Artificial neural network	ELPI+	Electrical Low-Pressure Impactor	OPS	Optical particle sizer
APS	Aerodynamic particle sizer	FAST	Friction assessment screening test	PIV	Particle image velocimetry
BLCF	Brake linings' coefficient of friction	FEA	Finite element analysis	PM	Particulate matter
CA	Cellular automaton	FMPS	Fast mobility particle sizer	PM_{10}	Particulate matter 10 μm or less in diameter
CFD	Computational fluid dynamics	GDP	Gross domestic product	$PM_{2.5}$	Particulate matter 2.5 μm or less in diameter
CMB	Chemical mass balance	HDV	Heavy-duty vehicle	R&D	Research and development
CVS	Constant-volume sampling	HEPA	High efficiency particulate air	RDE	Real driving emission
DMS	Differential mobility spectrometer	LDV	Light-duty vehicle	SEM	Scanning electron microscopy
DLPI	Dekati Low Pressure Impactor	MCA	Movable cellular automata	TEM	Transmission electron microscopy
Dyno	Dynamometer	ML	Machine learning	TRAKER	Testing Re-entrained Aerosol Kinetic Emissions from Roads
EDXS	Energy dispersive X-ray spectroscopy	MLR	Multiple linear regression	VAPI	Vehicular Air Pollution Inventory
EEA	European Environment Agency	MOUDI	Micro-orifice uniform deposit impactor		

Due to the inherent features of non-exhaust wear particles, they can be either airborne or sedimentary depending on their aerodynamic diameter. Emitted wear particles that become dispersed and suspended in the air are known as airborne particles, whereas others may become deposited on various disposed areas, such as the ground, roads, tunnels, and agricultural farms, or even become sedimented on the brake hardware [10]. It has been reported that approximately 30–50% of pads' wear is dispersed as airborne particles [11–13]. Also, in their study, Perricone et al. reported that 35–58.5% of the particles resulting from wear emitted by the brake system, discs, and pads became airborne [14]. Furthermore, Sanders et al. reported that the wear particles generated by a vehicle's brakes are 50–70% airborne, whereas 15–25% of them remain on the wheel [15]. Table 2 presents the minimum and maximum sizes of the particles found in the literature.

According to Table 2, the aerodynamic diameter of the coarse particles is limited to 10 μm. Furthermore, the frequency of the recurrence of 2.5 μm diameters is quite evident. As a result, the concept of particulate matter (PM), one of the eminent traffic-related emissions, was defined by academics with particular concerns about the health of urban residents. Previous studies investigated PM in terms of its toxicity and negative effects on the human body [31–35]. Some of the most toxic particulates are those with an aerodynamic diameter of 10 μm or less, known as PM_{10}, which mostly put the respiratory system of the body into danger. Investigations have even shown that exposure to PM_{10} during pregnancy can result in adverse birth outcomes with different critical periods [36–38]. Furthermore, the emissions' adverse effects can be drastically increased when their size decreases. So-called "$PM_{2.5}$", i.e., emission particles with an equivalent aerodynamic diameter of 2.5 µm or less, has exhibited even more intense adverse effects on exposed people. Previous studies showed that the mass size of PM_{10} particles follows a unimodal distribution, in which the peak fluctuates between 1 µm and 5 µm [39–41].

Table 2. Minimum and maximum sizes of particles considered in previous studies.

Reference	Ultrafine Particles		Fine Particles		Coarse Particles	
	Min (µm)	Max (µm)	Min (µm)	Max (µm)	Min (µm)	Max (µm)
Nosko et al. [16]	0.0056	0.1	0.1	2.5	2.5	-
Nosko et al. [17]	0.0056	0.1	0.1	0.56	0.56	10
[18–23]	-	0.1	0.1	2.5	2.5	10
Kumar et al. [24]	-	0.1	-	2.5	-	10
[25,26]	-	0.15	0.15	2.5	2.5	10
Waheed et al. [27]	0.02	0.1	0.26	1	1	10
Niu et al. [28]	0.057	0.1	0.1	1	1	10
Chang et al. [29]	0.05	0.1	1	2.5	5	10
Valavanidis et al. [30]	-	0.1	-	2.5	-	-

Following air quality standards, PM emissions are represented with the units $g \cdot h^{-1}$ or $kg \cdot y^{-1}$ (mass per time). In some cases, PM concentrations may be used for further study of PM particles, represented as $\mu g \cdot m^{-3}$ (mass per air volume). PM emission factors, which are utilized to investigate the particles in the emission models, are expressed with the units $g \cdot km^{-1}$ or mass per traveled vehicle distance (activity) [42].

In Europe, scholars have shown that more than half of the mass of non-exhaust PM_{10} particles and 21 percent of the mass of traffic-related PM_{10} particles are caused by brake wear [43–45]. The tribological formation mechanisms of PMs produced by brake system have been discussed in [46]. Based on the report by the European Environment Agency (EEA), almost 34% and 26.7% of the particles generated by brake and tire wear are PM_{10} and $PM_{2.5}$, respectively [47]. Thus, restriction rules were set in Europe and by the United States Environmental Protection Agency to limit the level of PM emissions [48,49].

Brake wear, one of the most essential sources of non-exhaust emissions, is counted as a considerable part of traffic-related emissions, accounting for the 55% of total non-exhaust emissions in urban areas [44,50,51]. It has been estimated that 30–50% of brake wear is exposed as airborne particles [11,52,53]. However, Wahlström declared that this percentage could be as high as 50–70% [54]. Brake wear, based on its size, can be generated in four phases: gaseous, volatiles, semi-volatiles, and solid. The most important factor which strongly designates the type of brake wear is temperature [55]. In previous studies, various tests have been implemented on different type of discs and pads using distinct testing machines to find a critical temperature that could be considered as a volatile wear boundary. For instance, Perricone et al. reported that a significant amount of volatile brake wear is produced at temperatures above 200 °C, which was identified as critical temperature [56]. However, in other studies in the literature, this critical temperature was identified as being in the range from 120 to 300 °C from test-determined features [57–60]. According to Perricone et al. [56], particles with sizes less than and greater than 200 nm can be considered as semi-volatile and non-volatile, respectively. The gaseous part consists of volatile materials and, depending on the particle size, may remain in the air or be altered to solid particles. Solid emission produced by wear, which, in some cases, can be seen with the naked eye, is affected by tribological, mechanical, thermal, chemical, and fluid-dynamics phenomena, and its result is characterized by various indices, especially the number and distribution of particles [61].

Several studies have shown that a vehicle's braking system is one of the most relevant sources of PM particles [62–66]. Furthermore, previous investigations showed that the particles generated by the cast iron discs are an important fraction of PM particles, with average sizes below 20 µm [11,67]. Also, there are some influential parameters that can increasingly affect the amount of PM brake wear debris. Friction materials [58], the quality of brake system compositions [68], driving styles [69], and the severity of braking [70] are some parameters that can be counted. The release rate of PM particles may also be different in terms of the vehicle parameters. For instance, the weight of a vehicle is one of the critical features that may influence the rate of brake wear, as was shown for electric vehicles [71].

Conducting investigations into the braking system using a lab environment or physical experiments in fields may produce acceptable results. However, depending on the case, it may be necessary to benefit from other tools. For instance, predictions of the temperature, wear, and contact pressure of a braking system in various driving styles are common [72,73].

Simulation of a braking system is a fruitful tool that can help scholars compensate for the conditions that cannot be incorporated in lab or field experiments. The goals of these simulation-based methods are to analyze the phenomena that happen in the sliding contact during braking, to propose an estimation of the brake wear and temperature during brake operation, and to predict the effects of design changes in details. One of the main challenges of brake disc simulation is the existence of various physical phenomena with different size scales. As a result, choosing a simulation model to characterize the details of pad-to-disc contact is challenging.

Previous studies focusing on emissions produced by the brake system can be divided into three main categories: the subsystem level, system level, and environmental level. Those dealing with the features of braking system components in a laboratory environment were categorized in the subsystem level whereas the studies in which all the data collection and the investigation of brake wear particles were implemented on-road or in the laboratory environment by using real cars, chassis, or brake wear tracers were categorized in the system level. Finally, those studies in which the sampling was directly performed in the environment, such as in roads, rivers, agricultural farms, and runoffs, were categorized in the third level, the environmental level. This categorization is remarkably beneficial not only in the study of experimental tests, but also for the simulation-based methods used in brake wear investigation. As is shown in Figure 1, hierarchically, the complexity of the measurement, configuration, and investigation of brake wear increases as the levels rise from subsystem to the environmental level.

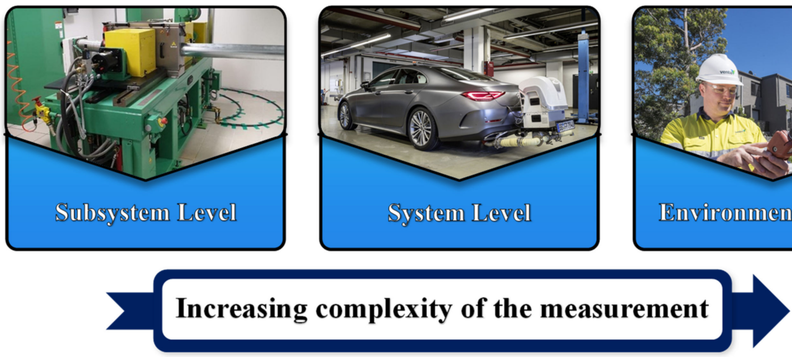

Figure 1. Hierarchical levels of investigation.

This categorization is useful in understanding the levels of the various emission phenomena involved. At the subsystem level, the braking system is under study and the mechanisms of production of the pollutants are investigated. At the system level, the dynamics of the vehicle and the particle local interaction with fluid are also examined, and the behavior of the complete braking system (e.g., four brakes for a standard car) is observed. 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. The aim of the present literature review was to organize the main results of state-of-the-art research according to the proposed categorization and outline some conclusions and possible developments for the simulation and experimental test approaches. Figure 2 shows an overview of the proposed brake wear categories in the simulation and testing approaches.

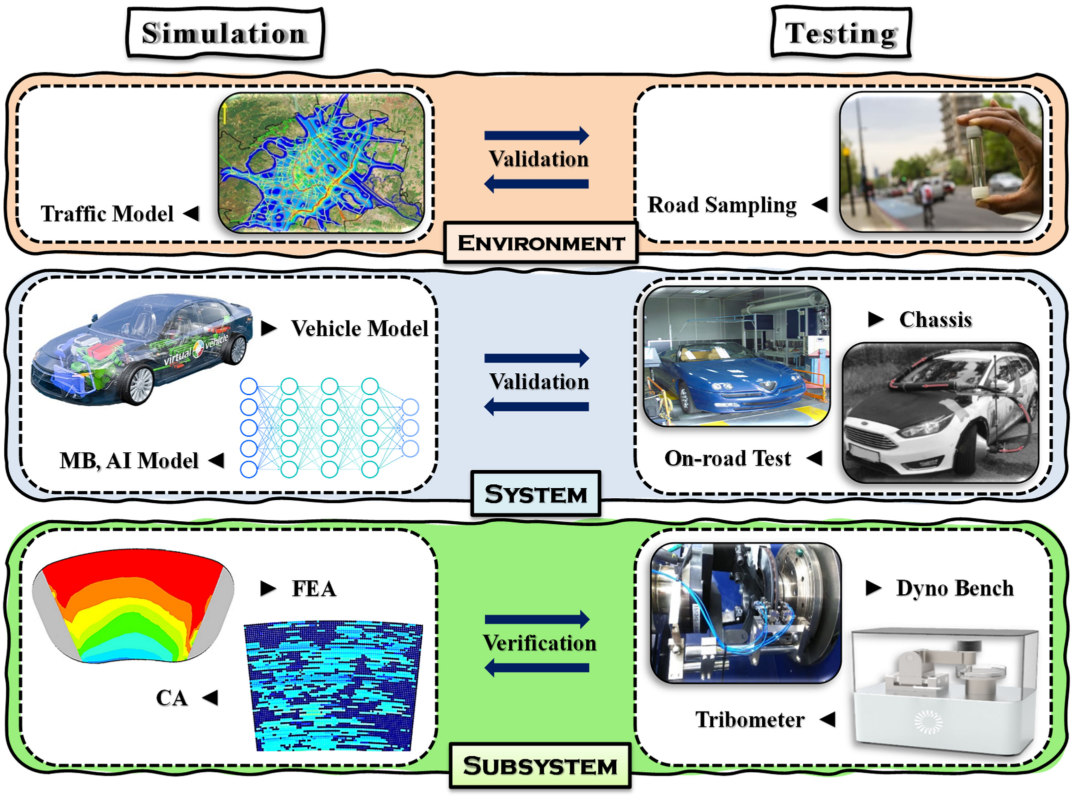

Figure 2. An overview scheme of the proposed brake wear categories.

2. Subsystem Level

The subsystem level is the fundamental category introduced as the first level of the investigation; it deals with the smallest components of the existing system in a microscopic analysis of the brake system. This level is based on the reproduction and deep study of some key aspects of the braking action. A remarkable advantage of implementing the studies at this level is the possibility of keeping the test under control and undertaking a deep study of the basic physical phenomena. There are some limitations to this level. The vehicle dynamic is reproduced by its equivalent inertia. Moreover, the operative conditions (intensity and duration of the braking action) may only be relatively representative. Therefore, it is necessary to consider effective strategies to overcome these restrictions. The main metrics applied at this level are the coefficient of friction, the wear of pads and disc, the emission rate in terms of mass/time and traveled distance, and the emission factor.

To provide and develop air quality management and a reasonable estimation of the emissions generated by the vehicles, validated models and emission estimators are needed. In some cases, these models may be restricted to the modeling of the parameters that have direct impacts on the rate of brake wear generation; for instance, the models established based on the brake linings' coefficient of friction (BLCF) to monitor the brake operation [74,75].

2.1. Subsystem Classification

Basically, brake systems inherently operate stochastically. The main problem with measuring the airborne debris from brake wear in the field is that distinguishing the original sources of the particles is overwhelming. Debris may have originated from the braking pads or disc, resuspended road dust, tires, or other sources. Thus, a reliable environment is needed to provide the different scenarios and circumstances for braking operations in different driving conditions. In the subsystem level, the evaluation of the characters of brake wear particles is implemented in the laboratory environment. There are many studies investigating brake particle features by using well-known tribometer machines, such as the pin-on-disc and dynamometer. Speed, acceleration, deceleration, pad wear, disc wear, continuously changing temperature due to the friction of pads and discs, and noises are the most influential parameters for the interaction of brake pads and discs in the subsystem level. Philippe et al. [76] suggested that the best option to examine the brake wear is the use of pin-on-disc and dynamometer tests. The particles' properties, like size distribution, are similar between these two tests. However, the emission rates obtained from these two tests are not compatible because of the different testing temperatures.

The use of laboratory methods for estimating brake wear emissions enables implementation of determined testing programs [77]. One of the benefits of implementing such tests in labs is to provide comparisons between brake emissions from the different types of brake components and evaluate their value on the market. Furthermore, the results obtained from different tests can allow scholars to distinguish the pads that generate an unacceptable amount of wear, whether airborne or sedimented, from environment-friendly pads.

There are several instruments employed to assess the different brake wear parameters in lab-based measurements. Scales are commonly used to measure the weights of the test samples before and after testing. Techniques like scanning electron microscopy (SEM), transmission electron microscopy (TEM), and energy dispersive X-ray spectroscopy (EDXS) are used to characterize the wear debris captured on filters after testing. Particle instruments based on different measurement techniques are available, such as fast mobility particle sizers (FMPSs), optical particle sizers (OPSs), differential mobility spectrometers (DMSs), the Electrical Low-Pressure Impactor (ELPI+), micro-orifice uniform deposit impactors (MOUDIs), electrical aerosol analyzers, aerodynamic particle sizers (APSs), the Dekati Low Pressure Impactor (DLPI), and image analysis.

2.1.1. Material Level

Pin-On-Disc Test

The pin-on-disc tribometer test is one of the most popular tests which many scholars have benefited from in studies focusing on brake pads and disc wear particles [61,78–86]. This test has been validated by previous investigations and named as an authentic experimental method for inquiry into airborne particles from vehicles' disc brakes contact [87,88].

In this test, all airborne wear particles generated by the friction at the sliding contact between a dead weight- or a hydraulic system-loaded steel pin and a horizontal rotating disc are collected. Due to the simplicity of the pin-on-disc tribometer test, it cannot totally represent the real condition of the vehicle braking system. To determine the real condition, further considerations are needed in addition to the steady interaction of pressure and sliding velocity [89]. However, scholars introduced the pin-on-disc test as a reliable method for evaluating brake pads' wear and their friction behaviors when sliding against a cast iron disc [43,64]. As claimed in [78] at least, the pin-on-disc test can be beneficial for research and development (R&D) objectives, especially in the initial phase of the development of new materials. Moreover, its lower costs and operation times, compared to other tests, may be essential in projects dealing with many problems related to budgets [90].

For brake wear testing using the pin-on-disc tribometer, the ambient air is passed through the high efficiency particulate air (HEPA) filter to control the cleanness of the outlet air. The outlet air is led through an inlet pipe to a chamber. A closed climate chamber should be used to provide the conditions for testing at different humidity and temperature levels. To prevent errors (leakages) and increase the accuracy of results, all the connections must be sealed. Otherwise, the airflow rate conveyed in the chamber varies and causes a mismatch of the particle concentration measurements [91]. In 2020, this procedure was performed by Gomes et al. [92] to investigate the particle size and mass of particles released from a pin-on-disc machine. However, they reported a non-correlation of emissions and the friction coefficient.

In 2015, Chandra Verma et al. [93] examined the different aspects of braking pads' wear in terms of their behavior during sliding on a rotating iron disc by implementing lab studies using a pin-on-disc machine.

2.1.2. Component Level

The component level in investigations of airborne brake emissions comprises experiments which involve sliding surfaces characterized by more representative dimensions. At this level, the instrument developed for the experimental characterization of the braking behavior of the components being tested is the dynamometer.

Dynamometer Test

Innumerable studies have investigated the emissions of brake wear with dynamometer testing (dyno), which can simulate the real conditions (driving in urban or suburban areas) of a braking system of a vehicle in a lab environment [56,63,94–99]. A brake dynamometer provides a more representative and controlled environment for the disc and pad test. Like the pin-on-disc machine, using a chamber is necessary to determine the airborne particles during the braking process [100]. A dynamometer machine usually has a blower providing a constant flow of air through the braking system that simulates the real conditions and carries the particles to a tunnel, which is known as constant-volume sampling (CVS) [101].

One of the substantial differences between the pin-on-disc and dynamometer tests is the provision of the appropriate power per unit area or mass of samples to realize the correct temperature on the area of contact friction. Although the pin-on-disc tribometer can provide sufficient power to the pin sample, it is common to load powers which can simulate the common braking power in cities; this is why the maximum mass wear of the dynamometer is two times more than the pin-on-disc tribometer results [102–104].

Scholars have classified dynamometers into two major types: the inertia dynamometer and the CHASE dynamometer. The inertia dynamometer is used to investigate full-sized brakes. Although it can be both time-consuming and expensive, it shows more accurate results in comparison to the CHASE dynamometer. The CHASE dynamometer, despite the low capital expenditure and shorter test time, can only be used for quality control or similar non-essential subjects [105].

Inertia Dynamometer

Inertia dynamometers are dynos that incorporate a full- or reduced-sized brake. Compared to other dynamometers, these dynos can reproduce the braking system operating conditions in a reasonably reliable way [106]. Based on the literature, there are two types of inertia dynamometers: full-scale and reduced-scale.

- Full-Scale Dynamometer

One of the tribological tools that can be used for the investigation of these new achievements is the full-scale dynamometer [107]. The rotating body used for full-scale dynamometers is relatively large, which simulates the vehicle's total mass during the brake operation.

In 2019, Hagen et al. studied brake wear particle emissions using a full-scale brake dynamometer by presenting a novel measurement setup to reduce particle transport losses [108]. In this research, the brake wear particles were calculated during either braking or driving to obtain more realistic results.

Mamakos et al. designed a dilution tunnel aimed at providing more accurate and reliable measurement of the brake wear in a brake dynamometer. This dilution tunnel enabled the minimization of particle losses for sizes less than 10 µm [109].

In 2020, Matějka et al. investigated the amount of airborne wear particles generated by the braking system by means of a full-scale dyno-bench [110]. By investigating the data obtained by utilizing the PM_{10} and electric low-pressure impactors, they found that the maximum disc temperature and brake duration had the most significant impacts on the rate of brake wear generation.

- Reduced-Scale Dynamometer

Reduced dynamometers are known as tools that decrease the unnecessary expenses and time associated with full-scale dynos. Previous studies introduced reduced-scale friction testing for investigations into the quality of friction materials, assessing their properties and linings. For instance, Sanders et al. used a reduced-scale inertia brake dynamometer to determine the frictional characteristics of lining materials [111]. Anderson et al. also investigated the brake lining materials in a brake disc in terms of friction stability [112]. In this research, they claimed that their test, named the Friction Assessment Screening Test (FAST), was reproducible and could highly correlate with vehicle performance. However, Kermc et al. discussed the limitations of the FAST in presenting the quantitative values of the coefficient of friction [113].

In the literature, the reduced-scale dyno is also known as a small-scale dynamometer. While a reduced dynamometer benefits from the simple assembly of the pads and disc, it has a reasonable and acceptable correlation with full-scale dynamometers. Recent studies have demonstrated reliable approximation of the collected data obtained by evaluating the temperature tests of the sliding surface for the reduced and full-scale brake discs [114]. Thus, it can be a useful tool for screening brake linings and calculating friction coefficients [111]. The small scale of these kinds of machines helps scholars avoid the negative effects of the brake pad geometry and implement a uniform distribution of pressure on the pads and disc during the braking operation. This uniform distribution means that the brake system performs acceptably even in severe conditions, like high temperatures [113]. Beyond all these merits, reduced-scale dynos cannot provide 100% realistic performance for braking systems due to the less realistic simulation of operating conditions [115].

Furthermore, it is necessary for full-scale dynamometers to respond dynamically to the vast surrounding systems and because of this they may show less accuracy in their results in comparison to reduced dynamometers due to the existence of caliper and bracket deflection and pressure fluctuations [113]. On the other hand, there are some issues that increase the complexity of designing reduced-scale dynos, such as the cooling rates of the brake system configuration. Therefore, tuning of scaled parameters is mandatory when using this type of dynamometer [114,116].

CHASE Dynamometer

Differently from the inertia dynamometer, which provides the full scale of friction materials, the CHASE dynamometer simulates the braking system by implementing a small number of friction materials rubbing against a drum. In 1980, Liu et al. measured the wear rates of a drum lining and a disc pad [117]. However, in light of the significant changes in pads and disc materials and the development of vehicle braking systems in recent years, the recent results on braking wear using the previous approach are not completely reliable.

Inherently, due to its design, the CHASE dynamometer cannot simulate the realistic state of the braking system in terms of the physical and chemical state of the friction contact during system operation. Tsang, by comparing the results of both inertia and CHASE dynos, proved that the CHASE dynamometer is not reliable for the prediction of the performance of materials with the inertia dyno and for the screening of automotive friction materials [105].

The running time of the sample evaluation using the CHASE dyno is much lower than with the inertia dyno. An inertia dyno needs an appropriate number of full-size braking systems, including pads, rotor, discs, and linings [118], together with proper inertial capacity; therefore, the analysis of the results requires a time-consuming procedure of disassembling the pads and evaluating the samples. Also, testing with the CHASE dynamometer can be carried out by using small samples, while the inertia dyno needs an appropriate number of linings and other segments [105].

2.2. Simulation Methodologies

2.2.1. Finite Element Analysis (FEA)

FEA is an effective tool used to simulate the different conditions of the braking system in various situations. This tool can provide quite good details of the phenomena related to the braking contact at the macro-scale [81,119].

This simulation method is described as a popular approach in the literature. Not only the brake wear but also the brake noises have been investigated using the FEA method [120]. To simulate the brake wear using an FEA simulation approach, the pressure distribution on the contact surface together with Archard's wear law [121] and Euler's integration scheme were used in previous studies [81,122,123]. Furthermore, AbuBakar et al. investigated the contact pressure between the rotor and the braking pads [124].

Introducing thermo-mechanical models is another merit of the FEA approach, which is now known as a useful and effective tool in the industry. Some previous studies used the FEA simulation method to undertake a transient analysis of the thermoelastic contact problem for brakes [125–130]. In 2012 and 2015, Yevtushenko et al. and Li et al. conducted FEA simulation experiments for the evaluation of transient heat problems with friction in the brake components [131,132]. Moreover, Sarkar et al., by performing static thermal analysis and using an FEA model, evaluated the temperature distribution of discs [133]. This thermal analysis of discs was recently improved by using ANSYS finite element simulation software [134]. In addition, Bortoleto et al. simulated a pin-on-disc machine by implementing an FEA model to analyze the stress and contact pressure field distributions [135].

In 2009, Wahlström et al. used an FEA simulation model to determine the brake wear amounts generated during the braking process [136]. First, they used a pin-on-disc test to evaluate the wear rate and particle coefficient and then they implemented an FEA simulation at the component level with the obtained wear rate and coefficient. They also compared the number of distributions obtained from the simulation model with the experimental measurement to validate the simulation results. The results of this research show that using the FEA simulation method can be effective in predicting the number and distribution of airborne particles, as do the similar results obtained in [137]. Using the FEA approach, scholars have even shown that the amount of PM_{10} generated by a braking system can be reduced to 65% by using NAO pad materials based on the European Standards [138].

In 2018, Goo presented a numerical simulation approach based on an FE model of a brake system and a coupled thermo-mechanical analysis to evaluate the correlation between the brake wear and the non-uniform contact pressure [139]. Schmidt et al. indirectly estimated the contact pressure between the brake disc and pads by using an FEA method and infrared thermal images [140]. Riva et al. proposed a simulation-based method to predict dry sliding wear by considering a three-dimensional transient non-linear FEA model [81]. Shahid et al. presented a numerical simulation-based method that involved an FEA approach to evaluate the wear behavior of the drum brake [141].

Riva et al. investigated the correlation between brake wear and airborne particles using the sliding speed and local contact pressure from a full disc brake with an FEA macroscopic simulation approach. In this research, the scholars implemented a pin-on-disc experiment to determine the maps of emissions generated by the braking pads. To compare the results obtained from the pin-on-disc data with another experimental test, an inertia dynamometer tribometer was also used. The results of this research showed a 19% error for the simulated wear [81].

In 2018, Hatam et al., by using an algorithm implementing Archard's wear equation, simulated the brake wear in ABAQUS finite element software using the Python language [142]. In addition, to calculate the coefficients of the friction under contact, they implemented a pin-on-disc test and validated the proposed algorithm.

In 2019, Zhang et al. provided a direct calculation of the brake wear particles using DEFORM, an FE simulation-based software [143]. This study showed a rapid increase in wear in the early stages of brake operation. They also described how the amount of wear is intensified under heavy braking loads and high initial braking speed.

2.2.2. Cellular Automaton (CA)

Despite all the advantages of using the FEA approach at the macro-scale, at present, it cannot be effectively used for the simulation of the plateau dynamics (particular flat spots, existing in normal pads, affecting a pad's wear) and tribofilm creation (a cover consisting of the mix of wear particles that form on the contact surface). This is due to the sizes of the scales of time and length involved, i.e., milliseconds and millimeters. Thus, to simulate the friction behavior and the particle flow at the nano-scale level, the scholars introduced the movable cellular automata (MCA) approach [144,145]. In this research, it was demonstrated that the MCA approach can numerically evaluate friction behavior at the nanometer scale.

CA is an approach introduced by scholars to simulate the wear and friction of the disc braking system in three-dimensions [146,147]. In addition, the mesoscopic scale (10 to 1000 nm) of the plateau dynamics has been investigated by Mueller et al. and Müller et al. [148,149]. In this research, the size changes of contact plateaus (interaction of pads and discs) were also evaluated at the mesoscopic scale.

Furthermore, in 2011, the CA approach was implemented as a reliable method to estimate the number of wear particles dispersing during the braking operation [147]. As a result, several further studies used this approach to simulate the brake system at the scale of seconds (time) and centimeters (length) [54,81,97,150,151].

2.2.3. Computational Fluid Dynamics (CFD)

CFD is a simulation-based tool for analyzing particles' behavior and their dispersion and depositions by investigating the complex flow systems. Basically, thanks to its versatile capabilities, the CFD approach is known as a dependable tool for various scientific issues. Historically, the CFD model has been widely used for analyzing and optimizing disc brake cooling [152–157], transfer of flow and heat through the brake system [158–160], brake disc contamination [161], and brake dust particles [162,163].

In 2011, Augsburg et al. developed a numerical CFD approach to improve the accuracy of results for brake wear obtained during brake operations [162]. By using ANSYS software, they evaluated the character of brake particles and the particle flow paths. In addition, they validated the results of the simulation by implementing particle image velocimetry (PIV) together with a CFD model providing a better and more reliable estimation of brake wear and flow behavior.

In 2019, Hesse et al. introduced the constant-volume sampling (CVS) method to collect samples of brake emissions under real driving emission (RDE) conditions [163]. They used a CFD-based method to investigate and analyze the behavior of the particles and their deposition using the ANSYS fluent simulation tool, which provides high-quality estimations.

3. System Level

Hierarchically, the next level is the level that deals with the full vehicle, named the system level. When the amount of emissions generated by the brake system of the whole car is considered, it can be defined as the emissions at the system level. This means that a single car, as a confined environment, is considered as an ensemble of devices that interact, and it therefore constitutes an "emitting system". These emissions can be evaluated by assessing cars either in laboratories or on-road environments. Studies at this level address the emissions in real driving conditions; therefore, the vehicle dynamics (including the drivetrain), the driving style, road geometry, and slope are incorporated. The inherent feature of this level is that the emissions that are continuously emitted by the system, even when deceleration and speed reduction are carried out by engine, can be estimated. One limitation of the system level is that it does not allow deep study at the microscopic level since the brake is installed on the vehicle and only a limited number of instruments can be installed. The main metrics applied in this level are the emission rate in terms of mass/traveled distance, the emission factor, and the loss of performance when over-heated [164].

Despite the advantages of the subsystem level tools, like dynamometers or pin-on-disc tests, for scrutinizing brake-related 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.

At the system level, there are two ways to study brake wear particles. First, it can be done under real-world conditions on the road, which is called an on-road driving test, and second, it can be implemented in the laboratory through relatively controlled ambient conditions. One of the approaches involving such a controlled environment is the use of a single car on a chassis dynamometer in the lab (as an agent). Although both of these methods can provide reliable results, they can also be used simultaneously to make comparisons. For instance, in 2020, Beji et al. compared the non-exhaust emissions obtained from the testing of similarly instrumented vehicles and collected samples in three distinct environments, including a fully controlled laboratory (chassis dyno), a semi-controlled test track, and on-road urban areas [165]. In addition to brake wear particles, they calculated the tire–road contact and resuspension particles and specified their features. Thanks to the achievements of this research, it was found that over 70% of brake wear particles originated from brake pads. Furthermore, it was found that the speed variations influenced the amount of wear generated by brakes and tires. Thus, Beji et al. suggested that, regardless of the driving conditions, the rate of wear can be remarkably reduced at various speeds and braking force frequencies.

3.1. Emission Factor

Emission factors (EFs) are representative values chiefly implemented to quantify the emissions generated by vehicles, i.e., they relate the vehicle's activity to the amount of pollution emitted in the air [166,167]. There are many such factors, including vehicle characteristics, fuel consumption, fuel type, and the quality of the fuel, and driving conditions directly affect the EFs [44]. As a result, the levels of emissions in numerous regions with varying traffic conditions can be easily predicted by EFs. EFs can be calculated directly by performing laboratory tests, on-road measurements, or receptor modeling [168]. Tables 3 and 4 show the emission factors of brake wear and vehicles presented in the literature for light-duty vehicles (LDVs) and passenger cars, respectively.

Table 3. Emission factors of brake wear reported in the literature for LDVs and passenger cars (mgkm^{-1} brake^{-1}).

Reference	Measurement	Emission Type	Emission Factor
zum Hagen et al. [69]	On-road measurement	PM	Conventional brake material: 1.8–2.1 Novel material composition: 1.4–1.7
Mamakos et al. [109]	Brake dyno and dilution tunnel	PM	4.8
Hagen et al. [108]	Brake dynamometer	PM_{10}	4.6
Timmers et al. [169]	Review	PM_{10} $PM_{2.5}$	9.3 2.2
Perricone et al. [14]	Brake dynamometer	PM	Low steel pads: 13.7–46.4 NAO pads: 8.5–9.2
Bukowiecki et al. [170]	Sampling	PM_{10}	1.6 ± 1.1
Hesse et al. [171]	Bedding process	PM_{10} $PM_{2.5}$	1.2–12.4 0.8–6

Table 4. Emission factors of vehicles reported in the literature for LDVs and passenger cars (mgkm^{-1} vehicle^{-1}).

Reference	Measurement	Emission Type	Emission Factor
Lawrence et al. [172]	Sampling	PM_{10}	3.8–4.4
Hulskotte et al. [173]	Sampling	Brake wear	8.0–15
Grigoratos et al. [168]	Review	PM_{10}	6.7
Iijima et al. [174]	Brake dynamometer	PM_{10} $PM_{2.5}$	5.8 3.9
Garg et al. [52]	Brake dynamometer	PM_{10}	2.9–7.5
Piscitello et al. [175]	Review	Brake wear	1–18.5

3.2. Laboratory (Chassis Dynamometer)

The chassis dynamometer method can be undertaken using a full vehicle, which leads to ground-truth data and provides a reproduction of the real braking conditions. Although there is a lot of previous work on subsystem level-related laboratory tests, studies focused on the system level are scarce. This may be related to the high costs and extensive methodology that scholars must necessarily deal with.

A chassis dynamometer can evaluate various parameters related to brake wear in laboratory environments. Humidity and its effects on the rate of pad or disc wear is one example of such a parameter, which has been comprehensively studied in [176,177].

In 2018, Chasapidis et al. estimated the brake wear particles generated by running a minivan with a chassis dynamometer under various initial speeds, deceleration rates, and ambient temperatures [178]. In this study, the authors declared that dealing with a system that includes different sources of particles, like brakes and tires, under custom configurations is challenging. They also showed that the ambient temperature had trivial effects on the generation of brake wear particles.

In 2019, Mathissen et al. used an instrumented passenger vehicle together with a novel approach to study brake wear particles in a laboratory environment [179]. This chassis dynamometer included a large vacuum hose, a cone-shaped capturer, and the sampling modules in the vehicle's trunk. Although the brake cooling was one of the limitations of this study (brake emissions are temperature-dependent), the authors found a remarkable amount of total brake PM_{10} emissions (up to 30%) generated by the particles emitted from the braking system while the brakes were being not applied.

To summarize, thanks to a variety of influential advantages, it seems that the measurements obtained using a chassis dynamometer are reliable for the investigation of brake wear particles. In addition to its capacity to prevent the intervention of environment parameters, chassis dynamometers can be assessed as reasonable tools to evaluate the impact levels of phenomena like particle loss. However, this approach has some restrictions and disadvantages. The main problem with using a chassis dynamometer is the limited representativeness of the ventilation rate, which produces a low level of cooling for the brake system. As demonstrated in [179], despite the remarkable advantages of chassis dynos, such as the evaluation of changes in a vehicle's chassis, this problem results in the accumulation of particles in the chamber, leading to the use of artificial brake ventilators.

3.3. On-Road Driving Test

In comparison to laboratory tests, on-road driving tests are more expensive and complicated. Due to this, there are few studies related to on-road driving tests in the literature. In 1983, Cha et al. measured the asbestos emissions of a vehicle's braking system through field studies [180]. By performing a computer-based emission test, they investigated the brake wear debris emitted from a front-wheel disc brake in a passenger car driving downtown in the city and simulated the brake wear dynamics.

Sanders et al. investigated on-road emissions by using sampling tubes installed in the vehicle's wheels to minimize sampling losses [11]. 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. In 2013, Kwak et al. calculated the physical and chemical properties (like the mass distribution) of 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 [70]. 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. A similar approach was carried out by Kwak et al. to investigate the physical and chemical characteristics of ultrafine particles generated from non-exhaust origins when driving an equipped vehicle on-road [181].

Utilizing a novel approach, Mathissen et al. successfully investigated the non-exhaust PM emissions generated by a brake system and resuspension of road dust, which were obtained with an instrumented mobile trailer attached to a lightweight passenger vehicle [182], similarly to the procedure introduced by Fitz et al. in 2002 [183]. They implemented their survey studies by driving more than 800 km on unpaved roads and dust-loaded paved agricultural roads. These scholars also investigated the dispersion of particles in the wake of the vehicle by implementing a tracer gas test. Emission factors calculated in this research showed lower results on motorways.

In 2015, Wahlström et al. presented field study measurements of brake wear by collecting data in the outer areas of Stockholm, Sweden [184]. 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. Farwick zum Hagen et al. introduced an innovative sampling approach using the dynamometer test [69]. In this study, the authors collected entire sets of brake wear emissions using a semi-closed vehicle setup. 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.

In 2020, Perricone et al. conducted a field road test by using an LDV equipped with temperature and pressure sensors on the brake system [185]. 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.

3.4. Wheel Sampling

Puisney et al., by sampling the brake system of a passenger car under different driving conditions, investigated the characterization of nanoparticles and their toxic effects in the environment and on human body cells [186]. They also obtained samples from a dynamometer bench to compare the results. They concluded that brake wear debris has adverse effects on the human lungs due to the notable amount of metallic nanoparticles, which accounted for 26% of the total brake wear particle mass. Varrica et al. investigated the airborne Sb particles generated by brake systems by sampling from the wear residues on vehicles' wheels and brake linings along with road dust and atmospheric particles [187]. By specifying the different types of Sb particles existing in various samples, they introduced Sb as a good tracer of emission classification.

3.5. Simulation Methodologies

Nowadays, artificial intelligence (AI) is known as a tool that has revolutionized industry and helps scholars maximize the chances of carrying out studies successfully. AI functions through learning. There are many AI models that have been introduced to the world, such as linear/logistic regression, decision trees, naive Bayes classifiers, and so on. One of the most popular approaches related to the subject of wear is the artificial neural network (ANN), which mimics the human biological brain [188]. It is a well-known model thanks to its capacity to accurately predict the nonlinear behavior of wear parameters [189,190]. ANN models were widely used in studies in the literature to investigate the wear particles emitted from brake systems [191–195].

Predicting the friction coefficient of brake materials is one of the most popular topics studied by scholars using the ANN model [196–198]. Additionally, a simple model of linear regression (single-variable) was deployed by Gailis et al., who used the mileage of the vehicle as the only variable in the model to predict the brake wear out [199]. In 2006, Durmuş et al. investigated the rate of wear loss and surface roughness of an aluminum alloy by using a model based on the artificial neural network [200], and similar studies have been undertaken in [201–203]. A neural model of brake wear prediction was developed by Aleksendrić based on the complete formulation of the friction materials [204].

An ANN-based intelligent forecasting model, established on the basis of experimental data, was introduced by Yin et al. to provide online monitoring of the semimetal brake lining of vehicles [205]. In this study, the scholars equipped a disc braking system with a self-made braking tester to assess the brake wear function. Due to their effective ANN model, they concluded that the wear rate has a direct relationship with the braking speed and pressure. The authors of two studies [206,207] also predicted the standard deviation and friction coefficient of the brake linings using ANN models.

In 2016, Hassan et al., by implementing a two-layered ANN model using the MATLAB program, introduced a new model for brake wear and temperature prediction under various conditions of rotational speed and friction period in their examination of steel and aluminum brake discs [195]. The proposed model was successfully used with data and presented sensible results which were the same as those in [208]. These studies showed that by increasing the sliding speed, load, and contact time, the rate of wear is increased.

To validate an ANN model, it is necessary to compare its results with those obtained from experimental tests on brake wear, as was carried out in [209]. For the experimental part of this study, the authors used a pin-on-disc test for the calculation of wear and the friction coefficient factor. This research showed that using the ANN model is a reliable approach to predicting parameters in the wear process.

In 2018, Ikpambese et al. compared the results of two wear prediction models [210],: multiple linear regression (MLR) and the ANN, for data obtained from the analysis of novel brake pads produced from palm kernel shells. In this study, the predicted wear rates and the coefficient of friction of the contact spots were analyzed and compared along with statistical parameters.

Harlapur et al. conducted multivariate linear regression analysis using a machine learning (ML) model to determine the relationship between the brake pad wear and the stopping distance of a vehicle [211]. By recording the various pad thicknesses associated with different vehicle stopping distances, assuming some parameters to be constant, and fitting an appropriate ML model, they presented an ML-based model of prediction.

4. Environmental Level

Naturally, the environment collects emissions and produces further modifications in their distribution. The environmental level is the level where all the emissions are finally collected. It does not constitute just a passive level, as many complex phenomena occur and produce further re-distribution of the emissions, with relevant implications for local pollution and the related risk for health. In order to implement experiments on the wear generated by brake systems, it is necessary to collect samples from the surfaces and areas that are supposed to be subjected to the emissions. These emission-prone areas include road surfaces, vehicle surfaces, plant leaves, oceans, rivers, agricultural farms, soils, and runoffs. Since the origins of particles are unknown, as they can be generated from various sources, it is necessary to use experimental methods to distinguish them. Research at this level cannot address the details of the emission sources but rather focuses on the external phenomena, like resuspension, weather, wind, and the morphology of the environment (valleys, mountains, etc.). Large-scale statistical models are also developed at this level.

It is indisputable that the automobile industry develops new materials each year as the environmental restriction rules are updated by legislators. Since 1978, more than 100 formulations related to the friction materials used in the brake system have been introduced, and nowadays, according to [212], it is difficult to count the number of existing materials in brake components. This makes it much more difficult to evaluate the chemical compositions of the samples.

4.1. Sampling Place

Non-exhaust particles, including those from tire and brake wear, are a substantial source of road dust contamination. Tunnels in particular can be cited as important places where particles, dust, and brake wear debris are carried and accumulated by wind or runoffs originating in precipitations. As mentioned by Wang et al. [213], tunnels are one of best places to obtain real-world emissions. However, data collection and sampling from tunnels should be done regularly to update emission models [213]. The size distributions of particles can be also measured by the samples collected from tunnels. Abu-Allaban et al. showed that the contributions of HDVs dominated the particles generated by LDVs in the ultrafine particle distribution [214]. However, the impressive contributions of these emissions to PM concentrations should not be neglected [172].

As has been shown in previous studies, the dominant sources of PM particles are non-exhaust emissions generated by transportation fleets [13,215,216], especially in the countries located in the north of Europe [217]. The main source of the road dust is the wear generated by studded tires [218], especially in countries where using these kinds of tires is common [219].

Many studies can be found in the literature that have investigated the existence of tire wear debris in road dust samples [220–222]. The brake system is another source of road dust. These kinds of wear are generated by the occurrence of friction between the brake pads and disc while the temperature during the braking operation goes up. In urban areas, places such as intersections and traffic lights are prone to showing an excessive amount of sedimented debris from wear due to repeated braking.

As has been shown in several previous studies, emissions of road dust can be evaluated by the Testing Re-entrained Aerosol Kinetic Emissions from Roads (TRAKER) system [223–225]. In 2009, Pirjola et al. presented an innovative road dust measurement system using a mobile SNIFFER laboratory to determine the levels of emissions on various streets [226]. Adamiec et al. investigated the dust from brake linings and tires on motorways and urban and mountain roads [212]. In cities, additional contamination from wear dust exists due to the resuspension of the pre-sedimented particles on surfaces. Therefore, greater amounts of emissions are likely to be reported in cities compared to mountainous areas. Based on the results of this study, the diameters of non-exhaust particles should not be greater than 250 μm, as was also stated in [227]. The authors also concluded that the finest fraction of the Pd element was much lower in mountain roads in comparison to urban areas.

In 2016, Gonzalez et al. studied atmospheric PM particles by sampling from two major European cities at the street level [228]. They implemented their field studies at sites with variable traffic densities. They found that Zn and Cu isotopes are most commonly generated by non-exhaust emissions.

4.2. Non-Exhaust Emission Models

Over the years, non-exhaust emission models, which are used to estimate emissions across various applications by presenting observed data on a distinct spatial and temporal scale, have been improved from the initial model introduced by the US-EPA in 1984 to the more developed models used in emission measuring approaches; the size of data used to validate these models has also increased [229–233]. The authors of [42] used emission factors to compare the emission models available in various European countries.

In 2003, Abu-Allaban et al. used two techniques, chemical mass balance (CMB) receptor modeling and SEM, to estimate the emission factors of various vehicle modal splits—the contributions of different types of vehicles to the total number of transportation fleets—by implementing on-road survey studies and obtaining samples directly [234]. The detection of a large amount of brake wear debris at freeway exit sites in comparison to other locations was one of the results of their research.

The different variables that scholars have implemented in their non-exhaust emission models are controversial. Kukkonen et al. presented a semi-empirical model to estimate the PM_{10} concentration based on a linear regression approach to emissions [235]. Besides the road dust, road surface moisture is also essential to consider in emission models, as it can influence the dispersion of particles resuspended from the road surface. In order to investigate this variable, researchers introduced a non-exhaust emission model that can predict the main features of particles by considering both surface moisture and dust variables [217,231]. They used ground-truth data to calibrate their model with real conditions. This local measurement dependency of their model was reduced in the model presented by Berger et al. [236].

Denby et al. presented a comprehensive model of non-exhaust emissions entitled "NORTRIP" that took into account the road surface moisture, road wear, surface dust, sand, salt loading, and their suspension, together with the wear from the road, tires, and brakes [218]. The model was applied to seven years of data collected from two locations exposed to moisture. However, the authors declared that the uncertainty of their model was approximately ±40% for long-term perspectives. A similar model was used for the modeling of road dust emission abatement in [237], and it was shown that the NORTRIP model could be used as a reliable model for air quality planning.

In 2015, Mawdsley et al. introduced a novel method to calculate non-exhaust emissions based on the SIMAIR model, an internet-based, coupled model system that was devised in Sweden to calculate air quality [238]. This model can provide comprehensive data related to the parameters influencing the amount of annual reported non-exhaust emissions, like the use of studded tires. A database of the emission factors related to the road and vehicle and a model for calculating the non-exhaust emissions are the main parts of the SIMAIR model, which covers all the transportation networks of Sweden. The SIMAIR model was successfully validated by Gidhagen et al. [239]. Furthermore, Mawdsley et al. utilized the NORTRIP non-exhaust model to compare the results of the two approaches [238]. Investigation of the resuspension results for the SIMAIR and NORTRIP models was another strategy of their project. Regarding the operational production condition of the SIMAIR model in Sweden, they concluded that this model could present more regular calculations of emissions in comparison to the NORTRIP model.

Nagpure et al. estimated exhaust and non-exhaust emissions simultaneously by deploying the Vehicular Air Pollution Inventory (VAPI) model in Delhi [240]. The VAPI model can estimate the emissions generated by vehicles in terms of their age and technology using the econometric Gompertz equation tool [241]. The emission analysis consisted of an investigation of emissions in the period from 1991 to 2020 through the implementation of a gross domestic product (GDP) and per capita-based econometric model. The results of this study showed a drastic increase in the PM_{10} emissions produced by non-exhaust sources.

5. Concluding Remarks

Airborne particles are known as one of the most critical aspects of non-exhaust emissions, accounting for 50–70% of the wear debris emitted by brake systems [15]. The review of the literature concerning this topic highlighted that the brake system is a key contributor to the overall levels of emissions produced by a vehicle, attracting wide and intense research activity.

The state of the art of the research on this topic 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 amount of wear may be different depending on the material 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 mass, road characteristics and, last but not least, the driving style.

As a consequence, the present study investigated the airborne brake wear debris by dividing the relevant research into three categories. Studies on the subsystem level focus on the emissions generated by all of the brake system components, whereas in those on the system level, the vehicle dynamics together with driving behaviors (aggressive or non-aggressive) and driving conditions (road geometry, weather, etc.) are investigated. At the third level, the emissions are observed as they finally affect the environment, which constitutes an active collector where they may be deposited, resuspended, mix, and undergo further transformations.

The results obtained for the controlled configuration and environment at the subsystem level were more accurate with lower uncertainty. In fact, due to the scale of this level, these kinds of experiments benefit from better repeatability and the boundary conditions are accurately defined. 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 [179]. This results in a limited capacity to predict the levels of emissions produced, for instance, by the same tested vehicle in different driving conditions or when driven by a different driver.

One possibility for improving the prediction of vehicle brake emissions may lie in multi-level approaches. Full-focus testing on dynamometers by implementing different test cycles results in various kinds of emission factor maps, which can take speed and load into account as a function. The results may be useful for the prediction and/or evaluation of the emissions produced by a vehicle, in a given driving scenario and subject to a defined driving behavior, if a simulation model is built embedding all the relevant contributors (brakes, vehicles, roads, drivers). According to this approach, the subsystem level results can act as useful data to increase the certainty of the system level results. Once the prediction capabilities for emissions produced by vehicles are improved, this may constitute a key component of a traffic-based model that combines data on different vehicles subject to different driving styles and environmental conditions, providing the possibility of better understanding the relevant sources involved at the environmental level.

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