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Particle emissions from car brakes: the influence of
contact conditions on the pad-to-rotor interface

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A Lorenzò e Nunciata

Abstract

Due to their adverse health effects emissions have been regulated for over three decades. Brake wear particulate matter is the most important non-exhaust source, however current knowledge is mainly limited to observational studies. This thesis aims to investigate relations between the brake system contact conditions and the related emissions on a model scale; validate the results on a component level; and understand to what extent they are significant on a full-scale.

Paper **A** investigates the influence of nominal contact pressure on a model scale. Results show that higher pressure corresponds to higher emissions

Paper **B** investigates the influence of the nominal contact pressure, for different friction materials, on a model scale. A temperature threshold, responsible for a relevant emission increase, is identified.

Paper **C** investigates particle characteristics and wear mechanisms for different nominal contact pressures, on a model scale. Results show an enhanced tribo-layer at higher pressure levels.

Paper **D** investigates the influence of brake system conditions on emissions, on a model scale. Results show that frictional power is the most important parameter. A transition temperature independent of the contact condition is identified.

Paper **E** investigates similarities occurring on a component scale and a model scale in terms of emissions. Results show a promising correlation, and the possibility of using a pin-on-disc tribometer for R&D activities.

Paper **F** investigates analogies occurring on a component scale and a model scale, in terms of friction performance, fictional surface and chemical composition. Results show similar phenomena occurring for the two test stands.

Paper **G** analyses real brake system working conditions in a urban environment defining, by means of an inertia dyno bench, the related emissions. Results reveal emission factors compliant to EURO6 and EURO2 regulations, in terms of number and mass, respectively.

Keywords:

Car brakes emissions, transition temperature, working conditions, environmental design, pin-on-disc

Sammanfattning

På grund av deras negativa hälsoeffekter har partikel emissioner reglerats i över tre årtionden. Bromsslitagepartiklar är den viktigaste icke-avgaskällan, men nuvarande kunskaper är huvudsakligen begränsade till observationsstudier. Avhandlingen syftar till att undersöka förhållandena mellan bromssystemets kontaktförhållanden och de relaterade utsläppen på modellskala. Validera resultaten på komponentnivå och förstå i vilken utsträckning de är betydande i full skala.

Papper **A** undersöker påverkan av nominellt kontaktryck i en modellskala. Resultat visar att högre tryck motsvarar högre utsläpp.

Papper **B** undersöker påverkan av det nominella kontaktrycket, för olika friktionsmaterial, i modellskala. En temperaturtröskel, för en emissionsökning identifieras.

Papper **C** undersöker partikelegenskaper och slitagemekanismer för olika nominella kontaktryck, i en modellskala. Resultat visar ett förbättrat triboskikt vid högre trycknivåer.

Papper **D** undersöker påverkan av bromssystemets förhållanden på utsläpp i en modellskala. Resultat visar att friktionskraften är den viktigaste parametern. En övergångstemperatur oberoende av kontaktförhållandet identifieras.

Papper **E** undersöker likheter som uppträder på komponentskala och modellskala när det gäller emissioner. Resultatet visar en lovande korrelation, och möjligheten att använda en pinne-på-skiva-tribometer för FoU-aktiviteter.

Papper **F** undersöker analogier som förekommer på en komponentskala och en modellskala, vad gäller friktionsprestanda, friktionsyta och kemisk sammansättning. Resultat visar liknande fenomen som förekommer för de två testskalorna.

Papper **G** analyserar verkliga bromssystem arbetsförhållanden i en stadsmiljö som definierar, med hjälp av en tröghetsdyno bänk, de relaterade utsläppen. Resultatet visar utsläppsfaktorer som är förenliga med EURO6 och EURO2-reglerna, i fråga om antal respektive massa.

Nyckelord:

Bilbromsutsläpp, övergångstemperatur, arbetsförhållanden, miljödesign, pinne-på-skiva

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Mattia Alemani

Stockholm, September 2017

List of appended publications

Paper A

Mattia Alemani, Ulf Olofsson, Guido Perricone, Anders Söderberg, Jens Wahlström, Alessandro Ciotti. “*A Study on the load level influence on particulate matter emissions from the sliding contact between a low steel friction material and cast iron*”. Eurobrake 2015 Conference Proceedings, EB2015-FMC-004, Dresden, Germany, 4-6 May

Mattia Alemani planned and carried out the experimental work, did most of the writing and the results evaluation.

Paper B

Mattia Alemani, Oleksii Nosko, Ibrahim Metinöz, Ulf Olofsson. “*A study on emissions of airborne wear particles from car brake friction pairs*”. SAE Int. J. Mater. Manf. 9(1):2016, doi:10.4271/2015-01-2665

Mattia Alemani planned and carried out the experimental work, contributed to the writing and the results evaluation.

Paper C

Mattia Alemani, Stefano Gialanella, Giovanni Straffelini, Rodica Ciudin, Ulf Olofsson, Guido Perricone, Ibrahim Metinöz. “*Dry sliding of a low steel friction material against cast iron at different loads: characterization of the friction layer and wear debris*”. Wear, 376-377 (2017) 1450-1459, doi: 10.1016/j.wear.2017.01.040

Mattia Alemani did most of the planning and carried out the experimental work, contributed to the writing and the results evaluation.

Paper D

Mattia Alemani, Jens Wahlström, Ulf Olofsson. “*On the influence of car brake system parameters on particulate matter emissions*”. Submitted to Wear

Mattia Alemani formulated the research questions and developed the methodology to answer them, planned and carried out the experimental work, and did most of the writing and the results evaluation.

Paper E

Mattia Alemani, Jens Wahlström, Vlastimil Matějka, Ibrahim Metinöz, Anders Söderberg, Perricone Guido, Ulf Olofsson. “*On the scaling effect of measuring disc brake airborne particulate matter emissions – a comparison of a pin-on-disc tribometer and an inertia dynamometer bench under dragging conditions*”. Submitted to IMechJ: Journal of Tribology

Mattia Alemani formulated the research questions and developed the methodology to answer them, planned and carried out the experimental work, did most of the writing and the evaluation.

Paper F

Ibrahim Metinöz, Vlastimil Matějka, Mattia Alemani, Jens Wahlström, Guido Perricone “*Could pin-on-disc tribometer be used to study the friction/wear performance of disc brake materials?*”. Eurobrake 2016 Conference Proceedings, EB2016-MDS-010 ,Milan, Italy, 13-15 June

Mattia Alemani planned and carried out the experimental work to answer the research questions, contributed to the writing and the results evaluation.

Paper G

Guido Perricone, Mattia Alemani, Jens Wahlström, Ulf Olofsson. “ *A test stand investigation on a real driving cycle emission factor for car brakes*”. To be submitted to IMechE: Journal of Automobile Engineering

Mattia Alemani planned and carried out the experimental work to answer the research questions, contributed to the writing and the results evaluation.

List of non-appended publications

Mattia Alemani, Perricone Guido, Ulf Olofsson, Anders Söderberg, Jens Wahlström, Alessandro Ciotti. “*A proposed dyno bench test cycle to study particle emissions from disc brakes*”. Eurobrake 2014 Conference Proceedings, EB2014-SE-001 ,Lille, France, 13-15 May

Oleksii Nosko, Mattia Alemani, Ulf Olofsson. “*Temperature effect on emission of airborne wear particles from car brakes*”. Eurobrake 2014 Conference Proceedings, EB2015-TEF-014 ,Dresden, Germany, 4-6 May

Guido Perricone, Jens Wahlström, Mattia Alemani, Ulf Olofsson, Ciotti Alessandro. “*A novel dyno bench design focussing on measurements in controlled air of particle emission from brakes*”. Eurobrake 2015 Conference Proceedings, EB2015-EFP-005 ,Dresden, Germany, 4-6 May

Piyush Chandra Verma, Mattia Alemani, Stefano Gialanella, Luca Lutterotti, Ulf Olofsson, Giovanni Straffelini. “*Wear debris from brake system materials: A multi-analytical characterization approach*”. Trib. Int, 97(2016) 510-511

Guido Perricone, Mattia Alemani, Ibrahim Metinöz, Vlastimil Matějka, Jens Wahlström, Ulf Olofsson. “*Towards the ranking of airborne particle emissions from car brakes – a system approach*”. Proc IMechE Part D: J Automobile Engineering 1-17 (2016)

Vlastimil Matějka, Ibrahim Metinöz, Mattia Alemani, Jens Wahlström, Andrea Bonfanti, Ulf Olofsson, Guido Perricone “*Dependency of PM10 particle emission on stability of friction coefficient and character of friction surface*”. Eurobrake 2016 Conference Proceedings, EB2016-MDS-010 ,Milan, Italy, 13-15 June

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I Appended papers

Chapter 1

Introduction

“Corpus omne perseverare in statu suo quiescendi vel movendi uniformiter in directum, nisi quatenus illud a viribus impressis cogitur statum suum mutare”.

In his book “Principia Mathematica”, Sir Isaac Newton taught us that to stop a body in motion, a force acting upon it is needed. This is the basic working principle for brake systems.

From the first steam-driven wheeled vehicle crash, in 1769, the transport sector made this principle a concealed masterpiece of engineering. This especially after the introduction of the combustion engine in the late 19th century. Indeed, the brake system’s most famous and familiar application, the car brake, is able to dissipate three times the engine power promoting safety for the 907 million vehicles circulating on roads worldwide.

Safety and progress, however, are not free of charge. While braking, the system components are worn. This generates debris that can become airborne particulate matter, well known for its adverse health effects and its contribution to global warming.

For over 30 years, the European Union and the World Health Organization, have been working to reduce air pollution from different sources. The high quality research done on engine emissions - also called “exhaust” emissions - has led to a significant reduction, enough to make brake systems, tyres and road wear emissions - the “Non-Exhaust” emissions – equal to almost half of the total road vehicle contribution. Brake emissions are the most significant non-exhaust emissions of road vehicles.

1.1 Background

Air pollution is one of the biggest challenges of the 21st century. Indeed, it is the main environmental cause of premature death in Europe [1], and has negative effects on both the ecosystem and the climate [2]. In addition, the Organization for Economic Co-operation and Development (OECD) estimates that pollution-related costs will reach 2% of the European Gross Domestic Product (GDP) by 2060 [3].

The European Union (EU) and the World Health Organization (WHO) have been developing guidelines and legislation [4,5] for decades, resulting in a clear reduction in pollutants in the EU-28 countries [2]; however, the WHO has estimated that more than 400 000 European citizens died prematurely in 2012 because of air pollution [6].

Among the addressed pollutants, particulate matter (PM) is one of the less affected by the adopted countermeasures [2], but the one that induces the most severe [7] health effects [8–10] such as cardiovascular and respiratory diseases [11,12], and cancer [13]. Consequently, the mean life expectancy in European urban areas is reduced by 0.63 years per person, with peaks of 1.2 YLL [14,15], due to particulate matter air pollution.

In the aforementioned areas, one of the major contributors to particulate matter emissions is the road transport sector, accounting for up to 64% [16,17]. In this sector, emissions are divided into exhaust and non-exhaust ones, indicating respectively: particles generated by vehicle engine combustion processes and particles generated by brakes, tyre and road wear, and dust resuspension.

Over the past decades, significant efforts have been made by the EU to regulate exhaust emissions (see Fig. 1). This has led to a comprehensive knowledge of the related phenomena and to specific regulations, the so called “euro emissions standards” which have forced car manufacturers to produce less and less emissive vehicles [18].

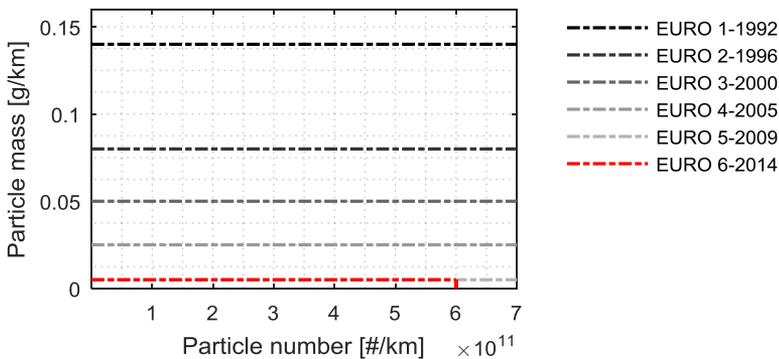


Fig. 1: Euro emission standards limits

Continuous improvements in exhaust technologies have meant that non-exhaust emissions now equal exhaust ones [19]. In addition, recent studies indicate that, even without tail-pipe emissions, traffic will continue to contribute to fine and ultrafine emissions [20,21], forecasting that 90% of the total road traffic emissions by 2020 [22] will come from non-exhaust sources.

As far as non-exhaust sources are concerned, particles generated by the braking systems are a primary emission source, contributing by 55% for PM₁₀ and 21% PM_{2.5} [19].

According to the aforementioned values, it can be estimated that brake particulate matter in Europe is responsible for 0.043 YLL per person on average (i.e. 16 days of life lost), with peak values up to 0.08 (i.e. 27 days of life lost), as shown by Fig.2. Nonetheless, no regulations are available yet. This is especially because still little is known about brake system contact conditions and their relations with particle emissions.

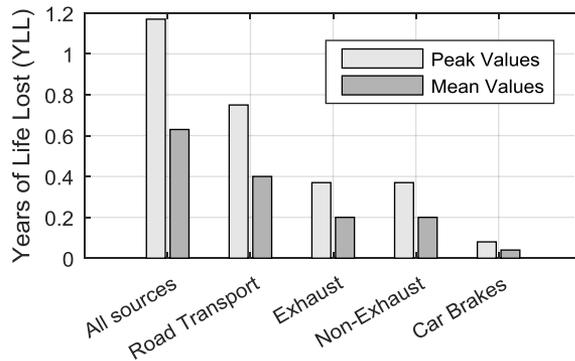


Fig. 2: Years of Life Lost (YLL) in European urban areas due to different PM sources

1.2 The car brake system

The aim of a car brake system is to slow down or stop the vehicle, according to the driver's will, by dissipating its kinetic energy and transforming it into frictional heat. On modern passenger cars, two different kinds of brake systems can be used [23]: disc brake systems or drum brake systems. The latter, still in use on modern cars, consists of a spread mechanism that pushes two brake shoes against the inner surface of a cast iron or steel brake drum, connected to the wheel. Nowadays, this system is mainly used in rear car brake systems whereas the front one usually consists of a disc brake system (see fig.3) which is also the subject of this research. A disc brake system consists of three main parts: the calliper, pads and the rotor.

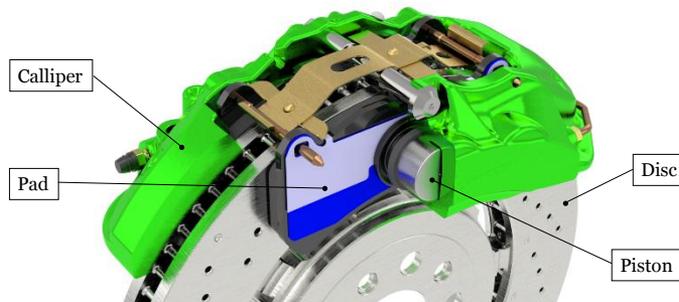


Fig. 3: A detailed view of the disc brake system assembly

1.2.1 The calliper

To allow a braking action to take place, the driver pushes a pedal generating a force that is multiplied and transformed into pressure. This is carried through the system hydraulics, by means of the brake fluid, to the calliper; the static component in the system. This is mounted on the car knuckles and is responsible for generating the forces required to stop the vehicle and absorb the related counterforces. From a purely machine design perspective, the calliper body can be seen as a ground constraint.

There are two main calliper families: fixed and sliding. The latter is characterized by having a single active piston and a sliding passive part (Fig. 4a). Conversely, the former (Fig. 4b) is made by a rigid body where two to eight pistons are evenly distributed on both sides of the calliper. This thesis will deal with a fixed calliper.

When the brake fluid crosses the calliper, it eventually comes to the pistons where the fluid pressure is transformed into a force acting on the pads. This force is dependent on the calliper design and, more specifically, on the ratio between the pistons and the pad area.

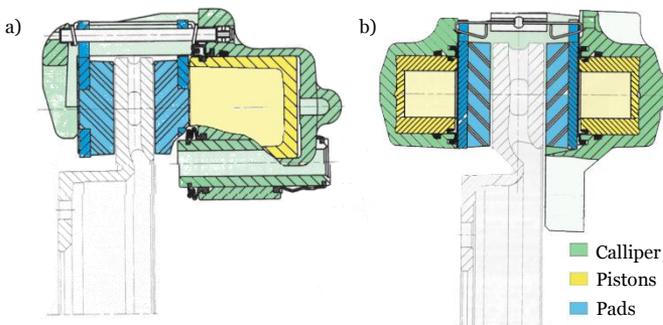


Fig. 4: Cross section of a sliding (a) and a fixed (b) calliper

1.2.2 The pads

Two pads are placed inside the calliper. Pads consist of: an iron back-plate, as a solid base for the piston contact which can be equipped with a shim, a thin metallic sheet, for noise reduction; an under-layer, mainly responsible for thermal insulation and dumping, which is a mixture of organic materials; the friction material, made from about twenty different materials and finely tuned to obtain a desired friction coefficient. The different friction material families are listed and explained in Table 1.

Pads represent one of the two main actors in the brake system sliding contact. Depending on the composition of the friction material, different pad families [24] can also be defined, as shown in Table 2.

Table 1. Friction materials families and their function

	Function	Material examples
Binders	Guarantee mechanical properties and pad integrity throughout pad life	Organic fibres, phenolic resin, friction powders
Abrasives	Tune the friction coefficient and avoid material deposits during the braking action	Oxides powders and metal powders
Lubricants	Reduce wear and stabilize the friction coefficient	Graphite, coke, Antimony, Molybdenum sulphide and other metals
Metals	Absorb the vehicle energy as heat, and avoid overheating of the sliding surfaces	Steel, copper, Zinc, Tin fibres

Table 2. Pad families according to the friction material composition

	Composition	Characteristics
NAO	Up to 10% wt. Cu and Cu alloys	Common in USA and Japan Market. Low COF (0.3-0.4), low wear and noise
Low-Steel	10-50% wt. Fe, Steel, Cu and Cu alloys	Common in Europe. High COF (0.35-0.5), stable for high speeds and temperatures. Higher wear than NAO
Semi-metallic	Ferrous metal content up to 40% wt.	Low COF (0.25-0.35), high wear but improved performance at high temperatures

1.2.3 The rotor

The pads act directly on the rotating part of the system: the rotor. This is connected to the wheel axle, thereby having the same rotational speed, by a rigid joint through the rotor bell. The bell is then connected to the braking surfaces in different ways which are also typical features of different rotors families: when the full rotor is a unique casted part of the same material, it is called integral; when the braking surface and the bell materials differ, but the connection is due to a casting process, it is called a co-casted rotor; when the connection is obtained by bolts or rivets, it is called a floating rotor. In addition, the two braking surfaces can be a solid part or can have ventilation channels to improve heat exchange with the ambient air. In the latter case, the rotor is called ventilated (see Fig. 5).

The most common brake rotor material used is grey cast iron which has good thermal conductivity, mechanical strength and damping capacity (up to 100 times more than iron, and 800 times more than aluminium) [25]. In addition, it is a very cheap and easy to cast material. These features mean that cast iron dominates the rotor market, irrespective of its considerable weight.

Carbon-ceramic disc brakes are also available on the market. However, even though their weight is one third of the cast iron ones and performance is better, their costs are prohibitive for most Europeans.

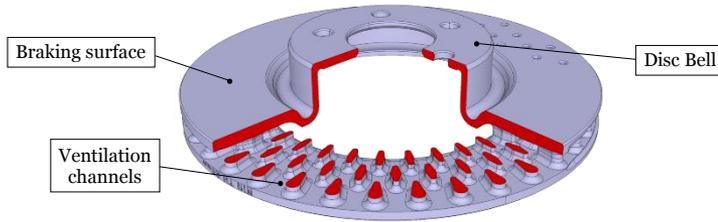


Fig. 5: Cross section of a ventilated rotor

1.3 Airborne particulate matter

Airborne particulate matter, also referred to as aerosols, is defined in its simplest form as a collection of solid or liquid particles suspended in a gas [26]. These particles are usually stable for a variable time period ranging from a few seconds to years.

It is possible to distinguish between primary and secondary aerosols depending on whether particles are introduced directly into the atmosphere or are formed in the atmosphere by the chemical reaction of gaseous components, also known as precursor gases. Among them, the most important are SO_2 , NO_x , NH_3 and VOCs (Volatile Organic Compounds) [27].

In addition, they can be monodispersed or poly-dispersed depending on whether the particle size is unique for the whole aerosol or different sizes coexist. The former is usually artificially generated for particle instrument calibration[28].

This thesis will deal with primary poly-dispersed aerosols since brake wear particles are directly introduced into the air, and cover a wide size range.

1.3.1 Particle Size

To characterize particles, the most important parameter is the particle size [26]. However, since particles have different shapes which can also differ substantially from spheres, it is seldom possible to characterize them by a real diameter. Therefore equivalent diameters have been defined as the diameter of the sphere that has the same value of a particular physical property as that of an irregular particle [26]. This thesis will deal with the following equivalent diameters:

- **Aerodynamic diameter:** defined as the diameter of a spherical particle with a density of 1000 kg/m^3 and the same settling velocity as the considered particle [26,28]. This is one of the most used in aerosol science as well as in this thesis.

Note that the settling velocity is the velocity a particle under gravitational forces reaches when the latter forces are in equilibrium with the drag forces. For further details on how to calculate the settling velocity, appropriate literature is recommended [26,28].

- **Mobility diameter:** this is defined as the diameter of a spherical particle that has the same mobility, defined as the particle velocity produced by a unit external force, as the considered particle [26]. In this work, we measure the electrical mobility, therefore motion of particles is induced by an electrical force.
- **Optical diameter:** this is the diameter of a spherical particle that has similar optical properties to the considered particle; this is measured in this thesis by an optical particle counter, therefore light scattering detected by a photometer is considered [26,28].

Particles can be classified in different ways according to their diameter. The most widespread method, generally used in regulations and guidelines, is to classify particles by their aerodynamic diameter:

- **PM₁₀:** indicates all the particles with a diameter of less than 10 μm
- **PM_{2.5}:** indicates all the particles with a diameter of less than 2.5 μm
- **PM_{0.1}:** indicates all the particles with a diameter of less than 0.1 μm

The most commonly addressed classes in regulations (PM₁₀ and PM_{2.5}) are exemplified in Fig. 6 [29].

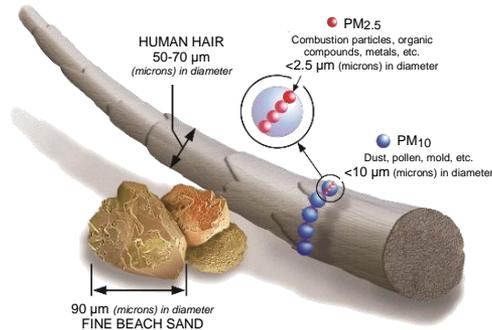


Fig. 6: Size comparison for PM particles [29]

This methodology is convenient because the aerodynamic diameter is related to particle transport and removal from the air and their deposition in the respiratory system [30].

Another widespread method used to address particle sizes, especially in the scientific literature, is to group them according to the following size fractions:

- **Coarse fraction:** for particles with a diameter $10 \mu\text{m} < d_p \leq 2.5 \mu\text{m}$
- **Fine fraction:** for particles with a diameter $2.5 \mu\text{m} < d_p \leq 0.1 \mu\text{m}$
- **Ultrafine fraction:** for particles with a diameter $d_p < 0.1 \mu\text{m}$

Note that some researchers prefer to set the coarse fraction lower limit to 1 μm .

1.3.2 Particle concentration and size distribution

When assessing airborne particulate matter, another important factor is the particle concentration. Two standard methods are used to measure concentration: by mass and by number.

Mass concentration is obtained by measuring the mass of the particulate matter in a unit volume of aerosol. It is commonly expressed in g/m^3 , mg/m^3 , or $\mu\text{g}/\text{m}^3$ and measured by weighing the samples collected on properly made filters using scales, or by specially made instruments. Another possibility is to calculate it by estimating or knowing the particle density.

Number concentration, on the other hand, is the number of particles per aerosol unit, commonly expressed in $\#/\text{cm}^3$. It is generally measured by instruments that can make use of electrical charges or optical features to detect particles and count them.

When investigating poly-dispersed aerosols, particle size distribution is also a parameter that should be taken into account. This represents the occurrence of a specific aerosol property (number, mass, etc.) over the particle size range of interest [28]. Since it is strongly dependent on the measurement instrument design, and more specifically its resolution, a common practice is to normalize the investigated parameter by each sub-size range. This allows size distributions obtained by different instruments to be compared.

1.4 Challenges for brake emissions

A small part of the brake system community has been assessing brake emissions for more than 20 years. Since, in the past, exhaust emissions were more important than non-exhaust ones, there has been no attempts for examine the latter topic. Indeed, an Environmental Protection Agency report [31] assessing brake wear particulate matter emissions shows how little research has been performed on it. One of the earliest works was done in 1983 by Cha et al. [32], who assessed asbestos brake pads, nowadays forbidden by regulations. Following this, Garg et al. [33] were the first to assess non-asbestos brake pads from the current market using an inertia dyno bench. Over time, other studies [34,35] have helped to deepen knowledge of the topic, due to an increasing interest in brake emissions. This is especially due to the aforementioned improvements in exhaust emissions. However, since there was no need for regulations, most of the scientific studies consist of observational studies, focused on characterizing the typical size distributions of particles in order to assess the harmfulness of different brake system couples.

In addition, industry has always been more interested in brake contact phenomena to reduce wear and better govern the friction coefficient than environmental aspects. This led the scientific community to focus on how contact conditions affected performances, starting to model the pad-to-rotor interface [36], and

introduce simulation routines to predict friction coefficient performances [37]. Nevertheless, some researchers have attempted to better explain phenomena occurring on the pad-to-rotor interface by simulating the contact on a mesoscopic scale [38]. However, the output is generally limited to the wear volume. How this volume becomes airborne and to what extent is still unknown, and generally addressed by the particle size distribution and that a fraction becomes airborne, usually defined on laboratory tests [38].

To do so, a system simplification developed in pin-on-disc tribometers has been extensively used in recent years [39,40]. This has helped to better and more easily assess particle emissions from brake systems. However, most of the studies are still focused on distribution characterization. In addition, few studies try to assess the comparability between different test set-ups [41].

We can see that the field of brake emissions is rather new and unexplored. In particular, while there is rather good knowledge concerning size distributions and related health effects, not much is known about the basic relationships between brake systems contact conditions and particle emissions. Moreover, while different authors [33,35,42] make use of their available set-up, providing knowledge on different scales, it is still not clear whether all the provided information can be considered reliable or whether substantial differences occur.

When aiming to face future regulations, such knowledge is important, especially since with regulations, it will be necessary to include environmental aspects directly in the design phase of the brake system.

1.5 Objectives

With this background in mind, as well as the challenges the brake emission field will have to face in the future, the present work aims to investigate the relationships between brake wear particle emissions and the contact conditions on the pad-to-rotor interface. Its intention is to lay the basis, on a model scale, for the introduction of environmental aspects in the brake system design phase.

Since the pin-on-disc tribometer simplifies the real system, result validation is also important when trying to understand to what extent acquired knowledge would be meaningful for industrial applications. Therefore, this work also aims to validate the obtained results by analysing and comparing different test set-ups: the pin-on-disc tribometer representing a model scale; the inertia dyno bench representing the component scale; and the real vehicle, representing the full scale.

To address these objectives, two research questions have been formulated as following:

- *How do airborne particle emissions respond to changes in contact conditions on the pad to rotor interface?*
- *Can the model scale be representative of component and full scale?*

Chapter 2

Methodology

As suggested in the previous chapter, even though the brake system has a unique and very simple aim, along an apparently simple design, the phenomena that lead to good performance are complex and involve different engineering aspects from material science to thermal-fluid dynamics.

In addition, the main objective of this work, wear particle emissions, is an even less known and more complex science, especially when it comes to measurements.

It is therefore important to set up a proper methodology (see Fig. 7), to investigate this topic, which tries to reduce uncertainties as far as possible. A good way to proceed is to develop a simplified model of the real system which can then be validated. This by comparing particle and contact surface properties obtained under similar working conditions for the model and the component scales. In addition, brake parameters obtained on a full scale under urban driving conditions are analysed, to understand which are the most significant contact conditions.

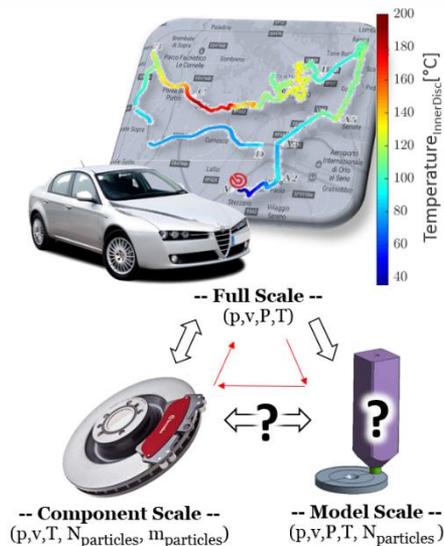


Fig. 7: Methodology overview

2.1 Car brake system parameters

The brake system as a whole has been described in Section 1.2. From its working principle it is clear how important the sliding contact generated on the pad-to-rotor interface is. The brake system behaviour is partially influenced by its design and mostly by the driver's attitude.

The main parameters characterizing it are: nominal contact pressure, sliding speed and friction coefficient.

Nominal contact pressure results from the will of the driver to stop in a defined space or slow down the vehicle. Irrespective of the calliper and pad design, when the driver presses the pedal, the pads are pressed on the sliding rotor. The developed force per pad can be therefore calculated as:

$$F_{pad} = p_{fluid} \cdot n_{pistons} \cdot \frac{\pi d_{piston}^2}{4} \quad \text{Eq.(1)}$$

Where p_{fluid} is the brake fluid pressure, $n_{pistons}$ is the number of calliper pistons acting on a single pad, and d_{piston} their diameter. This force, divided by the pad area (A_{pad}) provides the nominal contact pressure (p).

$$p = \frac{F_{pad}}{A_{pad}} \quad \text{Eq.(2)}$$

This pressure is therefore the one generated on the sliding contact surface, assuming perfectly smooth surfaces both on the pads and the rotor.

Another important parameter, once again imposed by the driver, is the sliding speed (v_{sl}) at the contact surface. This is directly related to the vehicle speed ($v_{vehicle}$) through the wheel. The sliding speed in this work is calculated at the effective radius (R_{eff}) of the rotor [43].

Since the rotor and the wheel rotate at the same angular speed (ω) it is possible to write as follows:

$$\omega = \frac{v_{sl}}{R_{eff}} \quad \text{Eq.(3)}$$

$$\omega = \frac{v_{vehicle}}{R_{wheel}} \quad \text{Eq.(4)}$$

where R_{wheel} is the wheel radius. Combining eq.(3) and eq.(4) the vehicle speed can be related directly to the sliding speed, as in eq. (5):

$$v_{sl} = \frac{R_{eff}}{R_{wheel}} \cdot v_{vehicle} \quad \text{Eq.(5)}$$

Finally, the friction coefficient is a parameter that drivers cannot directly control, but usually request. Indeed, each brake system friction coefficient is designed and verified by the suppliers. It is mainly dependent on the pad material and rotor material coupling, and it can be finely tuned usually by varying the pad material composition. However, it is known that the European markets wants higher performance, i.e. higher friction coefficients typically of 0.45, whereas Japanese and US markets want tidiness which is typically obtained by NAO materials with friction coefficients of 0.35.

The aforementioned parameters are directly or indirectly imposed by the driver/customer. Nevertheless, to allow the system to work properly, it is important to take into account two more parameters: the frictional power developed at the contact surface and the consequent developed temperature.

The frictional power is an important design parameter. Indeed, depending on the vehicle and brake system characteristics, it varies according to eq.(6):

$$P = \mu \cdot F_{pad} \cdot v_{sl} \quad \text{Eq.(6)}$$

It is common procedure in the brake system industry to design the rotor according to the maximum power a braking action could produce [43] so that a safe, durable brake system can be obtained which also dissipates as much heat as possible.

Eventually, depending on the brake system, especially on the rotor design and the developed frictional power, a specific temperature (T) will be reached. Temperature is the last important parameter describing the brake system. However, temperature cannot be at any extent controlled since it depends on the actual driver behaviour, the brake system cooling conditions and design, and ambient conditions. This is therefore a response parameter that can only be measured.

In this thesis the disc temperature is assumed to be representative of the system temperature. This since cast iron properties as good thermal conductivity and homogeneity, promote measurements reliability and repeatability. Conversely measuring the temperature in the friction material introduces higher uncertainties, especially systematic errors, due to the material heterogeneity.

According to the parameters describing the brake system condition on the contact interface, it is clear how the latter is a classical tribological system [44].

Involving complex geometries and different phenomena such as heat transmission, wear, airborne generation, it is useful to simplify the real system and make a model out of it where to focus only on the interesting parameters, control them individually and better identify the system conditions.

2.2 The Pin-on-Disc tribometer: a model scale

A typical experimental device used in tribology to study phenomena occurring at the contact surface between two mating objects in relative motion is the pin-on-disc tribometer [45]. This, along with careful modifications [39], is the proper

device to correlate the system conditions occurring on a modelled pad-to-rotor interface with the generated airborne wear particles.

2.2.1 Experimental set-up

Most of this thesis was performed using a pin-on-disc tribometer with a horizontal rotating disc and a dead weight loaded pin. Fig. 8 shows a scheme of the experimental set-up used.

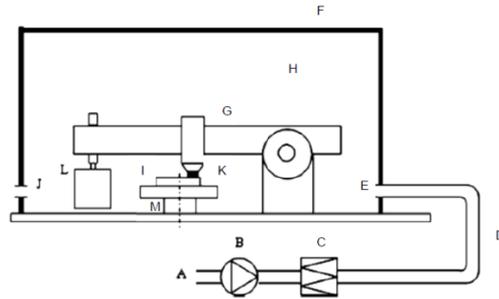


Fig. 8: Pin-on-disc tribometer scheme[39]. (A) Room air; (B) Fan; (C) HEPA filter; (D) Flexible tube; (E) Clean air inlet;(F) closed box; (G) Pin-on-disc machine; (H) sampled air volume; (I) Rotating disc sample; (J) Air outlet/sampling point;(K) Pin sample; (L) Dead weight; (M) Rotating base

Ambient air (A), is forced by a pump (B), set to a flow-rate of $7.7 \text{ m}^3/\text{h}$, through a HEPA filter (C). The latter removes particles with a collection efficiency of 99.95%, at the Maximum Penetrating Particle Size (Class H13 according to standard EN 1822). The now clean air enters the sealed test chamber (F) through the inlet (E). Here, the air-flow is continuously controlled by a hot-wire anemometer. The pin-on-disc tribometer lies inside the chamber. The approximate volumes are 0.035 m^3 and 0.135 m^3 respectively for the pin-on-disc and the chamber, giving an air-volume exchange rate of about 77 exchanges/h.

A thermal insulating ROBURIT® back-plate is fixed on the rotating base (M) and the disc sample (I) is screwed on top of that. The latter can rotate up to 3000 rpm thanks to a synchronous servo motor. Conversely, the pin (K) is mounted in a stationary pin-holder that is fixed on an arm (G) at the end of which a dead weight (L) is positioned. The ratio between the arm hinge, the pin position, and the dead-weight is fixed, intensifies the normal force by 2.1 times (e.g. a normal force of 30N at the tip of the arm provides 63N on the pin). The tangential force, on the other hand, is measured by a beam load cell with a nominal load of 100 N and a nominal sensitivity of 2 mV/V.

When the system is loaded and the disc is rotating, the generated airborne fraction is well mixed to the clean air volume (H). This is because of the complicated internal geometries. The air flux finally passes through the chamber outlet (J) where it is sampled by the particle instruments (see Section 2.4).

Temperatures from the disc and the pin were sampled using k-type thermocouples, positioned 3 mm from the contact surface in both specimens. In addition, a thermocouple was also placed at 6 mm from the pin surface in order to better understand the thermal gradient in the pin material. All the thermocouples were located at the mean point of the contact area, i.e. on the pin diameter as well as 25 mm from the disc centre.

2.2.2 Specimens and materials

In order to be as close as possible to the real system, pins and discs used in this work were directly machined from real pads and rotors. This was done according to the same guidelines as in Fig. 9-10, for the pins and the discs respectively.

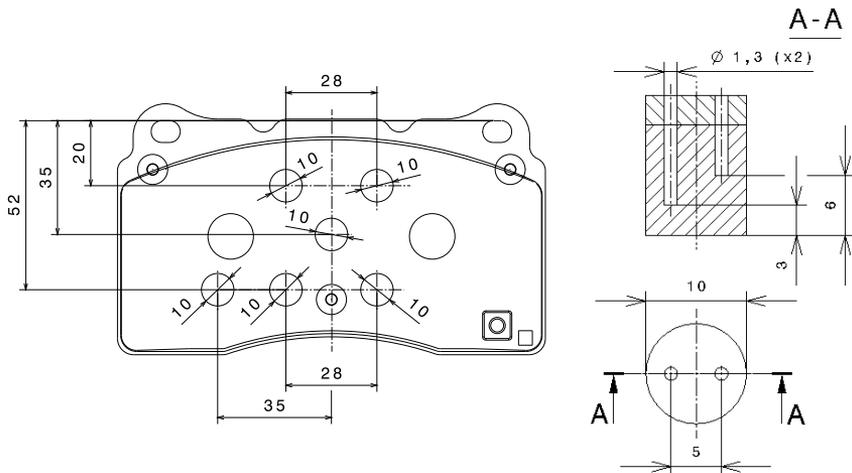


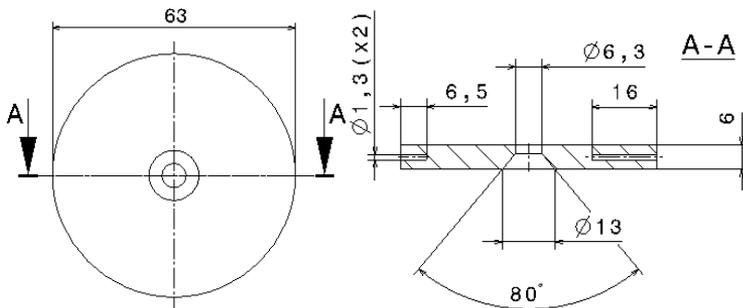
Fig. 9: Machining guidelines for the reference system pad (left) and for pin design (right)

The pins were cylindrical in shape with a 10 mm diameter. Their height was equal to 14 mm, including the friction material, under-layer and back-plate. The shim was removed due to difficulties in the machining process. Two 1.3 mm holes were drilled in order to allow temperature measurements 3 mm and 6 mm away from the surface, along the pin diameter.

The chemical composition of the pins varied according to the tested material. Up to six different mixtures were tested, including both Low-steel materials and very-low-steel/NAO. Such materials were code-named M_x , where M stands for material and x is a progressive number from 1 to 6, given by the testing order. However, M1 is the most used in this work whereas M3 is the material belonging to the reference vehicle. Table 3 shows the X-Ray Fluorescence (XRF) analysis for all the pad compositions [Paper B].

Table 3: XRF chemical composition (wt%) of the tested pad material [Paper B].

Element	Friction material					
	M1	M2	M3	M4	M5	M6
Mg	10.4	1.3	8.7	11.6	16.1	2.6
Al	9.1	3.5	8.4	1.4	5.7	1.1
Si	5.8	3.0	6.3	11.2	4.6	3.9
P	0.9	0.13	0.29	0.05	0.15	0.01
S	5.2	2.8	7.1	3.7	7.7	6.4
K	0.67	3.7	0.48	2.1	0.9	4.0
Ca	5.0	3.6	1.5	3.4	1.2	2.3
Ti	0.17	9.7	0.11	4.2	0.14	9.0
Cr	3.3	–	2.0	3.3	1.7	0.05
Fe	7.1	4.2	9.8	12.2	19.4	0.88
Cu	5.4	5.9	20.1	9.9	8.2	2.7
Zn	12.5	3.2	7.0	4.3	5.5	0.05
Sr	0.01	–	0.03	–	–	0.46
Zr	0.14	24.7	3.1	4.4	–	15.3
Mo	–	–	1.6	–	2.2	0.89
Sn	8.8	2.2	0.38	5.5	4.8	1.7
Sb	–	–	4.6	–	–	–
Ba	–	3.9	1.5	0.16	–	27.7
Bi	0.81	0.98	–	0.27	0.95	–
C	22.4	23.7	16.2	19.1	20.3	19.8
F	2.1	2.5	0.44	3.2	0.28	0.47

**Fig. 10:** Guidelines for disc machining

The discs outer diameter, equals to 63 mm (see Fig. 10), was limited by the braking surface dimensions. Each sample was drilled with two 1.3 mm holes, at a depth of

3 mm below the contact surface. One of those was 6.5 mm deep in the radial direction from the outer disc diameter. This measure point corresponded to the mean radius at the sliding contact, i.e. 25 mm from the disc centre. The second hole was drilled 16 mm in the radial direction from the outer disc diameter, therefore out of the contact area. The aim of this second hole was to measure the temperature gradient. However, due to equipment limitations, this second measurement point was never used.

All the tested disc samples had the same chemical composition, shown by the XRF analysis in Table 4.

Table 4: XRF chemical composition (wt%) of the disc sample [Paper D]

C	Si	Mn	P	S	Cu	Cr	Fe
3.40	1.70	0.57	0.03	0.26	0.24	0.20	93.6

2.3 Results validation: component and full scale

In order to address to what extent results obtained on a model scale can be significant for the real brake system, they need to be properly validated. To do this, an inertia dynamic bench, typically used for industrial applications, was designed for particle measurement [46], as shown in Fig. 11.

Moreover, to analyse which brake system conditions are significant for real urban driving conditions, a full vehicle was set up to measure the different brake system parameters.

2.3.1 Component scale experimental set-up

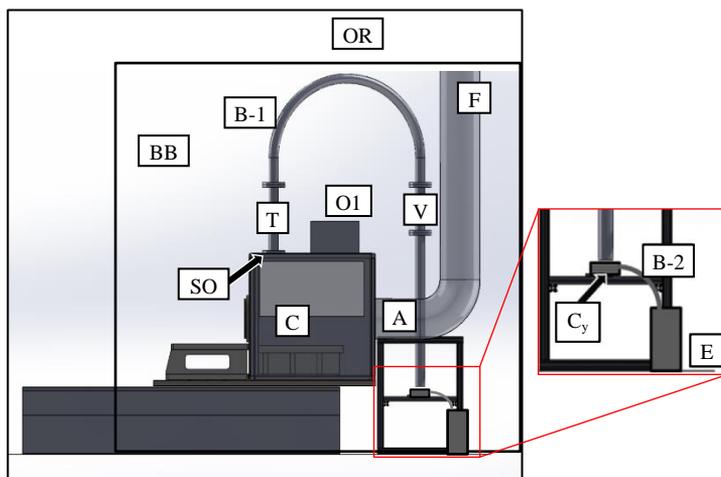


Fig. 11: Schematic diagram of the modified inertia dynamic bench [46]

Similarly to the pin-on disc set-up, ambient air taken from the outdoor room (OR) is filtered through a HEPA filter (F) with 99.95% efficiency (Class H13). The now clean air enters the chamber (C), having a volume of 0.817 m³, through the inlet (A). The flow rate at the inlet can be adjusted between 500 m³/h to 2500 m³/h by software to obtain a desired exchange rate in the box, i.e. different dilution factors. Inside the chamber lies the reference brake system, as defined in Section 1.2, consisting of a cast iron rotor, a four piston monolithic calliper and two pads with a surface area of 77 cm². Additional information on the reference system can be found in Table 5 [Paper E]. The produced airborne wear particles are well mixed with the incoming air flow, thanks to the complex internal geometry. The obtained aerosol is then forced to leave the system through two different outlets positioned at the top of the chamber. The bigger outlet (O1) section can be tuned using a shutter device. This is to regulate the air flow passing through the smaller outlet (SO). Indeed, only the aerosol from SO is sampled. This pass by a circular straight section (T) before encountering a 180°C bend (B-1). Finally, a straight section (A), starting with a venturi tube (V), in order to regulate the flow speed, ensure the right conditions for isokinetic sampling: a sample speed equal to the sampling speed and a well-developed speed profile [26]. Before being sampled, the aerosol is forced through a cyclone (Cy) in order to remove particles that are bigger than 10 µm. This is then connected to the particles instrument (E) by a 90°C bended tube (B-2). The full system is embedded in a safety chamber (BB).

Since the inertia dynamic bench is industrial equipment, its functioning principles are designed by the suppliers. More specifically, the test rig requires the vehicle speed, before and after the braking action, the initial braking temperature and the deceleration as input parameters. As output, it provides the measured speed, fluid pressure, and friction coefficient. The latter derives from torque measurements, combined with the fluid pressure (i.e. tangential and normal force acting on the braking surface). Temperature is measured as well by adding k-type thermocouples. Although pad temperatures are measured using standard thermocouples, embedded 3 mm from the braking surface, to improve comparability with the pin-on-disc tribometer, the rotor temperature is measured using copper nuts. These are copper cylinders, with a thin hole in the middle where the two thermocouple wires are placed. When the copper nut is pushed into a hole in the braking surface, smaller than the nut dimension, the hole is closed and the thermocouple joint is formed. All the parameters were measured with a sampling frequency of 50 Hz, as standard for rig applications.

2.3.2 Full scale experimental set-up

The reference vehicle was selected according to specifications related to a typical medium size European passenger car [47] and availability. Specifically, an Alfa Romeo 159, 1.9 JTDM, with a 1910 m³ gasoline engine, was selected.

Table 5 shows the essential design parameters for the vehicle and the related brake system [Paper E].

Table 5: Alfa Romeo 159, 1.9 JTDm - vehicle and brake system parameters

General vehicle parameters – only driver	
Total weight [kg]	1702
Front axle [kg]	1068
Rear axle [kg]	634
Centre of gravity height [mm]	520
Wheelbase [mm]	2675
Max speed [Km/h]	226
Wheel radius [mm]	295
Rotor parameters – front axle	
Rotor external diameter [mm]	330
Rotor internal diameter [mm]	208
Effective radius [mm]	134.5
Pad parameters	
Area [cm ²]	77

The front left wheel corner was equipped with four k-type thermocouples: two copper nuts sunk into both rotor braking surfaces, and two standard thermocouples embedded in each pad 3 mm from the braking surface. In addition, the brake fluid pressure was measured.

The vehicle speed was registered by means of a rotating encoder, positioned on the right rear wheel, and a GPS which also provided the vehicle coordinates.

The sampling rate was set at 5 Hz during normal driving conditions and increased to 10 Hz, during the braking actions. A fluid pressure value of 3 bar constituted a trigger for sampling rate switch.

This set-up did not include particle measurements due to the difficulties in avoiding and distinguishing emission sources that are not the brake system [Paper G].

2.4 Particle measurement

Particle measurement can be performed by means of different instruments, each making use of a specific working principle depending on the equivalent diameter of interest. In this thesis, the following particle instruments were used:

- **Electrical Low Pressure Impactor (Dekati ELPI+)** [48,49]: this measures real-time particle distribution and concentration according to aerodynamic diameter. This is in the size range of 6 nm – 10 µm with up to 10 Hz sampling rate on 14 size fractions. Particles are first charged to a known charge level in a corona charger. Particles are then classified in a low-pressure cascade impactor according to their inertial forces. The particles collected in a specific impactor stage produce an electrical current, recorded by the respective electrometer channel which is

proportional to the number concentration. The 13 impactor stages operating in the 17 nm- 10 μm range collect the samples on filters so that chemical analysis can subsequently be performed. The final stage, in the 6nm – 17nm range, is a back-up filter stage.

- **Optical Particle Sizer (TSI OPS):** this measures particle concentration and their size distribution in the range 0,3 μm - 10 μm , divided into 16 channels, according to their optical diameter. The optical particles sizer uses optics with 120° light collection, with a single count technology. A sheath flow surrounds the aerosol inlet, focusing the latter to enhance size resolution. The aerosol crosses a laser beam, creating a light pulse. The intensity of the flash is used to count and size the particles.
- **Fast Mobility Particle Sizer spectrometer (TSI FMPS) :** this measures particles in the range from 5.6 to 560 nm, with 32 channels of resolution, according to their mobility diameter. Particles are positively charged using a corona charger and transported down a high voltage electrode column via a HEPA-filtered air sheet. The electric field created repels particles according to their electrical mobility. Multiple, low-noise electrometers detect particles when stroked.

Results are mainly presented in terms of aerodynamic diameter, by means of the Dekati ELPI+. However Paper B makes use of the TSI FMPS and OPS because of the higher resolution provided by the aforementioned instrument which best fitted the aim of the paper. Nevertheless, it should be mentioned that during the entire PoD experimental work, TSI FMPS and OPS were used as control instruments. This is to verify the reliability of the observed phenomena. Indeed, similar size distributions and total concentration were given by the different instruments according to their working size range.

Chapter 3

Summary of the appended papers

Paper A: *A Study on the load level influence on particulate matter emissions from the sliding contact between a low steel friction material and cast iron*

The aim of this paper is to investigate how different nominal contact pressures, i.e. load levels affect emissions from a low-steel pad material (M1) sliding against a cast iron disc in terms of particle number concentration and size distribution, and their relation with the system temperature.

Tests were conducted in a pin-on-disc machine specially designed for airborne particulate research. A clean chamber technique was used to ensure that measured airborne particulates were only generated by the sliding contact. A thermal insulating plate, placed between the disc and the rotating base allowed the system to reach up to 350°C with only frictional heating. A constant sliding speed of 1.3 m/s and a time length of 3 hours were imposed, ensuring the same sliding distance for all tests. The time was chosen to ensure a long steady state regime. The applied loads varied from 1 kg to 7 kg, resulting in an average contact pressure range of 0.29 MPa - 1.95 MPa. The number concentration and the size distribution were measured using an Electrical Low Pressure Impactor (Dekati ®ELPI+).

Results show a clear emission dependence on the nominal contact pressure. Specifically, low pressures up to 0.83 MPa generate low and stable emissions, clearly involving ultrafine, fine and coarse particles; Pressures of between 0.97 MPa and 1.11 MPa show transient behaviour, with unstable emissions and a distribution shift towards ultrafine particles; high pressures of over 1.39 MPa produce a significant emission increase, showing a strong predominance of the ultrafine fraction. It is argued that a temperature threshold responsible for a change in particle emissions can be identified. Above this temperature, corresponding to approximately 200°C in the disc, a sharp increase in the total number concentration can be detected.

Paper B: *A study on emissions of airborne wear particles from car brake friction pairs*

The main objective of this paper is to understand how emissions from different pad materials can be influenced by nominal contact pressure variation and identify

possible differences between them. It extends the studies in paper A and tries to confirm or discredit its results.

The emission of airborne wear particles from friction material / cast iron pairs used in car brakes was investigated, paying special attention to the influence of temperature. Five low-metallic materials and one non-asbestos organic material were tested using a pin-on-disc machine. The latter was placed in a sealed chamber to allow airborne particle collection. The concentration and size distribution were obtained by a fast mobility particle sizer (FMPS) and an optical particle sizer (OPS). The experiments show that as the temperature increases from 100 to 300 °C, the emission of ultrafine particles intensifies while that of coarse particles decreases. A critical temperature at which the ultrafine particle emission rate rises stepwise by 4 to 6 magnitude orders was identified. It is argued that for the investigated frictional pairs, the critical temperature was found to be between 165 and 190 °C. Below the critical temperature, fine particles outnumber coarse and ultrafine particles, although coarse particles make up the bulk of the particulate matter mass. The friction pairs differ in the ultrafine particle emission rate by 1 to 2 orders of magnitude. Above the critical temperature, ultrafine particles constitute almost 100% of the total particle number and their relative mass contribution can exceed 50%.

Paper C: *Dry sliding of a low steel friction material against cast iron at different loads: characterization of the friction layer and wear debris*

This paper investigate particles chemical composition, morphology and wear mechanisms induced by different nominal contact pressures.

Pin-on-disc testing was used to investigate the sliding behaviour and the wear products of a low steel friction material (M1) against a cast iron disc at different applied loads. The test stand was placed in a clean chamber with a purified incoming air flux. The outgoing flux carries wear particles to a Dekati ELPI+ impactor that counts, sorts and collect them by their aerodynamic diameter. Results show that as the nominal contact pressure rose, the coverage of both pin and disc surfaces by the friction layer was seen to increase. The relevant X-Ray diffraction patterns revealed the presence of a large amount of graphite and different compounds originating from the friction material and from the disc, mainly iron oxides. After the test at the lowest load, the disc worn surface exhibited abrasive grooves and a friction layer mainly made of compacted iron oxide particles. At the highest load (above the transition temperature), the disc surface is covered by a compact friction layer. As concerns the friction layer on the pins, most of the ingredients from the friction material were detected, in association with the iron oxides from the disc. The characterization of the collected airborne wear debris showed that the smallest particles (below 1 µm) are equi-axed whereas the coarser ones would mostly display a plate-like morphology. The mechanisms of their formation and relevance to wear behaviour are discussed.

Paper D: *On the influence of car brake system parameters on particulate matter emissions*

The main objective of the paper is to enhance previous knowledge, extending the emissions for different brake system contact conditions and mapping them. This includes main parameters as well as design and derivative parameters.

The influence of car brake system parameters on particulate matter emissions was investigated using a pin-on-disc tribometer. Samples from a low-steel friction material (M1) and a cast iron disc were tested considering different sliding velocities from 0.66 m/s to 7.68 m/s, nominal contact pressures from 0.55 MPa to 1.67 MPa, and frictional powers from 28 W to 87 W. Disc temperatures were also measured. Their impact on total concentration, size distribution, particle coefficient and transition temperature was analysed. Results show that frictional power is the most significant brake system parameter. However, temperature, as a response parameter, is the most influential, inducing a shift towards the ultrafine particulate fraction and raising emissions. A transition temperature, independent of the system conditions, was identified.

Paper E: *On the scaling effect of measuring disc brake airborne particulate matter emissions – a comparison of a pin-on-disc tribometer and an inertia dynamometer bench under dragging conditions*

The aim of this paper is to investigate how the transition temperature, now identified as the most influencing parameter for emissions, is affected by the different test scales. New and used low-steel pins/pads (M1) were tested against cast iron discs/rotors on both a pin-on-disc tribometer and an inertia dyno-bench. The latter was used under dragging conditions to simulate the PoD working conditions. A constant nominal contact pressure and rotational velocity were imposed in both test stands. Results show that a transition temperature can always be identified. However, it is influenced by the test scale and the frictional pair status. It is argued that emissions are assessed in a similar way by the two set-ups when an equivalent frictional pair status is analysed (e.g. run-in). Further investigations for fully run-in samples on the pin-on-disc should be performed in order to confirm the possibility of using the tribometers for the initial assessment of different friction materials.

Paper F: *Could pin-on-disc tribometers be used to study the friction/wear performance of disc brake materials?*

The aim of this paper is to investigate and discuss whether a simplified set-up could reproduce the friction and wear behaviour of the disc brake assembly by comparing the friction surfaces with diverse microscopy techniques. Coefficients of friction, wear, and collected airborne particles are also compared. Although the tests are based on different testing procedures (tribometers - drag test and dyno-bench test–

single stop), the results show that tribometers provide information related to the friction wear performance, the character of the friction surfaces and the character of the wear particles which mirror the behaviour of the samples during dyno-bench tests. In addition, the third body layers formed using the two different test stands can be considered comparable, indicating similar wear mechanisms. This indicates that PoD can also correctly evaluate the friction coefficient differences between frictional couples. The PoD set-up can therefore be a useful tool for a preliminary assessment of new friction materials.

Paper G: *A test stand investigation on a real driving cycle emission factor for car brakes*

This paper focuses on understanding how real driving conditions can be reproduced on an inertia dyno bench and on an analysis of brake parameters obtained from a real vehicle, under urban driving conditions.

The reference vehicle was equipped in order to acquire and capture different brake system parameters in an urban environment. A road test cycle was specifically designed to simulate everyday usage of EU cars, by driving in the Bergamo city area. Four different sections were set-up in order to “warm-up” the brake system, go through “city traffic” for a first time, “cool down” the system, and conclude in “city traffic” for a second time.

Obtained data were post-processed and simplified in order to develop a test cycle suitable for an inertia dyno-bench and calculate the related emission factors.

Results indicate brake emission factors were equal to 0.056-0.061 g/km and 0.033-0.049* 10¹¹ #/km, and rotor temperatures never exceeded 180°C. This corresponds to better emissions than a EURO6 engine in terms of particle number and equivalent to a EURO2 in terms of mass. It is argued that a real driving cycle can be reproduced in a dedicated laboratory test stand by assessing the corresponding brake emission factors.

Chapter 4

Discussion and future work

The results provided in this thesis represent a first attempt to explain the relations between brake system contact conditions, as a combination of parameters, and airborne particle emissions. Few studies [42] have investigated this topic before, but different studies [33,35], which have focused on the characterization of emissions, provide some interesting hypotheses with regard to related observed phenomena.

Since the car disc brake is a complex system, most of the presented research was performed using an appositely designed pin-on-disc tribometer. This allowed us to simplify the geometries and control relevant parameters more easily. In addition, the adopted approach, i.e. investigating the influence of single parameters [Paper A, Paper B] before studying their combination [Paper D], or system conditions, provided a structured method to better tune the ongoing research. Simplifying the system, however, introduces important limitations. Indeed, the analysed conditions are restricted by the test stand working range, i.e. maximum applicable load, rotational speeds and temperatures. In addition, the obtained results need to be validated in order to understand the level of representativeness for real systems [Paper E, Paper F, Paper G].

The brake system contact conditions are the results of different influencing factors. Indeed, three actors that play a major role can be identified: the designer - who has to satisfy customer needs while avoiding failures and guaranteeing safety – can establish the working ranges in terms of pressure, speed and frictional power, define the friction coefficient of the system, and optimize the cooling conditions; the driver – who has to safely slow down the vehicle or stop it according to his/her will – influencing the market requirements, therefore the designer choices, and governing the sliding speed and the nominal contact pressure; the ambient conditions – unpredictable – which mainly influence the system cooling conditions.

While the ambient cannot be modified and drivers can be barely influenced, most of the responsibility for emissions reduction is in the designers' hands, influencing the final outcome by system optimization.

The considered parameters are classified in this thesis as: main parameters – braking pressure, sliding speed, COF – independent of each other; derivative parameters – frictional power – a combination of the previous ones; and response parameters – temperature – which can be influenced but not controlled. Note that in the real world, the brake system contact condition can only be described by main and derivative parameters since temperature is usually unknown.

This study shows that each of the considered parameters has an individual effect on emissions, but what truly affects them is the system temperature. In particular, results shows that a transition temperature, defined as a threshold after which the number concentration increases by several magnitude orders [Paper B] can be identified irrespective of the system contact conditions or the choice of frictional couple. Figure 12 shows the transition temperature effect considering most of the performed tests from this thesis and presented in the collection of papers. An emission increase of several magnitude orders in the range 170-200°C, for all the investigated conditions can clearly be identified.

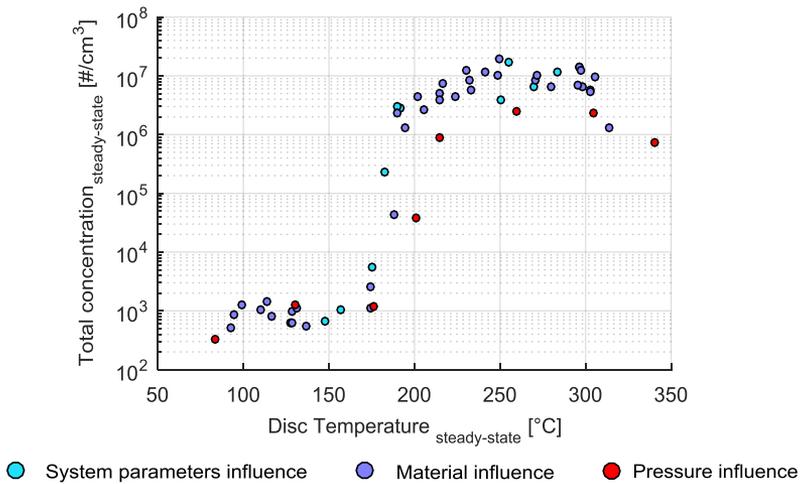


Fig. 12: Transition temperature for different testing conditions. Data collection from the investigated papers

This phenomena is in accordance with previous studies [33,35], performed on a component scale using inertia dynamic benches, that observed a steep increase in emissions for temperatures values in the range 300-400°C.

An additional consequence of the temperature increase, especially overtaking of the transition temperature, is a progressive shift in the number size distribution towards the ultrafine fraction. The latter is generally dominant for almost any contact condition but, once the transition has been overcome, it constitutes almost 100% of the emitted particles [Paper B].

Understanding why this shift in particle size and rise in total concentration occur would be beneficial for emissions reduction. An interesting hypothesis, also introduced in previous studies [35], is degradation of the phenolic resin [Paper C, Paper D]. Indeed, its degradation temperature is in the range of 300-350°C [50], it faces a rubbery state at 320°C [51], and shows a glass transition near 280°C [50]. The temperature measurements performed in this study are taken 3 mm below the contact surface, using the disc as a reference because it has better thermal conductivity than the pad material. Therefore, the phenolic resin degradation temperatures can be easily reached at the contact area, if not locally overcome [52], affecting the organic binder which consequently releases particles in the air.

It can be argued that a first important step for emission reduction is to keep the system temperature as low as possible. However, this is not a controllable parameter since the ambient temperature and the driving style [Paper G] are the two main influencing factors. Nevertheless, some expedients to influence the system temperature can be adopted.

Results show that the higher the brake power is, the higher the emissions are. Nominal contact pressure, sliding speed and COF do not play a major role when considered alone, but it is when they are combined, giving the developed frictional power, that counts [Paper D].

Reducing the COF would not provide any advantage since the driver will increase the nominal contact pressure in order to provide the same braking power, aiming to brake in a given stopping distance. In addition, a braking style cannot be imposed on a driver whereas it could be suggested by smart devices adopted on-board.

According to what has been argued, two solutions can therefore be recommended: improve the system cooling conditions, and/or work on possible alternative binders if the phenolic resin role is confirmed.

While the latter needs additional investigation to be taken into account, the former can be adopted with the aid of simulation routines.

Indeed, making use of the proposed specific particle coefficient maps, the brake system design phases could embrace a new step towards environmental evaluations. Starting from structural simulations, a thermal model can be run afterwards, obtaining necessary inputs to enter the maps with the system working conditions and the temperature. This would then provide a corresponding outcome in terms of particle emissions and size distribution which can be used to compare different designs.

Maps, such as the one proposed in this thesis [Paper D] would be easier to develop on a model scale. This would save time and allow different frictional couples to be quickly tested, whether they are in production or prototypes. However, this could only be done if results on a model scale are representative of the real system.

Results show that the PoD and the dynamic bench provide comparable indications in terms of emissions when similar working conditions and frictional couple status

(run-in or new) are ensured [Paper E]. In addition, analogous assessment is provided also in terms of friction coefficient, loss on thickness, surface phenomena, and wear particles chemical composition [Paper F]. Even though further investigations are needed, the PoD can be considered a reliable test stand for R&D activities when providing a first assessment of different frictional pairs.

The presented study focuses on urban driving conditions; nevertheless, it can be argued that the given results are generally valid since the transition can be considered irrespective of the system conditions. However, the system conditions determine whether this threshold can be reached or not on road [Paper G]. Indeed, it has been demonstrated that under urban driving conditions, temperatures not higher than 180°C are usually reached, with mean values in the range of 110-130°C. This implies emission levels that are nowadays competitive in terms of particulate number with respect to EURO6 engines, but comparable with EURO2 when looking at mass emissions. Indeed particle mass emission factors were equal to 0.056-0.061 g/km, worse than the EURO3 limit of 0.05, thereby falling into the EURO 2 classification. Conversely the particle number emission factors were 0.033-0.049* 10¹¹ #/km, therefore a long way from the EURO6 limits of 6* 10¹¹ #/km. Comparing the mass emission factor with other non-exhaust sources (see Fig. 13), the relevant contribution of the brake system is clear. Indeed, literature shows that under high speed conditions [53], i.e. the most emissive ones [54] for road surface wear and resuspension due to turbulent air flow, the mass emission factors are respectively 0.0039-0.0045 g/km and 0.009-0.01 g/km. Thanks to the REBRAKE project technology [55], the car brake mass emission factor can be reduced to 0.019 g/km, however, it is clear that additional effort is needed to at least equal other non-exhaust emission sources.

Since urban driving conditions are the most interesting for legislation, but not the only ones occurring in a vehicle's life-time, and particle emissions are a concrete health-related issue, future works should focus on expanding and verifying the present study for different frictional couples, investigating the role of phenolic resin in emissions and improving the understanding of relations between the model scale and the component scale.

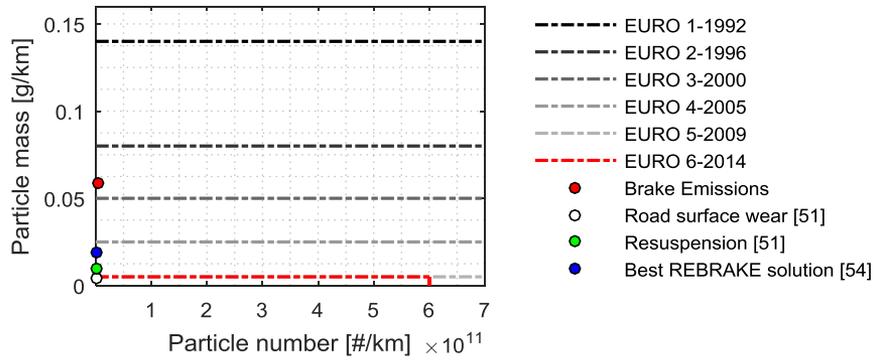


Fig. 13: Brake emissions for urban driving conditions (red dot) compared with Euro emission standard limits

Chapter 5

Conclusions

In this work, relations between the brake system contact conditions and particle emissions have been investigated on a model scale, using a PoD tribometer. The latter has been afterward compared with an inertia dynamic bench and real urban driving conditions have been characterized to assess the representativeness of the results.

The following research questions have been answered:

How do airborne particle emissions respond to changes in contact conditions on the pad to rotor interface?

Emissions can vary according to the developed frictional power on the contact surface and cooling conditions. In particular, higher frictional power – as a result of the combination between nominal contact pressure, sliding speed and COF - induce higher emissions. This is mainly due to a system temperature rise.

In addition, an increase in emissions of several magnitude orders, along with a shift of the size distribution towards the ultrafine fraction, occurs when the system temperature overcomes a threshold located in the range 180-200 °C.

This is similar for every tested pad composition and is independent of the contact conditions. A hypothesis for this phenomena is the degradation of the phenolic resin, a binder common to all the investigated pads.

Can the model scale be representative of component and full scale?

Results show that similar indications are provided by the PoD tribometer and the dynamic bench test rig if similar working conditions and frictional couple status are ensured. Both the set-ups show the existence of a transition temperature. However, that has been demonstrate to variate depending on the system status (run-in or not) only for inertia dyno bench tests.

In addition, information provided about the friction wear performance, the character of the friction surfaces and the character of wear particles are similar among the two test stands. Also the third body layers can be considered comparable, indicating similar wear mechanisms.

It can be concluded that the pin-on-disc tribometer can be used for preliminary studies to assess different frictional couples, however additional studies are recommended to identify the best methodology to be used in order to obtain reliable measurements on a model scale.

When real urban driving conditions are assessed, it is possible to notice that the transition temperature range is hardly reached, especially when used frictional couples are used, showing a mean system temperature of around 110-130°C and a maximum temperature of 180°C. It can be therefore concluded that on a full scale, brake emissions will very seldom be significant in terms of number concentration. Conversely they can significantly contribute in terms of mass.

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