Relevance of pin-on-disc and inertia dynamometer bench experiments for braking emission studies

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Abstract. Over the last years, the task of reducing automobile pollution was focused on the car’s engine. Now, the non-exhaust emission becomes a major contributor, and its control is the next objective to reach the zero-emission car. A major part of those non-exhaust emissions comes from brake wear, caused by the friction between the brake disc and pads. This emission is the result of complex tribological phenomena that has still to be determined. Nevertheless, this emission remains controllable and is the next lever for reducing car pollution. The problem of this field is the non-comparable results obtained by stakeholders due to their different measurement protocol. The first challenge is, thus, to define the best protocol in order to get a representative, reliable and repeatable measurement of particle emissions. The present article discusses a step of the selection process: which laboratory indoor method is the best for simulating the generation of braking particles? The pin-on-disc and the inertia dynamometer bench are the only two existing methods for braking simulation.

1. Introduction

Over the last years, the task of reducing automobile pollution was focused on the car engine, whose exhaust emissions decreased by more than 60\% in the UK \cite{1} in the past 15 years. Consequently, the non-exhaust emissions become a major contributor, and their control is the next objective to reach the zero-emission car.

A part of those non-exhaust emissions comes from brake wear, caused by the friction between the brake disc and pads. Though the consequence of a simple need, i.e. to stop the car, this emission is the result of complex microscopic tribological phenomena which is, for now, still out of the scope of modelling \cite{2}. Nevertheless, this emission remains controllable and is the next lever for reducing car pollution.

Modelling the contact between the brake disc and a pad is today out of reach, and investigations have to lean onto experimental methods. Various experimental systems are available in order to simulate and measure braking events. Some investigations onto actual vehicles exist \cite{3,4}, but this contribution will only relate the most practical systems in view of aerosol analysis and compares the two most common simulation systems: the pin-on-disc and the inertia dynamometer bench \cite{5}. Most of the time, dynos are owned by industrial companies, meanwhile, pin-on-disc is likely typical to tribology laboratories. This article exposes the abilities to simulate braking, and to emit particles of...
Particle contamination is known as a high source of measurement uncertainties [6]. It is now a consensus that braking emission systems must be confined in a controlled air chamber.

2. Definitions

2.1. Pin-on-disc

Pin-on-disc, or tribometer (Fig. 1), is a common tool for tribology laboratories. Highly depicted in the literature [7,8] they provide a simplified tribological system and are commonly used to study tribological parameters such as friction coefficient, or generation of tribofilm [9], etc. Pin-on-disc is a versatile system that is widely used and which benefits from high cost-effectiveness. Pin-on-disc are simple and low-cost experiments that can grant a precise coefficient parameter estimation, which is a very valuable parameter in tribology.

Referring to Fig.1, for the braking investigations, the pin is a small cylinder collected from braking pad (typically less than 10mm of diameter [7]). The disc is a chosen material disc, which is rotating driven by an electrical motor. This motor is a further source of particle emissions; and for aerosol measurement it has to be placed out of instrumentation reach i.e. out of the confinement. The best option is to take out the motor from the confining chamber to prevent any contamination from the engine.

The pin is compressed onto the rotating disc with a constant force value (usually around 50 N), equivalent to the dead mass weight.

![Pin-on-disc schematic diagram](image)

**Figure 1. Schema of a pin-on-disc**

Due to its design, pin-on-disc does not support high normal forces, which can damage the guiding system. Either the force warps the disc with a flexion effort, or the mechanism ensuring the disc rotation cannot handle such transversal force. The solution to this problem is to apply an opposite force onto the other side of the disc. This solution is employed for most of the frictional brakes, but it would tend to complicate the system. Thus, only small forces are performed in pin-on-disc experiments. As the pressure is a major tribological parameter, reducing the contact surfaces is the only option; hence, tribometer experiments use small pins (< 10 mm diameter).
2.2. Inertia dynamometer bench

Inertia dynamometer bench, also named dynamometric bench or dyno, is specific to braking applications. The principle of dynamometer bench is similar to car brakes. An inertia dynamometer bench is composed of a rotating disc, of which deceleration is ensured by a pair of biting pads. Alike car brakes, a calliper supports those pads and ensure precise parallel contact between pads and disc. Dynos have been developed in order to characterize the frictional brake system in indoor conditions. They are engineered to perform experiments close to reality. In contrary to pin-on-disc, commercial components like braking pads, disc or calliper compose a usual dynamometer bench experiment. Apart from environmental conditions, dynos are close to real life experiments. An extensive control of parameters is indeed possible. The inertia of the vehicle or the possibility to program sequences of braking events is part of the easily manageable parameters. Hence, it is possible to simulate real vehicle parameters, such as real braking forces performed by pads onto disc (around 5kN).

In contrary to tribometers (cf. part 2.1.), dynos are designed for “aggressive” standard tests. Those standard tests are “aggressive” in the sense that such high pressures and high decelerations are rarely reached in real life driving conditions. Thus, forces that can be simulated are commonly higher than in real car braking.

3. Comparison

3.1. Representativeness

3.1.1. Cycle

A key element of simulating braking emissions is the relevance of the simulated braking events. In the earlier investigations, stakeholders were using braking event series (AK-Master, BSL procedures, etc), which are aggressive for the brake system. Those braking event series, or cycles [10], were standard tests performed to ensure brake quality. The problem is that no driving condition is represented. Those cycles were repetition of exact same braking events. For example a repetition of braking from 50 km/h to 0 km/h at a deceleration rate of 2,94 m/s² (BSL-035) [11]. In order to represent more efficiently driving conditions, existing data previously collected for exhaust emission studies, Worldwide harmonized Light vehicles Test Procedures or WLTP data, were exploited. Thanks to those data, a new cycle, closer to most of the worldwide driving habits has been proposed [12]. This cycle called WLTP is a 4h24 long sequence, which is now largely recommended to run for every braking particle investigation.

As shown in part 2.2, performing a cycle on an inertia dynamometer bench is simple; since they are thought for performing cycles. Whereas, pin-on-disc cannot perform complex cycles such as WLTP cycle. Pin-on-disc are simple systems that cannot provide a car inertia notion during experiment, but only a frictional speed. Indeed, as part 2.1 points out, it is impossible to apply a strong force onto the disc unless it is “bitten”. Thus, decelerating the disc with friction is impossible. Moreover, pin-on-disc are often simple lever system that is not thought for precise, exigent cycles, like WLTP. Adapting a whole pin-on-disc for a precise cycle is a difficult task that has been avoided until now.

3.1.2. Temperature

Temperature is one of the main tribology parameters: The friction converts some of the mechanical energy into thermal energy. Simultaneously, this rise of the temperature continuously affects the tribological system. For braking emission, the temperature effect is largely reported in the literature [5,13,14]. More precisely, as temperature increases, the number of particles emitted increases as well. This effect is hugely amplified between 150°C and 200°C, where a pad component (the filler - phenolic resin) starts to evaporate [13].

In a pin-on-disc experiment, only a small sample of the pad is involved in the friction. Thus, the friction surface is usually lower than a percent of an actual braking friction. The flash temperature, which depends on contact pressure and speed, could be the same, but considering this low surface friction, the bulk temperature controlled by cumulating thermal energy resulting from friction is much
lower. Therefore, a lower amount of thermal energy is released, and temperature barely rises. Thus, emission rates from both tribological systems will be proportionally incompatible. For a same considered amount of friction material, pin-on-disc tends consequently to emit a lower quantity of particle than dynos.

3.1.3. Representativeness summary

Bear in mind the WLTP cycle is a sequence of braking events, with corresponding temperatures, defined with a particular cooling system specific to one dyno [12]. Even if a pin-on-disc is adapted with aim to perform WLTP cycle, temperatures obtained will always remain different. An additional heating system for pin-disc can be added to simulate temperature effect. But, in contrary to actual series of braking events simulated temperatures will remain stable.

Considering the cycle incompatibility of tribometer, and the temperature discrepancy, pin-on-disc experiments cannot fit the representative requirements. Inertia dynamometer benches are arguably the best option when talking about representativeness. Literature show that pin-on-disc has capability in determining properties of emitted particles in braking conditions [13,15]. While, their measurements in number and mass does not fit with real life, there are mainly used in the particle characterization of braking emissions.

3.2. Investigation details

3.2.1. Investment

The pin-on-disc system is a very common experiment for tribology laboratories, it is practical and cost-efficient. A pin-on-disc that has only theoretical application costs around 30 k€. A pin-on-disc that has industrial purposes can costs around 100 k€. Pin-on-disc is a powerful experimental system as it can fit a large range of application and is appropriate to large range of topics (brakes, horology, energy efficiency, etc.). Studying braking particles requires to adapt it, with a sealed clean chamber [7], but the purchase is affordable. In pin-on-disc case, the most consistent investment is the instrumentation.

In the meantime, dynos only relate to braking studies. They are very specific and represent a considering investment, compared to pin-on-disc. An inertia dynamometer bench, with a sealed chamber [6,16] is a more expensive investment (more than 1M€) that provide representativeness in braking emission investigations.

3.2.2. Bibliometry

Since the beginning of braking particles investigations, pin-on-disc is considered as a relevant option for emission studies. Pin-on-disc experiments were compared several time to dynamometer bench investigations, and their relevance in braking emission has been discussed and confirmed [5,17,18]. Still, pin-on-disc researches remain as a minority (Graph.1).

In the last 10 years, the interest toward braking emission grew. In 2008, only three articles were proposed, meanwhile twenty articles were published in 2018. However, new stakeholders were mainly industrial laboratories which already possessed an inertia dynamometer bench without a chamber (cf. part 3.1.). Adding a ventilated and hermetic chamber on a dyno is a minor investment (< 50k€), and ensure braking emission studies in the best conditions (cf. 3.1.3). The Royal Institute of Technology (KTH) is a major academic actor in braking emission and is one of the biggest contributor on the topic [7]. Their tribometer is the only one to be adapted for braking emissions; And it has shown a high efficiency for determining braking particles properties [13,15]. However, only KTH publishes
Dynamometric bench
Pin-on-disc

Graph 1. Braking particles investigations:
Number of publications between 2008 and 2018

Graph 2. Publication affiliation (only the first nine laboratories)

3.2.3. Emission rate
The emission rate of a system define its capacity to emit particles. The tribological contact between disc and pad materials is responsible of the emission in dynos and tribometer. But in a pin-on-disc, the pad material surface is usually at least 100 times smaller than actuals pads used on dynamometer (cf. part 2.1.). The emission rate can be roughly approximated as directly proportional sur the surface of friction. In first instance, we assume that for the same exact conditions (pressure, temperature, friction duration, speed, etc.) pin-on-disc emit 100 times or less than dynos. Combined with the lower temperature phenomena (cf. part 3.1.), particles emitted from tribometer are significantly low. Studying braking particles with a pin-on-disc requires a different air treatment system than those used for a dyno.
3.2.4. **Experimental conditions**

Through experimental studies, experiment setups evolved. The tribological system must now be confined into an overpressurized chamber ventilated with filtered air (with \(<1.10^{-2}/\text{cm}^3\) of external contamination).

On inertia dynamometer bench systems, an average airflow of \(1.10^3\ \text{m}^3/\text{h}\) perform a strong ventilation in order to cool the tribological system \([16,19]\), close to driving conditions. Combined with a HEPA 14 filter, the contamination by external particle becomes negligible. The contamination threshold is often not detected by ELPI. This fact tends to be wrong with the use of ELPI +, which is more sensitive. Still, with measured particle concentrations exceeding \(1.10^4#/\text{cm}^3\), measurements are poorly impacted by instrument uncertainties.

Referring to part 3.2.3., the emission rate of pin-on-disk is strongly lower than dynos and could lead to an undetectable emission for ELPI detection range. In order to obtain exploitable measurements, concentrations must be significantly higher. To make that point possible, the dilution of particles should be managed to be lower dyno systems by decrease of the airflow rate. To do so, KTH use airflow rate of 7.92 \(\text{m}^3/\text{h}\), and a HEPA 13 filter in an overpressurized chamber \([7]\). With this aeraulic system, a low emission rate can be studied with measured concentrations of braking particles.

4. **Conclusion**

The pin-on-disk setup represents a relevant option for braking particle characterization. It can be considered as a versatile apparatus with a low investment and low immobilization cost. This could be the best option for laboratories who plan to do investigations. Pin-on-disc experiments can provide tribology data such as wear constants, but also makes possible characterization of particles \([15]\), which is really helpful for instrument calibration. But all results about concentrations (number and mass) cannot be obtained to braking emission. The properties of the particles emitted by pin-on-disc or dynamometer are consistent and the same. For example, the aerosol size distribution shows similar modes \([20,21]\). But due to lower testing temperatures, the emission from a pin-on-disc cannot be considered proportional to dyno emissions. For this reason, pin-on-disc systems are not used for representative measurements.

The dynamometric bench is arguably the best option for those who can handle the investment. Quality and quantity of measurement are ensured on a wide range of study. For this reason, when starting this topic, new stakeholders orient their investment towards the dyno method. Considering the PMP \([22]\), looking for a standard, repeatable and reliable protocol, dynos will be surely implemented in this protocol, as a basic simulation process to estimate braking emission.

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