

# A Study on Emission of Airborne Wear Particles from Car Brake Friction Pairs

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## ABSTRACT

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 machine was placed in a sealed chamber to allow airborne particle collection. The concentration and size distribution of 0.0056 to 10  $\mu\text{m}$  particles were obtained by a fast mobility particle sizer and an optical particle sizer. The temperature was measured by a thermocouple installed in the disc. The experiments show that as the temperature increases from 100 to 300  $^{\circ}\text{C}$  the emission of ultrafine particles intensifies while that of coarse particles decreases. There is a critical temperature at which the ultrafine particle emission rate rises stepwise by 4 to 6 orders of magnitude. For the friction pairs investigated, the critical temperature was found to be between 165 and 190  $^{\circ}\text{C}$ . 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%. Analysis of the particle size distributions revealed peaks at 0.19-0.29, 0.9 and 1.7  $\mu\text{m}$ . Above the critical temperature, one more peak appears in the ultrafine particle range at 0.011-0.034  $\mu\text{m}$ .

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## 1. INTRODUCTION

Airborne particles can penetrate the human body in many ways, including through skin contact, breathing, and eating. Submicron airborne particles can reach the deepest part of the lungs, the bronchioles and alveoli, and enter the bloodstream [1]. Particle penetration may have adverse health effects, for correlations have been found between high concentrations of airborne particulate matter and increased morbidity due to asthma, lung cancer, cardiovascular disease, respiratory diseases, and skin diseases [2, 3, 4, 5]. Humans living in urban environments are subject to higher health risks due to various anthropogenic sources of airborne particles [6], including the burning of fossil fuels to generate electricity for manufacturing and household purposes, construction / demolition, and road transport [7]. The latter has an especially significant influence in the vicinity of traffic arteries [8,9]. Traffic-related particles are classified into exhaust and non-exhaust particles. The main source of traffic-related exhaust particles is combustion of fuel in the engine. Non-exhaust traffic-related particles are generated by

wear on transport vehicle friction components and road surfaces [10]. Another source of non-exhaust traffic-related particles is vehicle-caused turbulence, which results in resuspension of material previously deposited on the road surface.

It has been reported that car brakes contribute considerably to non-exhaust traffic-related particulate matter [11,12]. Modern cars are equipped with disc brakes in which braking torque is provided by the friction of two pads against a disc. Most brake discs are made of cast iron. Brake pads are manufactured from a variety of materials which are usually classified into three groups: non-asbestos organic (NAO), low-metallic (LM), and semi-metallic (SM) materials [13]. NAO pads use insignificant quantities of ferrous metals (iron and/or steel) in the formulation. Their friction coefficient,  $\mu$ , is typically 0.3-0.4, and they have high wear resistance at temperatures below about 220  $^{\circ}\text{C}$ , and low noise propensity. LM pads include up to 20% ferrous metals. With  $\mu \approx 0.35$ -0.5, their wear and noise characteristics are generally not as good as those of NAO pads, but their performance is more stable at

high temperatures. SM pads contain up to 40% ferrous metals and have  $\mu \approx 0.25-0.35$ . During braking, wear particles are emitted from the friction surfaces of the pads and disc, and some of these particles become airborne. Since disc brakes are not sealed off, these particles are released to the environment.

There have been a number of studies investigating car brake materials in relation to airborne wear particle emissions and associated ecological problems [14]. Garg et al. [15] used a brake dynamometer to study the generation of wear particulate matter from car brakes with NAO and SM pads. They analyzed the emission rate, size distribution, and elemental composition of airborne wear particles at rotor temperatures from 100 to 400 °C. The particle measurements were made using a Dekati electrical low-pressure impactor (ELPI) with 0.03–10  $\mu\text{m}$  aerodynamic diameter range, a micro orifice uniform deposit impactor (MOUDI) with 0.1–18  $\mu\text{m}$  aerodynamic diameter range, and a TSI electrical aerosol analyzer (EAA) which counts particles larger than 0.01  $\mu\text{m}$  in aerodynamic diameter. Sanders et al. [16] conducted measurements of airborne wear debris from car brakes with LM, NAO, and SM pads. The tests were conducted on a brake dynamometer in two regimes: in a wind tunnel and driving on a test track. ELPI, MOUDI, and a TSI aerodynamic particle sizer (APS) with 0.5–20  $\mu\text{m}$  aerodynamic diameter range were used for particle measurements. Mosleh et al. [17] performed a pin-on-disc study of wear particles from SM truck brake pad / cast iron disc pairs. They analyzed the particle size distribution using a 0.04–262  $\mu\text{m}$  range laser scattering analyzer (LSA). Schauer et al. [18] reported a study on particle emissions from brake and tire wear. In their tests, the brake dynamometer was installed inside a sealed chamber. The non-exhaust airborne particle concentration was measured by a 0.1–10  $\mu\text{m}$  range TSI DustTrak aerosol monitor 8520 (DustTrak). Iijima et al. [19] investigated abrasion dust from NAO pad / cast iron car brakes on a brake dynamometer. The particle measurements were conducted using a Tokyo Dylec APS at rotor temperatures of 200, 300, and 400 °C. Wahlström et al. [20, 21, 22] conducted a study of airborne particulate matter emissions from LM and NAO car brake materials. A number of tests were done using a pin-on-disc machine and disc brake assembly test stand, as well as by counting particles online in field tests. When conducting tests on the pin-on-disc machine and disc brake assembly test stand, the friction pair was installed inside a sealed chamber. Particles were counted using various instruments such as a 0.01–0.52  $\mu\text{m}$  range TSI scanning mobility particle sizer (SMPS), a 0.02–1  $\mu\text{m}$  range TSI condensation nuclei counter P-Trak, a 0.02–0.3  $\mu\text{m}$  range NanoCheck 1300 sensor, a 0.25–32  $\mu\text{m}$  range GRIMM 1.109 optical aerosol spectrometer, and DustTrak. Another study of LM car brake pad / cast iron disc pairs was performed by Kukutschová et al. [23]. They used a brake dynamometer with the friction pair placed in a sealed chamber. During brake cycles, the rotor of the dynamometer was frictionally heated up to about 330 °C. The particle measurements were conducted using SMPS and TSI APS. Alemani et al. [24] performed a pin-on-disc study of airborne wear particles generated from a LM / cast iron pair by using a Dekati ELPI+ 2E10-10 with 0.006–10  $\mu\text{m}$  aerodynamic diameter range. Nosko et al. [25] investigated particle emissions from LM / cast iron pairs on

a pin-on-disc machine. The tests were done in the regime of acceleration-deceleration at disc temperatures of 20–250 °C. Airborne wear particles were counted by a 0.0056–0.56  $\mu\text{m}$  range TSI fast mobility particle sizer 3091 (FMPS) and 0.3–10  $\mu\text{m}$  range TSI optical particle sizer 3330 (OPS). The studies mentioned above are summarized in Table 1.

Table 1. Overview of studies on airborne particle emissions from car brakes.

| Reference                | Type of study                                                               | Friction materials                                | Particle measurements                                                                                                                                               |
|--------------------------|-----------------------------------------------------------------------------|---------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Garg et al. [15]         | Dynamometer, sealed chamber                                                 | NAO, SM                                           | 0.03–10 $\mu\text{m}$ ELPI;<br>0.1–18 $\mu\text{m}$ MOUDI;<br>>0.01 $\mu\text{m}$ EAA                                                                               |
| Sanders et al. [16]      | Dynamometer, wind tunnel and test track                                     | LM, NAO, SM                                       | 0.03–10 $\mu\text{m}$ ELPI;<br>0.1–18 $\mu\text{m}$ MOUDI;<br>0.5–20 $\mu\text{m}$ TSI APS                                                                          |
| Mosleh et al. [17]       | Pin-on-disc                                                                 | SM                                                | 0.04–262 $\mu\text{m}$ LSA                                                                                                                                          |
| Schauer et al. [18]      | Dynamometer, sealed chamber                                                 | Dodge Caravan minivan brake;<br>Ford Escort brake | 0.1–10 $\mu\text{m}$ DustTrak                                                                                                                                       |
| Iijima et al. [19]       | Dynamometer                                                                 | NAO                                               | 0.5–20 $\mu\text{m}$ APS                                                                                                                                            |
| Wahlström et al. [20–22] | Pin-on-disc, sealed chamber;<br>dynamometer, sealed chamber;<br>field tests | LM, NAO                                           | 0.01–0.52 $\mu\text{m}$ SMPS;<br>0.02–1 $\mu\text{m}$ P-Trak;<br>0.02–0.3 $\mu\text{m}$ NanoCheck;<br>0.1–10 $\mu\text{m}$ DustTrak;<br>0.25–32 $\mu\text{m}$ GRIMM |
| Kukutschová et al. [23]  | Dynamometer, sealed chamber                                                 | LM                                                | 0.01–0.445 $\mu\text{m}$ SMPS;<br>0.5–20 $\mu\text{m}$ TSI APS                                                                                                      |
| Alemani et al. [24]      | Pin-on-disc, sealed chamber                                                 | LM                                                | 0.006–10 $\mu\text{m}$ ELPI+                                                                                                                                        |
| Nosko et al. [25]        | Pin-on-disc, sealed chamber                                                 | LM                                                | 0.0056–0.56 $\mu\text{m}$ FMPS;<br>0.3–10 $\mu\text{m}$ OPS                                                                                                         |
| Perricone et al. [26]    | Dynamometer, sealed chamber                                                 | LM, NAO                                           | 0.006–10 $\mu\text{m}$ ELPI+                                                                                                                                        |

The aim of this study was to investigate the emission of airborne wear particles from friction material / cast iron pairs used in car disc brakes with a special focus on the effect of temperature.

## 2. EXPERIMENTAL EQUIPMENT

### 2.1. Pin-on-Disc Machine

The tests were performed using the pin-on-disc machine depicted in Figure 1. The pin sample **a** is a cylinder with a diameter of 10 mm (cross-section area  $A=78 \text{ mm}^2$ ). A dead weight **b** presses it against a horizontally positioned disc **c** with a force  $N$ . Accordingly, the contact pressure is  $p = N/A$ . The average friction radius is 25 mm. The disc is driven by a motor. The friction force acting on the pin sample is measured by a load cell. The friction coefficient  $\mu$  is calculated as the ratio of the friction force to  $N$ . The temperature  $T$  is measured in the disc by a chromel-alumel thermocouple with sliding electric contact. The hot junction of the thermocouple is installed at a distance of 3 mm from the sliding surface.

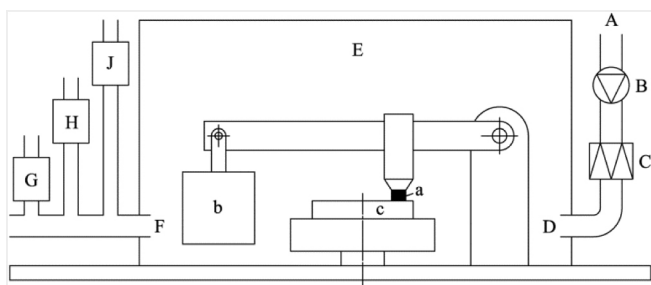


Figure 1. Schematic of the experimental set-up: a pin sample; b dead weight; c disc; A room air; B fan; C filter; D inlet for clean air; E air inside chamber; F outlet for air with airborne wear particles; G FMPS; H OPS; J ELPI+.

## 2.2. Sealed Chamber and Particle Collection

The pin-on-disc machine is located in a sealed chamber to avoid external sources of particles. This experimental set-up was proposed by Olofsson et al. [27]. The room air A is drawn in by a fan B and goes into the chamber via a filter C and inlet opening D. The air flow  $Q$  of 2.2 l/s provides an air exchange rate of about 1.3/min. The filter removes particles from the passing air flow with a certified collection efficiency of 99.95% at the most penetrating particle size. The air E inside the chamber is well mixed due to the high air exchange rate and the complicated shape of the pin-on-disc machine. It absorbs wear particles and transports them to the air outlet F. The air coming out of the chamber is analyzed by FMPS G, OPS H and ELPI+ J. These instruments allow measurement of the concentration  $C$  and distribution of particles with characteristic size  $d$  from 0.0056 to 10  $\mu\text{m}$  (FMPS classifies 0.0056–0.56  $\mu\text{m}$  particles in 32 stages, OPS classifies 0.3–10  $\mu\text{m}$  particles in 16 stages, ELPI+ separates 0.006–10  $\mu\text{m}$  aerodynamic diameter particles in 14 stages). In addition, ELPI+ collects size-classified particles on its filters for chemical analysis. The test data were sampled at a frequency of 1 Hz.

The load cell, thermocouple, FMPS, OPS, and ELPI+ were carefully calibrated. Before each experiment, the pin-on-disc machine and chamber were cleaned, and the whole set-up was tested in the absence of friction. If the particle concentrations measured by FMPS, OPS, and ELPI+ were zero, the experiment was started. Otherwise, the set-up was cleaned again, and the filter C was checked.

## 2.3. Friction Materials

Friction pairs corresponding to those used in passenger car brakes were investigated. The disc was cast iron. Six different materials code-named M1, ..., M6 were used as pin samples. Of these, five (M1, ..., M5) were LM with phenolic resin as a binder and different reinforcements and abrasives. M6 is an NAO. The pin samples and discs were milled from real brake pads and discs. Their sliding surfaces remained unaltered during the milling. The elemental compositions of the materials obtained by the X-ray diffraction technique are presented in Table 2.

Table 2. Elemental compositions of the friction materials (weight %).

| 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  |
| 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 |

## 2.4. Friction Conditions

The tests were conducted under constant friction conditions. The sliding velocity  $v_s$  at the average friction radius was maintained at 1.3 m/s. The contact pressure  $p$  was 0.5, 1, or 1.5 MPa. The test duration was 170 min. Figure 2 presents typical plots of  $\mu$  and  $T$  vs. time for a single test. One can see a transient process during which  $T$  increases from about 20 °C (ambient temperature) to a stationary value  $T_s$  due to frictional heating. The friction coefficient  $\mu$  also tends to some stationary value. The values of  $p$  and  $v_s$  are set so that  $T_s$  covers a temperature range approximately from 100 °C ( $p=0.5$  MPa) to 300 °C ( $p=1.5$  MPa), which is typical for standard tests of brake performance [28].

## 3. RESULTS

The emission rate of airborne wear particles is presented in various dimensions, depending on the friction regime and measurement procedure. The emission rate when testing brakes is usually expressed as particle number per stop (Garg et al. [15]) or particulate matter mass per stop (Sanders et al. [16]). For long-duration sources of airborne particulate matter, the particle emission rate is calculated in terms of the particle number or particulate matter mass per unit sliding distance (Schauer et al. [18]; Olofsson et al. [27]), per unit time (Abbasi et al. [29]), or per unit friction energy (Nosko et al. [25]). This study makes use of the last approach, describing the airborne particle generation by the energy particle emission rate

$$e = \frac{CQ}{\mu N v_s}$$

which is equal to the number of wear particles emitted from the sliding contact and becoming airborne per one Joule of the friction energy.

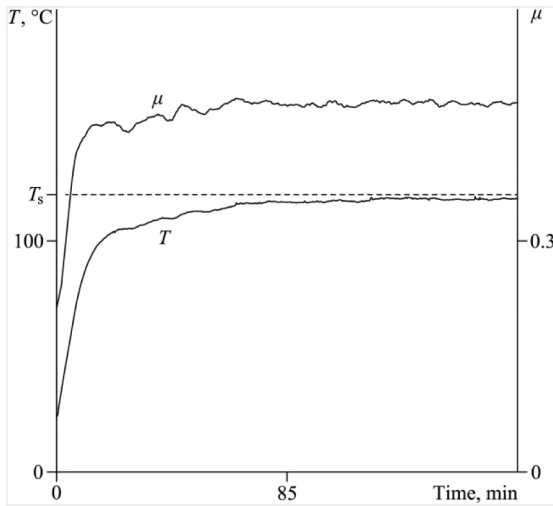


Figure 2. Evolution of the friction coefficient  $\mu$  and temperature  $T$  for the M3/cast iron pair at  $p=0.5$  MPa.

Particles are classified into three types: ultrafine particles with  $d=0.0056-0.1$   $\mu\text{m}$ , fine particles with  $d=0.1-0.56$   $\mu\text{m}$ , and coarse particles with  $d=0.56-10$   $\mu\text{m}$ . The  $0.56$   $\mu\text{m}$  limit between fine and coarse particles coincides with the upper limit of the FMPS measurement range. The energy particle emission rates corresponding to the specified particle types are denoted by  $e_u$ ,  $e_f$ ,  $e_c$ .

### 3.1. Particle Emission Critical Temperature

Figure 3 plots  $e_u$ ,  $e_f$  and  $e_c$  for the M3/cast iron pair at  $p=0.5$  MPa. Note that the particle emission rates are presented using a logarithmic scale. It is seen that  $e_f$  varies between  $10^4$  and  $10^5$  no/J, while  $e_c$  stabilizes at a value near  $10^3$  no/J. Ultrafine particles were not detected during the first 60 minutes. Then their emission rate  $e_u$  increases to a level of  $10^3$  no/J. In contrast, Figure 4 shows the result for the same friction pair obtained at  $p=1.5$  MPa. During the first 20 minutes,  $e_u$  rises dramatically to a level of  $10^8$  no/J. The emission rate  $e_f$  is  $10^4-10^6$  no/J,  $e_c$  varies between  $10^2$  and  $10^3$  no/J.

The dramatic increase in  $e_u$  in Figure 4 can be explained by the increase in the temperature  $T$ . Figure 5 shows the relation between  $T$  and  $e_u$ . At low temperatures,  $e_u$  is independent of  $T$ . When  $T$  reaches a value  $T_u$ , which we call “critical temperature”,  $e_u$  rises stepwise by several orders of magnitude. When  $T$  is above  $T_u$ ,  $e_u$  may change in the course of time, but its magnitude remains several orders larger than that at  $T < T_u$ . It is important to mention that  $p$  and  $v_s$  are constant within a single test and, consequently, the curve  $e_u(T)$  cannot be affected by their variations. Figure 6 illustrates the values of  $T_u$  and  $T_s$  obtained. In the tests with  $p=0.5$  MPa,  $T_s$  is below  $T_u$ , i.e.,  $T$  does not reach  $T_u$ , and the behavior of  $e_u$  is similar to that depicted in Figure 3. At higher pressures,  $T_u$  is reached, and the stepwise increase in  $e_u$  takes place, as shown in Figure 4. For each friction pair, different values of  $T_u$  were obtained at  $p=1$  MPa and  $p=1.5$  MPa. The difference between these two values is less than  $10$  °C. It was found that  $T_u$  is within  $165-190$  °C for all the friction pairs.

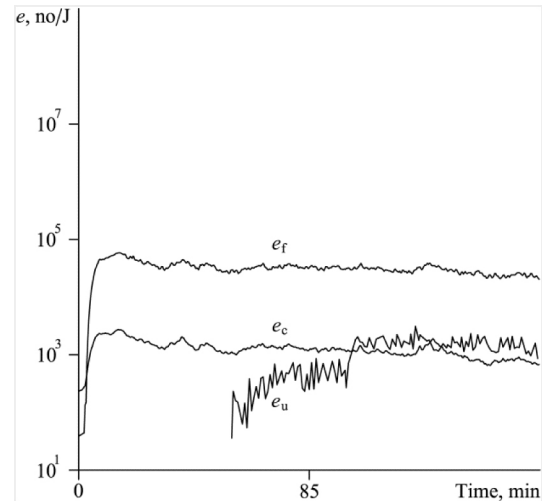


Figure 3. Evolution of the energy particle emission rates  $e_u$ ,  $e_f$  and  $e_c$  for the M3 / cast iron pair at  $p=0.5$  MPa.

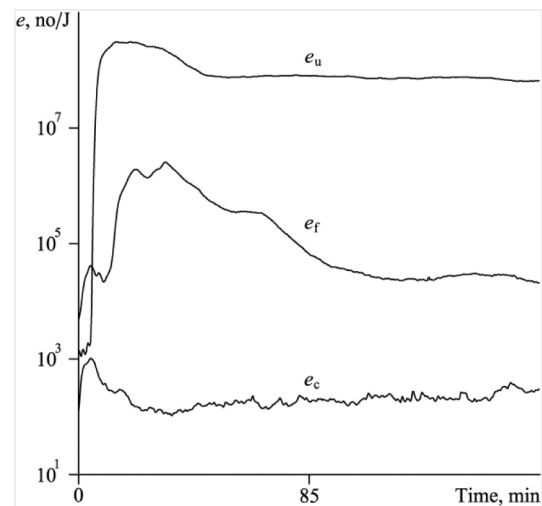


Figure 4. Evolution of the energy particle emission rates  $e_u$ ,  $e_f$  and  $e_c$  for the M3 / cast iron pair at  $p=1.5$  MPa.

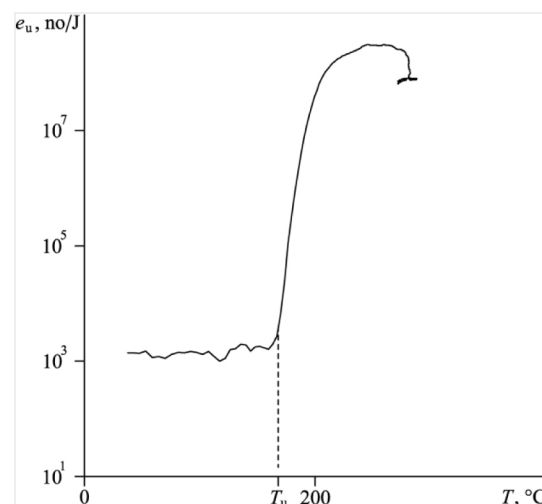


Figure 5. Stepwise change in the energy ultrafine particle emission rate  $e_u$  at the critical temperature  $T = T_u$  (M3 / cast iron,  $p=1.5$  MPa).