보건학석사 학위논문

# Characterization of wear particle emission from automobile brake by operating conditions

# 자동차 브레이크의 제동 조건에 따른 마모 입자의 특성 연구

2020 년 8 월

서울대학교 보건대학원

환경보건학과 산업보건전공

오 영 석

# Characterization of wear particle emission from automobile brake by operating conditions

# 자동차 브레이크의 제동 조건에 따른 마모 입자의 특성 연구

지도교수 윤 충 식

이 논문을 보건학석사 학위논문으로 제출함

2020 년 6 월


서울대학교 보건대학원

환경보건학과 산업보건전공

오 영 석


오 영 석의 보건학석사 학위논문을 인준함

2020 년 7 월

| | | |
|---|---|---|
| 위 원 장 | 이 승 묵 | (인) |
| 부 위 원 장 | 이 기 영 | (인) |
| 위 원 | 윤 충 식 | (인) |

# Abstract

## Characterization of wear particle emission from automobile brake by operating conditions

Youngseok Oh

*Department of Environmental Health Sciences*

*Graduate School of Public Health*

*Seoul National University, Korea*

Advisor Chungsik Yoon, Ph.D., CIH

***Objective*** As interest in air pollutants increases, regulations on pollutants generated in vehicles are also gradually being strengthened. However, research and policies on non-exhaust emissions are insufficient because the focus is mainly on exhaust emissions from internal combustion engines of vehicles. The purpose of this study was to characterize the characteristics of wear particles generated by the brake during braking of vehicles among non-exhaust emissions through experiments.

***Methods*** This study minimized the effects of other pollutants such as exhaust emissions from the vehicle and tire wear dust using a device called a dynamometer that can be tested only with the brake parts of the vehicle. In the chamber of this device, experiments were conducted by adjusting the type of vehicle, the temperature of the disc, the deceleration strength, and the speed of the vehicle. A real-time monitoring device was used to measure particle generation and the chemical composition was determined using ICP-MS after MCE filter sampling.

***Results*** The amount of brake wear particles generated varied depending on the vehicle type, braking strength, disc temperature, and vehicle speed. Particularly, when the speed was reduced by a large difference at a driving speed of 120 km/h, and the temperature of the disc exceeded 200℃, the amount of particles was significantly increased. In addition, as the temperature of the disk increased, the generation amount of fine particles of less than 100 nm increased significantly. The braking, which had the most particle generation, was when two people were on board, decelerating at a speed of 30 km/h from 120 km/h with a braking strength of 0.3 g and a disk temperature of 120℃.

***Conclusions*** In this study, it was confirmed through each independent braking experiment that the difference in the amount of generated brake wear particles could occur depending on the operating conditions of the brake and the driving method of the vehicle. The heavier the weight of the vehicle, the stronger the braking strength, and the higher the temperature of the brakes, the greater the amount of particles generated. Helps to control the amount of brake wear particles generated through administrative measures, such as regulating driving speed, maintaining a gap between vehicles, and traffic volume, as well as driving habits such as reducing unnecessary weight and not taking rapid braking in the vehicle. It seems to be.

**Keywords**: Non-exhaust emissions, brake wear particles, size distribution, nanoparticles

**Student number: 2018-25346**

# Contents

# List of Tables

# List of Figures

# 1. Introduction

As the quality of life increases, airborne particulate matter has become a global concern for what it is, where it comes from, and how to manage it. Particulate matter (PM) has three categorizations according to particle size. Particle sizes smaller than 10 μm, 2.5 μm, 1 μm are called coarse particle ($PM_{10}$), fine particle ($PM_{2.5}$), and ultrafine particle ($PM_1$), respectively. Previous studies have reported to adversely affect the respiratory and cardiovascular systems (WHO 2013.)

The sources of PM of vehicles are largely divided into exhaust and non-exhaust emission. Exhaust emission is generally called engine exhaust, which is mainly caused by combustion. Non-exhaust emission refers to occurring in the form of crushing and wearing rather than combustion, and recently, many studies have been conducted on emission sources such as harmful factors generated by internal combustion engines (Amato et al., 2014; Denier Van der Gon et al., 2013; Pant and Harrison 2013). Moreover, diesel vehicles have known as the main culprit for the generation of $PM_{2.5}$. In addition, related regulations are mainly focused on diesel exhaust emissions.

However, some of studies have reported that the generation for non-exhaust emission sources was also important. Representatively, the German environmental measurement and nature protection research institute (Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg, LUMW) have found to be account for 85% of the fine dust generated on the road, tire wear, brake pad wear, and tire and road wear. According to the results of a study, it is composed of non-emission fine dust such as dust and scattering dust generated by friction (Barlow et al., 2007; Boulter 2006).

When the vehicle is braking, brake wear particles are generated in the brake system due to frictional contact. The composition of the friction material, the braking strength and the cycle affect to the particle emission and composition (Kukutschová et al., 2011). About 50% of the particles worn on the brakes are discharged into the atmosphere, most of which are known to be PM10 and PM2.5. However, there is still insufficient scientific information on what percentage of actual brake wear particles are released into the atmosphere, what typical emission factors and particle size distribution are and how they contribute to the concentration of fine particulate matter (PM10, PM2.5) in the atmosphere. As the relative importance of non-exhaust wear particles has been emphasized due to the recent tightening of regulations on automobile emissions, relevant research on measurement methods, risks, and abatement technologies has been conducted in Europe (LOWBRASYS, REBRAKE project, etc.), Japan (Japan Automobile Research Institute, JARI).

Among the factors to be considered when studying the toxicity of brake dust, particle size and chemical composition are reported to be important. Several epidemiological studies have correlated health effects with specific chemical species such as carbonaceous substances and trace elements in fine dust (Kelly and Fussell 2012). The chemical composition of commercial lining materials varies widely, but nevertheless, most studies have reported that Fe, Cu, Zn and

Pb are the metals mainly detected in brake linings (Kukutschová et al., 2011; Iijima et al., 2008). Heavy metals contained in fine dust are reported to have adverse health effects in various studies (Ostro et al., 2006).

In summary, while many studies have been conducted on exhaust emissions from internal combustion engines of vehicles, information on non-exhaust emissions, including brake emissions, has only recently been conducted, so there is still insufficient information. In the future, if environmentally friendly fuels such as electric vehicles and hydrogen fuel vehicles are used, studies on brake wear dust will have greater significance.

Therefore, the purpose of this study was to analyze the characteristics of brake pad dust that actually occurs during braking of vehicles among non-emission fine dust through experiments.

This study was conducted by varying conditions such as the type of vehicle, the weight loaded on the vehicle, the speed of the vehicle, the strength of deceleration, the temperature at the time of brake operation, etc., and the particle size distribution, water concentration, and particle composition are measured.

# 2. Materials and methods

## 2.1. Operating conditions

In this experiment, by using a brake dynamometer (Brake dynamometer model-3300, Link engineering Company, USA) capable of realizing braking conditions similar to a real vehicle, the effects of tire wear dust, road wear dust, and exhaust emissions generated during the experiment with a real vehicle were excluded. The brake dynamometer used in the test includes a chamber to control wind speed. The outside air flowing into the chamber was used through a filter. Measuring devices for collecting dust generated inside the chamber were connected to the chamber.

There are three types of vehicles used in the experiment: a Sonata (Sonata LF, Hyundai, Korea) set to the weight of two people, a Sonata with the highest weight that the vehicle can load, and a Sorrento (Sorrento UM, Kia, Korea) set to the weight of two people. The actual vehicle is not used, and the function of the dynamometer is employed to realize the weight of each vehicle and the load on the parts when braking. Because the dynamometer can perform experiments with only one wheel, the experiment was conducted with the front wheel that is more loaded when braking (Wahlström 2009). The brakes used were the basic parts provided by each vehicle manufacturer.

Sonata and Sorrento with two passengers were tested with a braking strength of 0.15g and 0.3g, and sonata with the maximum loaded were tested with a braking strength of 0.3g only. In each setting, the condition for starting the operation of the brake is the temperature of the disc, and three conditions of 80°C, 100°C, and 120°C were applied. When braking starts, the temperature of the disc increases, and then gradually starts to drop from the moment the braking ends. After that, when the temperature and the braking start temperature set in the next experiment match, the braking starts.

The driving speed of the vehicle was adjusted to the initial driving speed and the speed after deceleration. When the initial driving speed was 30 km/h, 60 km/h, and 90 km/h, it was set to stop completely until 0 km/h. Under the condition that the initial driving speed is 100 km/h and 120 km/h, the driving speed after deceleration is set to 30 km/h, 60 km/h, and 90 km/h. Brake was applied twice in each of the conditions presented above.

## 2.2. Instrumentation

The devices used to measure the particle size and concentration of the dust generated from the brakes included Electrical Low-Pressure Impactor (ELPI, Dekati, Finland), Optical Particle Sizer (OPS, model 3330, TSI, USA), DustTrak (DRX Aerosol Monitor 8533, TSI, USA), and Portable Aerosol Spectrometer (PAS, model 11-A, Grimm, Germany). The generated particles were measured in real time using these devices. ELPI divides the number size distribution of particles with aerodynamic diameters from 6 nm to 10 μm into 14 stages at 1 second intervals, and measures them at a flow rate of 10 lpm. OPS, DustTrak, and PAS were used at intervals of 1 minute. Using a dusttrak, particles from 0.1 μm to 15 μm were detected through a light scattering sensor to measure a mass of 0.001 mg/m3 to 150 mg/m3. OPS and PAS were used to compare and complement the results. OPS were used to measure the particle concentration and size distribution in the range of 300nm−10 μm. PAS were used to measure PM10 and PM2.5 mass concentrations

For heavy metal analysis, samples are collected by installing a Mixed Cellulose Esters Membrane filter (MCE, diameter 37 mm, pore 0.8 μm, SKC, USA) on a personal sampler (Personal air sampler, Gillian, USA) set at 4.0 ℓ/min. Each individual sampler is measured before and after measurement with a dry flow calibrator (Bios Drycal, Mesa Laboratories, Lakewood, CO, USA) three times each to utilize the average value.

The hose extending from the measuring instrument was connected to the dynamometer chamber and the sampling point was located between the brake and the air outlet.

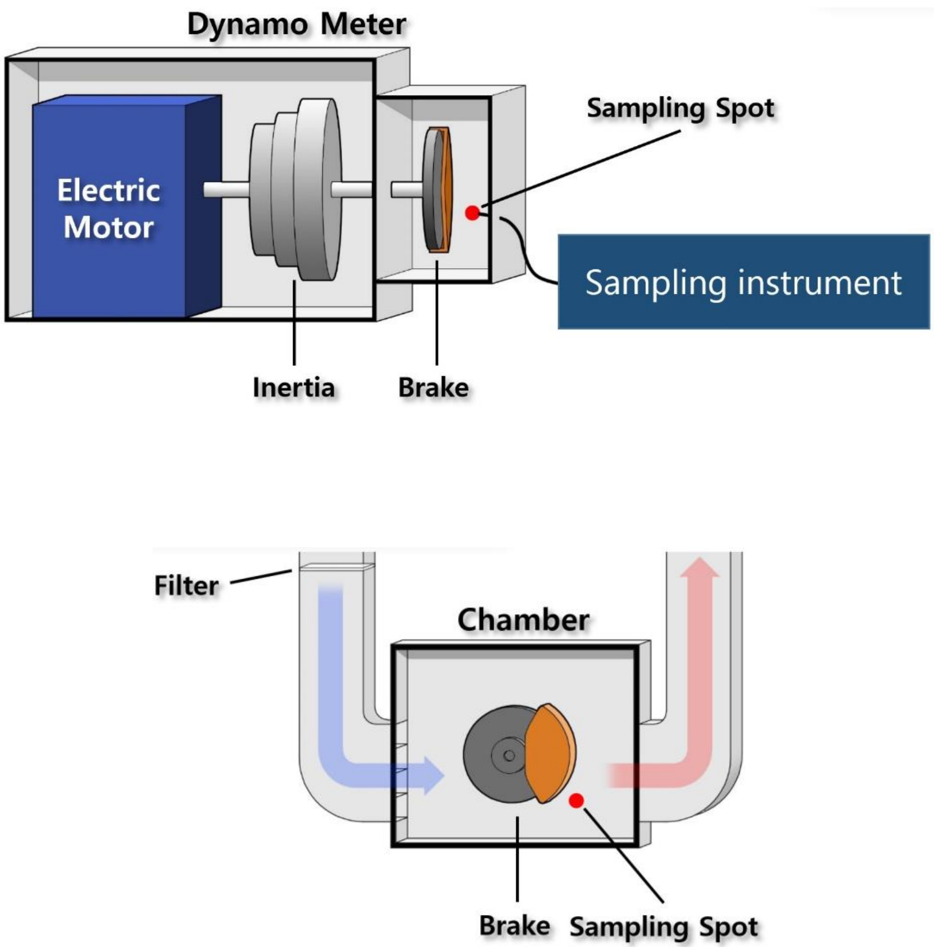


**Figure 1.** Conceptual diagrams of the cross section of a brake dynamometer.

**Table 1.** The conditions of vehicle type and brake setting.

| Vehicle type | Strength of deceleration (g) | Starting disk temperature (℃) |
|---|---|---|
| Sonata with 2 passengers | 0.15 | 80 |
| | | 100 |
| | | 120 |
| | 0.30 | 80 |
| | | 100 |
| | | 120 |
| Maximum loaded Sonata | 0.30 | 80 |
| | | 100 |
| | | 120 |
| Sorrento with 2 passengers | 0.15 | 80 |
| | | 100 |
| | | 120 |
| | 0.30 | 80 |
| | | 100 |
| | | 120 |

**Table 2.** The conditions of driving speed at the before and after deceleration.

| Initial driving speed (km/h) | Decelerated driving speed (km/h) |
|---|---|
| 30 | 0 |
| 60 | 0 |
| 90 | 0 |
| 100 | 30 |
| 100 | 60 |
| 100 | 90 |
| 120 | 30 |
| 120 | 60 |
| 120 | 90 |

## 2.3. Chemical analyses

An Inductively Coupled Plasma mass spectrometer (ICP-MS, Model NexION 350D, PerkinElmer Inc., Houston, TX, USA) was used to determine the chemical composition of dust generated in the brake.

ICP-MS analysis was used to detect the presence of target elements, such as barium (Ba) and iron (Fe). To remove the organic matrices, the aqua regia solution in combination with hydrochloric acid and nitric acid at a ratio of three to one was added to each vessel, and then, the total volume was adjusted to 5 mL. All samples were digested using a microwave digestion device (Model MARS 6 230/60, CEM Corp.), and the initial temperature was set to 60°C for 20 minutes, followed by heating at 30°C with a ramp time of 20 minutes to 210°C for final holding time of 20 minutes. The inner pressure of each vessel was also kept <500 psi. The digested samples were finally diluted to 40 mL in a volumetric flask with distilled water and then analyzed using an ICP. The quantification was conducted using calibration curves from multi-element standard solutions including the metallic ingredients, that is, Ba, Fe, silver (Ag), aluminum (Al), chromium (Cr), manganese (Mn), nickel (Ni), copper (Cu), zinc (Zn), lead (Pb), and magnesium (Mg) (Multi-element Calibration Standard 3, N9301720, PerkinElmer Inc). The limit of detection (LOD) of each element was estimated from the threefold deviation of seven replicates at the lowest concentration (0.1 ppb).

## 2.4. Data analysis

Statistical analysis was performed on data obtained from real-time monitoring. Descriptive statistics were used to compare the concentration levels of brake dust for each condition. The Shapiro-Wilk test indicates that the data follow a lognormal distribution, so we used log transform data for statistical analysis. The geometric mean (GM) and geometric standard deviation (GSD) for metrics such as particle number and mass were derived.

# 3. Results

## 3.1. Brake wear particle generation according to disc temperature

Braking was performed twice as conditions changed, and **Figure 2** is an example. Between braking and braking, the heated brake was cooled and needed time to reach the temperature for the next experiment, so the concentration of brake wear particles that naturally rose during braking was lowered to the background concentration level before the next braking.

The disc temperature at the beginning of braking was set constant, but the disc temperature at the completion of braking showed a large difference according to each experimental condition. **Figure 3** shows the concentration of particles generated during a single braking of Sorrento decelerating from 120 km/h to 30 km/h. In **Figure 3(a)**, 0.15g braking strength was applied, and when braking was set to 80℃, the temperature increased to 152.2℃, 100℃ to 176.3℃, and 120℃ to 202.15℃. **Figure 3(b)** shows the result when the braking strength of 0.3g is applied. When the disc temperature started at 80℃, the temperature rose to 176.2℃, 100℃ to 202.3℃, and 120℃ to 228.5℃.

The stronger the braking strength, the greater the temperature of the disc, and the higher the temperature during braking of the disc, the more particles are released. In addition, the particle emission amount in Figure 3 **(b)**, which has a large increase in temperature, was higher than that in Figure 3 **(a)**, where the temperature increase was relatively small.

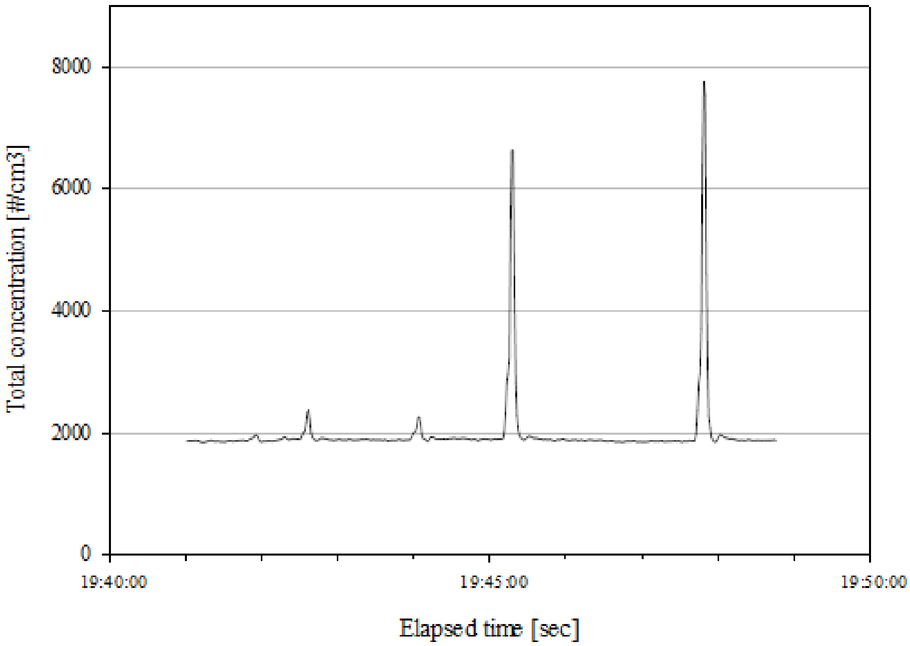


**Figure 2.** An example of time series profile of brake wear particle release.

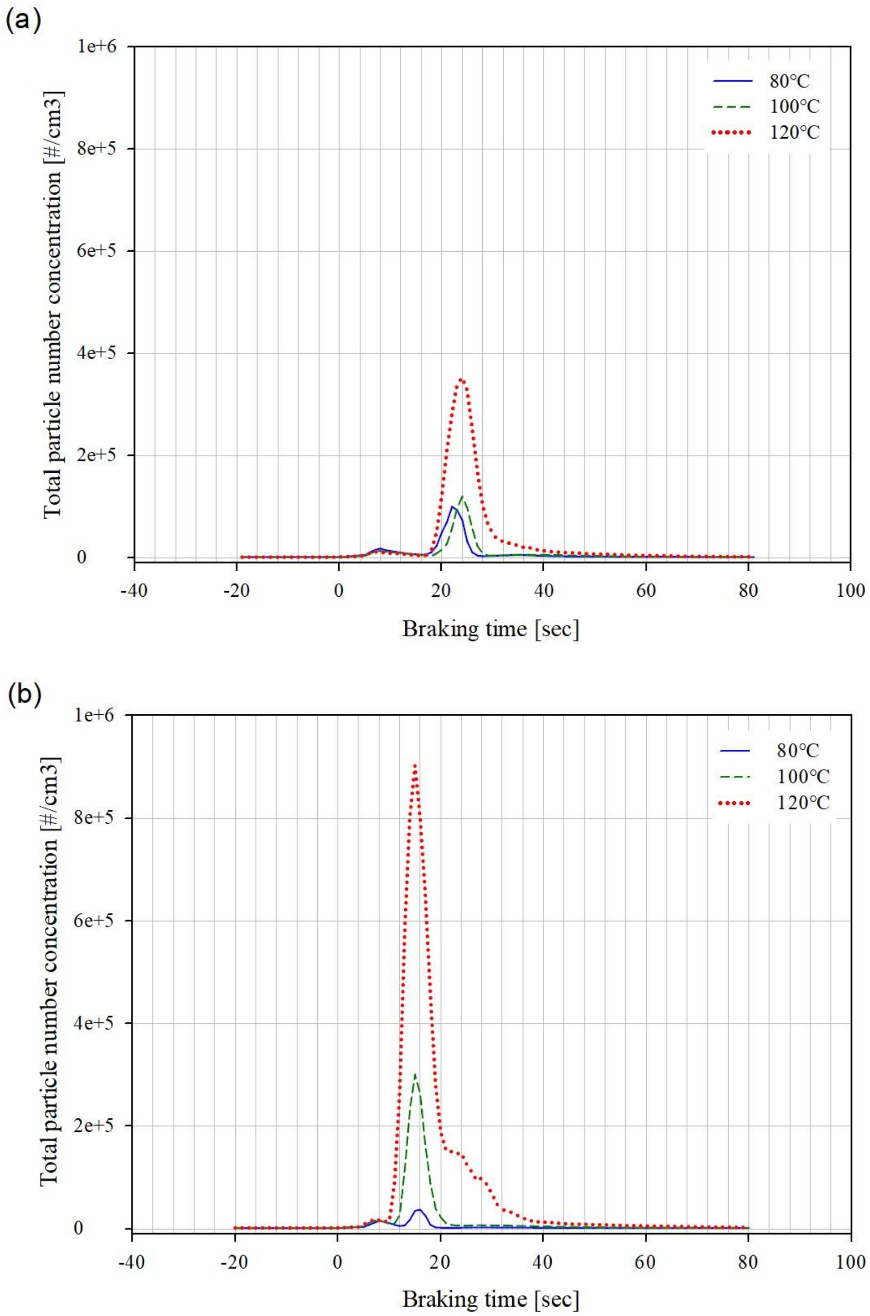


**Figure 3.** Comparison of brake wear particle concentration according to disk temperature conditions of Sorrento with two passengers. Deceleration setting from 120km/h to 30km/h. The braking strength was set to 0.15 g (a) and 0.3 g

(b).

## 3.2. Brake wear particles generation according to vehicle type

Differences in brake wear particle emissions were also observed depending on the type of vehicle. **Figure 4** shows the braking when the disc temperature is 120℃ with a braking strength of 0.3g from 120km/h to 30km/h, and only the vehicle type is changed under the same conditions. The heavier the vehicle weight, the more brake wear particle emissions were observed. In this case, the temperature of the disk reached at the end of braking was similar to 235.7℃ for a sonata with two persons, 237.6℃ for a sonata with the maximum load, and 228.5℃ for a Sorrento with two persons.

**Figure 5** shows the total braking from 60 km/h to 0 km/h, the brake wear particle generation by vehicle type under the condition that the amount of particles generated is 0.3 g and the disk temperature is 80℃. The difference in particle generation between vehicle types was significantly less than in **Figure 4**. The temperature of the disc reached at the end of braking for each vehicle was 111.6℃ for a sonata with two people, 112.0℃ for a sonata with the maximum load, and 103.4℃ for a Sorrento with two people.

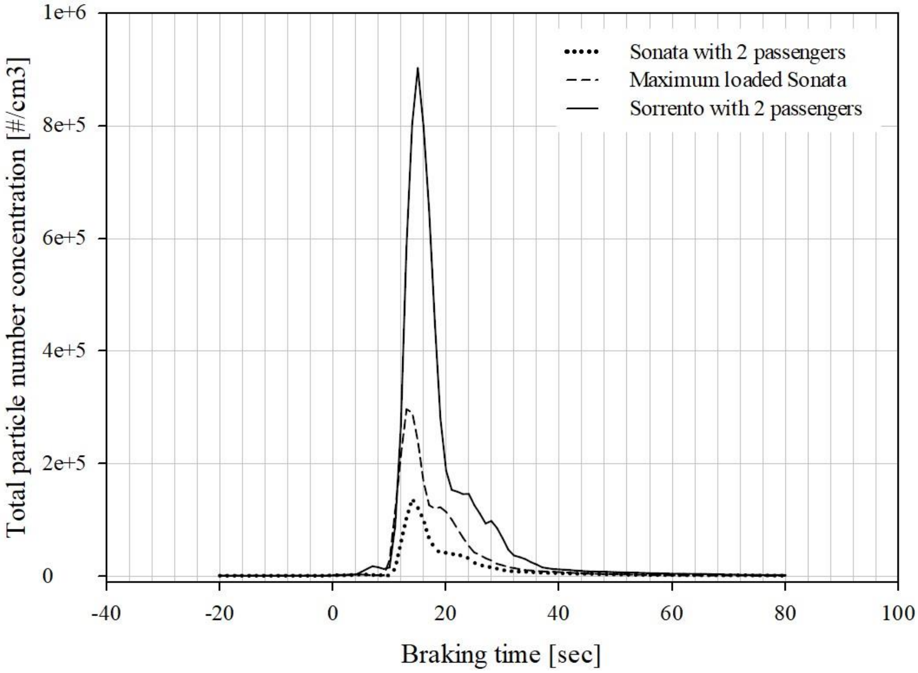


**Figure 4.** Comparison of brake wear particle concentration according to Vehicle type. Deceleration setting from 120km/h to 30km/h. The braking strength was set to 0.3 g. The disk temperature was set at 120℃.

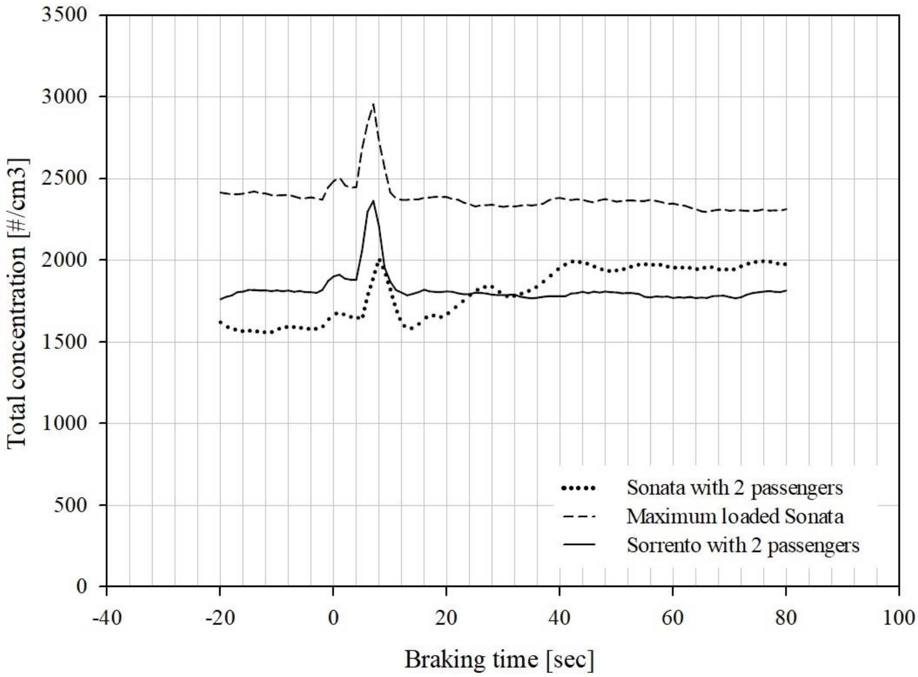


**Figure 5.** Comparison of brake wear particle concentration according to Vehicle type. Deceleration setting from 60km/h to 0km/h. The braking strength was set to 0.3 g. The disk temperature was set at 80℃.

## 3.3. Changes in the characteristics of brake wear particles generation during a single braking

When braking starts, brake dust continues to be generated until it is over (**Fig. 5**). At this time, the size distribution of particles generated as the braking time elapses changes. In the early stage of braking, particles with a size of about 1 um are mainly generated, whereas as the braking time increases, the incidence of particles of less than 100 nm increases significantly.

**Figure 6** shows the particle size distribution at a specific moment during braking, and **Figure 7** shows the entire process of one braking. At the beginning of braking, particles over 100nm are generated in the first 10 seconds, and after 10 seconds, the emission of particles increases in the total particle size. Particles below 100nm begin to be produced from this point. In both pictures, the two-person Sorrento decelerated from 120 km/h to 30 km/h, braking at a disc temperature of 120℃ with a braking strength of 0.3 g.

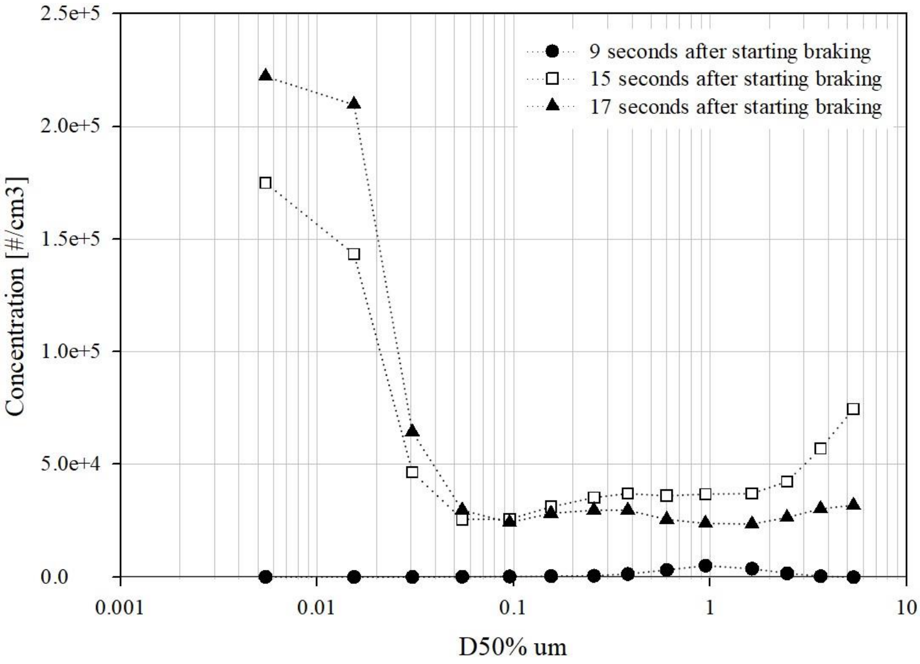


**Figure 6.** Distribution of particle number density of airborne brake wear particles over time during braking

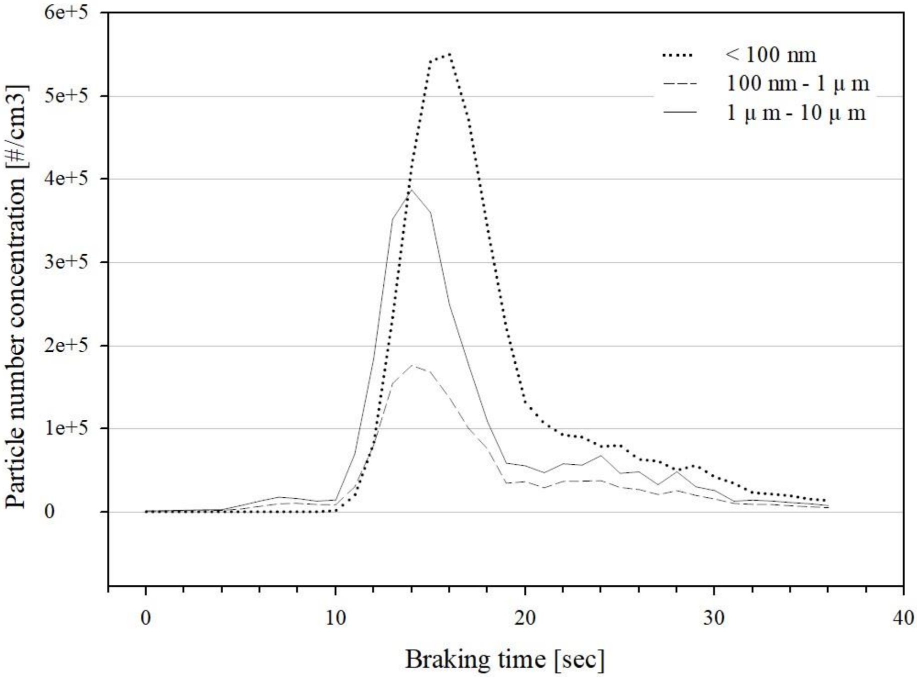


**Figure 7.** Brake wear particle concentration during braking by particle size.

## 3.4. Difference in emission of brake wear particles according to vehicle speed

**Figure 8** compares the amount of brake dust generated according to temperature and vehicle speed with the Sorrento 0.3g braking strength of two people.. As the initial driving speed increased, the difference in particle generation according to the disk temperature condition increased, and the largest particle emission was observed in the deceleration condition from 120 km/h to 30 km/h, which decelerated to the greatest extent at the fastest initial driving speed.

The difference in particle emissions according to the braking conditions is shown in **Figure 9**. The experiment was conducted under the condition of a disk temperature of 120℃ in Sorrento, where two people boarded. Particle emissions increased at high initial speeds, and differences between braking conditions also occurred.

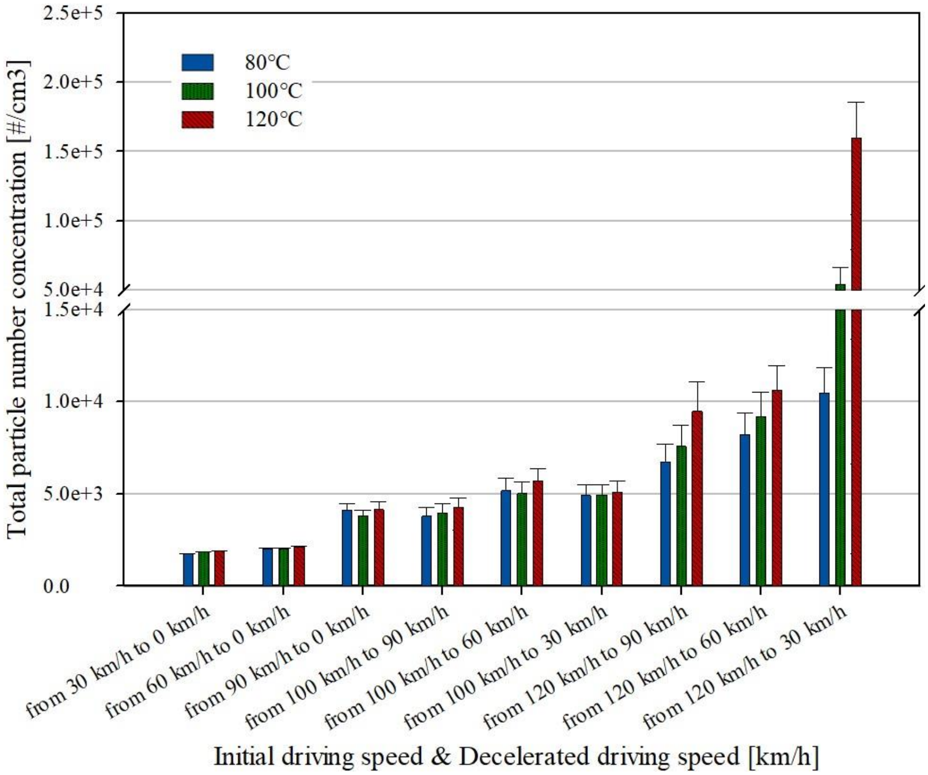


**Figure 8.** Comparison of the amount of brake wear particle concentration according to the disc temperature and driving speed.

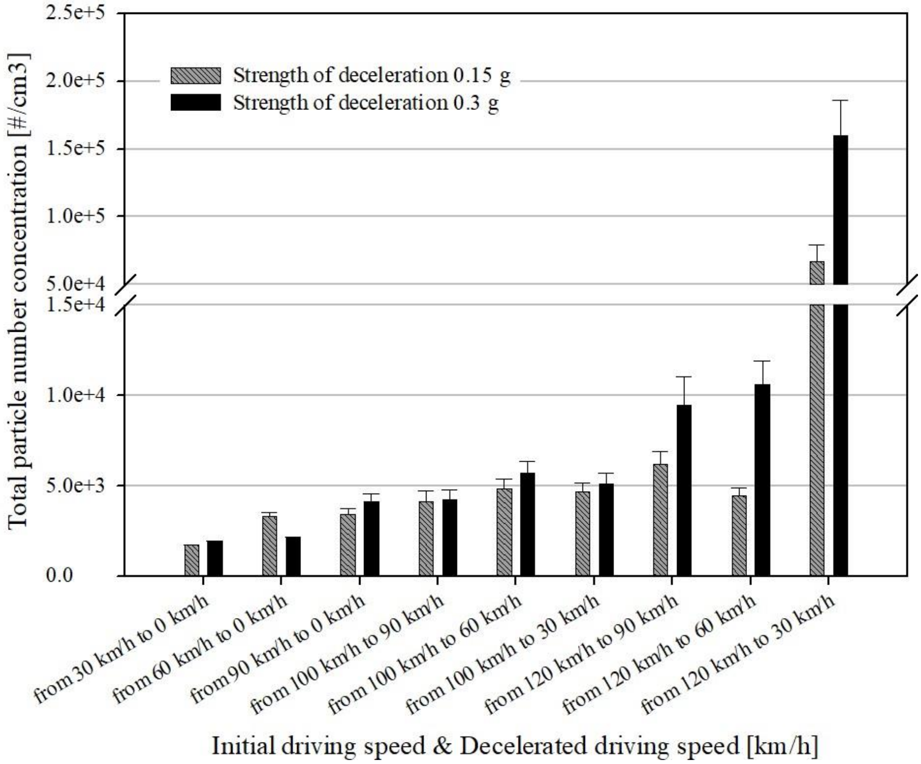


**Figure 9.** Comparison of the amount of brake wear particle concentration according to the vehicle's braking strength and driving speed.

**Figure 10** was tested at a disc temperature of 120℃ at a braking condition of 0.3g, with different vehicle types and driving speeds. At low driving speeds, there was case in which the particle number concentration in Sorrento carrying two people was smaller, but the highest particle emission amount was observed when the vehicle's driving speed exceeded 90 km/h. When the vehicle's initial driving speed exceeded 120 km/h, the emission of particles was noticeably increased in Sorrento, while the sonatas with two passengers and the maximum loaded sonata did not. When the Sonata braked from 120 km/h to 30 km/h, with the greatest width at the fastest driving speed, the emission of particles increased significantly.

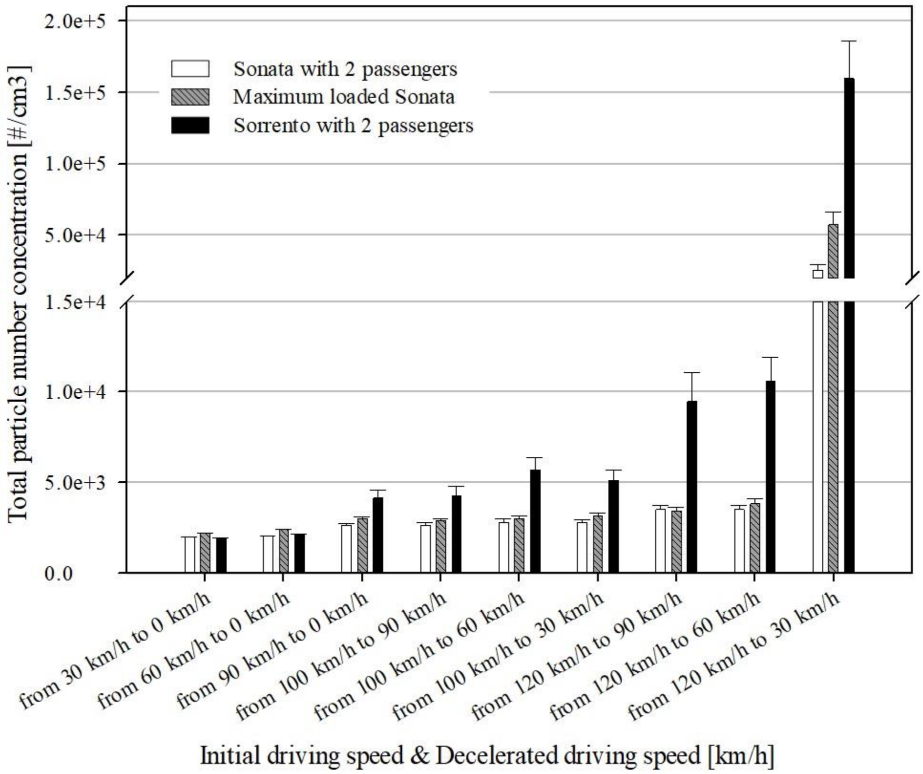


**Figure 10.** Comparison of brake wear particle concentration according to vehicle type and driving speed.

## 3.5. Chemical characterization of brake wear particles

**Table 3** summarizes the elements detected in the brake wear particles during two experimental conditions; one with Sonata's entire experimental process with two passengers, and other with Sorrento's entire experimental process with two passengers. Each sample is expected to contain abrasive particles from the brake pads and disc. The difference between the two Sonata and Sorrento experiments was noticeable in Mg, Al, Fe, and Ba. In Sonata, Fe accounted for 69.58%, a very high percentage of the total. In Sorrento, the proportions of Mg, Al, and Ba were significantly higher than those of Sonata, and Fe was less.

**Table 3.** Elemental Concentrations in Abrasion Dusts Originating from Pads.

| | Content (wt. %) | |
|---|---|---|
| Element | Sonata with 2 passengers | Sorrento with 2 passengers |
| Mg | 1.8509 | 13.2883 |
| Al | 10.3979 | 21.6548 |
| Fe | 69.5882 | 35.4460 |
| Cr | 0.6460 | 0.3523 |
| Mn | 0.1739 | 0.1432 |
| Ni | 0.1166 | 0.1560 |
| Cu | 2.6804 | 3.3759 |
| Ba | 11.3126 | 20.8655 |
| Pb | 0.1212 | 0.1149 |

# 4. Discussion

This study evaluated the wear particles generated from the vehicle's brakes under different braking conditions. To avoid the effects of exhaust emissions, a dynamometer was used, and changes in the characteristics of the particles generated by controlling the type of vehicle, braking strength, disc temperature, and driving speed of the vehicle were observed.

Previous studies on the particles generated by the brakes have been carried out in various ways. In some cases, a dynamometer was used as in this study. but in some cases, it was conducted in a laboratory using an actual vehicle. In addition, studies have been conducted to evaluate both exhaust and non-exhaust emissions on real roads. In the case of using a real vehicle, in addition to the brakes, exhaust emissions from the vehicle, tire wear and dust can affect the measured results (Beji et al., 2020). Since the dynamometer used in this study is a device that can perform experiments with only the disc and pad used for the brake, it was an appropriate environment to study the dust generated in the brake.

In the previous study, the profile for operating the brakes was varied, but when using what was used in other vehicle studies, it has the advantage of setting conditions similar to the actual driving of the vehicle (Beji et al., 2020). There was also a method of evaluating the entire section after repeatedly performing braking under one experimental condition, which has the advantage of comprehensively evaluating particles generated from when the disk temperature is low to high (Kukutschová et al., 2011). However, in the above studies, there was a limit to independently evaluate only the brake dust generated from a single braking. Therefore, in this study, the experiment was conducted by constructing a new profile to minimize the impact between each braking and to facilitate evaluation by condition.

Real-time monitoring and filter sampling were performed to evaluate the dust generated from the operation of the brake. Information about particle size and number concentration generated through real-time monitoring was collected, and chemical composition was analyzed using an MCE filter.

The chemical composition of brake wear particles in Sonata and Sorrento was very different. As the current manufacturer does not provide information on vehicle parts, it is necessary to analyze the bulk component of the brake parts. When comparing Sonata and Sorrento, the difference in the amount of particles generated was large, so the conditions under which the particles were produced seemed to be quite different, but it is reasonable to assume that the chemical composition was due to the difference in the components of the parts.

There are some limitations in this study. First, the performance of the filter attached in front of dyanmometer that sieves the outside air entering the chamber is poor, so the effect of dust flowing in from the outside air cannot be completely excluded. Second, since all the dust generated during the brake operation was not collected, but the ventilation system with a constant flow rate was operated, there is a possibility that there is a deviation in the dust collected in the sampling device depending on the particle size, weight, and behavior characteristics. Lastly, unlike the previous study, this study had a small number of total braking, and because of this, filter sampling was conducted in a large framework of vehicle types, not according to detailed conditions. Therefore, additional research is needed on the chemical composition of brake dust that varies under conditions other than the type of vehicle.

# 5. Conclusion

In this study, it was confirmed through each independent braking experiment that the difference in the amount of brake generated may occur depending on the driving method of the vehicle. This result was ruled out using a brake dynamometer chamber to exclude the effects of exhaust emissions.

The heavier the weight of the vehicle, the stronger the braking strength, and the higher the temperature of the brakes, the greater the amount of particles generated. The faster the vehicle traveled and the greater the degree of deceleration, the more particles were generated. When the temperature of the brake exceeds a certain threshold, the occurrence of particles smaller than 100 nm has increased significantly.

Regarding the driving method, it is thought that reducing unnecessary weight in the vehicle and not applying strong braking will help reduce the amount of brake wear dust. In addition, administrative regulations such as the speed of the vehicle, the distance between the vehicles, and the amount of traffic can be one way to control the amount of dust generated by the brakes.

# References

A. Beji, K. Deboudtb, S. Khardia, B. Muresana, P. Flamentb, M. Fourmentinb ,L. Lumièrea 2020. Non-exhaust particle emissions under various driving conditions : Implications for sustainable mobility. Transportation Research Part D: Transport and Environment, 81, 102290, ISSN 1361-9209,

Amato F, Cassee FR, Denier Van der Gon H, Gehrig R, Gustafsson M, Hafner W, Harrison R, Jozwicka M, Kelly F, Moreno T, Prevot ASH, Schaap M, Sunyer J, Querol X 2014. Urban air quality: the challenge of traffic non-exhaust emissions. J Hazard Mater 275:31–36

Barlow TJ, Boulter PG, McCrae IS, Sivell P, Harrison RM, Carruthers D, Stocker J 2007. Non-exhaust particulate matter emissions from road traffic: summary report. TRL report for DEFRA. Scottish Executive. Welsh Assembly Government. DoENI

Boulter PG 2006. A review of emission factors and models for road vehicle non-exhaust particulate matter. TRL report PPR065. TRL Limited, Wokingham

Denier Van der Gon H, Gerlofs-Nijland M, Gehrig R, Gustafsson M, Janssen N, Harrison R, Hulskotte J, Johansson C, Jozwicka M, Keuken M, Krijgsheld K, Ntziachristos L, Riediker M, Cassee F 2013. The policy relevance of wear emissions from road transport, now and in the future—an international workshop report and consensus statement. J Air Waste Manag Assoc 63:136–149

Iijima A, Sato K, Yano K, Kato M, Tago H, Kato M, Kimura H, Furuta N. 2007. Particle size and composition distribution analysis of automotive brake abrasion dusts for the evaluation of antimony sources of airborne particulate matter. Atmos Environ 41:4908–4919

Kelly FJ, Fussell JC. 2012. Size, source and chemical composition as determinants of toxicity attributable to ambient particulate matter. Atmos Environ 60:504–526

Kukutschová J, Moravec P, Tomášek V, Matějka V, Smolík J, Schwarz J, Seidlerová J, Šafářová K, Filip P. 2011. On airborne nano/microsized wear particles released from low-metallic automotive brakes. Environ Pollut 159:998−1006

Ostro B, Feng WY, Broadwin R, Green S, Lipsett M. 2007. The effects of components of fine particulate air pollution on mortality in California: results from CALFINE. Environ Health Perspect 115:13−19

Pant P, Harrison RM 2013. Estimation of the contribution of road traffic emissions to particulate matter concentrations from field measurements: a review. Atmos Environ 77:78–97

Wahlström J 2009. Towards a simulation methodology for prediction of airborne wear particles from disc brakes: licentiate thesis. Department of Machine Design Royal Institute of Technology, Stockholm, ISBN 978-91-7415-391-0

WHO (World Health Organization) 2013. Health effects of particulate matter. Policy implications for countries in eastern Europe, Caucasus and central Asia

# 국문초록

## 자동차 브레이크의 제동 조건에 따른 마모 입자의 특성 연구

오 영 석

서울대학교 보건대학원

환경보건학과 산업보건전공

지도교수 윤 충 식

**연구배경:** 대기오염물질에 관한 관심이 증가하면서 차량에서 발생하는 오염물질에 관한 규제도 점차 강화되고 있다. 그러나 차량의 내연기관에서 발생하는 배기 배출물에 그 초점이 주로 맞추어져 있어 비배기 배출물에 대한 연구와 정책은 부족한 실정이다. 본 연구의 목적은 비배기 배출물 중 차량의 제동 시 브레이크에서 발생하는 마모 입자의 특성을 실험을 통해 파악하는 것이다.

**연구방법:** 본 연구는 차량의 브레이크 부품만을 가지고 실험이 가능한 다이나모미터라는 장치를 이용해 차량에서 배출되는 배기 배출물, 타이어 마모 분진 등의 기타 오염원의 영향을 최소화하였다. 이

장치의 챔버에서 차량의 종류, 디스크의 온도, 감속 강도 그리고 차량의 속력을 조절하여 실험을 진행하였다. 입자 발생을 측정하기 위해 실시간 모니터링 기기를 사용했으며 MCE필터를 이용해 화학 조성을 파악하였다.

**결과:** 차량의 종류, 제동 강도, 디스크 온도 그리고 차량의 주행 속도에 따라서 브레이크 마모 입자의 발생량의 차이가 발생했다. 특히 주행 속도가 120km/h인 상태에서 큰 차이로 감속을 했을 때와 디스크의 온도가 200℃를 넘겼을 때 입자 발생량이 두드러지게 높아졌다. 또한 디스크의 온도가 높아질수록 100nm 미만의 미세한 입자의 발생량이 크게 증가했다. 가장 입자의 발생량이 많았던 제동은 2인이 탑승한 쏘렌토, 0.3g의 제동 강도, 120℃의 디스크 온도로 120km/h에서 30km/h의 속도로 감속한 경우였다.

**결론:** 이 연구에서는 브레이크의 작동 조건, 차량의 주행 방식에 따라 브레이크 마모 입자의 발생량의 차이가 생길 수 있음을 각각의 독립적인 제동 실험을 통해 확인하였다. 차량의 무게가 무거울수록, 제동 강도가 강할수록 그리고 브레이크의 온도가 높을수록 발생하는 입자의 양이 증가했다. 차량에서 불필요한 무게를 줄이고 급제동을 차지 않는 등 운전 습관 차원에서, 그리고 차량의 주행 속도, 차량 간의 간격 유지, 교통량의 조절 등 행정적인 조치, 규제를 통해서 브레이크 마모 입자의 발생량을 조절하는 데에 도움이 될 것으로 보인다.

**주요어**: 비배기 배출물, 브레이크 마모 입자, 크기 분포, 나노 입자
**학번**: 2018-25346