

# Brake and tire particles measured from on-road vehicles: Effects of vehicle mass and braking intensity

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## ABSTRACT

Vehicle exhaust emissions have been decreasing due to stricter regulations and advancements in control strategies. However, non-exhaust emissions from brake and tire wear have not been extensively regulated in the past, and their relative contribution to particulate matter (PM) in urban areas is increasing. We examined the effect of a vehicle's mass and braking intensity on brake and tire particles based on on-road data collected from three different types of vehicles under real-world driving conditions. PM<sub>2.5</sub> and PM<sub>10</sub> concentrations and particle size distributions were measured near the center and rear of the right front wheel, respectively. During the braking, the highest peaks in brake PM<sub>2.5</sub> (520–4280 µg/m<sup>3</sup>) and PM<sub>10</sub> (950–8420 µg/m<sup>3</sup>) concentrations were observed from the heaviest vehicle, while the lowest peaks in brake PM<sub>2.5</sub> (250–2440 µg/m<sup>3</sup>) and PM<sub>10</sub> (430–3890 µg/m<sup>3</sup>) concentrations were observed from the lightest vehicle. Similarly, the observed peaks in tire PM<sub>2.5</sub> (340–4750 µg/m<sup>3</sup>) and PM<sub>10</sub> (810–8290 µg/m<sup>3</sup>) concentrations of the heaviest vehicle were shown to be the highest among the test vehicles, while the peaks in tire PM<sub>2.5</sub> (220–2150 µg/m<sup>3</sup>) and PM<sub>10</sub> (370–3840 µg/m<sup>3</sup>) concentrations of the lightest vehicle were lower than other vehicles. A statistically significant difference in the peak values of PM<sub>2.5</sub> and PM<sub>10</sub> concentrations was observed between the heaviest and lightest vehicles for both brake and tire particles. The braking deceleration rate was found to be an important factor in predicting the peaks in PM<sub>2.5</sub> and PM<sub>10</sub> concentrations during major braking events for all three test vehicles. Brake particles showed a unimodal mass size distribution with a mode diameter of 3–4 µm, while tire particles showed a slightly larger mode diameter of 4–5 µm. The finding of this study provides insight into the effects of driving conditions and vehicle mass on brake and tire emissions.

## 1. Introduction

During the past decades, remarkable efforts have been made to reduce vehicle exhaust emissions, which are one of the major sources of particulate matter (PM) in urban environments. These efforts were based on a large body of research that has been focused on exhaust emissions such as particle size distribution, spatiotemporal distribution, and associated health effects (Beelen et al., 2008; Wang et al., 2016; Zhu et al., 2006). As a result, governments have gradually increased regulations to reduce exhaust emissions. In contrast, non-exhaust emission sources, including brake and tire wear, have not been investigated comprehensively, and therefore, have not been extensively regulated.

It has been shown that the contribution of the non-exhaust emission sources to PM<sub>10</sub> (PM with aerodynamic diameters less than or equal to 10 µm) is at a comparable level to the exhaust emissions (Bukowiecki et al., 2010). Moreover, the contribution of non-exhaust emission

sources to PM<sub>2.5</sub> (PM with aerodynamic diameters less than or equal to 2.5 µm) has increased in recent years, while exhaust emissions have been continuously decreasing (Jeong et al., 2020). Given a predicted increase in the sales of electric and hybrid vehicles with low or zero exhaust emissions in the future (Axsen and Wolinetz, 2018), non-exhaust sources are likely to become more important worldwide (Rexeis and Hausberger, 2009).

The key contributors to non-exhaust PM are road dust and brake and tire wear, with minor contributions from the clutch and engine dust (Pant and Harrison, 2013). The contribution of brake wear particles to non-exhaust PM<sub>10</sub> varies depending on the sampling location and measurement method. Previous studies have shown that brake wear particles could contribute to 55 % of non-exhaust PM<sub>10</sub> in areas with high braking frequency (Harrison et al., 2012). It has been shown that the contribution of brake wear particles to PM<sub>2.5</sub> at highways is approximately three times higher than the downtown sampling location

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(Jeong et al., 2019). In addition, the contribution of brake wear particles to  $PM_{2.5}$  has been reported to increase during morning rush hours as a result of congested traffic condition. Brake wear particles have been found in ultrafine, fine, and coarse size ranges (Garg et al., 2000; Kwak et al., 2013; Sanders et al., 2003). More recently, brake wear particles have been reported in the nanometer size range (Farwick zum Hagen et al., 2019a; Liati et al., 2019; Puisney et al., 2018). A few factors, such as the driving style and braking intensity (Kwak et al., 2013), brake temperature (Gramstat et al., 2020; Kukutschová et al., 2011), and maintenance condition of the brakes (Grigoratos and Martini, 2015), have been reported to affect brake wear emissions.

On the other hand, fewer studies have focused on investigating tire wear emissions. Previous studies have shown that tire wear particles could contribute to 11% of total  $PM_{10}$  (Baensch-Baltruschat et al., 2020). While tire wear particles were mostly reported in the coarse size range (Gustafsson et al., 2008; Mathissen et al., 2011; Sommer et al., 2018), ultrafine particles have been observed in a few studies (Kim and Lee, 2018; Kumar et al., 2013), which are presumably generated during the evaporation and condensation processes of volatile tire compounds (Baensch-Baltruschat et al., 2020). The physical and chemical characteristics of the tire wear particles were shown to be a function of road features (Gustafsson et al., 2008), tire characteristics (Gustafsson and Eriksson, 2015), driving conditions and inertia load (Kim and Lee, 2018) based on different experimental setups.

A number of methods have been used for the measurement of brake and tire wear particles. Aside from the studies based on source apportionment, a large number of the previous studies on brake and tire wear emissions were performed in laboratory settings. Brake dynamometers were used for measuring brake wear particles where the brake pads were tested under different conditions inside a chamber without being attached

to any vehicle (Garg et al., 2000; Iijima et al., 2008; Kukutschová et al., 2011). Moreover, road simulator systems have been used for modeling the interaction between the road surface and tire, and studying tire wear particles under different road conditions (Gustafsson et al., 2008; Gustafsson and Eriksson, 2015). While laboratory measurements provide consistency across different tests, they cannot adequately represent real-world driving conditions. A few studies have been carried out on brake and tire wear emissions using on-road sampling (Farwick zum Hagen et al., 2019a; Kwak et al., 2013; Mathissen et al., 2011; Pirjola et al., 2010; Sanders et al., 2003). While these previous studies have discovered valuable information on the brake and tire wear particles, each study only focused on one vehicle, thus could not address the differences of brake and tire wear emissions across different vehicles.

In this study, we measured the brake and tire mass concentrations and size distributions from three test vehicles under real-world driving and braking conditions and investigated the effects of the vehicle mass and braking intensity on the brake and tire particles. To the best of our knowledge, this is the first study to investigate the effect of these factors on brake and tire particles using on-road measurements.

## 2. Methods

### 2.1. Experimental design

A schematic of the sampling system is provided in Fig. 1. The brake and tire particles were sampled from the right front wheel of the test vehicles. This is because during the braking event, the weight of the vehicle shifts forward; therefore, the front wheels experience more friction (Grigoratos and Martini, 2015). Three sampling inlets were installed near the brake and tire of the right front wheel as well as on the

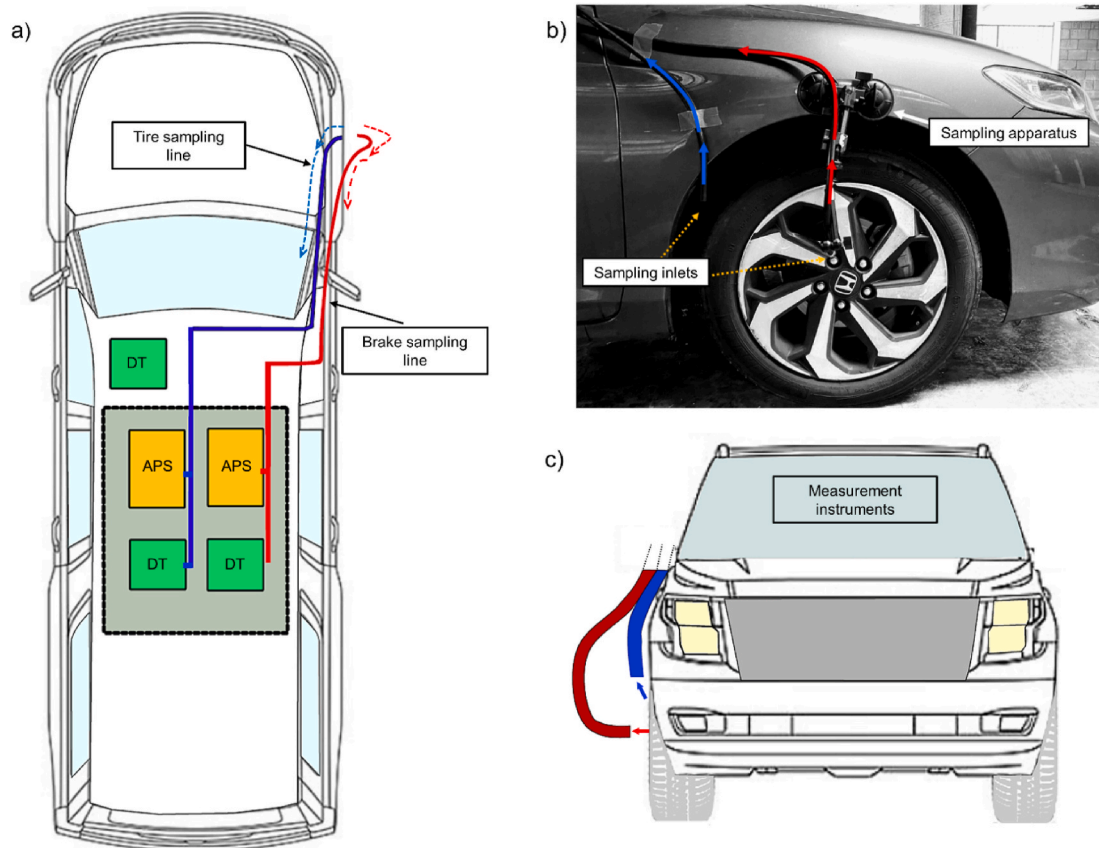


**Fig. 1.** Schematic diagrams for the test vehicle with the sampling configuration. (a) Top view. Illustration of the sampling instruments installed inside the vehicle, including APS (TSI APS 3321) and DT (TSI DustTrak 8532). (b) The test vehicle and sampling apparatus. Arrows show the direction of the sampling flow from the brake and tire. (c) Front view. The tire particles are measured from the rear side of the right front wheel. The brake particles are measured at the center of the right front wheel.

roof of the test vehicle for ambient PM measurements. A custom-made apparatus was used, which provided sufficient space between the sampling probe and the wheel under both straight and cornering driving conditions. The brake sampling probe was located 5 cm from the center of the wheel, while the tire sampling inlet was installed 2.5 cm from the top of the wheel. The brake and tire inlets were installed 30 cm apart from each other. Isokinetic sampling probes (8 mm ID) were used. Particle losses due to settling and curvature as well as aspiration efficiency were calculated based on classic aerosol theories (Hinds, 1999). The details of the isokinetic sampling design are discussed in Section A.1 of the supplemental information.

In this study, “brake particles” and “tire particles” refer to the particles collected from the brake and tire sampling inlets, respectively. While these particles were collected near the brake and tire, they could be mixed with other emission sources, whose relative contribution cannot be estimated without chemical speciation analysis and source apportionment. The mixing between the brake and tire particles at both inlets is also plausible. Therefore, the collected data should not be interpreted as solely constitute the brake and tire wear particles. Nevertheless, we do expect brake and tire wear emissions to have a great impact on the particles collected from their respective sampling inlets.

Since adding substantial and balanced loading to a vehicle without changing its center of gravity was not feasible, the on-road sampling was performed on three vehicles with different masses. A full-sized SUV (2016 Chevrolet Suburban), a mid-sized sedan (2016 Honda Accord), and a compact sedan (2017 Nissan Sentra) were tested on a pre-determined route. The details of the test vehicles are presented in Table 1. All of the test vehicles were equipped with all-season non-studded tires as well as ceramic disc brakes. Ceramic brakes can provide a stable thermal performance (Kumar and Kumaran, 2019; Sundarkrishnaa, 2015) and generate less PM compared to other types (Seo et al., 2021). While ceramic brake pads have been mostly popular in high-end vehicles due to their high cost (Li et al., 2020), they have become more widespread in recent years due to their durability and superior performance (Li et al., 2021).

The sampling route was a 5.5 km path in the Westwood neighborhood in Los Angeles. The sampling route included a mildly downhill terrain, with fairly straight residential streets, multiple stop signs, and low traffic. The instantaneous driving speed during the measurement did not exceed 75 km/h. On-road sampling took place between March and June 2019. Measurements generally took place between 7 p.m. and 11 p.m. when traffic was minimal. For each vehicle, brake temperature was measured before and after each round of sampling using a digital infrared thermometer (1052D, Etekcity Corp., Anaheim, CA). There was a minimum of 30 min resting period between two consecutive sampling sessions to ensure the brake temperature was less than 80 °C before each experiment. Section A.2 in the supplementary information summarizes the average brake temperatures before and after sampling sessions for each vehicle. The average ambient temperature and relative humidity during the sampling sessions were 21.2 °C and 73.7 %, respectively.

## 2.2. Instrument

Three DustTraks (8532, TSI Inc., Shoreview, MN) were used to concurrently measure PM<sub>2.5</sub> and PM<sub>10</sub> concentrations from the brake and tire as well as in the ambient air. The brake and tire particle size distributions in the size range of 0.5–20 µm were determined by two Aerodynamic Particle Sizers (APS 3321, TSI Inc., Shoreview, MN) with a log

interval of 1 s, respectively. Velocity and GPS coordinates were logged using the GlobalSat data logger (DG-500, New Taipei City, Taiwan). The total sampling flow rate was 8 L per minute (LPM), which was provided by APS (5 LPM) and DustTrak (3 LPM). The electric power for running APS inside the vehicle was provided by a marine dual-purpose AGM Battery (AGM 105, West Marine, Watsonville, CA) and a power inverter (TruePower, 2000 PS, Promariner, Menomonee Falls, WI).

## 2.3. Quality assurance and quality control

Before the sampling began, the DustTrak monitors were zero-calibrated in the laboratory, and the GlobalSat data logger was synced to the global time. The DustTrak monitors were also collocated for 10-min before and after sampling on each vehicle. The resulting linear relationships were applied to adjust DustTrak data. Section A.3 of the supplemental information presents the collocation test results.

Previous studies have calibrated DustTrak data against gravimetric measurements for brake wear particles and reported an underestimation. A calibration factor of  $5.7 \pm 2.1$  was reported during the measurement of PM<sub>2.5</sub> from brake wear particles (Hagino et al., 2015). While a calibration factor for PM<sub>10</sub> was found to be  $2.3 \pm 0.2$  during on-road brake wear sampling (Farwick zum Hagen et al., 2019a), laboratory measurements reported a calibration factor of  $6.4 \pm 0.7$  for brake wear PM<sub>10</sub> (Farwick zum Hagen et al., 2019b). Based on these reported calibration factors in the literature, the average calibration factors of 5.7 and 4.4 were used for correcting brake and tire PM<sub>2.5</sub> and PM<sub>10</sub> data from DustTrak in this study. PM<sub>2.5</sub> and PM<sub>10</sub> DustTrak data collected at the roof of the vehicles were corrected with previously reported ambient calibration factors of 0.52 and 0.33, respectively (Chung et al., 2001; Rivas et al., 2017).

## 2.4. Data analysis

The correlation between the brake and tire PM concentrations and the average deceleration rates for all three vehicles was determined by linear regression analysis. Shapiro-Wilk and Kolmogorov-Smirnov tests were used to examine if the maximum brake and tire PM<sub>2.5</sub> and PM<sub>10</sub> datasets at different braking intensity levels are normally distributed. Kruskal-Wallis ANOVA on ranks with a Bonferroni-Dunn post hoc was used to determine the significant differences in the brake and tire PM concentrations among different vehicles since some of the datasets did not pass the normality tests. R 3.4.0 and Microsoft Excel 2016 (Microsoft, Seattle, WA, USA) were used to summarize data and perform statistical analysis. All figures were generated with Sigmaplot 14.0 (Systat Software Inc., San Jose, CA).

## 3. Results and discussion

### 3.1. Determining major braking events

A decrease in the vehicle's velocity can occur with or without braking. Previous studies reported various ranges for the longitudinal deceleration rates during the braking events (Maurya and Bokare, 2012; Smith et al., 2003). It has been shown that only 5% of braking events occur under the deceleration rate of 0.5 m/s<sup>2</sup> and lower (Lee et al., 2007). In this study, deceleration events with (a) continuous deceleration for more than 3 s and (b) instantaneous deceleration rates of 0.5 m/s<sup>2</sup> or greater in magnitude were selected as major braking events. For each braking event, the arithmetic mean of the instantaneous

**Table 1**  
Specifications of the test vehicles.

| Make/Model         | Year/Trim | Vehicle type   | Mass (lbs) | Brake pad thickness (mm) | Tire make/model       |
|--------------------|-----------|----------------|------------|--------------------------|-----------------------|
| Nissan Sentra      | 2017/S    | Compact sedan  | 2857       | 6.2                      | Michelin Primacy MXV4 |
| Honda Accord       | 2016/LX   | Mid-size sedan | 3543       | 8.8                      | Michelin Primacy MXV4 |
| Chevrolet Suburban | 2016/LS   | Full-size SUV  | 5808       | 7.5                      | Michelin Defender LTX |

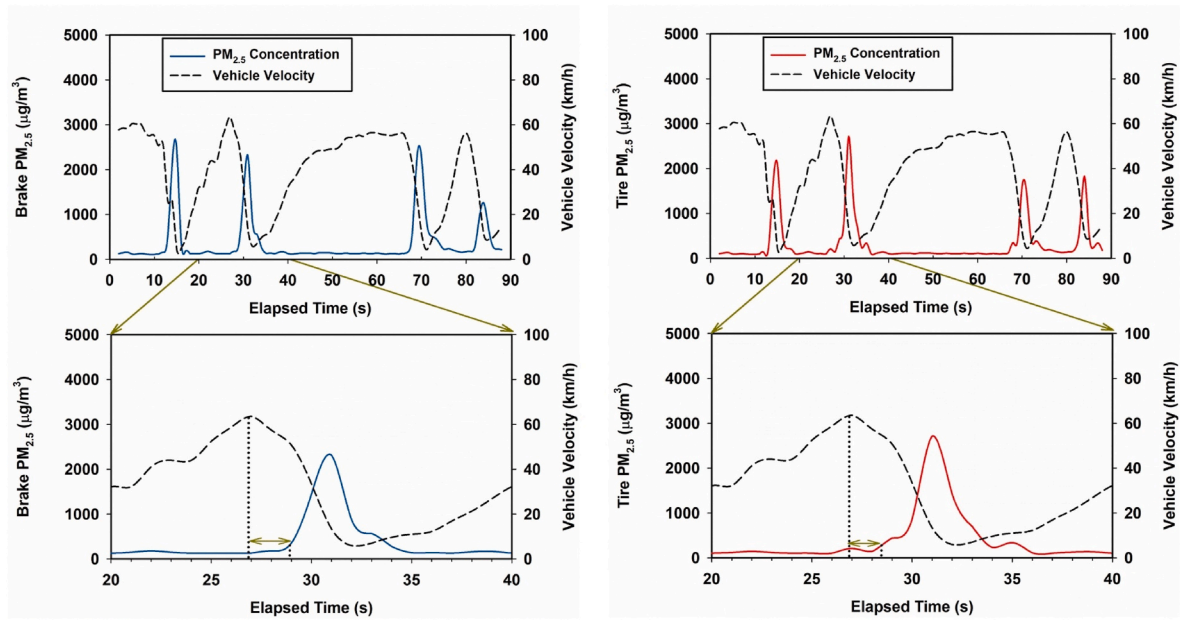


Fig. 2. A typical temporal profile of PM<sub>2.5</sub> concentration and driving velocity of the Chevrolet Suburban (a) brake PM<sub>2.5</sub>, (b) tire PM<sub>2.5</sub>.

deceleration rates was calculated to represent the braking intensity.

Fig. 2 shows a representative time series of the PM<sub>2.5</sub> concentration measured at the brake inlet of the Chevrolet Suburban and its instantaneous velocity. As shown in Fig. 2, braking leads to substantial increases in brake and tire PM concentrations and generates a peak in the PM concentration profile. Peak values in brake and tire PM<sub>2.5</sub> and PM<sub>10</sub> concentrations during each braking event were identified and further used for analysis on the effect of braking intensity and mass. Fig. 2 also shows that there could be a delay between the onset of the braking and the observation of a peak in PM concentrations. This lag effect was taken

into consideration when identifying major braking events and their associated PM concentrations. A similar effect was reported in a recent study, presumably due to the particle residence time in the sampling line (Farwick zum Hagen et al., 2019a).

### 3.2. Effect of the braking intensity and vehicle mass on PM mass concentration

Fig. 3 shows that the deceleration rate was a statistically significant predictor of the brake and tire PM<sub>2.5</sub> and PM<sub>10</sub> concentrations during

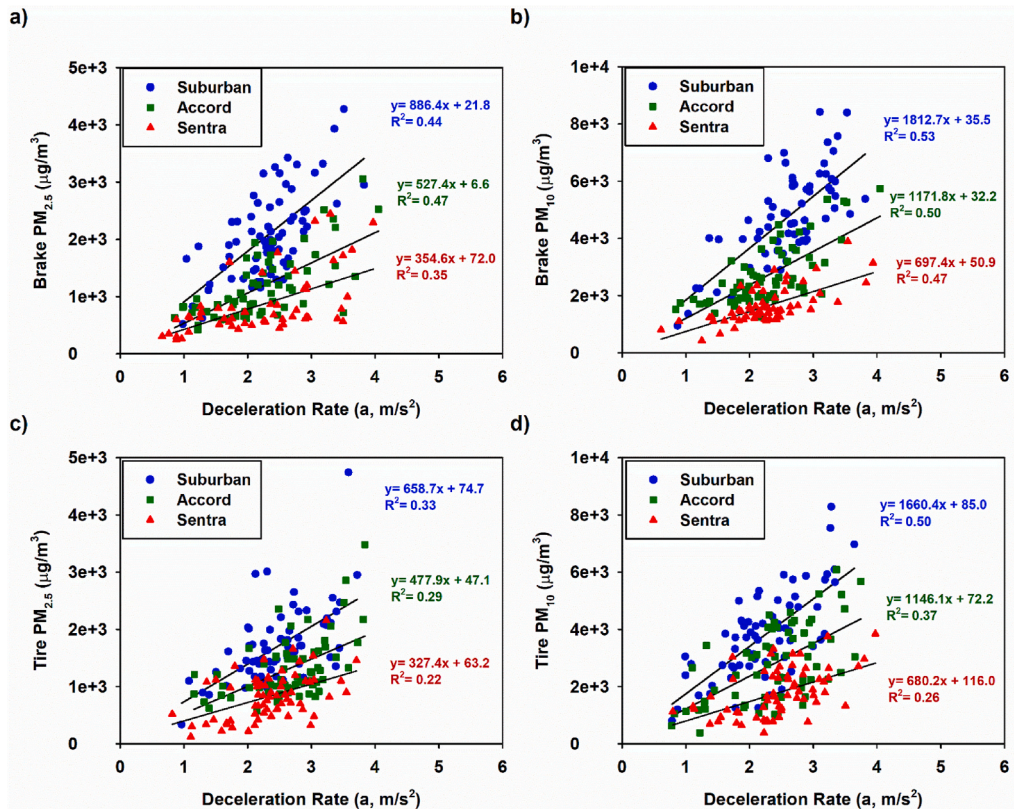


Fig. 3. Relationships between the peak values in PM concentrations and the average deceleration rate (p-value < 0.001) (a) brake PM<sub>2.5</sub>, (b) brake PM<sub>10</sub>, (c) tire PM<sub>2.5</sub>, (d) tire PM<sub>10</sub>.

major braking events. The strength of the linear regression ( $R^2$ ) varies across the vehicles. In general, the correlation improves as the vehicle's mass increases, except for the Accord's brake  $PM_{2.5}$ , which shows a slightly stronger correlation compared to Chevrolet Suburban. For brake particles,  $PM_{10}$  shows a stronger positive correlation with the deceleration rate ( $p < 0.001$ ,  $R^2 = 0.47\text{--}0.53$ ) than  $PM_{2.5}$  ( $p < 0.001$ ,  $R^2 = 0.35\text{--}0.47$ ). A similar trend was observed for tire particles, where a stronger linear relationship existed between the deceleration rate and  $PM_{10}$  ( $p < 0.001$ ,  $R^2 = 0.26\text{--}0.50$ ) than  $PM_{2.5}$  ( $p < 0.001$ ,  $R^2 = 0.22\text{--}0.33$ ). In comparison, the deceleration rate was a stronger predictor for brake  $PM_{2.5}$  ( $p < 0.001$ ,  $R^2 = 0.35\text{--}0.47$ ) than tire  $PM_{2.5}$  ( $p < 0.001$ ,  $R^2 = 0.22\text{--}0.33$ ). For both  $PM_{2.5}$  and  $PM_{10}$  concentrations, the slope of the regression for the brake PM concentrations was consistently greater than that for the tire. Section A.2 in the supplementary information summarizes the average ambient  $PM_{2.5}$  and  $PM_{10}$  concentrations during the on-road sampling for each test vehicle.

The braking intensity was defined based on the arithmetic mean of the vehicle's instantaneous deceleration rate during each braking event. A braking deceleration of 0.2 g ( $g = 9.81 \text{ m/s}^2$ ) has been used as the comfortable braking index level (Wu et al., 2009). Moreover, while 50% of the braking longitudinal deceleration rates were reported to be under 0.2 g, only 15% of the braking events were shown to have deceleration rates higher than 0.3 g (Lee et al., 2007). Therefore, braking events with an average deceleration rate of 0.3 g and higher were marked as heavy brakes ( $a > 3.0 \text{ m/s}^2$ ); braking events with an average deceleration rate of 0.2 g and lower were marked as light brakes ( $0.5 < a < 2.0 \text{ m/s}^2$ ); and those in between were categorized as moderate brakes.

As the braking becomes more intense, a more rapid decrease in the velocity of the vehicle and an elevated deceleration rate occurs. During heavy braking, as the vehicle's velocity decreases quickly, the kinetic energy of the vehicle is absorbed and further transformed into heat

through abrasion processes. The required friction force is mainly generated by the abrasion between the brake pad and the disc as well as the friction between the tire and the road pavement. The generated thermal energy affects the friction surfaces and eventually produces wear particles in various sizes. Since a stronger friction force is required for stopping heavier vehicles, a higher concentration of brake and tire particles would be expected. To verify this, the distribution of the brake and tire wear  $PM_{2.5}$  and  $PM_{10}$  concentrations for three vehicles during the major braking events with respect to the braking intensity were compared.

Fig. 4 demonstrates the distribution of the brake and tire  $PM_{2.5}$  and  $PM_{10}$  concentrations for three test vehicles with respect to the braking intensity. For both brake and tire particles, the differences in the median values of  $PM_{2.5}$  and  $PM_{10}$  concentrations are statistically significant among the three vehicles regardless of the braking intensity level (Kruskal-Wallis  $P < 0.05$ ), suggesting that there is a statistical difference between at least one pair of vehicles. A multiple comparison procedure (Dunn's Method) was then used to determine if the PM concentration distribution of a vehicle or vehicles was statistically different from the others. The  $PM_{2.5}$  concentrations were significantly different between the Chevrolet Suburban and Nissan Sentra, regardless of the braking intensity level for both brake and tire particles (Dunn's Method,  $p < 0.05$ ). Likewise, a significant difference was observed in the  $PM_{10}$  concentration between the Chevrolet Suburban and Nissan Sentra for both brake and tire particles regardless of the braking intensity level (Dunn's Method,  $p < 0.05$ ). The differences in the  $PM_{2.5}$  and  $PM_{10}$  concentrations between the Chevrolet Suburban and Honda Accord were always significant during heavy and moderate brakes for both brake and tire particles. However, for the light braking intensity, the difference between the Chevrolet Suburban and Honda Accord was not significant. A statistically significant difference was not observed between the Honda

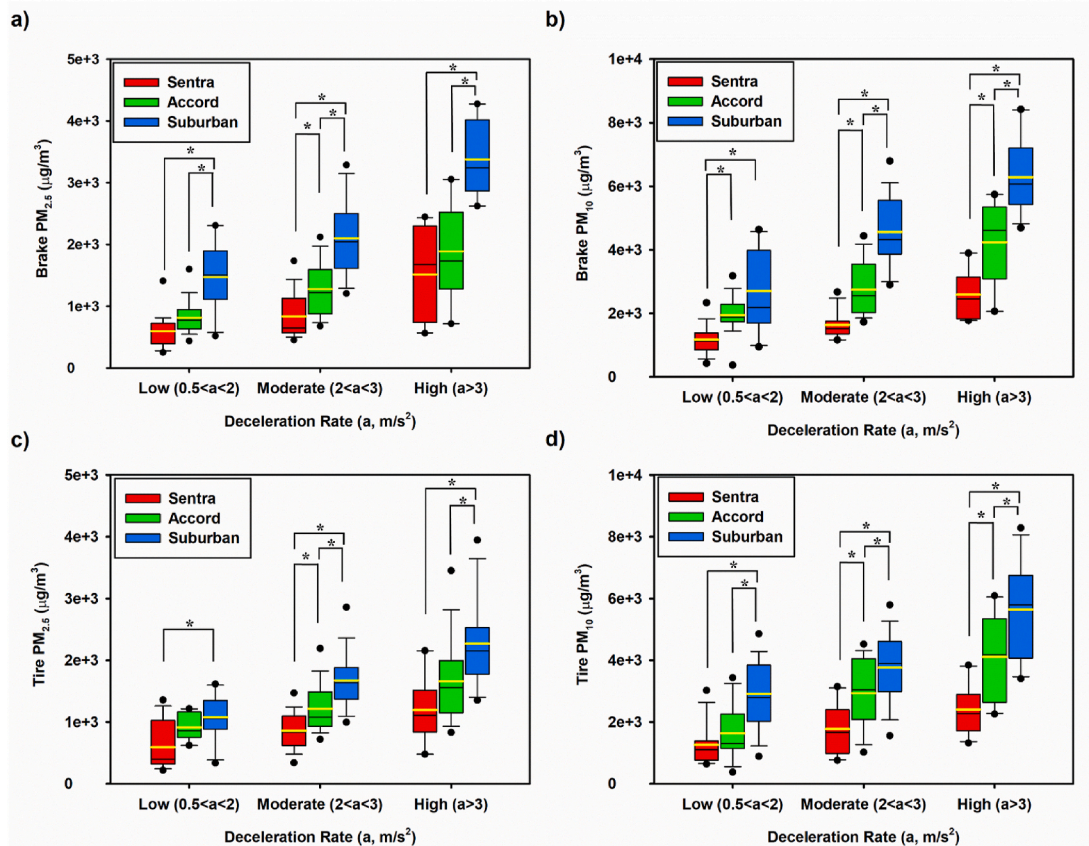


Fig. 4. Peak values in PM concentrations for the test vehicles at three deceleration rate (i.e., braking intensity) levels (a) brake  $PM_{2.5}$ , (b) brake  $PM_{10}$ , (c) tire  $PM_{2.5}$ , (d) tire  $PM_{10}$ .

Accord and Nissan Sentra, presumably due to a smaller difference in the masses of the two vehicles.

There are few studies that have discussed the effect of vehicle mass on non-exhaust PM emissions. Computer modeling of tire wear properties has previously suggested that vehicle inertia load can affect tire wear particle generation (Salminen, 2014). Moreover, studies on brake wear particles have discussed that inertia load is likely to affect brake wear particles (Garg et al., 2000). In addition, life cycle data have been used for estimating non-exhaust emissions based on the mass of the vehicles, expressing the significance of inertia load on non-exhaust PM generation (Simons, 2016). Overall, the results of this study confirm the findings in the previous works and indicate that vehicle mass can play a major role in predicting brake and tire PM concentrations during the braking.

### 3.3. Particle size distribution

Mass-based particle size distributions of the brake and tire particles are shown as contour plots in Fig. 5. To obtain mass-based size distributions, we assume particles are perfect spheres with a uniform density of 2.6 and 2.8 g/cm<sup>3</sup> for brake and tire wear particles, respectively (Alemani et al., 2016; Hussein et al., 2008; Kwak et al., 2013). In Fig. 5,

the x and left y coordinates present the sampling elapsed time in seconds and the aerodynamic particle diameter in the logarithmic scale, respectively. The normalized mass concentration ( $dM/d\log d_p$ ) for the particle diameters in the range of 0.5–20  $\mu\text{m}$  at a given time is shown in different contour colors. The right y-axis shows the average deceleration rate during the braking events. As shown in Fig. 5, while not all braking events increase PM mass concentration, high PM concentrations were observed for most of them. Similar to Fig. 4, for both the brake and tire particles, higher PM concentrations are generated from the heavier vehicles during braking. This is more noticeable for the Chevrolet Suburban, presumably because its mass is approximately twice as heavy as that of the Nissan Sentra and approximately 60 % heavier than that of the Honda Accord. A substantial difference between the mass-based size distribution of the brake and tire particles was not observed.

Fig. 6 plots the average mass-based particle size distributions for the three test vehicles. Both brake and tire particles showed a unimodal mass size distribution with a mode diameter of 3–4  $\mu\text{m}$  and 4–5  $\mu\text{m}$ , respectively. The reported brake particle size distributions in the previous studies vary depending on the sampling setup and instrumentation. The brake particles have been reported in various size ranges, including ultrafine, fine, and coarse sizes (Farwick zum Hagen et al., 2019b; Kwak et al., 2013; Nosko and Olofsson, 2017). The results of this

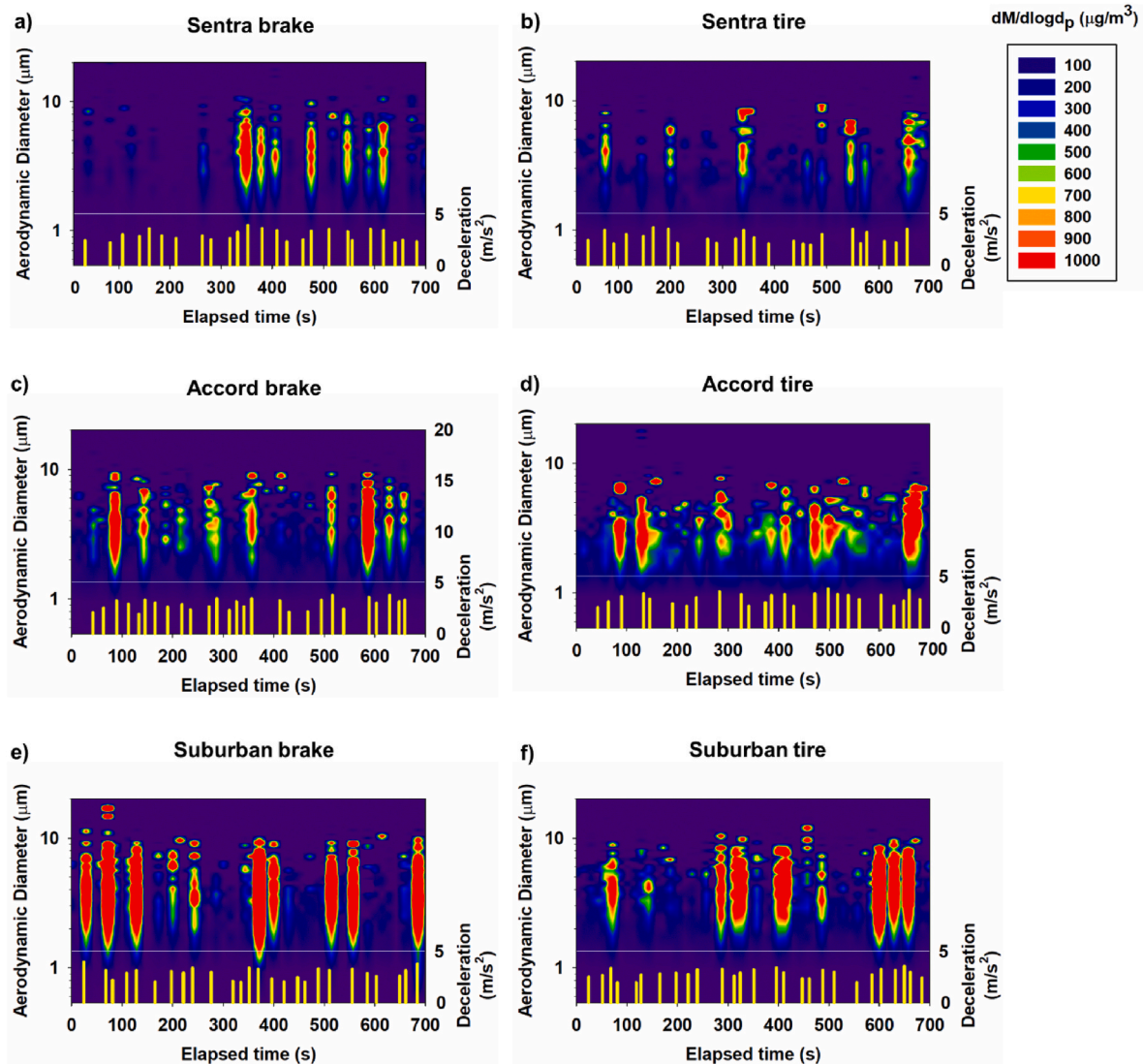


Fig. 5. Mass-based particle size distributions for brake and tire particles with regard to the braking deceleration rate during moderate and heavy braking events (a) Sentra brake, (b) Sentra tire, (c) Accord brake, (d) Accord tire, (e) Suburban brake, (f) Suburban tire.

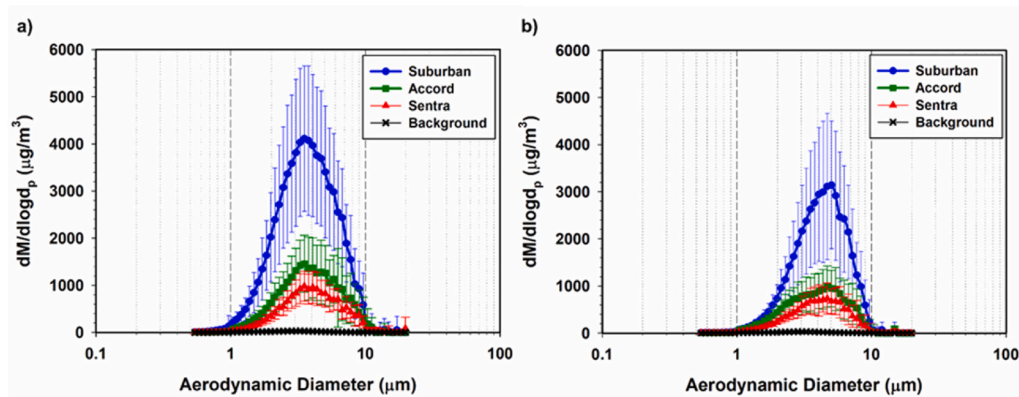


Fig. 6. Average mass-based particle size distribution during braking events for (a) brake particles and (b) tire particles (error bars: standard deviation).

study are in agreement with the findings of the previous study that reported a mass-based particle size distribution in the 1–10  $\mu\text{m}$  size range (Kwak et al., 2013). Moreover, unimodal tire mass-based particle size distributions with mode diameters of 2–3  $\mu\text{m}$ , 3–5  $\mu\text{m}$ , and 3–4  $\mu\text{m}$  have been reported (Hussein et al., 2008; Kim and Lee, 2018; Kwak et al., 2013). In general, our results on tire particle size distributions agree with the findings of these studies.

#### 4. Discussion

One of the goals of this work was to study the effect of braking intensity on brake and tire particles. As shown in section 3.2, for each vehicle, higher brake and tire  $\text{PM}_{2.5}$  and  $\text{PM}_{10}$  concentrations are observed during more intense braking events. However, it is important to note that at any given initial and final speed, the braking events with higher deceleration rates take less time, and therefore the particles are produced for a shorter period of time. Overall, the average durations of light ( $0.5 < a < 2 \text{ m/s}^2$ ) vs. heavy ( $a > 3 \text{ m/s}^2$ ) braking events for all test vehicles were  $7.3 \pm 0.5 \text{ s}$  and  $5.2 \pm 0.4 \text{ s}$ , respectively, showing an approximately 40 % difference. This shorter braking time offsets the total amount of generated brake and tire particles during heavy braking events.

There are a few other factors that can affect the brake and tire particles. For instance, the aerodynamic drag may affect the vehicle braking intensity and concentrations of brake and tire particles. The aerodynamic drag has been reported to increase during windy conditions (Selvaraju and Parammasivam, 2019; Windsor, 2014) and affect the stopping distance and stopping time at higher driving speeds ( $V > 100 \text{ km/h}$ ) (Haggag, 2016). However, in this study, the effect of aerodynamic drag on braking intensity was expected to be negligible due to low to medium driving speeds and low wind.

The brake temperature can also affect the brake wear particle size distribution. At a certain critical brake temperature ( $T_{\text{crit}}$ ), particle number concentration has been shown to rapidly increase due to the generation of ultrafine particles (Alemani et al., 2018; Farwick zum Hagen et al., 2019a). While  $T_{\text{crit}}$  has been shown to be a function of brake lining material, most studies reported  $T_{\text{crit}}$  to be in the range of 140–190  $^{\circ}\text{C}$  (Alemani et al., 2018; Farwick zum Hagen et al., 2019a; 2019b; Nosko and Olofsson, 2017). A previous study using the Los Angeles City Traffic (LACT) cycle has shown that temperature transition occurs gradually (Farwick zum Hagen et al., 2019a). In fact, the brake temperature was reported to reach  $T_{\text{crit}}$  after 1 h of continuous driving (Farwick zum Hagen et al., 2019a). In this study, the brake temperature was below 80  $^{\circ}\text{C}$  at the beginning of each sampling session and reached up to 120  $^{\circ}\text{C}$  at the end of each 12-min session (Table A.2). Therefore, the range of brake temperature in this study was expected to be well below the  $T_{\text{crit}}$  (140–190  $^{\circ}\text{C}$ ) which is required for excessive ultrafine particle generation.

The goal of this work was to study the effect of vehicle mass on non-exhaust PM during different braking intensity levels. The effects of vehicle mass on non-exhaust PM emissions have received more attention in recent years with the global efforts for transportation electrification. Battery electric vehicles have shown to be heavier than vehicles with internal combustion engines due to the excessive battery weight (Timmers and Achten, 2018). While recent studies have shown the frequency of braking in the battery electric vehicles can be eight times lower due to the application of the regenerative braking system (Hall, 2017), more recent studies based on updated emission inventories have discussed that excessive weight of battery electric vehicles can minimize the positive effect of regenerative braking in reducing non-exhaust PM emissions (Beddows and Harrison, 2021). Therefore, future research is needed to better understand the overall impact of vehicle electrification on brake and tire wear emissions. The findings from the current study can provide insight into the effect of vehicle mass on brake and tire particles during various braking intensity levels and alleviate the gap of knowledge in this area.

#### 5. Study limitations and future work

Chemical speciation has been shown to be useful in the identification of brake and tire wear particles (Lough et al., 2005). For instance, specific chemical elements have been used for tracing brake and tire wear particles (Wang et al., 2021). However, chemical speciation analysis would require collecting a large amount of PM samples during lengthy on-road sampling sessions, which was logistically prohibitive in the current study.

Accurate calibration factors for correcting PM concentrations measured by DustTrak is important. To the best of our knowledge, the DustTrak calibration factor for tire wear particles is not available in the literature. While DustTrak calibration factors for brake wear particles have been reported, they vary widely across different brake lining materials and sampling methods. Therefore, future studies are needed to provide more details about the DustTrak calibration factors of brake and tire wear particles.

Finally, the results of the current study showed that there could be a lag between the onset of the braking and observation of an increase in the concentration of the brake and tire particles. A similar observation has been reported previously during the on-road sampling of the brake wear particles (Farwick zum Hagen et al., 2019a). Since the instrument response time can vary, future research is needed to investigate the instrument response time during the real-time measurement of brake and tire wear particles.

#### 6. Conclusion

In this study, three vehicles with different masses were tested to

investigate their effects on brake and tire particles under real-world driving conditions. On-road measurements were performed on three test vehicles with masses ranging from 2800 to 5800 lbs. A significant difference was observed in the brake and tire PM<sub>2.5</sub> and PM<sub>10</sub> concentrations between the heaviest and lightest vehicles, indicating that there is a positive association between the vehicles' mass and the PM concentration at the brake and tire inlets. This study also demonstrated that the braking intensity is a strong predictor of the brake and tire PM<sub>2.5</sub> and PM<sub>10</sub> concentrations. The brake and tire particles were measured in size range of 0.5–20 µm. Brake particles showed a unimodal mass size distribution with a mode diameter of 3–4 µm, while tire particles showed a slightly larger mode diameter of 4–5 µm. The findings of the current work provide novel information on the effect of vehicle and driving conditions on brake and tire particles.

## CRediT authorship contribution statement

**Farzan Oroumijeh:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft. **Yifang Zhu:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Validation, Writing – review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.aeaoa.2021.100121>.

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