TECHNICAL NOTE
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Aerosol and Air Quality Research

Effects of Payloads on Non-exhaust PM Emissions from A Hybrid Electric Vehicle during A Braking Sequence

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ABSTRACT

Vehicles equipped with internal combustion engines are known as important sources of particulate matter (PM) emissions. Many countries are aware of this issue. They are keen in converting internal combustion engine vehicles to electric vehicles (EV) to reduce PM problems. However, various past research works claimed that EV also emit PM like conventional vehicles due to their non-exhaust emissions from brake wear, tyre wear, road surface wear, and resuspension of road dust. In addition, strong evidence showed that there was indeed a positive correlation between the weight of vehicle and amounts of non-exhaust PM emissions.

The current study is aimed to measure on-road non-exhaust PM emissions from a hybrid electric vehicle during a braking sequence at various payloads. An onboard PM measuring device is attached nearby the center cap bore of the left front wheel on the tested hybrid electric vehicle. PM_1, $PM_{2.5}$, and PM_{10} measurements are monitored during braking sequences in the electrified vehicle mode. The increase payloads that affect tendency of non-exhaust PM emissions are observed. The PM emission pattern during braking sequence is captured by the current PM measuring setup as seen in the literature. Based on this experiment, the additional payloads of 60–70 kg increase the amount of non-exhaust $PM_{2.5}$ and PM_{10} emissions almost 25%. The effects of increasing payloads on $PM_{2.5}$ and PM_{10} emissions can be clearly observed as a linear relationship. However, for PM_1 emissions, when increasing payloads, a certain cut point is observed at the payload of 130 kg. Adding payloads more than 130 kg do not affect the amount of PM_1 emissions.

Keywords: Non-exhaust PM emissions, Hybrid electric vehicle, Onboard PM measuring device

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1 INTRODUCTION

PM has been known as one of the most important air pollutants harming human health. It is mainly divided into PM_{10} and $PM_{2.5}$, which represent particles with a diameter of less than 10 µm and 2.5 µm, respectively. PM can be found mostly in cities and urban areas where vehicles equipped with internal combustion engines are used. Many countries have introduced the use of EV to cope with this PM problem. Governments consider EV as a promising way since it is believed that EV produces zero emissions and, therefore, should not create air pollutants. However, when EV are being more and more used, it has become evident that PM_{10} emissions remain (Soret *et al.*, 2014; Kuenen *et al.*, 2014). In fact, both conventional vehicles and EV emit PM, such as tyre wear, brake wear, road surface wear/abrasion, and resuspension of road dust (Timmers and Achten, 2016), which are considered as non-exhaust emissions. PM emitted by EV are mostly PM_{10} with a significant amount of $PM_{2.5}$ containing heavy metals such as zinc (Zn), copper (Cu), iron (Fe) and lead (Pb), among others (Thorpe and Harrison, 2008). Road dust (from surface wear/abrasion) and tyre wear are caused by the friction between the tyre thread and road surface, while brake wear is caused by the friction between the brake pad and disc brake. Resuspension of road dust is caused by the diffusion of air current underneath and behind vehicles and mostly considered as PM_{10} (Simons, 2016).

Among these non-exhaust PM emissions, brake wear is considered as a major contribution because of high frequencies of its usage. The contribution of brake wear emissions can be as high as 42% of total non-exhaust PM emissions (Simons, 2016). It was already hypothesized that PM emissions from brake wear were highly influenced by vehicle weight, as stated in past studies (Barlow, 2014; Garg *et al.*, 2000). They focused on measuring non-exhaust PM emissions between passenger cars and light duty vehicles (LDV). Their result showed that LDV emitted more brake wear PM than passenger cars (Luekewille *et al.*, 2001). It was also mentioned that the inertia weight while the vehicle being stopped could be one of the most important factors contributing to brake wear rates. However, no test has been done to absolutely confirm this hypothesis and verify the observation on various vehicle weights from the same vehicle.

Therefore, this research focuses on investigating of non-exhaust PM emissions emitted from a hybrid electric vehicle (HEV) during a braking sequence. The test is done by using a PM Mobile onboard measuring equipment attached directly onto a moving vehicle at the spot nearby the centre cap bore of the front wheel. Payloads on EV are varied to study the effects of weights on non-exhaust PM emissions during braking sequences.

2 METHODS

An experimental setup is done by attaching real-time PM monitoring equipment near the left front brake of a hybrid midsize passenger car as shown in Fig. 1. The specification of the tested vehicle is shown in Table 1. All hardware of this real-time PM monitoring equipment is shown in Fig. 2. Table 2 shows the specifications of the dust sensor used in the current study.

The measurement concept is as the follows. PM is detected by a dust sensor connecting to ESP32 board (WIFI + Blutooth), that is run by Arduino IDE, for sending and receiving commands. ESP32 needs to upload a code program, namely, Bluetooth32 to connect a Bluetooth, PMS_MCU to EMS32 for command sensor, and Plantower PMS5003 for detecting PM_1, $PM_{2.5}$, and PM_{10}. A schematic of all equipment connection is shown in Fig. 3.

PM readings from the current setup are compared to the PM standard measuring tool, namely, Tapered Element Oscillating Microbalance (TEOM) as seen in Fig. 4. Results show good agreements between the current PM measuring device and TEOM.

In the current study, all tests are performed on a hybrid electric vehicle. The braking and resuspension systems are Original Equipment Manufacturer, and the vehicle is always in a routine regular maintenance. All tests are done on the same road within a closed road to minimize PM diffusion from another vehicle. The vehicle velocities are increased from 0 to 40 km h^{-1} to ensure

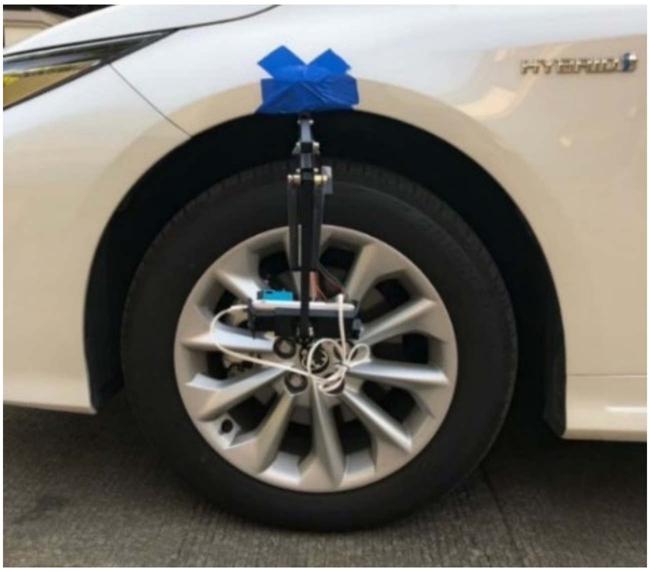

Fig. 1. Measurement setup with instruments.

Table 1. Specifications of tested vehicle.

Parameter	Index
Engine	
Type	4 Cylinder in-line, SOHC 16 valve
Capacity (L)	1.798
Bore x Stroke (mm.)	80.5 × 88.3
Compression Ratio	13:1
Max. Output EEC net kw (ps)/rpm	72 (98)/5,200
Max. Torque EEC net Nm (kg-m)/rpm	142 (14.5)/3,600
Electric Motor	
Type	Synchronous Motor with Permanent Magnet
Max. Voltage (V.)	600
Max. Output (kw.)	53
Max. Torque	163
Hybrid Battery	
Type	Nickel-metal Hydride
Voltage (V.)	201.6
No. of Module	28 Modules 168 Cells
Capacity (Amr-Hr)	6.5 (3)
Engine and Electric Motor Max. Output kw (ps)	90 (122)

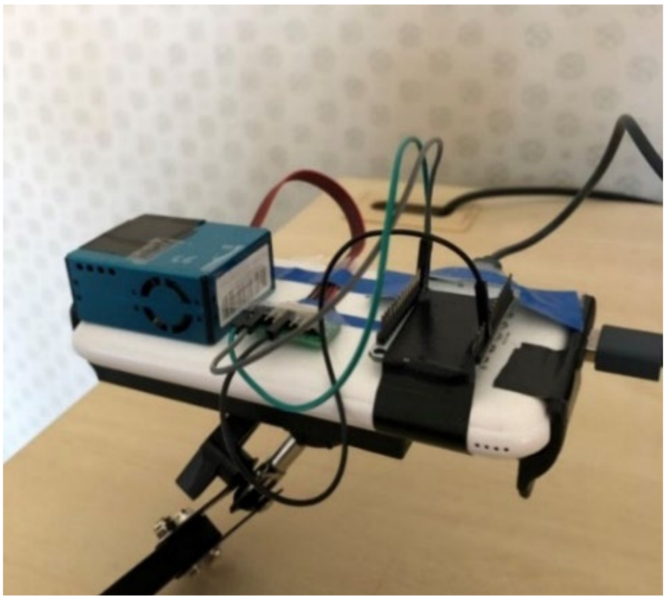

Fig. 2. Real-time PM monitoring equipment.

that the vehicle is in the electrified mode and all PM that are emitted from the tested vehicle come from non-exhaust sources. The stopping distance from the velocity of 40 km h^{-1} is set within 5 meters until the vehicle is fully stopped. Tests are repeated by increasing various payloads on the tested vehicle. The payload is increased by adding approximately 70 kg, ranging from 2 to 6 passengers in the vehicle. The analysis of relationships between non-exhaust PM emissions and payloads are shown in the next section.

3 RESULTS AND DISCUSSIONS

Fig. 5 shows an example of raw data from PM measurements during a brake sequence. At 0 second, the onboard PM measuring device is started while the vehicle is in a park mode. PM emissions are read as the background level (approximately 22 µg m^{-3}). At 10 second, the vehicle is

Table 2. Specifications of dust sensor: PMS5003.

Parameter	Index	Unit
Range of measurement	0.3–1.0	Micrometer (µm)
	1.0–2.5	
	2.5–10	
Counting Efficiency	50% @ 0.3 µm	
	98% @ ≥ 0.5µm	
Effective Range	0–500	µg m^{-3}
Maximum Range	≥ 1000	µg m^{-3}
Resolution	1	µg m^{-3}
Maximum Consistency Error	±10% @ 100–500 µg m^{-3}	
	±10 µg m^{-3} @ 0–100 µg m^{-3}	
Standard Volume	0.1	Litre (L)
Temperature Operating	–10 to +60	°C
Humidity Range	0–99%	
Storage Temperature	–40 to +80	°C
Dimension	50 × 38 × 21	Millimeter (mm)

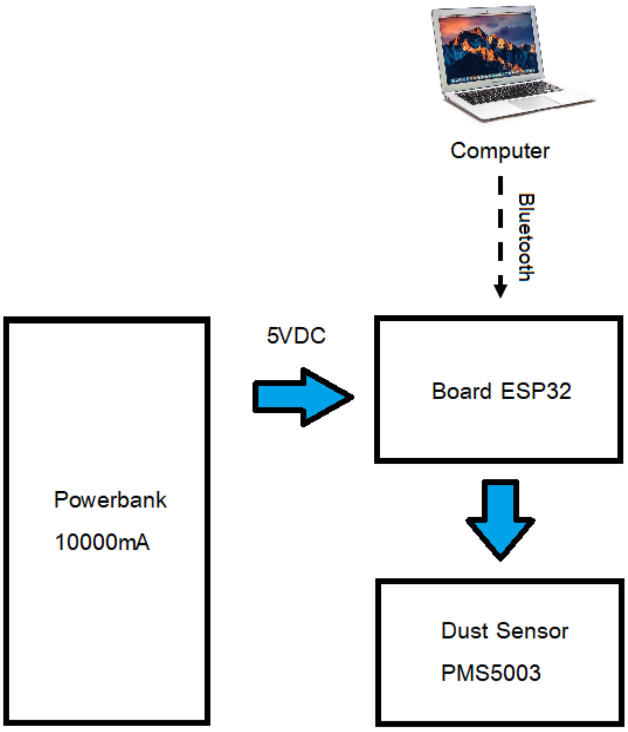

Fig. 3. A schematic of PM measuring devices.

started, and the vehicle speed is increased. PM readings during this period are due to resuspension of road dust effect (approximately 33 µg m^{-3}). Until the speed reaches 40 km h^{-1}, the brake is applied (approximately at 20 second). PM emissions increases rapidly. The vehicle is completely stopped at 26 second. However, PM emissions continuously increase for 5 seconds and slowly decreases until PM readings are equal to the background level again. Note that during this sequence, as shown in Fig. 5, the vehicle is still in the electrified mode. The levels of non-exhaust PM emissions are found to correspond to the trend observed in the past literature (Mathissen *et al.*, 2018).

Prior to variation of payload tests, the effect of braking behavior is on trial. Figs. 6 and 7 show a comparison between soft (slowly decrease the vehicle velocity) and hard (rapidly decrease the vehicle velocity) brake tests. As we clearly observe from both figures, the hard brake generates

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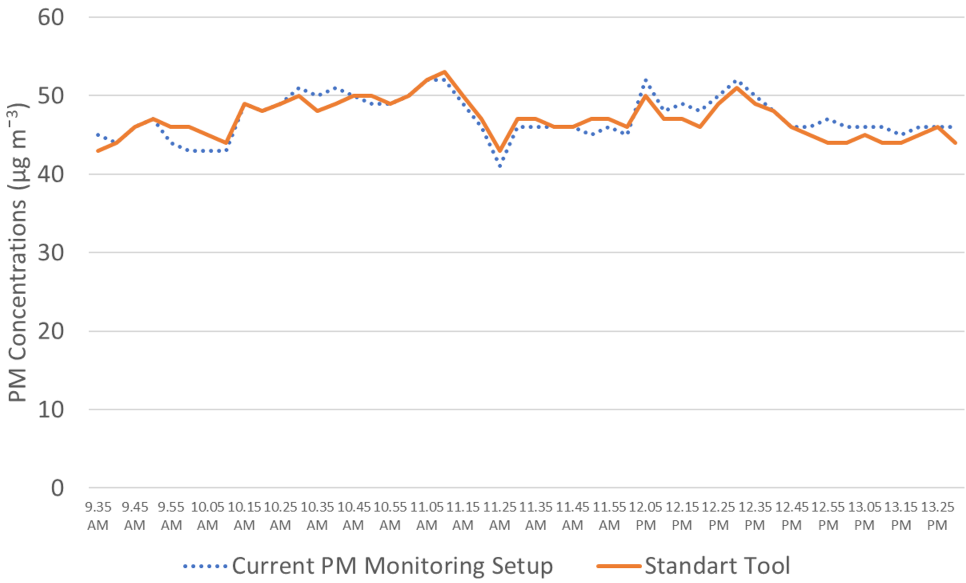

Fig. 4. A comparison of PM concentrations measuring by the current setup and TEOM.

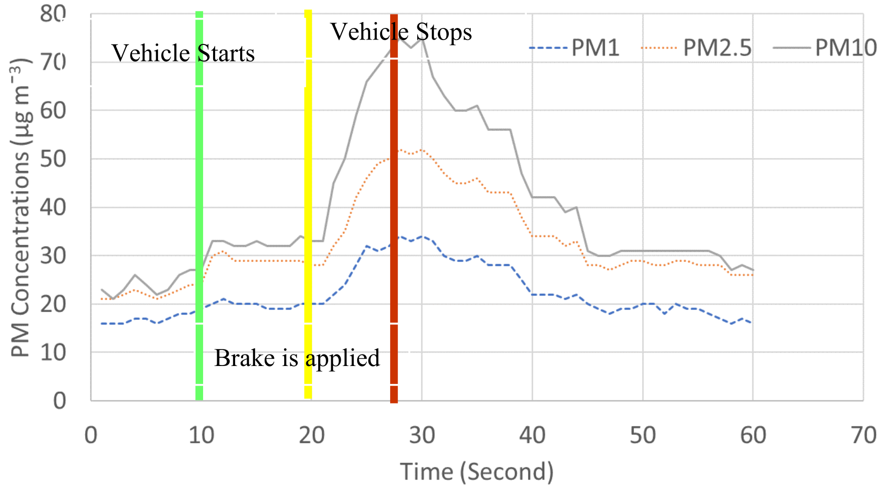

Fig. 5. An example of non-exhaust PM measurement during a braking sequence.

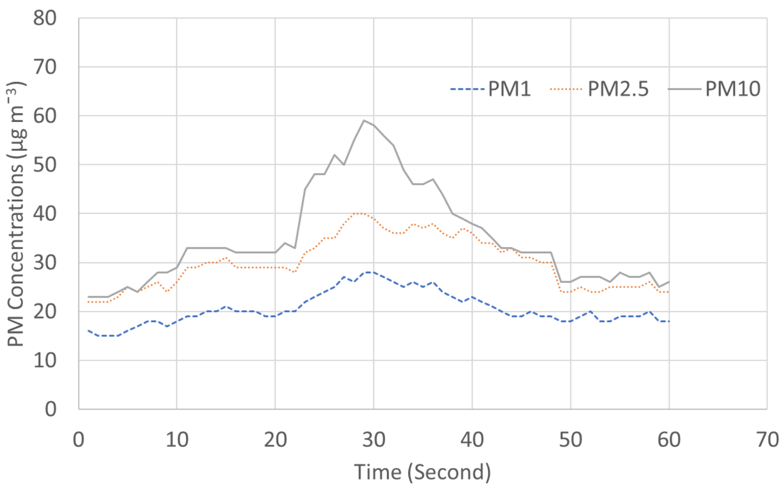

Fig. 6. PM emissions during soft brake test.

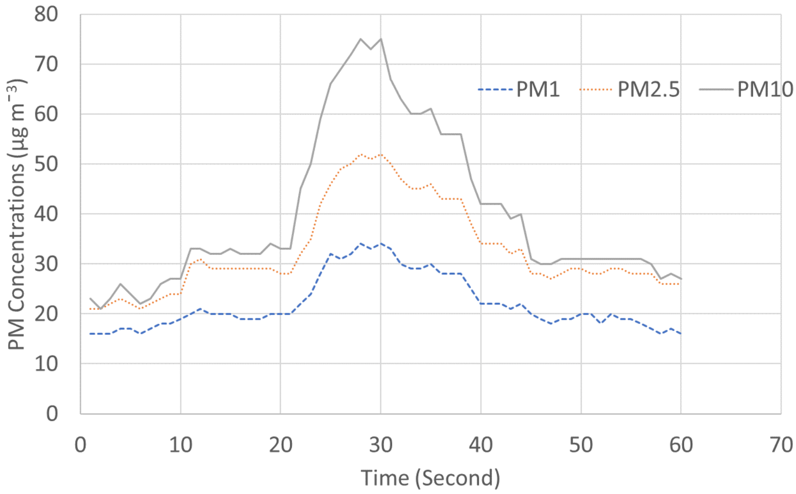

Fig. 7. PM emissions during hard brake test.

Table 3. Measuring data of $PM_{2.5}$ on various moisture levels.

$PM_{2.5}$	Normal Drive (µg m^{-3})	Peak (µg m^{-3})	Ranges of PM Emissions (µg m^{-3})
Time: 10.20 AM Temperature: 29°C Humidity: 70%	55	75	+20
Time: 01.20 PM Temperature: 34°C Humidity: 54%	56	76	+20
Time: 04.30 PM Temperature: 33°C Humidity: 60%	52	70	+18

more PM emissions than the soft one. This corresponds to results demonstrated in some literatures (for example, Hagino *et al.*, 2016). However, both methods of testing yield similar PM emissions' trend. For the current study, the hard brake test is chosen for investigating the payload effect.

Past literatures indicated that the moisture level of the road surface might affects the retention of dust on the road (Amato *et al.*, 2012). Experiments on PM measurements on various temperature and humidity are done and an example of $PM_{2.5}$ measuring data are shown in Table 3. The first column indicates time, temperature, and humidity levels. The second column shows the average values of PM measuring data between the vehicle starts and when the brake is applied. The third column represents the maximum value of measuring data. The fourth column shows the difference between the third and second column representing the range of PM emissions. Based on these results seen in Table 3, there is no substantial impact of moisture level on non-exhaust PM measurement found in the current study.

Fig. 8 shows the time-averaged values of PM_1, $PM_{2.5}$, and PM_{10} emissions on various payloads. Payloads are increased with additional passengers whose weight is approximately 60–70 kg each. PM data in each payload and size are presented in two columns. Data from 0–10 seconds represent the time-averaged values of PM emissions in background (before the vehicle starts). Data from 21–40 seconds represent the time-averaged values of PM emissions after the brake is applied until PM diffusions stop. Time duration of the braking sequence described here is referred to what is previously shown in Fig. 5. Error bars indicate the variability of PM measuring data.

Fig. 9 shows the difference between two columns in Fig. 8 for each PM size in each payload. By considering 2 passengers as the base line case (+0 kg), results show that by increasing payloads on the vehicle, the amounts of PM_{10} emissions are greater during the braking sequence. This result corresponds to literatures found in Amato (2018). However, past results were only focused

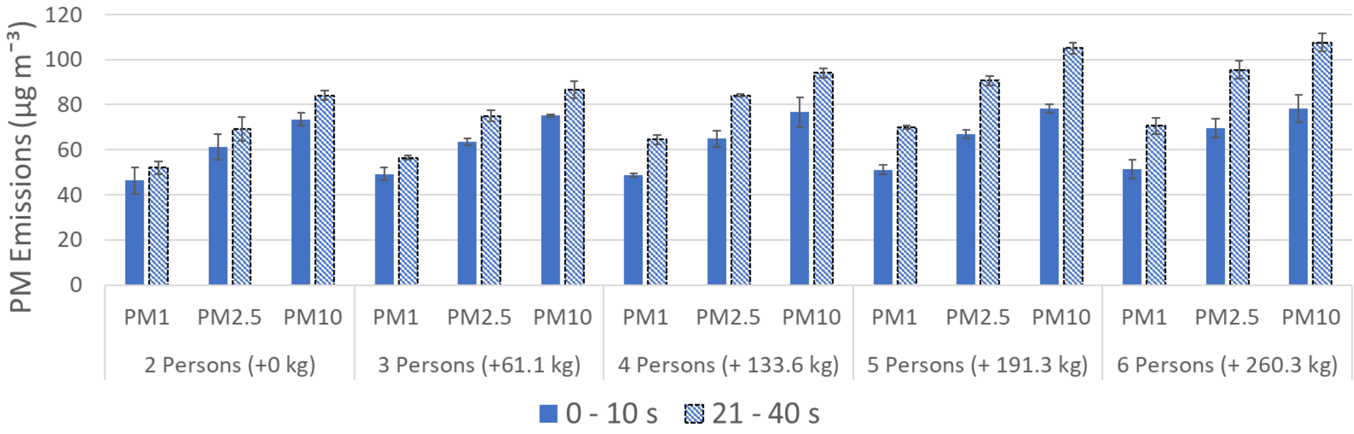

Fig. 8. Time-averaged emissions of PM_1, $PM_{2.5}$, and PM_{10} on various payloads.

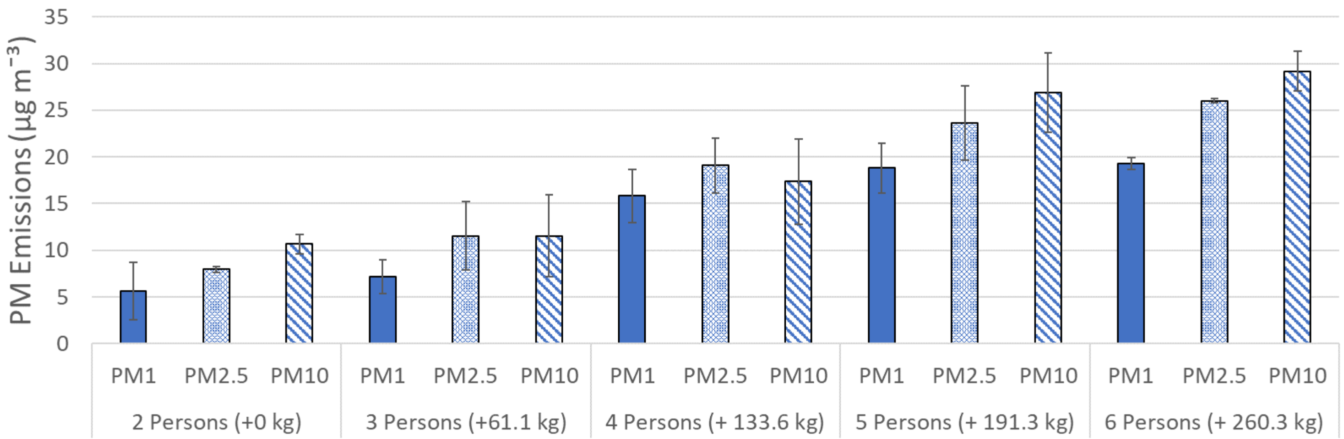

Fig. 9. Effects of payloads on non-exhaust PM_1, $PM_{2.5}$, and PM_{10} emissions.

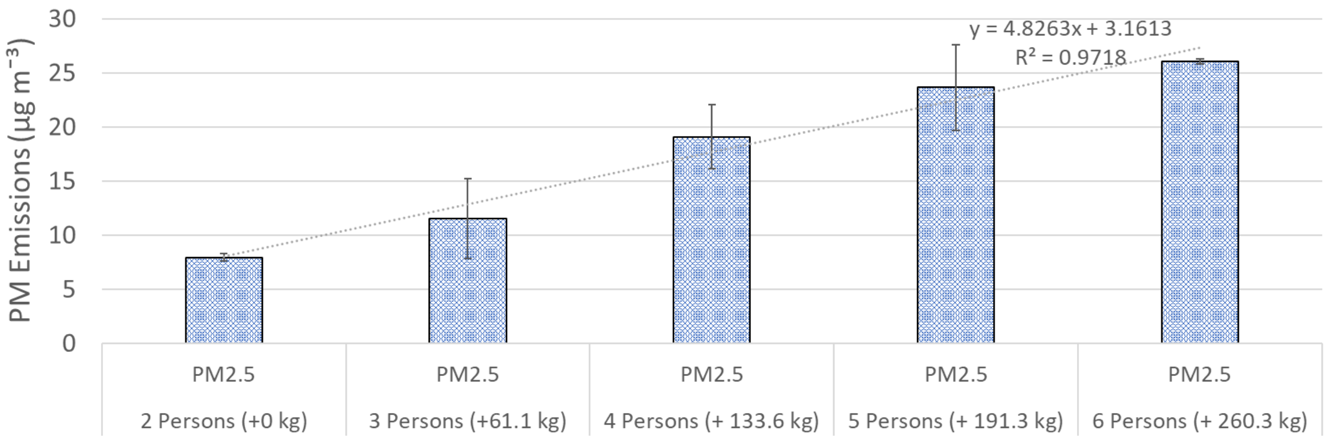

Fig. 10. Non-exhaust $PM_{2.5}$ emissions under various payloads, with the dotted line indicating a linear relationship.

on different sizes of the tested vehicles, that is, larger size vehicles emit more non-exhaust PM_{10} than smaller size ones. In the current study, it is observed that each passenger can yield almost up to 25% increase in PM_{10} emissions. With 6 passengers in the vehicle comparing to 2 passengers, non-exhaust PM_{10} can emit more than 3 times. Same trends are found for non-exhaust $PM_{2.5}$ emissions as shown in Fig. 10. The linear relationship between the payload and $PM_{2.5}$/PM_{10} emissions are observed.

On the contrary, when considering PM_1 emissions, results from Fig. 9 demonstrate that a certain cut point is observed between 3 and 4 passengers. With 2 and 3 passengers, PM_1 emissions are mostly the same. Once there are 4 passengers in the vehicle, PM_1 emissions are doubled and remain the same for 4 to 6 passengers. PM_1 emissions are mostly from the brake wear (Songkitti *et al.*, 2022) whereas $PM_{2.5}$ and PM_{10} emissions are due to resuspension and road dust effects (Simons, 2016). This indicates that the effects of payloads significantly impact PM emissions from resuspension and road dust. However, they have limited effects on the brake wear from a hybrid electric vehicle. This speculation will be investigated thoroughly in the future work.

4 CONCLUSIONS

This research study focuses on the effect of payloads on non-exhaust PM emissions from the hybrid electric vehicle. The onboard PM monitoring device is attached nearby the wheel on the vehicle for real-time PM measurement. Payload is varied from 2 to 6 passengers and data are collected during braking sequences. Results show that by increasing the payload at approximately 60–70 kg for each test, $PM_{2.5}/PM_{10}$ emissions can be increased up to 25%. With 6 passengers in the vehicle comparing to 2 passengers, the non-exhaust $PM_{2.5}/PM_{10}$ is found to increase by 3 times. The linear relationship can also be found between $PM_{2.5}/PM_{10}$ emissions and increased payloads. In the case of PM_1 emissions, variations of payloads have a limited effect. A certain cut point of PM_1 emissions increase can be found with additional mass of 130 kg.

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