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EFFECTS OF VENTILATION MODES ON THE CONCENTRATIONS OF PARTICULATE MATTER (PM2.5) AND INDOOR TEMPERATURE INSIDE VEHICLE CABIN DURING MOBILE CONDITIONS

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ABSTRACT

Indoor Air Quality (IAQ) may come from various field of studies and normally it is related to the air quality level inside a building. Other than building, vehicle cabin can also be considered as one of the indoor spaces and it is known as Vehicle Indoor Air Quality (VIAQ). Recently, vehicle has become one of the most important requirements for a living standard. People use vehicle to travel from one place to another without realizing the exposure to the air pollutant inside the cabin. The high exposure to the many types of pollutants may affect the human health. This study was conducted to investigate one type of pollutants which is the concentrations of Particulate Matter (PM2.5) when a vehicle is moving on the road with different ventilation modes. The data for PM2.5 concentrations and indoor temperatures were collected using direct-reading instruments such as Environmental Monitoring Instrument (EMI) and Thermal Recorder. It was found that different ventilation modes had a significant effect to the concentrations of PM2.5 and indoor temperature.

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Keyword: *Indoor Air Quality, Vehicle Indoor Air Quality (VIAQ), Particulate Matter (PM2.5), Environmental Monitoring Instrument (EMI)*

INTRODUCTION

Recently, there has been an increase in the awareness about the importance of environmental protection. In general, there are nine recognized sources of pollutant that can damage the environment such as air pollutant, water pollutant, soil pollutant, noise pollutant, radioactive pollutant, thermal pollutant, light pollutant, visual pollutant and personal pollutant (Rana, 2006). However, in a study related to the IAQ, the most related pollutant is air pollutant. Air pollutant comes from a wide variety of sources such as dust or excessive gases like carbon dioxide or other vapours that cannot be effectively removed through natural cycles, such as the carbon cycle or the nitrogen cycle. The most excessive sources of air pollutant include vehicle or manufacturing exhaust, forest fires, volcanic eruptions, dry soil erosion, and building construction or demolition (Sanidas et al., 2017). These pollutants were normally found in the outdoor environment and may penetrate inside indoor environment such as inside a building or vehicle. VIAQ is a common term used to represent IAQ level inside vehicle cabin. Based on several studies, the IAQ level inside vehicle cabin was influenced by several factors such as the material used to construct the vehicle interior components, pollutants from the outside cabin and the user of the vehicle itself (Abi-Esber & El-Fadel, 2013; Xu et al., 2015; You et al., 2007).

A liquid droplets and mixture of solid particles that were found in the air is known as Particulate Matter (PM)((USEPA), n.d.). PM comes in two shapes which are coarse and fine. The range of sizes or diameters of coarse particles is from 2.5 to 10 micrometres, whereas for fine particles, the diameters are smaller than 2.5 micrometres. In Malaysia, one of the existing criteria to measure air pollutants is PM10 and an amendment has been done by adding a new criteria which is PM2.5 (DoE, 2013). In the micro-environment such as inside vehicle cabin, most of the analysis done in the previous studies used PM2.5 as an indicator to represent the air quality level in different ventilation modes as shown in Table 1. Instead of ventilation modes, the other parameters used to analyse PM2.5 concentrations inside vehicle cabin is vehicle age. A study conducted by Abi-Esber & El-Fadel

(2013) revealed that by combining both parameters; ventilation modes and vehicle age, the concentration of PM2.5 is much lower for a new vehicle if the ventilation mode used is AC Rec (Air Conditioning on with recirculation air). This is due to the enhanced air tightness and absence of cracks and leaks in new vehicle cabins compared to old ones. The other reason is the new and enhanced particle filtration system for a new vehicle, which also contributed to the lower PM2.5.

Table 1. Comparative Assessment of PM2.5 Concentrations inside Vehicle Cabins

Study	Location	Level	Type of Reading	Type of Vehicle	Method of Measurement	Ventilation Mode
(Charles Rodes, Linda Sheldon, Don Whitaker, Andy Clayton, 1999)	Sacramento CA	10.8	Mean	Sedan Cars	Gravimetrically	Window closed, medium fan speed, vents open or closed
(Charles Rodes, Linda Sheldon, Don Whitaker, Andy Clayton, 1999)	Los Angeles CA	43	Mean	Sedan Cars	Gravimetrically	Window closed, medium fan speed, vents open or closed
(Riediker et al., 2003)	Raleigh NC	23	Mean	Patrol Trooper	Gravimetrically and with a DataRam nephelometer	AC on recirculation
(Boogaard et al., 2009)	Netherlands	48.9	Mean	Sedan Cars	Portable TSI DustTrak, no calibration	Window closed, AC off, fan on
(Adams et al., 2001)	London, UK	35.7	Mean	Sedan Cars	Gravimetrically	Open windows
(Levy et al., 2002)	Boston MA	100	Media	Sedan Cars	Potable TSI DustTrak calibrated to tapered element oscillating microbalance	Open windows
(Huang et al., 2012)	Beijing, China	31.6	Mean	Taxi	Portable LD-6S spectrometer calibrated gravimetrically	Window closed, AC on
(Both et al., 2013)	Jakarta, Indonesia	87	Median	Sedan Cars	Portable TSI DustTrak calibrated to beta attenuation monitor	With and without AC
(Abi-Esber & El-Fadel, 2013)	Beirut, Lebanon	71	Mean	Sedan Cars	Portable TSI DustTrak, no calibration	Window half opened, AC on recirculation, AC on fresh air

(Source: Author)

Ding et al. (2015) conducted an experiment to measure indoor and outdoor ratio (I/O) for PM2.5 concentration in different ventilation modes. It is found that when the air inside vehicle cabin circulated with outdoor air, the high ratio indicates that outside PM2.5 is the main contributor to the high concentration of PM2.5 inside vehicle cabin. If the air inside vehicle recirculated with outdoor air, the ratio that was obtained differed. The lower value of ratio indicates that the vehicle body could block the entry of PM2.5 concentration from the outside. Comparing the two figures, it can be concluded that the influence of ventilation mode on the I/O values and PM2.5 concentration levels inside the vehicle is significant. To monitor the exposure limit for PM2.5, United States Environmental Protection Agency (USEPA) and World Health Organization (WHO) had introduced the guideline that can be used as a reference by public. Table 2 shows the summary of PM2.5 permissible exposure limit (PEL) for these two agencies. USEPA had set two different standards for annual concentration limits which are primary and secondary. The primary standards set limits to protect public health, including the health of at-risk populations such as people with pre-existing heart or lung disease (such as asthmatics), children, and older adults, while the secondary standards set limits to protect public welfare, including protection against visibility impairment, damage to animals, crops, vegetation, and buildings.

Table 2. Summary of PM2.5 Permissible Exposure Limit (PEL)

Averaging Time	Permissible Exposure Level (PEL), USEPA, 2012	Permissible Exposure Level (PEL), WHO, 2005
24-h	35μg/m3	25μg/m3
Annual	12μg/m3 (Primary)	10μg/m3
	15μg/m3 (Secondary)	

(Source: Author)

In studies related to vehicle indoor air quality, there are many types of instruments and methods used to measure pollutants inside the car cabin. The instruments or methods to be used are determined by the types of pollutants to be measured. Normally, most of the previous studies used direct-reading instruments due to ease of operation and the data recorded is more accurate. For instance, Abi-Esber and El-Fadel (2013) used DustTrak analyzers to measure PM2.5 in their study, where the accuracy of this instrument is 0.1% of the reading. Other than PM2.5, a few studies such as the study conducted by Xu et al., (2015) used direct-reading instruments to measure total volatile organic compounds (TVOCs). TVOCs does not represent all types of volatile organic compounds (VOCs). Theoretically, there are many types of VOCs and there is no direct-reading instrument in the market that is able to measure all the VOCs types concurrently. Besides, active air sampling is a method usually used by the researchers to identify the types and the concentrations of VOCs. Yoshida and Matsunaga (2006) used this method to analyse 162 organic compounds in their study.

People use vehicle to travel from one place to another for various purposes. According to the statistic from the portal of Malaysia Local Authority which is Road Transport Department, in 2015, the total number of vehicles active on the road was about 18 million units (JPJ Malaysia, 2015). This large figure strongly supports that vehicle is an important and essential necessity in human life for daily activities. The large number of vehicles commuting on the road contributes to traffic congestion especially in the major cities and this has increased the travelling time. Due to this situation, vehicle cabin is essentially a part of a living environment. However, the awareness among people about it is still lacking. There are a lot of previous studies that have been done in order to gain new knowledge regarding VIAQ and the same thing goes to this study, where it aims to investigate the effects of different ventilation modes to the concentration of PM2.5 and indoor temperatures.

METHODOLOGY

For this study an experimental design was employed. The experimental work was conducted in three different ventilation modes which are air conditioning off and circulated with outside air, air conditioning on and circulated with outside air, and air conditioning on and circulated without outside air. Table 3 shows the details of ventilation modes that were set in this study. Since this study also aim to investigate the effect of indoor temperature to PM2.5 concentration, data collection activity was conducted between 10.00 am to 4.00 pm as the sun loads within this period is the highest (Jasni & Nasir, 2012).

Table 3. Detail of Ventilation Modes

Types of Ventilation	Description
AC off RC off	Air conditioning off and circulated with outside air
AC on RC off	Air conditioning on and circulated with outside air

AC on RC on	Air conditioning on and circulated without outside air

(Source: Author)

The vehicle was driven on the selected route around Universiti Teknologi MARA, Shah Alam at a constant speed as 30 ± 5km/h, in which can be considered as a safe speed with an optimum air exchanged rate from outside (Xu et al., 2015). This took 20 minutes for the measurement under each ventilation mode before switching to another. The test was conducted on a national sedan car and the detailed specifications is shown in Table 4. The studied vehicle was manufactured in 2011, which can be considered as an old car.

Table 4. Detailed Specification of the Studied Vehicle

Model	Dimension	Year of Manufacture
Nationally Made Sedan Car	Length, 4,257 mm Width, 1,680 mm Height, 1,502 mm Cabin Volume, 10,742 mm3	2011

(Source: Author)

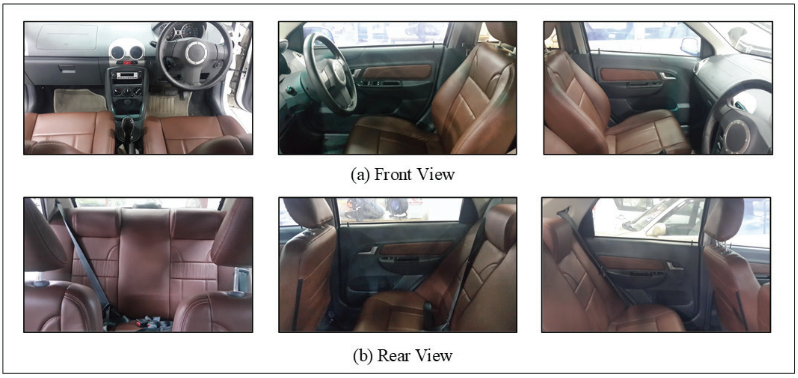


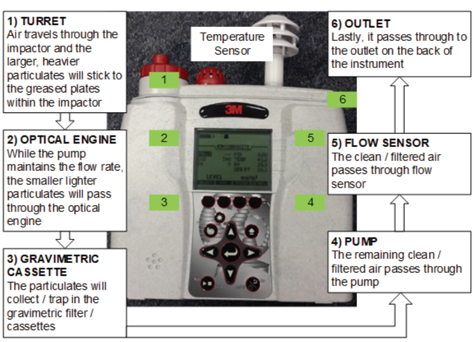
Figure 1. Interior Condition of Studied Vehicle

(Source: Author)

Data were collected using direct reading instrument which are Environmental Monitoring Instrument (EMI) and Thermal Recorder. EMI was used to measure the concentration of PM2.5. Meanwhile, Thermal Recorder was used to record the indoor temperature inside vehicle cabin. Table 4 shows the EMI and Thermal Recorder together with the detailed specifications. EMI is a portable area monitoring instrument with a laser-photometer that measures and stores concentration levels of airborne-dust over time. EMI has four settings which include 2.5µm, 4µm, 10µm, or none (100µm). Once the impactor setting was selected, the EMI measures real time aerosol/dust concentration using a 90º optical light scattering photometer to determine the total mass concentration (in units of mg/m3) of particulate matter. Additionally, gravimetric sampling, a more accurate method, was also used to determine the mass of particulates. The gravimetric sampling is a type of filtering process in which the particulates are collected and filtered into the gravimetric cassette after the dust passes through the optical engine of the EMI. The pump was used in the particulate sampling process as a source of air movement, so the particulates were aspirated (or suctioned out) and collected for measurement. The flow rate was 1.67 L/min. The pump was typically calibrated before each gravimetric sampling.

Thermal recorder is a temperature and humidity data logger. It was designed to measure and record the data in wide range and more precision with the accuracy of ±2.5% RH. The data can also measure and record in the range of 0 to 99% RH at temperatures from -30 to 80 ˚C. The type of temperature sensor used in this instrument was platinum resistance and electrostatic capacitance type sensors. The logging capacity is 8000 data sets at one time. Recording interval can be set from 1 second to 60 minutes.

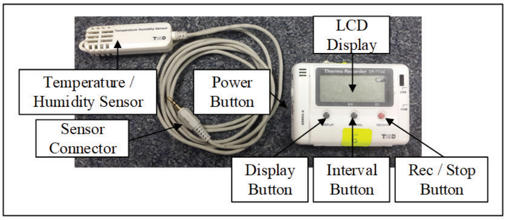
Table 5. Instrument with Detail Specifications

<table>
<tr><th>Instrument</th><th>Detail Specification</th></tr>
<tr><td>Environmental Monitoring Instrument (EMI)

</td>
<td>To measure the concentration of PM2.5

Method – photometer

Display range – 0 – 20,000 µg/m3

Accuracy - +/- 15% (Calibrated to Arizona road dust; ISO 12103, A2 Fine Test Dust)</td></tr>
</table>

Thermal Recorder 	To measure the indoor temperature inside vehicle cabin Sensor types - Platinum resistor Accuracy - +/- 0.5˚C

(Source: Author)

The experimental works were conducted in two different days (MP1 and MP2) and the flow process is illustrated in Figure 2. Data collection for both days were collected in 1 hour with three different ventilation modes and the procedure was as follow;

1. All direct-reading instruments were allocated to the adult's breathing zone as shown in Figure 3.
2. To achieve a steady state condition, ventilation process was performed for all the test procedures by opening the entire vehicle's doors for 15 minutes.
3. The doors of the vehicle were closed, and the entire direct-reading instruments were switched on to start data collection. Then, the vehicle was driven through the dedicated route. The data collection started with ventilation mode (AC off RC off), followed by AC on RC off and finally AC on RC on. It took a total of 1 hour to complete the data collection for all ventilation modes, and each of the ventilation modes was changed for every 20 minutes. The measurement activities for mobile test took place from 2.00 pm until 4.00 pm.
4. The results recorded from the direct-reading instruments were exported to the desktop for further analysis.

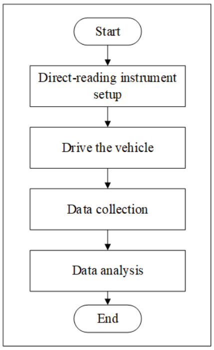


Figure 2. Process Flow

(Source: Author)

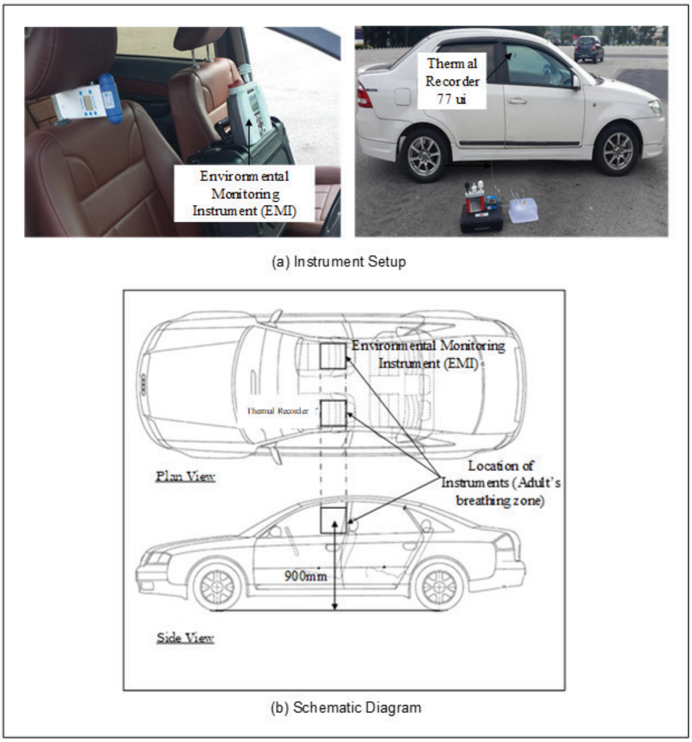


Figure 3. Experimental Setup and Schematic Diagram

(Source: Author)

RESULTS AND DISCUSSIONS

Figure 4 shows the results obtained from the experimental works for both indoor temperatures and concentration of PM2.5. As mentioned earlier in the research methodology section, experimental works were conducted in two different days represented by MP1 and MP2. Overall, the concentration of PM2.5 shows an inconsistent result for all ventilation modes (AC off RC off, AC on RC off and AC on RC on). However, on average the patterns for each ventilation mode express the downward trend. Under ventilation mode AC off RC off, the concentration of PM2.5 was high, and this is possibly due to the dusk or particle that entered the vehicle cabin when the air was exchanged between the inside and outside. Another possible factor is the existing dusk or particle inside the vehicle that entered during the experimental setup. The concentration of PM2.5 was lower for ventilation mode AC on RC off. This condition could be due to the dusks or particles that were removed from the vehicle cabin by the air conditioning blower.

Under ventilation mode AC on RC on, the low concentration of PM2.5 indicated that the dusks or particles from outside of the vehicle was not able to enter vehicle cabin due to the no air exchange between inside and outside air. The similar finding was reported by Ding et al. (2015) and Abi-Esber and El-Fadel (2013) where the PM2.5 concentrations decreased when ventilation mode was changed from (AC on RC off) to (AC on RC on). The results gained from this study also showed a strong argument with the theoretical transport or mass balance model that was derived by Switzer (1992), where the in-cabin concentrations under ventilation mode (AC on RC off) and (AC on RC on) were influenced by air exchange rate from infiltration through vehicle crack (λinf) and air exchange rate from the heating, ventilation and air conditioning (HVAC) system (λhvac).

Therefore, it is recommended to use ventilation mode (AC on RC on) when driving a vehicle to get a better air quality level. However, it depends on the driving route where it is suggested to use ventilation AC on RC off if the route was in the green area without any potential air pollutants to encourage the air exchange that brings clean air with the oxygen and remove the carbon dioxide produced from driver breathing activity.

When the studied vehicle was moving with the AC off RC off mode for both days MP1 and MP2, the data for final measurements of indoor temperature increased about 6% from the initial measurements. These conditions occured due to the air conditioning system that was not working and accelerated the sensible heat especially produced by the driver and it was accumulated inside vehicle cabin. Besides that, the heat accumulation also came from the outside environment, where it entered the vehicle cabin through the air exchange process inside and outside.

The measurements of indoor temperature suddenly decreased by about 6% for both days MP1 and MP2 after the ventilation mode was changed from AC off RC off to AC on RC off. This was because the sensible heat and outdoor heat from environment that accumulated inside the vehicle cabin was absorbed and released to the outdoor environment by the air conditioning system. Under the last ventilation mode, which was AC on RC on, the measurements of indoor temperature keep decreasing until the end of the experimental works for both days MP1 and MP2. The air inside vehicle cabin was circulated without outdoor air and subsequently the heat from the outside environment was unable to enter the vehicle cabin. Therefore, the air conditioning system kept working to absorb and remove only sensible heat inside the vehicle cabin.

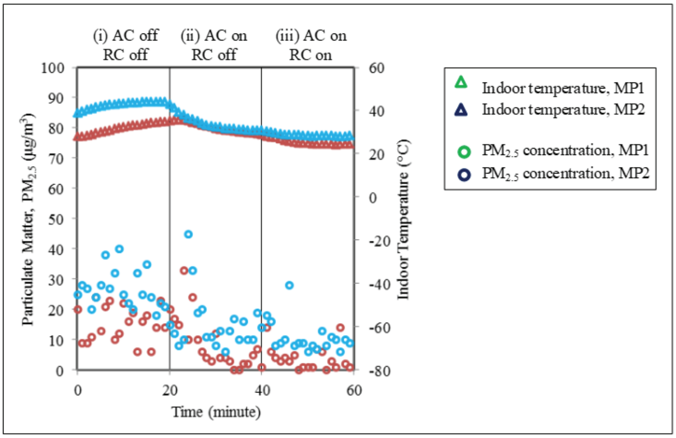
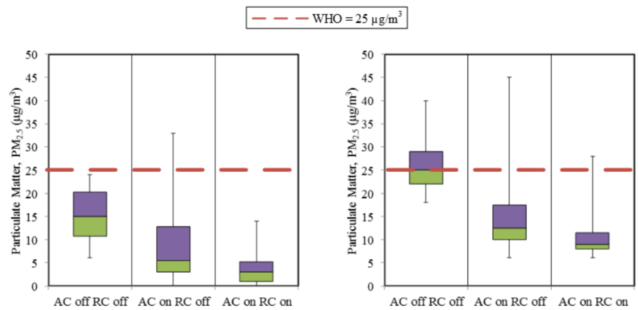


Figure 4. Variation of Indoor Temperature and PM2.5 During Mobile Test
(Source: Author)

Figure 5(a) and (b) show the comparison of PM2.5 concentrations obtained from this study with the standard guideline introduced by WHO. Overall, the result showed that the concentration of PM2.5 was the lowest when the vehicle was driven using air-conditioning system and air recirculation mode (AC on RC on), in which the median recorded for both cases MP1 and MP2 were 8 and 3 times lower than the allowable limit. Furthermore, the average concentration of PM2.5 which was lower than the allowable limit by WHO guideline indicated a good air quality level during this mode. As aptly put by Praml and Schierl (2000), the concentration of particle inside vehicle cabin was originated from external sources such as road traffic, where different location of the study resulted in a different concentration level.



(a)

	AC off RC off	AC on RC off	AC on RC on
Minimum (μg/m³)	6.0	0.0	0.0
Median (μg/m³)	15.0	5.5	3.0
Maximum (μg/m³)	24.0	33.3	14.0

(b)

	AC off RC off	AC on RC off	AC on RC on
Minimum (μg/m³)	18.0	6.0	6.0
Median (μg/m³)	25.0	12.5	9.0
Maximum (μg/m³)	40.0	45.0	28.0

Figure 5. Comparison with Standard Guideline for (a) case MP1 and (b) case MP2

(Source: Author)

CONCLUSION

As a conclusion, the results gained from this study show that ventilation modes did affect the concentration of PM2.5 and indoor temperature. It is suggested to use ventilation mode (AC on RC on) to get a better air quality level especially related to PM2.5 concentration as this is where the lowest concentrations were recorded in this mode. Other than better air quality, it also provides a low indoor temperature which contributes to the comfortable environment especially to the driver. However, this depends on the environment of the driving route. If the area was clear from any potential air pollutant, it is better to use ventilation mode (AC on RC off) to encourage more oxygen getting into the vehicle cabin and concurrently remove the carbon dioxide produced by the driver's breathing activity.

A comparison with the standard guideline introduced by WHO shows that the concentration of PM2.5 does not exceed the maximum allowable limit for ventilation AC on RC off and AC on RC. This indicates that these two ventilation modes are recommended to be used when a driver drives a vehicle.

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