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Personal exposure and inhalation doses to PM_1 and $PM_{2.5}$ pollution in Iraq: An examination of four transport modes

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Abstract

Particulate matter (PM) is a major indicator of urban air quality deterioration due to its impact on human health, atmospheric visibility and climate change. However, sufficient data on personal exposure to air pollution is still rare or unavailable in developing countries such as Iraq. Thus, this paper investigated the personal exposure and inhalation doses of PM_1 and $PM_{2.5}$ in Al-Hillah city, Iraq, for four common motorized transportation modes, namely open windows car, closed window car, bus, and motorbike. A portable monitoring device was used to collect the data during morning and afternoon hours in two main streets in the city. A t-test examination of the obtained results showed that the mean exposure concentration for both $PM_{2.5}$ and PM_1 were significantly different in the two streets form most of the transportation modes. The difference in the means of the measured PM_1 and $PM_{2.5}$ in the morning and afternoon trips were statistically significant for all the transportation modes except for bus in 60 street. This highlights the special and temporal variation of air pollution in the city. This is largely due the deteriorated infrastructure and lack of control policies in the city. Overall, $PM_{2.5}$ and PM_1 measured exposure concentrations were higher in the morning trips than in the afternoon ones. Regardless of the time or place of measurements, closed windows cars always had the lowest exposure concentrations to PM_1 and $PM_{2.5}$. The alarming observation in this study was the high levels of PM_1 and $PM_{2.5}$ that exceeded the recommended WHO limits, and were higher than the reported concentrations in the world bank database. The study findings present preliminary data on personal exposure concentrations and inhalation doses for travelers in Al-Hillah city, which can be utilized for global studies of air contamination in countries in similar situations as Iraq and for developing local control strategies.

Keywords: Air Pollution, Transportation, Particulate Matter, Inhalation dose, Al-Hillah, Iraq

1. Introduction

Several health impacts such as respiratory and cardiovascular morbidity result from increasing the levels of ambient air pollution. Particulate matter (PM) with an aerodynamic diameter ≤2.5 μm and ≤1 μm ($PM_{2.5}$ and PM_1) can easily enter the lungs through inhalation (Manojkumar et al., 2019). Studies have shown that long-term exposure to $PM_{2.5}$ can impact lung development (Heal et al., 2021; Gehring et al., 2013; Zwozdziak et al., 2016), neurological development and cognitive function development (Sunyer et al., 2015; Basagaña et al., 2016). Exposure to $PM_{2.5}$ and PM_1 pollutions, especially among the elderly, children, and those with pre-existing cardio-pulmonary diseases, could negatively impact their health as they are considered more vulnerable (Segalin et al., 2017). Many factors could increase PM doses and accelerate their movement into children's lungs, such as their mouth-to-nose breathing high ratio, their developing system, and high inhalation rate (Saadeh and Klaunig, 2014; Sharma and Kumar, 2018). A study has shown that ambient $PM_{2.5}$ was the 5th among the mortality risk factor in 2015 (Cohen et al., 2017). The Global Burden of Diseases data in 2015 also indicated that exposure to $PM_{2.5}$ was the cause of 4.2 million deaths and about 103.1 million global disability-adjusted life-years (Forouzanfar et al., 2016; Cohen et al., 2017). Ambient PM_1 contributed nearly to 80% of $PM_{2.5}$ in most PM observation stations in China (Wang et al., 2015). The smaller size fractions of PM have more toxic mortality impacts (Hu et al., 2018). This portion is more likely to reach deeper into the respiratory system carrying with it more toxins derived from anthropogenic emissions (Liu et a., 2013; Meng et al., 2013). PM_1 is comprised of primary organic aerosols, sulfate, ammonium, nitrate, and chloride (Niu et al., 2020). These chemical components of PM_1 could be originated from traffic, cooking emissions, and coal combustions (Niu et al., 2020; Zhang et al., 2018). The main composition of $PM_{2.5}$ is carbon compounds, ions, and elements derived from different sources such as industrial emissions, traffic, sea salt, and biomass burning (Hajizadeh et al., 2018; Yarahmadi et al., 2018; Pio et al., 2020).

It has been reported that dust storms originating from Syrian and Iraqi deserts were considered as the main contributors to $PM_{2.5}$ concentrations in the Middle East (Farahani and Arhami, 2020; Ali-Taleshi et al., 2021). This makes Iraq more prone to increasing levels of air pollutants as the climate gets drier. Additionally, meteorological factors such as wind speed, wind direction, relative humidity, and atmospheric temperatures significantly affect the diffusion, accumulation, deposition, transportation, and emission intensity of particulate matter (Buonanno et al., 2011; Landguth et al., 2020).

Traditionally, a conventional monitoring station is usually employed to assess the individuals' exposure to air pollutants (Steinle et al., 2013). The collected data from the fixed station cannot truly represent the actual concentration in a particular urban environment such as highly polluted roads within a range of a few meters, there might be a large spatial variability of airborne particles (Targino et al. 2018; Kumar et al., 2015). Studies have shown that portable monitors exhibited a higher level of air pollutants than data collected from the fixed stations (Jerrett et al. 2005). Motorized transportation modes (car, bus, and train) and non-motorized modes (cycling and walking) have been carried out to measure the personal exposure to particles matter throughout the world (Kumar et al., 2018; Karanasiou et al., 2014).

For instance, in Salt Lake City, Utah (USA), a study was conducted to measure the personal exposure to $PM_{2.5}$ in six transportation modes namely bicycle, walking, driving with windows open and closed, bus, and light-rail train using portable SidePak^{TM} (Chaney et al., 2017). The study concluded that commuters using motorized transportation modes receive less $PM_{2.5}$ doses and have less exposure rates than the active commuters. Further, driving with windows closed is protective against traffic-related $PM_{2.5}$ exposure. Similarly, a SidePak portable device was also utilized to measure $PM_{2.5}$ in London underground network (Saunders et al. 2019). Results showed that in London Underground train carriages, $PM_{2.5}$ concentrations were 18 times higher than street level. Molle and his colleagues investigated the passengers' exposure to traffic air pollution inside Parisian buses in three positions (front, middle and rear) (Molle et al., 2013). They found that the mean $PM_{2.5}$ mass concentrations inside the bus were the same at the three studied positions.

According to United Nations, by 2050, the urban dwellers in both Africa and Asia is expected to increase from 55% to 68% of the world's population (United Nations, 2018) and about 70% of the Iraqi population lives in the urban areas (Iraq population, 2020). As a result, more individuals will be exposed to particulate matter derived from motorized transportation and other sources of pollutions. Global atmospheric modelling research showed that the Middle East is a hot spot for photochemical air pollution (Lelieveld et al., 2009). Hence, there is growing concerns regarding the regional and global environmental consequences of the elevated air pollution in this area. Iraq may significantly contribute to air pollution in the region due to the absence of regulations and control policies. Studies concerning air quality in Iraq are mainly focused on the capital city of Baghdad (Hamad et al., 2015). However, these studies measured only the ambient $PM_{2.5}$ in fixed monitoring stations and they did not include the personal exposure to PM concentrations. There is very limited data available for air quality and personal exposure to air pollutants in other provinces in Iraq due to the lack of monitoring stations. It was previously reported that Al-Hillah city had high level of Polycyclic Aromatic Hydrocarbons (PAHs) and different heavy metals found in the street dust indicating the prevalence of particulate matter in the air (Grmasha et al., 2020; AL-SAREJI et al. 2021). As there is a growing interest among the broad scientific community in submicron particulate matter (Samek et al., 2017), and the lack of PM data especially in Iraq that has been through wars, dramatic economic and environmental changes, this study aims to provide for the first time quantitative measurements of personal exposure to air pollution in Al-Hillah city. Availability of air quality data would help validating air pollution estimation models developed based on remote sensing and machine leaning techniques such as the recent work conducted by Jing and his co-workers on studying $PM_{2.5}$ in Iraq and Kuwait (Li et al., 2021). These large-scale studies are useful for tracking the transboundary transport of air pollutants. The aim of this work aligns well with the third Sustainable Development Goal of the United Nations for ensuring healthy lives for the global population at all ages (Sustainable Development Goals, 2022).

In this work, insights into the reality of variations in ambient air quality experienced during travel on different modes of motorized transport are provided for the studied site. Four common modes of motorized transportation namely open windows car, closed windows car, bus, and motorbike were chosen in this study. A portable SidePak^{TM} was used for measuring PM_1 and $PM_{2.5}$ levels on site. measurement. This device was selected for performing the measurements due to its reliability and wide use for measuring particulate pollution in air. The determination of personal exposure concentrations and inhalation doses in congested routes of Al-Hillah city during both morning and afternoon peak hours was carried out. Statistical analysis of the collected data were performed to study the spatial and temporal differences.

2. Materials and Methods

2.1. Instrumentation

A portable SidePak^{TM} aerosol type AM520, TSI Inc., USA, was utilized in this work to measure both PM_1 and $PM_{2.5}$. This device was employed in different locations worldwide to measure personal exposure to particulate matter (Saunders et al., 2019; Shezi et al., 2020; Maji et al. 2021; Vinnikov et al., 2021, Manojkumar and Srimuruganandam, 2021; Lenssen et al., 2022). While this device is widely accepted in the literature, it has some shortcomings that is important to highlight such as the provision of indirect measurements and high noise (Sloan et al., 2016). The measurement principle of AM520 monitoring instrument depends on light-scattering by airborne particles in real-time. The particles are drawn to the sensing chamber, which is illuminated with laser light. The particles in turn scatter the light. The scattered light is then collected by focusing optics and its intensity is measured by photo detector. The measured light is converted to voltage. It is proportional to the number of particles, which can be converted to mass concentration through the estimation of the particle density. As mentioned previously, this indirect measurement of particles concentration is one of the most concerning drawbacks of the device and it can be a potential source of error. The final reading of particles mass concentration is produced by multiplying the voltage by internal calibration constant. It should be noted that light scattering depends not only on mass concentration of particles, but also on their density morphology and reflection index. The sensing volume of the AM520 is constant and defined by the intersection of the aerosol stream and the laser beam. Mass concentration is calculated from the intensity of light scattered by the aerosol within the fixed sensing volume. Since the sensing volume of the AM520 is known, the reading can be converted by the device microprocessor to units of mass per volume (mg/m^3) (TSI Incorporated, 2016). The device detection range is between 0.001 and 100 mg/m^3, and the operating temperature and the relative humidity ranges are 0–50 °C and 0- 95%, respectively. Based on the manufacturer recommendations, the specified detection range of the device to be suitable for $PM_{2.5}$ and PM_1 measurements. Additionally, the same device was used in many recent studies for measuring PM_1 and $PM_{2.5}$ (Manojkumar et al, 2021; Li and Peng, 2022). $PM_{2.5}$ and PM_1 impactor inlets were placed upon the measurements of each target PM to remove any particles greater than 2.5 and 1 µm respectively. Cleaning the impactors as well as checking the battery and the memory of AM520 were performed before each run. SidePak default calibration was set by the factory to the respirable fraction of the International Organization for Standardization 12103–1, A1 Ultrafine Test Dust.

The optical properties of the ambient aerosols such as density, size morphology, size distribution, and refractive index are different from A1 Test Dust, and this could cause an overestimate in measuring PM exposure concentrations (Wang et al., 2018; Li et al., 2019). A1 Test Dust was originally selected as the ISO 12103 photometric calibration standard as it is fairly representative of a range of windblown dust. However, it does not represent the ambient measurement of urban pollution sources. An ambient calibration factor of 0.38 would be closer to actual reference method concentrations than utilizing the factory default calibration factor of 1 in case of calibration cannot be performed. Thus, a photometric calibration factor (PCF) of 0.38 for reporting the measured values was selected based on the recommendations of the manufacturer for fugitive emissions measurements of ambient aerosol in an urban environment (TSI Incorporated, 2013 and 2022). Thus, the AM520 measurements were multiplied by this factor to compensate when recording aerosols with different photometric properties than the one employed during the factory calibrations. The recommended PCF by the manufacturer is based on the outcome of a study conducted by Wallace et al. (2011) that was found to be the most suitable correction factor for the device compared to other reported factors by studies used the same device.

The relative humidity also influences the measurements through the uptake of water vapour by the ambient aerosol particles (Chakrabarti et al., 2004). Equation (1) was employed to correct the effect of relative humidity (Chakrabarti et al., 2004, Yang et al., 2019), which was applied for some data points in this study where relative humidity exceeded the threshold of 60 %.

$$\mathrm{CF} = 1 + \frac{0.25 \times RH^2}{1 - RH} \quad (1)$$

Where RH is the relative humidity and CF is the correction factor

AM520 was calibrated by the manufacturer within the recommended yearly intervals. For the purpose of obtaining a constant flowrate (about 1.7 L/min), a TSI model 4146 flowrate calibrator was used. The collected data was uploaded to the TrakPro™ software and checked. Data were rejected prior outlier detection tests for runs where the device was noticed to be malfunctional such as recording low air flow. The detection for outliers was performed applying Grubbs test. OriginPro 2018 software was utilized to conduct Grubbs test. The difference between the means of the measurements' sets conducted for the selected locations, time periods and transportation modes were studied applying *t-test*.

2.2. Dose estimation

According to (Ramos et al., 2017 and Manojkumar et al, 2021) the estimated inhaled dose can be calculated by the following equation (2).

$$\text{Inhalation dose } (\mu\text{g}) = C \times \text{MV} \times T$$

$$\text{Inhalation dose per kilometre travelled } (\mu\text{g/Km}) = \frac{\text{Inhalation dose}}{D} \quad (2)$$

Where:

C is the exposure concentration (μg/m^3)

MV is minute ventilation (m^3/ min)

T is sampling trip duration (min)

D is the distance (km)

In this study values indicated by the US EPA Exposure Factors Handbook were adopted (US EPA, 2011). The minute ventilation rate of 0.01 m^3/min for all motorized commutes was selected (US EPA, 2011).

2.3. Sampling site description

The current work was performed in Babylon governorate, Iraq, particularly in Al-Hillah city. The governorate is located between longitudes (44°2'43''E and 45°12'11''E) and latitudes (32°5'41''N and 33°7'36''N) (Chabuk et al., 2018). It is located about 100 km south of Baghdad, the capital of Iraq, with a total of 2.15 million inhabitants (Iraqi Ministry of Planning, 2016) and a 5315 km^2 area (IMMPW, 2009). The average annual wind speed in the investigated area is 7.2 km/h, with the average annual precipitation in Babylon is 102 mm (Chabuk et al., 2018). Two major streets were examined in the investigated area as they are located in the middle of Al-Hillah city. Figure 1 illustrates the city location and the two selected major streets (60 and 80 streets). The maps were constructed using Quantum Geographic Information System (QGIS) software version 3.18 and by using the following websites to download the shapefiles in this work:

https://www.efrainmaps.es/english-version/free-downloads/world/; https://www.diva-gis.org/gdata. Plugins (QGIS cloud) was installed in QGIS to work on Open Street Map humanitarian data model. The 60 street, 6 km long and 60 meter wide with three lanes in each direction, is considered one of the major streets in Al-Hillah city that connect the south governorates with the capital city. It starts from Nader bridge to Al-thawra bridge. The street suffers from the absence of basic infrastructures such as the lack of sewer and rain network and ventilation cover on the sidewalk. Recently, there have been significant movements of clinics to this street. The street combines residential, commercial areas, government organizations, and private and government hospitals.

The 80 street is 11.5 km long and 60 meter wide with three lanes in each direction, is also an important path that connects the city with two provinces, Al-Najaf and Karbala. The street is a fast-growing one in terms of new residential, commercial areas, and some governmental organizations. The street begins from Najaf-Al-Hillah street to Karbalaa-Al-Hillah street. Originally, it was an illegal open canal sewer. Then, it was converted to a street. Similar to 60 street, 80 street also lacks basic infrastructure facilities. Figure S1 shows site photos of both streets.

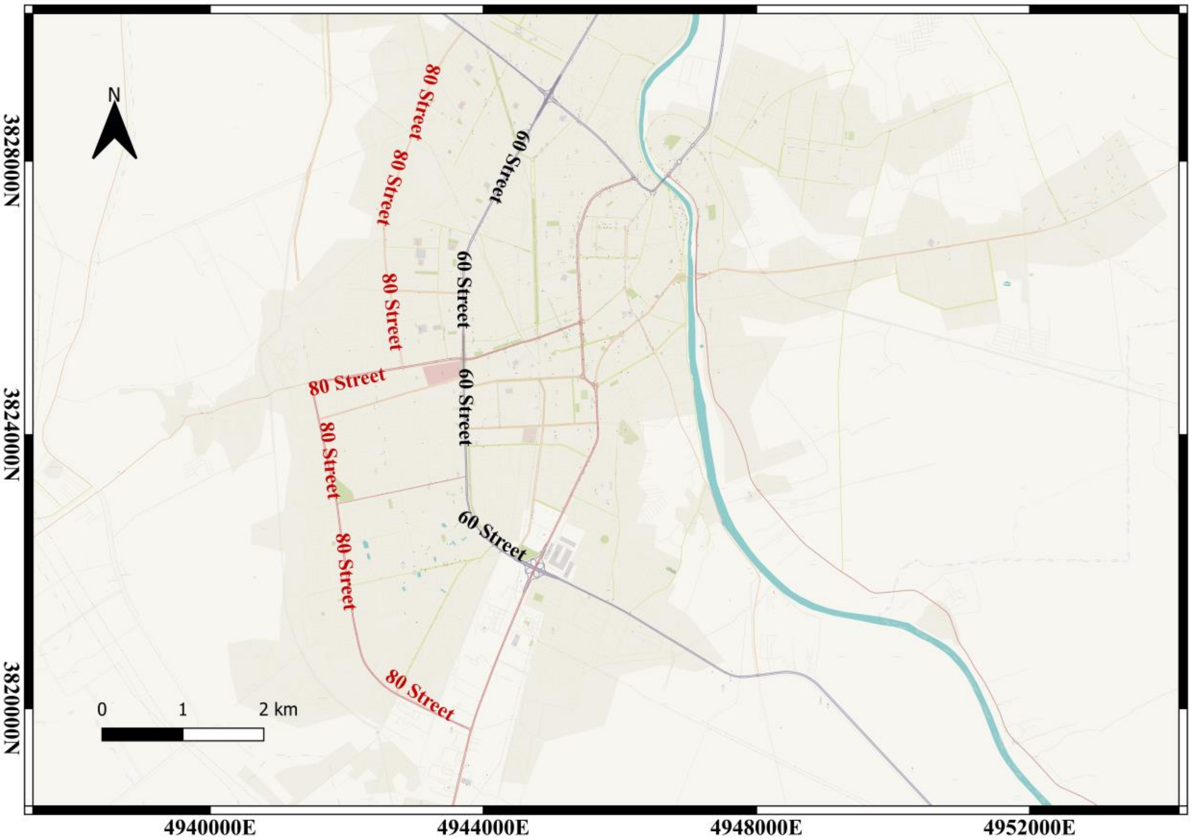


Figure 1 the investigated two major streets (60 and 80) locations in Al-Hillah city.

2.4. Transportation modes

Four common modes of motorized transportation, such as open windows car, closed windows car, mini-bus (16 seats), and motorbike, were utilized to calculate commuters' exposure to $PM_{2.5}$ and PM_1 concentrations. A car mode is a common mode in the whole city and even the county (Albayati and Lateif, 2018). The bus in the city does not have designated stops on the selected roads, and where it stops largely depends on individuals that are randomly hailing the bus in the street. Thus, during the bus trips, random stops have been made during morning and afternoon trips. Both cases of open windows car and the bus were employed without air-conditioning. The air-conditioning mode (closed windows car) was with an open-external air vent to allow air to come in from outside the car. The authors owned the selected diesel-powered transport modes except for the bus that was hired. The measurements were performed in the peak hours in the morning (8:00 to 11:00 am) and the afternoon (12:00 to 3:00 pm). The AM520 was placed on the commuter's lap, and the device inlet was near the breathing zone. During the measurements, the commuters were sitting in the passenger seat or they were seated behind the driver in the case of the bus. All the measurements were performed between mid of August to early October 2020, excluding the weekends days. A total of 40 one-way routes for both major streets (60 and 80) were taken for each transport mode. The four modes of motorized transportation were driven for equal runs in each street with 20 runs in each street. For instance, the car mode drove 40 runs in total, in which 20 times in 60 street and 20 time in 80 street. A total distance of 1400 km was travelled with 480 and 920 km for 60 and 80 streets, respectively. A target driving speed of 30 km/h was applied for all runs. 60 street travel time during all conducted trips was from 20 to 30 mins in which most trips registered 25 mins. This fluctuation was influenced by traffic conditions. The travel time for 80 street was almost the same with fewer more congestion events that led to increase the measuring time in some instances. In both streets, the average wind speed was 7±2 km/h (Grmasha et al., 2020). QGIS 3.18 was utilized to map the average concentrations of both $PM_{2.5}$ and PM_1 for all runs. All other analyses were made by using OriginPro 2018 software.

3. Results and discussion

3.1. Overview of PM exposure concentrations

Prior to processing the collected data for determining exposure concentrations of PM_1 and $PM_{2.5}$, the outliers were excluded based on Grubbs test as shown in Figures S2 and S3. Figure 2 illustrates the morning and afternoon measured exposure concentrations ranges (minimum and maximum) of $PM_{2.5}$ and PM_1 for four motorized transportation modes in 60 and 80 streets**.** $PM_{2.5}$ and PM_1 exposure concentrations in the four motorized transportation modes varied during morning and afternoon trips. With regards to the nature of traffic in these streets, private cars made up the highest component of the traffic volume in both the morning and afternoon followed by bus and then motorbike. Private cars in both routes contributed to 87% of the total traffic as they are the common transport mode. The remaining traffic volume is divided into 9% for the buses and about 4% for the motorbike commuters. Closed windows car always had higher range of PM_1 for 80 street compared to 60 street. However, $PM_{2.5}$ ranges varied depending on the travel period. The afternoon trips recorded lower range of $PM_{2.5}$ in 80 street compared to 60 street. For open windows car mode, PM_1 ranges were higher for 60 street as opposed to 80 street, however, $PM_{2.5}$ showed an opposite trend for morning and afternoon periods. Buses consistently showed higher ranges of PM_1 and $PM_{2.5}$ in 60 street than those recorded in 80 street. The recorded $PM_{2.5}$ ranges for motorbike mode were higher for 60 street compared to 80 street. However, PM_1 range for the same mode was slightly higher in 80 street compared to 60 street for morning trips. Knowledge of the specific ranges of $PM_{2.5}$ and PM_1 levels is useful, but it does not give a clear picture of spatial-temporal variation of these pollutants in the city. PM_1 and $PM_{2.5}$ data will be scrutinized in the following section.

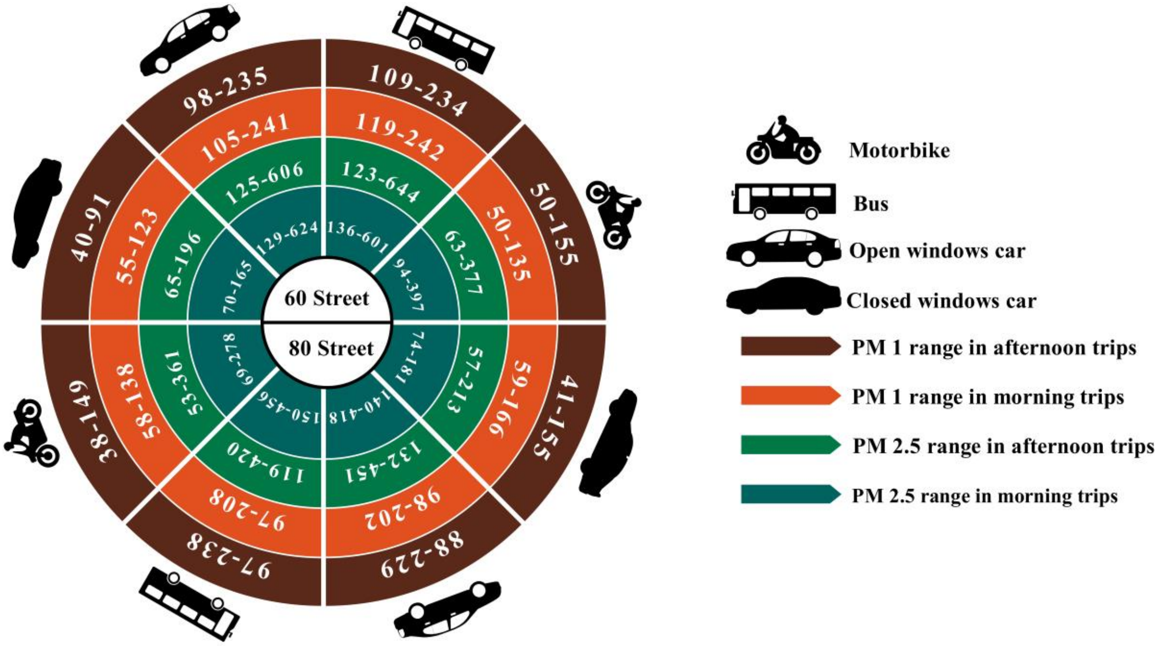


Figure 2 $PM_{2.5}$ and PM_1 (µg/m^3) exposure concentrations ranges (minimum and maximum) in the morning and afternoon trips for four motorized transportation modes in 60 and 80 streets.

3.2. Exposure concentrations of the four common modes of motorized transportation

In Al-Hillah city, cars are popular means of transport and are used extensively by most Iraqi citizens. Figure 3 shows $PM_{2.5}$ (A) and PM_1(B) exposure concentrations in both streets for all the studied transport modes during the whole sampling period. This figure shows detailed analysis for the data. The 1% and 99% marks of the collected data are highlighted. The scale of interquartile range rule (IQR) is also marked. The means and medians of the data ranges are also marked. In general, similar trends were observed in both streets, 60 and 80 where open windows car had the highest concentration, whilst closed windows car had the lowest concentration. The $PM_{2.5}$ exposure concentration of other two transportation modes fell in between these two extremities. The case is slightly different for PM_1 as bus equally with open windows car recorded the highest concentrations. Regarding 60 street, the median $PM_{2.5}$ values for open windows car were 338 and 290.5 µg/m^3 for the morning and the afternoon trips respectively, while PM_1 median exposure concentrations for morning and afternoon trips recorded 185.5 and 151 µg/m^3 respectively. For 80 street, the median $PM_{2.5}$ values for open windows car were 239 and 229.5 µg/m^3 for the morning and the afternoon trips respectively, while PM_1 median exposure concentrations for morning and afternoon trips recorded 156 and 152 µg/m^3 respectively.

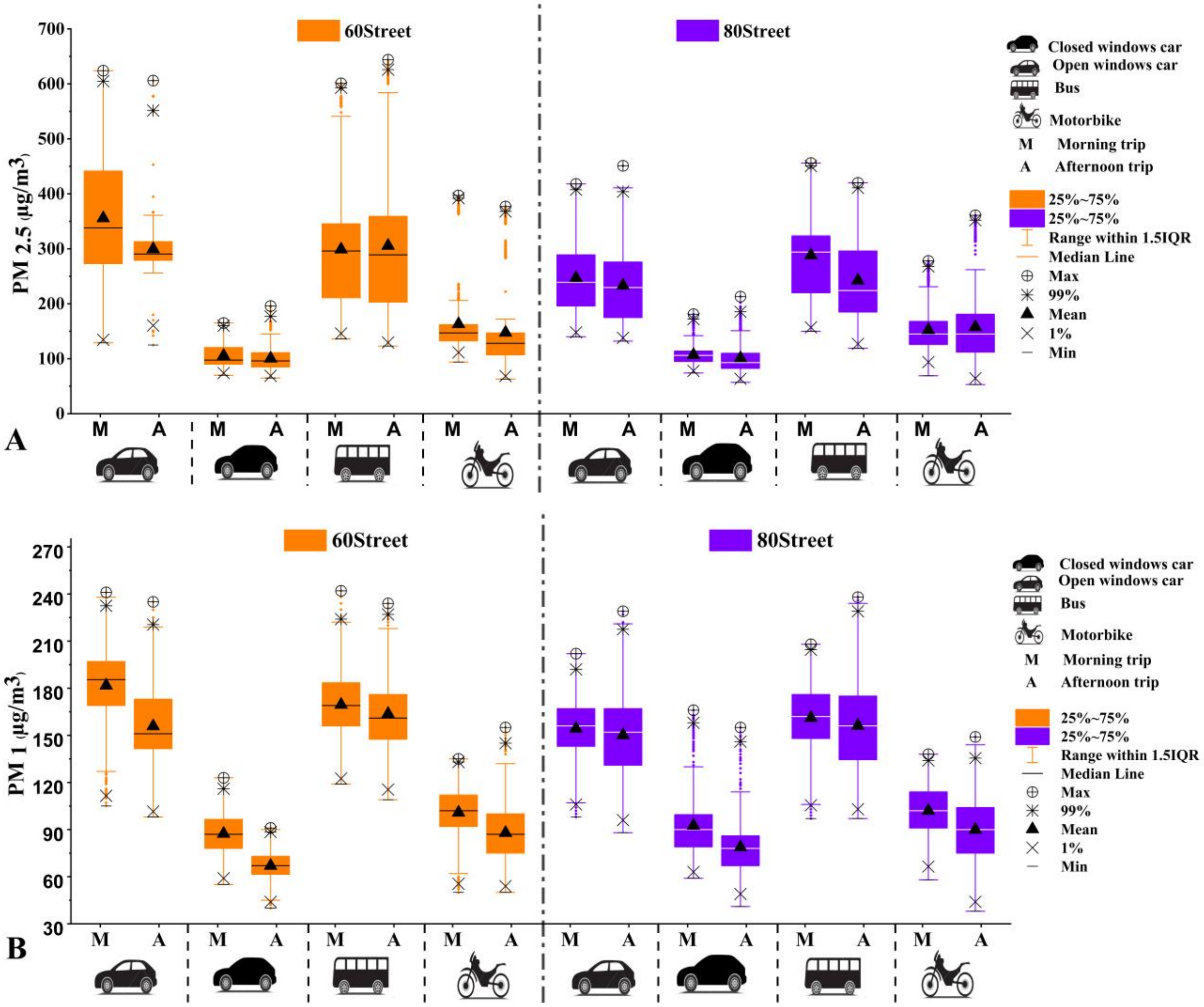


Figure 3: the exposure concentrations of $PM_{2.5}$ (A) and PM_1 (B) for all transportations modes in streets 60 and 80 during morning and afternoon trips.

Exposure concentration in the case of the closed windows car in 60 street exhibited the lowest values for $PM_{2.5}$ and PM_1 compared with other modes. In 60 street, $PM_{2.5}$ median exposure concentrations were 97.5 and 96 µg/m^3 for the morning and afternoon trips respectively. For 80 street, the PM_1 was recorded as 87 and 67 µg/m^3 for the morning and afternoon trips, respectively. However, in 80 street, $PM_{2.5}$ medians of 106 and 93 µg/m^3 for morning and afternoon trips were recorded respectively.

Buses usually are taking 60 street heading to other Iraqi cities. In addition, students' buses for most schools, universities, and even the kindergarten are passing through these two streets. The $PM_{2.5}$ median exposure concentrations for bus mode were 296 and 289 µg/m^3 for the morning and afternoon trips respectively, while PM_1 recorded 169 and 161 µg/m^3 for the morning and afternoon trips respectively. In 80 street, the median exposure concentrations values for $PM_{2.5}$ were 294 and 225 µg/m^3 for morning and afternoon trips respectively, while values of 162 and 156 µg/m^3 were recorded as median PM_1 exposure concentrations for morning and afternoon trips respectively.

The motorbike is the least used transport mode in Al-Hillah. There is no exact lane for the motorbike commuters; therefore, most of them are preferring to take the slow lane in the street. Regarding 60 street, the median $PM_{2.5}$ exposure concentrations for motorbike commuters were 147 and 128 µg/m^3 for both morning and afternoon trips respectively, while PM_1 recorded 102 and 87 µg/m^3 for morning and afternoon trips respectively. However, the exposure concentrations in 80 street for both $PM_{2.5}$ and PM_1 were higher than the values recorded in 60 street. $PM_{2.5}$ median exposure concentrations were 272 and 353 µg/m^3 for morning and afternoon trips respectively. Furthermore, PM_1 was recorded as 135 and 144 µg/m^3 for morning and afternoon trips respectively. It is noteworthy that there is an accumulated dust on the curbs and the sidewalks where most of motorbike commuters are driving on this specific area which leads to an obvious dust agitation. It also was observed that about 99% of motorbike commuters do not wear helmets during driving which allows them to easily inhale the dust. Figure 4 shows $PM_{2.5}$ and PM_1 mean exposure concentrations for morning and afternoon trips in both streets.

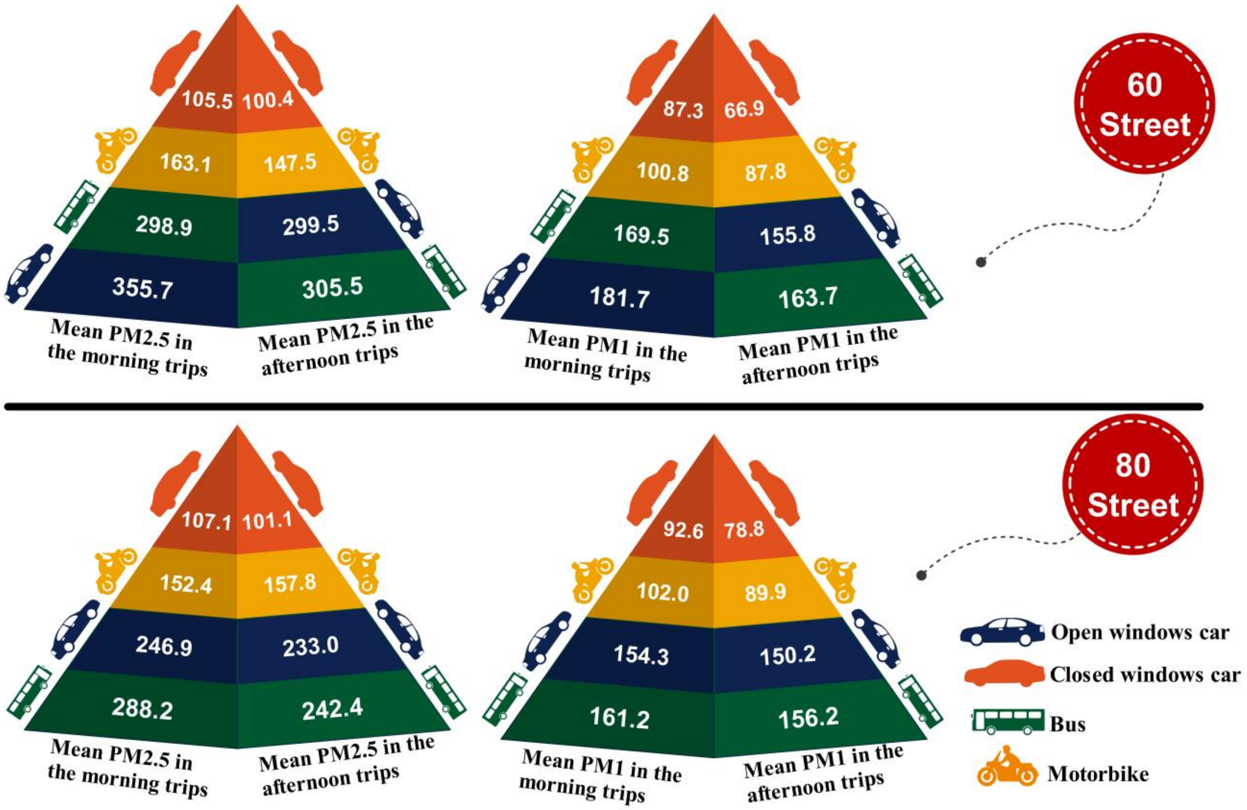


Figure 4 PM$_{2.5}$ and PM$_1$ (µg/m^3) mean exposure concentrations (from highest to lowest) for all motorized transportation modes during morning and afternoon trips in both streets.

As it can be noticed from Figure 4, in 60 street, the mean PM$_{2.5}$ exposure concentrations during the morning trips for the four motorized transportation modes were 355.7, 298.9, 163.1, and 105.5 µg/m^3 for open windows car, bus, motorbike, and closed windows car respectively. PM$_1$ mean exposure concentrations during the morning runs for the motorized transportations were 181.7, 169.5, 100.8, and 87.3 µg/m^3 for open windows car, bus, motorbike and, closed winnows car respectively. The mean PM$_{2.5}$ exposure concentrations during the afternoon trips were 305.5, 299.5, 147.5, and 100.4 µg/m^3 for bus, open windows car, motorbike, and closed windows car while PM$_1$ mean exposure concentrations during the afternoon runs for the motorized transportations were 163.7,155.8, 87.8, and 66.9 µg/m^3 PM$_{2.5}$ and PM$_1$ mean values for all trips in both streets.

PM$_{2.5}$ and PM$_1$ mean exposure concentrations in 80 street also registered high values in four motorized transportations modes. During the morning measurements, the mean PM$_{2.5}$ exposure concentrations were 246.9, 288.2, 152.4, and 107.1 µg/m^3 for open windows car, bus, motorbike, and closed windows car respectively while PM$_1$ mean exposure concentrations during the morning recorded 161.2, 154.3, 102.0, and 92.6 µg/m^3 for bus, open windows car, motorbike, and closed windows car respectively. Furthermore, the mean values of PM$_{2.5}$ during the afternoon trips were registered as 242.4, 233.0,157.8, and 101.1 µg/m^3 for bus, open windows car, motorbike, and closed windows car respectively. PM$_1$ mean exposure concentrations for the afternoon trips were 156.2, 150.2, 89.9, and 78.8 µg/m^3 for bus, open windows car, motorbike, and closed windows car respectively.

A *t-test* mean comparison of PM$_1$ and PM$_{2.5}$ in the two streets for different transportation modes during morning and afternoon trips has been conducted and results are presented in Table 1. The exposure concentrations for morning and afternoon are marked by M and A letters, respectively in this table and the following figures in this section. In general, PM$_1$ and PM$_{2.5}$ values are significantly different for the two streets confirming both spatial and temporal variation in air quality in the city. There are only two cases where the means of the measurements were insignificantly different for the two streets. These are PM$_1$ for closed windows cars in the morning trips and PM$_{2.5}$ for motorbike during afternoon trips.

A mean comparison has also been established between the measurement periods for all the transportation modes in the two streets as shown in Table 2. It can be seen that most of the transportation modes exhibited significant difference between the measurements' means of PM$_1$ and PM$_{2.5}$ for morning and afternoon trips. The means of the measured PM$_1$ and PM$_{2.5}$ values were statistically insignificant for bus mode in 60 street. The means of PM$_{2.5}$ measurements in morning and afternoon trips was also statistically insignificant for open car windows and motorbike modes in 80 street, and for closed windows car in 60 street. This indicates the necessity of implementing mobile air quality measurements in order to monitor air pollution adequately in the city.

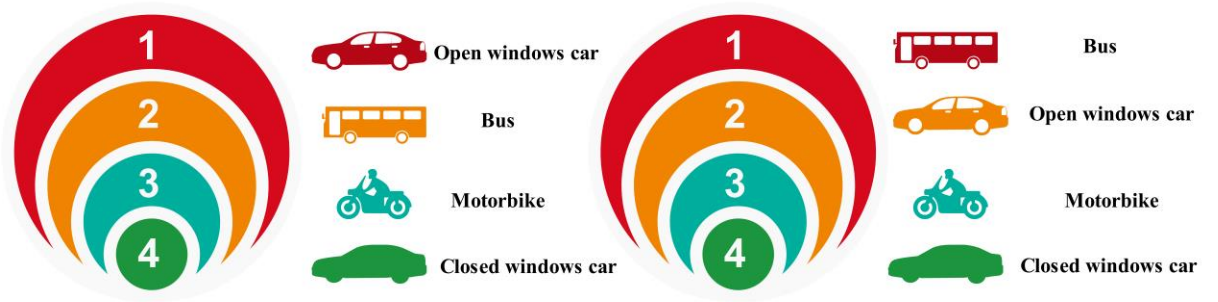
Table 1: PM$_1$ and PM$_{2.5}$ *t-test* means comparison for 60 and 80 streets during morning and afternoon trips for studied transportation modes.

60 Street and 80 Street															
Open windows car				Closed windows car				Bus				Motorbike			
PM$_{2.5}$		PM$_1$		PM$_{2.5}$		PM$_1$		PM$_{2.5}$		PM$_1$		PM$_{2.5}$		PM$_1$	
(M)	(A)	(M)	(A)	(M)	(A)	(M)	(A)	(M)	(A)	(M)	(A)	(M)	(A)	(M)	(A)
3.5E-32	4.5E-39	7.6E-57	0.047	7.7E-09	0.030	**0.592**	0.034	0.047	2.2E-09	6.1E-13	1.7E-10	0.032	**0.889**	0.000	0.001

Table 2: PM_1 and $PM_{2.5}$ *t-test* means comparison of morning and afternoon trips for 60 and 80 streets using different transportation modes.

T.test	Open windows car		Closed windows car		Bus		Motorbike	
	$PM_{2.5}$	PM_1	$PM_{2.5}$	PM_1	$PM_{2.5}$	PM_1	$PM_{2.5}$	PM_1
	Morning and Afternoon Trips							
60 street	0.000	0.000	**0.608**	0.000	**0.065**	**0.0710**	0.0008	0.000
80 street	**0.131**	0.000	0.012	0.000	0.000	0.0001	**0.9340**	0.000

Figure 5 describes the ranking of $PM_{2.5}$ and PM_1 mean during both morning and afternoon trips for all motorized transportation modes. Table 3 shows the mean PM values measured in Iraq and other countries (µg/m^3).



Mean $PM_{2.5}$ ranking in morning trips for both streets and PM_1 mean ranking in morning trips in 60 street (from highest to lowest)

Mean $PM_{2.5}$ and PM_1 ranking in the afternoon for both streets and mean PM_1 ranking in the morning in 80 street (from highest to lowest)

Figure 5 Mean $PM_{2.5}$ and PM_1 exposure concentrations in both streets within afternoon and morning trips.

As it can be observed from Figure 5, the mean ranking in $PM_{2.5}$ morning measurements in both streets were as follows: open windows car, bus, motorbike, and closed windows car. This situation was also same during PM_1 mean determination in the morning and with 60 street. The means $PM_{2.5}$ and PM_1 ranking in the afternoon for 60 and 80 streets as well as mean PM_1 ranking during morning in 80 street were all as follows: bus, open windows car, motorbike, and closed windows car. The recorded high $PM_{2.5}$ and PM_1 exposure concentrations in bus mode in both streets could result from many factors. Open windows in the bus allow more PM to penetrate through the vehicle (Onat et al., 2019). Another factor is opening the bus door and the stop/start driving condition increases the level of both $PM_{2.5}$ and PM_1 exposure concentrations (Zuurbier et al., 2010). The frequent congestion (especially in 60 street) and the bus fuel type significantly affect the recorded PM concentrations. In addition to the traffic flow and fuel types, the reasons for high $PM_{2.5}$ and PM_1 values recorded by open window car were the case of the opening windows which permit more PM entering the car cabin which is similar to bus mode. Motorbike and closed windows car modes occupied a similar hierarchy in all modes within both streets with less PM exposure concentrations in our study.

Table 3: Selected literature results for mobile measurements of mean particle mass exposure concentrations in Iraq and other regional countries (µg/m^3).

Country (City)	PM	Trip Time	Car*	Bus	Motor bike	References
Egypt, Cairo	$PM_{2.5}$	M(E)	47(33)	-	-	(Abbass et al., 2020)
Kazakhstan, Nur-Sultan	PM_1	E	-	11-99	-	(Torkmahalleh et al., 2020)
India, Chennai	$PM_{2.5}$	M,A,E	-	255	251	(Raj and Karthikeyan,2019)
China, Nanjing	PM_1	M,A,E	-	56	-	(Shen and Gao, 2019)
	$PM_{2.5}$		-	75	-	
Lebanon, Beirut	$PM_{2.5}$	-	38-93	-	-	(Abi-Esber and El-Fadel, 2013)
Turkey, Istanbul	$PM_{2.5}$	M,A	36	37	-	(Onat et al. (2019)
Iraq, Al-Hillah	$PM_{2.5}$ (60 st.)	M(A)	355.7(299.5)	298.9(305.5)	**163.1(147.5)**	The present study
	$PM_{2.5}$ (80 st.)		246.9(233)	288.2(**242.4**)	**152.4(157.8)**	
	PM_1 (60 st.)		181.7(155.8)	**169.5 (163.7)**	**100.8 (87.8)**	
			154.3(150.2)	**161.2(156.2)**	**102(89.9)**	

	PM_1 (80 st.)

* Values for open windows car was taken as it is registered higher values. M is Morning trip; A is Afternoon trip; E is Evening trip; St. is street.

Comparing these study results with those from nearby and heavily populated countries, it can clearly be seen from Table 3 that for cars the PM_1 and $PM_{2.5}$ mean exposure values are higher than those for all other cities. The $PM_{2.5}$ and PM_1 measured by motorbike mode in both street was less than the recorded value in Chennai, India. This may be explained by the slow lane the motorbikes take in Al-Hillah city that is unlikely to exist in other cities in the world. However, our results were similar to another study conducted in Vellore city, India (Manojkumar et al., 2021) as both studies showed that morning trips showed higher concentrations of PM_1 and $PM_{2.5}$ compared to afternoon trips. The same study also showed that motorbike had lower PM concentrations compared to cars. These similarities may suggest that there is a resemblance between the traffic environment in India and Iraq. The $PM_{2.5}$ afternoon trip in 80 street and PM_1 values in both streets also registered less $PM_{2.5}$ than Chennai, India, for the bus mode. In any case, both our study and the quoted studies from different countries in Table 3 showed high concentration of $PM_{2.5}$ that exceeded the WHO recommendation limits of 10 $\mu g/m^3$ (WHO, 2005). What is more concerning is that the mean of measured levels of $PM_{2.5}$ in this study is higher than the reported limit by the World Bank for 2017 of 69 $\mu g/m^3$ (The world bank, 2021). This could be attributed to two reasons; the deteriorating air quality in Iraq and the inadequacy of governmental measurement facilities that are likely to be in the form of fixed stations that cannot produce a true representation of the situation.

There are several reasons associated with such unusual high PM measured concentrations in these two main streets. Increasing the number of vehicles during the beginning and the end of the working day (the selected measuring times) leads to elevating the PM level in the air. The level of sulfur contents in the Iraqi gasoline reached 500 ppm which leads to environmental problems. Additionally, Iraq diesel fuel contains 10000 ppm as sulfur contents which is considered the worst worldwide (Atiku et al. 2016; Ahmed and Chaichan 2012). The increased contents of the sulfur in the gasoline and the diesel could contribute to PM formation in Al-Hillah air. In addition to the vehicles, the other possible source of pollution of such high PM concentrations in Al-Hillah is regular gas and fuel combustion activities which may be accompanied by PAHs and different heavy metals (Grmasha et al., 2020). Utilizing gasoline and diesel-powered generators in most parts of the city could lead to a vital source of PM pollution (Hamad et al., 2015). Moreover, dust storms originated from Iraqi and Syrian deserts which are loaded with particulate pollutants that also contribute to elevating the PM levels in the air (Ali-Taleshi et al., 2021).

3.3. The average exposure concentrations ($PM_{2.5}$ and PM_1) of the four common modes of motorized transportation

The trips average exposure concentrations of $PM_{2.5}$ and PM_1 for both streets registered concerning values. It largely exceeded the safe annual limits recommended by WHO, 10 µg/m^3 (WHO, 2005). In the case of open windows car in 60 street, the average exposure concentrations of $PM_{2.5}$ in the morning and the afternoon trips recorded were 355.72 and 299.54 µg/m^3, while the average exposure concentrations of PM_1 in the morning and the afternoon were 181.74 and 155.84 µg/m^3. Like 60 street, 80 street also recorded high $PM_{2.5}$ and PM_1 exposure concentrations. The average $PM_{2.5}$ exposure concentrations in the morning and afternoon trips for the open windows car mode registered as 246.96 and 233.03 µg/m^3, and PM_1 recorded average exposure concentrations of morning and afternoon trips were 154.27 and 150.16 µg/m^3.
The bus mode also registered high levels of $PM_{2.5}$ and PM_1 exposure concentrations. It recorded 298.98 and 305.59 µg/m^3 as average $PM_{2.5}$ exposure concentrations in the morning and afternoon respectively, whereas PM_1 average readings were 169.52 and 163.72 µg/m^3 for the same trips. However, bus mode registered higher $PM_{2.5}$ and PM_1 values in 80 street than 60 street with average $PM_{2.5}$ exposure concentrations of 288.23 and 242.44 µg/m^3 for the morning and afternoon trips whereas the averages PM_1 exposure concentrations were 161.15 and 156.16 µg/m^3 for morning and afternoon trips. This increase in pollution levels in 80 street compared to 60 street was likely to be due to illegal burning of household waste dumped near the sidewalk occurred in 80 street which was not the case for 60 street.

In the cases of open windows transportations, dust agitated from vehicles in front can enter other vehicles' interiors through windows and cooling systems. Another reason noticed for dust agitation is most cars, especially during congested times, are driving over the sidewalk leading to the breakdown of the soil and sidewalk structure. This leads to an increase in the PM exposure concentrations and results in higher inhalation doses. Moreover, as mentioned previously, there are no specific locations for bus stops. This, in turn can also disrupt the compacted dust on the roadside.

The closed windows car mode recorded the lowest averages for both $PM_{2.5}$ and PM_1 among all four common modes of motorized transportation. $PM_{2.5}$ registered average values of 105.51 and100.40 µg/m^3 for the morning and afternoon trips while PM_1 were 87.34 and 66.96 µg/m^3 as the average exposure concentrations for the morning and afternoon in 60 street trips. The $PM_{2.5}$ average exposure concentrations of 80 street was 107.06 and 101.15 µg/m^3 for the morning and afternoon trips, whereas PM_1 average exposure concentrations were 92.56 and 78.76 µg/m^3 for morning and afternoon trips. Although these recorded values are still high, the type of unmaintained roads and other vehicles fumes have also played a significant role in increasing pollution, leading to high personal exposure to PM concentrations (Lowenthal et al., 2014; Abbass et al., 2020).

The Motorbike mode has recorded average exposure concentrations for both $PM_{2.5}$ and PM_1 in 60 street of 163.18 and 147.52 µg/m^3 for morning and afternoon trips while PM_1 average exposure concentrations were 100.80 and 87.90 µg/m^3 for the morning and afternoon 60 street trips. The $PM_{2.5}$ average exposure concentrations of 80 street was 152.36 and 157.75 µg/m^3 for morning and afternoon trips, whereas PM_1 average exposure concentrations were 102.00 and 89.88 µg/m^3 for the morning and afternoon trips.

Figure 6 illustrates the average exposure concentrations of $PM_{2.5}$ and PM_1 in the morning and afternoon in both streets. Every arrow represents the average exposure concentration ranges of PM constituents in both morning and afternoon trips for one kilometer. It can be seen that the average exposure $PM_{2.5}$ concentrations in 80 street (panel A) were ranging from 70 to 311 µg/m^3. Open windows car and bus registered high average exposure $PM_{2.5}$ concentrations with a range from 232 to 311 µg/m^3 while the closed windows car average $PM_{2.5}$ exposure concentration exhibited low values ranging from 70 to 150 µg/m^3. Motorbike average $PM_{2.5}$ exposure concentration was mostly ranged between 151to 231 µg/m^3. In contrast, average exposure $PM_{2.5}$ concentrations in 60 street (panel B) were ranging from 70 to 392 µg/m^3 with the highest recorded values. Closed car windows average exposure $PM_{2.5}$ concentrations occupied the lowest values ranging from 70 to 150 µg/m^3 while open windows car registered the highest $PM_{2.5}$ average exposure values ranging from 312 to 392 µg/m^3. Both bus and motorbike average exposure $PM_{2.5}$ concentrations in 60 street fluctuated from 70 to 392 µg/m^3. The measured PM constituents were higher in 60 street compared to 80 street due to the previously mentioned factors related to the difference in the quality of the infrastructures of the two streets and the external factors such as driving behavior of vehicles.

The average exposure PM_1 concentrations in both 80 and 60 streets (panel C and D) were ranging from 70 to 231 µg/m^3. The average exposure PM_1 concentrations in closed windows car and motorbike modes in 60 and 80 streets were ranging from 70 to 150 µg/m^3 while the average exposure PM_1 concentrations in the bus (both streets) and open windows car (in 60 street) were ranging from 1151 to 231 µg/m^3. The average exposure PM_1 values in open windows car (80 street) was between 70 to 231 µg/m^3.

In general, in 60 street, the $PM_{2.5}$ average exposure concentrations per kilometer were ~ 324, ~101, ~ 300, and ~150 µg/m^3 for open windows car, closed windows car, bus, and motorbike respectively. Furthermore, PM_1 average exposure concentrations for one kilometer were ~ 170, ~77, ~166, and ~ 93 µg/m^3 for open windows car, closed windows car, bus, and motorbike respectively. Regarding 80 street, as shown in Figure 6, the average exposure concentrations of PM recorded per kilometer were relatively the same as 60 street. For instance, the $PM_{2.5}$ average exposure concentrations were ~237, ~ 104, ~267, and ~153 µg/m^3 for open windows car, closed windows car, bus, and motorbike respectively. PM_1 average exposure concentrations in the same street were ~152, ~85, ~157 and, ~95 µg/m^3 for open windows car, closed windows car, bus, and motorbike respectively.

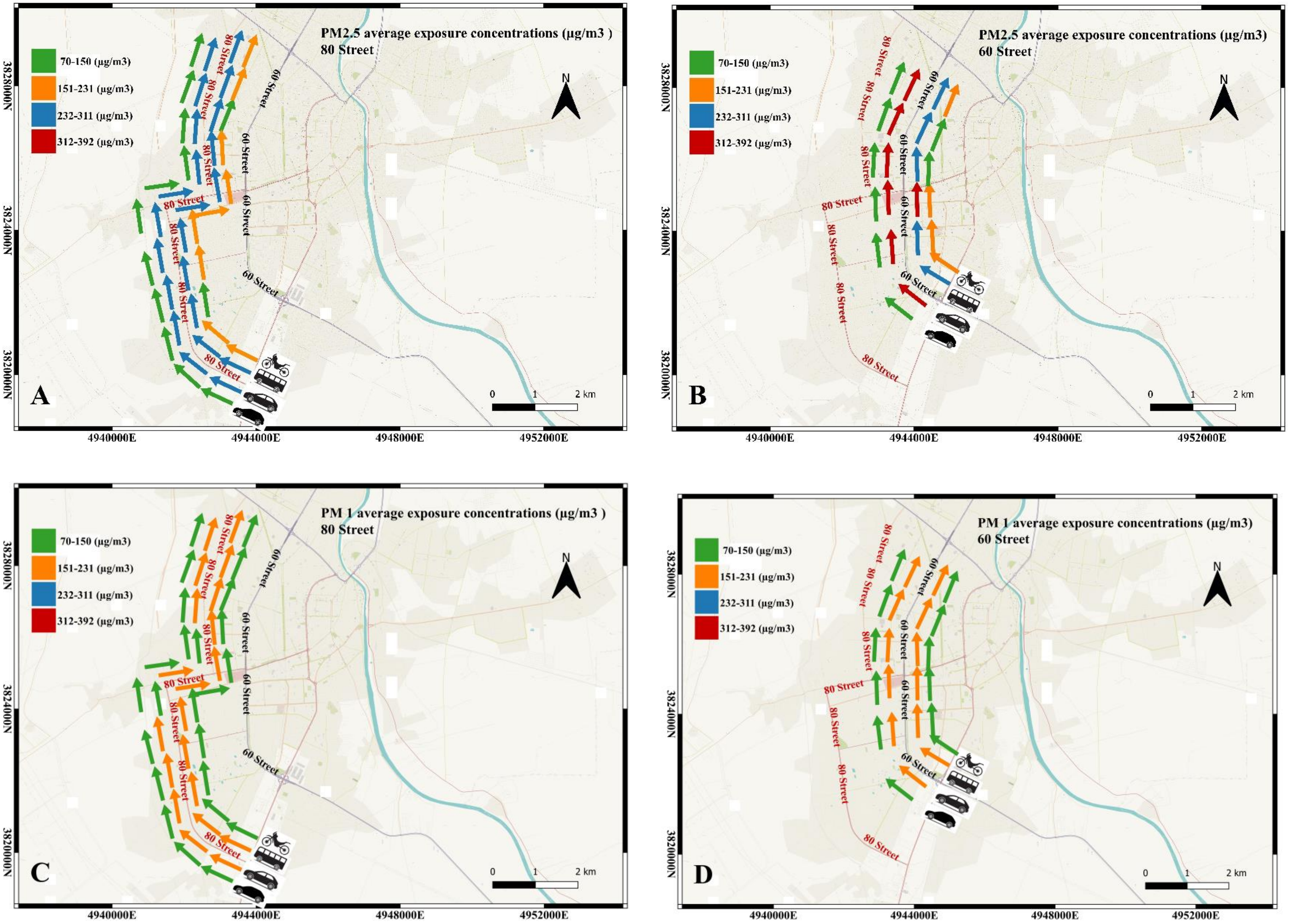

PM2.5 average exposure concentrations (µg/m3)
80 Street
🟩 70-150 (µg/m3)
🟧 151-231 (µg/m3)
🟦 232-311 (µg/m3)
🟥 312-392 (µg/m3)
N
80 Street
60 Street
0 1 2 km
A
PM2.5 average exposure concentrations (µg/m3)
60 Street
B
PM 1 average exposure concentrations (µg/m3)
80 Street
C
PM 1 average exposure concentrations (µg/m3)
60 Street
D
3828000N
3824000N
3820000N
4940000E
4944000E
4948000E
4952000E

Figure 6 the average morning and afternoon exposure concentrations of $PM_{2.5}$ and PM_1 in both streets: A) is the average $PM_{2.5}$ exposure concentrations for 80 street, B) is the average $PM_{2.5}$ exposure concentrations for 80 street, C) is the average PM_1 concentrations for 80 street and D) is the average PM_1 exposure concentrations for 60 street.

3.4. Inhalation doses

The four common modes of motorized transportation experienced a considerable amount of exposure to both $PM_{2.5}$ and PM_1. Figure 7 illustrates the inhalation doses per trip and per kilometer in both routes in terms of $PM_{2.5}$ and PM_1. As for 60 street, it was noticed that both open windows car and the bus modes registered the highest inhalation dose for each kilometer with maximum doses of 13 and 7 µg/km for $PM_{2.5}$ and PM_1, respectively. Other transport modes recorded lower inhalation dosages with closed windows car having the lowest dosages for 60 street. The 80 street had lower inhalation doses compared to 60 street. For instance, the average $PM_{2.5}$ inhalation per kilometer for open windows car and bus were 7 and 8 µg/km respectively. The inhalation doses of PM_1 for the same transport modes were 4.6 and 4.5 respectively.

Overall, the morning trips in both streets recorded higher inhalation concentrations for $PM_{2.5}$ and PM_1 than the afternoon ones. Although the length of 80 street is double than that of 60 street, 60 street exhibited higher inhalation doses for all motorized transportation modes as it experiences much dust pollutions. These differences in inhalation doses could be related to several factors. The stop/start driving condition contributes to agitating the accumulated dust on the streets (see Figure S1) and raises the level of PM in the surrounding area which leads to an increase in the inhalation dose. Opening the vehicle door (especially bus mode) would result in penetrating more PM in the cabin which, in turn, leads to an increase in the inhalation doses of both $PM_{2.5}$ and PM_1. Additional factors such as traffic densities especially in 60 street (see Figure S1) and weak quality fuel participated to the elevated inhalation dosages in both streets. It has been stated the PM_1 is a better indicator of vehicular emission pollution than $PM_{2.5}$ (Lee et al., 2006), and this suggests that not just dust, but also vehicle emissions are higher in 60 street as opposed to 80 street.

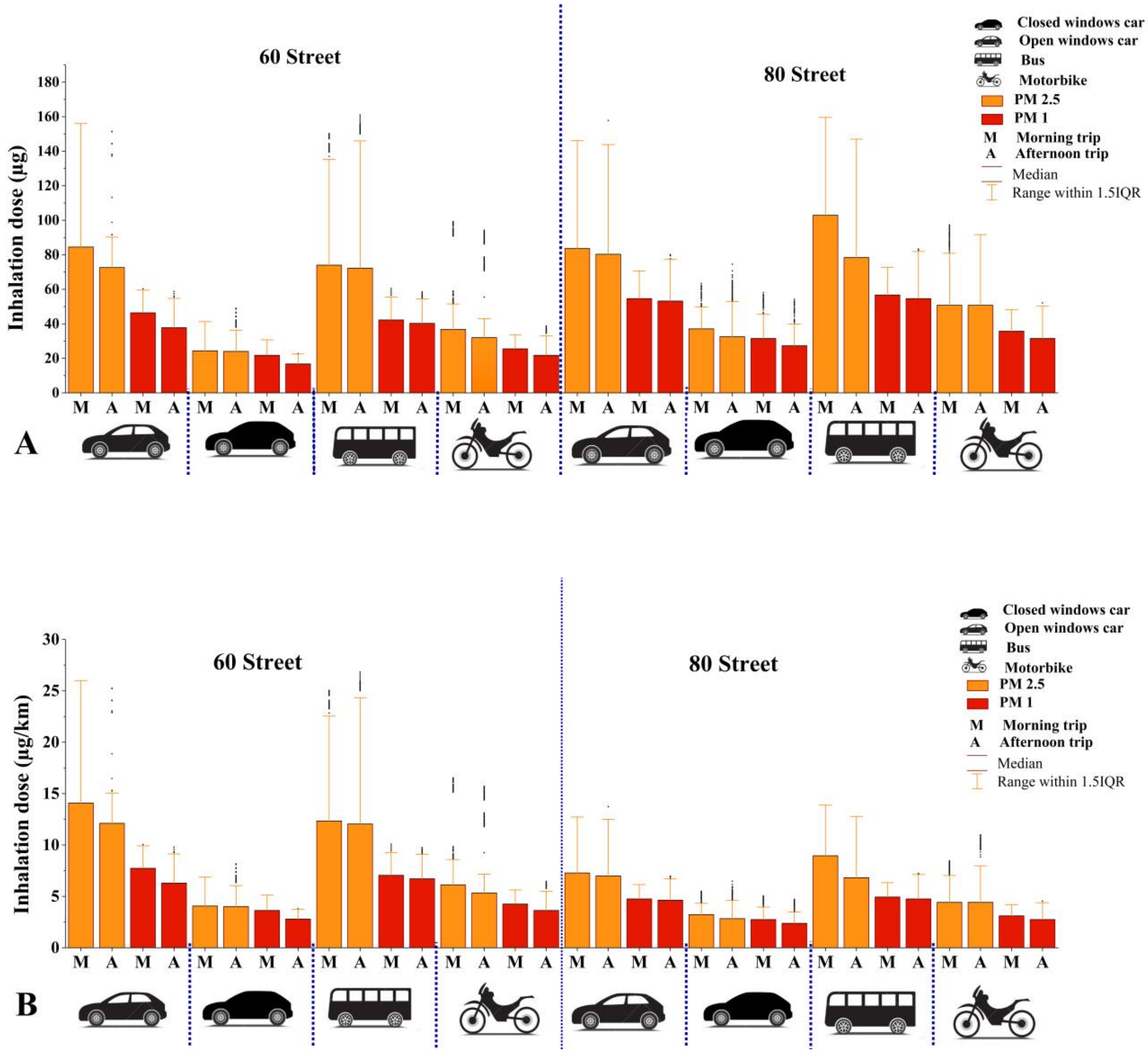


Figure 7 (A) is the inhalation doses per the trip µg in both streets and (B) is the inhalation doses per kilometer µg in both streets µg/km.

4. Conclusion and recommendation

In this study, personal exposure concentrations of particulate matter (PM_1 and $PM_{2.5}$) in Al-Hillah city in Iraq was investigated. Four common modes of motorized transportation, such as open windows car, closed windows car, mini-bus (16 seats), and motorbike, were utilized in two main streets (60 and 80 streets). SidePak^{TM} aerosol device was employed to measure the PM concentrations during peak hours in the morning and the afternoon. The study has provided some valuable insights for the size and the nature of the particulate pollution in Iraq.

All four motorized transportation modes recorded high $PM_{2.5}$ and PM_1 mean values in both open windows car and bus. Motorbike and closed windows car mode with an open-external air vent recorded the lowest means for both $PM_{2.5}$ and PM_1 among other modes of motorized transportation. A t-test means comparison showed that PM_1 and $PM_{2.5}$ measurements are significantly different in the two streets confirms the spatial variation of air quality in the city. A similar comparison was established between the morning and afternoon measurements which also shows that the means of the measurements were significantly different for all measurements except for bus mode in 60 street. This indicates temporal variation of the measured air pollutants in the city. Higher inhalation concentrations for $PM_{2.5}$ and PM_1 found in the morning trips in both streets. When comparing, the measured $PM_{2.5}$ and PM_1 with neighboring and heavily populated countries, it was obvious that the particulate pollution in Iraq or at least in the sampled area was much higher than that of all compared countries except for India were PM levels were almost on par. These high concentrations of $PM_{2.5}$ and PM_1 result in high inhalation dosages.

Overall, the measured $PM_{2.5}$ and PM_1 mean values were much higher than those recorded in most of regional countries and largely exceeded the WHO recommended limits and reported values by World Bank. The main reasons of such uncommon $PM_{2.5}$ and PM_1 pollutions in Al-Hillah city, Iraq are increased the number of vehicles that associated with usage of high level of sulfur content in gasoline and diesel fuel. Moreover, vehicles play significant roles in agitating the accumulated particles near the street which leads to more PM pollutions. Gasoline and diesel small generators utilizations widely in this area is another reason for PM high values. These data along with other data collected for the capital city of Baghdad can help in validating remote sensing measurements and machine learning models. The outcome of this study will be of a great use to local and central governmental organization to develop strategies and control policies for mitigating air pollution in Iraq. Future research should take into consideration a long-term continuous monitoring for PM in city. Conducting seasonal measurements would be beneficial to understand the impact of commuters' behavior and weather impact on particulate pollution in the studied area.

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