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Abstract

Introduction Personal exposure to elevated vehicle exhaust and non-exhaust emissions at urban roadside leads to carcinogenic health effects, respiratory illness and nervous system disorders. In this paper, an attempt has been made to investigate the exhaust and non-exhaust emissions emitted from selected roads in Delhi city. Methods Based on the vehicular density per hour and speed, three categories of roads have been considered in the present study: (a) low density road (≤ 1000 vehicles/hour, V≥10m/s); (b) medium density road (>1000 vehicles/hour but ≤ 2000 vehicles/hour, V≥ 7.5m/s < 10m/s); and (c) high density road (>2000 vehicles/hour, V<7.5m/s). At the selected roads, real-world exhaust emissions were measured using AVL DiTEST 1000 analyser. The silt load measurements were also carried out as per EPA AP-42 methodology at the selected roads. Results Results indicated real-world NO exhaust emissions of 0.5 g/m3 (2.03 g/km) on high-density roads and 0.23 g/m3 (0.67 g/km) on low and medium density roads. These values were significantly higher than the Bharat Standard (BS) IV (0.25 g/km). The silt load on the different types of roads indicated 3, 25 and 44 g/m2 -day dust deposition on, low, medium and high-density road, respectively. PM2.5 and PM10 emission rates were measured using US-EPA AP-42 methodology and were found to be least at low-density roads with values of 0.54 and 2.22 g/VKT (VKT -Vehicle Kilometer Travelled) respectively, and highest for high density roads with values of 12.40 and 51.25 g/VKT respectively. Conclusion The present study reveals that both tailpipe (exhaust) and resuspend able road dust (non-exhaust) emissions contributes significantly and deteriorates local air quality. Although there exists emission standards, but there are no enforced regulations for non-exhaust emissions (resuspension of road dust). Hence, there is need to regulate non-exhaust emissions on urban roads.

Keywords	Exhaust Emissions; Non-exhaust Emissions; Nitric Oxide; Resuspendable Road Dust; Urban Road Emissions
Taxonomy	Environmental Degradation, Environmental Planning

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Characteristics of Tail Pipe (Nitric Oxide) and Resuspended dust Emissions from Urban Roads – A Case Study in Delhi City

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Methods

Based on the vehicular density per hour and speed, three categories of roads have been considered in the present study: (a) low density road ($\leqslant$ 1000 vehicles/hour, V$\geqslant$10m/s); (b) medium density road (>1000 vehicles/hour but $\leqslant$ 2000 vehicles/hour, V$\geqslant$ 7.5m/s < 10m/s); and (c) high density road (>2000 vehicles/hour, V<7.5m/s). At the selected roads, real-world exhaust emissions were measured using AVL DiTEST 1000 analyser. The silt load measurements were also carried out as per EPA AP-42 methodology at the selected roads.

Results

Results indicated real-world NO exhaust emissions of 0.5 g/m^3 (2.03 g/km) on high-density roads and 0.23 g/m^3 (0.67 g/km) on low and medium density roads. These values were significantly higher than the Bharat Standard (BS) IV (0.25 g/km). The silt load on the different types of roads indicated 3, 25 and 44 g/m^2 -day dust deposition on, low, medium and high-density road, respectively. $PM_{2.5}$ and PM_{10} emission rates were measured using US-EPA AP-42 methodology and were found to be least at low-density roads with values of 0.54 and 2.22 g/VKT (VKT -Vehicle Kilometer Travelled) respectively, and highest for high density roads with values of 12.40 and 51.25 g/VKT respectively.

Conclusion

The present study reveals that both tailpipe (exhaust) and resuspend able road dust (non-exhaust) emissions contributes significantly and deteriorates local air quality. Although there exists emission standards, but there are no enforced regulations for non-exhaust emissions (resuspension of road dust). Hence, there is need to regulate non-exhaust emissions on urban roads.

1. Introduction

Urban areas are prone to degradation of air quality due to significant contributions from industries, transport sectors, open burning, domestic burning, secondary particulates and resuspension of road dust. The air pollution due to industries can be managed by the implementation of strategies such as local air quality management for industrial clusters and positioning of industries in outskirts of the city. Among the air pollutants in urban areas like Delhi, particulate pollution is a major concern as some of the severe health problems such as respiratory disease, cardiovascular disease, lung cancer, stroke etc., are associated with it. World Health Organization (WHO) study estimated an 4.2 million deaths in 2016 due to ambient air pollution from urban and rural sources worldwide out of which approximately 91% of the premature deaths occurred in developing countries, and nearly 0.79 million deaths in Europe (Lelieveld et al., 2019; WHO, 2018). In 2017, of the 4.9 million deaths recorded due to air pollution, India has accounted for 1.2 million deaths (Balakrishnan et al., 2019; Health Effects Institute, 2019).

Over the past two decades researchers have been conducting source apportionment studies on suspended particulate matter in Delhi city. Investigations have found vehicular emissions and resuspended road dust to be the major contributor to the atmospheric suspended particulate matter concentration (Pant et al., 2015; Srivastava, Gupta, & Jain, 2008, 2009; Srivastava & Jain, 2007). Resuspended road dust are the major contributors of larger particles (<20µm), whereas, particles of size less than 2.5 µm are mainly due to vehicle exhaust (Kristensson et al., 2004; Pant et al., 2015; Srivastava et al., 2008, 2009; Srivastava & Jain, 2007). Even though source apportionment studies cannot be conducted on gaseous pollutants, vehicles are known to emit high concentrations of gaseous emissions. In urban environment vehicular emissions found to contribute nearly 75% of atmospheric NO_x concentration (Auto Fuel Policy, 2014; Gurjar, Ravindra, & Nagpure, 2016). NO_x has the tendency to react with the atmosphere resulting in formation of nitrate aerosols. These nitrate aerosols are the major contributors of ambient and kerbside $PM_{2.5}$ concentration in urban areas (Kumar & Joseph, 2006). In one of the studies conducted for health effects in Delhi, it has been reported that 32.1% of children in Delhi suffered from respiratory problems due to air pollution (Siddique, Ray, & Lahiri, 2011). The particulate pollution may also lead to transboundary health effects and global climate change. From the various epidemiologic studies done in the field of air pollution, it can be inferred that health impacts due to PM are a function of its chemical characteristics, exposure time, concentration and the particle size distribution (Mukherjee & Agrawal, 2018; Pope & Dockery, 2006).

In the present scenario of urban air pollution, road transport is one of the major contributors to global emissions. Pollution from road transport can be classified into exhaust and non-exhaust emissions. Motor vehicles running on different fuels such as diesel, petrol or gasoline, CNG, and biogas are the source for exhaust emissions. Whereas for non-exhaust emissions, tyre wear, brake wear, and resuspendable road dust are some of the sources. Primary pollutants from vehicular emissions consists of particulate matter ($PM_{2.5}$ & PM_{10}), nitrogen oxides (NOx), sulfur oxides (SOx), carbon dioxide (CO_2), carbon monoxide (CO) and hydrocarbons (HC) (Gurjar et al., 2010; Jaikumar, Nagendra, & Sivanandan, 2017; Johnson, 2016; Kuppili, Kumar, & Kim, 2015). Meanwhile, the non-exhaust emissions such as resuspension of road dust are contributing eminently to the PM concentrations in ambient air. The attenuation of road dust is one of the significant research problems being worked on, by air quality researchers in recent years. It is also a challenging research problem for researchers working in the field of sustainable transportation as vehicles are the major contributors for resuspension of road dust causing high pollution exposure to heavy metals and other carcinogenic compounds.

Management of air quality in cities is a very complex process involving monitoring, analysis, source identification, modelling, health exposure assessment, implementation of emission control strategies, and policy intervention. The regulatory bodies are successful to some extent in managing the exhaust emissions from vehicles, whereas the non-exhaust emissions related to the transport sector is not being controlled effectively in developing nations like India. In this paper, the characteristics of nitrogen oxide and non-exhaust emissions in Delhi city has been presented with an objective to understand the concentrations of various pollutants.

2. Material and Methods

2.1. Study area

City of Delhi is considered as one of the extremely polluted cities in the world due to its high vehicular and industrial emissions (Nagpure, Sharma, & Gurjar, 2013). Over the past ten years, the average count of vehicle registration in Delhi is nearly 0.42 million vehicles/year and is growing at a rate of 5.8% (Ministry of Road and Transport). Vehicular population in Delhi city is increasing exponentially day by day. Researchers across the globe have followed different parameters to classify and categorise the roads based on the traffic volume and average speed. Parameters such as vehicular speed and percentage of travel time at free speed were used to distinguish roads into four types (Marwah, 2000). Similarly, Tyagi, Kalyanaraman, & Krishnapuram, 2012, and Warghade & Deshpande, 2017 had classified roads into free flow (>40 kmph), medium density (10 – 40 kmph) and congested (<10 kmph). In this study vehicular speed and traffic volume parameters are considered similar to the Kanpur study (Marwah, 2000).

The study area was divided into three categories namely (a) Low density road (≤ 1000 vehicles, V≥10 m/s); (b) Medium density road (>1000 but ≤ 2000 vehicles, V≥7.5 m/s < 10 m/s); and (c) High density road (>2000 vehicles, V<7.5 m/s) based on traffic flow density during the trip and average speed as shown in Table 1. The different category of roads are shown in the Figure 1. Study areas for exhaust and non-exhaust emission measurements were selected based on the observed traffic characteristics and density during weekends and weekdays. JNU road and Qutub institutional area were identified as low-density (LD) traffic roads because these areas were found to be in the vicinity of residential properties and the institutional area. IIT Delhi main road and JNU main road were identified as medium density (MD) roads as a moderate traffic density was observed during morning and evening peak traffic hours. Munirka, Mahipalpur road is categorised as a heavy density (HD) road in Delhi, as it connects the major business centres. Thus, Qutub Institutional road, IIT Delhi main road and Munirka roads were identified for low, medium and high-density roads respectively to collect resuspension dust emissions. Simultaneously, NO emissions were measured for the test car while travelling on these roads.

Table 1. Classification of vehicular exhaust emission test routes in Delhi city

Road	Classification	Average traffic volume per hour	Average speed (V) (m/s)	Vehicle type/model
Qutub Institutional area	Low-density	≤ 1000 vehicles	V ≥ 10 m/s	Maruti Swift Dzire/2014
IIT Main Gate	Medium-density	1000 < vehicles ≤ 2000	7.5 m/s ≤V < 10 m/s	Maruti Swift Dzire/2012
Munirka	High-density	> 2000 vehicles	V < 7.5 m/s	Maruti Suzuki Ertiga/2014

2.2. Data Collection

During the months of March and April of 2018, a combined total of 15 trips were conducted on the selected routes in Delhi. Data collected includes exhaust emissions, traffic volume and non-exhaust emissions.

2.2.1. Traffic Volume

Traffic flow is recorded using a dash camera mounted in the test vehicle and was counted manually.

2.2.2. Exhaust Emissions

The AVL DiTEST 1000 was used in this study to perform vehicular emission tests. This instrument can analyse CO, CO_2 and O_2 in volume percentage and HC, NO in ppm from the vehicle exhaust. For this study, only NO emissions from cars were measured and projected. The DiTEST 1000 is a handy and portable instrument, which can be easily installed to any vehicles and measures with an accuracy of ± 2% ppm. The complete set of AVL DiTEST 1000 is shown in Figure 2. The instrument has four connections typically (i) a power cable connected to backup power supply using external battery (UPS); (ii) an engine data link connected to the OBD data port; (iii) an emissions sampling probe inserted into the tailpipe; and (iv) a USB connection between AVL and computer for data observation and recording. The instrument requires approximately 2 minutes to warm up including HC residue test and leak test.

2.2.3. Non-exhaust Emissions

US-EPA AP-42 sample collection methodology is used to collect the samples from specified locations and understand the PM emission rates due to road dust. Figure 3 show the accessories used for the study. To collect the samples, a suitable area of 4 to 9 sq.m is marked out on the road surface such that a minimum of 500 to 600 grams of dust is accumulated within 24 hours. The marked-out area is cleaned by sweeping to remove the coarser particles from the surface, and an air blower is used to clean the finer dust particles from the voids on the surface. The pavement is exposed to normal traffic flow so that the dust gets accumulated on it due to the movement of vehicles, wind action and other factors contributing towards it.

After 24 hours the deposited dust samples will be collected using a vacuum cleaner. Sample is then transferred from vacuum bag to a storage bin and during this process a 2% loss in sample weight was observed. This loss can be attributed to dust collected in vacuum bag pores. The collected sample is further sieved using IS sieve pans and the sample passing through a 75-micron sieve and collected in a pan, weighed and the silt load (g/area/day) estimated using equation 1. Further, $PM_{2.5}$ and PM_{10} emissions were calculated using emission factors from USEPA AP-42 methodology as represented in equation 2(USEPA, 2011).

$$Silt\ Load\ (\frac{g}{day * m^2}) = \frac{(Sample\ passing\ through\ 75 micron\ sieve)}{Area\ of\ pavement\ under\ consideration} \quad (1)$$

$$E = k * (sL)^{0.91} * (W)^{1.02} \quad (2)$$

E = PM emission factor units matching units of k

k = particle size multiplier, $PM_{2.5}$ - 0.15 g/VKT, PM_{10} - 0.62 g/VKT

sL = silt loading - g/m2

W = Average weight (tons) of vehicles on the road

3. Results and Discussion

3.1. Traffic Volume

During the exhaust emission measurement, a camera was installed at sampling locations to record the road trip which also helped in counting the number of vehicles for the study.

Least number of vehicles were counted near to Qutub institutional area, for which the location was marked as low-density area. However, a moderate traffic density was observed around the IIT campus. Maximum traffic density was observed in Munirka-Mahipalpur road, for which the places were marked as heavy density roads. Number of 4W and LDV vehicles were found to be highest in the present study. The traffic density for different category roads during morning (M), afternoon (A) and evening (E) are presented in Figure 4.

At the low-density area, number of 4-wheeler (4W) vehicles were found to be maximum of 350±100 followed by light-duty vehicles (LDV) (200±70), 3-wheelers (3W) (150±30), 2-wheelers (2W) (90±50) and heavy-duty vehicles (HDV) (25±5) per hour. During the evening period traffic density was found to be maximum (Eg: 4W:350±100) followed by 300±100 and 250±50 per hour during morning and afternoon hours, respectively. This could be due to business and school closure times. During the data collection, a maximum traffic density of >500±150 to >600±150 4Ws alone were observed in Munirka- Mahipalpur road, respectively. However, the traffic density was not constant at sampling locations, as it changes day by day and season to season. It was found that maximum traffic dense area for the present study was Munirka-Mahipalpur followed by IIT Delhi main road and Qutub Institutional area.

3.2. Exhaust emissions

Real-time exhaust emission measurements were made for 4W vehicles. Figure 5 shows the variation of concentration and speed profile related to time. It was observed that the vehicle speed for 4W vehicles was found to be in the range of 10 – 70 kmph in all the three roads. However, the average speed of 4W vehicles was higher in the low-density road which was measured at 37 kmph (10.3 m/s). Whereas, 4W vehicles on medium and high-density roads were measured at 31.1 (8.6 m/s) and 26 kmph (7.2 m/s) respectively.

For low-density roads, average NO emission is 0.003 g/s (0.23 g/m^3). A similar trend of slightly varying pollutant concentration profile was observed with 4W vehicles in medium density roads. However, the speed profile was found to be different at medium and high-density roads due to more traffic congestion. For 4W vehicles at high-density roads, average NO pollutant concentration is 0.009 g/s (0.5 g/m^3). Table 2 represents the comparison of NO exhaust emissions factor obtained in the current study with major emission standards.

Table 2. NO vehicular exhaust emission factor (g/km) on different roads (ARAI, 2018; EPA, 2000; ICCT, 2015; Williams & Minjares, 2016)

Road	Emission rate (g/km)	BS – IV (g/km)	EURO – V (g/km)	USA Tier - 2 (g/km)	China – 5 (g/km)
Qutub Institutional area	0.61				
IIT Main Gate	0.67	0.25	0.18	0.19	0.18
Munirka	2.03				

At speed ranges (0≤v≤40, >60 kmph) and during acceleration, NO concentration was found to be higher, which can be attributed to elevated engine temperatures and availability of high oxygen concentration. NO is usually formed at temperatures >1000 °C during fuel combustion inside the engine, whose emission concentration increases with engine temperature. During acceleration high volumes of fuel are injected into the engine combustion chamber, where lunder the presence of oxygen fuel is ignited instantly to achieve the necessary speed the vehicle driver is aiming to achieve. During this process the car engine temperature is measured to reach nearly 1200 °C, thus releasing high concentrations of NO (Flynn et al., 1999; L. & Michael S. Graboski, 2000).

3.3. Non-exhaust Emissions

Silt load measurements were carried out at three different locations in Delhi, and the details are presented in Table 3 and Figure 6.

Table 3. Concentration of silt load, $PM_{2.5}$ and PM_{10} at measuring locations in Delhi city

Road	Silt Loading (g/m^2.day)	$PM_{2.5}$ Emission (g/VKm)	PM_{10} Emission (g/VKm)
Qutub Institutional area	3	0.54	2.22
IIT Main Gate	25	7.55	31.20
Munirka	44	12.40	51.25

Results indicated that the highest amount of silt load was observed at high-density road (44 g/m^2.day) followed by medium-density (25 g/m^2.day) and low-density (3 g/m^2.day) roads.

3.4. Health Effects

In an urban environment, gaseous and secondary pollutants make-up for 90% of the pollutant mass (Münzel et al., 2018). Furthermore, NO_x and PM have high respiratory and cardiovascular mortality rates, and total mortality baseline incidence per 100,000 was reported to be 497 and 1013 respectively (A. Kumar & Mishra, 2018; Ajay Singh Nagpure, Gurjar, & Martel, 2014). From the local surveys conducted in Delhi during early 2000's, 30% of the population are found to be with respiratory related ailments due to air pollution (Gurjar et al., 2016; Kandlikar & Ramachandran, 2000). (Ajay Singh Nagpure et al., 2014) investigation on human health risks between 1991 to 2010 has revealed that the high mortality due to cardiovascular and respiratory ailments in the Delhi city are related to increased concentration of oxides of nitrogen and suspended particulate matter. During this period respiratory related cases were observed to be 12 times the national average (Gurjar et al., 2016). A recent study conducted in 2016 on mortality and morbidity cases around the transport corridors of National Capital Territory of Delhi due to air pollution has estimated 414,874 health risk cases, of which nearly 32,000 were mortality cases (Kumar & Mishra, 2018). With NO emissions recorded from the current study being at least 2.5 folds higher than the BS-IV standards, critical health effects from the transportation sector is imperative and is expected to worsen due to an average growth rate of 6.4% in motor vehicular registration since 2010 (Ministry of Statistics and Program Implementation, 2018).

Along with vehicular exhaust emissions, non-exhaust emissions (resuspendable road dust) was also reported as a major source for ambient PM concentration in Delhi (Guo et al., 2017; Srivastava et al., 2008; Srivastava & Jain, 2007). Studies have attributed $PM_{2.5}$ to 4.2 million deaths globally in 2015, of which 57% were reportedly of PM caused cardiovascular illnesses (Burnett et al., 2018; Cohen et al., 2017; Dey et al., 2012; Landrigan et al., 2018). Even though non-exhaust emissions are not regulated, but from the afore mentioned studies it can be understood that they pose major health risk. If a 100% exposure reduction can be achieved, it would have avoided at least 4 million deaths in 2015 (Burnett et al., 2018). Henceforth, stringent measures are needed to avoid a major global catastrophe.

4. Conclusion

In the present study exhaust (NO emissions) and non-exhaust (resuspendable road dust) emissions from vehicles on low (JNU road and Qutub institutional area), medium (IIT Delhi main road and JNU main road) and high-density (Munirka–Mahipalpur) roads were investigated. NO emissions were measured only for test vehicles, and do not represent exhaust emissions from all the vehicles travelling during test period. To further understand and project the real-time vehicular emissions of the entire road motor transport fleet, a wide range of motor vehicles must be tested. Additionally, ambient air sampling for both particulate matter and gaseous pollutants in the test corridor would help in understanding the pollutant characteristics and health risk assessment.

The real-world exhaust emission measurements indicated NO emissions to be highest (0.5 g/m^3, 2.03 g/km) at Munirka–Mahipalpur road with an average speed of 26 kmph. The minimum real-time exhaust emissions were found to be lowest on JNU (0.23 g/m^3, 0.61 g/km), followed by Qutub institutional area (0.23 g/m^3, 0.67 g/km) with an average speed of the vehicle was 37 kmph (10.3 m/s) and 31.1 kmph (8.6 m/s) respectively. Results indicated that vehicular emission concentrations were several times higher than the BS IV standards (0.25 g/km).

Results of silt load measurements on the low, medium and high-density roads showed maximum value of 44 g/m^2.day on high-density road and least (3 g/m^2.day) on low-density road. The present study reveals that both exhaust and non-exhaust emissions from vehicles are significant contributors to air pollution.

Over the last 10 years nearly 2.5% reduction in deaths due to air pollution was observed (India | Institute for Health Metrics and Evaluation). But, with the ever-growing population and vehicular fleet in the Delhi city they pose much bigger threat to the human health and prove to be difficult to optimize. In 2017, India was effected with 1.24 million deaths due to air pollution, and 0.65 million deaths were attributable to ambient particulate matter concentration with Delhi being at the epitome of it due to its high population weighted mean $PM_{2.5}$ concentration of 209 $\mu g/m^3$ (95% UI 120.9 – 339.5) (Balakrishnan et al., 2019). Under such circumstances, both exhaust and non-exhaust emissions will considerably increase and result in deterioration of local air quality. In the past several studies focused on exposure to ambient air pollutants specifically concerning exhaust emissions and also focused on their regulations. However, the non-exhaust emissions due to tyre-wear, brake wear, abrasion of the road surface can contribute to many toxic compounds which have a significant impact on health. Hence, there is a need to regulate non-exhaust emissions on urban roads as well. Non exhaust emissions can be controlled by employing stringent regulations for dust emitting from construction activities, crop burning activities, overloading of material transport vehicles as well as good practices such as curb to curb pavement, regular cleaning of roads, implementation of green barriers.

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FIGURE CAPTIONS

Fig. 1. Route map of the study areas from exhaust and non-exhaust emissions in the city of Delhi

Fig. 2. (a) AVL DiTEST 1000 instrument (b) OBD data port (c) Bluetooth device and (d) USB device

Fig. 3. Accessories for road dust collection (a) vacuum cleaner (b) blower (c) Sieve and sieve shaker

Fig. 4. Road traffic density based on type of vehicle and duration of the day

Fig. 5. Speed and NO(%vol) concentration variation w.r.t. time (a) low-density (b) medium-density and (c) high-density roads

Fig. 6. (a) Silt load (g/day.m2) (b) $PM_{2.5}$ emissions (g/VKT) (c) PM_{10} emissions (g/VKT) at three monitoring locations in Delhi

TABLE CAPTIONS

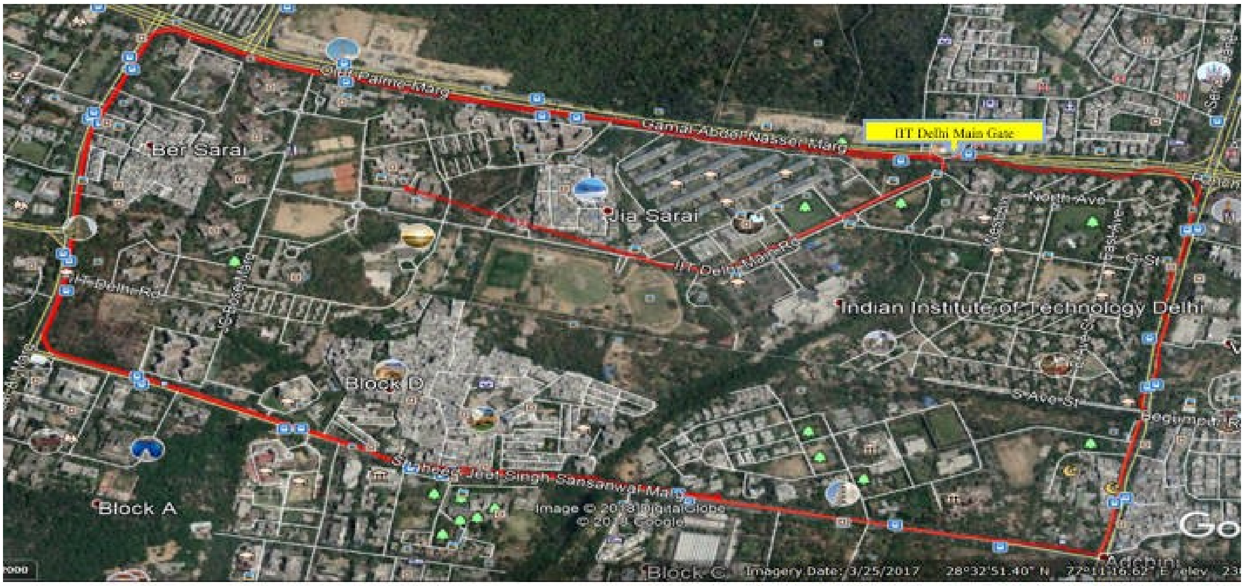
Table 1. Classification of vehicular exhaust emission test routes in Delhi city

Table 2. NO vehicular exhaust emission factor (g/km) on different roads (ARAI, 2018; EPA, 2000; ICCT, 2015; Williams & Minjares, 2016)

Table 3. Concentration of silt load, $PM_{2.5}$ and PM_{10} at measuring locations in Delhi city

Qutub Institutional Area
Olof Palme Marg
IIT Delhi Main Rd
Shaheed Jeet Singh Sansanwal Marg
Aruna Asaf Ali Marg
Jogging Track
Image © 2018 DigitalGlobe
© 2018 Google
Imagery Date: 5/7/2017

(a)



IIT Delhi Main Gate
Ber Sarai
Jia Sarai
Indian Institute of Technology Delhi
Block D
Block A
North Ave
Image © 2018 DigitalGlobe
© 2018 Google
Imagery Date: 3/25/2017
28°32'51.40" N

(b)

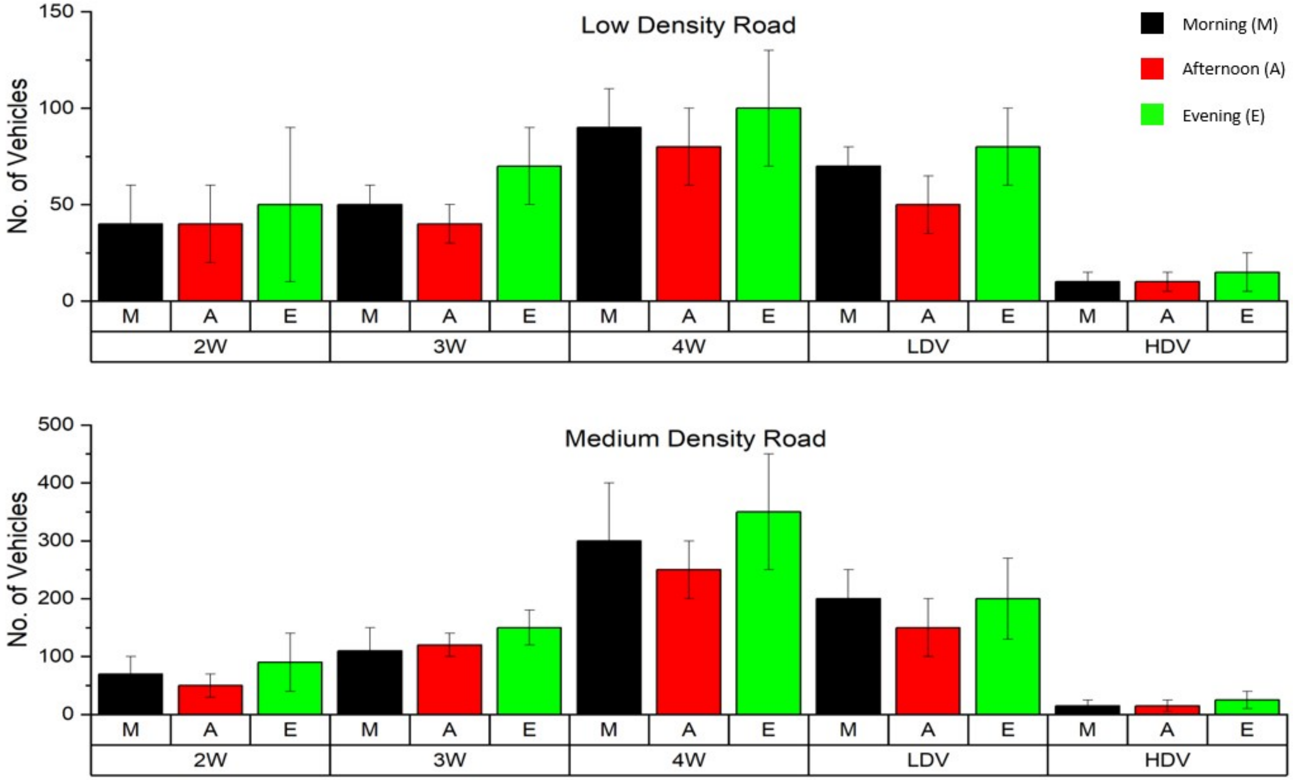
Munirka
Olof Palme Marg
Baba Ganganath Marg
Nelson Mandela Marg
AH 1
Image © 2018 DigitalGlobe
© 2018 Google
Imagery Date: 3/25/2017
28°33'59.74" N
77°09'06.61" E

(c)


AVL
DITEST
1 2 3 4 5 6 7 8
9 10 11 12 13 14 15 16
WIFI
MINI
Supports all OBDII protocols
ELM 327
Interface

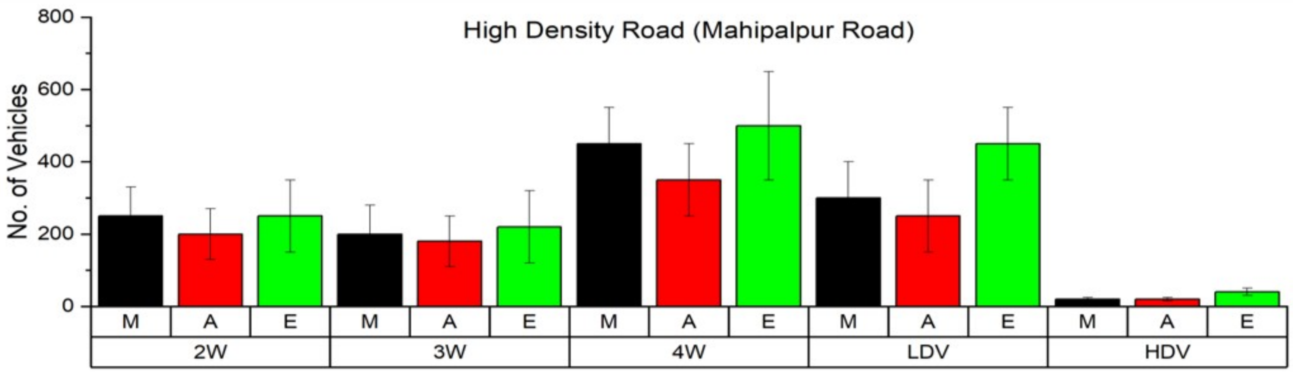
(a) (b) (c) (d)

(a) (b) (c)

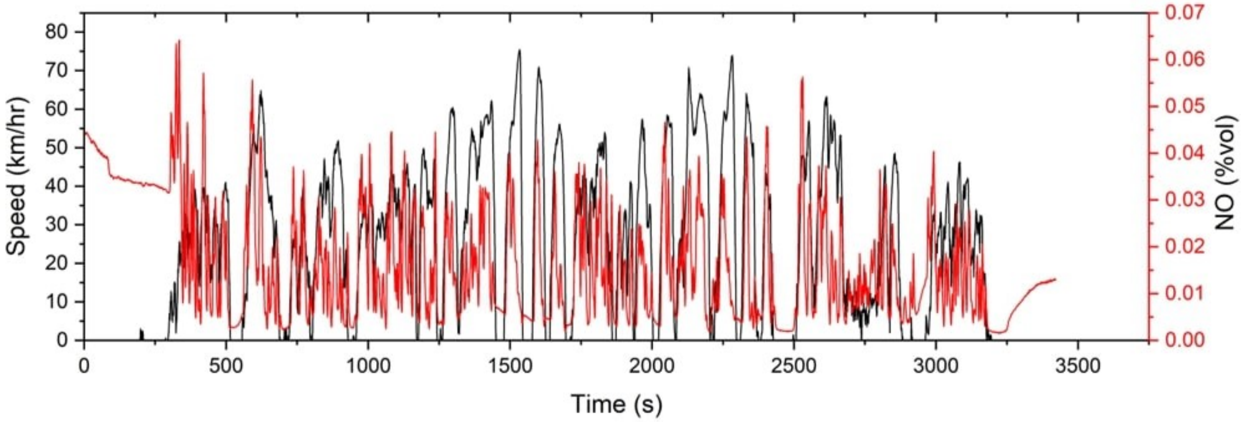


Low Density Road
Morning (M)
Afternoon (A)
Evening (E)
No. of Vehicles
0
50
100
150
M A E M A E M A E M A E M A E
2W 3W 4W LDV HDV
Medium Density Road
No. of Vehicles
0
100
200
300
400
500
M A E M A E M A E M A E M A E
2W 3W 4W LDV HDV

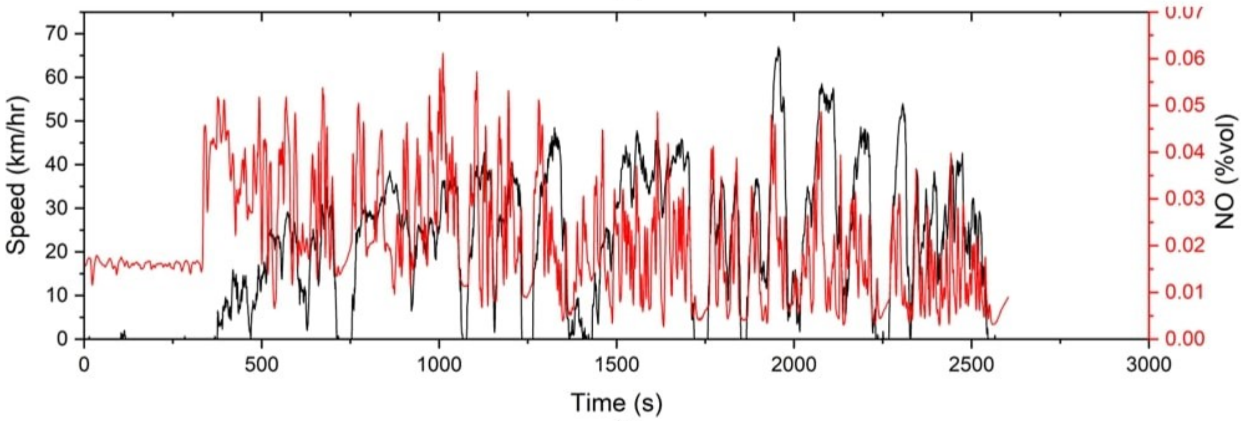
[redacted]



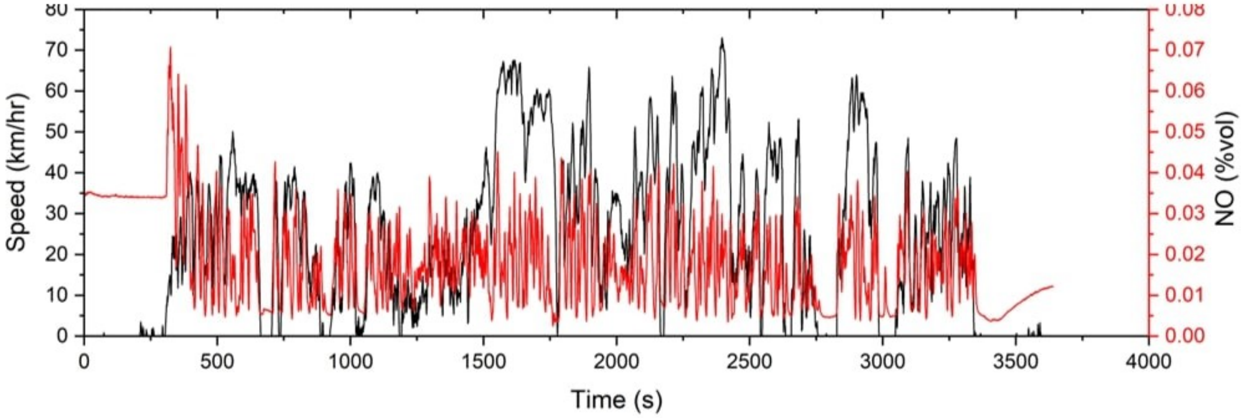
High Density Road (Mahipalpur Road)
No. of Vehicles
0
200
400
600
800
M A E M A E M A E M A E M A E
2W 3W 4W LDV HDV


Speed (km/hr)
NO (%vol)
Time (s)

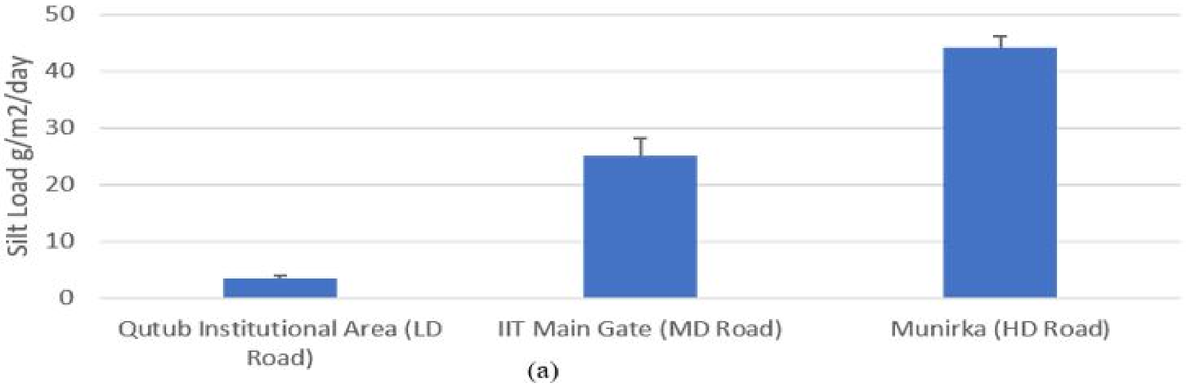
(a)


Speed (km/hr)
NO (%vol)
Time (s)

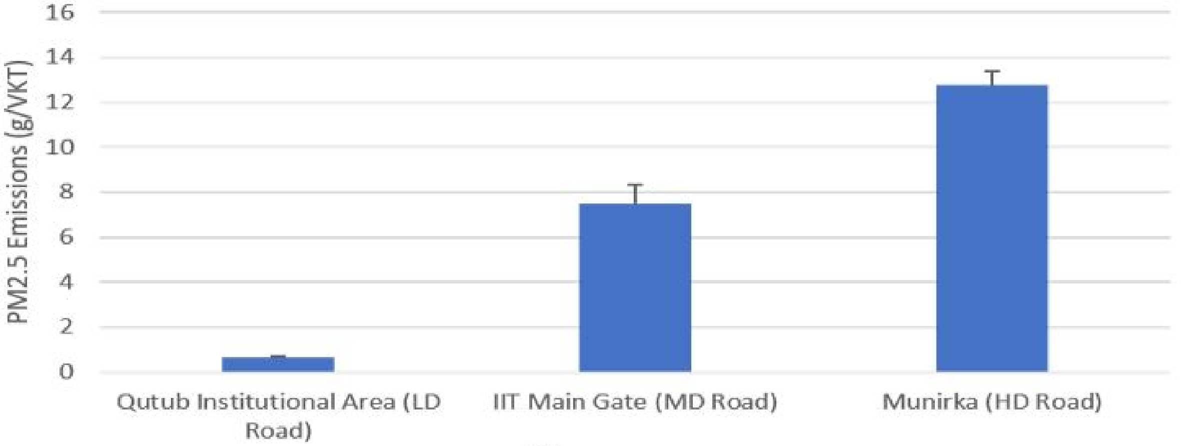
(b)


Speed (km/hr)
NO (%vol)
Time (s)

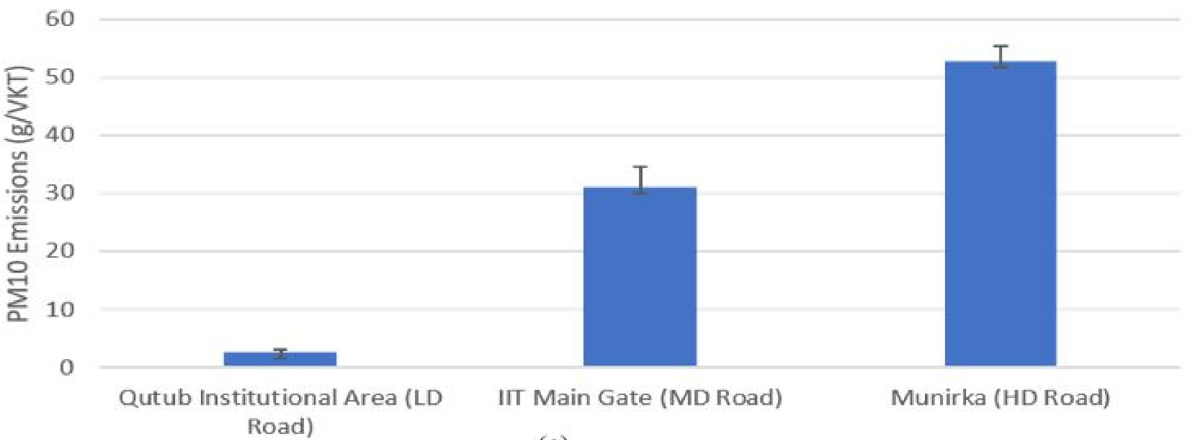
(c)


Silt Load g/m2/day
50
40
30
20
10
0
Qutub Institutional Area (LD Road)
IIT Main Gate (MD Road)
Munirka (HD Road)

(a)


PM2.5 Emissions (g/VKT)
16
14
12
10
8
6
4
2
0
Qutub Institutional Area (LD Road)
IIT Main Gate (MD Road)
Munirka (HD Road)

(b)


PM10 Emissions (g/VKT)
60
50
40
30
20
10
0
Qutub Institutional Area (LD Road)
IIT Main Gate (MD Road)
Munirka (HD Road)

(c)

Table 1. Classification of vehicular exhaust emission test routes in Delhi city

Road	Classification	Average traffic volume per hour	Average speed (V) (m/s)	Vehicle type/model
Qutub Institutional area	Low-density	≤ 1000 vehicles	V ≥ 10 m/s	Maruti Swift Dzire/2014
IIT Main Gate	Medium-density	1000 < vehicles ≤ 2000	7.5 m/s ≤V < 10 m/s	Maruti Swift Dzire/2012
Munirka	High-density	> 2000 vehicles	V < 7.5 m/s	Maruti Suzuki Ertiga/2014

Table 2. NO vehicular exhaust emission factor (g/km) on different roads (ARAI, 2018; EPA, 2000; ICCT, 2015; Williams & Minjares, 2016)

Road	Emission rate (g/km)	BS – IV (g/km)	EURO – V (g/km)	USA Tier - 2 (g/km)	China – 5 (g/km)
Qutub Institutional area	0.61				
IIT Main Gate	0.67	0.25	0.18	0.19	0.18
Munirka	2.03				

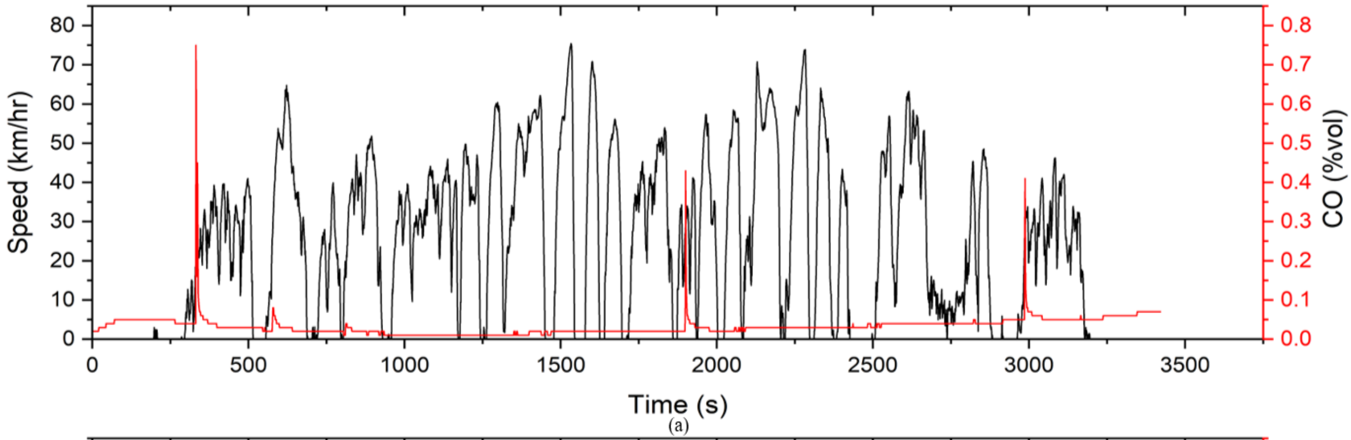
Table 3. Concentration of silt load, $PM_{2.5}$ and PM_{10} at measuring locations in Delhi city

Road	Silt Loading (g/m^2.day)	$PM_{2.5}$ Emission (g/VKm)	PM_{10} Emission (g/VKm)
Qutub Institutional area	3	0.54	2.22
IIT Main Gate	25	7.55	31.20
Munirka	44	12.40	51.25

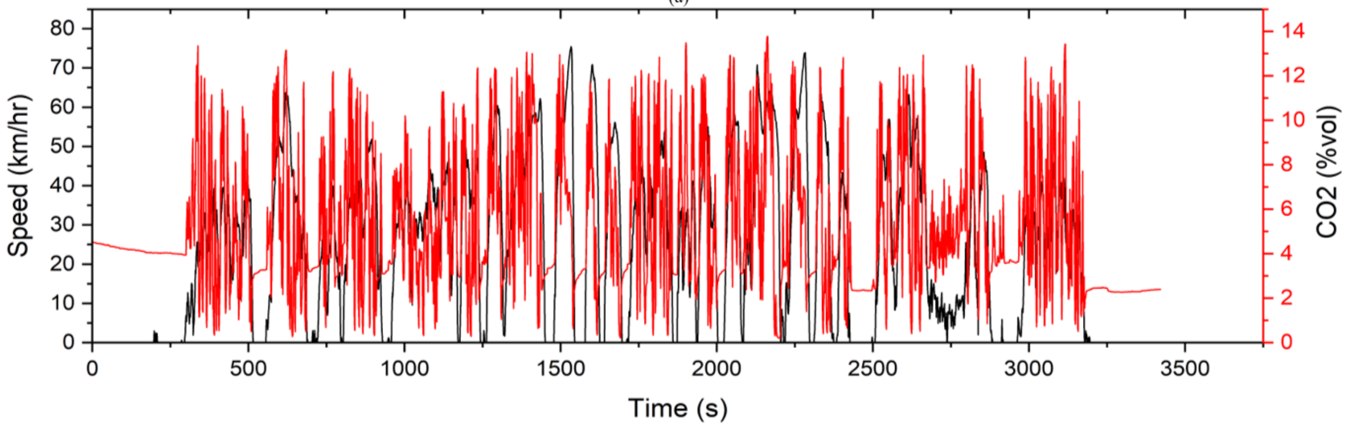
Title: Characteristics of Tail Pipe – NO and Resuspended Road-dust Emissions from Urban Areas – A Case Study in Delhi City

Supplement data:

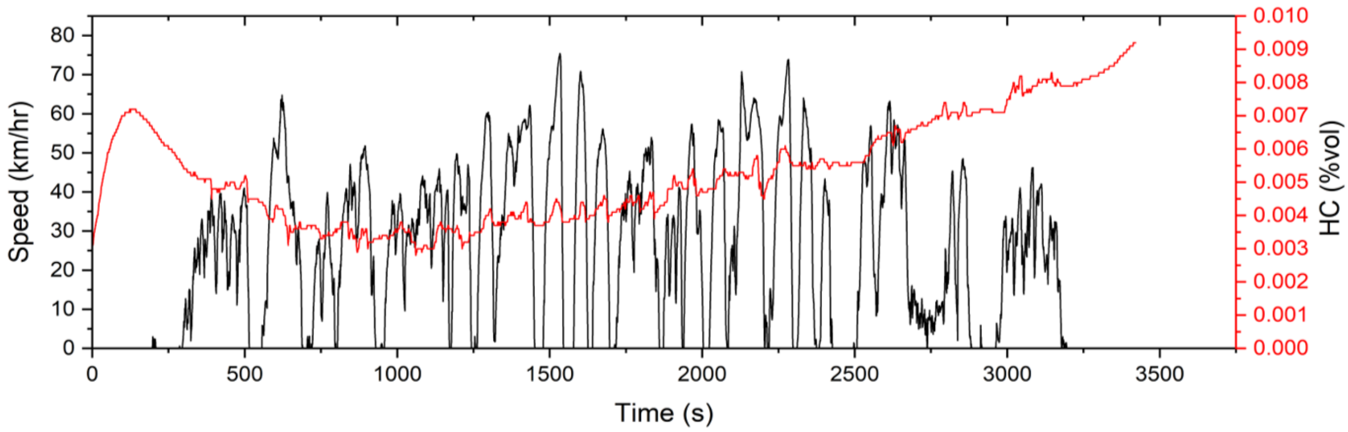
CO, HC, CO_2 emission data



(a)

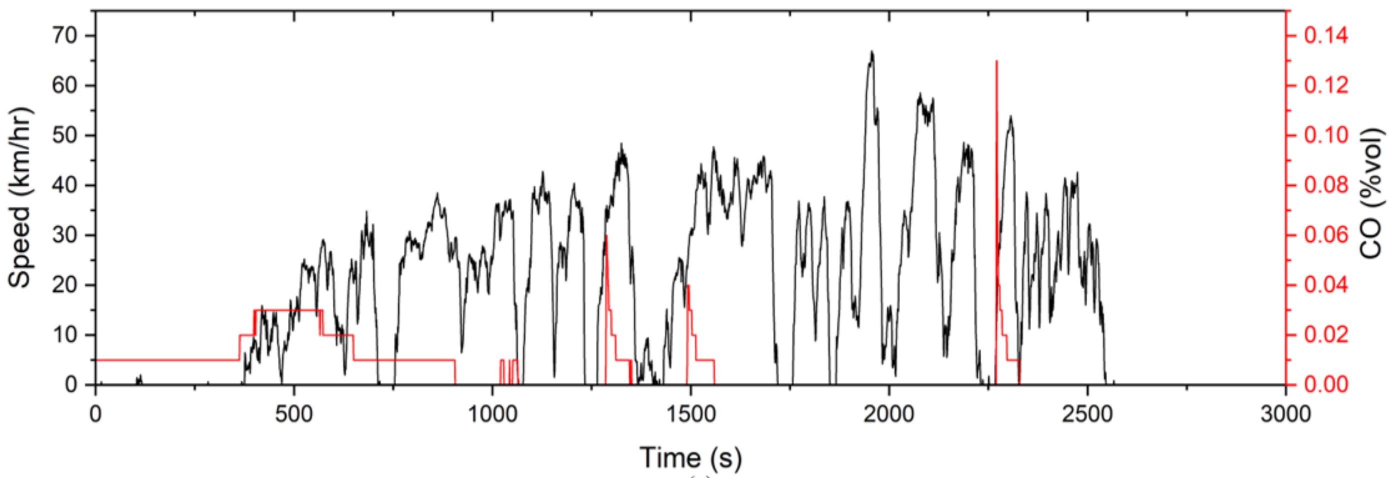


(b)

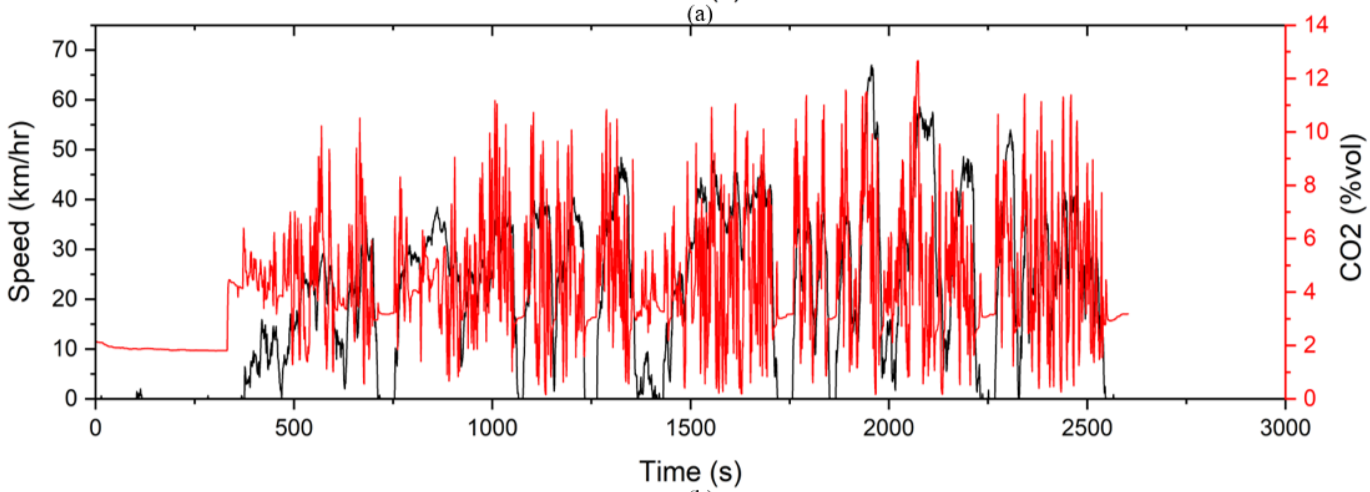


(c)

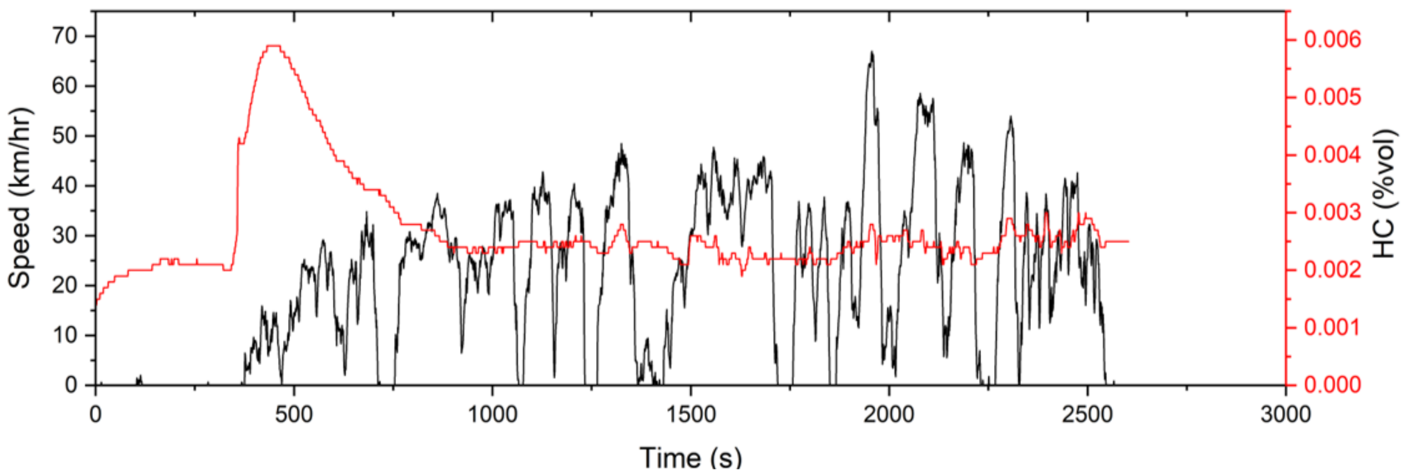
Supplement data Figure 1: a) Speed and CO(%vol) concentration b) Speed and CO_2 (%vol) concentration c) Speed and HC (%vol) concentration w.r.t. time for low-density road



(a)

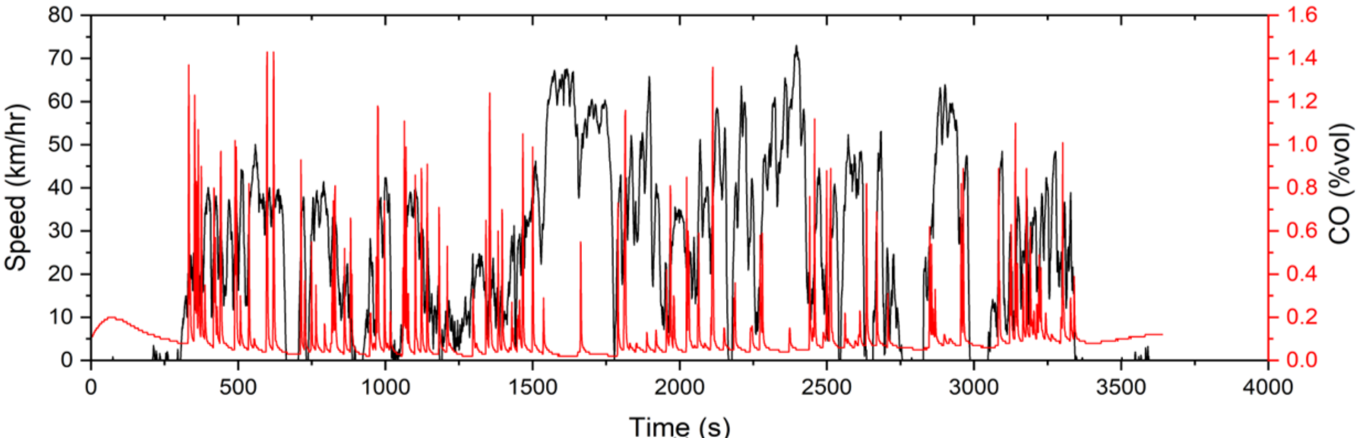


(b)

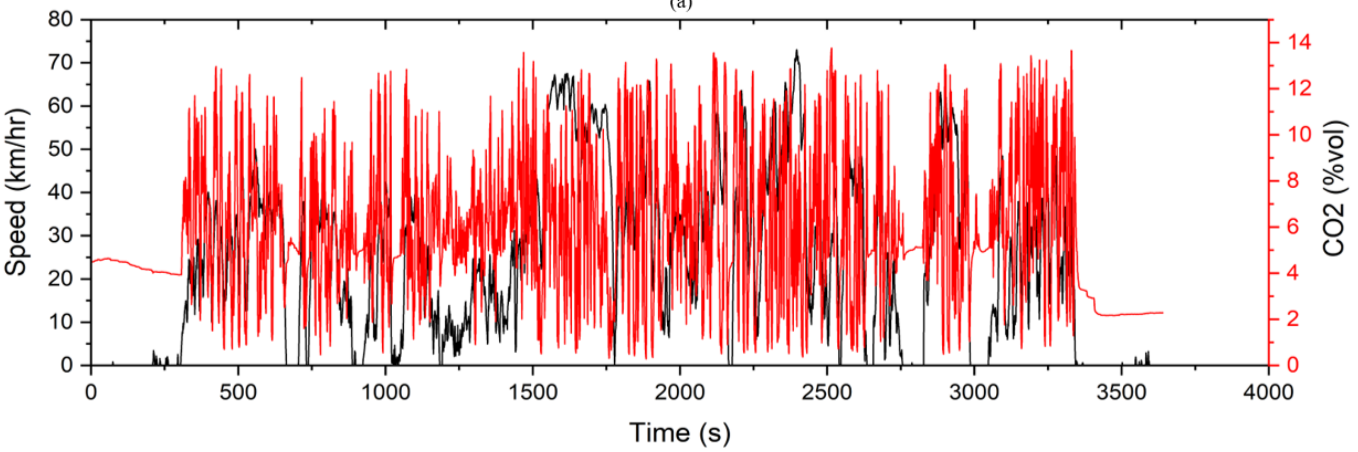


(c)

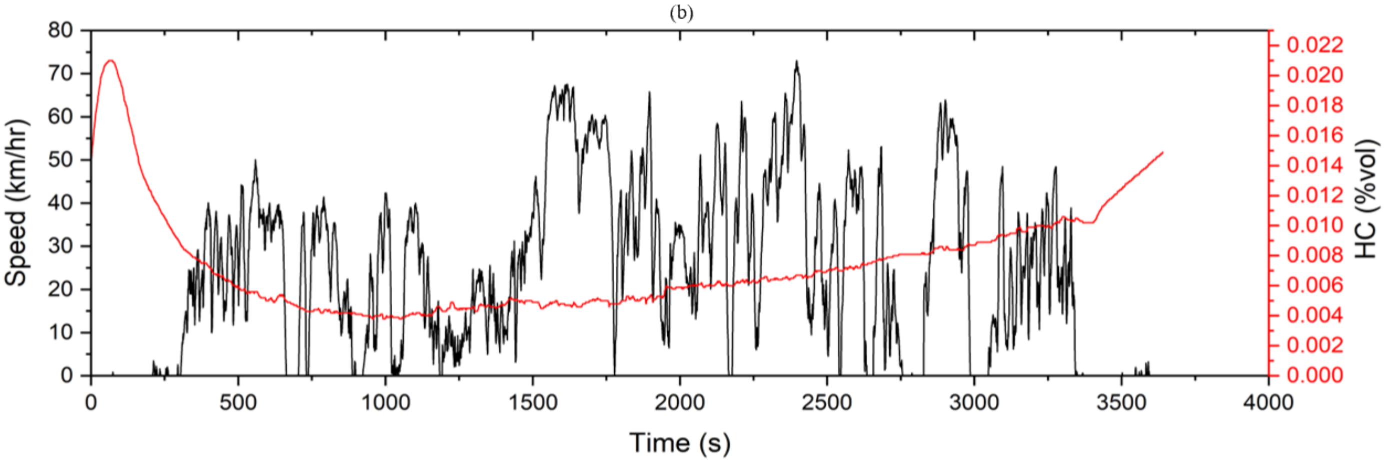
Supplement data Figure 2: a) Speed and CO (%vol) concentration b) Speed and CO_2 (%vol) concentration c) Speed and HC (%vol) concentration w.r.t. time for medium-density road



(a)



(b)

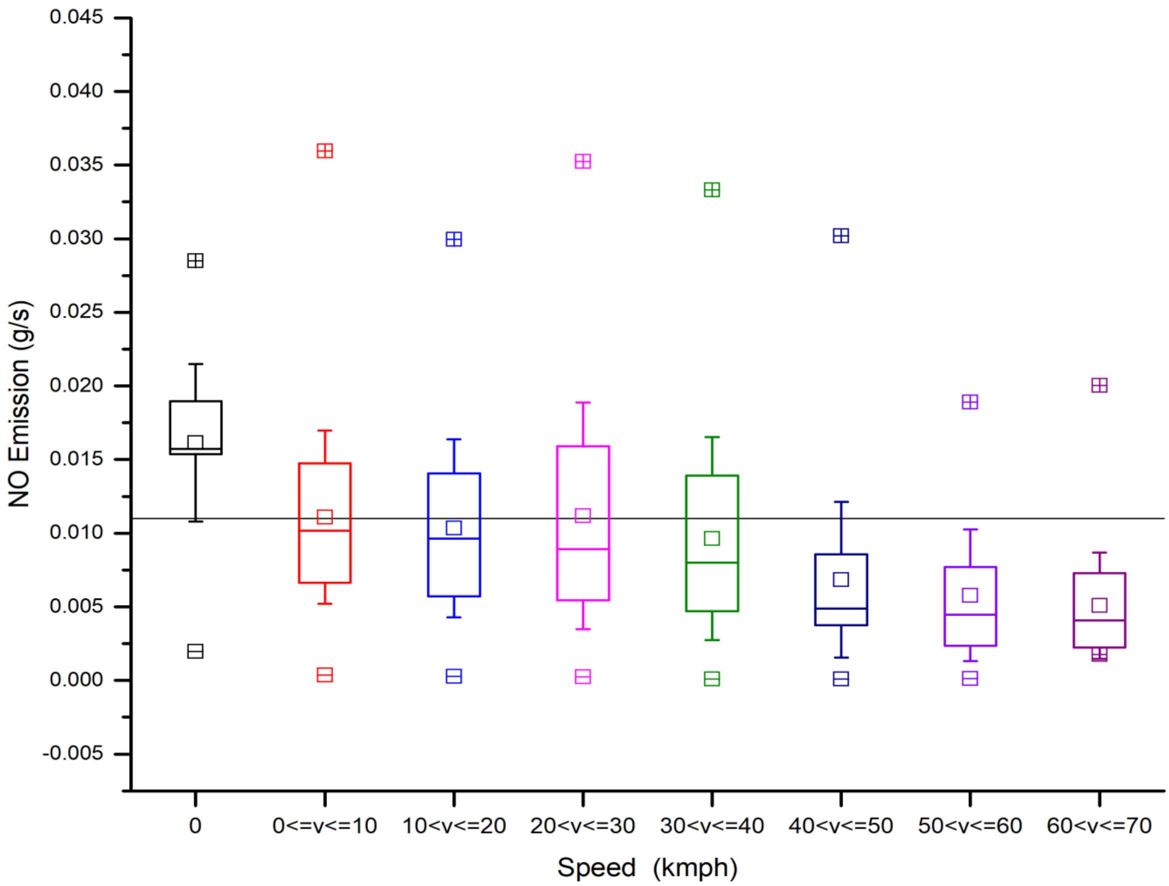


(c)

Supplement data Figure 3: a) Speed and CO(%vol) concentration b) Speed and CO_2 (%vol) concentration c) Speed and HC (%vol) concentration w.r.t. time for high-density road

Modal analysis of NO exhaust emission:

Vehicular speed was segregated into 8 speed ranges (1 during idling + 7 during the trip) and corresponding NO emission rate is quantified as shown in Figure 1. The average NO emission rate was highest (0.016 g/s) during idling and lowest at 60<v≤70 kmph speed range. It was also observed that at lower speeds (0≤v≤30 kmph) emission rates were higher, and this can be attributed to presence of high oxygen content or lean fuel mixture. Additionally, reduction in NO emissions was observed with increase in speed. To further understand vehicle activity and emissions, vehicle specific power (VSP) method was used for each of the speed range. In this approach, vehicle activity was divided into operation mode (Op Mode) bins, and for each bin, activity time and NO emissions were quantified in Table 1. As observed in Table 1, during the trip, vehicle have spent 33.4% of the time in idling (Opmode 1), nearly 14% in braking or decelerating (Op Mod -10, -10 – 0), 25.4% in cruising or accelerating at lower speed (Op Mod 1-4), 6.1% in cruising or accelerating at medium speed (Op Mod 5-6), 4.3% in coasting (Op Mod 7-8), and 16.9 in cruising and accelerating at high speed (Op Mod 9-10, >11). Hence, it is understood that in urban roads, vehicle spents majority of time either in idling or at lower speeds, during which NO emissions will be higher.



Supplement Figure 4: Vehicular speed ranges and corresponding NO emission rates

Table 1: Distribution of time spent in each speed range and operation mode, and NO exhaust emission rate (g/s)

Op Mode bin	Description	VSP	Speed Range (Kmph)								Percentage (%)
			Idling Before Trip	During Trip							
			v = 0	0≤v≤10	10<v≤20	20<v≤30	30<v≤40	40<v≤50	50<v≤60	60<v≤70	
			Time (s)	Time (s)	Time (s)	Time (s)	Time (s)	Time (s)	Time (s)	Time (s)	
< -10	Decel, Braking	VSP ≤ - 10.5	0	2	6	10	10	4	2	1	1
-10 - 0	Decel, Braking	- 10.5 ≤ VSP ≤ 0	0	201	129	69	33	20	6	0	12.9
1	Idle	0 ≤ VSP ≤ 0.5	400	1142	24	14	5	3	0	0	33.4
1-2	Cruising; accel;	0.5 ≤ VSP ≤ 2.5	0	251	246	68	26	14	4	1	17.1
3-4	Cruising; accel;	2.5 ≤ VSP ≤ 4.5	0	18	116	79	58	18	5	1	8.3
5-6	Cruising; accel;	4.5 ≤ VSP ≤ 6.5	0	3	35	72	73	28	6	0	6.1
7-8	Coasting	6.5 ≤ VSP ≤ 8.5	0	1	13	36	61	37	3	2	4.3
9-10	Cruising; accel;	8.5 ≤ VSP ≤ 10.5	0	0	1	20	43	56	12	1	3.7
>11	Cruising; accel;	10.5 ≤ VSP	0	0	6	32	64	147	126	94	13.2
	Time (s)		400	1618	576	400	373	327	164	100	
	Avg. Speed		0	2.4	14.7	25	34.9	44.9	54.5	63	
	Average Emission Rate (g/s)		0.016	0.011	0.01	0.011	0.01	0.007	0.006	0.005	
	SD		0.005	0.006	0.006	0.008	0.007	0.005	0.004	0.004	
	min		0.00198	0.00038	0.00028	0.00025	0.00010	0.00009	0.00012	0.00176	
	max		0.028	0.036	0.030	0.035	0.033	0.030	0.019	0.020	

*Percentage (%) of time spent in different operating modes was calculated for only during trip (Idling time before trip is excluded)