Characteristics of Real-World Gaseous Exhaust Emissions from Cars in Heterogeneous Traffic Conditions

Sudheer Kumar Kuppili[1], Dheeraj Alshetty V.[1], Diya M[1], S. M. Shiva Nagendra[1*], Gitakrishnan Ramadurai[1], Ramesh A.[2], Sunil Gulia[3], Anil Namdeo4[4], Kamal Maji[4], Margaret Bell[5], Paul Goodman[5], Enda Hayes[6], Jo Barnes[6], James Longhurst[6], Laura De Vito[6]

[1]Department of Civil Engineering, Indian Institute of Technology Madras, Chennai -600 036

[2]Department of Mechanical Engineering, Indian Institute of Technology Madras, Chennai -600 036

[3]CSIR-NEERI Nehru Marg, Nagpur-440 020, India.

[4]Northumbria University, Newcastle upon Tyne NE1 8QH, UK

[5]Newcastle University, Newcastle upon Tyne NE1 7RU, UK

[6]University of West England, Coldharbour Ln, Stoke Gifford, Bristol BS16 1QY, UK

---

*Corresponding author: S.M. Shiva Nagendra

Environmental and Water Resource Engineering Division, Department of Civil Engineering, IIT Madras, India-600036
T: 91-44 – 22574290 (O) ;91-44-22576290 (R);F: 044-22574252
E-mail addresses: snagendra@iitm.ac.in, shivanagendra@yahoo.com

Abstract

In this study, researchers have explored real-world driving conditions and developed emission factors for 58 passenger cars using on-board emission measurement technique while driving on five different routes in Delhi. The measured average emission factors of CO, HC, and NO were 3.99, 0.34, and 0.54 g/km for diesel vehicles, 7.26, 0.17, and 0.62 for petrol vehicles respectively. Road, traffic, vehicle type, and driving characteristics affect the quantity of emissions released. However, speed and acceleration significantly impact emission rates increasing with the increase in speed and acceleration. Also, emissions were minimal at 40 – 60 kmph and -0.5 – 0.5 m/s^2. The estimated city-wide CO, HC, and NO emissions were 60.8, 4.8, and 9.72tonnes/day. These results demonstrate the importance of monitoring the real-world exhaust emissions given the substantial difference between test cycle measurements used for compliance testing of new vehicles.

Keywords

Real-world exhaust emissions; Portable emission monitoring system (PEMS); Passenger cars; Emission factors; Emission rate;

1. Introduction

The transportation sector has always been a critical component of the delivery of economic growth. Whilst a well-planned transportation infrastructure can lead to the sustainable development of a nation, it is necessary not to ignore the role of the vehicular fleet diversity, quantity and their corresponding exhaust emissions (Gilles and Matthew, 2012; Pradhan and Bagchi, 2013; Timilsina and Shrestha, 2009) as new vehicle technologies are introduced and the fleet ages. In addition, the contribution to the total of emissions by on-road vehicles to the urban environment is increasing invariably due to unrestrained growth in vehicle ownership (Frey and Unal, 2002). In India alone, whilst the road length has increased from 3.4 million kilometres in 2001 to over 5.5 million kilometres in 2018 at a Compound Annual Growth Rate (CAGR) of 3.5% (IBEF, 2019), during the same period domestic vehicular sales increased from 5.3 million units per year to 26.3 million units per year with a CAGR of 22% (DataGov, 2016; SIAM, 2019).

During the period 2001-2015 Delhi has observed a rapid growth in vehicle registration from 0.36 million to 0.88 million with a CAGR of 7.1%. However, the proportional growth in road link length has not been achieved (Ministry of Statistics and Program Implementation, 2018). This means that whilst network capacity is to some extent being managed, the traffic demand is not, resulting in higher traffic flows and longer periods of congestion. Also, traffic conditions in India are highly heterogeneous, comprised of motorbikes, cars, light commercial vehicles (LCV), and heavy commercial vehicles (HCV) and non-motorised vehicles. Such diversity in vehicular traffic characteristics causes problems related to the disparity of speeds, acceleration, and manoeuvrability (Dhamaniya and Chandra, 2013). This results in reduced road carrying capacity leading to congestion and a decrease in average vehicular speed (Bajaj et al., 2017). Additionally, higher gasoline (petrol) prices are increasing the sales of diesel engine passenger cars which are known to emit more particle matter (PM) and primary nitrogen dioxide, (NO_2) concentration than petrol vehicles (Busse et al., 2009; Mahesh et al., 2018).

Technological advancements in improving engine performance and controlling emissions are occurring, but not at a rate sufficient to counteract the growth in number and use of vehicles with a detrimental effect on air quality of the Indian cities (Ghose et al., 2004). NO_2 exhaust from on-road vehicles undergoes a photochemical reaction to form ozone, which is a respiratory irritant and causes allergic asthma whereas, excess Carbon Dioxide, (CO_2) release in still weather results in the urban heat island effect. Additionally, NO_2, sulphur dioxide (SO_2), and volatile organic compounds (VOC) exhaust emissions are the precursor gases for secondary PM formation (Kumar & Mishra, 2018). In 2017, an estimated 4.7 million premature deaths in the world were due to air pollution, of which 1.2 million, almost a quarter of life loss was recorded in India alone (Balakrishnan et al., 2019; Health Effects Institute, 2019).

To reduce the emissions and its detrimental effects on human health, regulatory bodies recommended the adoption of control device and implementation of emission norms. Since 2000, Indian regulators have adopted Bharat stage emission standards set by the Central Pollution Control Board (CPCB) to regulate exhaust emissions. Emission rates per vehicle have reduced significantly (~85%) since the implementation of norms, however due to drastic increase in vehicular population, the total emissions are increasing (Sassykova et al., 2019). Implementation of control measures have also reduced the emissions in major Indian cities like Delhi (Chelani and Devotta, 2007). Lead free fuel, sulfur reduction, ban of older commercial vehicles, and use of only CNG based public transport vehicles are some of the other major implementations that were successful in significant emissions reduction in Delhi and other Indian cities (Goel and Guttikunda, 2015). Transport intervention policies such as Odd Even policies are also one of the mitigation measures adopted in Delhi city to reduce the impact of vehicular emissions, where PM concentrations were found to reduce up to 70% (Kumar et al., 2017). Fuel efficiency standards improvement and limiting the use of diesel vehicle fleet on Indian roads are necessary measures to be implemented immediately to mitigate the impact of vehicular emissions (Goel et al., 2016; Guttikunda and Mohan, 2014).

Under these circumstances, it is of prime importance to study vehicle exhaust emissions. Many researchers across the world have attempted to understand the characteristics to quantify the emissions through technologies which involve inventory-based models (COPERT, EMFAC) (Nagpure and Gurjar, 2012) or direct measurement employing conventional methods (dynamometer studies (Wang et al., 1998)), and in-situ monitoring (tunnel studies (Mancilla et al., 2012), car-chase method (Shorter et al., 2005), remote sensing (Bishop and Stedman, 1996)). Some of the studies have also reported the use of MOVES model that uses a conceptual approach, based on vehicle specific power (VSP) binning. Vehicle specific power (VSP) is an indicator for engine load that highly influences the emissions (Zhai et al., 2008). Whilst real-world measurements for homogenous traffic have been reported extensively in the UK (Carslaw and Rhys-Tyler, 2013; Noland et al., 2004; Rhys-Tyler and Bell, 2012; Ropkins et al., 2009) and Europe (Kristensson et al., 2004; Lawrence et al., 2016; Platt et al., 2014; Schmitz et al., 2000; Sjödin et al., 1995), they do not properly represent the real-world driving conditions in India and more specifically megacities with heterogeneous traffic conditions like Delhi. Most of the studies conducted in India have used vehicle chase method and on board measurement methods for determining the driving cycles (Arun et al., 2017; Jaikumar et al., 2017; Jaiprakash and Habib, 2018; Mahesh et al., 2018). Some of the recent studies have also used VSP based model MOVES for emission modelling in Indian cities (Perugu, 2019).

Recent studies with real world emissions monitoring systems shows that emissions are dependent on driving cycle and traffic conditions (Christopher Frey et al., 2006). Driving cycles can be determined by various methods such as trip-based cycle construction, the microtrip approach, cluster analysis, the trip segment method, Markov Chain Monte Carlo simulation and micro simulation model. However, trip based and micro trip approach are widely used in Indian studies (Arun et al., 2017; Desineedi et al., 2020; Sithananthan and Kumar, 2020). A study on influence of speed and acceleration on CO_2 emissions reported that every 1m/s increase in speed will emit 0.034g/s to 0.041g/s of CO_2, whereas an increase in acceleration by $1m/s^2$ will produce 0.008g/s to 0.025g/s of CO_2 emission. Similar observations have been made with other gaseous pollutants as well (Oduro et al., 2013).Thus, the purpose of this paper is to provide important insights into real-world vehicular emissions and highlight some issues related to the management of pollution arising due to gaseous emissions from heterogeneous traffic. Therefore, the study was carried out to characterise real-world driving conditions and develop emission factors for petrol and diesel passenger cars using an on-board portable emission measurement system (PEMS) for Delhi city. The outcomes of the current study will provide emission factors for real world driving conditions in heterogenous traffic and the data will add a great value to the existing literatures. The detailed discussions on the effect of vehicular speed and acceleration on the emission rate will provide researchers a better understanding of emissions in heterogenous traffic. The contributions of current study will also assist policymakers around the world in understanding the parameters affecting vehicular emissions for heterogeneous traffic and frame policies in accordance.

2. Methodology

2.1 Study Area

Delhi is a metropolitan city and the capital territory of India. According to the 2011 census, it occupies an area of 1483 km^2 with a population of 16.78 million (equivalent to a density of 11,320 per km^2). With more than 11 million registered vehicles moving on 33,198 km road length and 1282 traffic intersections, Delhi's arterial roads are extremely congested during peak hours.

Five routes were selected in Delhi to perform real-world vehicular emission measurements. These routes have different geometric dimensions, vehicular density, and land-usage, as shown in Figure 1 and Table 1.

Table 1: Study area in Delhi, length and land-use

Route	Length (km)	Traffic Signals	Road width/condition	Land Use
IIT Delhi Perimeter (D1)	9.1	12	4 lane with divider/black tar road/low speed	Institutional, Commercial
Residential Area (D2)	15	8	2-4 lane with divider/black tar road/high speed	Institutional, Residential, commercial
Munirka – Mahipalpur Road (D3)	25	26	2-6 lane with divider/black tar road/medium speed	Commercial, Residential
Airport Road (D4)	23	17	6 lane road, black tar/High speed,	Commercial
IIT D flyover (D5)	13.1	6	6 lane road, divider /flyovers, medium speed	Institutional, Recreational, Commercial

(a)
IIT D perimeter

(b)
JNU – Qutub Institutional Area

(c)
Munirka - Mahipalpur Road

(d)
Airport Road

(e)
IIT D Main Road – RTR Flyover

Figure 1: Study area (a) IIT Delhi perimeter (b) residential area (c) Munirka - Mahipalpur Rd (d) Airport Rd and (e) IIT D flyover

2.2 Test Vehicles

As of March 2016, Delhi has 3.1 million registered passenger cars, which constitutes nearly one-third of the registered vehicular fleet, increasing at a compound annual growth rate of 8% (MoRTH, 2018). Cars of different make, model, and age were used in this study, to represent the passenger car section of Delhi. The details are provided in Appendix A Table S1 and Supplementary Figure S1.

2.3 Data Collection

AVL DiTest-1000 is a five-gas portable emission measuring system (PEMS) and was used to measure real-time exhaust emissions from passenger cars. It measures CO, CO_2 and O_2 in volume percentage and HC, NO in ppm every second and is stored on a computer using Data

Acquisition System (DAS) software. DiTest 1000 operates with an accuracy of ± 0.002%vol for CO, and O_2, ± 0.3%vol for CO_2, ± 4ppm for HC and ± 5ppm for NO. Simultaneously, an ELM 327 model auto scanner is connected to the On-Board Diagnostics (OBD -II) link of the vehicle to collect the engine operation data during the exhaust measurements.

Before every trip, the instrument was calibrated and checked for leaks and HC deposition. A total of 58 cars were used and 170 exhaust emission measurement trips were conducted during the period of March, April, June, July, and December 2018, covering five study routes (Appendix A). Trips were made in the morning (8:00 – 10:00 AM), afternoon (12:00 – 2:00 PM), and evening (4:00 – 6:00 PM), and almost 350,000 second-by-second samples of emission measurements were gathered. Throughout the study, passenger cars were run with windows closed and air conditioning was kept on. As BS-IV fuel was implemented from 2010 in Delhi-NCR region, it is assumed that all the passenger cars involved in this study has been fuelled with BS-IV standard diesel and gasoline (ARAI, 2018). Road grade of all the study routes considered for the present study has an average gradient of 0.014 radians. As it is quite low, it does not have any significant effect on the emissions. During the study, the average ambient temperature was 29.5˚C (85.2˚F), with an average maximum and minimum temperature of 33.3˚C (92˚F) and 25.8˚C (78.4˚F) respectively. Also, experiments were conducted at a maximum ambient temperature of 42.2˚C (108˚F) during June 2018 and minimum of 4.4˚C (40˚F) during December 2018.

2.4 Data Analysis

Emission rate (g/s), emission factor (g/km), average speed, and time spent in different vehicle operation modes (idling, acceleration, deceleration, and cruising) were estimated using the monitored data. Conditions to segregate the recorded data into vehicle operation modes (Table 2) are adopted from previous studies (Mahesh et al., 2018; Saleh et al., 2009).

The emission rate, ER, was calculated using gas concentrations from DiTest 1000 and exhaust mass airflow rate from OBD – II as follows:

$$ER = P * M_{Exhaust} * \rho_{fraction} \tag{1}$$

Where P is the second-by-second concentration of the pollutant in %Vol or ppm, $M_{Exhaust}$ is the mass of exhaust gas in g/s and $\rho_{fraction}$ is ratio of density of pollutant and density of exhaust gas (1.249 kg/m^3) at 25˚C and 1 atmosphere pressure. $M_{Exhaust}$ is the sum of the weight of fuel used in g/s and mass airflow rate in g/s.

An emission factor is obtained by summing up the emissions released during the travel and dividing with distance travelled. Where, t is the time, and d is the total distance travel in a route.

$$EF = \frac{\sum_0^t ER}{d} \tag{2}$$

Table 2: Operation mode and conditions for vehicles

Operation Mode	Mode Condition
Idle	$v < 2.5$ km/h and $-0.1 \leq a \leq 0.1$ m/s^2
Acceleration	$a > 0.1$ m/s^2
Deceleration	$a < -0.1$ m/s^2
Cruising	$v \geq 2.5$ km/h and $-0.1 \leq a \leq 0.1$ m/s^2

3. Results and Discussion

3.1 Emission Factors of Passenger cars

Emission factors (EF) were estimated for 58 passenger cars, and they are from 37 different make and model (tested multiple cars from same make and year), as shown in Figure 2(a) and Figure2 (b). Table S1 and Figure S1 in Appendix A provides a detailed list of passenger cars and emission factors. In the passenger cars category, 2013 Chevrolet Enjoy (diesel), and 2016 Wagon R (petrol), were observed to have the highest CO emission factors, i.e. 14.7 and 14.3

g/km whereas for HC+NO emissions 2015 Renault Duster (diesel) and 2016 Wagon R (petrol) had the highest EF, i.e. 1.75 and 1.37 g/km.

Among the same make for both diesel and petrol passenger cars; older model cars have higher emission factors, which can be attributed to engine condition and combustion efficiency. A similar trend was observed by Choudhary & Gokhale, 2016, Dheeraj Alshetty et al., 2020 and Mahesh et al., 2018. However, gaseous exhaust emissions concentrations from Toyota Innova model passenger cars did not particularly follow any trend and this could be due to the maintenance and working conditions of exhaust after-treatment devices fitted to passenger cars.

3.2 Comparison with Previous Studies

Table 3 shows the EF of diesel and petrol passenger cars in comparison with Bharat Standards (BS-IV) and other studies. In the current study, an average emission factor for diesel passenger cars was observed to be 3.99, 0.34, and 0.54 g/km were observed for CO, HC, and NO respectively. All the diesel cars tested for real-time emissions have crossed the EF limit of BS-IV. 2017 Chevrolet Enjoy (14.7 g/km) was recorded to emit 29.4 times more CO than the BS-IV limit (0.5 g/km). In the case of HC+NO emissions, 2015 Renault Duster emitted 5.8 times, more than the BS-IV limit (0.3 g/km). The average CO, HC emission factor measured in this study is quite high compared to other studies Chikhi et al., 2014; Jaikumar et al., 2017b; Jaiprakash & Habib, 2018; Mahesh et al., 2018; May et al., 2014. However, the average NO emissions in this study were close to those measured by Mahesh et al., 2018 and May et al., 2014 studies, but higher than Chikhi et al., 2014. The average NO emission factor reported in Jaikumar et al., 2017b and Jaiprakash & Habib, 2018 were 2.4 and 1.9 times respectively, higher than this the EF in this study.

Table 3: Comparison of passenger car emission factors with different studies

Diesel Vehicles

	Pollutants	This study	BS-IV(ARAI, 2018)	Jaikumar et al., 2017b	Mahesh et al., 2018	Jaiprakash & Habib, 2018	May et al., 2014	Chikhi et al., 2014
Emission Factor (g/km)	CO	3.99	0.5	0.68	1.28	0.3	0.47	0.80
	HC	0.34	0.05	0.07	0.13	-	0.04	0.20
	NO	0.54	0.25	1.32	0.59	1.0	0.5	0.30
	HC + NO	0.84	0.30	1.39	0.72		0.54	0.5

Petrol vehicles

	Pollutants	Petrol	BS-IV (ARAI, 2018)	Qu et al., 2015	May et al., 2014	Jaiprakash & Habib, 2018	Chikhi et al., 2014
Emission Factor (g/km)	CO	7.26	1	6.47	0.75	2.2	0.75
	HC	0.17	0.1	0.46	0.02		0.05
	NO	0.62	0.08	0.41	0.07	1.0	0.52
	HC + NO	0.84	_	0.87			0.57

For gasoline passenger cars an average emission factor of 7.26, 0.17, and 0.62 g/km for CO, HC, and NO were recorded. Emission factors from this study are 7.26 (CO), 1.7 (HC), and 7.75 (NO) times higher than BS-IV standards. The results for CO, HC+ NO were consistent with those recorded by Qu et al., 2015 whilst the average CO emission factor is nearly 10 times higher than those measured by May et al., 2014 and Chikhi et al., 2014 and 3.3 times more than Jaiprakash and Habib, 2018 study. Similarly, NO and HC emissions were higher than other studies, except Jaiprakash and Habib, 2018 recorded NO 1.6 times that of the present work. This variation in results can be expected as the methodology, equipment for measuring the real-time vehicle exhaust emissions, the number of test drives conducted, types and number of passenger cars, study area, built environment, traffic levels and flow regimes (free and smooth flow, unstable, congested), meteorological conditions and many other factors are different from study to study.

A notable difference in the current study compared with previous studies is the higher levels of CO emissions. Having taken steps to demonstrate that this is not due to any systematic error in the measuring equipment, we conclude that this is due to a combination of the following reasons:

1. The route length – In most Indian studies, route length were short, straight roads and many are non-Delhi studies. Our study included local roads, arterial roads, and highways. Road length in our study varied between 9 - 25km

2. Frequent acceleration, Deceleration causes higher CO emissions. Our study shows that the Delhi driving cycle has 60-70% of acceleration and deceleration modes. Hence higher emissions.

3. Wide range of passenger cars tested. Other studies were limited to less than 10 cars and especially few variants. Whereas, we have tested 58 cars of different make and model.

4. Irregular vehicle maintenance by the users.

5. Usage of different drivers for different vehicles.

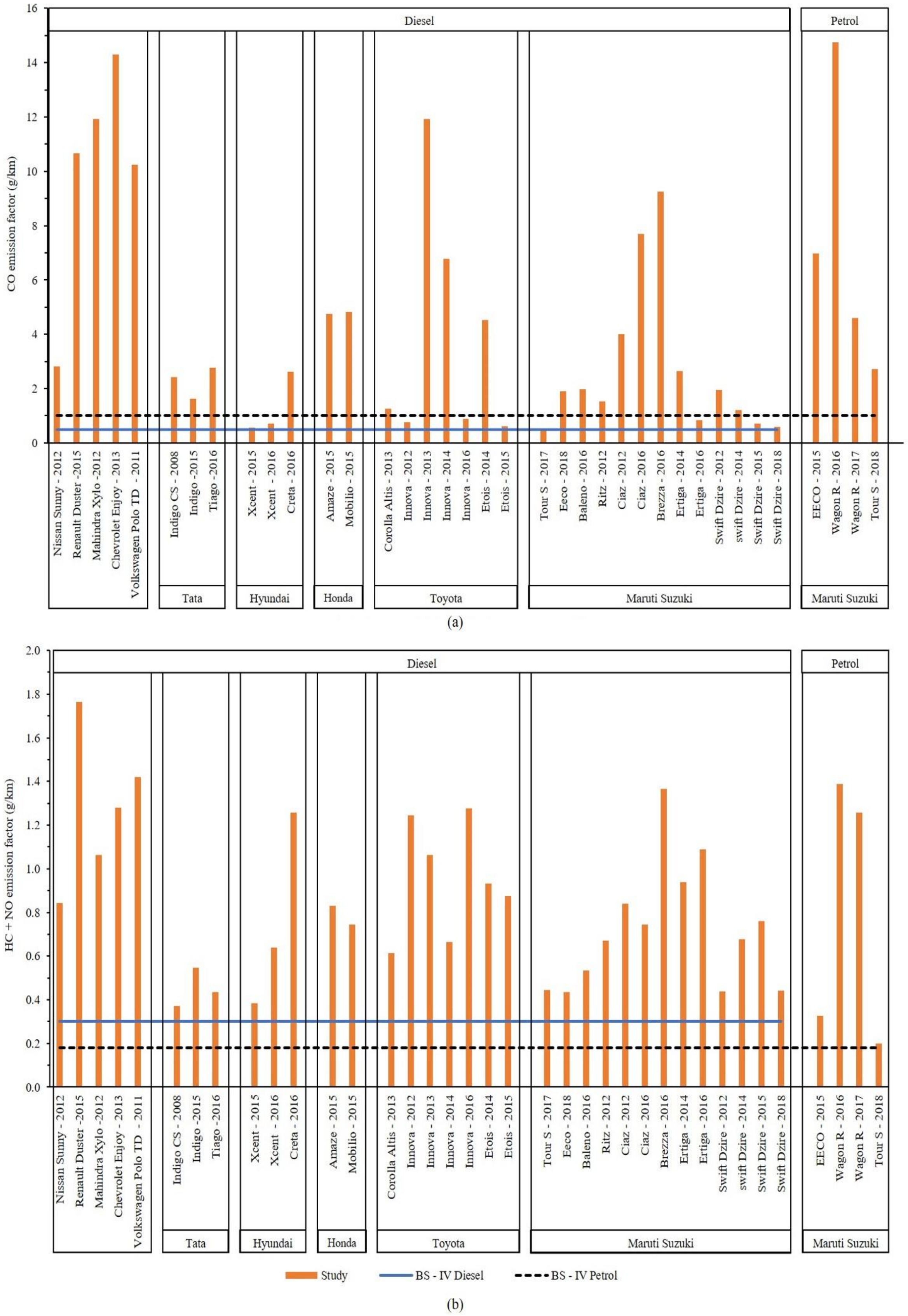

Figure 2: Cars emission factors (a) CO (b) HC + NO

3.3 *Effect of Road and Driving Conditions*

The routes used in this study are a mixture of both arterial and local roads. Each route has local roads of length ranging from 3 – 6.5km, as it is important to have a range of both for replicating the daily travel patterns of drivers/passengers. The effect of road characteristics on vehicular emissions, the variations in speed on the study routes was investigated. Table 4 and Appendix-A Figure S2 represent the speed variations and driving characteristics in the five study routes, respectively. The Residential Area route had more stretches of roads with free-flow traffic, therefore the highest average vehicle speed, i.e., 29.9 kmph was recorded. This was followed by IIT D RTR flyover road, Airport Rd, Munirka – Mahipalpur area, and IIT D perimeter with 28, 24.5, 23.3, and 23kmph respectively. IIT D Perimeter and Munirka – Mahipalpur study routes involved arterial roads with interrupted and congested flows, frequent traffic signals, and 90-degree turns. This affected the driving profile and, in these areas, the higher acceleration and deceleration rates were observed. IIT D perimeter recorded the highest acceleration of 8.8m/s^2 followed by Munirka – Mahipalpur route with 8.6m/s^2.

In India, the emission compliance of the vehicles in question or sometimes the representative vehicles are determined by operating them on Modified Indian Driving Cycle (IDC) using a chassis dynamometer (Khan and Frey, 2018). However, the standard driving cycle do not represent the real-world driving conditions in majority of the Indian cities. In Table 4, driving characteristics observed in this study and modified IDC are reported. The percentage of different operational modes (idling, acceleration, deceleration, and cruising) in real-world driving conditions are completely different from modified IDC (ARAI, 2010). In this study for real-world driving conditions, average acceleration and deceleration combinedly accounted for 64.8%, whereas Modified IDC is dominated by cruising and idling (70.7%). The average running speed (without idling) of real-world is nearly two-thirds of the modified IDC. Also, the observed maximum acceleration and deceleration were 10.5 and 7.5 times that of modified

IDC. From the Supplementary Table S3, it was also observed that in real-world emission rate during acceleration and deceleration is 1.3-1.5 times of idling and cruising. As, IDC is dominated by high cruising and idling time along with lower acceleration/deceleration values (m/s^2), vehicle tested under IDC can be expected to emit lower emissions than in real-world conditions.

Table 4: Driving characteristics of the five study routes

	Real-world Driving						Chassis Dynamometer Test
	IIT D Perimeter (D1)	Residential Area (D2)	Munirka – Mahipalpur Road (D3)	Airport Road (D4)	IIT D RTR Flyover (D5)	Average	Modified IDC (ARAI, 2010)
Idling (%)	14.7	14.9	17	14.7	8.5	14.5	30
Acceleration (%)	34.7	35.1	33.3	31.3	36	34.3	18.3
Deceleration (%)	31	30.7	29.7	28	32.6	30.5	11
Cruising (%)	19.6	19.3	20	26	22.9	20.7	40.7
Avg. speed (kmph)	23.3	29.9	23	25.4	28	25.3	32.5
Avg. running speed (kmph)	28.2	36	28.5	30.5	31.8	30.2	46.4
Max. acc. (m/s^2)	8.8	5.7	8.6	5.9	5.5		0.83
Max. dec. (m/s^2)	10.3	5.6	5.4	6.0	6.5		1.39

During any one journey; a vehicle undergoes idling (I), acceleration (A), deceleration (D), and cruising (C) modes, and emissions are released accordingly. Table 4, shows that the maximum time spent by vehicles in acceleration (36%) and deceleration (32.6%) modes was on IIT D RTR Flyover compared to the other routes followed by the Residential Area route. Vehicles experienced longer period cruising on Airport Road (26%) due to its combination of longer sections of arterial road and fewer traffic signals per kilometre travelled. Idling was maximum on Munirka – Mahipalpur road (17%), due to many traffic signal-controlled junctions, intersections, and turns.

Higher emissions are emitted during acceleration, followed by cruising, deceleration, and idling (Choudhary and Gokhale, 2016). A similar trend has been observed in this study and was supported by the Pearson correlation measured between pollutants and driving modes using Statistical Package for the Social Sciences (SPSS) as shown in Appendix-A Supplementary Table S2. Vehicular emissions have a stronger correlation with acceleration and were followed by cruising, deceleration and idling. Also, acceleration has a correlation coefficient >0.01 and higher than others, which means acceleration has a higher impact on vehicular emissions than other driving modes.

Appendix A Supplementary Table S3 shows the average emission rate of CO, HC, and NO for each of these driving modes. In this study, the CO emission rate was highest during acceleration and lowest whilst idling; however, similar emission rates were observed in deceleration and cruising modes except on the Residential Area route. Nonetheless, this trend is pronounced more in HC, and NO gases, i.e., emission rates were higher during acceleration, followed by cruising, deceleration, and idling. Choudhary & Gokhale, 2016, May et al., 2014, Qu et al., 2015b, and Shukla & Alum, 2010 have reported a similar trend. Qu et al., 2015b also observed that higher emission rates were more prevalent during periods of high speed and acceleration, which is visible clearly in the NO emission rate. When a vehicle accelerated, more air and fuel are injected into the engine cylinders, increasing the engine load, thereby causes higher CO and HC emissions. CO emissions from engines are due to incomplete combustion, especially during deceleration, where the engine can misfire and release higher CO and HC emissions. Acceleration and deceleration also result in rich and lean fuel mixture conditions closer to the stoichiometric ratio, which creates favourable combustion temperature for the formation of

NO, thereby releasing higher NO emissions (Choudhary and Gokhale, 2016; Wang et al., 1998). The average emission factors of CO, HC, and NO on the five study routes are shown in Appendix A Supplementary Table S4. All the roads have contributed emission factors higher than BS-IV standards for vehicles, with Residential Area registering the highest CO emission factor of 5.26 g/km, and IIT D Perimeter with lowest, i.e., 3.72 g/km. IIT D RTR Flyover recorded highest NO emissions, i.e., 7.2 g/km and lowest HC, i.e., 0.10 g/km, while Residential area recorded the lowest NO and highest HC emissions, i.e., 0.3 and 0.44 g/km respectively. It is evident that vehicular emissions depend on the road and driving characteristics, which affect the vehicle's speed and acceleration. Therefore, it is necessary to probe into different ranges of speed and acceleration to suggest the preferable combination for curbing the emissions.

3.4 *Effect of Speed and Acceleration*

Quick and sharp acceleration and deceleration consumed more fuel, leading to higher emissions. It is necessary to find the optimum combination of speed and acceleration at which both fuel consumption and resultant emissions can be reduced. The average percentage of time spent by passenger cars in different speed bandwidths is represented in Appendix A Figure S3 (a), and Figure S3 (b). During the test drives, vehicles spent more than 61% of the time below a speed of 30kmph, out of which almost half of the time was below 10kmph. It was also observed that vehicles had spent nearly 70% of the time between $-0.5 < a < 0.5$ m/s^2 acceleration range. This is due to the prevailing traffic conditions on the roads of Delhi.

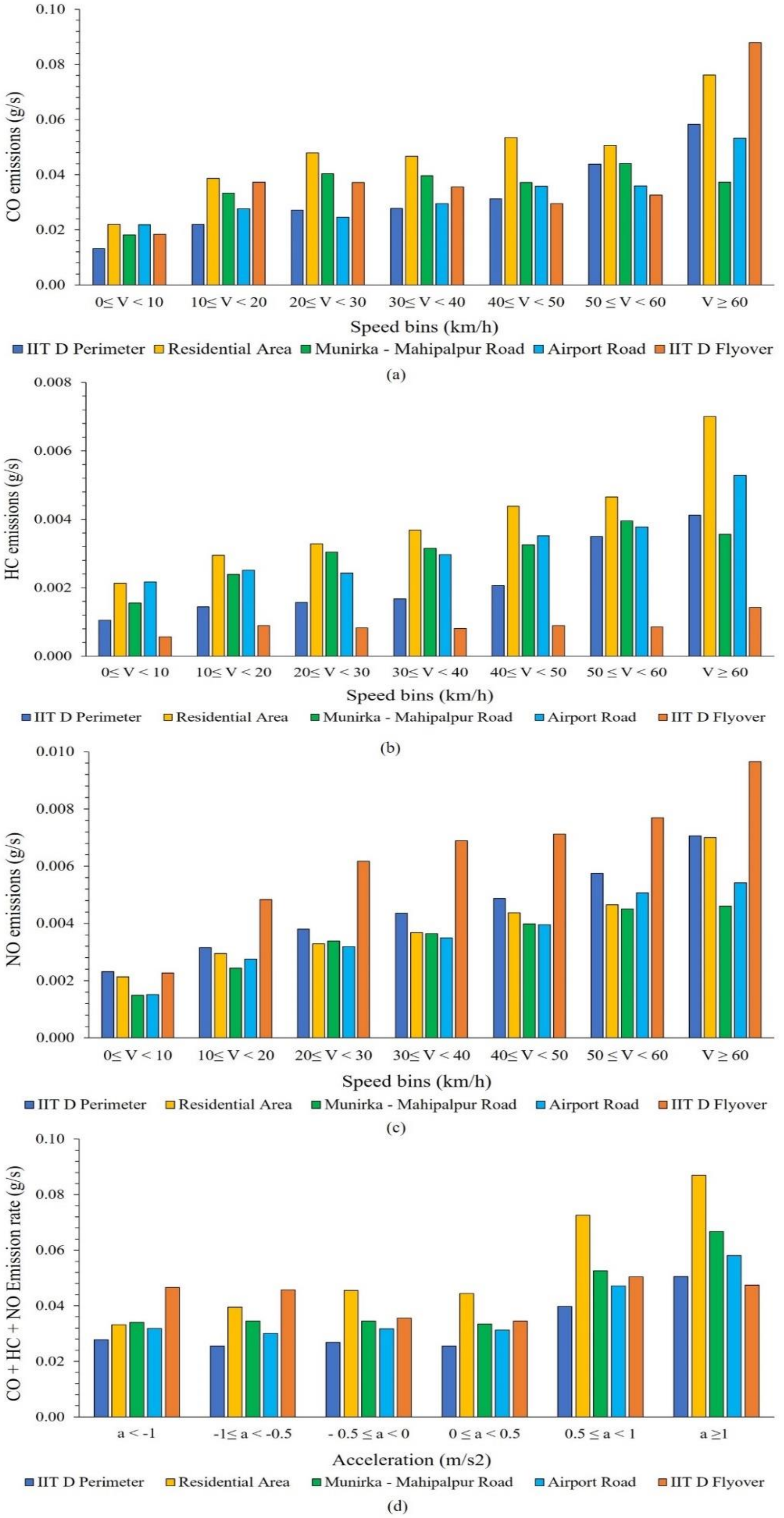

Figure 3: Emission rates of (a) CO, (b) HC, (c) NO in different speed bins and (d) Combined emission rates of CO, HC, and NO in different acceleration bins

The emission rate of the pollutants from the vehicle subject to its speed and acceleration is shown in Figure 3(a), Figure 3(b), Figure 3(c) and Figure 3(d). The speed emission rates of the gases increased rapidly up to 40kmph; however, between 40 – 60kmph, emission rates appeared to be stable. Similar observations were made by Stead, 1999, Jaikumar et al., 2017b and Mahesh et al., 2018. Supplement Fig S4, and S5 displays graph of average emission rate versus speed for diesel and petrol vehicles respectively. Supplement Fig S6 shows aggregated emission rates versus speed. Aggregate speed emission curve provides with the emission trend w.r.t. speed, and it helps in understanding the variation of emission rate at different speeds and also the supports the trends observed in speed bin- emission analysis. In Supplement Fig S4, the emission rate has increased with speed, albeit a negative slope was observed at 35- 40kmph and a positive slope (0.0017 g/s/km) between 55-70 kmph. On the other hand, emission rates were found to be more stable at low levels of acceleration between ranges of $-0.5 < a < 0.5$ m/s^2 and increased thereafter. Even though emission rates were much lower between 0 – 30kmph, this range cannot be considered as an acceptable vehicle operating speed, because the emissions released were nearly 3.5 times higher than 40 – 60 kmph range due to the amount of time spent by vehicles in that range. This argument was tested by calculating the emission factors for each speed range and presented in Figure 4. Emission factors of CO, HC, and NO levels were highest at 0 – 10 kmph speed range and decreased until 40 kmph. Between speeds of 40 – 60 kmph emission factors are at their lowest and slightly increase thereafter, thus validating the statement.

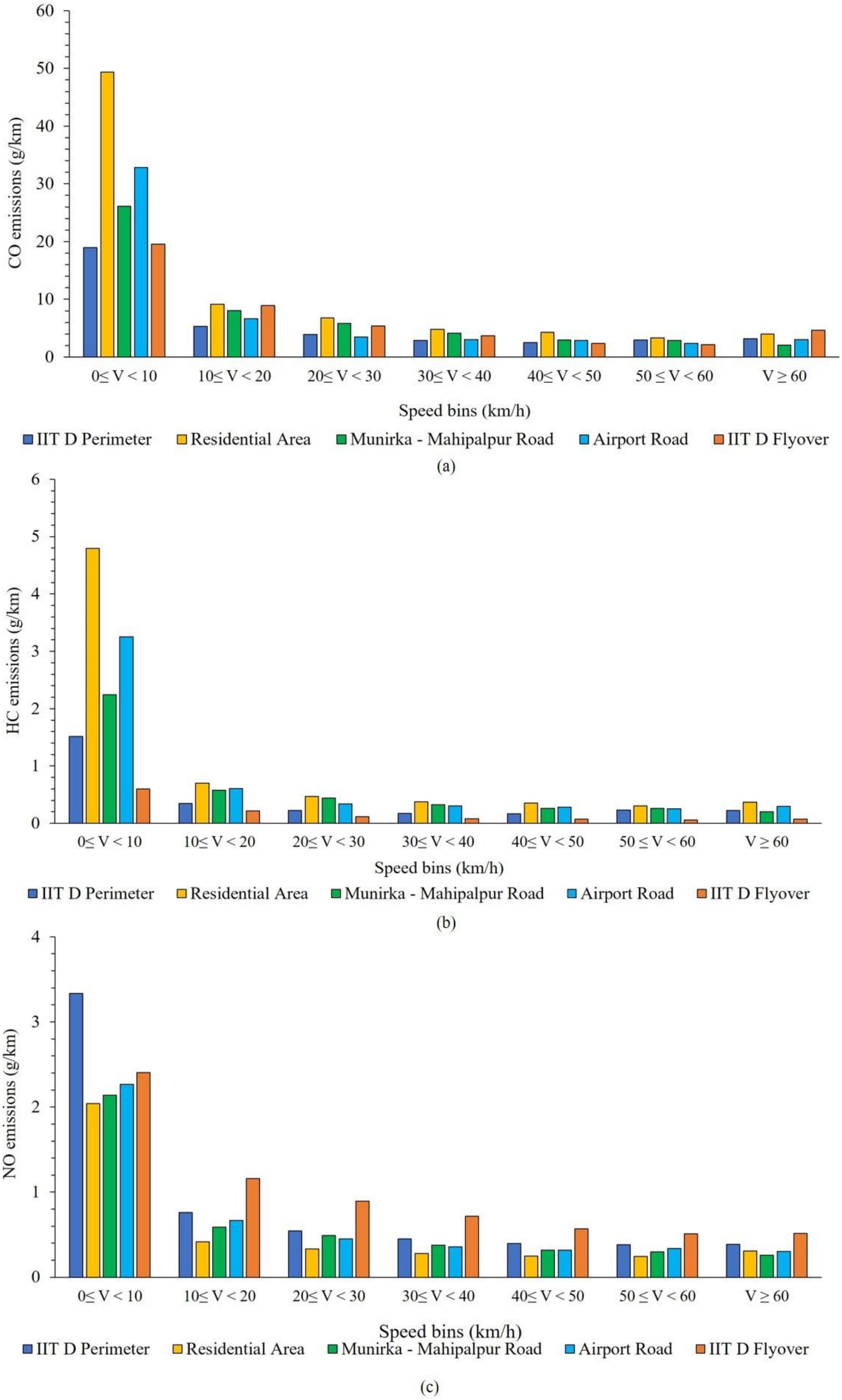

Figure 4: Emission factors of (a) CO, (b) HC, and (c) NO in different speed bins

3.5 Estimation of Total Emissions

In Delhi City, on-road vehicles are increasing rapidly, especially passenger cars. It is important to understand the total amount of emissions being released to influence the regulations and standards accordingly. The total emissions (E_{Total}) are calculated based on the average emission factor from the study and vehicle kilometre travelled (VKT) per day.

$$E_{Total} = EF * VKT \quad (3)$$

The average emission factors of CO, HC, and NO are 3.8, 0.3, and 0.54 g/km respectively. Roychowdhury & Dubey, 2018 reported that in Delhi the passenger cars clock nearly 16 million VKT/day. Using this data, the estimated CO, HC, and NO emissions are 60.8, 4.8, and 9.72tonnes/day respectively. Curbing of emissions can happen only through a series of mitigation measures, which will be discussed in the next section.

3.6 Vehicular Emission Regulation and Standards

The emissions from vehicles became a major concern in the middle of the twentieth century when the mass production of cars reached its peak. Due to the environmental and health impacts of vehicular pollution (Balakrishnan et al., 2019; Khillare and Sarkar, 2012; Kumar and Mishra, 2018; Ngoc et al., 2018; Shekarrizfard et al., 2018), legislative bodies across the US, Europe, and other developed nations acknowledge the need to curb vehicle-related emissions. Countries such as India and China have improvised and adopted the norms prescribed by these agencies. Since 1992, when the "EURO 1" was introduced to regulate emissions, by systematically tightening the emission standards for diesel and petrol passenger cars levels have reduced significantly and the most recent EURO 6 standards was announced in 2014. Over the period of 22 years, the CO emission standards were reduced from 2.72 to 0.5 g/km, NOx emission standards from 0.5 to 0.08 g/km, HC + NO_x from 0.97 to 0.17 g/km and PM from 0.14 to 0.005 g/km indicating a significant reduction of 82%, 84%, 82% and 96% respectively (Sassykova et al., 2019). Similarly, India has adopted Bharat stage emission standards set by the Central Pollution Control Board (CPCB) to regulate exhaust emissions. The Bharat standards, which were based on Euro 1 norms, were introduced for the first time in 2000. Similarly, BS-VI synonymous with EURO-6 was introduced in April 2020. The reduction of emissions from India 2000 to BS-VI is similar to Euro standards for diesel passenger cars.

In order to meet specified standards, regulatory bodies recommended the adoption of control equipment for enforcement, process modification such as retrofitting the older vehicles with new emission control technology and fuel injection system, introduction of clean and advanced fuels, and interventions including – reducing VKT using transit oriented development, (Nesamani, 2010) subsidies for alternative fuels and hybrid vehicles, developing green zones, and improvising the vehicular pollution testing methods. Catalytic converters were introduced in the global automobile market during the 1970s as an after-treatment system to achieve upcoming standards. Initially, two-way converters were used to reduce CO and HC; later, three-way converters came into the market to reduce NO_x as well (Srinivasa Chalapati and Venkateswara Rao, 2018). Diesel particulate filters were introduced into the market in the late 1980s when stringent emission norms for Heavy-duty diesel engine vehicles were introduced. Filter regeneration technology in Diesel Particulate Filters (DPF) have made it low maintenance and most widely used in diesel engines. Exhaust gas recirculation (EGR) is another popular technology being used in automobiles to control NO_x emissions (Brijesh and Sreedhara, 2013). Along with this many control strategies were implemented in Delhi.

Many researchers have studied the impact of some of these control measures. According to Chelani and Devotta, 2007 the reduction in SO_2, Suspended Particulate Matter (SPM) and PM_{10} concentration due to switching of diesel vehicles to CNG during 2000 to 2003 were 35%, 2.8% and 7% respectively. However, few studies reported an increase in NOx concentration (Kathuria, 2004; Ravindra et al., 2006). A study conducted by Foster found that the air quality regulations in Delhi during 1997-2002 had a significant impact on respiratory health or lung function of the local residents of New Delhi. The odd-even policy trials in Delhi showed a considerable reduction in PM10 and PM2.5 concentration up to 74% during the hours of the trial; however, the influence on emissions from heavy-duty vehicles running during night times reduced the overall efficiency of the strategy (Kumar et al., 2017).

With all the embedded technologies and control equipment, passenger cars manufactured today successfully meet the current emission standards when tested in a laboratory environment. However, in on-road real-world emission tests, they failed to meet the standards. This calls for the need to develop more-advanced technology that meets emission standards in real-world operation. Along with this, a combination of interventions such as congestion charging, carpooling, convenient public transport, hybrid vehicles, express lanes, clean energy, and new testing methods must also be implemented. Framing and implementing these mitigation policies in the context of local traffic conditions and reducing fossil fuel dependency will make positive steps to improve the air quality in Indian cities.

4. Conclusion

Deterioration of urban air quality due to vehicular pollution has always been of much debate and there is much evidence that there is a discrepancy between emissions compliance for new vehicles and those emitted during real-world driving. In order to better understand vehicle-related pollution, real-world emission testing of vehicles is necessary and has been adopted by many governments internationally. However, India has yet to implement this method. In this study, real-world exhaust emissions of 54 diesel and 4 petrol passenger cars of different makes and models driving on urban roads in Delhi were measured, at a sampling frequency of 1Hz, using an on-board portable exhaust emission monitoring system. All the cars tested exceeded the limits of BS-IV standards for CO, HC, and NO gases and other studies made similar observations. The average emission factors of CO, HC, and NO were 3.8, 0.3, and 0.54 g/km respectively. The study of real-world exhaust emissions from vehicles has revealed that road; traffic, vehicle, and driving characteristics play a vital role in the quantity of emissions released. Also, speed and acceleration were discovered to have a major impact, i.e. with an increase in speed and acceleration, emission rate increases. Nevertheless, a speed and acceleration combination of 40 – 60kmph and -0.5 – 0.5m/s^2 respectively, appeared to emit the lowest concentration of pollutants. The city-wide CO, HC, and NO emissions were estimated to be 60.8, 4.8, and 9.72tonnes/day, respectively by considering the VKT of passenger cars per day in Delhi and the emission factors projected in this study. This endorses the need to tackle air pollution caused by vehicular emissions on multiple fronts.

This research has demonstrated clearly the importance of monitoring the real-world exhaust emissions given the substantial difference between test cycle measurements used for compliance testing of new vehicles. The need to curb the number of vehicles on Delhi roads to a level where traffic flows are flowing smoothly avoiding stop-start and congested states should become an aspiration of policymakers. This requires a commitment to introducing hybrid-electric and electric vehicles into the fleet, but such policies should be introduced alongside measures which reduce the vehicle kilometers driven and the need to travel per se.

5. Acknowledgement

We would like to extend our sincere thanks to the Ministry of Earth Sciences (MOES) for providing the necessary financial support for the Clean Air for Delhi Through Interventions, Mitigations, and Engagement (CADTIME) project. Also, the support given by colleagues at the Indian Institute of Technology -Delhi, to carry out the measurements is acknowledged with gratitude.

6. References

ARAI, 2018. Indian Emissions Regulations - Limits, regulations, Mesurement of Exhaust Emissions and Calculation of Fuel Consumption.

ARAI, 2010. Chapter 3 TYPE I TEST ON S.I. ENGINES, CNG, LPG AND DIESEL ENGINE VEHICLES (VERIFYING THE AVERAGE TAILPIPE EMISSION) OF GASEOUS AND PARTICULATE POLLUTANTS.

Arun, N.H., Mahesh, S., Ramadurai, G., Shiva Nagendra, S.M., 2017. Development of driving cycles for passenger cars and motorcycles in Chennai, India. Sustain. Cities Soc. 32, 508–512. https://doi.org/10.1016/j.scs.2017.05.001

Bajaj, N., Sharma, T., Suneja, D., Jain, S., Kumar, P., 2017. Determinants of respiratory and cardiovascular health effects in traffic policemen: A perception-based comparative analysis. J. Transp. Heal. 4, 30–39. https://doi.org/10.1016/j.jth.2016.12.003

Balakrishnan, K., Dey, S., Gupta, T., Dhaliwal, R.S., Brauer, M., Cohen, A.J., Stanaway, J.D., Beig, G., Joshi, T.K., Aggarwal, A.N., Sabde, Y., Sadhu, H., Frostad, J., Causey, K., Godwin, W., Shukla, D.K., Anil Kumar, G., Varghese, C.M., Muraleedharan, P., Agrawal, A., Anjana, R.M., Bhansali, A., Bhardwaj, D., Burkart, K., Cercy, K., Chakma, J.K., Chowdhury, S., Christopher, D.J., Dutta, E., Furtado, M., Ghosh, S., Ghoshal, A.G., Glenn, S.D., Guleria, R., Gupta, R., Jeemon, P., Kant, R., Kant, S., Kaur, T., Koul, P.A., Krish, V., Krishna, B., Larson, S.L., Madhipatla, K., Mahesh, P.A., Mohan, V., Mukhopadhyay, S., Mutreja, P., Naik, N., Nair, S., Nguyen, G., Odell, C.M., Pandian, J.D., Prabhakaran, D., Prabhakaran, P., Roy, A., Salvi, S., Sambandam, S., Saraf, D., Sharma, M., Shrivastava, A., Singh, V., Tandon, N., Thomas, N.J., Torre, A., Xavier, D., Yadav, G., Singh, S., Shekhar, C., Vos, T., Dandona, R., Srinath Reddy, K., Lim, S.S., L Murray, C.J., Venkatesh, S., Dandona, L., State-Level Disease Burden Initiative Air Pollution Collaborators, I., 2019. The impact of air pollution on deaths, disease burden, and life expectancy across the states of India: the Global Burden of Disease Study 2017. Lancet Planet. Heal. 3, e26–e39. https://doi.org/10.1016/S2542-5196(18)30261-4

Bishop, G.A., Stedman, D.H., 1996. Measuring the Emissions of Passing Cars. Acc. Chem. Res. 29, 489–495.

Brijesh, P., Sreedhara, S., 2013. EXHAUST EMISSIONS AND ITS CONTROL METHODS IN COMPRESSION IGNITION ENGINES: A REVIEW. Int. J. Automot. Technol. 14, 195–206. https://doi.org/10.1007/s12239−013−0022−2

Busse, M., Knittel, C., Zettelmeyer, F., 2009. Pain at the Pump: The Differential Effect of Gasoline Prices on New and Used Automobile Markets. Cambridge, MA. https://doi.org/10.3386/w15590

Carslaw, D.C., Rhys-Tyler, G., 2013. New insights from comprehensive on-road measurements of NOx, NO2 and NH3 from vehicle emission remote sensing in London, UK. Atmos. Environ. 81, 339–347. https://doi.org/10.1016/j.atmosenv.2013.09.026

Chelani, A.B., Devotta, S., 2007. Air quality assessment in Delhi: Before and after CNG as fuel. Environ. Monit. Assess. 125, 257–263. https://doi.org/10.1007/s10661-006-9517-x

Chikhi, S., Boughedaoui, M., Kerbachi, R., Joumard, R., 2014. On-board measurement of emissions from liquefied petroleum gas, gasoline and diesel powered passenger cars in Algeria. J. Environ. Sci. (China) 26, 1651–1659. https://doi.org/10.1016/j.jes.2014.06.005

Choudhary, A., Gokhale, S., 2016. Urban real-world driving traffic emissions during interruption and congestion. Transp. Res. Part D Transp. Environ. 43, 59–70. https://doi.org/10.1016/j.trd.2015.12.006

Christopher Frey, H., Rouphail, N.M., Zhai, H., 2006. Speed- And facility-specific emission estimates for on-road light-duty vehicles on the basis of real-world speed profiles. Transp. Res. Rec. 6, 128–137. https://doi.org/10.3141/1987-14

DataGov, 2016. Category-wise Automobile Production - data.gov.in [WWW Document]. URL https://data.gov.in/catalog/category-wise-automobile-production?filters%5Bfield_catalog_reference%5D=194643&format=json&offset=0&limit=6&sort%5Bcreated%5D=desc (accessed 9.14.19).

Desineedi, R.M., Mahesh, S., Ramadurai, G., 2020. Developing driving cycles using k-means clustering and determining their optimal duration. Transp. Res. Procedia 48, 2083–2095. https://doi.org/10.1016/j.trpro.2020.08.268

Dhamaniya, A., Chandra, S., 2013. Concept of Stream Equivalency Factor for Heterogeneous Traffic on Urban Arterial Roads. J. Transp. Eng. 139, 1117–1123. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000581

Dheeraj Alshetty, V., Kuppili, S.K., Nagendra, S.M.S., Ramadurai, G., Sethi, V., Kumar, R., Sharma, N., Namdeo, A., Bell, M., Goodman, P., Chatterton, T., Barnes, J., De Vito, L., Longhurst, J., 2019. Characteristics of tail pipe (Nitric oxide) and resuspended dust emissions from urban roads – A case study in Delhi city. J. Transp. Heal. 100653. https://doi.org/10.1016/j.jth.2019.100653

Frey, H., Unal, A., 2002. Use of on-board tailpipe emissions measurements for development of mobile source emission factors. Proc. US Environ. Prot. Agency Emiss. Invent. Conf. 5–7.

Ghose, M.K., Paul, R., Banerjee, S.K., 2004. Assessment of the impacts of vehicular emissions on urban air quality and its management in Indian context: The case of Kolkata (Calcutta). Environ. Sci. Policy 7, 345–351. https://doi.org/10.1016/j.envsci.2004.05.004

Gilles, D., Matthew, A.T., 2012. Urban Growth and Transportation. Rev. Econ. Stud. 79, 1407–1440. https://doi.org/10.1093/restud/rds010

Goel, R., Guttikunda, S.K., 2015. Evolution of on-road vehicle exhaust emissions in Delhi. Atmos. Environ. 105, 78–90. https://doi.org/10.1016/j.atmosenv.2015.01.045

Goel, R., Mohan, D., Guttikunda, S.K., Tiwari, G., 2016. Assessment of motor vehicle use characteristics in three Indian cities. Transp. Res. Part D Transp. Environ. 44, 254–265. https://doi.org/10.1016/j.trd.2015.05.006

Guttikunda, S.K., Mohan, D., 2014. Re-fueling road transport for better air quality in India. Energy Policy 68, 556–561. https://doi.org/10.1016/j.enpol.2013.12.067

Health Effects Institute, 2019. State of Global Air 2019, Special Report.

IBEF, 2019. Roads.

Jaikumar, R., Shiva Nagendra, S.M., Sivanandan, R., 2017a. Modal analysis of real-time, real world vehicular exhaust emissions under heterogeneous traffic conditions. Transp. Res. Part D Transp. Environ. 54, 397–409. https://doi.org/10.1016/j.trd.2017.06.015

Jaikumar, R., Shiva Nagendra, S.M., Sivanandan, R., 2017b. Modeling of real time exhaust emissions of passenger cars under heterogeneous traffic conditions. Atmos. Pollut. Res. 8, 80–88. https://doi.org/10.1016/j.apr.2016.07.011

Jaiprakash, Habib, G., 2018. On-road assessment of light duty vehicles in Delhi city: Emission factors of CO, CO2 and NOX. Atmos. Environ. 174, 132–139. https://doi.org/10.1016/J.ATMOSENV.2017.11.039

Kathuria, V., 2004. Impact of CNG on vehicular pollution in Delhi: A note. Transp. Res. Part D Transp. Environ. 9, 409–417. https://doi.org/10.1016/j.trd.2004.05.003

Khan, T., Frey, H.C., 2018. Comparison of real-world and certification emission rates for light duty gasoline vehicles. Sci. Total Environ. 622–623, 790–800. https://doi.org/10.1016/j.scitotenv.2017.10.286

Khillare, P.S., Sarkar, S., 2012. Airborne inhalable metals in residential areas of Delhi, India: Distribution, source apportionment and health risks. Atmos. Pollut. Res. 3, 46–54. https://doi.org/10.5094/APR.2012.004

Kristensson, A., Johansson, C., Westerholm, R., Swietlicki, E., Gidhagen, L., Wideqvist, U., Vesely, V., 2004. Real-world traffic emission factors of gases and particles measured in a road tunnel in Stockholm, Sweden. Atmos. Environ. 38, 657–673. https://doi.org/10.1016/j.atmosenv.2003.10.030

Kumar, A., Mishra, R.K., 2018. Human health risk assessment of major air pollutants at transport corridors of Delhi, India. J. Transp. Heal. 10, 132–143. https://doi.org/10.1016/j.jth.2018.05.013

Kumar, P., Gulia, S., Harrison, R.M., Khare, M., 2017. The influence of odd–even car trial on fine and coarse particles in Delhi. Environ. Pollut. 225, 20–30. https://doi.org/10.1016/j.envpol.2017.03.017

Lawrence, S., Sokhi, R., Ravindra, K., 2016. Quantification of vehicle fleet PM10particulate matter emission factors from exhaust and non-exhaust sources using tunnel measurement techniques. Environ. Pollut. 210, 419–428. https://doi.org/10.1016/j.envpol.2016.01.011

Mahesh, S., Ramadurai, G., Shiva Nagendra, S.M., 2018. Real-world emissions of gaseous pollutants from diesel passenger cars using portable emission measurement systems. Sustain. Cities Soc. 41, 104–113. https://doi.org/10.1016/j.scs.2018.05.025

Mancilla, Y., Araizaga, A.E., Mendoza, A., 2012. A tunnel study to estimate emission factors from mobile sources in Monterrey, Mexico. J. Air Waste Manag. Assoc. 62, 1431–1442. https://doi.org/10.1080/10962247.2012.717902

May, J., Bosteels, D., Favre, C., 2014. An Assessment of Emissions from Light-Duty Vehicles using PEMS and Chassis Dynamometer Testing. SAE Int. J. Engines 7, 2014-01–1581. https://doi.org/10.4271/2014-01-1581

Ministry of Statistics and Program Implementation, 2018. MOTOR VEHICLES - Statistical Year Book India 2018 [WWW Document]. URL http://mospi.nic.in/statistical-year-book-india/2018/189 (accessed 7.24.19).

MoRTH, 2018. Road Transport Year Book (2015-2016).

Nagpure, A.S., Gurjar, B.R., 2012. Development and evaluation of vehicular air pollution inventory model. Atmos. Environ. 59, 160–169. https://doi.org/10.1016/j.atmosenv.2012.04.044

Nesamani, K.S., 2010. Estimation of automobile emissions and control strategies in India. Sci. Total Environ. 408, 1800–1811. https://doi.org/10.1016/j.scitotenv.2010.01.026

Ngoc, L., Kim, M., Bui, V., Park, D., Lee, Y.-C., Ngoc, L.T.N., Kim, M., Bui, V.K.H., Park, D., Lee, Y.-C., 2018. Particulate Matter Exposure of Passengers at Bus Stations: A Review. Int. J. Environ. Res. Public Health 15, 2886. https://doi.org/10.3390/ijerph15122886

Noland, R.B., Ochieng, W.Y., Quddus, M.A., North, R.J., Polak, J.W., 2004. The vehicle emissions and performance monitoring system: Analysis of tailpipe emissions and vehicle performance. Transp. Plan. Technol. 27, 431–447. https://doi.org/10.1080/0308106042000293480

Oduro, S.D., Metia, S., Duc, H., Ha, Q.P., 2013. CO2 vehicular emission statistical analysis with instantaneous speed and acceleration as predictor variables, in: 2013 International Conference on Control, Automation and Information Sciences (ICCAIS). pp. 158–163. https://doi.org/10.1109/ICCAIS.2013.6720547

Perugu, H., 2019. Emission modelling of light-duty vehicles in India using the revamped VSP-based MOVES model: The case study of Hyderabad. Transp. Res. Part D Transp. Environ. 68, 150–163. https://doi.org/10.1016/j.trd.2018.01.031

Platt, S.M., Haddad, I. El, Pieber, S.M., Huang, R.-J., Zardini, A.A., Clairotte, M., Suarez-Bertoa, R., Barmet, P., Pfaffenberger, L., Wolf, R., Slowik, J.G., Fuller, S.J., Kalberer, M., Chirico, R., Dommen, J., Astorga, C., Zimmermann, R., Marchand, N., Hellebust, S., Temime-Roussel, B., Baltensperger, U., Prévôt, A.S.H., 2014. ARTICLE Two-stroke scooters are a dominant source of air pollution in many cities. https://doi.org/10.1038/ncomms4749

Pradhan, R.P., Bagchi, T.P., 2013. Effect of transportation infrastructure on economic growth in India: The VECM approach. Res. Transp. Econ. 38, 139–148. https://doi.org/10.1016/J.RETREC.2012.05.008

Qu, L., Li, M., Chen, D., Lu, K., Jin, T., Xu, X., 2015. Multivariate analysis between driving condition and vehicle emission for light duty gasoline vehicles during rush hours. Atmos. Environ. 110, 103–110. https://doi.org/10.1016/j.atmosenv.2015.03.038

Ravindra, K., Wauters, E., Tyagi, S.K., Mor, S., Van Grieken, R., 2006. Assessment of air quality after the implementation of compressed natural gas (CNG) as fuel in public transport in Delhi, India. Environ. Monit. Assess. 115, 405–417. https://doi.org/10.1007/s10661-006-7051-5

Rhys-Tyler, G.A., Bell, M.C., 2012. Toward Reconciling Instantaneous Roadside Measurements of Light Duty Vehicle Exhaust Emissions with Type Approval Driving Cycles. Environ. Sci. Technol. 46, 10532–10538. https://doi.org/10.1021/es3006817

Ropkins, K., Beebe, J., Li, H., Daham, B., Tate, J., Bell, M., Andrews, G., 2009. Real-World Vehicle Exhaust Emissions Monitoring: Review and Critical Discussion. Crit. Rev. Environ. Sci. Technol. 39, 79–152. https://doi.org/10.1080/10643380701413377

Roychowdhury, A., Dubey, G., 2018. The Urban Commute: And how it contributes to pollution and energy consumption, Centre for Science and Environment, New Delhi.

Saleh, W., Kumar, R., Kirby, H., Kumar, P., 2009. Real world driving cycle for motorcycles in

Edinburgh. Transp. Res. Part D Transp. Environ. 14, 326–333. https://doi.org/10.1016/j.trd.2009.03.003

Sassykova, L.R., Sendilvelan, S., Bhaskar, K., Zhumakanova, A.S., Aubakirov, Y.A., Abildin, T.S., Kubekova, S.N., Mataeva, Z.T., Zhakupova, A.A., 2019. Norms of emissions of harmful substances generated from vehicles in the different countries of the world. Ser. Geol. Tech. Sci. 2, 181–190. https://doi.org/10.32014/2019.2518-170X.53

Schmitz, T., Hassel, D., Weber, F.-J., 2000. Determination of VOC-components in the exhaust of gasoline and diesel passenger cars. Atmos. Environ. 34, 4639–4647.

Shekarrizfard, M., Valois, M.F., Weichenthal, S., Goldberg, M.S., Fallah-Shorshani, M., Cavellin, L.D., Crouse, D., Parent, M.E., Hatzopoulou, M., 2018. Investigating the effects of multiple exposure measures to traffic-related air pollution on the risk of breast and prostate cancer. J. Transp. Heal. 11, 34–46. https://doi.org/10.1016/j.jth.2018.09.006

Shorter, J.H., Herndon, S., Zahniser, M.S., Nelson, D.D., Wormhoudt, J., Demerjian, K.L., Kolb, C.E., 2005. Real-time measurements of nitrogen oxide emissions from in-use New York City transit buses using a chase vehicle. Environ. Sci. Technol. 39, 7991–8000. https://doi.org/10.1021/es048295u

Shukla, A., Alum, M., 2010. Assessment of Real World On-Road Vehicle Emissions under Dynamic Urban Traffic Conditions i n Delhi. Int. J. Urban Sci. 14, 207–220.

SIAM, 2019. Domestic Sales Trends - Society of Indian Automobile Manufactures [WWW Document]. URL http://www.siamindia.com/statistics.aspx?mpgid=8&pgidtrail=14 (accessed 9.14.19).

Sithananthan, M., Kumar, R., 2020. A framework for development of real-world motorcycle driving cycle in India. Proc. Inst. Mech. Eng. Part D J. Automob. Eng. https://doi.org/10.1177/0954407020977533

Sjödin, Å., Cooper, D.A., Andréasson, K., 1995. Estimations of real-world N2O emissions from road vehicles by means of measurements in a traffic tunnel. J. Air Waste Manag. Assoc. 45, 186–190. https://doi.org/10.1080/10473289.1995.10467358

Srinivasa Chalapati, K., Venkateswara Rao, T., 2018. Design, fabrication and testing of a 4-way catalytic converter for reducing exhaust emission pollution in a diesel automobile engine. Int. J. Mech. Prod. Eng. Res. Dev. 8, 555–568. https://doi.org/10.24247/ijmperddec201859

Stead, D., 1999. Relationships between transport emissions and travel patterns in Britain. Transp. Policy 6, 247–258. https://doi.org/10.1016/S0967-070X(99)00025-6

Timilsina, G.R., Shrestha, A., 2009. Transport sector CO2 emissions growth in Asia: Underlying factors and policy options. Energy Policy 37, 4523–4539. https://doi.org/10.1016/J.ENPOL.2009.06.009

Wang, W.G., Clark, N.N., Lyons, D.W., Yang, R.M., Gautam, M., Bata, R.M., Loth, J.L., 1998. Emissions comparisons from alternative fuel buses and diesel buses with a chassis dynamometer testing facility. Environ. Sci. Technol. 31, 3132–3137. https://doi.org/10.1021/es9701063

Zhai, H., Frey, H.C., Rouphail, N.M., 2008. A vehicle-specific power approach to speed- and facility-specific emissions estimates for diesel transit buses. Environ. Sci. Technol. 42, 7985–7991. https://doi.org/10.1021/es800208d