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

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17 **Abstract**

18 In this study, researchers have explored real-world driving conditions and developed emission
19 factors for 58 passenger cars using on-board emission measurement technique while driving
20 on five different routes in Delhi. The measured average emission factors of CO, HC, and NO
21 were 3.99, 0.34, and 0.54 g/km for diesel vehicles, 7.26, 0.17, and 0.62 for petrol vehicles
22 respectively. Road, traffic, vehicle type, and driving characteristics affect the quantity of
23 emissions released. However, speed and acceleration significantly impact emission rates
24 increasing with the increase in speed and acceleration. Also, emissions were minimal at 40 –
25 60 kmph and $-0.5 - 0.5 \text{ m/s}^2$. The estimated city-wide CO, HC, and NO emissions were 60.8,
26 4.8, and 9.72tonnes/day. These results demonstrate the importance of monitoring the real-world
27 exhaust emissions given the substantial difference between test cycle measurements used for
28 compliance testing of new vehicles.

29 **Keywords**

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

32 **1. Introduction**

33 The transportation sector has always been a critical component of the delivery of economic
34 growth. Whilst a well-planned transportation infrastructure can lead to the sustainable
35 development of a nation, it is necessary not to ignore the role of the vehicular fleet diversity,
36 quantity and their corresponding exhaust emissions (Gilles and Matthew, 2012; Pradhan and
37 Bagchi, 2013; Timilsina and Shrestha, 2009) as new vehicle technologies are introduced and
38 the fleet ages. In addition, the contribution to the total of emissions by on-road vehicles to the
39 urban environment is increasing invariably due to unrestrained growth in vehicle ownership
40 (Frey and Unal, 2002). In India alone, whilst the road length has increased from 3.4 million
41 kilometres in 2001 to over 5.5 million kilometres in 2018 at a Compound Annual Growth Rate
42 (CAGR) of 3.5% (IBEF, 2019), during the same period domestic vehicular sales increased from
43 5.3 million units per year to 26.3 million units per year with a CAGR of 22% (DataGov, 2016;
44 SIAM, 2019).

45 During the period 2001-2015 Delhi has observed a rapid growth in vehicle registration from
46 0.36 million to 0.88 million with a CAGR of 7.1%. However, the proportional growth in road
47 link length has not been achieved (Ministry of Statistics and Program Implementation, 2018).
48 This means that whilst network capacity is to some extent being managed, the traffic demand
49 is not, resulting in higher traffic flows and longer periods of congestion. Also, traffic conditions
50 in India are highly heterogeneous, comprised of motorbikes, cars, light commercial vehicles
51 (LCV), and heavy commercial vehicles (HCV) and non-motorised vehicles. Such diversity in
52 vehicular traffic characteristics causes problems related to the disparity of speeds, acceleration,
53 and manoeuvrability (Dhamaniya and Chandra, 2013). This results in reduced road carrying
54 capacity leading to congestion and a decrease in average vehicular speed (Bajaj et al., 2017).
55 Additionally, higher gasoline (petrol) prices are increasing the sales of diesel engine passenger

56 cars which are known to emit more particle matter (PM) and primary nitrogen dioxide, (NO₂)
57 concentration than petrol vehicles (Busse et al., 2009; Mahesh et al., 2018).

58 Technological advancements in improving engine performance and controlling emissions are
59 occurring, but not at a rate sufficient to counteract the growth in number and use of vehicles
60 with a detrimental effect on air quality of the Indian cities (Ghose et al., 2004). NO₂ exhaust
61 from on-road vehicles undergoes a photochemical reaction to form ozone, which is a
62 respiratory irritant and causes allergic asthma whereas, excess Carbon Dioxide, (CO₂) release
63 in still weather results in the urban heat island effect. Additionally, NO₂, sulphur dioxide (SO₂),
64 and volatile organic compounds (VOC) exhaust emissions are the precursor gases for
65 secondary PM formation (Kumar & Mishra, 2018). In 2017, an estimated 4.7 million
66 premature deaths in the world were due to air pollution, of which 1.2 million, almost a quarter
67 of life loss was recorded in India alone (Balakrishnan et al., 2019; Health Effects Institute,
68 2019).

69 To reduce the emissions and its detrimental effects on human health, regulatory bodies
70 recommended the adoption of control device and implementation of emission norms. Since
71 2000, Indian regulators have adopted Bharat stage emission standards set by the Central
72 Pollution Control Board (CPCB) to regulate exhaust emissions. Emission rates per vehicle have
73 reduced significantly (~85%) since the implementation of norms, however due to drastic
74 increase in vehicular population, the total emissions are increasing (Sassykova et al., 2019).
75 Implementation of control measures have also reduced the emissions in major Indian cities like
76 Delhi (Chelani and Devotta, 2007). Lead free fuel, sulfur reduction, ban of older commercial
77 vehicles, and use of only CNG based public transport vehicles are some of the other major
78 implementations that were successful in significant emissions reduction in Delhi and other
79 Indian cities (Goel and Guttikunda, 2015). Transport intervention policies such as Odd Even
80 policies are also one of the mitigation measures adopted in Delhi city to reduce the impact of

81 vehicular emissions, where PM concentrations were found to reduce up to 70% (Kumar et al.,
82 2017). Fuel efficiency standards improvement and limiting the use of diesel vehicle fleet on
83 Indian roads are necessary measures to be implemented immediately to mitigate the impact of
84 vehicular emissions (Goel et al., 2016; Guttikunda and Mohan, 2014).

85 Under these circumstances, it is of prime importance to study vehicle exhaust emissions. Many
86 researchers across the world have attempted to understand the characteristics to quantify the
87 emissions through technologies which involve inventory-based models (COPERT, EMFAC)
88 (Nagpure and Gurjar, 2012) or direct measurement employing conventional methods
89 (dynamometer studies (Wang et al., 1998)), and in-situ monitoring (tunnel studies (Mancilla et
90 al., 2012), car-chase method (Shorter et al., 2005), remote sensing (Bishop and Stedman,
91 1996)). Some of the studies have also reported the use of MOVES model that uses a conceptual
92 approach, based on vehicle specific power (VSP) binning. Vehicle specific power (VSP) is an
93 indicator for engine load that highly influences the emissions (Zhai et al., 2008). Whilst real-
94 world measurements for homogenous traffic have been reported extensively in the UK
95 (Carslaw and Rhys-Tyler, 2013; Noland et al., 2004; Rhys-Tyler and Bell, 2012; Ropkins et
96 al., 2009) and Europe (Kristensson et al., 2004; Lawrence et al., 2016; Platt et al., 2014;
97 Schmitz et al., 2000; Sjödin et al., 1995), they do not properly represent the real-world driving
98 conditions in India and more specifically megacities with heterogeneous traffic conditions like
99 Delhi. Most of the studies conducted in India have used vehicle chase method and on board
100 measurement methods for determining the driving cycles (Arun et al., 2017; Jaikumar et al.,
101 2017; Jaiprakash and Habib, 2018; Mahesh et al., 2018). Some of the recent studies have also
102 used VSP based model MOVES for emission modelling in Indian cities (Perugu, 2019).

103 Recent studies with real world emissions monitoring systems shows that emissions are
104 dependent on driving cycle and traffic conditions (Christopher Frey et al., 2006). Driving cycles
105 can be determined by various methods such as trip-based cycle construction, the microtrip

106 approach, cluster analysis, the trip segment method, Markov Chain Monte Carlo simulation
107 and micro simulation model. However, trip based and micro trip approach are widely used in
108 Indian studies (Arun et al., 2017; Desineedi et al., 2020; Sithanathan and Kumar, 2020). A
109 study on influence of speed and acceleration on CO₂ emissions reported that every 1m/s
110 increase in speed will emit 0.034g/s to 0.041g/s of CO₂, whereas an increase in acceleration by
111 1m/s² will produce 0.008g/s to 0.025g/s of CO₂ emission. Similar observations have been made
112 with other gaseous pollutants as well (Oduro et al., 2013). Thus, the purpose of this paper is to
113 provide important insights into real-world vehicular emissions and highlight some issues
114 related to the management of pollution arising due to gaseous emissions from heterogeneous
115 traffic. Therefore, the study was carried out to characterise real-world driving conditions and
116 develop emission factors for petrol and diesel passenger cars using an on-board portable
117 emission measurement system (PEMS) for Delhi city. The outcomes of the current study will
118 provide emission factors for real world driving conditions in heterogenous traffic and the data
119 will add a great value to the existing literatures. The detailed discussions on the effect of
120 vehicular speed and acceleration on the emission rate will provide researchers a better
121 understanding of emissions in heterogenous traffic. The contributions of current study will also
122 assist policymakers around the world in understanding the parameters affecting vehicular
123 emissions for heterogeneous traffic and frame policies in accordance.

124 **2. Methodology**

125 ***2.1 Study Area***

126 Delhi is a metropolitan city and the capital territory of India. According to the 2011 census, it
127 occupies an area of 1483 km² with a population of 16.78 million (equivalent to a density of
128 11,320 per km²). With more than 11 million registered vehicles moving on 33,198 km road
129 length and 1282 traffic intersections, Delhi's arterial roads are extremely congested during peak
130 hours.

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

134 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

135

136

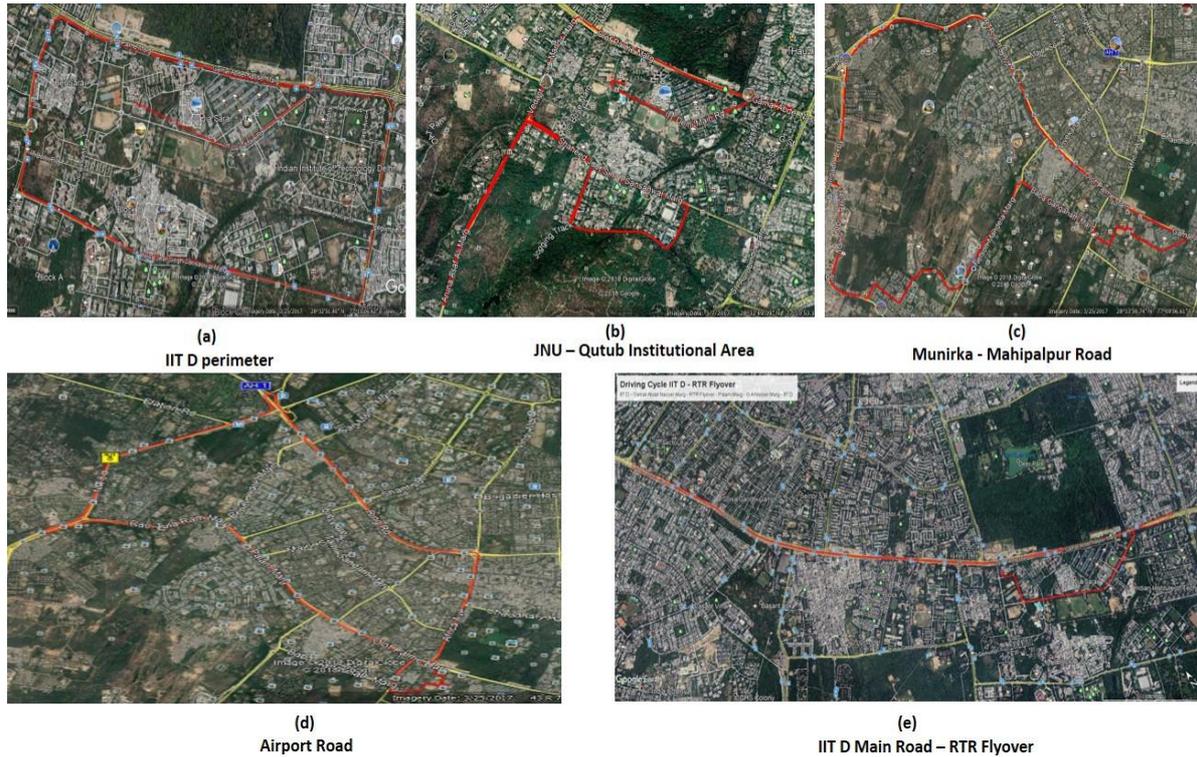


Figure 1: Study area (a) IIT Delhi perimeter (b) residential area (c) Munirka - Mahipalpur Rd (d) Airport Rd and (e) IIT D flyover

137 **2.2 Test Vehicles**

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

143

144 **2.3 Data Collection**

145 AVL DiTest-1000 is a five-gas portable emission measuring system (PEMS) and was used to
 146 measure real-time exhaust emissions from passenger cars. It measures CO, CO₂ and O₂ in
 147 volume percentage and HC, NO in ppm every second and is stored on a computer using Data

148 Acquisition System (DAS) software. DiTest 1000 operates with an accuracy of $\pm 0.002\%$ vol
149 for CO, and O₂, $\pm 0.3\%$ vol for CO₂, ± 4 ppm for HC and ± 5 ppm for NO. Simultaneously, an
150 ELM 327 model auto scanner is connected to the On-Board Diagnostics (OBD -II) link of the
151 vehicle to collect the engine operation data during the exhaust measurements.

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

167

168 ***2.4 Data Analysis***

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

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

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

175 Where P is the second-by-second concentration of the pollutant in %Vol or ppm, $M_{Exhaust}$ is the
 176 mass of exhaust gas in g/s and $\rho_{fraction}$ is ratio of density of pollutant and density of exhaust gas
 177 (1.249 kg/m^3) at 25°C and 1 atmosphere pressure. $M_{Exhaust}$ is the sum of the weight of fuel used
 178 in g/s and mass airflow rate in g/s.

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

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

181 Table 2: Operation mode and conditions for vehicles

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

182

183 3. Results and Discussion

184 3.1 Emission Factors of Passenger cars

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

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

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

198

199 ***3.2 Comparison with Previous Studies***

200 Table 3 shows the EF of diesel and petrol passenger cars in comparison with Bharat Standards
201 (BS-IV) and other studies. In the current study, an average emission factor for diesel passenger
202 cars was observed to be 3.99, 0.34, and 0.54 g/km were observed for CO, HC, and NO
203 respectively. All the diesel cars tested for real-time emissions have crossed the EF limit of BS-
204 IV. 2017 Chevrolet Enjoy (14.7 g/km) was recorded to emit 29.4 times more CO than the BS-
205 IV limit (0.5 g/km). In the case of HC+NO emissions, 2015 Renault Duster emitted 5.8 times,
206 more than the BS-IV limit (0.3 g/km). The average CO, HC emission factor measured in this
207 study is quite high compared to other studies Chikhi et al., 2014; Jaikumar et al., 2017b;
208 Jaiprakash & Habib, 2018; Mahesh et al., 2018; May et al., 2014. However, the average NO
209 emissions in this study were close to those measured by Mahesh et al., 2018 and May et al.,
210 2014 studies, but higher than Chikhi et al., 2014. The average NO emission factor reported in
211 Jaikumar et al., 2017b and Jaiprakash & Habib, 2018 were 2.4 and 1.9 times respectively,
212 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	
	CO	3.99	0.5	0.68	1.28	0.3	0.47	0.80
Emission Factor (g/km)	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		
	CO	7.26	1	6.47	0.75	2.2	0.75	
Emission Factor (g/km)	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	

214

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

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

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

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

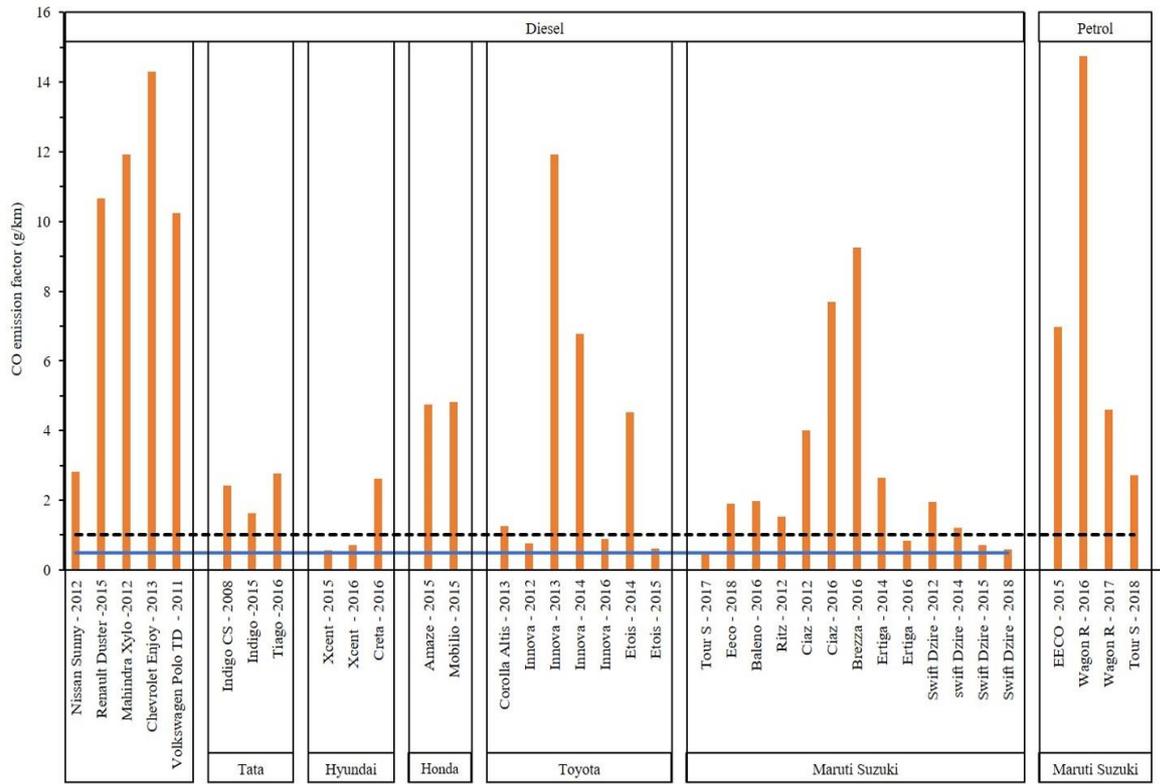
237 3. Wide range of passenger cars tested. Other studies were limited to less than 10 cars and
238 especially few variants. Whereas, we have tested 58 cars of different make and model.

239 4. Irregular vehicle maintenance by the users.

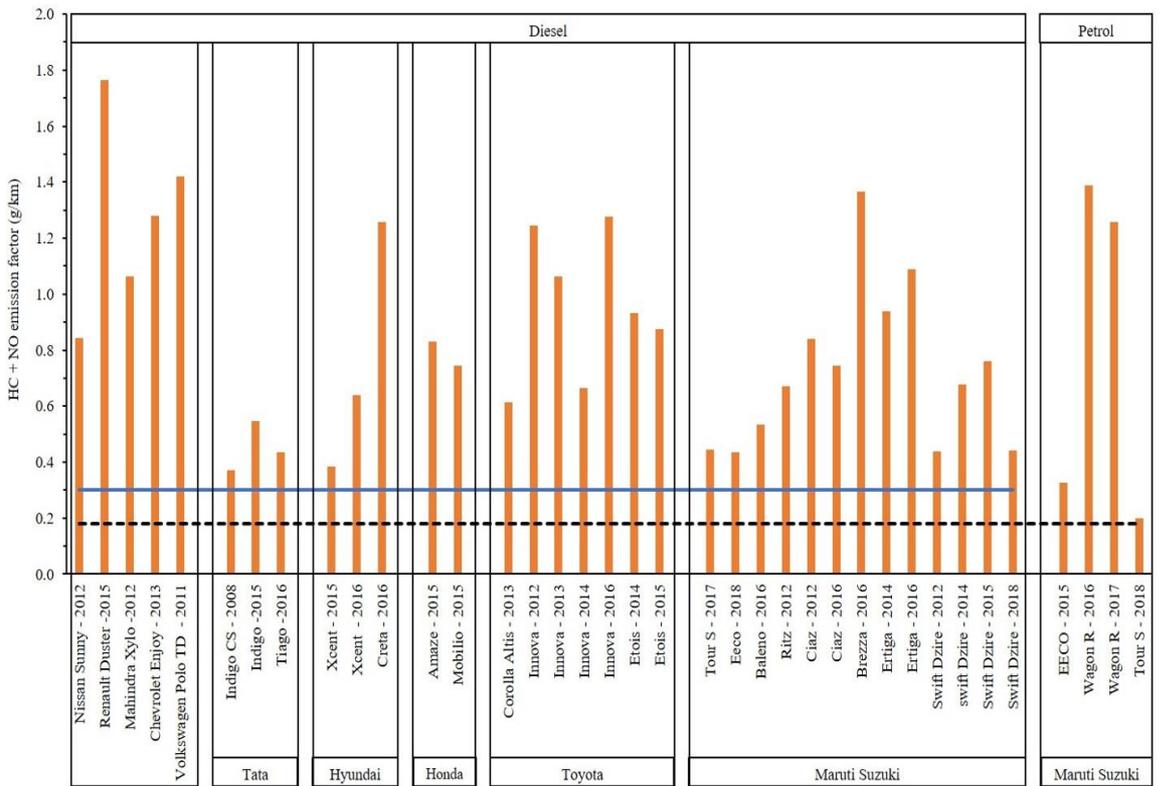
240 5. Usage of different drivers for different vehicles.

241

242



(a)



(b)

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

244 **3.3 Effect of Road and Driving Conditions**

245 The routes used in this study are a mixture of both arterial and local roads. Each route has local
246 roads of length ranging from 3 – 6.5km, as it is important to have a range of both for replicating
247 the daily travel patterns of drivers/passengers. The effect of road characteristics on vehicular
248 emissions, the variations in speed on the study routes was investigated. Table 4 and Appendix-
249 A Figure S2 represent the speed variations and driving characteristics in the five study routes,
250 respectively. The Residential Area route had more stretches of roads with free-flow traffic,
251 therefore the highest average vehicle speed, i.e., 29.9 kmph was recorded. This was followed
252 by IIT D RTR flyover road, Airport Rd, Munirka – Mahipalpur area, and IIT D perimeter with
253 28, 24.5, 23.3, and 23kmph respectively. IIT D Perimeter and Munirka – Mahipalpur study
254 routes involved arterial roads with interrupted and congested flows, frequent traffic signals,
255 and 90-degree turns. This affected the driving profile and, in these areas, the higher acceleration
256 and deceleration rates were observed. IIT D perimeter recorded the highest acceleration of
257 8.8m/s^2 followed by Munirka – Mahipalpur route with 8.6m/s^2 .

258 In India, the emission compliance of the vehicles in question or sometimes the representative
259 vehicles are determined by operating them on Modified Indian Driving Cycle (IDC) using a
260 chassis dynamometer (Khan and Frey, 2018). However, the standard driving cycle do not
261 represent the real-world driving conditions in majority of the Indian cities. In Table 4, driving
262 characteristics observed in this study and modified IDC are reported. The percentage of
263 different operational modes (idling, acceleration, deceleration, and cruising) in real-world
264 driving conditions are completely different from modified IDC (ARAI, 2010). In this study for
265 real-world driving conditions, average acceleration and deceleration combinedly accounted for
266 64.8%, whereas Modified IDC is dominated by cruising and idling (70.7%). The average
267 running speed (without idling) of real-world is nearly two-thirds of the modified IDC. Also,
268 the observed maximum acceleration and deceleration were 10.5 and 7.5 times that of modified

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

274 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

275

276 During any one journey; a vehicle undergoes idling (I), acceleration (A), deceleration (D), and
 277 cruising (C) modes, and emissions are released accordingly. Table 4, shows that the maximum
 278 time spent by vehicles in acceleration (36%) and deceleration (32.6%) modes was on IIT D
 279 RTR Flyover compared to the other routes followed by the Residential Area route. Vehicles
 280 experienced longer period cruising on Airport Road (26%) due to its combination of longer

281 sections of arterial road and fewer traffic signals per kilometre travelled. Idling was maximum
282 on Munirka – Mahipalpur road (17%), due to many traffic signal-controlled junctions,
283 intersections, and turns.

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

292 Appendix A Supplementary Table S3 shows the average emission rate of CO, HC, and NO for
293 each of these driving modes. In this study, the CO emission rate was highest during acceleration
294 and lowest whilst idling; however, similar emission rates were observed in deceleration and
295 cruising modes except on the Residential Area route. Nonetheless, this trend is pronounced
296 more in HC, and NO gases, i.e., emission rates were higher during acceleration, followed by
297 cruising, deceleration, and idling. Choudhary & Gokhale, 2016, May et al., 2014, Qu et al.,
298 2015b, and Shukla & Alum, 2010 have reported a similar trend. Qu et al., 2015b also observed
299 that higher emission rates were more prevalent during periods of high speed and acceleration,
300 which is visible clearly in the NO emission rate. When a vehicle accelerated, more air and fuel
301 are injected into the engine cylinders, increasing the engine load, thereby causes higher CO
302 and HC emissions. CO emissions from engines are due to incomplete combustion, especially
303 during deceleration, where the engine can misfire and release higher CO and HC emissions.
304 Acceleration and deceleration also result in rich and lean fuel mixture conditions closer to the
305 stoichiometric ratio, which creates favourable combustion temperature for the formation of

306 NO, thereby releasing higher NO emissions (Choudhary and Gokhale, 2016; Wang et al.,
307 1998). The average emission factors of CO, HC, and NO on the five study routes are shown in
308 Appendix A Supplementary Table S4. All the roads have contributed emission factors higher
309 than BS-IV standards for vehicles, with Residential Area registering the highest CO emission
310 factor of 5.26 g/km, and IIT D Perimeter with lowest, i.e., 3.72 g/km. IIT D RTR Flyover
311 recorded highest NO emissions, i.e., 7.2 g/km and lowest HC, i.e., 0.10 g/km, while Residential
312 area recorded the lowest NO and highest HC emissions, i.e., 0.3 and 0.44 g/km respectively. It
313 is evident that vehicular emissions depend on the road and driving characteristics, which affect
314 the vehicle's speed and acceleration. Therefore, it is necessary to probe into different ranges of
315 speed and acceleration to suggest the preferable combination for curbing the emissions.

316 ***3.4 Effect of Speed and Acceleration***

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

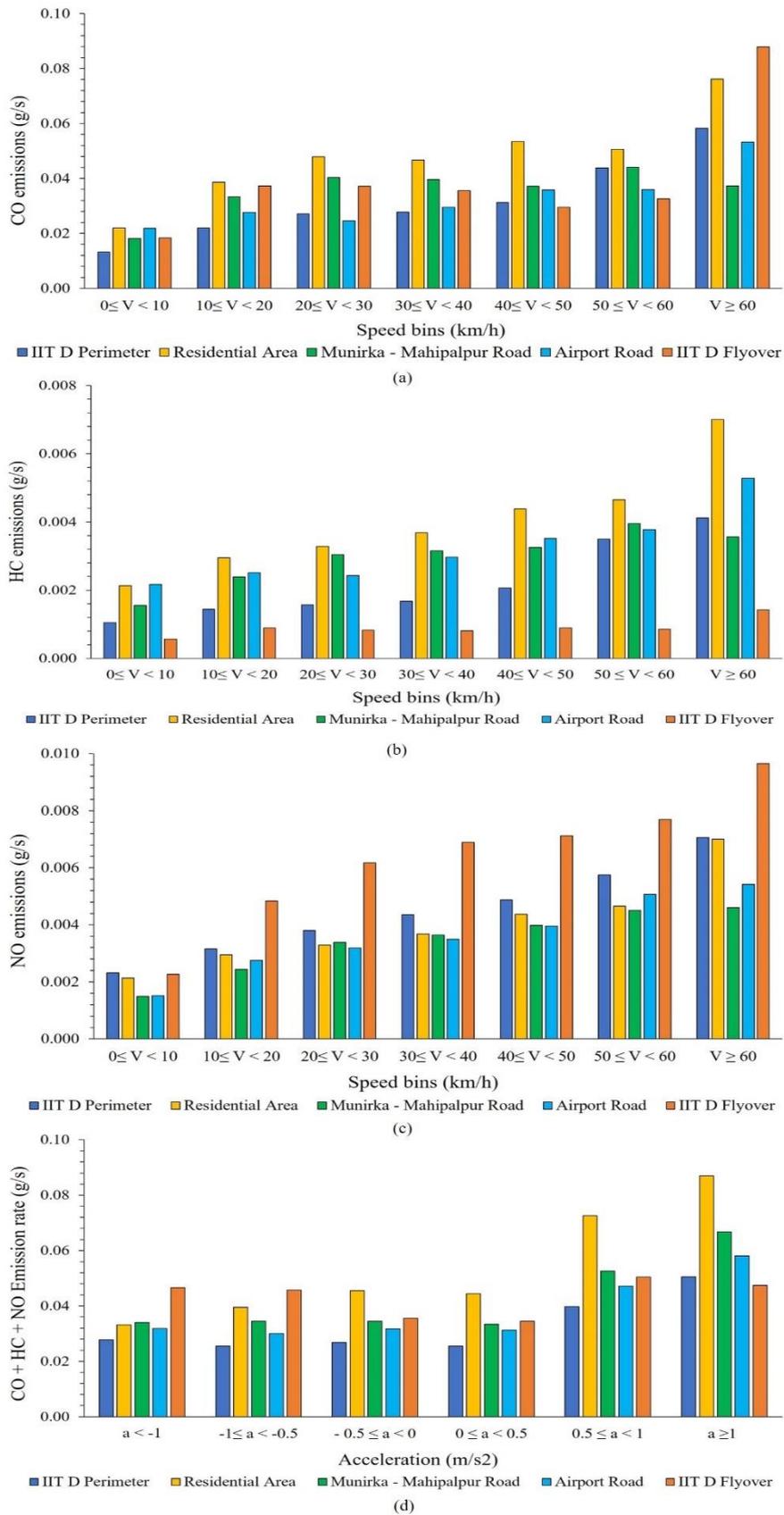


Figure 3: Emission rates of (a) CO, (b) HC, (c) NO in different speed bins and (d) Combined emission rates of CO, HC, and NO in different acceleration bins

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

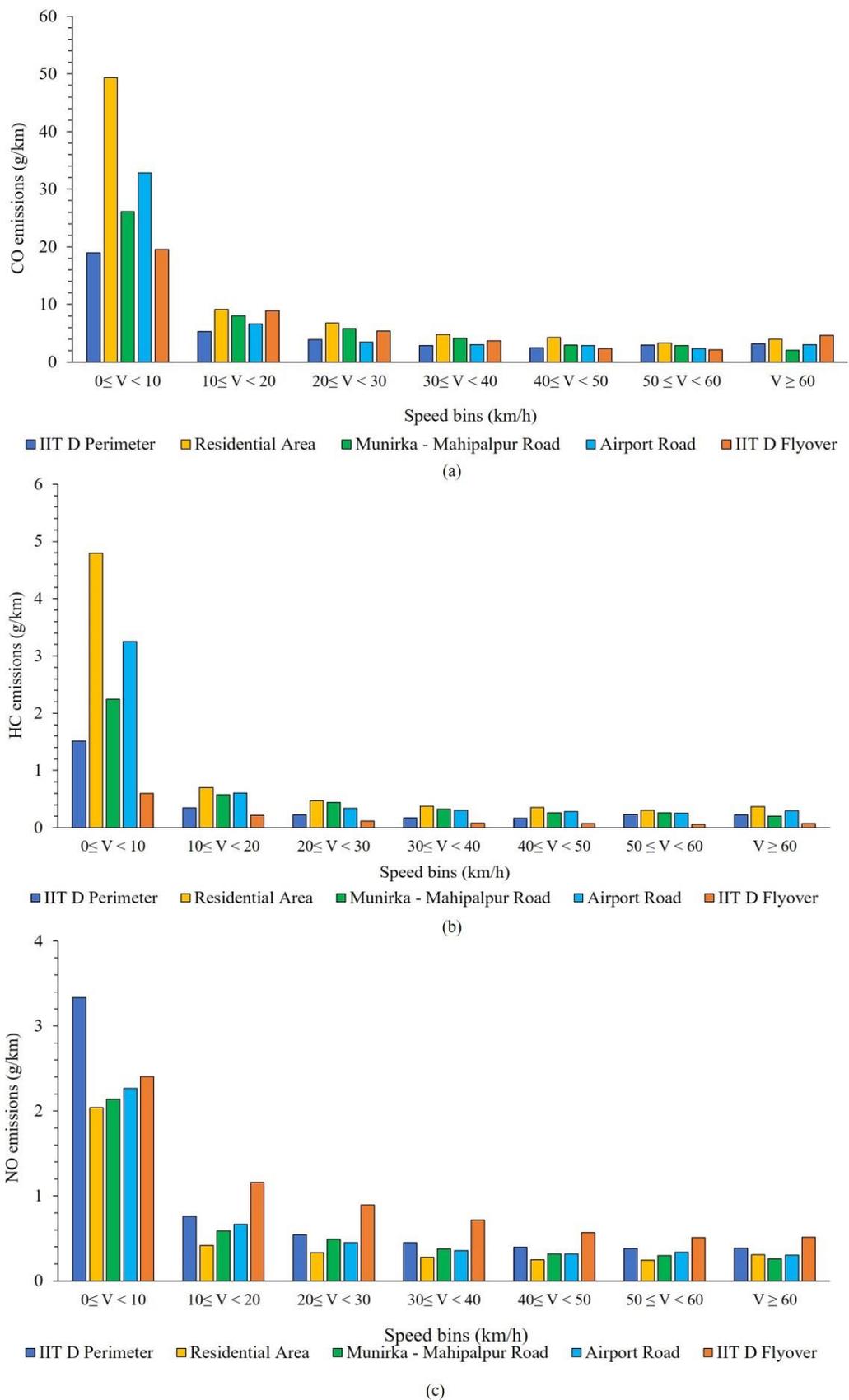


Figure 4: Emission factors of (a) CO, (b) HC, and (c) NO in different speed bins

347 **3.5 Estimation of Total Emissions**

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

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

352 The average emission factors of CO, HC, and NO are 3.8, 0.3, and 0.54 g/km respectively.
353 Roychowdhury & Dubey, 2018 reported that in Delhi the passenger cars clock nearly 16
354 million VKT/day. Using this data, the estimated CO, HC, and NO emissions are 60.8, 4.8, and
355 9.72tonnes/day respectively. Curbing of emissions can happen only through a series of
356 mitigation measures, which will be discussed in the next section.

357 **3.6 Vehicular Emission Regulation and Standards**

358 The emissions from vehicles became a major concern in the middle of the twentieth century
359 when the mass production of cars reached its peak. Due to the environmental and health impacts
360 of vehicular pollution (Balakrishnan et al., 2019; Khillare and Sarkar, 2012; Kumar and Mishra,
361 2018; Ngoc et al., 2018; Shekarrizfard et al., 2018), legislative bodies across the US, Europe,
362 and other developed nations acknowledge the need to curb vehicle-related emissions. Countries
363 such as India and China have improvised and adopted the norms prescribed by these agencies.
364 Since 1992, when the “EURO 1” was introduced to regulate emissions, by systematically
365 tightening the emission standards for diesel and petrol passenger cars levels have reduced
366 significantly and the most recent EURO 6 standards was announced in 2014. Over the period
367 of 22 years, the CO emission standards were reduced from 2.72 to 0.5 g/km, NO_x emission
368 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
369 g/km indicating a significant reduction of 82%, 84%, 82% and 96% respectively (Sassykova

370 et al., 2019). Similarly, India has adopted Bharat stage emission standards set by the Central
371 Pollution Control Board (CPCB) to regulate exhaust emissions. The Bharat standards, which
372 were based on Euro 1 norms, were introduced for the first time in 2000. Similarly, BS-VI
373 synonymous with EURO-6 was introduced in April 2020. The reduction of emissions from
374 India 2000 to BS-VI is similar to Euro standards for diesel passenger cars.

375 In order to meet specified standards, regulatory bodies recommended the adoption of control
376 equipment for enforcement, process modification such as retrofitting the older vehicles with
377 new emission control technology and fuel injection system, introduction of clean and advanced
378 fuels, and interventions including – reducing VKT using transit oriented development,
379 (Nesamani, 2010) subsidies for alternative fuels and hybrid vehicles, developing green zones,
380 and improvising the vehicular pollution testing methods. Catalytic converters were introduced
381 in the global automobile market during the 1970s as an after-treatment system to achieve
382 upcoming standards. Initially, two-way converters were used to reduce CO and HC; later,
383 three-way converters came into the market to reduce NO_x as well (Srinivasa Chalapati and
384 Venkateswara Rao, 2018). Diesel particulate filters were introduced into the market in the late
385 1980s when stringent emission norms for Heavy-duty diesel engine vehicles were introduced.
386 Filter regeneration technology in Diesel Particulate Filters (DPF) have made it low
387 maintenance and most widely used in diesel engines. Exhaust gas recirculation (EGR) is
388 another popular technology being used in automobiles to control NO_x emissions (Brijesh and
389 Sreedhara, 2013). Along with this many control strategies were implemented in Delhi.

390 Many researchers have studied the impact of some of these control measures. According to
391 Chelani and Devotta, 2007 the reduction in SO₂, Suspended Particulate Matter (SPM) and PM₁₀
392 concentration due to switching of diesel vehicles to CNG during 2000 to 2003 were 35%, 2.8%
393 and 7% respectively. However, few studies reported an increase in NO_x concentration
394 (Kathuria, 2004; Ravindra et al., 2006). A study conducted by Foster found that the air quality

395 regulations in Delhi during 1997-2002 had a significant impact on respiratory health or lung
396 function of the local residents of New Delhi. The odd-even policy trials in Delhi showed a
397 considerable reduction in PM10 and PM2.5 concentration up to 74% during the hours of the
398 trial; however, the influence on emissions from heavy-duty vehicles running during night times
399 reduced the overall efficiency of the strategy (Kumar et al., 2017).

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

409 **4. Conclusion**

410 Deterioration of urban air quality due to vehicular pollution has always been of much debate
411 and there is much evidence that there is a discrepancy between emissions compliance for new
412 vehicles and those emitted during real-world driving. In order to better understand vehicle-
413 related pollution, real-world emission testing of vehicles is necessary and has been adopted by
414 many governments internationally. However, India has yet to implement this method. In this
415 study, real-world exhaust emissions of 54 diesel and 4 petrol passenger cars of different makes
416 and models driving on urban roads in Delhi were measured, at a sampling frequency of 1Hz,
417 using an on-board portable exhaust emission monitoring system. All the cars tested exceeded
418 the limits of BS-IV standards for CO, HC, and NO gases and other studies made similar

419 observations. The average emission factors of CO, HC, and NO were 3.8, 0.3, and 0.54 g/km
420 respectively. The study of real-world exhaust emissions from vehicles has revealed that road;
421 traffic, vehicle, and driving characteristics play a vital role in the quantity of emissions released.
422 Also, speed and acceleration were discovered to have a major impact, i.e. with an increase in
423 speed and acceleration, emission rate increases. Nevertheless, a speed and acceleration
424 combination of 40 – 60kmph and $-0.5 - 0.5\text{m/s}^2$ respectively, appeared to emit the lowest
425 concentration of pollutants. The city-wide CO, HC, and NO emissions were estimated to be
426 60.8, 4.8, and 9.72tonnes/day, respectively by considering the VKT of passenger cars per day
427 in Delhi and the emission factors projected in this study. This endorses the need to tackle air
428 pollution caused by vehicular emissions on multiple fronts.

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

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