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Study of Tail-Pipe Emission from Petrol Driven Passenger Cars

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Abstract: ***Pollution from vehicles is due to discharge like Carbon monoxide (CO), Carbon dioxide (CO_2), Hydrocarbon (HC) and Oxides of Nitrogen (NO_x) through their tailpipe. Cars, being in leading proportions (38.4%) in Indian traffic stream with small cars above 56% in total car proportions, are the main contributors to pollutant. Literature reveals that all factors being constant, at signalized intersection, car emission rates are the function of speed and acceleration. Since it is difficult to collect speed and position data at the actual intersection, this study is conducted on link road between National Highway-28 and Madan Mohan Malaviya University of technology, Gorakhpur, India, replicating the queue leader at signalized intersection. Tailpipe emissions are measured using onboard emission measurement system and speed and position data are measured using GPS device. Study illustrates that tailpipe emissions like CO, HC and NO_x are sensitive to vehicle speed at similar acceleration level. Tailpipe emission rate initially decreases with increase in speed and then increase afterwards with further increase in speed, at similar acceleration level. Emission rates are found to increase with increase in vehicle acceleration rate. It was observed that deceleration does not influence tailpipe emission of small cars.***

Keywords: tailpipe emission, emission modeling, acceleration and deceleration.

I. INTRODUCTION

Vehicle emissions contribute substantially to total environmental pollution for Carbon monoxide (CO), Carbon dioxide (CO2), Hydrocarbon (HC) and Oxides of Nitrogen (NO_x). Measurement of vehicle emission is typically done through area wide driving cycle based models like MOBILE 5b, MOBILE 6, EMFAC, etc. The second by second data required for these models is taken from driving cycle based laboratory experiments using chassis dynamometer. However, dynamometer data does not consider short term episodes like acceleration, cruising, breaking, deceleration, etc., which are the characteristics of real world driving. Hence, dynamometer data is useful in area wide experiments, where occurrence of short term episodes is sparse and vehicle cruises most of the time (with less or no acceleration/ deceleration). But it is not suitable for explaining short term episodes as stated above (Frey et al., 2001). Emissions through such short term episodes (like acceleration, cruising, breaking and deceleration) are termed as *micro-scale* emissions and models explaining emissions during short term episodes are termed as *micro-scale* emission models. *Micro-scale* emissions form a substantial part of total emission inventory. *Micro-scale* emission models are, therefore, important for evolving the traffic control strategies at road sections where short term episodes are frequent (Frey et al., 2001).

Frey et al. (2001) measured the tailpipe emissions of individual vehicles using onboard instrumentation. They considered episodic nature (nature based on temporary episodes like acceleration, breaking and deceleration) of vehicle emission. They used OEM 1000 (a five gas analyzer) to collect emission data and engine diagnostic scanner to collect engine data like speed, engine rpm, etc. at a busy arterial with signalized intersection. Authors concluded that there is a significant variation in emission of vehicles during temporary events like acceleration, deceleration and cruising. Average emission during acceleration was found to be .8 times more than idling emission for HC and CO2 and 12 times more for NO and CO. Variation of vehicle emissions with time was found to be sensitive to short term episodes like acceleration and deceleration.

Unal et al. (2004) quantified emissions at *hot spots* (*spots where emissions are significantly high*) on highway corridor using onboard emission measurement instrument. They observed that other methods of emission measurement such as chassis dynamometer; remote sensing, etc. have limitations in recording field conditions of emissions. The onboard instrument can record real world emission under any ambient traffic and roadway condition. Authors concluded that variables such as average speed, average acceleration and standard deviation of speed, percent of time spent in cruising, minimum speed, maximum acceleration and maximum power have significant impact on vehicle tailpipe emissions.

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Wang et al. (2011) reported that vehicle speed and acceleration can be used as an input for vehicle emission models. They simulated 9.5 km freeway traffic from 15 hrs to 19 hrs to get speed trajectory, position and acceleration and deceleration. It is observed that emissions vary with variation in speed and acceleration. They concluded that emission estimates should incorporate the acceleration instead of mean speed of vehicle. Effect of acceleration on emissions is greater on lower speeds than at higher speeds. The NOx emissions suffered an increase of 34% when a correction factor for acceleration was applied.

Grace et al. (2004) reported that MOBILE5 model is widely used in emission estimation but it cannot be used in the evaluation of transportation projects improvements resulting in reduction in acceleration and deceleration. The authors included current and previous values of acceleration and deceleration along with durations of acceleration and deceleration while modeling emissions. Specific power (2 × speed × acceleration) directly determines the amount of emission. The emission models developed on the basis of these factors produced more accurate results than earlier modeling efforts. They compared emission models such as CHEM and POLY and concluded that the emissions measured by these models differ in themselves and also differed from measured values. But on evaluation, POLY model was found more reliable than other models.

Ahn et al. (2002) reported that 45% of the pollutant released in United States is consequence of vehicle emissions. They observed that most of the existing models offer simplified mathematical equations based on average link speed ignoring transient changes in speed and acceleration. They conducted various experiments to collect the data from field and chassis dynamometer for modeling vehicle energy consumption and emission rates as a function of vehicle's instantaneous speed and acceleration. These models resulted better prediction of the vehicle energy consumption and emission rates.

Above literature indicates that the vehicle emissions can well be quantified using models based on onboard emission measurement data rather than using chassis dynamometer data for episodic nature of vehicle operation. It also shows that the vehicle emission is highly dependent on episodes like idling, acceleration, cruising and (to some extent on) deceleration. Exiting emission models like MOBILE 5b cannot be used for predicting emissions through transportation improvement projects reducing acceleration and deceleration. Further, literature yields that no such emission related study has been conducted in developing country like India. Like other developing countries, the vehicle characteristics, road features and driver habits in India are different than that reported in literature (Arasan and Koshi, 2005).

Hence this study is undertaken in India at signalized intersection (where episodes such as acceleration and deceleration are more prominent than other parts of road), to assess the sensitivity of vehicle tailpipe emission to episodes like acceleration and deceleration. This study aims at quantifying the tailpipe emissions such as CO, HC and NO_x of lead car at a signalized intersection.

II. EXPERIMENTAL DESIGN AND DATA PROCESSING

One can well assess the effect of speed and acceleration on vehicle tailpipe emission by observing vehicle activity at intersection and in actual traffic on roads. However, heterogeneous and weak lane disciplined traffic at intersection in India often results in data that is inconsistent and difficult to analyze. At signalized intersections in India, generally smaller vehicles (like motorized and non-motorized two wheelers and three wheelers) creep through the gaps between other queued vehicles (like cars, trucks) and stop in front of the queues at intersection (Fig. 1 shows a typical scenario at intersection). Presence of smaller vehicle in front of the queues at intersection leads to inconsistent A/D behavior of other vehicles. Therefore, an alternative is, to observe driver behavior over short stretch and under controlled conditions (replicating signalized intersection lead vehicle acceleration/deceleration) as an acceptable surrogate for actual behavior. Such alternative processes are also used by earlier researchers (Wang et al., 2011; Joumard et al., 1995; Carcary et al., 2001; Belz and Aultman-Hal, 2011). Looking to major share of cars on Indian roads (36.5% of total on road vehicles) (Dey et al., 2008), this study aims at modeling the effect of speed, acceleration and deceleration on tailpipe emission rates of car. The catalytic converter fitted Brio (make Honda, model 2014, run 284 00 km, weight to horse power ratio 30 lb/hp, well maintained) car is used in this study.

A. Selection Of Study Stretch

In order to repeat the traffic conditions of a row lead at signalized intersection, a study stretch of following properties is chosen:

It should have free flow traffic;
It should be access controlled to avoid any obstruction to speeding;
Road geometry should be fairly straight (to have constant effect of road geometry on speed, acceleration and deceleration of vehicles);
Road surface should be in good condition to provide constant effect of rolling resistance.

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For that reason a study stretch is selected near main entrance of Madan Mohan Malaviya University of technology, Gorakhpur, India, confirming above criteria. This road links Madan Mohan Malaviya University of technology, Gorakhpur to National Highway-28 (GKP-LKO).

B. Instruments Used

This study involved use of two instruments, one to measure the speed profile and other to measure tailpipe emission of test vehicle. V-Box Global Positioning System (GPS) capable of recording vehicle position and speed at 1 Hz frequency (data recording once a second) is used for recording vehicle speed profile and a five gas analyzer, Automotive Exhaust Monitor PEA 205, manufactured by Indus Scientific India is used for onboard measurement of tailpipe emission of test vehicle at 1 Hz rate. This device is capable of recording each second data of vehicle emissions such as Carbon Monoxide (CO, by percent of volume), Hydrocarbons (HC, by parts per million, ppm, of volume) and Oxides of Nitrogen (NO_x, by parts per million, ppm, of volume). Both these devices are shown below.



Fig.-1 V Box

C. Experimental Procedure

The drivers of the vehicles were asked to accelerate to their desired speed (maximum speed at which driver feel safe for a given road geometry and environmental condition; after this referred as maximum speed) in minimum possible time and later they were asked to decelerate till stop condition replicating lead vehicle at signalized intersection. All trips were made during free flow traffic condition. A total of 45 such trips of test car (Honda BRIO) were recorded in sunny weather during March 2016. The Automotive Exhaust Gas Analyzer, PEA 205 device (Fig. 1-b) was installed on back seat of car. The device was connected to laptop computer to record second by second emission data. The emission recording probe was inserted in tailpipe of the test car and the connecting pipe was attached to PEA 205 device. V-Box (Fig. 1-a) was installed in the test car and used to record the speed profile during all trips. The time frame organization of V-Box and Automotive Exhaust Gas Analyzer data was done by the time records in observed data. The speed record at a particular second is matched with tail pipe emission record at that second. A typical sample of merged data is shown in Table 1. The observed speed and emission profiles are presented in Fig. 3. Speed profile in Fig. 3 indicates several acceleration/deceleration episodes and the episodes between one acceleration and deceleration cycle. It is seen that acceleration and deceleration episodes are repeated which are representative of acceleration and deceleration of queue leaders at signalized intersection. The maximum speed attained by any trip is (27.78 m/s) 100 km/h.

Similarly, Fig. 4 presents the profiles of tailpipe emissions such as Carbon Monoxide (CO), Hydrocarbon (HC) and Oxides of Nitrogen (NO_x). The emission profiles are superimposed on speed profile. It is seen that except for Hydrocarbons (HC), the variation in all other emissions are episodic in nature. These variations in emission profiles go with the episodes in speed, i.e. acceleration and deceleration. For Hydrocarbons (HC), initial rise in its concentration is due to un-burnt fuel due to cold start conditions. After stabilization of engine, the Hydrocarbons (HC), emission has stabilized. Salient features of speed and emissions in all trips are presented in Table 2.

The speed observed in this study matches with other researchers in India (Arasan and Koshi, 2005; Dey et al., 2008). The Coefficient of Variation (C.V.) values are highest for CO indicating higher dispersion and lowest for HC indicating lesser dispersion. This shows that the emission of CO is more sensitive to episodes like acceleration and deceleration whereas emission of

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HC remains more or less unaffected due to episodes. HC emission varies initially when engine is in un-stabilized condition and emits un-burnt petrol. After stabilization engine stops emitting un-burnt petrol hence emission of HC is stabilized resulting in lesser Coefficient of Variation.

"Perfect" Combustion = Fuel (Hydrocarbons) + Air (Oxygen and Nitrogen) +Carbon Dioxide + Water + Unaffected Nitrogen

Typical Engine Combustion

Fuel + Air Unburned Hydrocarbons + Nitrogen Oxides + Carbon Monoxide + Carbon Dioxide + Water

III. SI ENGINE EMISSIONS

S.I. engine emissions are divided into three categories as exhaust emission, evaporative emission and crank case emission. The major constituents which contribute to air pollution are CO, NO_x, and HC coming from S.I. engine exhaust(as shown in fig.-2).



Fig.-2 S. I engine

IV. EXHAUST POLLUTANT

A. Hydrocarbons (HC)

Hydrocarbon emission outcome when fuel molecules in the engine do not burn or burn only partially. Hydrocarbons react in the presence of nitrogen oxides and sunlight to form ground-level ozone, a major component of smog. Ozone irritates the eyes, damages the lungs, and aggravates respiratory problems. It is our most widespread and intractable urban air pollution problem. A number of exhaust hydrocarbons are also toxic, with the potential to cause cancer.

B. Nitrogen Oxides (NOx)

Under the high pressure and temperature conditions in an engine, nitrogen and oxygen atoms in the air react to form various nitrogen oxides, collectively known as NOx. Nitrogen oxides, like hydrocarbons, are precursors to the formation of ozone. They also contribute to the formation of acid rain.

C. Carbon Monoxide (CO)

Carbon monoxide (CO) is a product of incomplete combustion and occurs when carbon in the fuel is partially oxidized rather than fully oxidized to carbon dioxide (CO). Carbon monoxide reduces the flow of oxygen in the blood stream and is particularly dangerous to persons with heart disease.

D. Carbon Dioxide (CO_2)

In recent years, the U.S. Environmental Protection Agency (EPA) has started to view carbon dioxide, a product of "perfect" combustion, as a pollution concern .Carbon dioxide does not directly impair human health, but it is a "greenhouse gas" that traps the earth's heat and contributes to the potential for global warming.

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Time,s	Speed, m/s	CO,%	HC, ppm	NO, ppm
1	0.010	0.031	9	28
2	0.019	0.031	9	28
3	0.015	0.031	9	28
4	0.080	0.030	9	28
5	0.035	0.030	9	28
6	0.010	0.030	9	27
7	0.022	0.030	9	27
8	0.035	0.029	9	27
9	1.311	0.028	9	26
10	2.501	0.028	9	26
11	4.031	0.028	9	26
12	5.831	0.028	9	26
13	6.056	0.028	9	25
14	6.503	0.025	9	25
15	8.501	0.025	9	25
16	10.023	0.025	9	24
17	10.891	0.025	9	24
18	11.128	0.025	9	24
19	11.928	0.020	9	23
20	13.220	0.020	8	23
21	14.412	0.020	8	23
22	15.510	0.020	8	23
23	16.503	0.015	8	22
24	17.426	0.015	8	21
25	18.516	0.015	8	21
26	18.755	0.015	7	20
27	18.239	0.015	7	19
28	18.928	0.015	7	18
29	19.358	0.012	7	17
30	19.928	0.012	7	16
31	20.408	0.012	6	15
32	20.668	0.012	6	14
33	21.098	0.012	6	13
34	21.49	0.011	6	12
35	22.60	0.011	6	12
36	22.38	0.011	6	11
37	24.21	0.011	6	11
38	24.98	0.011	5	10
39	25.32	0.010	5	9
40	25.01	0.010	5	8
41	26.32	0.010	5	9
42	26.97	0.011	6	10
43	26.65	0.011	6	10
44	27.24	0.012	6	11
45	27.78	0.012	7	12

Table-1: Sample Speed and Emission Data during Acceleration plan

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Parameter	Speed, m/s	CO, %	HC, ppm	NOx, ppm
Maximum	26.97	6.93	943	735
Mean	13.47	4.51	778.9	387.89
Std. Dev.	8.25	0.63	28.72	59.32
Coefficient of Variation	65%	62%	13.89%	15.45%

Table- 2: Salient Features of Speed and Emissions

V. ANALYSIS AND RESULTS

Acceleration and deceleration were calculated to examine the average behavior of emission with speed, acceleration and deceleration data obtained using Eq. (1) and Eq. (2):

$$a = \frac{v_1 - v_2}{t_1 - t_2} \quad \text{..... (1)}$$

$$d = \frac{v_1 - v_2}{t_1 - t_2} \quad \text{..... (2)}$$

Where; a and d are acceleration and deceleration respectively in m/s^2, v_1 and v_2 are the speeds in m/s at time t_1 and t_2 respectively. The speed, acceleration, deceleration and emissions such as CO, HC and NOx are then averaged over a speed range of 1 m/s (Wang et al., 2004), to get an idealize value of these parameters. Thus one idealizes speed, acceleration, deceleration and emission record (CO, HC and NOx) is obtained for every 1 m/s speed range. This has been done to examine average behavior of emission with speed, acceleration and deceleration (Rakha et al., 2000; Wang et al., 2004; Bham and Benekohal, 2001).

A. Effect of Speed and Acceleration on Tailpipe Emission

In order to review the effect of speed of test car on tailpipe emission, idealize emissions are plotted against idealize speed without giving consideration to acceleration or deceleration levels (Fig. 3). It is seen from Fig. 3 that there is no consistent relationship between speed and various tailpipe emissions. Similar statements are also noted by other researchers like Frey et al. (2001), Joumard et al. (1995) and Oses et al. (2002). This is due to mixing of speed records with acceleration or deceleration records. Emissions are plotted corresponding to each speed level but at particular speed vehicle may have different acceleration levels. Therefore, to segregate the acceleration effect on vehicle emission, variation of tail pipe emission with vehicle speed should be studied at a particular acceleration or deceleration level.

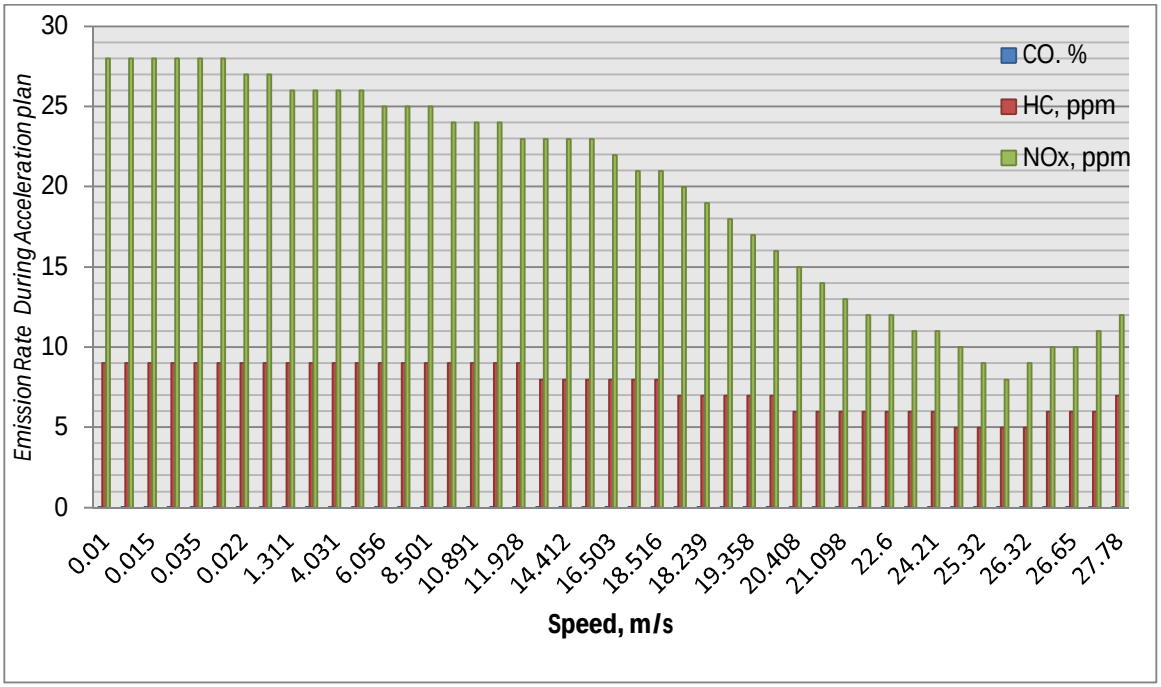


Fig. 3. Effect of Test Car Speed on its Tail Pipe Emission

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Hence, authors set speeds as per the acceleration or deceleration range and tried to find the relation between speed and emission (CO, HC and NOx) within a particular acceleration or deceleration range. For example the speed and emissions data (CO, HC and NOx) at acceleration level ≈ 1.0 m/s^2 are separate out and the relationship between speed and emission is tested again. It is found that at similar acceleration range, speeds and tailpipe emissions marked a noticeable relationship. Therefore, the speed and emission relationships are established for different acceleration ranges. Figs. 4a, 4b and 4c present the relationship of CO, HC and NOx respectively, with speed at two different acceleration levels, 1.0 m/s^2 and 1.6 m/s^2.

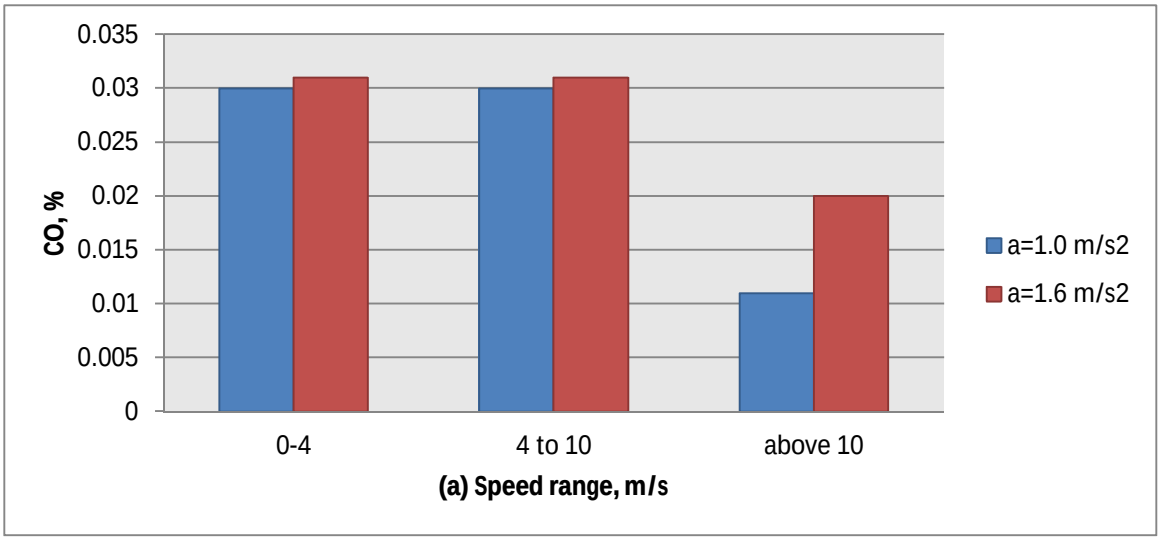
It is seen from Fig. 3 that tail pipe emission rate is high at lower speed which gradually lowers with increase in speed. Later with further increase in speed emission rate increases monotonically. Similar, trend is observed for all emissions like CO, HC and NOx. At lower speed, the engine exerts more power (in first or second gear, speed 0-4 m/s) with more consumption of fuel. Higher fuel consumption results in high tailpipe emissions. As the vehicle speed advances (in second or third gear, speed 4 to 10 m/s) the power goes on reducing and hence the fuel requirement of engine goes on reducing. This reduced fuel consumption results in reduced tailpipe emission. However, with further increase in speed (in fourth or fifth gear, speed above 10 m/s) engine consumes more fuel for speeding and results in increase in tailpipe emission. A similar behavior is also reported by Ahn et al. (2002), Joumard et al. (1995) and Rakha et al. (2000).

The lowest tailpipe emission rate is observed at the speed range of 4 to 10 m/s (refer Fig. 4) at acceleration rate ≈ 1 m/s^2 for all tailpipe emissions. However, the speed range corresponding to lowest tailpipe emission rate reduces with increase in acceleration range. It should be noted that speed range corresponding to minimum emission are not the cruising speed of vehicle. However, this speed range corresponds to minimum emission at a particular acceleration level (like 1 m/s^2 or 1 m/s^2).

Table 3 presents average tailpipe emissions at different speed ranges and acceleration levels. It is seen from Table 3 that there is significant variation in tailpipe emission rate with different speed range and acceleration combinations. Lowest emission rate is observed in speed range of 4 - 10 m/s. It can be observed that effect of acceleration on tailpipe emissions is more prominent at higher speeds. At higher speed range (above 10 m/s), all tailpipe emission rates (CO in %, HC in ppm and NOx in ppm) are substantially high for acceleration 1.6 m/s^2 than for acceleration 1.0 m/s^2, as can be seen from Table 3. This demonstrates the effect of speed and acceleration on tailpipe emission rates of test vehicle.

Speed range, m/s	CO, %		HC, ppm		NOx, %	
	a=1.0 m/s^2	a=1.6 m/s^2	a=1.0 m/s^2	a=1.6 m/s^2	a=1.0 m/s^2	a=1.6 m/s^2
0-4	0.030	0.031	9	9	28	28
4-10	0.030	0.031	9	9	27	28
Above 10	0.011	0.020	6	8	12	23

Table 3 Average Tailpipe Emission Rate at Different Speed Ranges and Acceleration Levels



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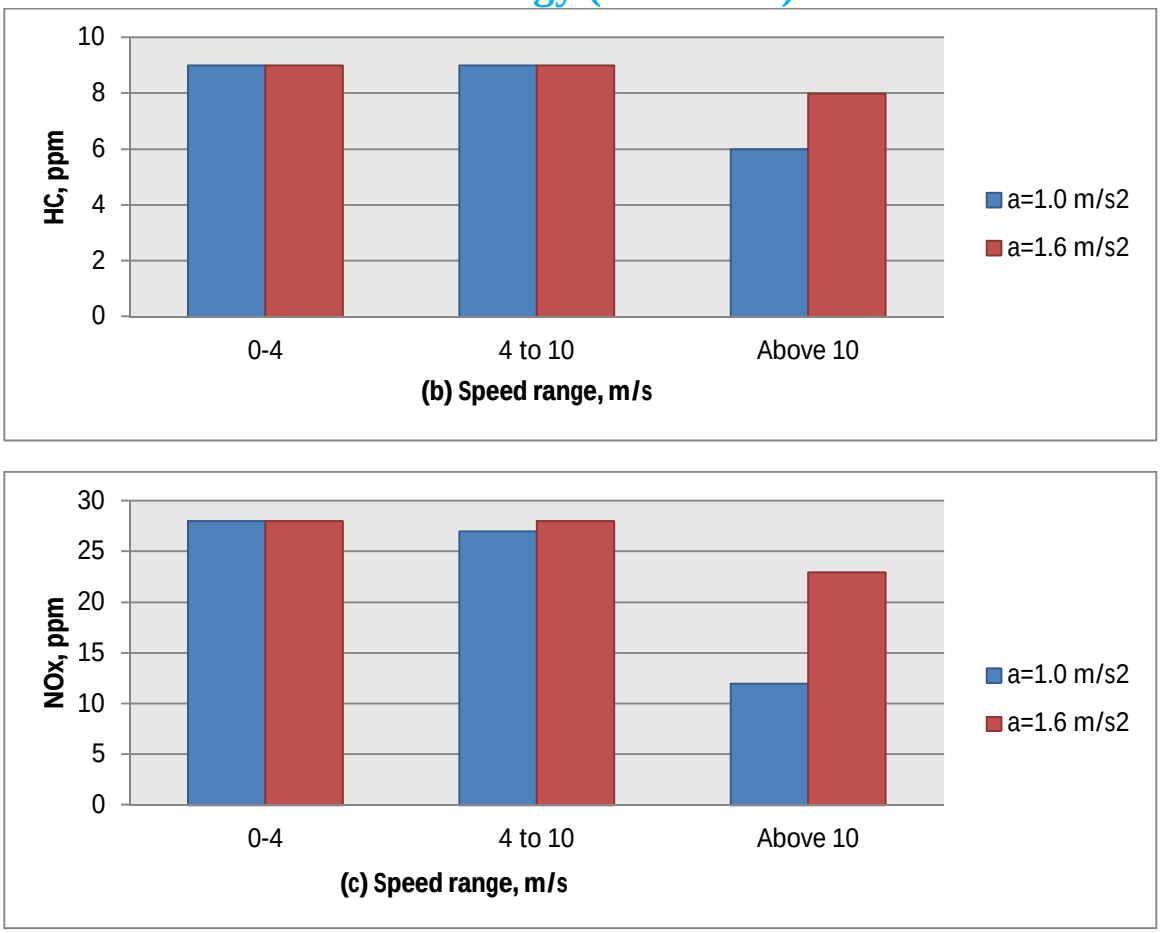


Fig. 4. Effect of Speed on Tailpipe Emission of Test Car at Particular Average Acceleration Level: (a) CO; (b) HC; (c) NOx.

B. Effect of Acceleration on Tailpipe Emission

Idealize tailpipe emission (CO, HC and NOx) are plotted against average acceleration (averaged over 1 m/s speed. It can be observed from the tailpipe emission increases with increase in vehicle acceleration. This implies lower tailpipe emission at lower acceleration and higher emission at higher acceleration.

C. Effect of Speed and Deceleration on Tailpipe Emission

The decelerations were also averaged over 1 m/s speed range and one statement was obtained for speed, deceleration and tailpipe emission rate for every 1 m/s speed range. Various plots were drawn to explore the relationship between speed, deceleration and tailpipe emission. However, no relationship was observed between speed, deceleration and tailpipe emission. One possible reason is that the deceleration of vehicles is achieved using application of brakes. During deceleration, engine is disconnected from vehicle and hence doesn't participate in the process of deceleration. Thus, tailpipe emission is unchanged by deceleration.

VI. CONCLUSIONS

This study attempts to present the effect of speed, acceleration and deceleration on vehicle tailpipe emission. Test car used in this study was Honda Brio model 2014 (fitted with catalytic converter). Following conclusions can be drawn from this study:

At similar acceleration level, vehicle tailpipe emission (CO, HC and NOx) is sensitive to vehicle speed. Tailpipe emission rate initially decreases with increase in speed; however, it increases afterwards with further increase in speed. Lowest tailpipe emission rate of test vehicle is observed at speed range 4-10 m/s at acceleration level 1 m/s^2. Ahn et al. (2002) reported that the emissions are lower up to speed of 6.056 m/s (21.8 km/h). This statement is in agreement with the lowest emission speed range of 4-10 m/s observed in this study. A similar statement is also reported by Joumard et al. (1995).

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Acceleration rate of vehicle significantly impacts the tailpipe emission. Emission rate increases with increase in vehicle acceleration. Ahn et al. (2002) and Rakha et al. (2000) also maintained the statement that emission is high at higher accelerations. Main conclusion from this is that the vehicles should be driven at approximately constant speed (at lower acceleration) as far as possible to result lower emissions. In a similar study reported by Frey et al. (2001), the minimum emission is observed at idling (at lower acceleration). At idling, since there is no power or speed requirement by engine (since there is no acceleration), the fuel consumption is minimum and hence the rate of emission is minimum. This endorses the statements by authors of present study that emission rates are lower at lower acceleration.

Statistically too, emissions are different at different acceleration levels.

Relationship between vehicle slowing down rate and tailpipe emission was not detected.

Tail pipe emission rate is high at lower speed which gradually lowers with increase in speed. Afterward with further increase in speed emission rate increases monotonically

A detailed study including different type of vehicles can be planned to develop the generalized relationship between vehicle speed, acceleration, deceleration and emission. Sensitivity of vehicle emission with its speed and acceleration/ deceleration emphasizes the need for emission consideration in designing of traffic control measures at road intersections.

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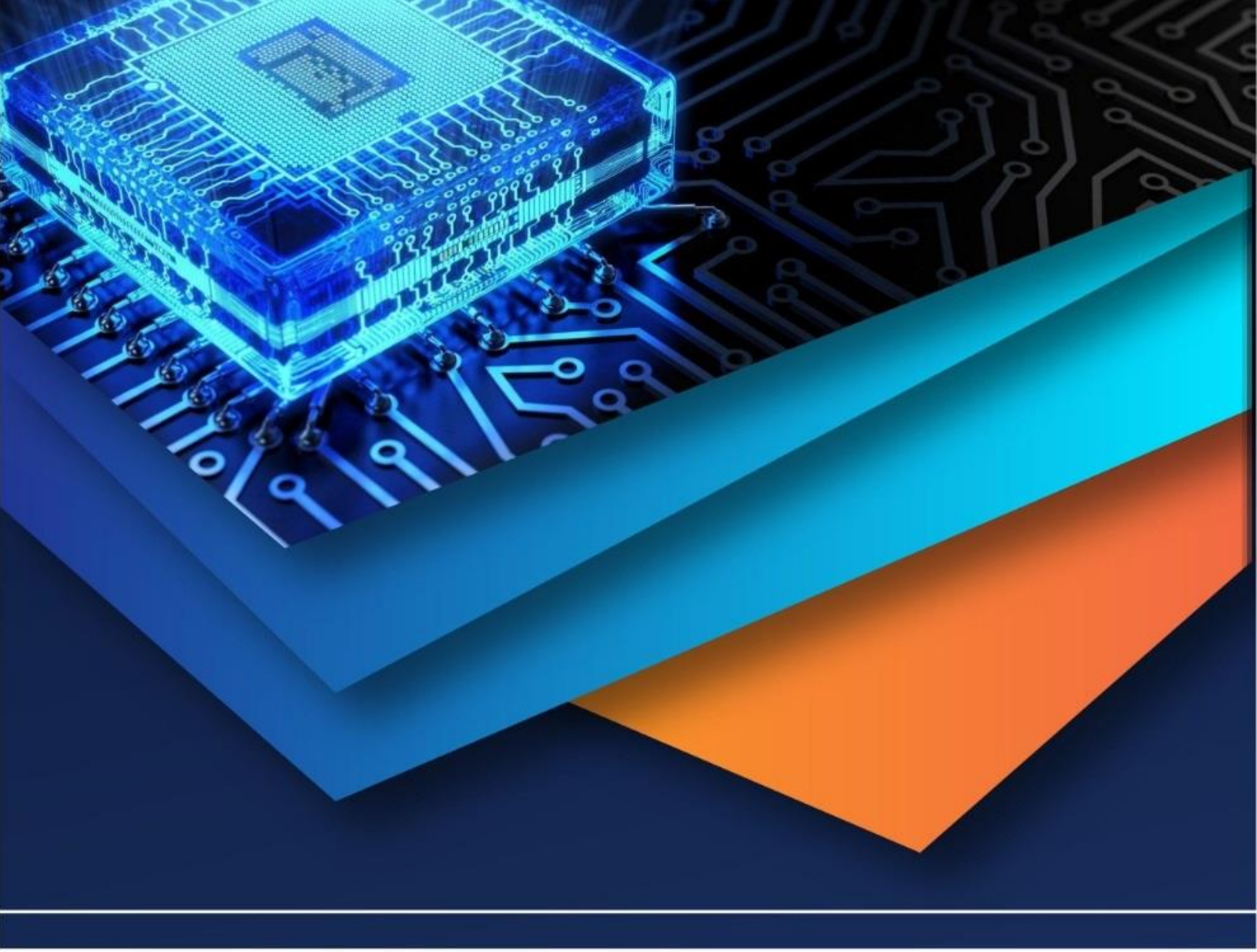
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