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EFFECT OF SPEEDING BEHAVIOUR OF PASSENGER CARS ON TAILPIPE EMISSIONS

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Abstract: Several studies, in the past, have used chassis dynamometer and remote-sensing method to describe effects of speeds on pollutant emissions. These studies reasonably lacked data on important modal events such as acceleration, deceleration, speed, and their effects on emissions. Present study includes on-road experiments carried out to examine the impacts of car speed, acceleration, and deceleration on their tailpipe emissions. The study was carried out on cars, with and without catalytic converter on a two-lane roadway in engine operating modes of acceleration and deceleration. The power to weight ratio of the cars was 0.03hp/lb. The relationships of pollutant emissions with the speeds were examined at two acceleration levels ($a \approx 1.0$ m/s^2 and $a \approx 1.6$ m/s^2). A prominent relationship of tailpipe emission with the averaged speed was seen at both accelerations. Further, the pollutant emissions were different at different speed ranges of 0-3 m/s (0-10.8 km/h), 3-6 m/s (10.8-21.6 km/h) and above 6 m/s (21.6 km/h). A second-order statistical emission - speed model has been presented and discussed. The effect of deceleration on tailpipe emission was not clear in the study.

Keywords: tailpipe emission, acceleration, deceleration, vehicle speed, emission model.

1. Introduction

Vehicular emissions contribute substantially to urban air pollution. Gases like carbon monoxides (CO), hydrocarbons (HC), carbon dioxides (CO_2) and oxides of nitrogen (NO_x) adversely affect the human health. These gases are emitted through tailpipe as a result of automobile engine operation. To estimate total concentration of pollutants in atmosphere, it is important to estimate the rates at which these pollutants are released from automobiles. Various approaches are used to estimate rates of releases of these gases from automobiles. Two important approaches are chassis dynamometer tests and real-world vehicle monitoring. Chassis dynamometer method uses driving cycle approach. However, many researchers (Ross, 1994; Black, 1991; Joumard *et al.,* 1995; Andrews *et al.*, 2004; Li *et al.*, 2005) have reported that driving cycles do not represent actual driving behavior of vehicles on roads. Particularly acceleration, creeping and other off-cycle events are not properly represented in driving cycles. This significantly distorts emission estimates. Moreover, most of the conventional testing is done on new or well-maintained engines, (Rakha *et al.,* 2000). This is not the case in real traffic. Therefore, methods based on dynamometer with conventional test cycles produce different

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emission factors than found in field studies, (Ropkins *et al.*, 2009).

Real world vehicle emission monitering approach (e.g., remote sensing, tunnel and inverse dispersion, probe vehicle and car chaser studies) is necessitied from poor validation of emission factors using dynamometer studies. These in-situ approaches provide data that are more representative of local general vehicle fleet than traditional dynamometer data. Hence thase are widely used for determining vehicle emission inventories, (Ropkins *et al.,* 2009). However, one thing is common in both the approaches (chassis dynamomneer and real world monitoring) that they use driving parameters like speed or acceleration as an explainatory variable for tailpipe emissions. Many researchers have investigated the relationship of speed and emissions using chassis dynamometer and real-world vehicle emission measurement approaches. A few relevant studies have been reviewed to support this argument.

Tailpipe emissions were measured by on-board instrumentation by, Frey *et al.* (2001). The study used portable instrument to measure emissions and considered episodic nature (nature based on temporary episodes like acceleration, breaking and deceleration) of vehicle emission. The emission during acceleration was 5 times more than the idling emission for CO_2 and HC and 10 times or more for NO_x and CO. The time traces for speed, emission and fuel consumption were also found to be episodic in nature. Unal *et al.* (2004), quantified emissions at hot spots (spots on highway where peak emissions exceed by more than a factor of 2 as compared with the average emissions for free flow or near free flow conditions) on highway corridor using on-board emission-measurement instrument. It was concluded that characteristics such as speed, acceleration, % time spent in cruise and maximum power have significant impact on vehicle tailpipe emissions.

Wang *et al.* (2004) reported that vehicle speed and acceleration could be the inputs for emission models to decide the effectiveness of traffic measures. It was found that the emissions were lower at lower speed and varied with accelerations. Therefore, lowering speed limit could be one of the measures to reduce the emissions.

Osses *et al.* (2002) stressed on the importance of accurate quantification of emissions at spatial and temporal levels in urban areas. Therefore, the emission estimates are often made through emission factors, which depend on mean speeds. It was concluded that emission estimates should not rely on mean speed but acceleration should be incorporated as an important variable. It is difficult to obtain acceleration values in traffic stream and there is a need to obtain acceleration values in free and congested traffic flows. Grace *et al.* (2004) reported that though MOBILE5 emission model is widely used, it cannot evaluate transportation project improvements, which result in the reduction of acceleration and deceleration. The study considered the acceleration and deceleration along with the durations for modelling emissions. Specific Power, S.P. (S.P. = 2 × speed × acceleration) directly determines the amount of emission. Emission models developed based on these factors produce more accurate results (Grace *et al.*, 2004). Emission models such as CHEM and POLY were compared and it was concluded that the emissions measured by these models differ in themselves and also differ from measured values. But POLY model was found more reliable on evaluation than the other models.

Ross *et al.* (1998) reported that the vehicles often emit more than the allowed level of emissions. Vehicle emissions of high-power driving cars with and without properly functioning emission controls were quantified. High uncertainties were identified in NO_x emissions due to malfunctioning of emission controllers in cars. It was concluded that real-world emissions from cars far exceed tail-pipe emission standards. Ahn *et al.* (2002) reported that vehicular emissions contribute to about 45% of the pollutants in United States. Most of the existing models use average-link speed and ignore the transient changes in speed and acceleration. Emissions have higher degree of dependability on acceleration. The emission models, as mentioned above, incorporate link-average speed as an explanatory variable for emission prediction. However, the emission rate was reported to be more sensitive to the instantaneous speed and acceleration (Rakha *et al.*, 2003). Most of the tailpipe emission models, reported in the literature, used chassis dynamometer approach for determining emission rates (ARAI, 2007; Ropkins *et al.,* 2009; Joumard *et al.,* 1995), which are not representative of realworld traffic characteristics (as already stated). Also these studies focused on vehicles from developed countries like US, Australia and Europe (Ahn *et al.,* 2002; Frey *et al.,* 2001; Joumard *et al.,*1995). However, the vehicle characteristics (and hence emission characteristics of vehicles) in developing countries are different (Arasan and Koshi, 2005). Among several traffic characteristics, traffic speed and the modes of traffic have relatively larger influence on the emissions of pollutants (Pandian *et al.,* 2009).

In India, cars form a significant proportion (36%) of traffic (Dey *et al.*, 2008). The research in the present study was, therefore, aimed at developing such relationships between car tailpipe emissions and instantaneous speed during different acceleration and deceleration modes. Traffic fleet in India is comprised of the cars with a catalytic converter and without a catalytic converter (particularly old cars are without catalytic converters). Hence, this study also quantified the difference between emissions of car with catalytic converter and without catalytic converter. The main objectives of the study were on-board measurements of car tailpipe emissions and speed profiles, investigate effect of catalytic converter on tailpipe emissions of cars, and investigate relationship between speed, acceleration, and deceleration of vehicles with its tailpipe emissions for both types of cars, with and without catalytic converter.

2. Experimental Design and Methodology

Effects of speed and acceleration on vehicle tailpipe emission can be assessed by observing the vehicle activities at intersection and in actual traffic on roads but it is operationally difficult. Moreover, data obtained may not always be consistent and easy to analyze. This is more evident when traffic streams are heterogeneous and lane discipline is poor. At intersections and mid-block sections, slow-moving vehicles often intercept the movement of fast-moving vehicles affecting its acceleration and speed. Hence, data collected at such sections are inconsistent and difficult to analyze and interpret. Also, the vehicle operations observed at such intersections may not represent maximum/ normal operating envelope of vehicles. An alternative is to observe such event over a short road stretch and under controlled conditions as an acceptable surrogate for actual traffic (Mehmood, 2009; Rakha *et al.*, 2000). However, while selecting the road stretch for study, care should be taken that the free traffic prevails without any hindrance to speeding, accelerating and decelerating of test vehicle. Two cars were used for the study. First one, with a catalytic converter (Make – Santro make 2009 from Hyundai) and the second, without catalytic converter (Make - ECO make 2009 from Maruti-Suzuki). Detailed specifications of cars have been presented in Table 1.

2.1. Model Roadway

The criteria followed in selecting the model roadway to carry out the proposed experiments were - free-flow traffic, access controlled to avoid any obstruction to speeding, straight road geometry (to have constant effect on speed and acceleration), and good road surface condition to provide constant effect of rolling resistance. In accordance with these criteria, a straight, two lanes stretch of 1.5 km roadway was selected.

Table 1

Characteristics of Car Engine

Car Type	Engine run (km)	Max Torque at 3000 rpm, (N-m)	Max (Bhp)	Weight (lb)	Power (kW)	Power/weight hp/lb	Power/weight kW/kg
Santro	62000	96	73	2160.51	54.44	0.034	0.055
Eco	65800	101	63	2021.62	46.98	0.031	0.051

Source: (Gearheads, 2021)

2.2. Experimental Procedure

Two different instruments were used to measure the speed profile and tailpipe emissions of test vehicles. A V-Box Global Positioning System (GPS) capable of recording vehicle position and speed at 1 *Hz* (data recording once a second) was used for recording vehicle speed profile. Further, a five-gas analyzer Automotive Exhaust Monitor PEA 205, manufactured by Indus Scientific India was used for on-board measurement of tailpipe emissions of test vehicles. This device records every second emission data for CO, HC, and NO_x. The device measures emitting pollutants by volume % for CO and by parts per million (ppm) for HC and NO_x.

The drivers of the vehicles were asked to accelerate to their desired speed (maximum speed at which driver feels safe for a given road geometry and environmental condition; hereafter referred as *maximum speed*) in minimum possible time, then cruise for some time and decelerate to stop. This replicates movement of queue leaders at signalized intersection. All trips were made during free-flow traffic condition. A total of 140 such trips of test cars (70 trips of Hyundai Santro with catalytic converter and 70 trips of Maruti-Suzuki ECO without catalytic converter) were observed. Both vehicles had similar kilometers of run on road and had similar engine and loading capacity. Table 1 presents engine characteristics of these cars. This ensured the test cars had similar characteristics except catalytic converter to compare their emission and quantify the effect of catalytic converter on their emissions.

Five-gas analyzer was kept on the back seat of car with its probe inserted in the tailpipes of the test cars. V-Box was installed on the roof top of the cars to record the speed profiles. The time frame synchronization of the V-Box and five-gas analyzer data was done by the time records in observed data. The data collected contained 4138 and 4758 records (every second) of car with and without catalytic converter, respectively. The parameters recorded were the measurements for time, speed, and emissions of CO, HC and NO_x. The vehicle maximum speed varied from 23 to 28 *m/s (82.6 km/h to 100.8 km/h).* A scatter plot of the speed and time for a few trips of the test car with catalytic converter has been presented in Fig. 1, which shows that deceleration was rapid as compared to the acceleration. Also, the slope of speed - time plot during acceleration mode changes approximately at the speed of 17 m/s indicating the higher rate of change of speed with time initially, which later reduced. It was zero with time at cruise. Rate of change of speed was very high during deceleration maneuver.

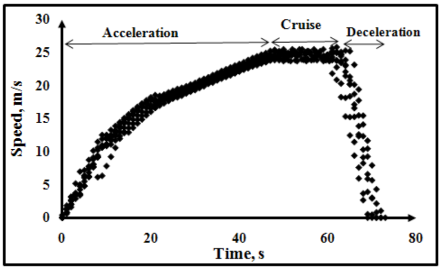

Fig. 1.
Scatter Plot of Speed-time

2.3. Calculation Methods

Vehicle acceleration and deceleration were calculated using Equation (1), (Wang *et al.*, 2004) and (2), (Wang *et al.*, 2005).

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

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

where, a and d, are the acceleration and deceleration (m/s^2), respectively, v_1 and v_2 are the speeds(m/s) at time t_1 and t_2 (s), respectively.

The speed records were averaged over a speed range of 1 *m/s* to get an idealized value of speed. Similar averaging was done for corresponding acceleration, deceleration and emission records to get their idealized values. Thus, one idealized record for speed, acceleration, deceleration and emission (for each pollutant) was obtained for every 1 *m/s* speed range. This was done to examine average behaviour of emission with speed, acceleration and deceleration. A similar procedure was adopted by Wang *et al.* (2005) for evaluating acceleration of passenger cars at stop-controlled intersections. The maximum acceleration was 2.035 m/s^2 and the idealized maximum acceleration was 1.63 m/s^2. Similarly, the maximum deceleration observed was 3.96 m/s^2 and idealized maximum deceleration was found to be 3.79 m/s^2. These values of acceleration and deceleration (average and maximum, both) agree with other researchers

(Wang *et al.*, 2004; Wang *et al.*, 2005; Maurya and Bokare, 2012).

3. Results of the Field Experiment

The results have been analyzed to develop relationships among various parameters. For example, a comparison of acceleration and deceleration (A/D) data observed in this study has been done with the results of the past studies. Further, speed data observed in this study has been compared with the speed of driving cycles of similar nature and the effect of speed, A/D and catalytic converter on tailpipe emissions is quantified.

3.1. Acceleration and Deceleration Behavior of Car

The idealized acceleration and deceleration have been plotted with speed, as shown in Fig. 2.

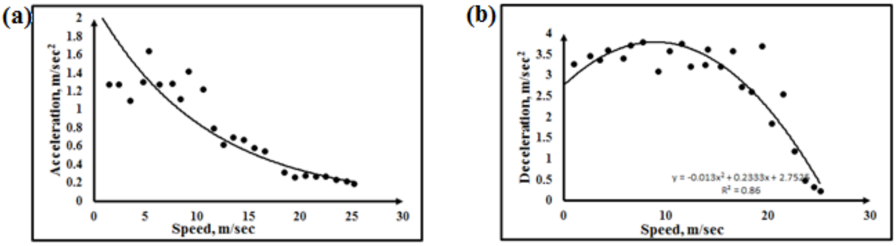

Fig. 2.
Idealized Plot of (a) Speed-acceleration (b) Speed-deceleration

It was observed that both acceleration and deceleration vary non-linearly with speed. The acceleration was more at the beginning of acceleration manoeuvre (i.e., when speed is low) and gradually decreased as the acceleration manoeuvre advanced (i.e. speed increases). It was observed that acceleration of car decreased exponentially with the increase in speed. Some researchers have reported that initially acceleration is less, and it quickly increases (Akcelik and Biggs, 1987; Bham and Benekohal, 2002). The results of this study did not support this observation, since the data were recorded at 1 sec frequency and the lower acceleration might have occurred before 1 sec. At the beginning of acceleration manoeuvre, drivers tend to use high rate of change of speed (acceleration) but as they approach the cruise speed, they reduce the rate of change of speed in a bid to achieve cruising speed, where rate of change of speed (acceleration) is minimum. Hence, accelerations were less at the end of acceleration manoeuvres as compared to the beginning of it. Similar observation was made by other researchers (Wang *et al.*, 2004; Rakha *et al.*, 2003; Akcelik and Biggs, 1987; Bham and Benekohal, 2002; Ackelik and Besley, 2002).

The deceleration behaviour of vehicles is also nonlinear with speed (second-order polynomial) but was different as compared to acceleration behaviour. In the beginning of the deceleration manoeuvre, indicated by high speed, the decelerations were low. As the driver approached to stop (lower speed), the decelerations were high. This is because at lower speed, drivers feel safe even applying higher deceleration to stop.

But towards the end of the deceleration manoeuvre, the drivers again reduced the deceleration rate. Similar observations were made by other researchers (Maurya and Bokare, 2012; Wang *et al.*, 2004; Akcelik and Biggs, 1987). Since acceleration/deceleration varied with speed and many researchers reported that tail-pipe emissions are sensitive to speed (Rakha *et al.*, 2003; Frey *et al.*, 2001; Joumard *et al.*, 1995) the results of the study were logical in inferring that tailpipe emissions were also sensitive to acceleration/deceleration.

3.2. Speed versus Driving Cycles for a Car with Catalytic Converter

Further, to compare real-world speed profile of the test car with catalytic converter and driving cycle speed profile, the speed profile obtained in present study was compared with the speed profile of Highway Fuel Economy Driving Schedule (HWFET), (US EPA, 2011) which represents highway driving schedules under 60 mph (26 *m/s*) speed, obtained by US Environmental Protection Agency (US EPA), dynamometer driving experiment. This schedule was selected since the maximum speed in this schedule matched with the maximum speed observed in this study. Kolmogorov – Smirnoff (k-s test) (Freund *et al.*, 2011) two sample test was used to compare the distributions of the speed values of the present study and speed values in HWFET. The null hypothesis was that both speed data are from the same continuous distribution whereas the alternative hypothesis was that they were from different continuous distributions. The computed *h* value by (using k-s test) was 1, indicating that the null hypothesis was rejected at 5% significance level. The speeds from two data sets were not from the same continuous distribution.

The cumulative frequency distribution of speed and acceleration for observed speed and HWFET speed has been presented in Figure 3 and the summary statistics for speed and acceleration, for both data sets (data from present study and HWFET), have been presented in Table 2.

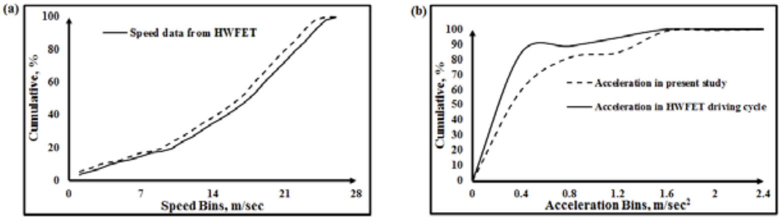

Fig. 3.

Cumulative Frequency Distribution, (a) HWFET Speed Profile and Speed Profile in Present Study (b) HWFET Acceleration Profile and Acceleration Profile in Present Study

Table 2
Statistical Comparison of Speed and Acceleration with HWFET

Parameter	Speed Data from HWFET	Speed Data from Present Study	Acceleration Data from HWFET	Acceleration Data from Present Study
Mean	18.23	15.81	0.27	0.53
Standard Deviation	4.63	6.93	0.35	0.43
kurtosis	3.90	-0.46	4.31	1.11
skewness	-1.91	-0.71	2.24	1.44

It was observed that the two data sets were from different populations, which indicated that EPA HWFET driving cycle did not match with traffic speed profile observed in this study. This is because the HWFET did not account for real traffic episodes such as creeping, acceleration, gear change, cruising and deceleration.

Hence, the chassis dynamometer studies (based on EPA driving cycle) in general fail to represent real-traffic conditions. Similar views were also reported by Frey *et al.* (2001) and Unal *et al.* (2004). Therefore, this study was mainly focused on the relationships of emission with speed, and acceleration and deceleration for the conditions replicating the queue leader on roads and at signalized intersections.

3.3. Effect of Speed, Acceleration and Deceleration on Tailpipe Emission

The effect of various traffic characteristics like speed, acceleration, and deceleration on tailpipe emissions of cars has been examined. Initially, the direct relationship between speed (without giving any consideration to acceleration or deceleration level) and emission was probed. Then the relationship between speed and emission at a particular acceleration level was investigated.

3.4. Effect of Speed and Acceleration on Emission

Figure 4 shows the effect of speed variation on tailpipe emission of the test car with catalytic converter.

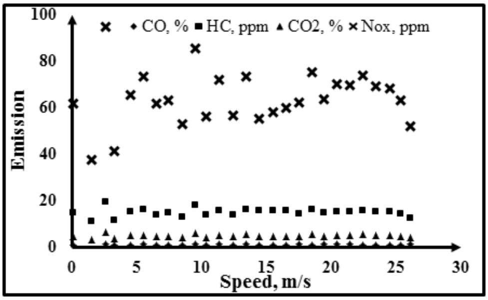

Fig. 4.
Effect of Speed on Tailpipe Emission

No consistent relationship or significant variation between car speed and tailpipe emission was observed. Similar observation was made by other researchers (Ahn *et al.*, 2002; Rakha *et al.*, 2000). It is because these speeds were mixed with acceleration i.e. similar speed at different acceleration levels. A similar attempt was made for the speeds and emissions of the car without catalytic converter but no consistent relationship was observed. For similar average speed the emission rates were different. Hence the way in which the test car reaches a specific speed is also important to understand the dependency of emissions on speed, which will improve the emissions further. For that vehicle-operating conditions should also be taken into account. Also, it is reported by Joumard *et al.* (1995) that at the given engine input, a slow moving vehicle accelerates at a higher rate than a fast moving vehicle. Hence, the dependency of emissions on acceleration and deceleration was further examined.

Speeds were arranged as per the acceleration range to find its relationship with the pollutant emissions for a specific acceleration range. For example, the speed and emissions at acceleration level ≈ 1.0 m/s^2 were segregated and the relationship between speed and emission was tested again. It was found that at similar acceleration range, speeds and tailpipe emissions manifested a prominent relationship. Therefore, the speed and emission relationships were developed for acceleration ranges like a ≈ 1 m/s^2, a ≈ 1.6 m/s^2 (where, 'a' is acceleration in m/s^2). Figure 5(a), 5(b) and 5(c) show the relationship of CO, HC and NO_x emission rates with speeds at two different acceleration levels (a ≈ 1 m/s^2, a ≈ 1.6 m/s^2) for the test car fitted with catalytic converter.

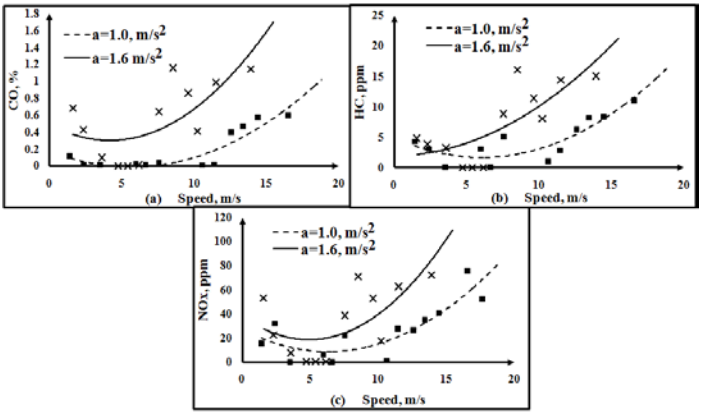

Fig. 5.
Effect of Speed and Acceleration on Tailpipe Emission of Car Fitted With Catalytic Converter

It was observed that the tailpipe emission rate was high at lower speed which gradually lowered with the increase in speed. After attaining the lowest value, emission rate started increasing with further increase in speed. Similar, trend was observed for all the pollutants CO, HC and NO_x. This is because, at lower speed, the engine exerts more power (in first or second gear, speed 0-3 *m/s*) with more consumption of fuel. Since, emission is directly proportional to fuel consumption, resulting in high tailpipe emissions. As vehicle speed advances (in second or third gear, speed 3 to 6 *m/s*) the power goes on reducing and hence the fuel requirement of engine goes on reducing, which results in reduced tailpipe emissions. However, with further increase in speed (in fourth or fifth gear, speed above 6 *m/s*) engine consumes more fuel for achieving higher speed, which results in increase in tailpipe emission. A similar observation was also reported by earlier researchers (Frey *et al.*, 2001; Unal *et al.*, 2004; Ahn *et al.,* 2002; Rakha *et al.*, 2000).

The lowest tailpipe emission rate was observed at the speed range of 3 to 6 *m/s* as shown in Figure 5 at average acceleration rate of ≈ 1 m/s^2 for tailpipe emissions of all the pollutants (CO, HC and NO_x). However, a consistent speed range for lowest tailpipe emission was not observed at high acceleration rate of 1.6 m/s^2. Similar analysis was carried out for the car without catalytic converter at similar acceleration level (like $a \approx 1\ m/s^2$, $a \approx 1.6\ m/s^2$). The resulting plots have been shown in Figure 6 (a, b, c).

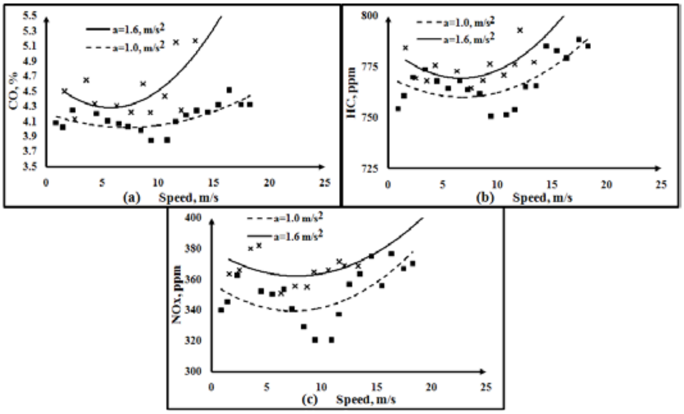

Fig. 6.
Effect of Speed and Acceleration on Tailpipe Emission of Car without Catalytic Converter

Figures 6(a), 6(b) and 6(c) show that the emissions pattern of car without catalytic converter was like the car with catalytic converter. The emissions were somewhat higher initially and gradually decreased and then increased with further increase in speed. A similar pattern of emissions was also reported by Rakha *et al.*(2003).

3.5. Effect of Catalytic Converter

On comparison of Figure 5 (a, b and c) and Figure 6 (a, b and c), it can be observed that CO, HC and NO_x emissions are significantly higher for the car without catalytic converter than the car with catalytic converter. Joumard *et al.* (1995) also reported that the CO and HC increased when the catalytic converter was not used. Table 3(a) and Table 3(b) present average tailpipe emissions at different speed ranges and acceleration levels for car with and without catalytic converter. It was observed that average emissions rates for cars without catalytic converter were significantly higher as compared to cars with catalytic converter.

Table 3
Average Tailpipe Emission Rate at Different Speeds and Accelerations
(a) For Car Fitted with Catalytic Converter

Speed Range (*m/s*)	CO (*%*)		HC (*ppm*)		NO_x (*ppm*)	
	a≈1.0 m/s^2	a≈1.6 m/s^2	a≈1.0 m/s^2	a≈1.6m/s^2	a≈1.0 m/s^2	a≈1.6 m/s^2
0-3	0.043	0.400	2.4	3.92	15.66	27.53
3-6	0.006	0.008	1.0	1.06	2.0	2.46
above 6	0.290	0.865	5.29	10.49	31.08	44.77

(b) For Car without Catalytic Converter

Speed Range (*m/s*)	CO (*%*)		HC (*ppm*)		NO_x (*ppm*)	
	a≈1.0 m/s^2	a≈1.6 m/s^2	a≈1.0 m/s^2	a≈1.6m/s^2	a≈1.0 m/s^2	a≈1.6 m/s^2
0-3	4.11	4.42	764	773	349	369
3-10	4.012	4.39	762	770	337	364
above 10	4.27	4.75	772	779	357	368

Table 3(a) and Table 3(b) also show that there was a significant variation in tailpipe emission rate with different combination of speed range and acceleration. Lowest emission rate was observed in speed range of 3 - 6 m/s and effect of acceleration on tailpipe emissions was more prominent at higher speeds. At higher speed range, tailpipe emission rates of all the pollutants, i.e., CO (%), HC (ppm) and NO_x (ppm) were substantially high for acceleration 1.6 m/s^2 than for acceleration 1.0 m/s^2, as shown in Table 3 (a). This reasonably demonstrates the importance of effect of both speed and acceleration on tailpipe emission rates. Similar conclusions can also be made for car without catalytic converter as shown in Table 3(b). However, the speed range in which the emissions were lowest was 3-10 *m/s* as compared to speed range of 3-6 *m/s* in case of car with catalytic converter. Another difference was in the magnitude of emissions. The emissions in car without catalytic converter were significantly higher than the car with catalytic converter.

3.6. Effect of Deceleration

To examine if the emissions were different in deceleration mode as compared to acceleration mode, speed during deceleration were separated from the speed data set. The speeds and emissions were then averaged over 1 *m/s* speed interval. The speeds and emissions data were segregated at different average deceleration levels. No consistent relationship between speed and emission at a particular deceleration level was observed. This may be due to the fact that during deceleration process, driver behavior is not as consistent as in acceleration process, i.e. they change the gears in inconsistence manner. Sometimes, driver changes the gear from top gear to lowest gear in one step by applying the clutch and brake simultaneously during entire deceleration process, while in other case gears might be changed in sequence. During acceleration process, drivers generally change the gear from lowest to highest in sequential manner. Further, when driver applies clutch along with the brake during entire deceleration process, application of clutch detaches engine from system (i.e. vehicle does not draw power from engine) which resulted reduction in fuel consumption, over which emission depends. Hence, during deceleration, the emission does not show any consistence relationship with the speed and deceleration.

4. Statistical Emission Model

Regression model for the relationship between speeds and pollutant emissions at a particular acceleration level has been developed. Linear, second order and third-order polynomials were tested to explain the dependency of emissions on speeds at a particular acceleration level. The criterion applied to choose the best fitting model was the one having lowest Residual Sum of Square (RSS), (Freund *et al.*, 2011). A second-order polynomial, as given in Equation 3, was found to be suitable for explaining dependence of emission on the speed.

$$e = k_1 \times v^2 + k_2 \times v + k_3 \tag{3}$$

where, e is the emission rate (CO (%), HC (ppm), NO_x (ppm)), v the instantaneous speed of vehicle in m/s and k_1, k_2 and k_3 are the model parameters. The observed speed and emission data were used to calibrate the model, the parameters of which are presented in Table 4.

Table 4

Model Parameters for Emissions at Different Acceleration Levels

(a) For Car Fitted with Catalytic Converter

Emission	Acceleration	Model Parameters			r^2
		k_1	k_2	k_3	
CO	1.0 m/s^2	0.006	-0.067	0.172	0.84
	1.6 m/s^2	0.010	-0.091	0.486	0.49
HC	1.0 m/s^2	0.090	-1.094	4.901	0.76
	1.6 m/s^2	0.078	**+0.028**	1.914	0.603
NO_x	1.0 m/s^2	0.468	-5.91	26.87	0.73
	1.6 m/s^2	0.809	-7.985	38.243	0.44

(b) For Car without Catalytic Converter

Emission	Acceleration	Model Parameters			r^2
		k_1	k_2	k_3	
CO	1.0 m/s^2	0.003	-0.050	4.20	0.54
	1.6 m/s^2	0.012	-0.142	4.68	0.39
HC	1.0 m/s^2	0.210	-3.006	770.11	0.53
	1.6 m/s^2	0.349	-4.66	785.02	0.359
NO_x	1.0 m/s^2	0.328	-4.91	357.63	0.45
	1.6 m/s^2	0.288	-4.47	379.23	0.15

The r^2 values produced by the model with the pollutant emission data were satisfactory and acceptable. For example, r^2 values were 0.84, 0.76 and 0.73 for CO, HC and NO_x, respectively (see Table 4 (a)) for the test car with catalytic converter, at the acceleration rate ≈ 1 m/s^2. However, for acceleration rate, a≈ 1.6 m/s^2, the model did not fit well. Similarly, for the car without catalytic converter (see Table 4 (b)), the model fitted well at the acceleration rate, a≈1 m/s^2 than at acceleration rate, a≈ 1.6 m/s^2.

4.1. Model Diagnostic

Paired *t* test was used to test the means of the observed and the predicted emissions using the model. Two hypotheses were tested – (i) null hypothesis: $\mu = \mu_o - \mu_m = 0$ where μ_o and μ_m were mean of observed and predicted emissions and (ii) alternate hypothesis: $\mu \neq 0$. The test statistic was calculated by Eq. 4 (Freund *et al.*, 2011).

$$t = \frac{\bar{\mu}}{s_d/\sqrt{n}} \tag{4}$$

where, $\bar{\mu}$ is the mean of difference between observed and predicted emission, S_d the standard deviation of difference in paired data and n is the number of data points. Hypothesis is tested for 95% confidence interval ($\alpha = 0.05$, where α is the significance level) in which null hypothesis was rejected for the condition $|t| \geq t_{\alpha/2}$. Table 5 presents values of *t*-statistics and $t_{\alpha/2}$.

Table 5

Results of Paired T-Test

Car Fitted with Catalytic Converter

a=1.0 m/s²				a=1.6 m/s²		
	|t|	$t_{\alpha/2}$	Remark	|t|	$t_{\alpha/2}$	Remark
CO	0.12	2.20	Null hypothesis cannot be rejected	0.63	2.20	Null hypothesis cannot be rejected
HC	0.04	2.20	Null hypothesis cannot be rejected	0.03	2.20	Null hypothesis cannot be rejected
NO_x	0.02	2.20	Null hypothesis cannot be rejected	0.15	2.20	Null hypothesis cannot be rejected

Car without Catalytic Converter

	a=1.0 m/s²			a=1.6 m/s²		
	|t|	$t_{\alpha/2}$	Remark	|t|	$t_{\alpha/2}$	Remark
CO	1.95	2.10	Null hypothesis cannot be rejected	0.37	2.20	Null hypothesis cannot be rejected
HC	1.12	2.10	Null hypothesis cannot be rejected	4.55	2.20	Null hypothesis cannot be accepted
NO_x	0.005	2.10	Null hypothesis cannot be rejected	4.68	2.20	Null hypothesis cannot be accepted

It was observed that the null hypothesis *i.e.* difference between means of observed and predicted values of emissions is zero, was true for CO but not for HC and NO_x emissions in car without catalytic converter at acceleration rate, a≈ 1.6 m/s^2. This indicated that the proposed model was not suitable to predict emissions of HC and NO_x in the car without catalytic converter at acceleration rate, a≈ 1.6 m/s^2. This reinforced the earlier observation that the model does not describe relationship of speed and emissions at higher acceleration level for cars without catalytic converter.

Further, Fisher's Least Significance Difference (LSD) test (Freund *et al.*, 2011) was also used to examine the error in predicted values. LSD method performs a *t* test for pair of means using Within Mean Square (MSW) as an estimate of standard deviation. It computes minimum difference at some desired significance level (generally 5%). This difference is known as LSD and is computed by Eq. 5.

$$LSD = t_{\alpha/2}\sqrt{\frac{2 \text{ x MSW}}{n}} \qquad (5)$$

where, *LSD* is the least significance difference, $t_{\alpha/2}$is$\alpha/2$ tail probability value from *t-distribution* and degrees of freedom, *n-1, n*is the number observations, and MSW is the WithinMean Square.

LSD declares as significantly different pair of means for which difference between sample means exceeds the LSD value. Table 6 presents the LSD values for the test cars with and without catalytic converter.

Table 6

Results of LSD Test

Car Fitted with Catalytic Converter

a=1.0 m/s²	1	2	3	4	5
	Mean of Observed Emission	Mean of Predicted Emission	Difference in Means (1)~(2)	LSD	Remark
CO	4.14	4.08	0.06	0.12	LSD>Difference
HC	350.64	350.62	0.02	8.96	LSD>Difference
NO_x	768.57	766.57	2.00	13.13	LSD>Difference
a=1.6 m/s²					
CO	4.49	4.46	0.03	0.25	LSD>Difference
HC	774	785	11	4.77	***LSD<Difference***
NO_x	366.08	379.11	13.03	5.76	***LSD<Difference***

Car without Catalytic Converter

a=1.0 m/s²					
	Mean of Observed Emission	Mean of Predicted Emission	Difference in Means (1)~(2)	LSD	
CO	0.18	0.17	0.01	0.17	LSD>Difference
HC	4.37	4.35	0.02	2.58	LSD>Difference
NO_x	25.59	25.65	0.06	17.81	LSD>Difference
a=1.6 m/s²					
CO	0.53	0.47	0.06	0.31	LSD>Difference
HC	7.10	7.07	0.03	4.82	LSD>Difference
NO_x	29.45	28.40	1.05	17.78	LSD>Difference

It was observed that the difference in mean of the observed and predicted values was less than the LSD values for all the pollutants at both acceleration levels (a≈ 1.0m/s^2anda≈ 1.6 m/s^2) for the test car with catalytic converter. However, for car without catalytic converter at acceleration 1.6 m/s^2, the difference (for HC and NO_x) was greater than LSD, indicating that model did not estimate HC and NOx well at higher acceleration level for cars without catalytic converter.

5. Conclusions

In this study, an attempt has been made to examine the effects of driving modes - speed, acceleration, and deceleration on tailpipe emission of cars with and without catalytic converter. The study developed a second-order polynomial model dependent on speed to estimate tailpipe emissions. The maximum acceleration was found to be 2.035 m/s^2 with an average value of 1.63 m/s^2 and the maximum deceleration was found to be 3.96 m/s^2 with an average value of 3.76 m/s^2. Results revealed that the variation of average (idealized) acceleration and deceleration with speed was nonlinear, for example, negative exponential for acceleration and second-order polynomial for deceleration.

Further, the tailpipe emission rates varied prominently with the speed at a particular acceleration. The emissions initially decreased when the speed was increased,then increased with the further increase in speed. Emissions of the pollutants varied over a range of speed. The range of speed observed was, 0-3 m/s (at $a \approx 1\ m/s^2$) corresponded the high initial emissions, 3-6 m/s for lowest emissions in the middle of acceleration maneuver and 6 m/s and above for maximum emissions in the end of maneuver. For higher acceleration , a consistant speed range for emission variation was not observed.

The results are promising and could be improved further by testing variety of cars and road types.

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