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Acceleration-Deceleration Behaviour of Various Vehicle Types

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Abstract

Acceleration/deceleration (A/D) behaviour of vehicles is important for various applications like length of yellow light at intersection, determination of sight distances at intersection, determination of length of A/D lanes, ramp design, traffic simulation modelling, vehicular emission modelling, instantaneous fuel consumption rate modelling, etc. Literature reports A/D studies for cars in lane disciplined homogeneous traffic. However, Indian traffic stream is weak lane disciplined and heterogenous, containing various vehicle types like truck, motorized three and two wheeler and diesel and petrol driven cars. Also, the reported studies are based on out of date data, collected using traditional and less accurate methods. Hence, this work aims to study the A/D behaviour of various vehicle types using modern instruments like Global Positioning System (GPS) in controlled manner including maximum A/D envelop.

It is observed that acceleration rates of vehicles observed in this study, differed from acceleration rates reported in literature. On finding existing acceleration models insufficient to explain the acceleration behaviour of vehicles observed in this study, new models have been proposed and validated using statistical tools. Acceleration behaviour of cars varied with the change in gears, though the pattern remained similar in all gears.

Keywords: Acceleration; Deceleration; Dual Regime Models; Statistical Modelling.

1. Introduction

Vehicle acceleration/deceleration (A/D) behaviour has significant impact on several traffic related factors like intersection design, deceleration lane design, ramp design, traffic simulation modelling, vehicular emission modelling, instantaneous fuel consumption rate modelling etc.

At signalized intersections, vehicles decelerate, stop, queue up (during red signal) and then accelerate during green and amber signal. The way vehicles decelerate, stop, crawl in queue, and accelerate to leave the intersection depends on number of factors such as, individual vehicle type, driver behaviour, number and type of vehicles at intersection

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etc. Stronger accelerations may be applied by vehicles with high A/D capability (like cars) to clear the intersection during amber and green phases. Aggressive or young drivers may also showcase similar behaviour.

In India (and in many Asian countries) the traffic is heterogenous (having vehicles with varying size, A/D capabilities and weight to power ratios, sharing same right of way) and weak lane disciplined. Hence, at signalized intersection, the movement of vehicles with high acceleration capability, like car, is restricted by presence of vehicles with low acceleration capability like motorized three wheelers, trucks etc. Therefore, to model such phenomena and to understand the effect of such restricted movements on design of duration of red, green and amber at signal intersection, fuel consumption and tailpipe emission, the precise knowledge of A/D behaviour of these vehicles is needed. Many other authors, (like AASHTO, 2011; Searle, 1999; Snare, 2002; Akcelik and Biggs, 1987; Rakha et al., 2001; Haas et al., 2004) also stated the importance of modelling A/D.

In past, A/D profile models are developed for different applications. Most of the A/D models reported in literature refer maximum acceleration capabilities of vehicles. Experimental reports indicate that vehicle drivers use maximum A/D capabilities at intersection and in the incidence of crash. Acceleration rate most frequently occurring at signalized intersection depends on, vehicle characteristics, geometry of intersection, nature and extent of hindrance to A/D of subject vehicle, driver attitude to speeding, etc. (Long, 2000). Due to numerous such factors influencing A/D of vehicles, less number of studies are available in this area (Snare, 2002; Fildes, 1991). Hence, there is a great need to study A/D behaviour of various vehicle types.

Furthermore, most of the existing models are based on outdated and limited data (for example - Bham and Benekohal (2002) model uses 1985 data, Akcelik and Biggs (1987) uses data prior to 1987, etc.) which are insufficient to describe the A/D behavior of current fleet of modern vehicles behaviour of drivers driving these modern vehicles. Many researchers (Searle, 1999; Gattis et al., 2010; RaiChowdhury and Rao, 1989; Bennet and Dunn, 1995; Dey and Biswas, 2011; Arasan and Koshy, 2005) used traditional methods for vehicle's speed measurements which may not provide precise speed measurement. In few recent studies, like Wang et al. (2004), GPS is used to measure the vehicle's speed and acceleration accurately.

Though, deceleration rate is an important input for duration of amber light at signalized intersection, limited work (Akcelik and Biggs, 1987; Bennet and Dunn, 1995; Wang et al., 2005)) is reported in the past on deceleration modelling of vehicles in comparison to acceleration modelling. Bennet and Dunn (1995) reported second order polynomial deceleration model for vehicles in New Zealand. With rapid change in engine technology and new generation drivers taking seat of older ones, it has become imperative to have a fresh look at the A/D behaviour.

1.1. Problem Statement

After an extensive review of literature related to A/D, it is found that

1. Some of the reported studies (Akcelik and Biggs, 1987; Bham and Benekohal, 2002) formulated acceleration models based on old data sets (of 1968 and 1985). The vehicle technology and driver response to control devices have changed since then.
2. Most of the existing A/D models are developed for a particular vehicle type (passenger car). In India however, the traffic stream consists of vehicles differing in size and shape and weight to power ratio (engine characteristics), (Arasan and Koshy, 2005). Their share in traffic stream is 36.5%, 19%, 6.8% and 16.5% respectively for truck, car, motorized three and two wheeler (Dey et al., 2008).
3. Limited studies (Dey et al., 2008; RaiChowdhury and Rao, 1989) related to acceleration behaviour for Indian traffic streams are found in literature. In these studies, speed data are collected using manual measurement of travel time to traverse a fixed distance. This method limits scope of experiment to get complete acceleration profile of vehicle.

Therefore, present study aims at

1. collecting data on using modern devices (Global Positioning System)
2. developing A/D models for various vehicle types plying on Indian roads.

2. Experimental Methods

To study the A/D behaviour of a vehicle one needs to observe the speed and position data of vehicle with time. Vehicle approaching to a signalized intersection has to decelerate and stop during red phase of signal and has to accelerate at the onset of green phase. Figure 1 presents the time-distance and speed-time diagram of a vehicle movement at signalized intersection showing cruising, deceleration, stopping, acceleration and cruising stages of a vehicle at signalized intersection. Therefore, data on A/D pattern of vehicles can be well collected by observing the vehicle

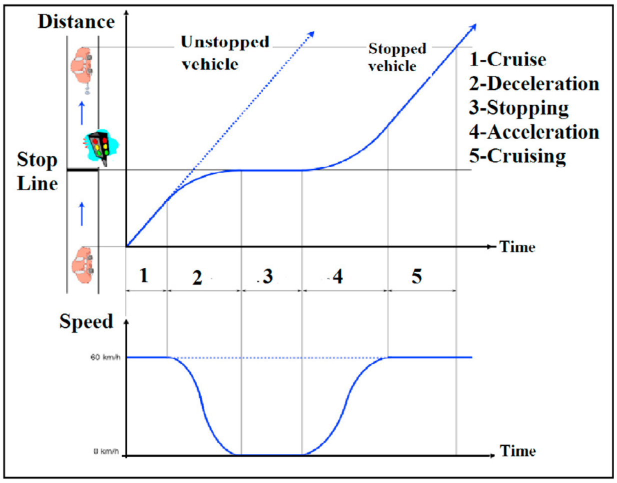


FIGURE 1 : Time-distance and speed-time diagrams showing the deceleration, waiting and acceleration manoeuver of a vehicle at signalized intersection.

movement at signalized intersection. However, heterogeneous and weak lane disciplined traffic at intersection in India often results in data that is inconsistent (in A/D manoeuver) and difficult to analyze. At signalized intersections, 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 (see Figure 2 showing a typical scenario at intersection).

FIGURE 2 : A photograph showing heterogeneity and congestion condition in front of the queues at urban signalized intersection at Nagpur, India)

The congestion condition at the front of queues can be seen from the Figure 2, which leads to inconsistent A/D behaviour of vehicles. Therefore, an alternative is, to observe driver behaviour over short stretch and under controlled conditions (replicating signalized intersection lead vehicle acceleration-deceleration) as an acceptable surrogate for actual behaviour. Such alternative procedures are also used by earlier researchers like Mehmood (2009); Carcary and Murray (2001); West et al. (1993); Belz and Aultman-Hall (2011); El-Shawarby et al. (2011); Rakha and Ding (2003). Therefore, the present study also collected the vehicle A/D data over selected stretch of road under controlled conditions, replicating lead vehicles at signalized intersection.

2.1. Data Collection

Road stretches for the study were so selected that vehicle travels under free flow traffic. Selected stretch of road is access controlled so that there is no obstruction to speeding. Road geometry is fairly straight to have constant effect of geometry on A/D and entire road surface is smooth to ensure constant effect of rolling resistance.

Accordingly, the study was conducted on 1.5 *km* stretch of a two lane Nagpur-Mumbai Highway on outskirts of Wardha Town,(about 70 *km* from Nagpur (India)) which satisfies above mentioned conditions. All vehicle types (like truck, car, motorized three-wheeler and motorized two-wheeler) are observed plying over this facility. GPS device with 1 *Hz* data logging capacity (data logged once in a second) is used to collect speed and position data of vehicles.

Most of the cars plying on this road are owner driven. They did not allow the volunteers to board the car and collect data using GPS device. Hence data collection of cars is undertaken at a link road joining Indian Institute of Technology Guwahati, India and National Highway No. 37 in India. Hired cars were used for experimentation. V-Box device, capable of logging data at 10 Hz. frequency was used for data collection. A similar device could not be used for other vehicle types since this device requires more time to install its antennae.

All the drivers were asked to speed up their vehicles from stop condition to achieve their desired speed (maximum speed at which driver feel safe for a given road geometry and environmental condition; hereafter referred as maximum speed) as early as possible. After allowing them to cruise at the maximum speed for some time, they were asked to decelerate to stop condition in shortest possible time (Snare, 2002). This replicated movement of queue leaders at signalized intersection.

Further, free flow speeds of uninterrupted vehicles/drivers (who were plying on study stretch and not participated in this study) were also measured using radar gun. Measured free flow speed of uninterrupted vehicles were found comparable (at 5% significance level) to maximum speed of participating vehicles (recorded using GPS). This indicates that the maximum speed data obtained in controlled experiment was not biased.

2.2. Analysis Methods

Position and speed data of different vehicles were collected using GPS during the designed experiment (i.e. acceleration, cruising and deceleration). All experiments (trips) were made during free flow traffic condition. Exponential smoothing algorithm was used for smoothing of GPS data, (Rakha et al., 2004). Following steps were used in analysis of collected GPS data for A/D study:

1. Acceleration was computed from second by second GPS speed data collected during acceleration manoeuver data, using Equation 1:

$$a_{t2} = \frac{v_2 - v_1}{t_2 - t_1} \tag{1}$$

   where, a_{t2} is acceleration at time t_2 and v_1 and v_2 are the speeds at time t_1 and t_2 respectively. It is assumed that acceleration process ended when the increment in speed between two successive data points is less than 0.1 m/s, for next five seconds (Wang et al., 2004).
2. Similar to acceleration calculation, deceleration was computed from second by second speed data obtained from GPS during deceleration manoeuver using Equation 2:

$$d_{t2} = \frac{v_1 - v_2}{t_2 - t_1} \tag{2}$$

where, d_{t2} is deceleration at time t_2 and v_1 and v_2 are the speeds at time t_1 and t_2 respectively. Starting of deceleration process was defined from the time onwards where deceleration values calculated from Equation 2 are greater or equal to 0.1 m/s^2 for five consecutive seconds (Wang et al., 2005). At the end of deceleration process vehicle speed become zero.

3. For all vehicle classes, speeds were averaged over every second. The average speed profile so obtained was termed as *idealized speed profile*.
4. For A/D behaviour modelling, idealized A/D - speed data were obtained by averaging A/D values over 1 m/s speed interval for each vehicle class. This idealized A/D - speed data is used to develop the A/D model.
5. Developed A/D models were evaluated using various statistical methods.

Summary of data collected (*i.e.* number of trips and number of data points for each vehicle type along with their weight to horsepower ratio) is presented in Table 1. It can be observed from the Table 1 that number of data points

TABLE 1 : Number of trips and data points collected for various vehicle types

Serial No	Type of vehicle	Weight to horsepower Ratio lb/hp^*	No. of trips**	
			Acceleration	Deceleration
1	Trucks	300 (183)	114(3231)	42(902)
2	Motorized three wheeler	100 (61)	116(3159)	67(1740)
3	Motorized two wheeler	31 (18.91)	59(1050)	29(594)
4	Car			
	• Diesel car	33 (20.13)	110(43862)	53(3982)
	• Petrol car	30 (18.3)	115(50152)	75(5808)

*In bracket kg/kW
**Figures in bracket are number of data points

for cars (petrol and diesel, both) are significantly higher than number of data points collected for other vehicles. This was due to higher frequency (i.e. 10 Hz) of data logging in V-Box.

Analysis results of collected field data are presented in next section.

3. Data Analysis

Figure 3 presents speed profiles (speed-time scatter) of vehicles during acceleration maneuver.

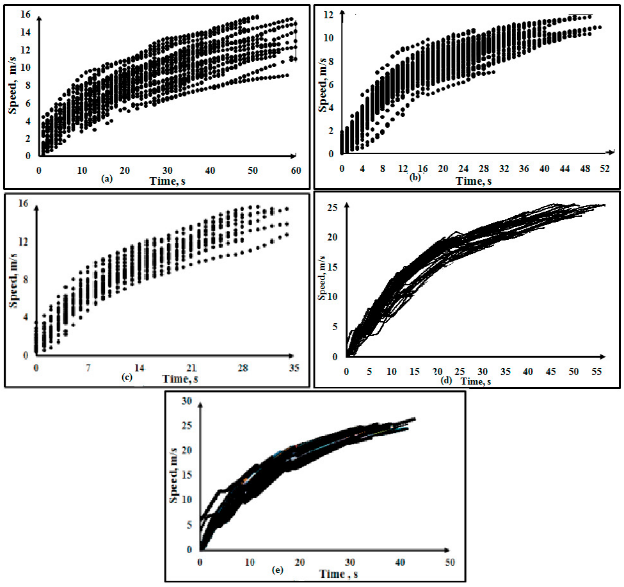


FIGURE 3 : Speed profiles of various vehicle types (a) Truck (b) Motorized three wheeler (c) Motorized two wheeler (d) Diesel car (e) Petrol car, during acceleration manoeuver

It is observed from Figure 3 that the time to achieve maximum speed varies with vehicle type and driver. Slope of speed time scatter is more in the beginning of acceleration maneuver and less at the end of acceleration maneuver. This indicates higher acceleration at the beginning of acceleration maneuver and lower accelerations at the end of acceleration maneuvers.

Figure 4 presents speed profiles (speed-time scatter) of vehicles during deceleration maneuver.

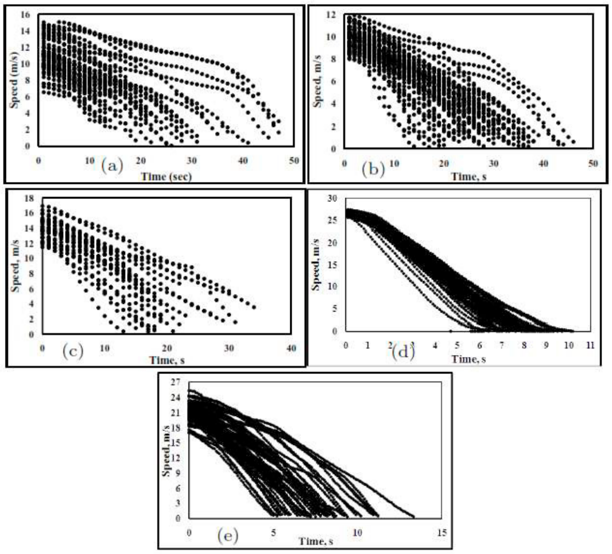


FIGURE 4 : Speed profiles of various vehicle types(a) Truck (b) Motorized three wheeler (c) Motorized two wheeler (d) Diesel car (e) Petrol car, during deceleration manoeuver

Figure 4 indicates that the deceleration time varies with vehicle type, driver and speed at which driver starts decelerating (**approach speed**). Vehicles having lower weight to horse power ratio take lesser time to complete deceleration maneuver. However, unlike Bennet and Dunn (1995) and Wang et al. (2005) no relationship between approach speed and deceleration time is observed in this study. The reason is that the rate of deceleration depends on many other factors like available deceleration space at intersection, vehicles' capacity to decelerate etc. rather than approach speed. Some authors like Samuels and Jarvis (1978); Bennet and Dunn (1995) and Wang et al. (2005) reported that the A/D parameters like, A/D time and distance, maximum and mean A/D rates and speed at maximum A/D (referred hereafter as **critical speed**) on maximum speed of trip. Therefore, the trips are segregated as per their maximum speed range and A/D parameters are evaluated within each range of maximum speed.

3.1. Acceleration Parameters

Table 2 presents these parameters during acceleration manoeuver for all vehicle types.

TABLE 2 : Various parameters corresponding to different maximum speed ranges of all vehicle classes during acceleration manoeuver

Vehicle Type	Max. Speed Range km/h (m/s)	Accel. Time (sec)	Accel. Distance (m)	Critical Speed* (m/s)	Max. Accel. Rate (m/s^2)	Mean Accel. Rate (m/s^2)
Truck	20-30 (5.55-8.33)	11	56.98	2.77	0.75	0.28
	30-40 (8.33-11.11)	17	98.26	1.53	1.00	0.29
	40-50 (11.11-13.89)	34	259.08	1.27	0.96	0.24
	50-60 (13.89-16.67)	35	361.20	1.08	0.87	0.24
Motorized three wheeler	15-25 (4.17-6.94)	27	94.50	2.04	0.54	0.21
	25-32 (6.94-8.88)	36	156.24	2.30	0.45	0.22
	32-36 (8.88-10.0)	40	220.80	1.53	0.60	0.22
	36-43 (10.0-11.94)	50	308.50	2.53	0.64	0.20
Motorized two wheeler	30-40 (8.39-11.11)	22	167.24	4.21	0.94	0.47
	40-50 (11.11-13.89)	34	337.68	3.27	1.08	0.39
	50-60 (13.89-16.67)	35	374.80	3.97	1.96	0.52
Diesel Car	68-76 (18.88-21.11)	34.80	519.18	1.46	1.89	0.55
	76-84 (21.11-23.33)	45.70	766.22	1.34	2.23	0.47
	84-92 (23.33-25.55)	52.50	923.64	1.21	1.97	0.52
Petrol Car	80-84(22.22-23.33)	28.80	425.99	2.4	2.24	0.82
	84-88(23.33-24.44)	31.60	545.01	2.78	2.47	0.64
	88-92(24.44-25.25)	34.80	620.90	3.74	2.87	0.70

Max.: Maximum, Accel: Acceleration, * : Speed at maximum acceleration

3.1.1. Acceleration time and acceleration distance

During acceleration manoeuver, acceleration time and acceleration distance for all vehicle type increase with increase in maximum speed (driver desired speed) in all speed ranges of vehicle (refer Table 2). This is because for higher speed, driver needs more time to achieve that speed. This time and distance is also related to the acceleration capability of vehicles. In similar speed range, acceleration distance (and time) of vehicle with lower acceleration capability (like motorized three wheeler) is more as compared to other vehicle types with higher acceleration capability (such as truck and motorized two-wheeler). A similar observation is reported by RaiChowdhury and Rao (1989) for passenger car.

3.1.2. Critical speed

The speed at which the maximum acceleration rate occurs (referred as **critical speed**) varies with vehicle type. The critical speed range is 1.08 m/s to 2.77 m/s for truck, 1.53 m/s to 2.53 m/s for motorized three-wheeler, 3.27 m/s to 4.21 m/s for motorized two- wheeler, 1.21 m/s to 1.46 m/s for diesel car, 2.40 m/s to 3.74 m/s for petrol car. Trucks achieve maximum acceleration quickly, whereas other vehicle types take more time to achieve their maximum acceleration rate. Hence, more data points could be recorded before vehicles' critical speed for other vehicle types as compared to truck. Also it is observed that since trucks achieve highest acceleration quickly, the proportion of time spend before achieving maximum acceleration is negligible as compared to total acceleration time (only 2 *sec* out of 60 *sec* acceleration manoeuver for truck). Further, it is observed that critical speed reduces (in most of the cases) with increase in driver desired speed. This implies that driver accelerates quickly when he/she plans to drive with higher speed.

3.1.3. Maximum and mean acceleration rate

It can be observed from Table 2 that the maximum acceleration rate varies with vehicle type and maximum speed of vehicle. The maximum and mean acceleration rates are higher at higher maximum speed, in majority of cases, of all vehicle types.

The maximum acceleration rate observed for truck is 1.0 m/s^2, for motorized three-wheeler 0.64 m/s^2, for motorized two-wheeler 1.95 m/s^2, for diesel car 2.23 m/s^2 and for petrol car 2.87 m/s^2 (refer Table 2). This indicates that petrol car employs highest acceleration rate among all vehicle types while motorized three-wheeler employs lowest maximum acceleration rate. Mean acceleration rates of different vehicles also follow similar trends.

Maximum acceleration rates of vehicles observed in this study are compared with maximum acceleration rates reported by earlier researchers. It is observed that rates observed in this study are higher than reported by Indian researchers, (Dey et al., 2008; Arasan and Koshy, 2005), whereas these are comparable with other researchers, (Bham and Benekohal, 2002; Wang et al., 2004). The detailed comparison is presented elsewhere, (https://iitg-in.academia.edu/DrPrashantBokare/Papers).

3.2. Deceleration Parameters

Various parameters of deceleration maneuver are presented in Table 3

TABLE 3 : Various parameters corresponding to different desired speed ranges of all vehicle classes during deceleration manoeuver

Vehicle Category	Maximum Speed Range km/h(m/s)	Deceleration Time (sec)	Deceleration Distance (m)	Speed at Maximum Deceleration (m/s)	Maximum Deceleration Rate (m/s^2)	Mean Deceleration Rate (m/s^2)
Truck	20-30 (5.55-8.33)	16.00	70.88	3.75	0.72	0.47
	30-40 (8.33-11.11)	21.30	124.39	3.82	0.75	0.46
	40-50 (11.11-13.88)	20.33	148.81	3.85	0.88	0.52
	50-60 (13.88-16.66)	30.75	243.54	3.93	0.88	0.51
Motorized three wheeler	27-31(7.5-8.61)	19.85	107.52	3.15	0.85	0.35
	31-35 (8.61-9.72)	27.33	159.33	3.21	1.12	0.31
	35-39 (9.72-10.83)	26.45	172.31	3.63	1.14	0.36
	39-43 (10.83-11.94)	28.42	201.05	3.21	1.06	0.36
Motorized two wheeler	40-50 (11.11-13.88)	18.30	152.01	7.52	1.60	0.58
	50-60 (13.88-16.66)	21.21	214.82	7.27	1.33	0.47
	60-65 (16.66-18.05)	23.00	292.79	9.65	0.59	0.41
Diesel Car	92-94 (25.55-26.11)	8.08	83.38	10.28	4.30	3.19
	94-96 (26.11-26.66	8.52	108.80	16.17	4.33	3.11
	96-98 (26.26-27.22)	8.60	113.04	23.28	5.00	3.36
	98-100 (27.22-27.77)	8.87	129.59	24.21	4.52	3.72
Petrol Car	61-72 (17-20)	7.61	85	2.97	3.36	2.42
	72-83 (20-23)	9.96	129	3.79	3.97	2.52
	83-91 (23-25)	10.27	134	5.69	4.33	2.59

Following observations were made from Table 3.

3.2.1. Deceleration time and deceleration distance

It can be observed from Table 3 that deceleration distance and time increases with increase in maximum (desired) speed (speed at which driver starts decelerating) in most of the speed ranges of all vehicle types. This implies that during deceleration manoeuver from higher speed to stop condition drivers require more distance (or time) as compared to deceleration manoeuver from lower speed ranges. Further vehicle with lower deceleration capability (like motorized three wheeler) requires more distance and time to complete the deceleration manoeuver in comparison to other vehicles with higher deceleration capability (like truck and motorized two wheeler) at a particular maximum speed range. These observations are in agreement with the observations made by researchers like Wang et al. (2005); Akcelik and Biggs (1987) but contradict with the findings of Bennet and Dunn (1995).

Variation in maximum speed of diesel car is less therefore corresponding variation in deceleration time is negligible. However, deceleration of petrol car varies with their maximum speed.

3.2.2. Maximum and mean deceleration rate

Maximum deceleration rates generally increases with increase in maximum speed of vehicle types observed in this study (except for motorized two wheeler). This observation is in agreement with the observation reported by Wang et al. (2005) and Bennet and Dunn (1995). The average maximum deceleration rates recommended by ITE (2009) are 3.0 m/s^2 and by AASHTO (2004) are 3.4 m/s^2 for cars. In present study the average maximum deceleration rates observed for petrol car is 3.88 m/s^2 and for diesel car is 4.53 m/s^2. In case of petrol cars the average maximum deceleration rates exceed the recommended rates where as for diesel cars the rates are within the limit recommended by ITE (2009) and AASHTO (2004). For all other vehicle types the average maximum deceleration rates are well within the recommended maximum rates.

Wang et al. (2005) reported that there is as such no relation between approach speed (speed at which driver starts decelerating) and maximum and mean deceleration rates. In this study, however, in case of cars (petrol and diesel) the maximum and mean deceleration rates are found to increase with increase in approach speed in most of the cases. This is because at higher approach speed driver is in hurry to stop. Hence they apply higher deceleration rate.

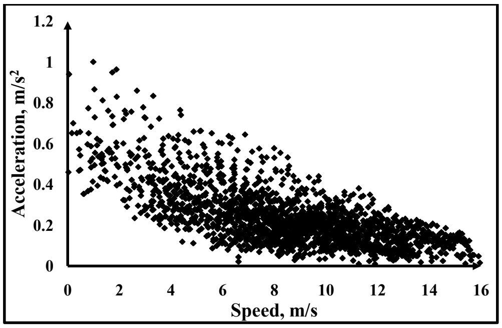
Petrol car employ highest deceleration rates while truck use the lowest among the vehicle types considered in this study. Deceleration rates reported by Bennet and Dunn (1995) for vehicles on free motor way in New Zealand, are similar to the maximum deceleration values observed at speed range $60 - 70$ km/h in present study.

4. Study of Acceleration Behaviour

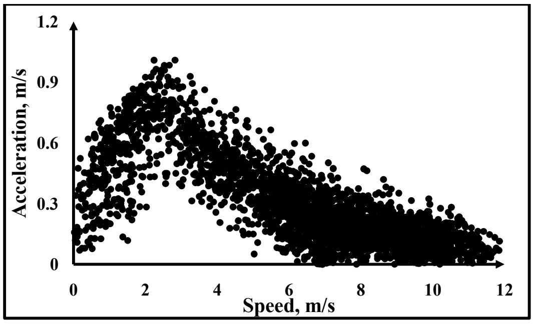
This section presents the acceleration behaviour of all vehicle types considered in this study. The speed data obtained from GPS are smoothed using exponential smoothing (Rakha et al., 2004). The resulting speed data for all trips is further used to compute acceleration as per Equation 1. The acceleration is then plotted against speed and presented in Figure 5.

It is observed from the plots in Figure 5 that;

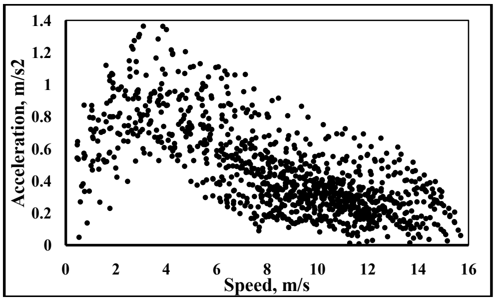
1. It is seen from Figure 5 that for all vehicle types, acceleration varies with speed. This shows that acceleration has a strong relationship with speed in all vehicle types. Bham and Benekohal (2002) reported that while modelling acceleration of vehicles, speed is preferred over distance as an independent variable since speed provides better fit (than distance). Since, distance is a cumulative measure, errors accumulate and magnifies over time resulting unrealistic errors. Many other authors (Akelik and Besley, 2001; Bham and Benekohal, 2002; Long, 2000) reported that vehicle acceleration has strong dependence on vehicle speed. This is also seen from Figure 5, at lower speed, acceleration is high and at higher speed acceleration is low, indicating strong relationship between acceleration and speed.
2. In case of truck, maximum acceleration is quickly achieved (due to high weight to horsepower ratio). There are very few data points before achieving maximum acceleration. Hence the regime before achieving maximum acceleration is negligible.
3. In case of motorized three and two wheeler, rate of acceleration initially increases up to a maximum value and then decreases to become zero at cruising speed (driver desired speed).
4. In case of cars, acceleration initially increases in first gear, achieves maximum value and decreases during gear change. Similar behaviour is repeated while changing second and third gears. Maximum acceleration is achieved in first gear. This behaviour fades in fourth and fifth gear change. The reason is, while shifting gears from third to fourth or from fourth to fifth gear, the change in speed is negligible. Hence the rate of change of acceleration is also not significant.
5. The speed at which maximum acceleration is achieved by vehicle and time taken by vehicle to achieve maximum acceleration are presented in Table 4, for all vehicle types. It is observed that the speed at which the maximum acceleration is achieved and time taken to achieve it, are different for different vehicles types due to their different weight to horsepower ratio and engine capacity. In case of car and truck, maximum acceleration is quickly achieved at the lower speed whereas in case of other vehicles maximum acceleration is achieved late.



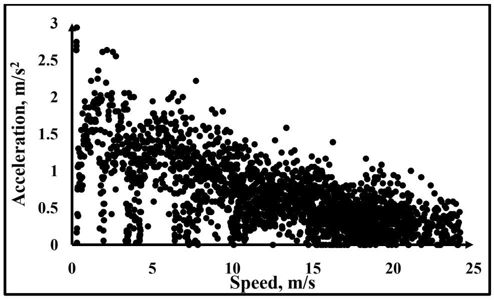
(a) Truck



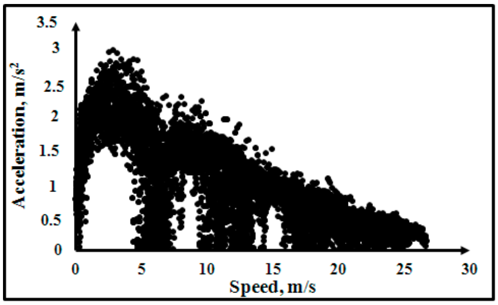
(b) Motorized three wheeler



(c) Motorized two wheeler



(d) Diesel Car



(e) Petrol Car

FIGURE 5 : Scatter plots of acceleration-speed

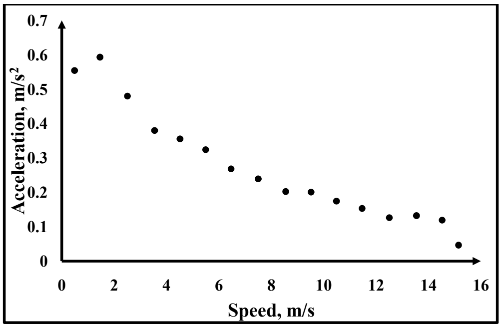
TABLE 4 : Speed at maximum acceleration and time taken to achieve maximum acceleration

Vehicle Type	Speed at max. acceleration, m/s	Time taken to achieve max. acceleration, sec.
Truck	1.45	2
Motorized Three-wheeler	2.5	4
Motorized Two-wheeler	2.97	3
Car		
Diesel car	1.38	0.8
Petrol Car	1.2	1

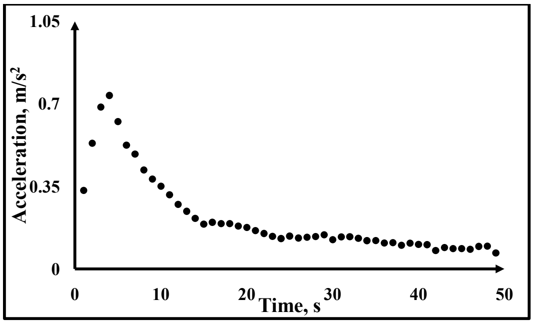
4.1. Acceleration Models

This section presents acceleration modeling for various vehicle types. The existing acceleration models are evaluated for the suitability to present data set and then fresh models are proposed.

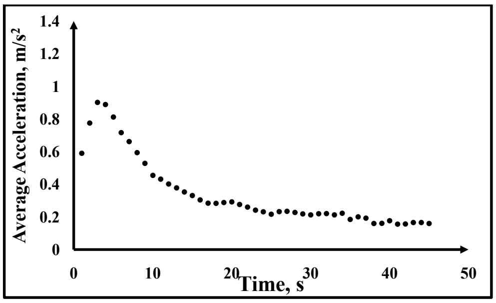
For modelling average behaviour of vehicles, acceleration and speed are averaged over every 1 m/s interval, (Wang et al., 2004) and the resulting idealized acceleration-speed plot for all vehicle types is presented in Figure 6.



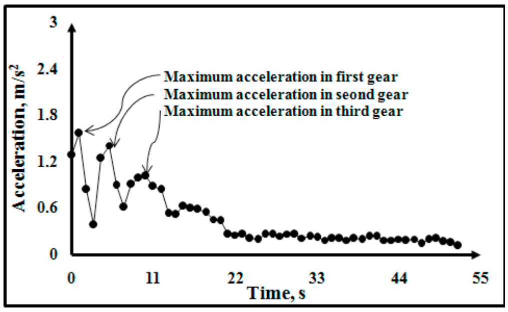
(a) Truck



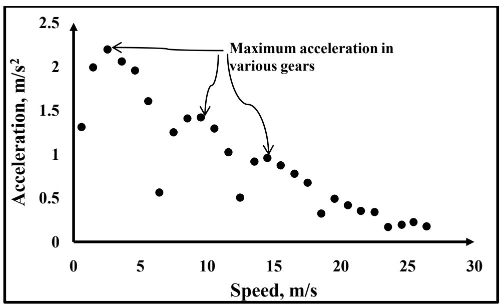
(b) Motorized three wheeler



(c) Motorized two wheeler



(d) Diesel Car



(e) Petrol Car

FIGURE 6 : Idealized plot of acceleration with speed for all vehicle types

The nature of idealized plot depicts similar behaviour like that of scatter plots of acceleration-speed presented in Figure 5.

The single regime model proposed by Samuels and Jarvis (1978) assumes constant acceleration throughout acceleration maneuver. This is the simplest model form that can be used to describe acceleration-speed relationship. However, the idealized plot of acceleration-speed for motorized three-wheeler and motorized two-wheeler (Figure 6b and 6c) indicate that there exist two separate regimes; regime-I before attaining maximum acceleration and regime-II after attaining maximum acceleration. Slope of acceleration-speed curve is opposite before and after a point of maximum acceleration. Hence, in case of motorized three and two wheelers the acceleration-speed is modelled in two separate regimes (dual regime) unlike Samuels and Jarvis (1978). It is assumed that the point of maximum acceleration will act as a separator point between two regimes. The dual regime model of acceleration-speed offers simplicity and ease of calculations as compared to polynomial model. This results in reduction in simulation time. Dual regime model contains only one point of discontinuity unlike several in linear model in the form of step function, (Bham and Benekohal, 2002; Wang et al., 2004; Maurya and Bokare, 2012). For car (diesel and petrol) and truck, however, the part of regime-I is very small (though it exists), since maximum acceleration is attained very fast at lower speed hence can be neglected. Hence for car, the acceleration-speed relationship is modeled as a single regime. The shape suggests non linear form of model, hence non-linear form is further evaluated.

4.1.1. Acceleration Model Formulation

Various model forms such as linear, polynomial and exponential are calibrated using linear regression for all vehicle types. To choose the best model among various model forms, Residual Sum of Squares (RSS), is used, as presented in Equation 3, (Freund and Wilson, 2011).

$$RSS = \sum_{i=1}^{n} \left[y_i - \hat{y}\right]^2 \tag{3}$$

where, RSS is Residual Sum of Squares, y_i is observed value of response, $\hat{y}$ is estimated value of response.

The RSS values for various vehicle types and various model forms are presented in Table 5

TABLE 5 : RSS Values for various acceleration model forms for various vehicle types

Vehicle Type	Regime-I			Regime-II		
	Linear Model	Exponential Model	Polynomial Model	Linear Model	Exponential Model	Polynomial Model
Motorized three wheeler	0.014	0.023	**0.004**	0.11	**0.02**	0.023
Motorized two wheeler	0.011	0.001	**0.0007**	0.001	**0.0008**	0.05
Truck[1]	0.03	**0.01**	0.17	–	–	–
Diesel Car[1]	0.59	**0.55**	0.81	–	–	–
Petrol Car[1]	2.78	**2.14**	12.86	–	–	–

[1]-Single Regime Model

It is observed from Table 5 that for motorized three-wheeler and motorized two-wheeler, minimum values of RSS are for **polynomial form for regime-I and exponential form for regime-II**. For truck, diesel and petrol cars minimum RSS values are for **exponential form**.

Linear regression (Freund and Wilson, 2011) is used to decide the model coefficients for all vehicle types. The general form of models and model coefficients are presented in Table 6.

4.1.2. Model Diagnostic

The linear regression model (which is used for formulating model) is based on several assumptions (Freund and Wilson, 2011). These assumptions are used to diagnose the correctness of model. The diagnostic procedures used are numerical (hypothesis test) and graphical (residual plots, observed and predicted value plots), (Freund and Wilson, 2011). The detailed analysis of model diagnostic is available elsewhere (https://www.academia.edu/7840630). Here, the result of only numerical diagnostic procedure (hypothesis test) is presented.

Numerical Procedure (Hypothesis Test). Paired 't' test is used to test the means of observed acceleration and predicted acceleration. Two hypothesis are tested −(i) null hypothesis: $\bar{\mu} = \mu_o - \mu_m = 0$, where μ_o and μ_p are mean of observed and predicted acceleration respectively and (ii) alternate hypothesis: $\bar{\mu} \neq 0$. The test statistic is calculated using Equation 4 (Freund and Wilson, 2011),

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

TABLE 6 : Model parameters for various vehicle types

Vehicle Type	Regime-I				Regime-II		
	$a = k_1 \times v^2 + k_2 \times v + k_3$				$a = k_4 \times e^{k_5 \times v}$		
	k_1	k_2	k_3	r^2	k_4	k_5	r^2
Motorized three wheeler	-0.23	0.98	-0.29	0.99	1.47	-0.26	0.95
Motorized two wheeler	-0.39	0.007	0.58	1	1.62	-0.15	0.98
	$a = k_6 \times e^{k_7 \times v}$						
	k_6	k_7	r^2				
Truck[1]	0.666	-0.13	0.92				
Diesel Car[1]	2.38	-0.1	0.88				
Petrol Car[1]	2.5	-0.09	0.83				

[1]-Single regime model

where, $\bar{\mu}$ is mean of the difference between observed and predicted acceleration, s_d is standard deviation of difference in paired data, n is number of data points. The hypothesis is tested for 95% confidence interval ($\alpha = 0.05$), where α is significance level. One cannot reject null hypothesis if $|t| \leq t_{\alpha/2}(= t_{0.025})$. Table 7 presents values of $|t|$ and $t_{\alpha/2}$ for various vehicle types.

TABLE 7 : Results of hypothesis test

Vehicle Type	—t—	$t_{\alpha/2}$	Remark
Truck	1.48	2.13	$\|t\| < t_{\alpha/2}$
Motorized three wheeler			
Regime-I	0.03	1.96	$\|t\| < t_{\alpha/2}$
Regime-II	0.99	1.96	$\|t\| < t_{\alpha/2}$
Motorized two wheeler			
Regime-I	0.24	2.16	$\|t\| < t_{\alpha/2}$
Regime-II	0.39	2.16	$\|t\| < t_{\alpha/2}$
Car			
Diesel	0.73	2.6	$\|t\| < t_{\alpha/2}$
Petrol	0.093	1.7	$\|t\| < t_{\alpha/2}$

For all vehicle types, $|t| \leq t_{\alpha/2}$, hence, null hypothesis that $\mu = \mu_o - \mu_m = 0$ cannot be rejected. This implies that there is no statistically significant difference between means of observed and predicted acceleration values.

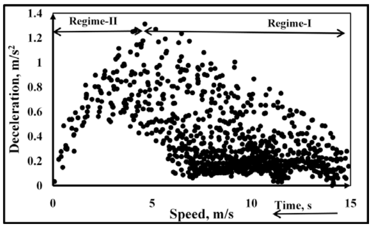
Therefore, it can be concluded that proposed models of acceleration-speed relationship are statistically robust.

5. Study of Deceleration Behaviour

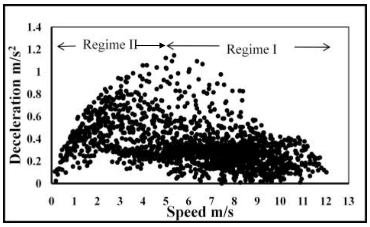
This section presents the deceleration behaviour of all vehicle types considered in this study. The speed data obtained from GPS are smoothed using exponential smoothing (Rakha et al., 2004). The resulting speed data for all trips is further used to compute deceleration as per Equation 2. The acceleration is then plotted against speed and presented in Figure 7.

It is observed from the deceleration-speed scatter plots that deceleration is strongly related to speed. To further reinforce this observation, the deceleration is averaged over 1 m/s speed interval and idealized deceleration and speed plots for all vehicle types are presented in Figure 8. While presenting idealized plots, cars are separated from other vehicles since the magnitude of deceleration is more in cars as compared to other vehicles.

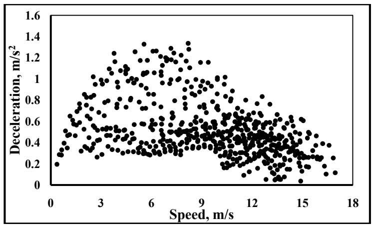
It is observed from Figure 7 and 8 that critical speed (speed where deceleration is maximum) depends on vehicle type. Critical speed is highest for petrol car and lowest for motorized three wheeler which has lowest deceleration capability in comparison to other vehicle types.



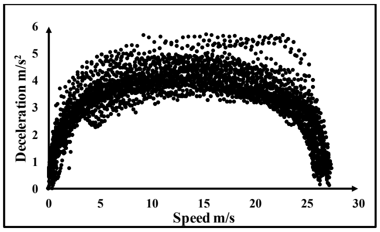
(a) Truck



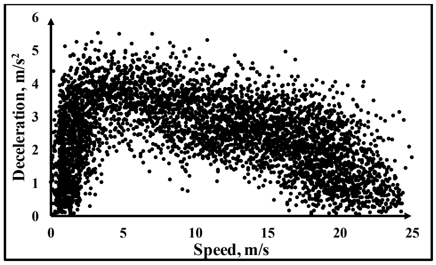
(b) Motorized three wheeler



(c) Motorized two wheeler

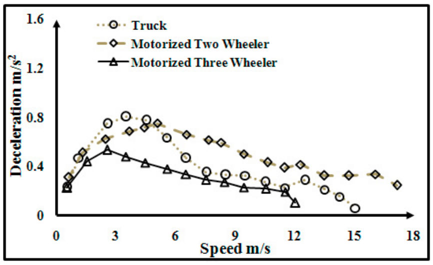


(d) Diesel Car

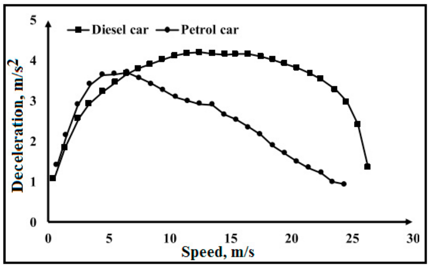


(e) Petrol car

FIGURE 7 : Scatter plots of deceleration-speed



(a) Truck, Motorized three wheeler and two wheeler



(b) Diesel car and Petrol car

FIGURE 8 : Idealized plots of deceleration-speed

5.1. Deceleration Models

The nature of idealized deceleration-speed curve (more specifically slope) is opposite before and after the critical speed, except in case of cars. Hence, a dual regime is proposed for all vehicle types except cars. Regime-I before attaining maximum deceleration and Regime-II after attaining maximum deceleration (refer 7). For cars, single regime model is proposed (as depicted in Figure 8b). In order to decide the form of model before and after a critical speed, Residual Sum of Squares (RSS) is used, as was used in case of acceleration modelling.

Residual Sum of Squares for three proposed forms of model such as linear, second order polynomial and exponential are evaluated and results are presented in Table 8.

It is observed from Table 8 that for all vehicle types (except for cars) negative exponential model for Regime I and linear model for Regime II are found suitable (minimum RSS values are shown by bold face letters). For diesel car, RSS values are minimum for second order polynomial and for petrol car RSS values are minimum for third order polynomial model.

Linear regression is used to obtain model parameters from the idealized deceleration and speed relationships of vehicles and presented in Table 9. Model forms for various models are also presented in Table 9.

TABLE 8 : Residual Sum of Squares (RSS) values for different model forms for deceleration-speed relationship of various vehicle types

Vehicle Category	Regime I			Regime II		
	Linear	Exponential	Second order Polynomial	Linear	Exponential	Second order Polynomial
Truck	0.066	**0.031**	0.038	**0.006**	0.10	0.086
Motorized Three Wheeler	0.007	**0.004**	0.005	**0.00045**	0.006	0.002
Motorized Two Wheeler	0.021	**0.016**	0.09	**0.017**	0.028	0.19
Petrol Car	1.62	0.93[1]	0.89[1]*	NA	NA	NA
Diesel Car	2.03	0.75[1]	0.61[1]	NA	NA	NA

[1]-Single regime model
∗-RSS for third order polynomial is also evaluated and found to be lower than for RSS for second order polynomial

TABLE 9 : Model parameters and r^2 for deceleration-speed models of various vehicle types

Vehicle Category	Calibrated parameter values						Critical Speed m/s
	Regime I			Regime II			
	$d_1 = k_1 \times e^{-k_2 \times v}$			$d_2 = \alpha + \beta \times v$			
	k_1	k_2	r^2	α	β	r^2	
Truck	1.58	0.017	0.86	0.104	0.225	0.92	3.83
Motorized three wheeler	0.806	0.130	0.90	0.163	0.152	0.94	2.09
Motorized two wheeler	1.106	0.080	0.95	0.342	0.087	0.86	11.46
Cars							
Diesel Car	$d_c = -k_3 \times v^2 + k_4 \times v + k_5$						
	k_3	k_4	k_5	r^2			
	-0.005	+0.15	+0.50	0.92			
Petrol Car	$d_c = k_6 \times v^3 - k_7 \times v^2 + k_8 \times v + k_9$						
	k_6	k_7	k_8	k_9	r^2		
	0.001	-0.52	+0.62	1.47	0.97		

where, d_c is deceleration (m/s^2) at speed v (m/s)
k_1, k_2, k_3, k_4, k_5,k_6,k_7,k_8,k_9, α, and β are the model parameters

5.2. Model Diagnostic

Similar to acceleration modelling, proposed models for both regimes (single regime in case of diesel and petrol car) are statistically evaluated using various diagnostic tools like graphical (residual plots, observed versus predicted deceleration plots) and numerical (hypothesis testing). The detailed analysis of model diagnostic is available elsewhere, (https://www.academia.edu/7840630). Here, numerical diagnostic analysis in the form of hypothesis test is presented.

Numerical Procedure (Hypothesis Test). Paired 't' test is used to test the means of observed deceleration and predicted deceleration. The results are presented in Table 10. It is observed that null hypothesis (i.e. mean of deceleration computed from observed speed and mean of deceleration obtained from model are same) can not be rejected.

TABLE 10 : Results of hypothesis test for deceleration models

Vehicle Type	—t—	$t_{\alpha/2}$	Remark
Truck			
Regime-I	0.45	2.17	$\lvert t\rvert < t_{\alpha/2}$
Regime-II	0.03	2.17	$\lvert t\rvert < t_{\alpha/2}$
Motorized three wheeler			
Regime-I	0.19	2.36	$\lvert t\rvert < t_{\alpha/2}$
Regime-II	0.29	1.96	$\lvert t\rvert < t_{\alpha/2}$
Motorized two wheeler			
Regime-I	0.54	2.16	$\lvert t\rvert < t_{\alpha/2}$
Regime-II	0.51	1.96	$\lvert t\rvert < t_{\alpha/2}$
Car			
Diesel	0.1.13	2.6	$\lvert t\rvert < t_{\alpha/2}$
Petrol	1.3	1.7	$\lvert t\rvert < t_{\alpha/2}$

For all vehicle types, $|t| \leq t_{\alpha/2}$, hence, null hypothesis that $\mu = \mu_o - \mu_m = 0$ cannot be rejected. This implies that there is no statistically significant difference between means of observed and predicted deceleration values.

Therefore, it can be concluded that proposed models of deceleration-speed relationship are statistically robust.

6. Conclusions

This study reported the acceleration and deceleration behaviour of various vehicle types running on roads in India. Following are the salient features of this study;

6.1. Acceleration Behaviour

1. The rate of acceleration was found to increase from lowest value to maximum value with increase in initial speed. After attaining maximum value, acceleration rate decreased with further increase in speed. This nature is witnessed for all vehicles except trucks. Since trucks achieve maximum acceleration quickly, the initial behaviour of acceleration rate couldn't be observed with GPS device having 1 second logging interval. The device with higher data logging interval may capture this behaviour.
2. The maximum acceleration rate observed for various vehicle types are; for truck 1.0 m/s^2, for motorized three-wheeler 0.64 m/s^2, for motorized two-wheeler 1.96 m/s^2, for diesel car 2.23 m/s^2 and for petrol car 2.87 m/s^2, Petrol car posted highest maximum acceleration rate. These rates are comparable with the rates reported by Wang et al. (2004); Bham and Benekohal (2002), whereas these rates are higher than that reported by Arasan and Koshy (2005); RaiChowdhury and Rao (1989); Dey and Biswas (2011).
3. The acceleration-speed relationship is modelled as a dual regime relationship (negative exponential in regime-I before attaining maximum acceleration and second order polynomial for regime-II after attaining maximum acceleration rate) for motorized three and two wheeler. For truck, diesel car and petrol car a single regime negative exponential model is proposed.
4. Models proved fairly accurate when various statistical model diagnostic tests are applied.
5. In cars, in a particular gear initially, acceleration increases with speed till acceleration attains its maximum value, afterwards it decreases with further increase in speed. Similar acceleration behaviour is observed in every gear during driving.

6.2. Deceleration Behaviour

1. The distance travelled and time taken to complete deceleration maneuver by various vehicle types during deceleration manoeuver is different and is found to vary with the speed at which driver start decelerating (**approach speed**). Driver takes more distance for decelerating if the approach speed is high.
2. The speed at which driver attains maximum deceleration (referred as **critical speed**), changes with vehicle type and approach speed. Critical speed also increases with approach speed. This indicates that at higher approach speed, the drivers achieve their maximum deceleration rate quickly to stop at the earliest.
3. The proposed models are dual regime models for truck, motorized three wheeler and motorized two wheelers. For diesel and petrol cars the single regime polynomial models are proposed.
4. Various statistical tests are applied to check the effectiveness of models for observed deceleration-speed data. It was found that the models tested well for all vehicle types.

The results of this study can be used to input proper values of acceleration and deceleration in various simulation models. The acceleration and deceleration of vehicles also affects the vehicular tailpipe emission. It is also reported that the delay of vehicles is affected by the acceleration and deceleration capabilities of various types of vehicles. Hence the results of this study can also be used for design of red, green and amber timings at signalized intersection.

The study can be further extended to observe acceleration and deceleration behaviour of various vehicle types at actual signalized intersection. The effect of acceleration and deceleration on tailpipe emission of vehicles types can also be studied.

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