Modelling of Acceleration and Deceleration Behaviour of Vehicles

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by

Prashant S. Bokare

Department of Civil Engineering,

Indian Institute of Technology Guwahati,

Guwahati, Assam, India-781039

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।। श्रीवरी व्यंकटेश बालाजी ।।
ह्यांस श्रद्धापूर्वक अर्पण

माझे कुटुंबीय, आप्त व मित्र,

ज्यांच्यामुळे मी हा प्रबन्ध पूर्ण करू शकलो

त्यांना कृतज्ञतापूर्वक समर्पित

Indian Institute of Technology Guwahati, Guwahati, Assam-781039, INDIA

CERTIFICATE

This is to certify that thesis entitled **'Modelling of Acceleration and Deceleration Behaviour of Vehicles'**, submitted by Prashant S. Bokare (Roll No. 08610410) to the Indian Institute of Technology Guwahati, for the award of degree of Doctor of Philosophy in Civil Engineering is a record of bonafide research work carried out by him under my supervision and guidance. In my opinion the thesis work has reached the requisite standard fulfilling the requirement for the degree of Doctor of Philosophy in Civil Engineering.

The results contained in this thesis have not been submitted in part or full to any other University or Institute for award of any degree or diploma.

(Dr. Akhilesh Kumar Maurya)
Thesis Supervisor
Assistant Professor
Department of Civil Engineering
Indian Institute of Technology Guwahati,
Guwahati, Assam, India-781039

February, 2013

Indian Institute of Technology Guwahati, Guwahati, Assam-781039, INDIA

Statement

I do hereby declare that the matter embodied in this thesis is the result of investigations carried out by me in the Department of Civil Engineering, Indian Institute of Technology Guwahati, Guwahati, Assam, India.

In keeping with the general practice of reporting scientific observations, due acknowledgements have been made where ever the work is based on the findings of other investigators.

(P. S. Bokare)
Department of Civil Engineering
Indian Institute of Technology Guwahati,
Guwahati, Assam, India-781039

February, 2013

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P. S. Bokare

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Abstract

Modelling of acceleration/deceleration (A/D) behaviour of vehicles are important for various traffic engineering related works like intersection design, deceleration lane design, ramp design, traffic simulation modelling, vehicular emission modelling, instantaneous fuel consumption rate modelling, etc. In this present study, A/D behaviour of various vehicle types (mid size truck, motorized three wheeler, motorized two wheeler, diesel car and petrol car) are analyzed. Further, it explores the impact of driver attributes (such as driver age, driving experience and driver education) on A/D characteristics. Vehicular tailpipe emissions and delays at signalized intersection have long been understood to have been affected by vehicle A/D. Hence the experiments are also conducted to understand the impact of A/D on vehicular tailpipe emission and average delay at signalized intersection. Brief summary of main findings of this study is presented in following section.

This study is divided in four parts: (i) acceleration behaviour of vehicles, (ii) deceleration behaviour of vehicles, (iii) effect of driver attributes on acceleration/deceleration of mid size truck, and (iv) impact of A/D on vehicular tail pipe emission and average delay at signalized intersection. It was observed that different vehicle types have different A/D behaviour. It was also found that A/D behaviour also depends on the vehicle's desired (or maximum). The salient points that come out from each part of study are:

- The acceleration behaviour of vehicles varies with vehicle type. It is found that the existing models of acceleration-speed failed to describe the acceleration-speed data observed in this study. Hence new models are proposed.

- The deceleration behaviour of vehicles also varies with vehicle type. It is found that the existing models of deceleration, explained speed time relationship during deceleration which is not enough to describe actual deceleration behaviour. Hence new models are proposed.

- Acceleration/deceleration behaviour is found to be influenced by driver attributes such driver age, driving experience and education. The impacts of these attributes on acceleration-deceleration are quantified in detail.

- The dependence of car tailpipe emission on acceleration/deceleration was estimated. It is observed that car tailpipe emission is sensitive to speed at particular acceleration level. Impact of deceleration on car tail pipe emission couldn't be observed. The average delay at signalized intersection was also affected by car acceleration/deceleration

Chapter 1

Introduction

1.1 General

Vehicle acceleration/deceleration (A/D) behaviour have significant impact on several traffic related factors like delay at signalized intersection, design of signalized intersection, micro simulation traffic modeling, design of roadway and intersection geometry, instantaneous fuel consumption and emission 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 individual vehicle type and driver behaviour. 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. Therefore, precise knowledge of A/D behaviour of vehicles is important to develop a reliable microscopic traffic simulation models, vehicle fuel consumption and emission models etc.

1.2 Background

The Guidelines on Geometric Design of Highways and Streets (AASHTO, 2011) states that the vehicle acceleration is a critical factor in designing geometry of highway. Geometric design of intersection ramps, climbing lanes, deciding grades are some of the victims of inadequate knowledge of vehicle acceleration and deceleration behavior. Searle (1999) and Snare (2002) opined that since acceleration and deceleration models control movement of vehicle in traffic, road accident investigation often need adequate knowledge of A/D behavior with respect to speed. Emission modeling and instantaneous fuel consumption model also find acceleration and deceleration model application as reported by Akcelik and Biggs (1987). Though it is difficult to model acceleration and deceleration of vehicles due to variability in their size, variability in driver response to road elements etc. (Snare, 2002; Fildes, 1991), the modelling A/D of vehicle is important due to their above mentioned applications.

In past, various speed profile models and A/D profile models are developed for different applications discussed above. Most of the A/D models reported in literature refer maximum acceleration capabilities of vehicles. However experiments show that drivers rarely use full vehicle acceleration capacity while driving in day to day traffic, but drive with normal acceleration (Fildes, 1991). Maximum acceleration capabilities are useful only as upper bound but can not be used for design purpose due to their rare occurrence. Actual acceleration rate (hereafter referred as normal acceleration rate) most frequently occurring on roadway, depends on vehicle characteristics, road way geometry, driver attitude to speeding, etc. Various factors like driver age, driving experience, education, etc. influence normal A/D on roadways (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 models giving due recognition to effects of above mentioned factors on A/D model.

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 acceleration behavior of current fleet and driver behavior. Some of the old researches uses traditional methods for vehicle's speed measurements which may not provide precise speed measurement. Searle (1999) and Gattis et al. (2010) uses radar gun and laser gun to track vehicle speed while loop detectors was used by Bennet and Dunn (1995) to acquiring vehicle speed. RaiChowdhury and Rao (1989) and Dey and Biswas (2011) used travel time measurement method between two predefined sections to get speed and acceleration of vehicle. Arasan and Koshy (2005) measured time and vehicle speed measurement from speedometer to get average speed and acceleration between different predefined sections. These methods lead to average speed and acceleration values instead of its continuous measurement. In few recent studies (like Wang et al. (2004)), GPS is used to measure the vehicle's speed and acceleration accurately.

Limited work (Akcelik and Biggs (1987), Bennet and Dunn (1995) and Wang et al. (2005)) is done in the past on deceleration modelling for cars and light commercial vehicles in comparison to acceleration modelling. Bennet and Dunn (1995) reported second order polynomial deceleration model for vehicles in New Zealand. Deceleration rates so obtained can be a useful tool in predicting speed in micro simulation traffic models. With rapid change in engine technology (since 1985) and new generation drivers taking seat of older ones, it has become imperative to have a fresh look at the A/D models, their formulation, calibration and validation.

Majority of studies (like Wang et al. (2004), RaiChowdhury and Rao (1989), Akcelik and Biggs (1987), Akelik and Besley (2001) and Bham and Benekohal (2002)) have reported acceleration behaviour of passenger cars only. In India however, the traffic stream is heterogeneous comprising of vehicles like truck, motorized three wheeler, motorized two wheeler and non motorized vehicles apart from car, enjoying the same right of way (lane) with weak lane discipline. These vehicles (other than car) have lesser accelerating capability and interfere with movement of vehicles with high acceleration capability. Therefore, separate A/D studies are need for such poor performance vehicles.

In India, only limited studies (RaiChowdhury and Rao (1989), Arasan and Koshy (2005), Dey and Biswas (2011)) of A/D behaviour have been conducted. Arasan and Koshy (2005) studied acceleration rates in Chennai using stop watch and speedometer data. They concluded that acceleration rate depends on speed range and type of vehicle. Rate of acceleration decreases with increase in speed as can be seen from Table 1.1 suggested by Arasan and Koshy (2005). Lower rates of acceleration are reported for heavier vehicles like buses, trucks and light commercial vehicles as compared to cars, three wheelers and two wheelers. RaiChowdhury and Rao (1989) and Dey and Biswas (2011) used travel time measurement method between two predefined sections to get speed and acceleration of vehicle which may not provide accurate speed and acceleration data. Therefore these studies fail to capture the fine variations in of acceleration with speed of vehicle.

Table 1.1: Acceleration Rates for Different Categories of Vehicles in India,(Arasan and Koshy, 2005)

	Acceleration value at various speed ranges m/s^2		
Vehicle type	0-20 km/h	20-40 km/h	above 40 km/h
Bus	0.89	0.45	0.33
Truck	0.79	0.45	0.33
LCV	0.82	0.60	0.35
Car	1.50	1.30	1.00
Three wheeler	1.01	0.58	0.34
Two wheeler	1.35	1.03	0.37

Hence, it is prudent to undertake the acceleration/deceleration studies of various vehicle types (keeping in view heterogeneous traffic India) using modern device (like Global Positioning System, GPS) plying on Indian road. It is also required to quantify the effect of driver attributes like driver age, driving experience and driver education on acceleration and deceleration of vehicles.

1.3 Objectives of This Thesis

Therefore, the current study is focussed on A/D pattern study of different vehicles generally observed on Indian highways. Further, impact of driver attributes on their A/D pattern are also explored. Main objectives of this work are:

1. Study of acceleration patterns of mid size truck, motorized three wheeler, motorized two wheeler and cars (including diesel and petrol, both).

2. Study of deceleration patterns of mid size truck, motorized three wheeler, motorized two wheeler and cars (driven using diesel and petrol both).

3. Study the effect of truck drivers' attributes (age, education and driving experience) on their A/D pattern.
4. To analyze the effect of A/D patterns of vehicles on their (i) tail pipe emission and (ii) average delay behaviour at signalized intersection.

The present work intend to model A/D patterns of different vehicle types at signalized intersection in India, using advanced data collection methods (Global Positioning System). Effect of road geometry (i.e. curve and grades) on A/D pattern are not considered in this study. Effect of various driver's attributes on A/D behaviour will also be explored. Further, two experiments are conducted to highlight the importance of such study.

1.4 Organisation of This Thesis

This thesis comprises eight chapters which explain the steps taken to achieve the objectives of this thesis. Each chapter start with an introduction that describes the structure of the chapter and end with a closing remark which identifies the main findings of that chapter. The thesis is organised as follows:

Chapter 1 introduces to the research undertaken in this study including its background, objectives and structure of the thesis.

Chapter 2 focuses on data collection methods adopted in A/D modelling, analysis of existing A/D models and studies related to effect of driver attributes. This also presents the studies related to influence of A/D rates on vehicular tailpipe emission. This chapter then highlights the gaps in exiting studies.

Chapter 3 presents the research methodology adopted for data collection and its analysis. This also includes a step by step method for model development and its evaluation.

Chapter 4 develops models for acceleration behaviour of mid sized truck, motorized three wheeler, motorized two wheeler and cars. This includes summary of collected data, its analysis and findings, model formulation and model diagnostics for all vehicle classes.

Similar to previous chapter, Chapter 5 describes the collected data, its analysis and main findings, model formulation and model diagnostics for deceleration behaviour of all vehicle classes.

Chapter 6 studies the effect of driver attributes (such as driver age, driving experience and driver education) on their A/D behaviour for mid size truck.

Chapter 7 quantifies the effect of A/D on vehicle's delay at signalized intersection. It also analyses the effect of A/D behaviour on tailpipe emission of petrol driven cars.

Chapter 9 outlines the conclusions of this study and makes suggestions for future research.

This thesis also has three appendixes which covers sample gps data, statistical methods used in the thesis and driver response sheet used for driver behaviour data collection.

Chapter 2

Literature Review

2.1 General

Modeling acceleration and deceleration behaviour of vehicles is important since it has several applications in traffic engineering. Dimensioning of intersections, ramps, climbing lanes and other roadway features need in-depth understanding of vehicle acceleration-deceleration behaviour (AASHTO, 2011). Microscopic traffic simulation models (such as INTEGRATION, CELLSIM, MITSIM, AIMSUN2 and so on.), need acceleration-deceleration models to decide fundamental movements of vehicles (Snare, 2002). Investigation of road accidents involve acceleration-deceleration understanding to arrive at initial speed of vehicle and speed at the time of crash. Fuel consumption and tailpipe emission of vehicles is reported to depend on acceleration-deceleration rate of vehicles (Akcelik and Biggs, 1987; Rakha and Ding, 2003). At signalized traffic intersection several vehicles decelerate, stop, crawl in queue and accelerate during normal traffic. The deceleration rate of vehicle affects vehicle delay. Similarly the acceleration rate of vehicle affects acceleration distance and time causing delay. Hence correct understanding of acceleration and deceleration of vehicles is required for geometrical design of signalized intersection and placement of signs, warning drivers of a indicating signalized intersection ahead.

The acceleration-deceleration (A/D) of vehicles is reported to depend on many factors. The factors influencing vehicle acceleration and deceleration include geometric alignment features, cross-section characteristics, roadside objects, adjacent land uses, traffic control devices, traffic volume, traffic calming measures, driver and vehicle characteristics and so on (Wang, 2006). It is also a function of driver attributes like, age, driving experience and driver age (Mehmood, 2009). The HCM (2000) states that the interaction among vehicles due to traffic density, proportion of trucks, buses and non-motorized vehicles (when all are using same right of way) in traffic composition are some of the factors that affect acceleration and deceleration of vehicles. Hence, vehicles cannot use maximum acceleration-deceleration capability, but use about 50% to 60% of maximum capacity. Figure 2.1 shows general factors that affect the speed (and hence acceleration and deceleration).

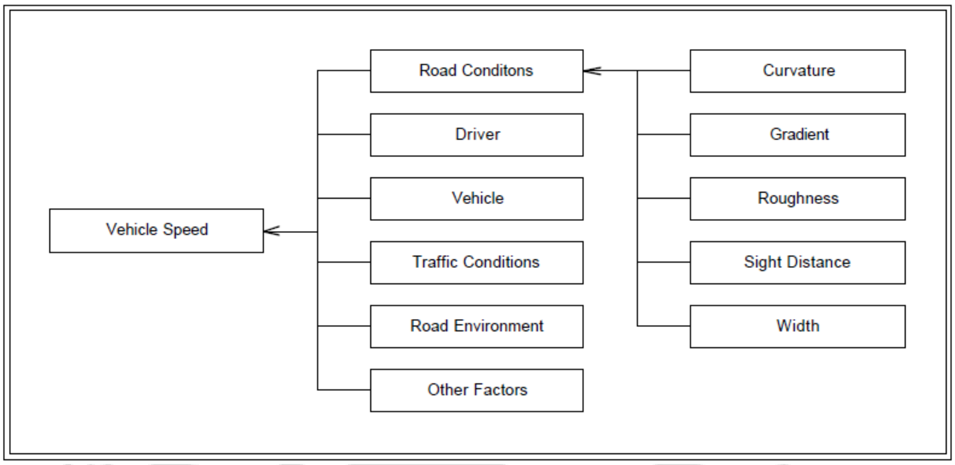

Figure 2.1: Factors affecting speed, (Wahlgren and Korkeakoulu, 1967).

Consequently, many researchers studied all or some of these factors affecting acceleration and deceleration behaviour of vehicles. Following sections present an account of research efforts that report various factors that affect acceleration and deceleration (A/D) and interrelations of these factors and A/D. The conclusion part of this chapter underlines the strength and weakness in existing research and the gap that is left over.

This chapter is divided in sections such as data collection methods for A/D; GPS data smoothing methods; acceleration modeling, deceleration modeling, effect of A/D on average delay of vehicles and on tail pipe emission of vehicles etc. The last section deals with conclusions of presented review and gap in existing A/D research.

2.2 Data collection methods

Traffic engineers are involved in various activities like transport modeling, simulation, operation optimization and development of methods to control and analyze traffic. These works may include large traffic data collection from field. Hence traffic engineers have to be equipped with newer and updated methodology and equipments regarding data collection.

Various researchers have used different methods of data collection for speed, A/D modelling of vehicles. The method of measurement tend to differ with study purpose and available technology. Table 2.1 presents data collection methods used by various researchers.

Table 2.1: Data collection methods used by various researchers

Serial No	Researcher (Year)	Data collection method used	Application
1	Beakey (1938)	Travel time at multiple locations	Vehicle speed[1]
2	Samuels and Jarvis (1978)	Radar speedometer	Vehicle speed[1]
3	Akcelik and Biggs (1987)	Chase car method	Acceleration rate
4	RaiChowdhury and Rao (1989)	Travel time measurement	Speed data[1]
5	Bennet and Dunn (1995)	Computerized data logger VDDAS	Speed measurements[2]
6	Hallmark (1999)	Laser gun	Speed measurements
7	Rakha et al. (2001)	GPS	Emission and Fuel consumption
8	Snare (2002)	GPS	Vehicle speed
9	Maya et al. (2003)	Intelligent Cruise Control, GPS	Vehicle speed[1]
10	Ogle (2005)	Instrumented vehicle	Vehicle position
11	Wang et al. (2004, 2005)	GPS	Vehicle position and speed[1]
12	Hong (2007)	GPS	Vehicle position and speed[1]
13	Boonsiripant (2009)	GPS	Speed and position measurements

[1]- studied acceleration rate, [2]-studied deceleration rate

Subsequent paragraphs list various methods of data collection used by earlier researchers.

Loop detector was the first technique used by traffic engineering researchers to collect data, whereas sophisticated V-Box technology is latest in use. Early studies suffered from low data resolution (i.e. low sampling rate) due to limitation in data collection technology (Boonsiripant, 2009).

Beakey (1938) determined the acceleration rate by measuring travel time at multiple locations along 950 ft. stretch. Acceleration rate was then calculated from measured travel time. Some studies used vehicle speedometer to collect speed data. Akcelik and Biggs (1987) used chase car method to collect data for acceleration. Second by second speed time data was collected by Sydney University Mechanical Engineering Department which using instrumented vehicle (Tomlin et al., 1983). Based on which Akcelik and Biggs (1987) reported a speed profile presented in Figure 2.2.

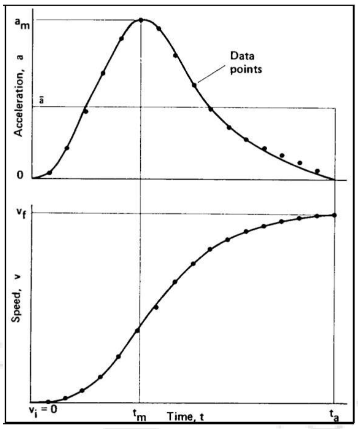

Figure 2.2: Acceleration Speed Plot–Polynomial Model, (Akcelik and Biggs, 1987)).

Authors however, observed that there is large variation in data and the speed and acceleration profiles are not as smooth as shown Figure 2.3.

Some researchers like (Snare, 2002; Wang et al., 2004, 2005; Rakha et al., 2001) used GPS equipped vehicle to collect speed and distance data. Bennet and Dunn (1995) used 16 channel computerized data logger called the Vehicle Detector Data Acquisition System (VDDAS) developed by Australian Road Research Institute. In this system 16 detectors were placed at different locations and the speed was measured at nearest millisecond accuracy. This method eliminated the sampling bias in manual method. The method noted the actuation from detectors like pneumatic tubes, treadles or triboelectricity sensors. This method measured speeds at different intervals and computed average decelerations from the speed data. Boonsiripant (2009) used GPS equipment to collect speed data of vehicles. Each second of GPS data contains trip ID, date, time, vehicle speed, position (latitude-longitude), travel direction, road ID with mile post, and satellite data quality information (used in automated data processing and quality assurance routines).

Hallmark (1999) predicted individual vehicle activity using hand-held laser range finding devices, also called "laser guns" (LRF) manufactured by Laser Atlanta Optics. These are portable hand held devices capable of measuring distance to an object at a high sampling frequency having manufacturers accuracy of 0.1 ft. over 2500 ft. The data can either be transferred to computer using data card or file can be outputted to computer via serial port interface. Each time the LRF trigger is pulled, all subsequent readings are stored to the first available null data file on the data card. Consequently, a unique file is stored on the card for each vehicle observed.

Ogle (2005) reported the use of in-vehicle instrumentation package for robust data collection. The system consisted of the Linux-based 386 computer using 12V vehicle power backup. The entire system was packaged in an aluminum extrusion case, approximately 8" × 6" × 2". The device is placed under the dash board or on the floor on passenger side. The onboard equipment monitors engine start date and time, second-by-second vehicle position (latitude and longitude), heading and speed.

Table 2.1 presents the summary of data collection methods used by various researchers and their application in traffic engineering research.

It is seen from Table 2.1 that very few researchers have used Global Positioning System and out of them very few used the data for studying acceleration and/or deceleration behaviour.

2.2.1 GPS data collection method

The GPS is fast becoming popular among researchers due to its lesser human involvement and accuracy. However, the output data given by GPS contains systematic and random errors which need to be taken care off. Following section describes how GPS collects data and ways to remove GPS data errors.

Global Positioning System GPS technology (which is used in this study), is a satellite based navigation system consisting 24 satellites orbiting the earth, at an altitude of approximately 11,000 miles. Department of Defence of Unite States initially developed it for military services and subsequently opened for non military operations too. It consists of three components,

- Space segment,
- Control segment,and
- The user

The space segment consists of 24 satellites that emit high-frequency radio waves. The control segment consists of five ground stations located around the world, which monitor the GPS satellites and upload information from the ground. The user segment is the GPS receivers, which detect, decode, and process GPS satellite signals, Lee (2007). The system works as shown in Figure 2.3,

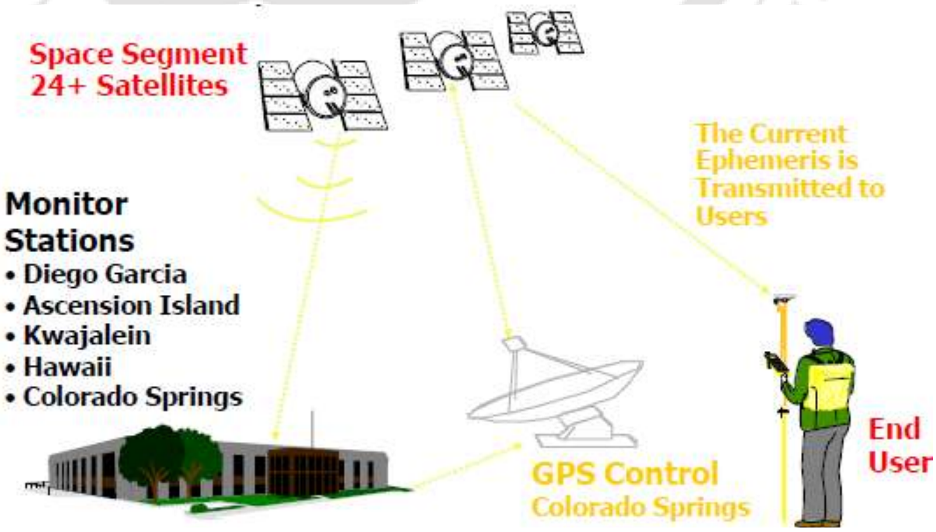

Figure 2.3: Working of GPS, Lee (2007)

GPS determines a location by calculating the distances between the receiver and 3 or more satellites. GPS measures distance by measuring the travel time of radio waves from satellite to the receiver. Assuming the positions of the satellites are known, the location of the receiver can be calculated by determining the distance from each of the satellites to the receiver.

2.3 Acceleration Models

Acceleration and deceleration models referred in literature can be broadly classified as models using kinematics of vehicles and those using dynamics of vehicles. Various types of kinematic and dynamic models can be classified as below:

- Kinematic Models
  1. Equations of motion.
  2. Empirical Relationship
- Dynamic Models
  1. Tractive Engine Force
  2. Opposing Resistance

Many researchers (Lee and Rioux, 1977; Wang et al., 2004; Bham and Benekohal, 2002; Hong, 2007) have undertaken research on kinematic and dynamic modeling of acceleration vehicles. Kinematic model takes into account mathematical relationship between acceleration speed and distance traveled. The models of acceleration using dynamics take into account various forces acting on vehicle. These forces are tractive force, frictional resistance, air resistance etc.

This study emphasizes on kinematic models. The section is divided in four subsections describing various acceleration model.

2.3.1 Kinematic acceleration models

Acceleration models can be broadly classified in four types given below:

- Constant acceleration model.
- Linear decreasing model.
- Polynomial model.
- Two phase (dual regime model)

Figure 2.4 shows typical acceleration speed plot for these four types of models. Acceleration models show mathematical relationship between acceleration-speed or between acceleration-time.

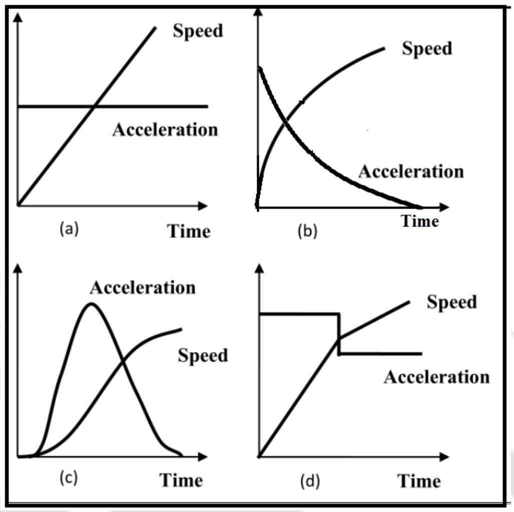

Figure 2.4: Speed and Acceleration Profile for Different Models like (a)Constant acceleration, (b)Linear decreasing, (c) Polynomial and (d)Two phase (dual regime)

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(Bham and Benekohal, 2002), has classified acceleration models into 14 categories. But some of the categories reported by them fall within above four categories and hence only four categories of acceleration models are considered in this report.

Constant Acceleration Model

Among various models shown in Figure 2.5, constant acceleration model is the simplest and most basic one. It assumes that vehicles keep accelerating at constant rate through entire acceleration process Akcelik and Biggs (1987); Bham and Benekohal (2002). This model depicts linearly increasing relationship of speed with time and slope of line represents rate of acceleration. Equation 2.1 shows mathematical relationship for constant acceleration model.

$$a_{avg} = \frac{2x}{t^2} - \frac{2v_i}{t} = \frac{(v_f - v_i)}{t} \tag{2.1}$$

where, $a(avg)$ is average acceleration rate, in m/s^2, x is distance covered in time t, in m, t is time required to cover distance x or to reach a velocity from v_i to v_f, v_i is startup velocity, in m/s and v_f is velocity at time t, in m/s.

For a particular case of $v_i = 0$, the equation reduces to,

$$a_{avg} = \frac{2x}{t^2} = \frac{(v_f)}{t} \tag{2.2}$$

Though this is the oldest and most frequently used model, field research shows (Bham and Benekohal, 2002; Long, 2000; Searle, 1999) that the vehicle acceleration is never constant but exhibits continuous change over the time, distance and speed. Studies have reported that the acceleration has higher rates when traveling at lower speeds and vice versa. Traffic simulation packages use constant acceleration models for the sake of simplicity. This model can be best suited when vehicle maneuvers in one particular gear at maximum acceleration rate (Searle, 1999).

Linear decay model

This model assumes that the rate of acceleration reduces with increase in speed, Drew (1968); Lee and Rioux (1977). Two types of linear decay models, acceleration-speed model and acceleration-time model, are reported in literature.

Acceleration-speed model Maximum acceleration occurs at speed zero and decreases linearly to zero at maximum speed as shown in Figure 2.4(b). Model presents vehicle acceleration behavior by a relationship $a = \alpha - \beta * v$ where a and v are acceleration and speed respectively, α represents maximum acceleration when speed is zero and β is slope of the line or rate at which acceleration decreases as speed increases.

Long (2000), has accounted effect of grade in the model and presented the model as $a = \alpha - \beta * v \pm Gg$, where g represents the acceleration due to gravity. Linearly decreasing acceleration model was rewritten by Long, (2000) as,

$$v = v_{max} - (v_{max} - v_0)e^{-\beta t}$$

$$d = v_{max}t - (v_{max} - v_0)\frac{(1 - e^{-\beta t})}{\beta} \quad and$$

$$v = \frac{d}{v_{max}} + \frac{(v - v_0)}{(\alpha \pm Gg)}$$

where, $\pm$ indicates time elapsed and d is distance traveled in time t. Long (2000) has further reported that it is not that easy to incorporate these equations in place of constant acceleration models since the constant accelerations are already incorporated in various simulation packages like ILLISIM and CELLSIM. He has reported that the values of β (slope) are similar for each type of vehicle and the values of α increase with decrease in weight to horse power ratio. This indicates that the maximum accelerating capacity increase with decrease in weight to horse power ratio.

Acceleration-time model Lee and Rioux (1977) presented linear acceleration model (linearly decreasing acceleration model) in which acceleration decreases as a function of time rather than function of speed. He described model as given in following equations.

$$a = a_0 + \beta t$$
$$v = v_0 + a_0 t + 0.5\beta t^2 \quad and$$
$$x = x_0 + v_0 t + 0.5 a_0 t^2 + 0.167\beta t^3$$

Though this model of Lee and Rioux (1977), is used in simulation models like INTELSIM and TEXAS. Bham and Benekohal (2002) have found a much stronger linearly decreasing relationship of acceleration with speed and hence they do not recommend the use of Lee model.

Dockerty (1966) conducted study to measure actual motorists behavior in traffic instead of conducting study on test track under controlled conditions and reported that the acceleration values are not maximum at $t = 0$ but they are zero at $t = 0$ and rapidly increase to its maximum value at a time t after $t = 0$. He measured distances at 1 second interval, commencing at beginning of the motion. The observations were separated for passenger cars, small vans, medium vans and heavy trucks. Though the report of Dockerty (1966) does not present the linearly decreasing relationship of acceleration with speed, Long (2000) discovered that a linearly decreasing model of the form $a = \alpha - \beta v$, with $\alpha = 1.88$ and $\beta = 0.1201$ fits the data reported by Dockerty (1966). His observations stated that the leading vehicles accelerated in outside travel lane a little slower. These findings of Dockerty (1966) are similar to that of Drew (1968). Dockerty (1966)'s data show that the leading trucks exhibited still slow acceleration values with α=1.49 and β=0.1455.

Polynomial model

Akcelik and Biggs (1987); Akelik and Besley (2001) proposed a nonlinear polynomial relation between acceleration and time depicted by an Equation 5.2 and shown in Figure 2.4(c).

$$a(t) = r a_m \theta (1 - \theta^m)^2 \quad m > -5 \tag{2.3}$$

where, $a(t)$ is acceleration rate at time t,in m/s^2, a_m is maximum acceleration, in m/s^2, θ is time ratio t/ta, t is acceleration time, in s, ta is time taken by vehicle to reach maximum acceleration, m is parameter that depends on initial and final speed, acceleration time and distance, and r is parameter that depends on value of m and given by Equation 4.8.

$$r = \frac{[(1 + 2m)^{2+\frac{1}{m}}]}{4m^2} \tag{2.4}$$

Researchers collected data from 1037 vehicles from urban and non urban area of Sydney Australia. The criteria they followed to collect acceleration data was initial speed, v_i between 0 and 1 km/h, time at the end of acceleration process, t_a was considered as when speed does not change for 5 sec and final speed, v_f greater than or equal to 20 km/h.

Inclusion of these criteria dealt with the whole process of acceleration. This model overcomes the unrealistic assumption of high acceleration at beginning. They pointed out following requirements for a realistic acceleration model shown in Figure 2.4(c).

- Speed profile should indicate an S shape.
- Acceleration rate must be zero at the start and end of acceleration run.
- Jerk (rate of change of acceleration with time) should be zero at the start and end of acceleration.

This model satisfies condition of zero acceleration and zero jerk at the start and end of acceleration. Acceleration rate is zero at the beginning but quickly reaches to maximum value. Similar observation was noted by Jarvis [1978].

Wang et al. (2004) reported that though Akcelik and Biggs, 1987's model gives very good fit to field data, complicated function form of this model as compared to other models (particularly linearly decreasing model) makes it inconvenient to use. Bham and Benekohal (2002) reported that the the lower acceleration at the beginning of acceleration maneuver (as reported by Akcelik and Biggs, 1987 is a temporary phenomena and ends immediately after the beginning of acceleration (hence should not be given much of the importance).

(Wang et al., 2005) presented a polynomial acceleration model given in Equation 2.5.

$$\sqrt{a} = \alpha - \beta v \tag{2.5}$$

where, a is acceleration rate, (m/s^2), v is speed in (m/s), α and β are constants based on empirical data. Wang's study is the first effort to apply regression analysis to acceleration process. This model does not provide a good fit to field observed accelerations (regression coefficient r^2 ranging between 0.359 to 0.413). Following equations show empirical constants for through and turning maneuvers of drivers respectively.

$$\sqrt{a} = 1.381 - 0.011v, \qquad r^2 = 0.424, \text{For Through maneuver}$$
$$\sqrt{a} = 1.289 - 0.009v, \qquad r^2 = 0.359, \text{For Turning maneuver}$$

The criteria for initial and final speed used in this study was, initial speed, $v_i = 0$ km/h, $v_f \geq 32$ km/h. Time of acceleration process, t_a is when speed increases less than 0.16 km/h between two one second interval.

The Wang et al.'s square root transform model, ignores initial low acceleration phase. The maximum acceleration computed using observed by Wang et al.'s model is 1.85 m/s^2 at a speed of 1.5 m/s at time $t = 1$, s for through maneuver whereas for turning maneuver the maximum acceleration is 1.64 m/s^2 at a speed of 0 m/s at time $t = 0$, s. This indicates that the Wang et al.'s model fails to predict the acceleration at the starting of acceleration maneuver.

Dual regime model

To overcome the shortcomings of constant acceleration model, two phase (dual regime) acceleration model was proposed by Bham and Benekohal (2002). It provides higher acceleration rate at lower speed and lower acceleration rate at higher speed. The reduction in rate of acceleration after achieving a particular speed (i.e. 13 km/hr) is due to engine limitation to produce more acceleration after a particular speed. Speed is evaluated similar to that single regime model using following equations for acceleration:

$$a_1 = \frac{v_n - v_{n-1}}{t} \qquad 0 \leq v < 13, m/s, \text{For Regime-I}$$
$$a_2 = \frac{v_n - v_{n-1}}{t} \qquad v \geq 13, m/s, \text{For Regime-II}$$

where, a_1 and a_2 are acceleration rates, in m/s^2, v_f and v_i are final and initial speeds, in m/s and t is time, in s.

Bham and Benekohal (2002) haven't elaborated the methodology of evaluating the speed limit at which the acceleration regime changes. The proposed speed limit of 13 m/s for acceleration regime change may not remain same in all conditions and it may vary with type of vehicle, prevailing traffic, driving conditions including road geometry, surface condition and driver habits.

2.3.2 Dynamic acceleration models

Motion of vehicle is affected by various forces that are acting on it. Resistance due to friction and tractive force are two such major forces determining performance of vehicles on road. Tractive force is produced by engine and this force is opposed by internal friction, air resistance, rolling resistance, grade resistance and frictional resistance, Drew (1968).

Earlier studies report very few acceleration models that incorporate vehicle dynamics. One such vehicle dynamic model is proposed by Rakha et al. (2004). The model computes maximum acceleration based on resultant force as shown by;

$$a = \frac{F - R}{M}$$

where, F is tractive force, R is frictional resistance and M is mass of vehicle. This equation was referred as *state-of-practice* equation of vehicle dynamics by Rakha et al. (2001). Then in 2002 (Rakha and Lucis, 2002) they accounted for various factors like grade resistance R_g, rolling resistance R_r, and aerodynamic resistance R_a.

When a constant vehicle power is assumed and knowing that acceleration is the second derivative of distance with respect to time, above equation reduces to a second-order ordinary differential equation (ODE) given below.

$$\ddot{x} = f(\dot{x}, x)$$

It is a function of the first derivative of distance, $\dot{x}$ (vehicle speed) because all forces (tractive effort, the rolling resistance, and aerodynamic resistance) are the functions of vehicle speed. In addition, the distance traveled, x, affects ODE if the roadway grade changes along the study section.

Searle (1999) also utilized vehicle dynamics to model acceleration behaviour of vehicles. The model differs from that of Rakha et al.'s model in the sense that it does not account for specific effect of resistances but vehicle performance is predicted using power constant k which is a function of engine out put and weight of vehicle as given below.

$$k = \frac{7.9 * \eta * P_m ax}{M} \tag{2.6}$$

where, k is power constant, bhp/ton, η is acceleration efficiency, $P_m ax$ is maximum engine power bhp (kilowatts), M is mass of vehicle in tons.

The acceleration efficiency (η) accounts for losses in transmission as well as resistance in motion. The power constant k is then used to predict speed and distance traveled, using following equations;

$$v^2 = v_0^2 + 2kt$$

$$v^3 = v_0^3 + 3ks$$

$$x = \frac{[(v_0^2 + 2kt)^{\frac{3}{2}} - v_0^3]}{3k}$$

This model provides reasonable approximation of speeds obtained within a specific time or over specific distance but fails to provide overall acceleration rate (which is required in simulation packages) as it is built on maximum acceleration rate. It does not describe the motion from the stop or at higher speeds.

Bham and Benekohal (2002), also commented that the model overestimates speed and distance during initial stages of acceleration. They recommended modification to Searle's model and suggested the model $k = \frac{v^2 - v_0^2}{2t} = \frac{9x^2}{8t^3} = \frac{v^3}{3x}$, which better fitted the observed data.

In yet another study Rakha et al. (2004) observed that the data sets used by earlier researchers were out of date (Bham and Benekohal (2002) used data set of 1983 and 1968 and Akcelik and Biggs (1987) used data set of 1984). The vehicle technology has changed over the years and hence the speeding and accelerating capacity of vehicles have changed. Hence, extrapolation of these results to accommodate advances in vehicle technology is not proper.

2.3.3 Other miscellaneous acceleration models

Bham and Benekohal (2002) mentioned fourteen acceleration models, which included kinematic as well as dynamic models. A list of these models is as below,

1. Gamma model.
2. Modified Searle model.
3. Linear acceleration model.
4. Two term sinusoidal model.
5. Three term sinusoidal model.

6. Haversine model.
7. Sinusoidal model.
8. Triangular model.
9. Modified triangular model.

They carried various statistical tests to decide the validity of these models for data collected by Federal Highway Authority (FHWA) in 1983. Based on these tests they concluded that modified Searle, Gamma and Dual regime model performed best to suit the data. Authors remarked that the Searle and Gamma models required detailed calibration and are difficult to use despite their ability to match field data. Therefore, they recommended dual regime model to be used in simulation models.

The polynomial model suggested by Akcelik and Biggs (1987), was tested against all the fourteen models for error tests and ranked fifth in fourteen models. Single regime model was better than Polynomial model in four out of six error tests for FHWA data and Non uniform and Two term sinusoidal model bettered in paired t-test. It is quite evident from this that effectiveness of each of the model depends on data set and comparison test applied.

Samuels and Jarvis (1978) studied acceleration behaviour of vehicles on straight, level and having smooth hot mix surface of Mulgrave Freeway in Melbourne. Radar speedometer was used to study the speeds of vehicles. The tests were carried out with varying initial and desired speed. Each test run was repeated twice to remove any driver induced bias. The recorded data was then analyzed for any variability, which were subsequently removed. The clean data was then regressed and following relation was obtained for acceleration at 5% significance level.

$$V^2 = A + BT \tag{2.7}$$

where, V is speed (km/h), T is time from commencement from speed change(sec) and A is constant. Above equation was integrated and the equation for speed was obtained as below,

$$X = \frac{(V^3 - A^{1.5})}{5.4B} \tag{2.8}$$

where X is distance from commencement of speed change (m) and A and B are constants. Authors plotted speed distance curves to asses acceleration performance. One such curve is presented in Figure 2.5.

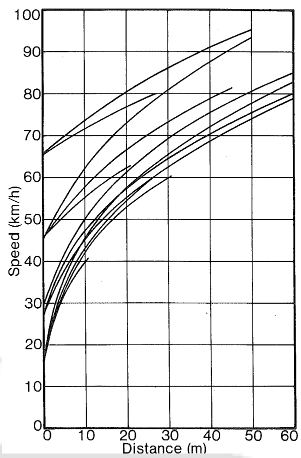


Figure 2.5: Speed-distance profile in acceleration, Samuels and Jarvis (1978).

The authors concluded that the modern vehicles had an improved acceleration performance and are better placed as regards acceleration performance compared to older vehicles.

Maya et al. (2003) suggested probabilistic approach to estimate the variation of accelerations and decelerations in traffic networks as a function of speed and road type. They developed acceleration distribution for every speed range and road type. They concluded that the road type has little effect on acceleration distribution but speed range has effect on acceleration distribution. They randomly selected 108 drivers from eight counties of South Eastern Michigan using same type of vehicle, 1996 Chrysler Concorde. The drivers were further classified into five categories viz;

1. Slow drivers
2. Planners (not so fast)
3. Close drivers
4. Extremist, satisfying more than one of above conditions
5. Flow conformist, regular drivers

Authors used sub-sample of 18 drivers each conducting 20 to 60 trips of less than 30 minutes duration. Each group of 18 drivers included two planners, three extremists, five hunters, four ultraconservatives, and four flow conformists drivers. Roads were classified as high-speed ramp, interstate highway, state highway, arterial, collector, light duty, alley or unpaved, unknown, and low-speed ramp. The data obtained from these trips was used for the purpose of developing the relationship between road type (independent variable) and acceleration (dependent variable). Authors plotted sample acceleration values (in speed range of 10 km/hr) and found that the distribution was similar to the half normal distribution with zero mean and some standard deviation (to be determined). The observed distribution and fitted half normal distribution of acceleration for all road types and driver types, were close to each other indicated by lower values of error terms. Hence authors concluded that the half normal distribution describes acceleration data to sufficient extent.

Ma and Andrasson (2007) used instrumented vehicle equipped with a GPS navigation system and an on-board computer, which can collect real-time signals from a number of sensors e.g. travel distance, speed, wheel angel, pedal pressure and so on, to study acceleration behaviour in car following mode. Authors separated the total driver car following behaviour into five regimes viz; approaching, following, continuous acceleration and breaking and opening. After undertaking multiple regression authors concluded that modeling different regimes in car-following separately is a feasible strategy and has advantages in detailed description of the general process. In addition, they found that models adopted for certain regimes including opening, braking and acceleration can be simple linear forms. However, complex behavior in stable following still needs further exploration of nonlinear models.

Viti et al. (2008) used image processing technique to retrieve speed, acceleration and deceleration data for longitudinal behaviour of vehicles in free driving and car following mode at microscopic level. Authors analyzed the empirical distributions of speeds and accelerations observed with this unique data set near and up to a few meters upstream of the stop-sign controlled intersection. The results were compared with simulation results and concluded that since the simulation programs do not incorporate real world values, the simulation results do not match with observed values.

Boonsiripant (2009) collected GPS data of position and speed and determined acceleration-deceleration rates and zone lengths for vehicles approaching and leaving intersections under un-congested traffic conditions. A series of data processing algorithms are developed, using speed profile obtained from GPS data, to measure the acceleration-deceleration behaviour of vehicles arriving and departing the intersection. Acceleration-deceleration zone lengths are determined from these algorithms and compared with zone lengths specified by AASHTO (2004). A controlled experiment was carried out using passenger cars of particular size, weight and engine power. Test drivers were asked to undertake acceleration and deceleration maneuver repeatedly at maximum capacity of vehicles. Authors observed acceleration rates as shown in Table 2.2

Table 2.2: Acceleration rates observed by Boonsiripant(2010)

Speed(m/s)	Acceleration rates(m/s^2) AASHTO (2004)	Observed acceleration rate(m/s^2)	Observed constant acceleration rate (m/s^2)
13.41	1.31	0.85	1.06
15.64	1.25	0.82	1.03
17.88	1.15	0.82	0.97
20.11	1.09	0.88	1.06

It is found that the actual acceleration rates are lower than that specified by AASHTO (2004).

Wang et al. (2011) approximated vehicle accelerations based on loop detector data and estimated fuel consumption and emissions from estimated acceleration data.

Gattis et al. (2011) observed that the tractor trailer trucks need longer acceleration lengths on freeway ramps. With increase in traffic volume on freeways, the provided acceleration length proved to be inadequate for tractor-trailer trucks.

The acceleration is termed as flip side of deceleration, (Roger P.Roess, 2004). Passenger cars accelerate at considerably higher rates than commercial vehicles. Typical maximum acceleration rates are presented in Table 2.3.

Table 2.3: Maximum acceleration rates ITE's(2000)

Speed Range (mi/h)	Acceleration rates(ft/s^2)	
	Typical Car (30 lbs/hp)	Typical Truck (200 lbs/hp)
0-20	7.5 (2.25)	1.6 (0.48)
20-30	6.5 (1.95)	1.3 (0.39)
30-40	5.9 (1.77)	0.7 (0.21)
40-50	5.2 (1.56)	0.7 (0.21)
50-60	4.6 (1.38)	0.3 (0.09)

values in bracket are in m/s^2

The authors stated that the acceleration is highest at lower speeds and decreases with increasing speed. The disparity between passenger cars and commercial vehicles is significant, considering the distance required for a car and truck to accelerate to 20 mi/h. For a passenger car to accelerate to the speed of 20 mi/h at a rate of 7.5 ft/s^2, $distance = 1.075(\frac{20^2}{7.5}) = 57.3ft$. For a truck to accelerate to the speed of 20 mi/h at a rate of 1.6 ft/s^2, $distance = 1.075(\frac{20^2}{1.6}) = 268.8ft$. This disparity of distance is striking. If a car is behind the truck at the signal, the truck will significantly delay the car, whereas if the car is ahead of truck, there will be significant headway as they accelerate, Roess(2004).

2.4 Deceleration Models

Capacity to decelerate is an important characteristic of vehicle, once breaks have been engaged. Considering distance traveled during stop is average speed multiplied by time taken to stop or;

$$d_b = \left(\frac{S}{2}\right) * \left(\frac{S}{a}\right) = \left(\frac{S^2}{2a}\right)$$

where, d_b is a breaking distance, ft, S is initial speed ft/s, a is deceleration rate, ft/s^2. If speed is expressed in mi/h,

$$d_b = \frac{1.075S^2}{a}$$

For design purpose the value of 'a' is 11.2 ft/s^2 (refer AASHTO, 2011) which is the rate of deceleration that can be developed by most of the vehicles during wet conditions of road surface.The factor 1.075 is conversion factor of ft/s to mi/h.

The rate of deceleration is used in deciding the breaking distance. Accident investigations largely depend on initial speed of a vehicle using skid marks and an estimated final speed based on damage assessment. In such cases actual values, rather than standard values, of 'a' are used.

Understanding of the deceleration characteristics of vehicle is important for various traffic engineering applications like intersection design, deceleration lane design, traffic simulation modeling, vehicular emission modeling, instantaneous fuel consumption rate modeling, etc. Traffic simulation or emission modeling requires deceleration characteristics of vehicles with wide variation in their physical dimensions, weight to power ratio and dynamic characteristics.

Majority of studies carried out in the past are restricted to study of deceleration behaviour of passenger cars or trucks. Some typical deceleration rates of passenger cars reported in literature are presented in Table 2.4. Bennet and Dunn (1995); Wang et al. (2005) presented maximum deceleration rate corresponding to different approach speed to the stop sign controlled intersection. Deceleration rates proposed/observed by most of the researchers differ with deceleration rates proposed by ITE (2009). ITE (2009) recommended deceleration rate of 3.0 m/s^2 whereas and AASHTO (2004) recommended a comfortable deceleration rate of 3.4 m/s^2). Table 2.4 summarizes the deceleration rates observed by various researchers world over (Bennet and Dunn, 1995).

Table 2.4: Deceleration rates observed by various researchers.

Author (Year)	Speed range (km/h)	Deceleration rate m/s^2)
Gazis and Herman (1960)	72	4.9
St. John and Kobett (1978)	–	1.07
Parsonson and Santiago (1980)	–	3
Bester (1981)	–	0.6 -1.9
Wortman and Matthias (1983)	48.3-80.5	2.1-4.2
Lee et al. (1984)	–	0.28-0.96
Wortman and Fox (1994)	57.6-76.4	2.5-4.0
Brodin and Carlsson (1986)	–	0.5
Watanatada et al. (1987)	–	0.4-0.6
McLean (1991)	–	0.5-1.47
Bennet and Dunn (1995)	60 - 70	1.39
	70 - 80	1.78
	80 - 90	2.22
	90 - 100	2.34
Akelik and Besley (2001)	60	3.09
Wang et al. (2005)	40 - 50	2.4
	50 - 60	2.39
	60 - 70	2.67
	70 - 80	2.52
	80 - 90	2.55

Akcelik and Biggs (1987) suggested non uniform deceleration rate depicting a polynomial behavior between deceleration and speed shown below;

$$a(t) = ra_m\theta(1-\theta^m)^2 \quad m > -5$$

where, $a(t)$ is deceleration rate at time t,in m/s^2, a_m is maximum acceleration, in m/s^2, θ is time ratio t/ta, t is acceleration time, in s, m is parameter that depends on initial and final speed, acceleration time and distance, and r is parameter that depends on value of m as shown in Equation 9.

Polynomial profile of deceleration model is shown in Figure 2.6.

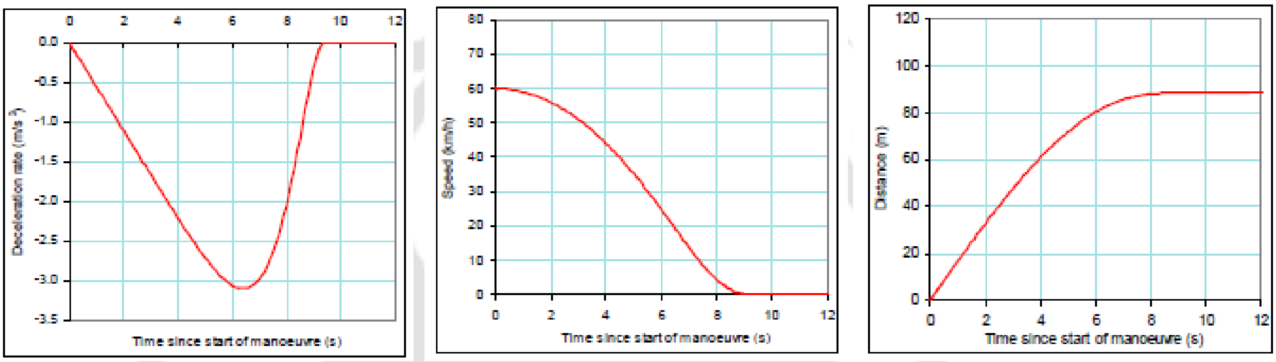


Figure 2.6: Polynomial profile for deceleration model, (Akelik and Besley (2001))

The study of Akelik and Besley (2001) observed an approach speed during deceleration as 60 km/h and a final speed of 0 km/h. Maximum and average deceleration rates observed are -3.09 m/s^2 and -1.78 m/s^2 respectively. This model implies that the drivers with higher approach speed decelerate over higher distance. This is in contradiction with the observation noted by Bennet and Dunn (1995).

Bennet and Dunn (1995) suggested a polynomial speed-time model of the form, $S = k_1 - k_2t - k_3t^2$ for deceleration maneuver depicting relation between approach speed and time during deceleration maneuver. Various models proposed by them are given in Table 2.5. Models presented above indicated

Table 2.5: Regression models by approach speeds, Bennet and Dunn (1995).

Approach speed (km/h)	Speed model	R_a^2
60-70	S=66.66-0.96t-0.18t^2	0.96
70-80	S=75.88-1.64t-0.22t^2	0.96
80-90	S=84.46-2.59t-0.0.25t^2	0.96
90-100	S=94.36-3.65t-0.3t^2	0.98
<100	S=105.69-4.95t-0.41t^2	0.97

that model coefficients increased with approach speed depicting the less deceleration distance with higher approach speed. Though these models give consistent results at higher speeds they fail to produce reproducible results at lower speeds. They also tried various models for various vehicle types.

Wang (2005) presented a square root model, given below. It is similar to one reported by Bennet and Dunn (1995).

$$\sqrt{a} = 4.6899 + 0.0505v - 7.5835t^2, \quad r^2 = 0.95$$

Contrary to Bennet and Dunn, Wang et al. concluded that there is no clear relationship between approach speed and deceleration rate. The influence of approach speed on deceleration behavior decreases with decrease in speed. The rate of deceleration remains more or less same since high approach speed drivers decelerate over longer distance and longer period.

These differences in observations may be due to fact that Wang et al. conducted study for signalized intersection where the limited road length is available for deceleration. Whereas the study conducted by Bennet and Dunn was on free motor way in New Zealand where ample road length was available for deceleration of vehicles. The drivers had a choice to choose deceleration rate and length since they were driving in free flow conditions.

Samuels and Jarvis (1978) suggested constant deceleration model given in following equation.

$$v = a_0 - a_1 t$$

where, v is vehicle speed in km/hr and t is deceleration time in seconds. a_0 and a_1 are the constants. The speed-distance profile obtained is presented in Figure 2.7.

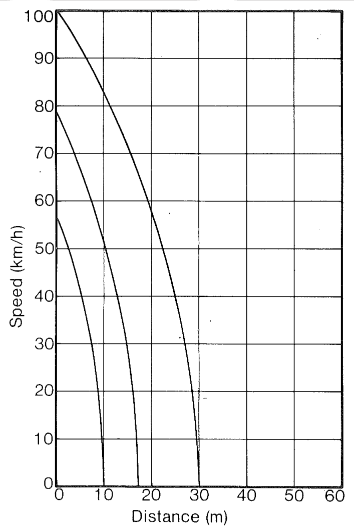


Figure 2.7: Speed-distance profile in deceleration, (Samuels and Jarvis, 1978).

An important conclusion that was drawn in Samuels and Jarvis's study is that the deceleration performance is independent of engine capacity or weight to horsepower ratio. The actual deceleration rate observed by Samuels and Jarvis was much lower than suggested by AASHTO. The curve showing this comparison is presented in Figure 2.8

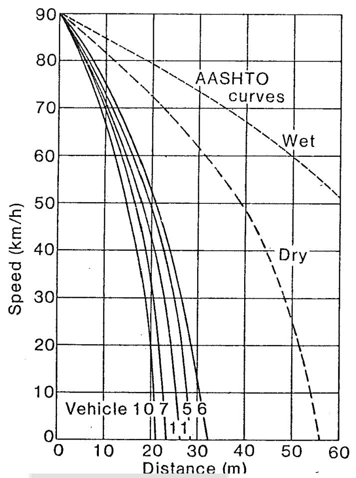


Figure 2.8: Deceleration curves-Observed and AASHTO, (Samuels and Jarvis, 1978).

Though this is the most simple model describing deceleration, many researchers claim that this is not the realistic assumption and does not reflect real driver behavior, (Akelik and Besley, 2001; Bennet and Dunn, 1995; Wang et al., 2005).

Zuriaga et al. (2010) used GPS speed data to develop more accurate operating speed models and studied speed and deceleration profiles of vehicles on tangent curves of two lane rural road segment. 85th percentile speed profiles obtained in data reduction was used to develop operating speed model. The authors developed operating speed models presented as below;

$$V_{85} = 102.048 - \frac{3990.26}{R} \qquad R^2 = 0.84, \text{For curve radius less than 400m}$$

The deceleration model obtained by authors is;

$$d = \frac{V_{85(\mathrm{i})}^2 - V_{85(\mathrm{i+1})}}{2D}$$

where, $V_{85(\mathrm{i})}$ and $V_{85(\mathrm{i+1})}$ are operating speeds at location (i) and (i+1) and D is distance between location (i) and (i+1). Finally authors concluded that simple subtraction of operating speed underestimates the actual values of speed differential. Its evaluation can be done accurately from the observed individual continuous speed profiles.

2.5 Effect of Driver Behaviour on A/D Pattern

Effect of driver behavior on speed and acceleration is a complex problem, needing higher understanding of driver belief and attitude towards speeding. This understanding would lead to effective geometric design of highway systems and would further lead to better knowledge of individual vehicle behavior and inter vehicle interaction, resulting in better microscopic and macroscopic model formulation (Mehmood, 2009).

Speeding and acceleration and deceleration behavior of drivers largely depends on road attributes. Road attributes such as pavement performance, lane width, horizontal and vertical alignment curves, the number of lanes, and the availability of shoulders affect the speeding and acceleration and deceleration performance of drivers (Friedman, 2006). Another important attribute that affects the driver speeding and acceleration and deceleration behavior is higher performance vehicles equipped with advanced systems. Drivers feel that they can stop fast enough to avoid crash. This results in change in speeding and acceleration and deceleration behavior of drivers (Silcock D., 2000).

Estimation of driving behavior with regard to speeding patterns can be assessed by actual observation of driver speed under various set of conditions like different traffic situations and road classifications. However actual behavior observation is rather financially and operationally very difficult and rather impossible (Mehmood, 2009). A self reported behavior of drivers can be an acceptable surrogate for actual behavior.

(Mehmood, 2009) studied driver speeding behaviour on roads of Al Ain (United Arab Emirates). Though observation of actual driver behaviour on roads under various conditions including different traffic conditions and road classifications is required to study the driver speeding behaviour, the self revealing questionnaire method is used as acceptable surrogate for the method. The data was collected based on the questionnaire designed for the research. Data was collected for three years from 2005 to 2007 in two main sections, one having demographic data like gender, age, nationality, education level, driving experience, location of driving, and type of vehicle and the other having data regarding attitudes on a 5 point Likert-type scale from 'strongly agree' to 'strongly disagree'. About 650 drivers were selected to respond out of which 67% were male and 33% were female. About 36% of the respondents were found to drive more than 30,000 km per year.

The results indicated that the attitudes and beliefs of drivers in Al Ain are significantly associated with self-reported speeding behavior. The speeding attitude of drivers in Al Ain is largely due to low probability of being caught for speeding, the ineffective mechanism for collecting speeding fines, the imitation of other drivers behaviors, and the lack of awareness about the consequences of speeding.

Fildes (1991) in Monash University, undertook study of driver speeding behaviour and revealed that drivers under age 34 were excessive speeders whereas drivers above age 55 were excessively slow travelers. These observations were true for all road geometry, straight and curved. Sex of the driver, however, was not associated with speeding.

Drivers in Korea were studied for speed selection by Kang (1998) taking into account factors such as personal, vehicle, attitudinal and trip characteristics. Male drivers with higher incomes tend to drive faster as compared to drivers with less income. Experienced drivers drove faster and trip distance and frequent road use were also important factors in choosing speed.

Russell Familar (2011) investigated the driver speeding behaviour using multilevel modeling approach. The primary source of data used for this study was second-by-second GPS data collected from 147 motorists in Sydney as part of a wider investigation into driving behaviour. The objectives of the study included observation of changes in driving behaviour in response to a charging regime based on kilometers driven, night-time driving, and speeding. The data was collected for 10 weeks in two phases, before and after, for five weeks each. In before phase the regular traffic observation was done and in after period monitoring was done. The 'before' data is used to analyze the speed and other parameters. The GPS data information was captured about the driver, vehicle, trip and weather conditions (specifically whether it was raining). In addition to driver demographics, measures of personality correlated with (self-reported) speeding behaviour were collected, including Aggression, Excitement, and Altruism measured on a ten point scale ranging from Not at All to Very Much.

Belz and Aultman-Hall (2011), collected data from 35 instrumented vehicles driven by drivers of two age groups; 19 drivers of age group over 70 years and 16 drivers of age group 20 years to 35 years. The data was collected on 7.2 miles (11.58 km) route familiar to drivers which enabled un-constrained driving. Data was collected using second by second GPS instrument. Acceleration of vehicles was recorded using axis accelerometers. A sample speed profile showing speeds from young and old drivers is presented in Figure 2.9, Authors concluded that there are statistically significant differences between

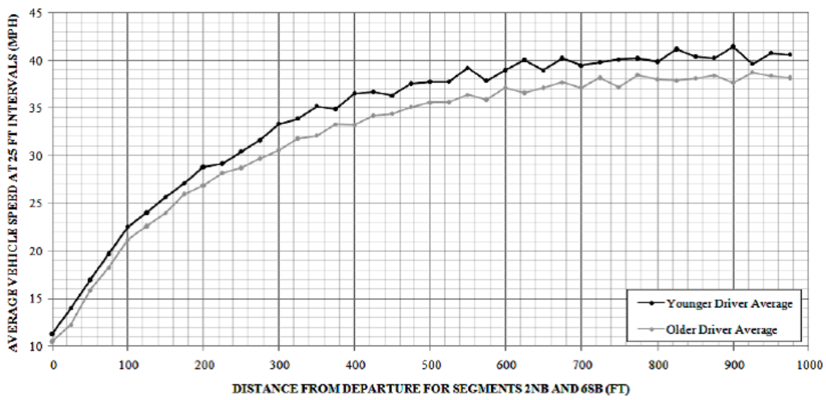


Figure 2.9: Average speed profile , (Beltz *et al.*, 2011).

speed and acceleration patterns for the older and younger drivers and that age accounts for a relatively large portion of the variation. This study has practical implications in that it identifies the roadway conditions under which younger and older drivers have marked differences. These differences indicate higher speeds for the younger drivers as expected (2.3 mph higher in 35 mph zones and 3 mph higher in 25 mph zones on average. Authors found effect of speed limit on driver speed and concluded that in 35 mph zones, the speed of younger drivers is influenced 64.5% more than older drivers. The accelerations of younger drivers are 17.3% greater than those of older drivers. In 25 mph zones, older driver speeds were affected by grade 87% more than younger drivers. From behavioral perspective the driving styles between age groups are dependent on road geometry. Hence age is an important variable in defining driver topology. The tailpiece emission also had an effect of driver age and driving style of drivers.

El-Shawarby et al. (2011) characterized driver deceleration behaviour in a controlled field environment on the onset of yellow signal at high speed signalized intersection approaches suing in-vehicle differential GPS. Study included effects of driver gender, age, roadway grade, mean approach speed, platoons scenarios (leading, following, or alone), and time-to-intersection (TTI) on the driver deceleration levels. study results indicated that deceleration levels are significantly higher than the 3 $m/s2$ deceleration level used in the state-of-the-practice traffic signal design guidelines. Ironically, mean deceleration level is more in the range of 3.6 to 4.1 m/s2. The driver deceleration level is found higher at shorter TTI. Older drivers (60 years of age or older) employ higher deceleration levels than younger drivers (under 40 years of age) and middle-aged (between 40 and 59 years old) drivers. Male drivers tend to show slightly higher rate of deceleration.

Yan et al. (2007) conducted driving simulator study to verify the effect of driver age and gender on gap acceptance phenomena and deduced that the age and gender have effect on left-turn gap decision, drivers acceleration rate, steering action, and the influence of the gap-acceptance maneuver on the vehicles in the major traffic stream. Compared to younger drivers and middle-age drivers, the older drivers tend to select larger gaps to make left turns, turn the steering wheel more slowly, and keep a further clearance distance from the following car. The conservative driving attitude of older drivers would compensate driving ability decrease. The results also showed that the male drivers accepted smaller gaps depicting conservative attitude of female drivers.

2.6 Effect of Speed Behaviour on Vehicular Tailpipe Emission Rates

Vehicle fuel consumption and emissions are important aspects in transportation planning process. It is estimated that about 45% of pollutants released in United States of America are from vehicle tail pipe (NRC) (1995). The intelligent transportation system incorporates energy and emission emphasized measures. However, the impact of these measures is not properly quantified. Factors that affect vehicular emissions can be classified into six broad categories;

1. Travel related
2. Weather related
3. Vehicle related
4. Roadway related
5. Traffic related

6. Driver related

The travel related factors account for the distance and number of trips traveled within an analysis period while the weather related factors account for temperature humidity and wind effects. Vehicle related factors include engine size, condition of engine, weather the engine is fitted with catalytic converter, functioning of air conditioner and soak time of engine.The roadway related factors include road grade and surface roughness while traffic related factors include vehicle to vehicle and vehicle control devices interactions. The driver related factors include driver behaviour and aggressiveness.

Since this study addresses the effect of speed, acceleration and deceleration (which are traffic related factors) on emission of vehicles, the literature pertaining to this is only reviewed. S.Pandian (2009), has reported literature regarding effect of these traffic related factors on vehicular emissions. The summary is presented below.

2.6.1 Emission rate models

Ahn et al. (2002) reported various shortcomings in existing emission models such as the models incorporated travel related, vehicle related and weather related factors but ignored roadway traffic and driver related factors. Hence current emission models are unable to evaluate environmental impacts of operational level projects where changes in traffic before and after project are critical. They developed a model to overcome these shortcomings by incorporating traffic and driver related factors. These models use instantaneous speed and acceleration levels to estimate emission levels.

The vehicles were tested in field for their maximum operating boundary and subsequently emission and fuel consumption rates were measured in laboratory on a chassis dynamo-meter within vehicles feasible speed and acceleration envelop. Vehicle energy consumption and emission rates are generated for instantaneous speed and acceleration which included emission measurements relating hydrocarbon (HC), oxides of nitrogen (NO_x) and carbon monoxide (CO). Five light duty automobiles and three light duty trucks were included in study. Vehicle acceleration values ranged from -1.5 to 3.7 m/s^2 at increments of 0.3 m/s^2. The vehicle speed ranged from 0 to 33.5 m/s at increments of 0.3 m/s. The models developed in this study are applicable only in this envelope of speed and acceleration. The important observation in this study is that the vehicle emission rate increases with increase in speed even though the vehicle is in deceleration mode. The authors developed a third degree polynomial relation between various parameters that affect emission rate of vehicle. The model developed by authors is found to have different behaviour in acceleration and deceleration. The reason being during acceleration vehicles exert power whereas in deceleration vehicles do not exert power. Hence authors developed separate models for acceleration and deceleration. However, the model suffered following limitations,

1. Models are applicable to light duty vehicles only.

2. Models are applicable to hot stabilized conditions and do not consider START condition.

3. Models are confined within envelope of Oak Ridge National Laboratory data.

Cappiello et al. (2002) developed statistical model, EMIT, (EMIssions from Traffic) for instantaneous emissions (CO_2, CO, HC and NO_x) of light duty vehicles. This model is composed of two modules as shown in Figure 2.10 Depending on vehicle category and second by second speed and acceleration of

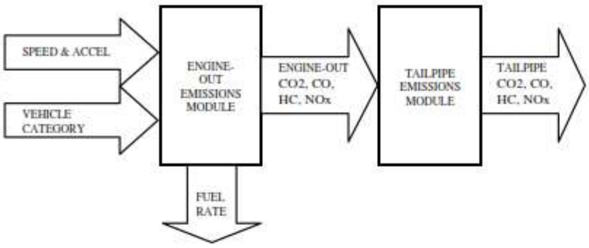


Figure 2.10: Model structure, (Alessandra *et al.*, (2002)).

vehicle, first module of model predicts the second by second fuel consumption and engine out emissions which are input to second module which predicts second by second tailpipe emissions. The authors have used load based formalism for generating the model. A typical fuel rate (FR) model proposed by author is given below;

$$FR = \begin{cases} \phi\left(K.N.V + \frac{P}{\eta}\right) & \text{if } P > 0, \\ K_{idle}.N_{idle}.V & \text{if } P = 0, \end{cases}$$

where, ϕ is fuel air equivalence ratio, K is engine friction factor in kJ/rev/liter, N is engine speed in rev/s, V is engine displacements in liters, η is engine indicated efficiency, K_{idle} is constant idle engine factor, N_{idle} is constant idle engine speed in rev/s and P is engine power output in kW.
When the engine power is zero, fuel rate is a small constant value. Otherwise fuel consumption depends on engine speed and demanded power. The authors modeled tailpipe emission as a fraction of engine out emission that leave the catalytic converter. Tailpipe CO_2 which not much different from engine out CO_2 is modeled as (refer Equation 2.9),

$$TP_{CO_2} = \begin{cases} \alpha_{CO_2} + \beta_{CO_2} + \delta_{CO_2} v^3 + \zeta_{CO_2} av & \text{if } P_{tract} > 0, \\ \alpha'_{CO_2} & \text{if } P_{tract} = 0 \end{cases} \tag{2.9}$$

where, v and a are speed (m/s) and acceleration (m/s^2) respectively.

Yi et al. (2004) developed micro-scale emission models in two steps. In first step light duty vehicles were classified as per criteria based on vehicle size, model year and emitter type. The proportion of vehicles in stream were decided on the basis of national level vehicle distribution. In second step micro-scale emission models were developed for each emission type using least square regression. The emission of type m that is produced by a vehicle with size i at time t, $e_{i,m}(t)$ is estimated as;

$$e_{i,m}(t) = \sum_{j} \sum_{i} e_{i,j,k,m}(t).P_{i,j,k}$$

Authors opined that the vehicle size is the only parameters that is related to vehicle emission and specified it explicitly in model.

Frey et al. (2001) used portable instrument $OEM - 2100^{TM}$ to measure on road tailpipe emissions of CO, NO, HC and CO_2 on a second by second basis during actual driving. The portable instrument used measured engine parameters such as vehicle speed, engine rpm, engine coolant temperature, manifold absolute pressure, percent of wide open throttle and open loop/closed loop flag. The data was recorded for gasoline vehicles. After analyzing data authors concluded that emission rates differ with the type of driving. Largest emission rates are associated with acceleration of vehicles. In other modes such as cruising, deceleration and idling the emission rates are low. In idling, emission rates are lowest followed by deceleration and cruising. This is true for all emitters such as CO, NO, HC and CO_2. The average modal emissions for a 1999 Ford Taurus Car are shown below, (refer Figure 2.11).

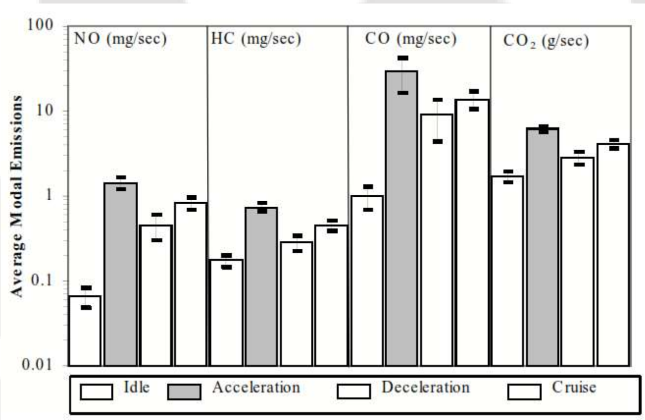


Figure 2.11: Average Modal Emissions, (H.Christopher Frey *et al.*, (2001)).

Greenwood et al. (2007) studied the effect of traffic congestion on fuel consumption and vehicle emissions. They concluded that since in congested condition the acceleration noise is significantly more as compared to free flow conditions, the emission rates are affected by congestion. Particularly the oxides of nitrogen NO are emitted more in congested traffic as compared to free flow traffic.

While discussing effect of speed on vehicular emission, S.Pandian *et al.*(2009) observed that emission factors derived in laboratories do not match with the real world emission. They also endorsed the view of H.Christopher Frey (2001) that the vehicular emission depends on mode of travel i.e. acceleration, cruise, deceleration and idling. Other speed related factors that affect emission are average acceleration, deceleration, mean length of driving period from start to stop, average number of acceleration-deceleration changes within one driving period etc.

Rakha and Ding (2003) observed that the hydrocarbon (HC) emission followed a convex function and higher cruise speed witnessed higher (HC) emission. The variation in (HC) emission rate constituted a difference in the range of 300% over a speed range of 10-120 km/h cruise speed. The minimum carbon monoxide (CO) rate was observed at a cruise speed of 20 km/h and maximum at 120 km/h with a variation of 600%. The oxides of nitrogen (NO_x) too followed a trend similar to (CO). As the facility speed limit increases, a major increase in emission rates is witnessed. When there is 1% increase in vehicle fuel consumption due to speed limit change, the increase in (HC) emission is 50% and (CO) emission is 100%. The authors also concluded that the impact of vehicle stop is minor on fuel consumption (10%) but emission suffers major effect of stop (100%). The effect of acceleration on fuel consumption and emission was observed by the authors and similar to effect of speed, it was concluded that the acceleration rate has a minor effect on fuel consumption but the emissions (CO and HC) are highly sensitive to acceleration rates. The high emission rates are associated with bypassing the catalytic converter at higher acceleration to avoid knocking. The NO_x however demonstrated that its emission rate decreases with increase in acceleration rate. These observations are shown graphically in Figure 2.12. Typically, (HC) emission rates are more sensitive to acceleration levels as compared

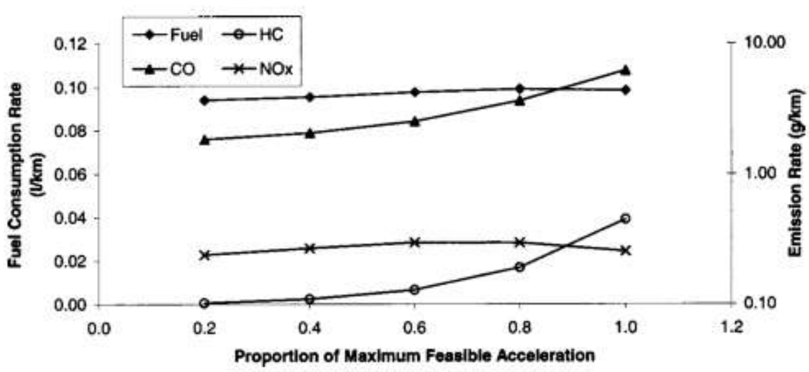


Figure 2.12: Variation in fuel consumption and emission rate as a function of acceleration level, Rakha and Ding (2003)

to other emissions and (NO_x) displayed a non linear behaviour with acceleration rates. The authors observed that the fuel consumption emission rates are generally insensitive to deceleration rates.

While writing discussion on this paper, Minocha (2005) raised following points,

1. Engine speed should be considered while modeling fuel consumption and emission.
2. Feasible acceleration levels reported in above study is 1.5 m/s^2 which is very low compared to reported in study.
3. Roadway related factors should have been taken in account to increase the robustness of model.

However, the authors opines that since vehicle speed is a linear function of engine speed in a particular gear, the vehicle speed shall suffice the purpose for emission model. The other acceleration level up to 3 m/s^2 is used by author in other work. The roadway characteristic is kept constant by the author.

2.7 Effect of A/D Rates on Control Delay

Traffic at signalized intersection is controlled by the timings of red, green and amber signals. When vehicle approaches intersection, deceleration delay takes place, when it stops at intersection stop delay occurs and when it leaves intersection, the acceleration delay occurs till it achieves original speed. Deceleration and acceleration delays, however, are not easy to capture without the help of sophisticated devices providing high resolution vehicle speed profiles, such as second-by-second speed an position data.

In contrast, stopped delay is relatively easy to measure in the field, which may explain why stopped delay has long been the primary field measured intersection delay and why control delay has been estimated based on the measured stopped delay. However, stopped delay does not reflect every aspect of intersection performance affected by traffic signals. The relationship between stopped delay and other delay components may not be established in a single all encompassing function, due to site-specific factors affecting the relationship, such as signal timing and driver characteristics.

Indeed, three different sources reported three significantly different relationships between control delay and stopped delay as follows.

1. Stopped delay = 0.76 × Control delay, (AASHTO, 2004)
2. Stopped delay = 0.96 × Control delay − 19.3, (Quiroga and D.Bullock, 1999)
3. Stopped delay = 0.58 × Control delay − 2.31, (Mousa, 2002)

Such different formulations of control delay makes it necessary to revisit the concept of control delay by way of formulating it using fresh data at signalized intersection.

2.8 Concluding Remarks

After reviewing literature pertinent to the topics of study in this thesis, following conclusions could be drawn;

1. Existing acceleration models were developed using out of date data set (for example - Bham and Benekohal (2002) used data collected in the year 1985, Akcelik and Biggs (1987) used data collected prior to year 1987, RaiChowdhury and Rao (1989) used data collected in the year 1989, etc.). The vehicle technology and driver habits changed since then.

2. Data used for developing existing acceleration/deceleration models was collected using less precise devices like radar gun (Searle (1999) used radar gun to track vehicle speed), loop detectors (Bennet and Dunn (1995) used axel (loop) detectors for acquiring vehicle speed and classification data for deceleration models), lidar gun (Gattis et al. (2010) used lidar gun to collect truck acceleration data at weighing station). This sometimes resulted in reporting of contradictory findings of model calibration and validation (Brackstone and McDonald, 1999).

   Data collection methods contained human intensive methods which are prone to errors. For example, RaiChowdhury and Rao (1989) and Dey and Biswas (2011) used time required to travel a predefined section to arrive at speed and then acceleration. Observers were stationed at these sections and measured time using stop watch. The data collected by Arasan and Koshy (2005) for reporting acceleration values of various vehicle types (to use as an input in simulation model) involved use of stop watch for recording vehicle speed from its speedometer. These data collection methods involved intensive human efforts which are prone to error in recording travel time.

3. Majority of studies have reported acceleration behaviour of passenger cars only. The acceleration models reported by Wang et al. (2004), RaiChowdhury and Rao (1989), Akcelik and Biggs (1987), Akelik and Besley (2001) and Bham and Benekohal (2002) pertain to passenger cars. In India however, the traffic stream is heterogeneous comprising of vehicles like truck, motorized three wheeler, motorized two wheeler and non motorized vehicles apart from car, enjoying the same right of way (lane) with weak lane discipline. These vehicles (other than car) have lesser accelerating capability and interfere with movement of vehicles with high acceleration capability .

4. Most of the studies report maximum acceleration capability of vehicles. The studies undertaken by Akcelik and Biggs (1987), Akelik and Besley (2001) and Bham and Benekohal (2002) report vehicle maximum acceleration capability. The maximum acceleration capability of vehicles is used by drivers during emergency only. Rest of the time drivers drive with normal accelerations which are substantially lower than maximum acceleration of vehicles.

5. The studies reporting deceleration models are very sparse. Akcelik and Biggs (1987), Bennet and Dunn (1995) and Wang et al. (2005) only reported deceleration models for passenger cars and light commercial vehicles. Deceleration is an important input required to decide the stopping distance of vehicles at signalized intersection.

6. Very few studies are found to report the acceleration models of vehicles plying on Indian roads. Most of the studies on acceleration models are undertaken on roads in United States of America (Wang et al. (2004), Rakha et al. (2001) and Zuriaga et al. (2010)) and Australia (Akcelik and Biggs (1987) and Akelik and Besley (2001)). The vehicle characteristics as regards engine type, capacity, use of emission control equipment etc, and driver characteristics as regards driver age (in

USA and Australia drivers are allowed to drive up to older age of 75 years) and habits are different as compared to their Indian counterpart.

7. No study is found in literature on effect of speed, acceleration and deceleration on vehicular tailpipe emission of vehicles plying on Indian roads.

8. Though deceleration capability of vehicle is an important parameter deciding stopping distance and delay at signalized intersection, no study reported deceleration of vehicles on Indian roads.

9. Many authors (Snare, 2002; Long, 2000) reported that the vehicle speeding (and hence acceleration/deceleration) depends on driver attributes like age, gender and mood etc. But no study was found in literature quantifying the effect of these and other (like driver education) driver attributes on vehicle acceleration/deceleration.

Hence, the study is undertaken to bridge some of the gaps that are found in present literature.

Chapter 3

Methodology

3.1 General

Acceleration/Deceleration (A/D) characteristics of vehicles are important for intersection design, deceleration lane design, traffic simulation modelling, vehicular emission modelling, instantaneous fuel consumption rate modelling, etc. To study the A/D behaviour of a vehicle one needs to observe the speed and position data of vehicle with time. The A/D behaviour of vehicles can be frequently observed on signalized intersection. Vehicle approaching to a signalized intersection has to decelerate and stopped during red phase of signal. Onset of green phase vehicle start accelerating to achieve its desired speed. Figure3.1 presents the time-distance and speed-time diagram of a vehicle movement at signalized intersection. A vehicle's cruising, deceleration, stopping, acceleration and cruising stages can be seen in the Figure3.1 on its approach to a signalized intersection.

Therefore, data on A/D pattern of vehicles can be well collected by observing the vehicle 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 the Figure 3.2 showing a typical scenario at intersection). As can be seen from the figure, the congestion condition in front of the queues at intersection 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) and Belz and Aultman-Hall (2011). Therefore, the present study also collected the vehicle A/D data over selected stretch of road under controlled conditions.

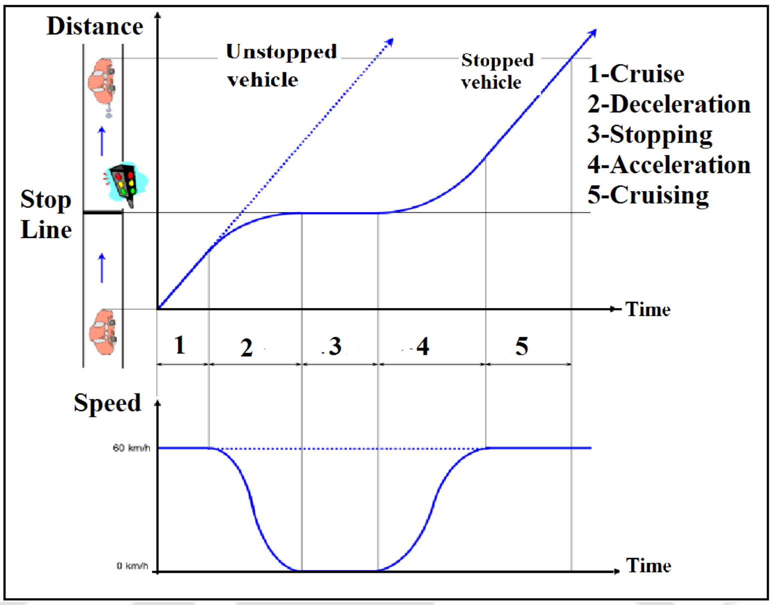


Figure 3.1: Time-distance and speed-time diagrams showing the deceleration, waiting and acceleration manoeuver of a vehicle at signalized intersection.

Figure 3.2: A photograph showing heterogeneity and congestion condition in front of the queues at urban signalized intersection at Nagpur, India)

3.2 Data Collection

3.2.1 Site selection

As discussed in previous section, A/D behaviour data was collected on selected stretch of road under controlled conditions instead of signalized intersection. Road stretches for the study were selected based on following factors:

1. The study stretch should have free flow of traffic (to avoid impact of neighboring vehicles on acceleration-deceleration).
2. It should be access controlled to avoid any obstruction to speeding.
3. Road geometry should be fairly straight (to have constant effect of road geometry on acceleration-deceleration of vehicles).
4. Entire road surface should be in good condition to provide constant effect of rolling resistance.

Based on above criteria, two study stretches were selected: (i) Nagpur- Aurangabad highway at Wardha and (ii) approach road of Indian Institute of Technology (IIT) Guwahati. The data for trucks, motorized two wheelers and motorized three wheelers were collected at first study stretch near Wardha, India. Whereas the observations for diesel and petrol cars were recorded at second stretch near IIT Guwahati. Details of both study stretches and collected data are provided in following subsections.

3.2.2 Data collection at Wardha study stretch

First study stretch of 1.5 *km* length was located at outskirts of Wardha town (80 *km* from Nagpur) on four lane Nagpur-Aurangabad highway in India (refer Figure 3.4). Horizontal layout of study section was fairly straight with some minor horizontal curvature which didn't affect speed of vehicle. Vertical layout of the stretch was fairly flat and surface condition was good. Road was free from side interruptions (since there was no human settlement on selected stretch) and also elevated 1.5 *m* from surrounding normal ground. The data collection on this stretch was carried out from 19^{th} August, 2009 to 30^{th} May, 2010.

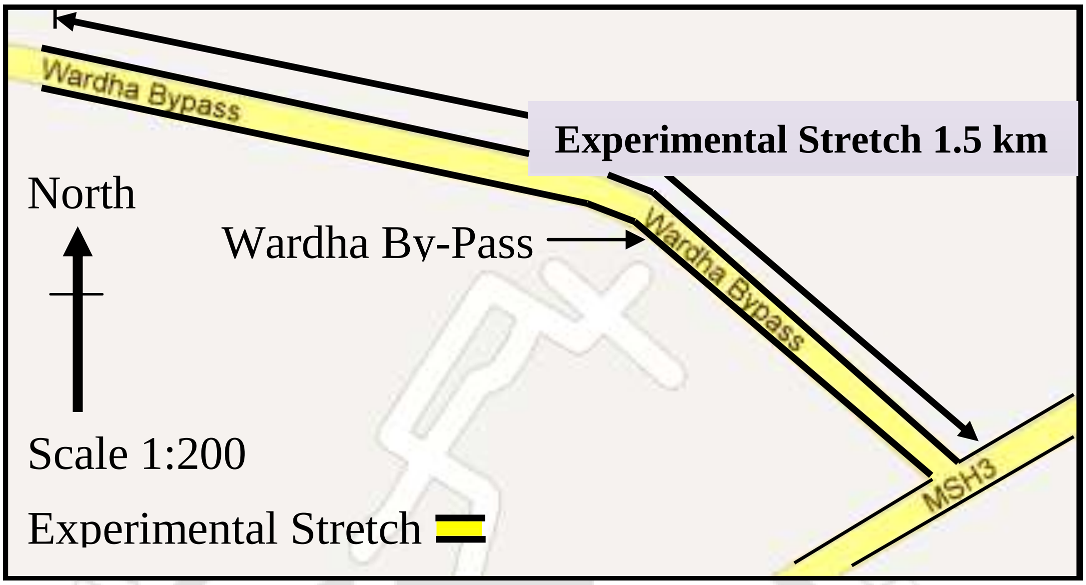


Figure 3.3: Location of stretch for data collection at Wardha, India

All variety of vehicles (like truck, car, motorized three-wheeler and motorized two-wheeler) are generally observed on this stretch. It was noticed that car drivers were hesitant to stop when requested by volunteers. Since most of the cars are owner driven, they did not allow volunteers to sit in the car to collect data using hand-held Global Positioning System (GPS) device. Hence A/D data collection of cars were carried out on hired cars driven with different drivers at second study location near IIT Guwahati. For other vehicles types (like truck, motorized three-wheeler and motorized two-wheeler) volunteers were allowed to sit in and collect the A/D data using GPS (GeoExplorer 2008 model) with 1 Hz data logging frequency. Figure 3.5 presents a photo of GPS used in this study.

Randomly, some vehicles (of all types except cars) from real traffic stream were selected and asked to participate in this study. Drivers were explained about the study and ensured that collected data will be used only for research purpose and not for enforcement purpose. 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) in earliest possible time and they were allowed to drive at their maximum speed for some time. Afterwards they were asked to deceleration quickly to the stopped condition. This complete one cycle of acceleration, cruising and deceleration manoeuver of the vehicle. This acceleration and deceleration manoeuver of vehicle replicates the lead vehicle behaviour at signalized intersection. Four such cycles of experiments were conducted for each vehicles and data of last cycle was used for further analysis. This helps in reducing the driver novelty factor.

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

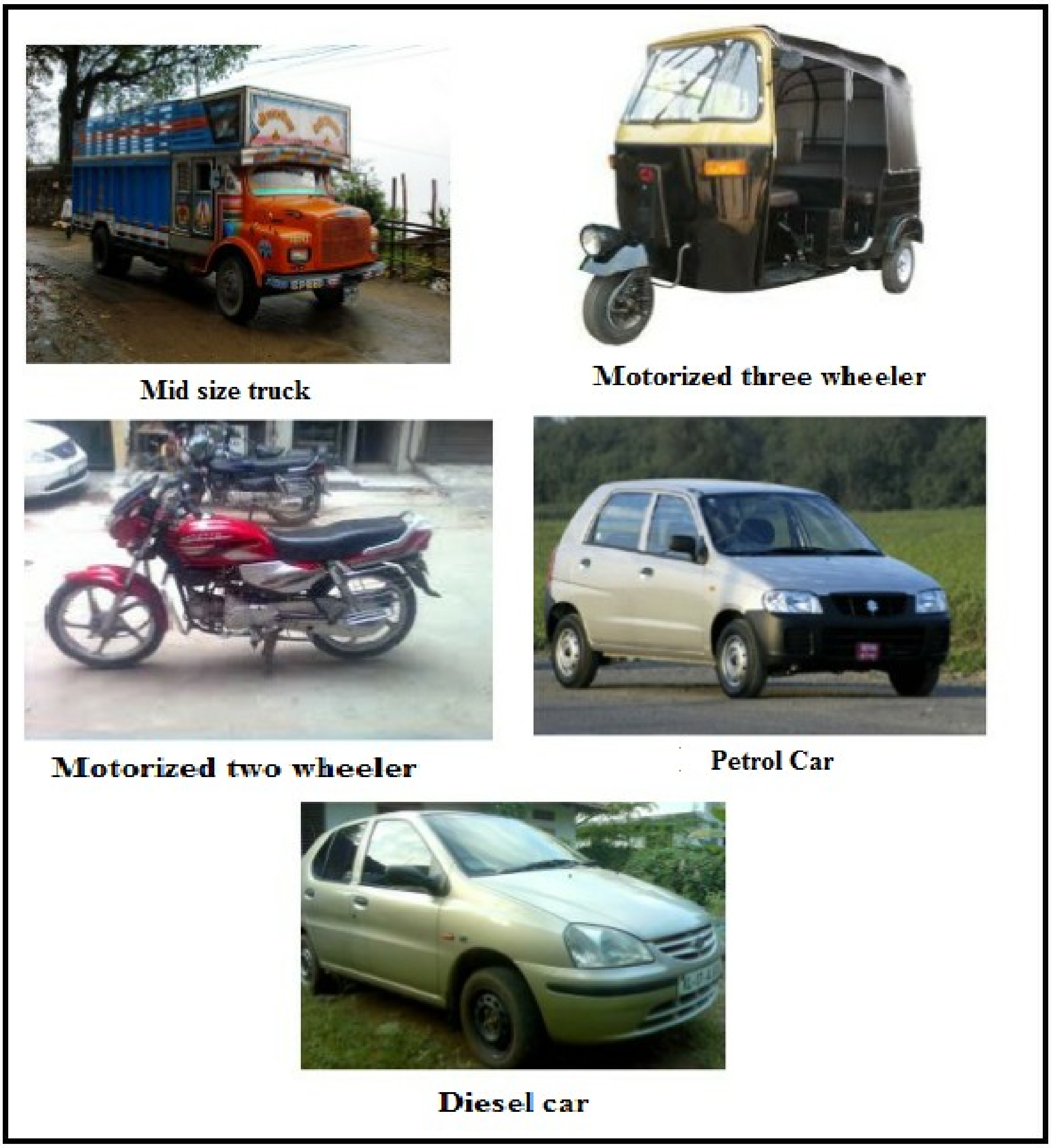


Figure 3.4: Various vehicle types observed in this study

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.

To study the effect of drivers' attribute on their A/D pattern, apart from GPS data, driver and vehicle attributes data were also recorded on a designed response sheet a copy of Driver response sheet is attached as Appendix C to this thesis). Response sheet was divided in three sections. First section

Figure 3.5: $TRIMBLE^{TM}$ Global Positioning System device used in this study.

contained the information regarding date and time of study, weather condition, volunteer name, etc. The second part contained driver information like name, age, driving experience, education, income, marital status, average driving hours and kilometers per day etc. The last part contained vehicle details like loading capacity, actual load, number of occupants, vehicle type and make, model and year, registration no., etc.

Volunteers were recruited for this data collection and were paid fifty rupees per trip of a vehicle. Volunteer interviewed each driver for necessary information and recorded his responses on the designed response sheet. The drivers were explained about the nature of experiment and were ensured that results will be used only for study purpose and not for enforcement. The subject drivers were paid fifty rupees per vehicle trip. This study were carried out along with A/D behaviour study of vehicle and vehicle speed and position data were collected .

As the driver behaviour study was time consuming and requires fund, this study was conducted only for truck drivers among all vehicle type considered at this study location (truck, motorized three wheeler and two wheeler). Among the truck vehicle category, only mid size trucks (i.e. 12 ton loading capacity) were considered for this study as they were observed in majority on this study location. These trucks were randomly chosen from trucks plying of the study stretch. In order to limit the impact of engine condition and engine parameters on their acceleration, only good condition trucks, manufactured after January, 2009 onwards and having mileage between 50,000 km to 70,000 km were selected for analysis among the observed trucks.

Vehicle data was used for segregating good conditioned mid-size trucks from other trucks moving on same facility and further those truck trips were segregated according to their drivers' attributes. Details of collected data and its analysis methodology are provided in subsequent sections of this chapter.

3.2.3 Data collection at near IIT Guwahati study stretch

This study stretch was located near the main entrance gate of IIT Guwahati, India. It connects the IIT Guwahati to National Highway (NH) 31. The characteristics of this experimental stretch confirms to the criteria set above. This stretch is similar to first study stretch (near Wardha) in regards to road geometry, number of lanes, surface conditions, horizontal and vertical profile of the road. Figure 7.2 shows the location of second stretch near IIT guwahati for data collection.

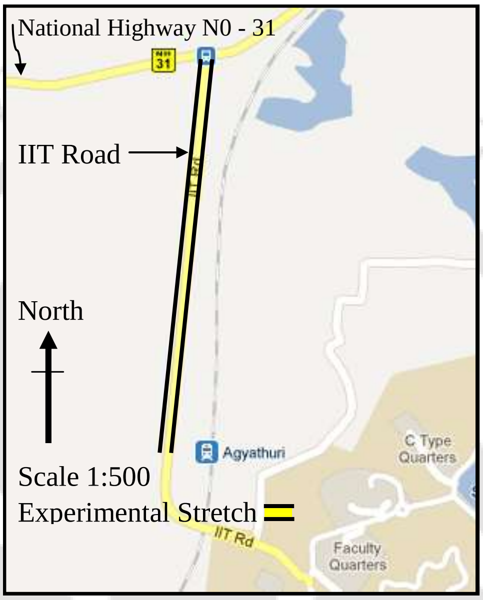


Figure 3.6: Location of stretch for data collection near IIT Guwahati, India

Data collection work at IIT Guwahati test section was carried out in November, 2010 and May 2011. Hatchback cars are in majority among cars in Indian traffic stream. Therefore two types hatchback cars, viz; Hyundai Santro (petrol car) and Tata Indica Vista (diesel car) were considered for this study.

Cars speed and position data were collected using V-Box (a kind of GPS) with 10 Hz data logging frequency (refer Figure 3.7). This equipment is not used in first location because of following three reasons:

Figure 3.7: V-Box device used in this study

1. V-Box requires 20 to 30 minute installation time which increases the delay of participating vehicles significantly.

2. Long installation time and complex connections of V-Box may increase the bias in the driver behaviour

3. V-Box requires electrical power to operate

At the second location, cars were hired for this study and VBox was connected to car plug to get power supply. Drivers were briefed about the experiment and told that collected data will be used only for study purpose and not for enforcement purpose. Different vehicles were run on rotation basis to avoid the driver fatigue effect. Similar to previous experiment, drivers were first asked to accelerate quickly form stop condition, then cruise for some time and finally decelerate to stopped condition in shortest possible time. Similar experiments were conducted on 4 numbers of both type of cars (i.e. Hyundai Santro and Tata Indica Vista) over different days in in November, 2010 and May 2011. Vehicle's position and speed data during experiments were collected using VBox at 10 Hz rate.

3.3 Methodology of Data Analysis

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. Similar to Rakha *et al.*(2004), exponential smoothing algorithm was used for smoothing of GPS data. Following steps were used in analysis of collected GPS data for A/D study:

1. Acceleration, cruising and deceleration manoeuver data were segregated form each trip for all vehicle classes.

2. Acceleration was computed from second by second GPS speed data collected during acceleration manoeuver data, using Equation 3.1:

$$a_{t2} = \frac{v_2 - v_1}{t_2 - t_1} \tag{3.1}$$

   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. This criteria is used to separate the acceleration manoeuver data from each trip GPS data.

3. Similar to acceleration calculation, deceleration was computed from second by second speed data obtained from GPS during deceleration manoeuver using Equation 3.2:

$$d_{t2} = \frac{v_1 - v_2}{t_2 - t_1} \tag{3.2}$$

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 3.2 are greater or equal to 0.1 m/s^2 for five consecutive seconds. At the end of deceleration process vehicle's speed become zero. This criteria is used to separate the deceleration manoeuver data from each trip GPS data.

4. Scatter plots of speed vs time, A/D vs time and A/D vs speed were generated from all trips of A/D manoeuver from GPS data of each vehicle class.

5. To get the average speed profile from speed vs time scatter plot, speeds were averaged over every second. The average speed profile so obtained was termed as *idealized speed profile*. Similarly, idealized A/D profiles were also generated for all vehicle class.

6. For A/D behaviour modelling idealized A/D - speed relationships (i.e. average A/D variation with speed) were obtained by averaging A/D values over 1 m/s speed interval for each vehicle class. These idealized A/D - speed relationships were used to develop the A/D model.

7. Developed A/D models were evaluated using various statistical methods.

To study the effect of driver attributes on their A/D pattern, following methodology was adopted:

1. Driver attributes affecting A/D pattern were identified through opinion survey of transportation professions.

2. Drivers/vehicles' trip were segregated based on the different identified attributes (like driver age, education and driving experience). These trips were further divided into subgroups based on each identified driver attribute (i.e. driver were divided in three subgroups based on his/her age like Below 25 years, 25 to 35 years and above 35 years).

3. Vehicle trips corresponding to each subgroups were segregated and their idealized acceleration-speed relationship were developed using the steps discussed above for A/D behaviour modelling.

4. Acceleration-speed relationships of different groups/subgroups were compared to each other to see the effect of different driver attributes on their A/D patterns.

Further, two experiments were conducted to understand the impact of different A/D pattern: (i) measurement of average delays at signalized intersection incorporating different A/D pattern in incoming vehicles using simulation model VISSIM, and (ii) measurement of tail pipe emission at different speeds and A/D levels.

To understand the impact of A/D pattern on average delay at signalized intersection, a simulation of single lane was carried out using VISSIM with a signalized intersection at midway. Simulation was carried out for a hypothetical traffic scenario. Traffic stream was assumed to consist of passenger cars only with certain flow value. A suitable signal phasing scheme and green time allocation were assumed. Average vehicular delay was computed at signalized intersection for various combination of A/D patterns. More details about this study is provided in the later chapter.

Further, an experiment was carried out to understand the effect of vehicle speed and A/D levels on vehicular tail pipe emission. In this experiment test vehicles were run on selected study stretch near IIT Guwahati under controlled condition similar to A/D behaviour study. Test vehicle was equipped with GPS along with a five gas analyzer automotive exhaust monitor (PEA 205). GPS were used to record vehicle's position and speed measurement at 1 Hz frequency while gas analyzer was used to measure the test vehicle tailpipe emission such as Carbon Monoxide *(CO)*, Hydro-carbons *(HC)*, Carbon-di-Oxide (CO_2) and Oxides of Nitrogen (NO_x), at every second. Similar to the A/D study experiment, driver were asked to accelerate to their desired speed in minimum possible time, then cruise for some time and decelerate to stop condition. Many such trips with different test vehicles were made and data of vehicular position, speed and tail pipe emissions were recorded. The time frame synchronization of GPS device and five gas analyzer data was done by matching time records in observed data. Vehicular acceleration at each second was computed using Equation 3.1 for each trip. Further, speed and emission data were segregated according to different acceleration levels. Relationship between speed and various tail pipe emission were explored at different acceleration levels. More details about this experiment and various results are presented in later chapter of the thesis.

Next chapter presents the collected data on acceleration behaviour of vehicles, its analysis for all vehicle types. This also discusses the proposed acceleration models for different vehicles and their evaluation results.

Chapter 4

Study of Acceleration Behaviour

Acceleration and deceleration behaviour are the important dynamic properties of vehicles. Their accurate measurement/estimate are necessary for various road related operations like geometric design of road way facility, traffic flow modelling, fuel consumption and emission modelling, deciding location of signals, etc. This chapter presents the details of acceleration behaviour data collected from field for different vehicle types and discusses the observations on acceleration behaviour of different vehicles. Existing acceleration models are evaluated for realistic description of observed acceleration behaviour of different vehicle types. On failure of existing models, new acceleration models are proposed. This chapter is organized under following headings:

- Field data collection
- Analysis of field data
- Study of acceleration behaviour of mid size truck
- Study of acceleration behaviour of motorized three wheeler
- Study of acceleration behaviour of motorized two wheeler
- Study of acceleration behaviour of car

4.1 Field Data Collection

As discussed in previous chapter, data collection of acceleration behaviour was carried out at two locations: (i) Nagpur- Aurangabad highway at Wardha and (ii) approach road of IIT Guwahati. Details of both sites are provided in Section 3.2. The data for trucks, motorized two wheelers and motorized three wheelers were collected at first study stretch near Wardha while diesel and petrol cars data were recorded at second stretch near IIT Guwahati. Acceleration data was collected on these selected stretches under controlled condition as data collected at Indian intersection generally results inconsistent data (refer detailed discussion in Section 3.1).

Drivers were asked to accelerate from stop condition to achieve their desired (or maximum) speed in earliest possible time and they were allowed to drive at their maximum speed for some time. Afterwards they were again asked to decelerate quickly to stop condition. This one cycle (or trip) of A/D manoeuver of vehicle replicates the lead vehicle behaviour at signalized intersection. Position and speed data of trucks, motorized two wheelers and motorized three wheelers were recorded at 1 Hz frequency using GPS at first study location while position and speed data of cars were recorded at 10 Hz frequency using V-Box at second study location during many such cycles of A/D manoeuver. 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 4.1.

Table 4.1: Number of trips and data points collected for various vehicle types during acceleration manoeuver

Serial No	Type of vehicle	Weight to horsepower Ratio, lb/hp (kg/kW)	No. of trips	No.of data points
1	Trucks	300 (183)	114	3231
2	Motorized three wheeler	100 (61)	116	3159
3	Motorized two wheeler	31 (18.91)	59	1050
4	i)Diesel car	33 (20.13)	110	43862
	ii) Petrol car	30 (18.3)	115	50152

It can be observed from the Table 4.1 that 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 is presented in next section.

4.2 Analysis of Field Data

A large number of designed trips (acceleration, cruising and deceleration) made by different vehicles were recorded using GPS (or V-Box) to get their position and speed profile with time as presented in Table 4.1. Based on the criteria described in Section 3.3, GPS data corresponding to acceleration manoeuver within each trip were segregated. These segregated acceleration manoeuver GPS data (in terms of position and speed vs time) of all trips of a particular vehicle type was grouped together. Thereafter, each acceleration manoeuver GPS data was smoothed using exponential smoothing technique (with smoothing factor as 0.08) to minimize the effect of random errors. In case of data collected using V-Box, in-built Kalman Filter smoothing algorithm were used. Corrected GPS data of all vehicles trips are analyzed and presented in the following subsections.

4.2.1 Speed-time relationship

Smoothed speed vs time GPS (or V-Box) data of all acceleration manoeuver was used to develop scatter plots of speed vs time for each vehicle class separately. Figure 4.1 presents speed vs time scatter plots of mid-size trucks, motorized three wheelers and two wheelers, petrol and diesel cars separately. Further average values of maximum (desired) speed, mean speed, time to achieve the maximum speed for each vehicle types were computed and presented in Table 4.2.

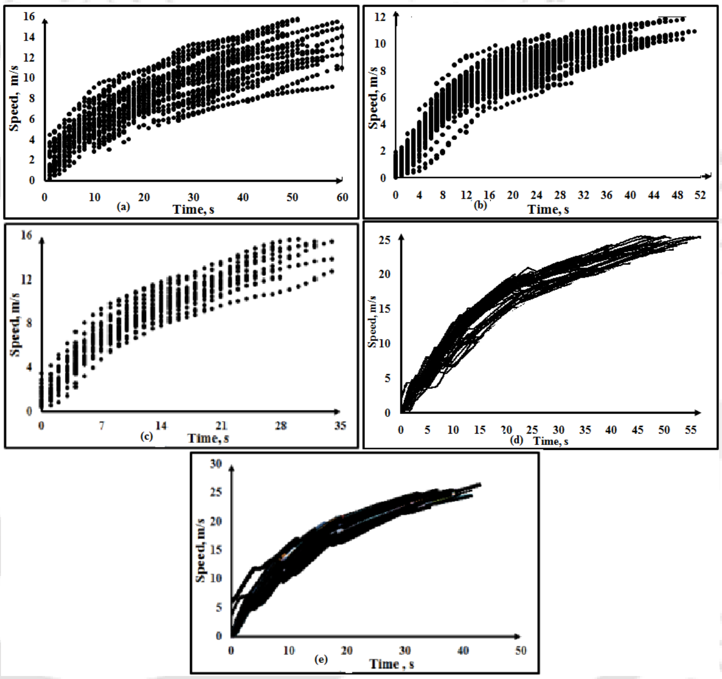


Figure 4.1: Speed profiles of various vehicle types (a) Truck (b) Motorized three wheeler (c) Motorized two wheeler (d) Diesel car (e) Petrol car during acceleration manoeuver

Table 4.2: Summary of speed related observations of different vehicle types in acceleration manoeuver

Serial No.	Type of Vehicle	Speed (m/s)			Avg. Time to Achieve
		Avg. Max.	Avg. Mean	Std. Dev.	Max. Speed, s
1	Truck	11.67	8.21	4.43	28
2	Motorized three-wheeler	9.18	6.22	3.42	26
3	Motorized two-wheeler	12.47	8.30	3.78	19
4	Car				
	i) Diesel car	21.09	11.19	7.75	39
	ii)Petrol car	24.12	16.02	6.52	34

Avg.: Average, Max.: Maximum, Std. Dev.: Standard Deviation

Following observations can be made from Figure 4.1 and Table 4.2:

- The maximum (desired) speed of every driver of a vehicle type is different and it also varies with vehicle types. Observed average maximum speed is highest in case of petrol car while lowest is case of motorized three wheeler. Average mean speed also shows similar trend like average maximum speed.
- Time to achieve the maximum speed also varies with driver and vehicle type.
- During initial phase of acceleration manoeuver, slope of speed-time scatter plots are higher while it gradually reduces with further increase in time (or speed). Higher slopes at lower speeds indicate higher acceleration value. Similar behaviour is observed for all vehicle types.
- The scatter plot of cars (petrol and diesel) indicates that trips data are more cohesive than other vehicle types. The reason might be that cars used in experiments are hired ones and hence variability among drivers and car models are limited.

4.2.2 Acceleration-time relationship

Further, acceleration for each trip is computed from the collected second by second speed data using Equation 3.1 provided in Section 3.3. Similar to speed-time scatter plots, acceleration-time scatter plots are generated for all vehicle types separately and presented in Figure 4.2. A Summary of computed average values of maximum and mean acceleration and time to achieve the maximum acceleration for each vehicle types are presented in Table 4.3. Following observations can be made from Figure 4.2 and Table 4.3:

Table 4.3: Summary of acceleration related observations of different vehicle types in acceleration manoeuver

Serial No.	Type of vehicle	Acceleration (m/s^2)			Avg.Time to Achieve
		Avg. Max.	Avg. Mean	Std. Dev.	Max. Acceleration, s
1	Truck	0.55	0.26	0.15	2
2	Motorized three-wheeler	0.76	0.30	0.21	4
3	Motorized two-wheeler	0.99	0.48	0.22	3
4	Car				
	(i) Diesel car	2.21	0.59	0.45	0.8
	(ii)Petrol car	2.51	0.76	0.53	0.7

Avg.: Average, Max.: Maximum, Std. Dev.: Standard Deviation

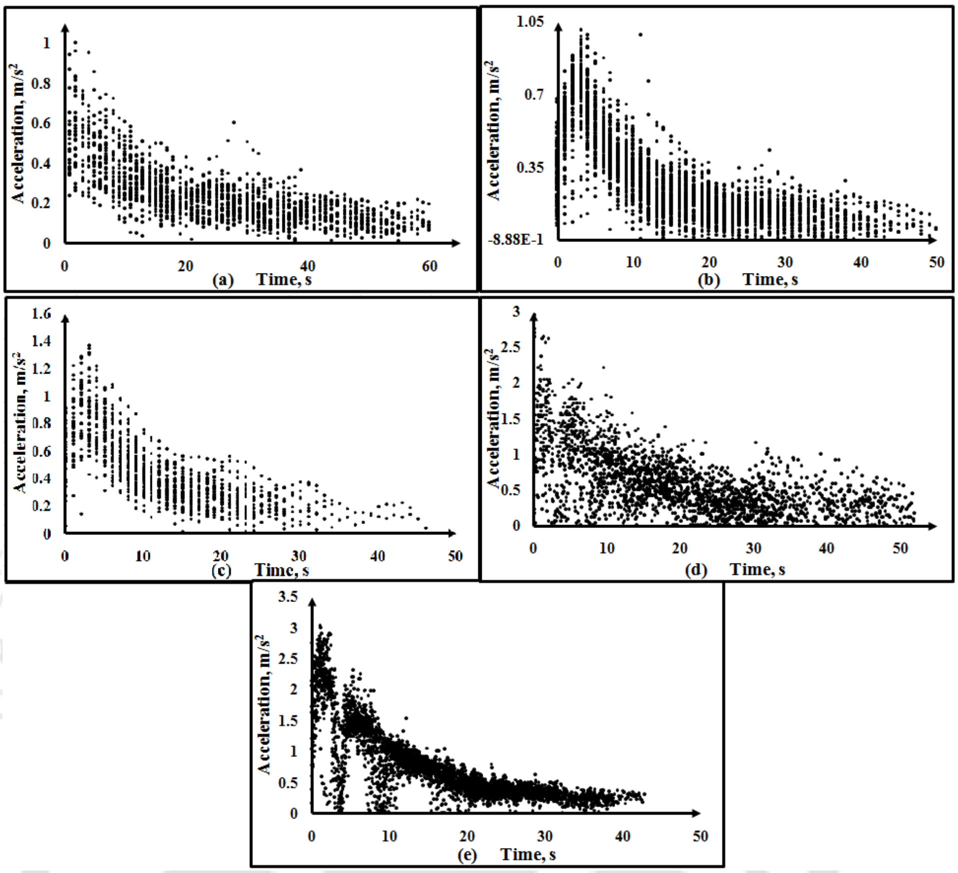


Figure 4.2: Acceleration-time scatter of various vehicle types (a) Mid Size Truck (b) Motorized Three Wheeler (c) Motorized Two Wheeler (d) Diesel Car (e) Petrol Car

- Acceleration is generally higher at startup of acceleration manoeuver and it decreases monotonically towards the end of acceleration manoeuver for each vehicle class. However, in case of motorized three wheelers, two wheelers and cars, acceleration values are lower at very start of acceleration manoeuver (i.e. near zero time) and it quickly attains it's highest values afterwards (refer Figure 4.2 b). Motorized three-wheelers took maximum time (4 s) to achieve maximum acceleration followed by motorized two wheelers (3 s). In case of cars, the maximum acceleration is achieved within a fraction of second (refer Figure 4.2e). The reason for this is explained later in Section 4.2.3.

- In case of petrol cars (refer Figure 4.2e), acceleration drops corresponding to every gear change. Drops in acceleration corresponding to each gear change are visible in case of diesel cars also but they are not so distinguishable as in case of petrol cars. This might be due to non uniform gear change behaviour of drivers and poor acceleration capability of diesel vehicles.

  In case of other vehicle types, these drops in acceleration corresponding to gear change are not observed. The possible reasons can be - (i) acceleration employed by other vehicles are much lower in comparison to car's acceleration, and (ii) V-Box with 10 Hz data logging capability were used to record the cars's speed and position while for other vehicles GPS with 1 Hz data logging capability were used to record the speed and position which may have failed to capture these momentarily dip in acceleration.

- Highest average maximum and mean acceleration is employed by petrol car followed by diesel car, motorized two-wheeler, motorized three-wheeler and truck.

4.2.3 Speed and acceleration relationship with desired (or maximum) speed

It is observed from Figure 4.1 that each trip of a vehicle type shows different desired (or maximum) speed as it is driven by different drivers. Speed and acceleration characteristics of trips depend on their maximum speed. Therefore, for all category of vehicles, different speed profiles are grouped as per their maximum speed range of trips. These speed ranges vary with vehicle types due to their variation in maximum (or desired) speed (for example, motorized three wheeler and truck's maximum speed are lower than car and motorized two wheeler's maximum speed).

The GPS data (like distance, speed and computed acceleration) of all trips for each vehicle type are analyzed for various parameters like acceleration time and distance, maximum and mean acceleration rates and speed at maximum acceleration (referred hereafter as *critical speed*) in maximum speed range of trips. Analysis results of these parameters are presented in Table 4.4 for each group based on the maximum speed range of trips of all vehicle types. Trips corresponding to different vehicle classes are divided into different maximum speed ranges according to variation in maximum speed of that vehicle class. Observations from Table 4.4 on each parameters are presented below:

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 4.4 and Figure 4.3a, 4.3b, 4.3c and 4.3d). This observation is in agreement with the observation reported by RaiChowdhury and Rao (1989) for passenger car that the acceleration distance increases with maximum speed of trip. In similar speed range, acceleration distance (or 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).

Among cars, petrol car has registered the lower acceleration distance (or time) than diesel car in similar speed range. The reason is that diesel cars have lesser accelerating capacity as compared to petrol car. Hence time taken to accelerate and reach a particular speed is high. The distance travelled by diesel cars during this period is more than petrol car. The acceleration distance of cars observed in this study matches with acceleration distance reported by RaiChowdhury and Rao (1989) in a particular speed range.

Table 4.4: Various parameters corresponding to different maximum speed ranges of all vehicle classes during acceleration manoeuver

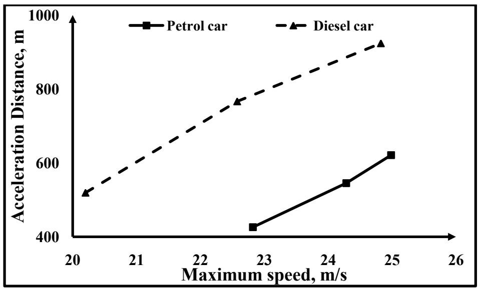
Vehicle Type	Max. Speed Range km/h (m/s)	Accel. Time (sec)	Accel. Distance (m)	Critical Speed* (m/s)	Max. Accel. Rate (m/s^2)	Mean Accel. Rate (m/s^2)
Truck	20-30 (5.55-8.33)	11	56.98	2.77	0.75	0.28
	30-40 (8.33-11.11)	17	98.26	1.53	1.00	0.29
	40-50 (11.11-13.89)	34	259.08	1.27	0.96	0.24
	50-60 (13.89-16.67)	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

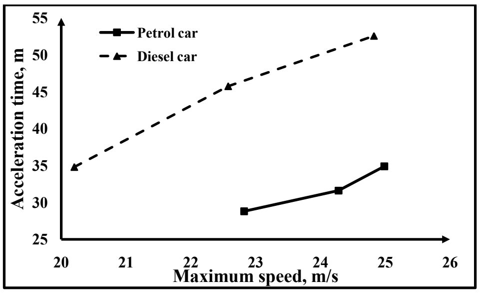
Critical speed

Several researchers (Samuels and Jarvis, 1978; Long, 2000; Dey et al., 2008) modeled vehicle acceleration as linear function of speed. In these studies, speed data is collected based on travel time of vehicle over predefined sections which results average speed of vehicle instead of its instantaneous speed. Therefore, these studies couldn't capture the speed at which acceleration is maximum **critical speed**. Some authors (Bham and Benekohal (2002);Akelik and Besley (2001)) who used modern equipments for speed measurement found that vehicle acceleration is zero at zero speed; it reaches a peak value quickly and then reduces gradually and again becomes zero at the end of acceleration manoeuver.

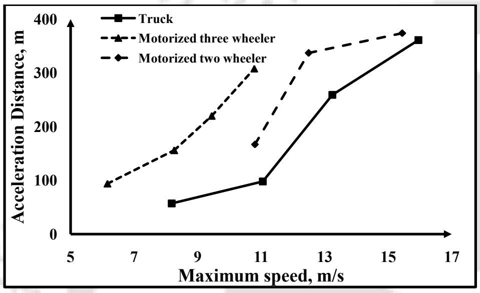
In present study which uses GPS (or V-Box) for speed data collection, a similar behaviour is observed for car, motorized three wheeler and two wheeler. All vehicle types (except truck) registered near zero acceleration at near zero speed and quickly achieved their maximum acceleration rate with further increase of vehicle speed. However, for truck trips with higher range of maximum speed, field data could not capture the lower acceleration values at near zero speeds as they achieve their maximum acceleration



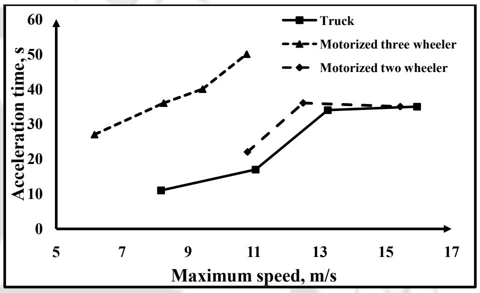
(a) Variation of acceleration distance of diesel and petrol cars



(b) Variation of acceleration time of diesel and petrol cars



(c) Variation of acceleration distance of truck, motorized three and two wheeler



(d) Variation of acceleration time of truck, motorized three and two wheeler

Figure 4.3: Variation of acceleration distance and time with vehicle type and average maximum trip speed

within a second of acceleration manoeuver. Therefore, this event was difficult to capture in GPS speed data with 1 Hz data logging interval. However, this event may be captured through V-Box with 10 Hz data logging interval.

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, 1.46 m/s to 1.21 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.

During data collection, when volunteer sits on two wheeler holding GPS device, the driver becomes cautious about safety and drives at lesser speed than normal speed. The driver average desired speeds for single occupancy and double occupancy (with pillion rider holding GPS) motorized two-wheelers are observed and 15% reduction in desired speed were found. The data collected in this study is for double occupancy (with second person holding GPS) motorized two-wheeler.

Maximum and mean acceleration rate

It can be observed from Table 4.4 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 4.4). 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 different vehicles at various speed reported in literature are presented in Table 4.5. It can be observed from Table 4.4 and Table 4.5 that maximum acceleration values of cars observed in this study are higher than reported acceleration value by previous Indian researchers (Dey et al., 2008; Arasan and Koshy, 2005). However, it is comparable with recent international studies (Bham and Benekohal, 2002; Wang et al., 2004). Previous Indian studies used travel time method for speed measurement which may under estimate the speed (hence acceleration) of vehicles. Similar observations holds true for acceleration values of truck. In case of motorized two wheelers, observed acceleration value is little lower than reported values in previous Indian studies. This underestimation of two wheeler's acceleration may due to driver's cautiousness during data collection in the present study (refer previous subsection for details).

4.3 Study of Acceleration Behaviour of Mid Size Truck

Data collection and analysis for all vehicle types are presented in previous sections of this chapter. Scatter plots of speed-time and acceleration-time for all observed truck trips are again presented in Figure 4.4 for its detailed analysis. Following salient features can be observed from these scatter plots:

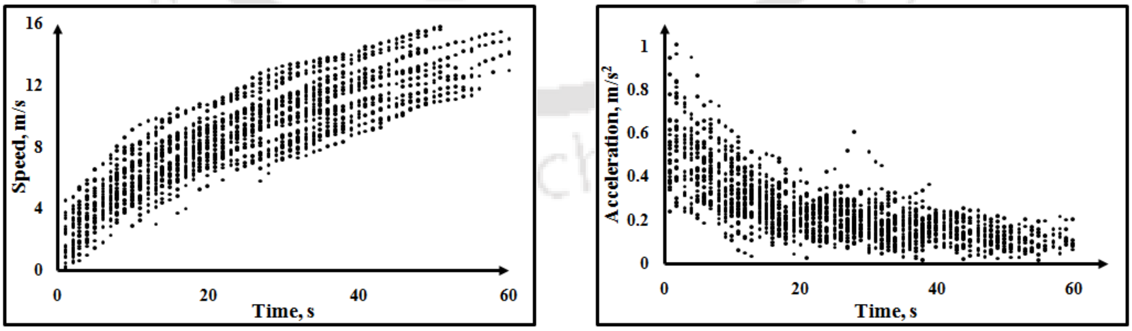
- Some of truck trips shown in the scatter plot (refer Figure 4.4a) do not start from zero speed. Since the data logging frequency of GPS was one second, the actual beginning of trips were not captured in some cases. Similar observation was also noted by Hong (2007).

- Different trucks posted different maximum speed (ranging from 9.09 m/s to 15.95 m/s) and they took different time durations (43 s and 60 s) to reach their maximum speed (refer Figure 4.4a). This variation in driver's maximum speed may be due to driver's attribute and vehicle characteristics.

Table 4.5: Maximum and Mean Acceleration Rates Observed by Various Researchers

Author	Country	Vehicle Type	Speed Range km/h	Max. Accel Rate m/s^2
Dey et al. (2008)	India	Truck	0-43	0.47
		Car	0-72	1.24
		Two-wheeler†	0-54	1.52
Arasan and Koshy (2005)	India	Truck	0-20	0.79
			20-40	0.45
			> 40	0.35
		Car	0-20	1.50
			20-40	1.30
			> 40	1.00
		Three-wheeler†	0-20	1.01
			20-40	0.58
			> 40	0.34
		Two-wheeler†	0-20	1.35
			20-40	1.03
			> 40	0.37
RaiChowdhury and Rao (1989)	India	Car	0-45	2.25
Dockerty (1966)	USA	Car	–	2.02
Glauz et al. (1980)	USA	Car	–	2.50
St.John (1989)	USA	Car	–	3.36
Bonesson (1992)	USA	Car	–	2.02
Bham and Benekohal (2002)	USA	Car	0-60	2.00
Wang et al. (2004)	USA	Car	0-60	1.86

† - Indicates motorized vehicles



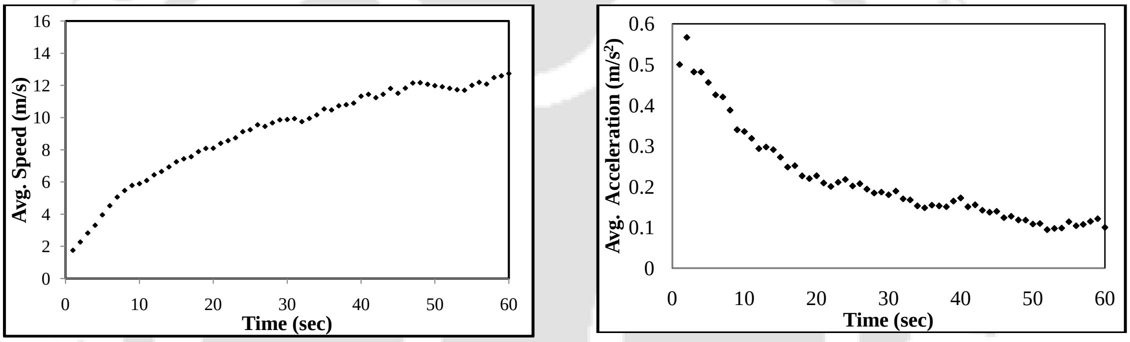
(a) Speed-time (b) Acceleration-time

Figure 4.4: Speed-time and acceleration-time scatter plots during acceleration manoeuver for mid size truck

These maximum speeds match with the speeds of trucks reported by Long (2000); Donnel et al. (2010).

- These observed speed profiles of trucks are not as smooth as suggested by Akcelik and Biggs (1987). They suggested 'S' shape speed profile depicting zero acceleration at the beginning and end of acceleration manoeuver. Due to high logging interval (1 s), it was not possible to capture exact starting time of acceleration manoeuver when accelerations are low.
- Applied acceleration values by trucks monotonically reduces with increase in time (or speed) during acceleration manoeuver. Maximum truck acceleration varied from 1.08 m/s^2 to 0.26 m/s^2.

The speed and acceleration are then averaged over every second and *idealized plot* plots of speed-time and acceleration-time (refer Section 3.3) are presented in Figure 4.5a and 4.5b. Following observations can be made from these idealized plots:



(a) Speed-time (b) Acceleration-time

Figure 4.5: Speed-time and acceleration-time idealized plots during acceleration manoeuver for mid size truck

1. The idealized plot of speed-time indicates that rate of change of speed with time is high in the beginning of acceleration manoeuver whereas it decreases towards the end (refer Figure 4.5a). This indicates that employed acceleration is high at the beginning and low towards end of acceleration manoeuver. This acceleration behaviour can be verified from Figure 4.5b. Similar observations were also made by Akcelik and Biggs (1987); Wang et al. (2004) and Hong (2007). Idealized maximum speed of truck is observed as 12.73 m/s.
2. Idealized maximum acceleration value of truck is 0.59 m/s^2 (Figure 4.5b). Maximum acceleration values for trucks reported by Long (2000) are from 2.95 m/s^2 to 0.45 m/s^2 depending upon load to horse power ratio. The load to horse power ratio of mid sized trucks used in this study is 300 lb/hp (183 kg/kW). For this load to horse power ratio the average maximum acceleration values reported by Long (2000) are 0.58 m/s^2 which is similar to the observed maximum acceleration

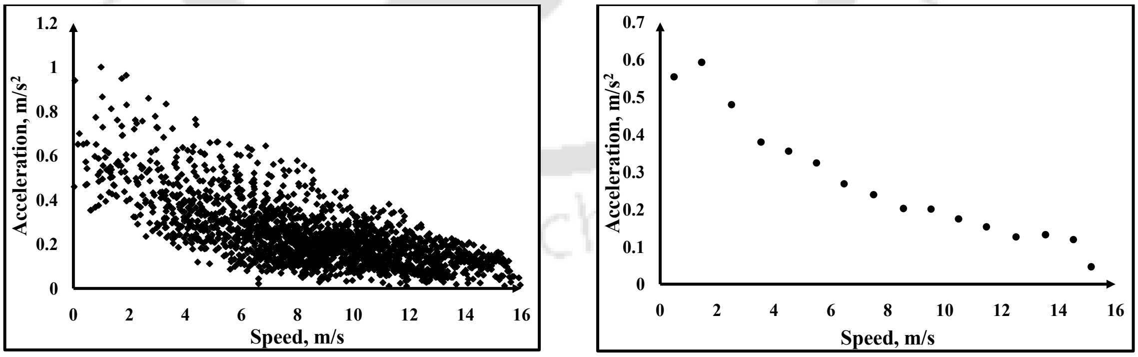
(idealized) of mid sized truck in this study. Average maximum truck acceleration values reported by Arasan and Koshy (2005) is 0.79 m/s^2 and by Dey and Biswas (2011) is 0.47 m/s^2. However, they have neither mentioned the type of truck used in their study nor did they mentioned the load to horse power ratio of used trucks. Hence it is difficult to compare these results with results of present study.

3. The average truck acceleration value computed from this study is 0.27 m/s^2 which is much lower than 1.26 m/s^2, the value recommended by ITE (2009) and higher than value of 0.12 m/s^2 reported by Dey and Biswas (2011).

4.3.1 Selection of acceleration model

While modelling acceleration of vehicles, speed is preferred over distance since speed provides better fit than distance. Distance is a cumulative measure and hence errors cumulate over time. Small initial error in distance profile magnifies over time. This results in not so good fit and errors are unrealistic. Therefore, appropriate model selection becomes difficult. Bham and Benekohal (2002) found that shape of distance profile of vehicle look similar for different speed models. Moreover, many authors (Akelik and Besley (2001); Bham and Benekohal (2002); Long (2000)) reported that vehicle acceleration changes over the vehicle speed. At lower speed acceleration is high and at higher speed acceleration is low, indicating strong relationship between acceleration and speed. Hence acceleration-speed model is developed in this thesis.

The acceleration values obtained from Equation 3.1 are plotted with speed and presented in Figure 4.6a.



(a) Acceleration-speed, scatter (b) Acceleration-speed, idealized

Figure 4.6: Scatter and idealized plot of acceleration-speed for mid size truck during acceleration manoeuver

Acceleration-speed scatter plot (refer Figure 4.6a) indicates that acceleration decreases with increase in speed. Acceleration and speed values are then averaged over every 1 m/s speed to get an idealized acceleration-speed plot as shown in Figure4.6b. It can be seen from idealized acceleration-speed plot that rate of change of acceleration with speed is high in beginning of acceleration manoeuver and stabilizes towards end of acceleration manoeuver. This is in agreement with the observations of Hong (2007) and Wang et al. (2004). Next subsection evaluates the various existing acceleration models to describe the observed acceleration-speed relationship shown in Figure 4.6b.

4.3.2 Evaluation of existing models

From existing literature, following models are chosen for evaluation to describe the observed acceleration-speed relationship in this study:

- Wang's polynomial model, (Wang et al., 2004)
- Akcelik's linear model, (Akcelik and Biggs, 1987)
- Akcelik's polynomial model, (Akcelik and Biggs, 1987)

These models are statistically evaluated one by one to describe the idealized acceleration-speed relationship (refer Figure4.6b) and results are presented in following paragraphs.

Evaluation of Wang's model The mathematical relationship of Wang's polynomial model is presented in Equation 4.1.

$$\sqrt{a} = k_1 - k_2 v \tag{4.1}$$

where, a and v are acceleration (m/s^2) and speed (m/s), respectively and k_1 and k_2 are model parameters. Regression analysis is used to compute k_1 and k_2 values using present data. The values of k_1 and k_2 are obtained as 0.784 and 0.060 respectively. So the calibrated Wang model is,

$$\sqrt{a} = 0.784 - 0.060v \tag{4.2}$$

The acceleration values computed from both (i) observed speed values and (ii) from Wang's polynomial model (presented in Equation 4.1) are compared using two sample Kolmogoroff-Smirnoff test. This test compares the distributions of two data vectors x_1 and x_2. The null hypothesis is that two vectors are from same continuous distribution. The alternative hypothesis is that they are from different continuous distribution. Result h is 1 if the test rejects the null hypothesis at 5% significance level, 0 otherwise (refer Appendix B.3). In present case, the 'h' values is '1' indicating that the null hypothesis cannot be accepted, indicating that Wang's model is not sufficient to describe present data set.

Single factor Analysis of Variance (ANOVA)[a] is used to further test the means of acceleration observed and acceleration computed using Wang's polynomial model. Table 4.6 presents the results of ANOVA.

[a]refer Appendix B.2 for details on ANOVA

Table 4.6: Results of ANOVA for observed acceleration vs Wang's polynomial model acceleration for mid size truck

Source of Variation	SS	*df*	MS	*F*-ratio	*p* value	*F*-critical
Between Groups	0.195	1	0.195	7.88	0.008	4.17
Within Groups	0.693	30	0.030			
Total	0.888	31				

In results of ANOVA F-ratio exceeding F-critical value at 5% significance level, indicates that mean of accelerations computed from observed speed and Wang's polynomial model are different. Acceleration obtained from Wang's model is also compared graphically with acceleration resulted from observed speed data and is presented in Figure 4.7. The plot indicates that there is difference between average

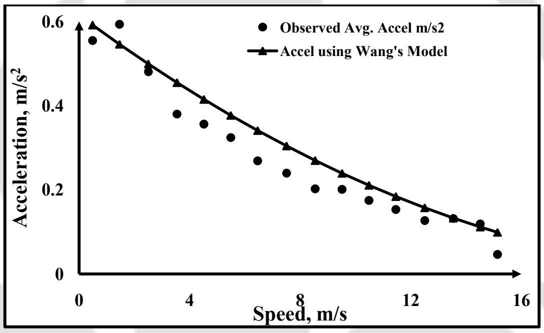


Figure 4.7: Comparison of average acceleration rate for Wang's model and observed acceleration for mid size truck

acceleration rate predicted using Wang's acceleration model and acceleration calculated from observed speed. The Wang's model overestimates acceleration throughout the acceleration manoeuver, except starting and end of acceleration manoeuver.

Evaluation of Akcelik's linear model The mathematical relationship of Akcelik's linear model is presented in Equation 4.4.

$$a(t) = 2x\frac{(1-\theta)(v_f - v_i)}{t_a} \tag{4.3}$$

where, $a(t)$ acceleration rate at time t, x is distance travelled during acceleration, m, θ is time ratio $\frac{t}{t_a}$ and v_f and v_i are final and initial speed respectively. The values of θ, $\frac{t}{t_a}$, v_f and v_i are used from observed data set and acceleration is computed for Akcelik's linear model. The acceleration values computed from observed speed values and Akcelik's linear model are compared using two sample Kolmogorov-Smirnov test. The 'h' value of 1 rejects null hypothesis that both set of accelerations come from same continuous distribution at 5% significance level. Also the single factor ANOVA is computed for acceleration computed from observed speed data and Akcelik's linear model. The F-ratio exceeding F-critical value indicates the rejection of null hypothesis. Hence the Akcelik's linear model does not fit present data set.

The acceleration obtained from Akcelik's linear model is plotted with acceleration computed from observed speed values and presented in Figure 4.8.

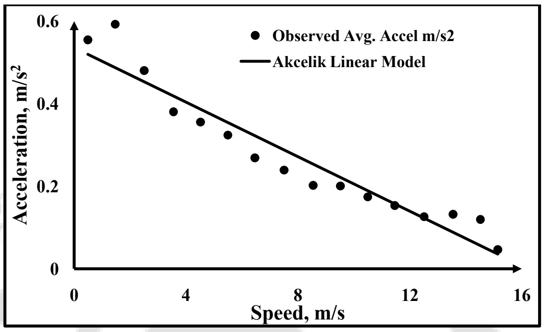


Figure 4.8: Comparison of average acceleration rate for Akcelik's linear model and observed acceleration for mid size truck

It is evident from Figure 4.8 that average accelerations resulting from Akcelik's linear model do not match with average accelerations from observed speed data. Akcelik's linear model predicts lower values at the beginning and end of acceleration manoeuver whereas at the middle portion of acceleration manoeuver Akcelik's model predicts higher values.

Evaluation of Akcelik's polynomial model The mathematical relationship of Akcelik's polynomial model is presented in Equation 4.4.

$$a(t) = ra_m\theta(1-\theta^m)^2 \quad m > -5 \tag{4.4}$$

where, $a(t)$ is acceleration rate at time t, in m/s^2, a_m is maximum acceleration, in m/s^2, θ is time ratio $\frac{t}{t_a}$, t is acceleration time, in sec, t_a is time taken by vehicle to reach maximum acceleration, m is parameter that depends on initial and final speed, acceleration time and distance, and r is parameter that depends on value of m. The model parameter m can be calculated using following steps,

1. Calculate ρ as follows,

$$\rho = \frac{3.6\frac{x_a}{t_a} - v_i}{(v_f - v_i)} \tag{4.5}$$

where, x_a is acceleration distance in m, t_a is time of acceleration in sec, v_i and v_f are initial and final speed in km/h.

2. Then calculate value of m, using following formula,

$$m = \frac{-A_1 + (A_1^2 - 4A_0A_2)^{\frac{1}{2}}}{2A_2}$$

$$A_0 = 27\rho - 19 \qquad A_1 = A_0 + 4 \qquad A_2 = 6\rho - 2$$

3. Then calculate value of ra_m from following formula,

$$ra_m = \left[\frac{2(m+1)(m+2)}{m^2}\right]\bar{a}$$

where, $\bar{a} = \frac{(v_f - v_i)}{t_a}$

The value of r can also be calculated using following formula,

$$r = \frac{[(1+2m)^{2+\frac{1}{m}}]}{4m^2} \tag{4.6}$$

Accordingly following values were obtained for the model parameters, $\rho = 0.703$, $A_0 = -0.019$, $A_1 = 3.981$, $A_2 = 2.218$, $m = 0.906$, $ra_m = 2.65$. So the calibrated Akcelik's polynomial model becomes;

$$a(t) = 2.65 \times \theta(1 - \theta^{0.906})^2$$

The acceleration values are then computed from Akcelik's polynomial model and compared with acceleration values computed from observed speed values. Figure 4.9 indicate that two sets of acceleration are distinctively different.

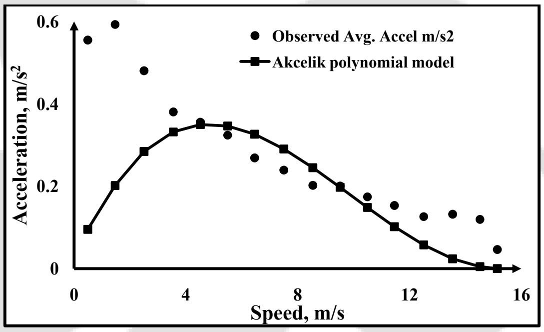


Figure 4.9: Comparison of average acceleration rate for Akcelik's polynomial model and observed acceleration for mid size truck

Also the acceleration values computed from, observed speed values and from Akcelik's polynomial model are compared using two sample Kolmogorov-Smirnov test. The 'h' value of 1 rejects null hypothesis that both set of accelerations come from same continuous distribution (distribution not known) at 5% significance level.

Therefore, Akcelik's polynomial model, similar to Wang's polynomial and Akcelik's linear model, fails to explain the observed acceleration-speed behaviour. So, a new model needs to be formulated which can explain the observed acceleration-speed relationship.

4.3.3 Acceleration-speed model

The idealized acceleration-speed plot (refer Figure 4.6b), shows that the acceleration values used by trucks monotonically decrease with increase in speed. To describe this acceleration-speed behaviour, linear and nonlinear forms (exponential and polynomial) are evaluated. Residual Sum of Squares[b] (RSS) is calculated for each proposed model forms. The appropriate model form is one which yields minimum RSS value. RSS is calculated using following formula (Freund and Wilson, 2011):

$$RSS = \sum_{i=1}^{n} \left[y_i - \hat{y}\right]^2 \tag{4.7}$$

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

The RSS values are 0.03, 0.01, 0.17 for linear, negative exponential and polynomial form respectively. These values indicate that **negative exponential form** yields the *lowest RSS value* and hence is best suited for description of variation of acceleration with speed. Following negative exponential form is proposed for acceleration-speed relationship of trucks:

$$\mathbf{a} = \mathbf{k_1 e^{(-k_2 \times v)}} \tag{4.8}$$

where, a is acceleration rate (m/s^2) at speed v (m/s), k_1 and k_2 are model parameters. Linear regression method is used to calculate the model parameters from field data. Values of parameters k_1 and k_2 are found as 0.666 and 0.13 respectively. The coefficient of determination, r^2, is 0.92 which indicates satisfactory fit of negative exponential form for present acceleration-speed data. The fitted model is presented in Figure 4.10.

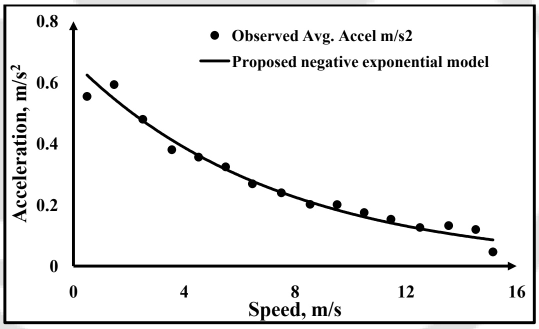


Figure 4.10: Proposed negative exponential model for acceleration-speed of mid size truck

Model Diagnostic

The linear regression model is based on several assumptions[c].

The model diagnostic procedures include:

1. Graphical procedure

    - Residual plots,

    - Plots of observed and predicted value, and

[b] refer Appendix B.6, for more details on Residual Sum of Squares, RSS

[c] refer Appendix B.8 and Freund and Wilson (2011); Pruim (2010) for more details on model diagnostics

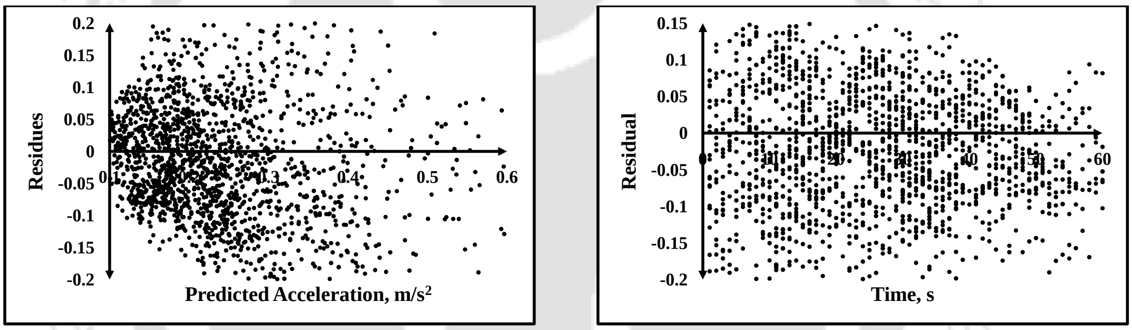
- Box plots of residues.

2. Numerical procedure

   - Comparing the means of observed acceleration (calculated using observed speed data) and modeled acceleration, using paired t-test, and
   - Post Hoc Fisher's Least Significant Difference (LSD) method.

Residual plots The residues are the difference between observed response and predicted response. Residual plot is a scatter plot of residues on *y-axis* and predicted values of response on *x-axis*. If the data is collected over time, the residues are also plotted against time. A regression model that has no violations of errors, will have a residual plot that appears roughly as a horizontal band around *x-axis*.

The residual plot (plot of residuals versus predicted values and plot of residues versus time) is presented in Figure 4.11a and 4.11b. The plot indicates a band of approximately constant width around



(a) Residues versus predicted (b) Residues versus time

Figure 4.11: Residual plot of (a) acceleration residuals versus predicted acceleration values and (b) plot of acceleration residues versus time for med size truck

x-axis depicting fulfillment of assumptions made in regression analysis. Also the residues are plotted against time and presented in Figure 4.11b. The plot indicates no trend of residues over time. Also the errors are not dependent on each other. This reinforces the compliance of assumptions.

Plots of observed and predicted values Figure 4.12 presents the plot of observed and predicted values using proposed acceleration-speed relationship. It indicates that points are clustered around a 45° straight line for a normally distributed variable(except for few data points at higher acceleration values), hence the assumption **'error terms are normally distributed'** is valid.

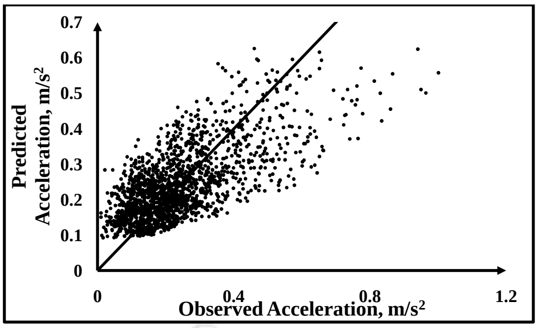


Figure 4.12: Plot of observed versus predicted value of acceleration calculated from field speed data and proposed acceleration-speed model for mid sized truck

Box plot of residues Figure 4.13 presents box plot of residues of proposed acceleration-speed relationship for medium size truck. The satisfactory clustering of quartiles and maximum and minimum values around median indicates uniform variance of residues.

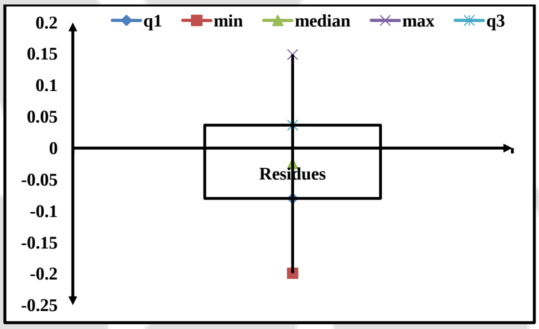


Figure 4.13: Box plot of residues of acceleration for mid size truck

Hypothesis test Paired 't' test is used to test the means of observed acceleration and acceleration computed using exponential model in Equation 4.8. Two hypothesis are tested −(i) null hypothesis: $\bar{\mu} = \mu_o - \mu_m = 0$, where μ_o and μ_m are mean of acceleration computed from observed speed and mean of acceleration obtained from model in Equation 4.8 and (ii) alternate hypothesis: $\bar{\mu} \neq 0$. The test statistic is calculated as follows[d],

$$t = \frac{\bar{\mu}}{s_d/\sqrt{n}} \tag{4.9}$$

where, $\bar{\mu}$ is mean of the difference between acceleration computed from observed speed and predicted speed, 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 can reject null hypothesis

[d] refer Appendix B.4 for more details on t-test

if $|t| \geq t_{\alpha/2}(= t_{0.025})$.

$$t = \frac{0.27 - 0.28}{0.027/\sqrt{16}} = -1.48, |t| = 1.48, t_{\alpha/2}(= t_{0.025}) = 2.13, \text{hence}, |t| \leq t_{\alpha/2}$$

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

Fisher's Post Hoc Least Significant Difference Test Rejection of null hypothesis alone does not convey the actual difference between means of observed (computed using observed speed) and modeled acceleration. A Least Significant Difference (LSD) Test[e] is used to compare the means. The LSD is computed as (refer Equation 4.10):

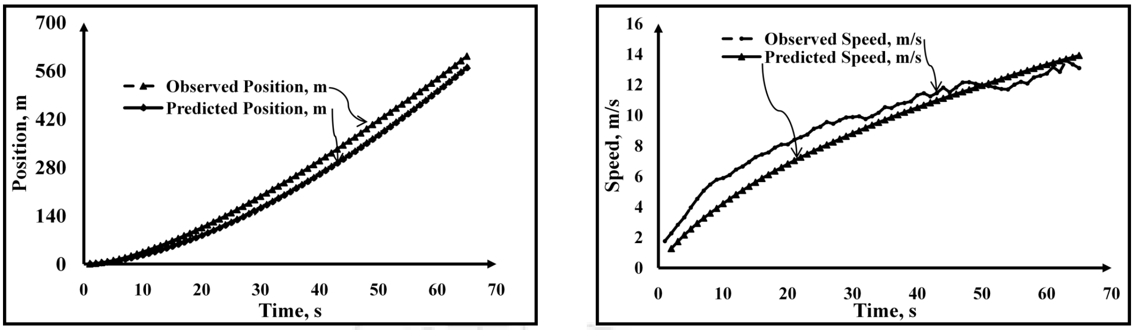
$$LSD = t_{\alpha/2}\sqrt{\frac{2 \times MSW}{n}} \tag{4.10}$$

where, $t_{\alpha/2}$ is the $\alpha/2$ tail probability value from t-distribution and the degrees of freedom (n-1), n is number of observations and MSW is mean squared error within group. Accordingly, for observed and predicted acceleration, LSD is found to be 0.529 at a significance level of 5% ($\alpha/2 = 0.025$). So, any difference between the means of observed (computed from observed speed) and predicted accelerations exceeding 0.529 is statistically significant. In this case the difference of means between observed and predicted acceleration is $0.242 - 0.237 = 0.005 < 0.529$. Hence the observed and predicted accelerations do not have statistically significant differences.

Observed and predicted trajectory and speed Further, a comparison of observed and predicted trajectories and speed profiles of truck are carried out and presented in Figure 4.14a and 4.14b. Observed trajectory of a truck is the idealized plot where position values of truck (obtained from their trajectories recorded using GPS) are averaged over every 1 second time interval. Similarly, observed speed profiles of truck are also obtained by averaging all speed data (obtained using GPS) of truck over every 1 second time interval. Predicted position and speed profiles for trucks are obtained from the proposed models as given in Equation 4.8.

Analysis of Variance (ANOVA) is used to compare the means of observed and modeled trajectories and speed profiles. Two hypothesis are tested at 95% confidence interval (significance level 5% $\alpha = 0.05$)– (i) null hypothesis: $\bar{\mu} = \mu_o - \mu_m = 0$, where μ_o and μ_m are mean of observed and modeled values and (ii) alternate hypothesis: $\bar{\mu} \neq 0$. Table 4.7 presents the ANOVA statistics. In both cases (speed and trajectory), since F critical exceeds the F ratio, the null hypothesis cannot be rejected. This indicates that proposed models for truck estimate the vehicle's trajectory and speed with fair accuracy.

[e] refer Appendix B.9 for more details on LSD test



(a) Trajectory (b) Speed

Figure 4.14: Observed and predicted trajectories and speed profiles for mid size truck during acceleration manoeuver

Table 4.7: Results of ANOVA for Observed and Predicted Speed and Trajectory of mid size truck

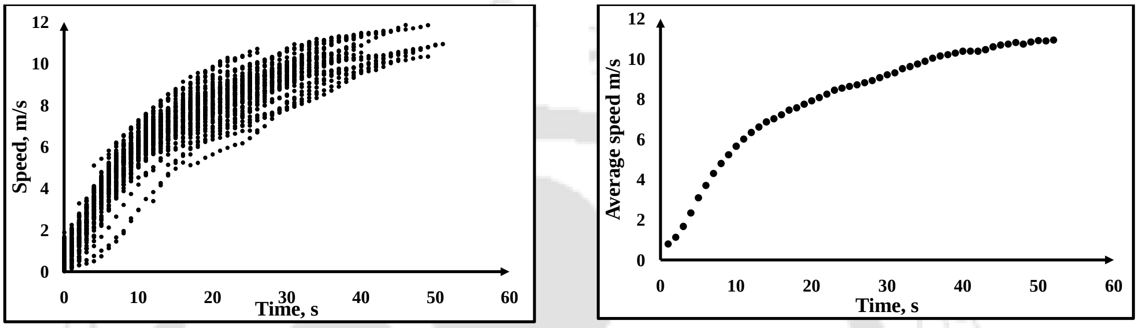
Source of Variation		Speed	Trajectory
Mean	Observed	9.00, m/s	446.56, m
	Predicted	9.21, m/s	442.80, m
Variance	Observed	9.67, m/s	113666.7
	Predicted	13.60, m/s	115454.3
F-value	F-Ratio	0.11	0.003
	F-Critical	3.72	3.92
p-value		0.73	0.95
Remarks		Null hypothesis cannot be rejected	Null hypothesis cannot be rejected

Therefore, it can be observed that proposed exponential model for acceleration-speed relationship of mid size trucks is statistically evaluated and found satisfactory. Next Section analyze and model the acceleration behaviour of motorized three wheelers.

4.4 Acceleration Behaviour of Motorized Three Wheelers

A significant composition (10% on urban arterial, Arasan and Koshy (2005) and 6.8% on highways, Dey et al. (2008)) of motorized three-wheelers are present on Indian highways. The motorized three wheelers plying on urban arterial are used as a feeder mode to travel a shorter distance (approximately 15km.) by people in urban area. These are a major means of passenger transport due to their flexibility of stops and frequency of plying in many urban conglomerates. Therefore, acceleration behaviour of motorized three-wheelers are also studied in present study.

As presented in Section 4.2, acceleration data of 116 trips of fully occupied motorized three wheeler have been collected and analyzed. Some of analysis results like speed profile, results of speed-time, acceleration-time and acceleration-speed relations, acceleration time and acceleration distance, critical speed, maximum acceleration rate, etc. are already discussed in Section 4.2. Scatter plots of speed-time for all observed motorized three wheeler trips is again presented here in Figure 4.15(a) for detailed analysis. Further speed values are averaged over every second to get the idealized speed-time relationship (refer Figure 4.15(b)). Following observations can be made from the speed-time scatter of motorized three wheelers.



(a) Scatter plot (b) Idealized plot

Figure 4.15: Scatter and idealized plots speed plots for motorized three wheeler during acceleration manoeuver

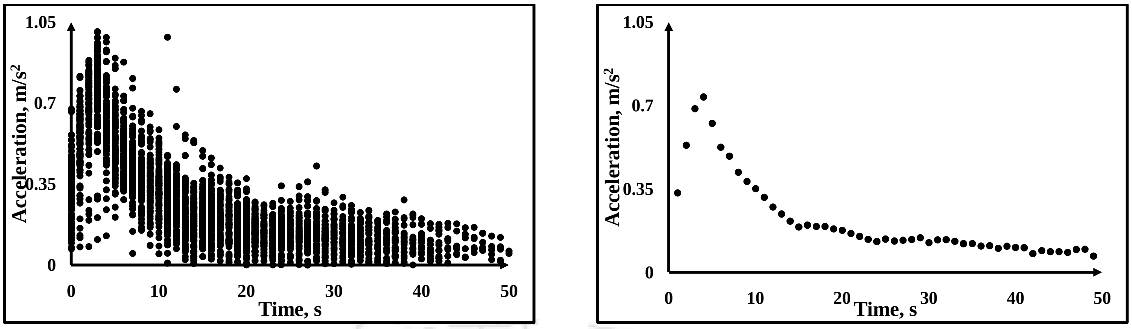
1. Most of the trips start from the rest (speed zero). Few trips do not seem to start from rest. This is because the GPS equipment could not capture their start within one second interval. The trips started somewhere between zero and first second.

2. The maximum speed achieved by three wheelers ranges from 5.47 m/s to 11.85 m/s. This maximum speed observed is in agreement with the speeds reported by Arasan and Koshy (2005) and Arasan and K.Krishnamurthy (2008). The time taken to achieve maximum speed ranges from 29 s to 51 s.

3. Similar to speed-time plots for mid size truck, 'S' shape speed profile depicting zero acceleration at the beginning and end of acceleration manoeuver is absent. Although variation of speed profile slope indicates application of higher acceleration values in the starting of acceleration manoeuver.

The acceleration of every trip was calculated using Equation 3.1 and presented in Figure 4.16a. Further, idealized acceleration -time relationship is developed (refer Figure 4.16b) by averaging acceleration values over every second. Following observations are noted from the scatter and idealized plot of acceleration of motorized three wheeler.

1. Unlike truck, acceleration of motorized three-wheeler is found to increase to maximum value from very low value at starting of trip and later it decreases to a lower values towards end of acceleration



(a) Scatter plot (b) Idealized plot

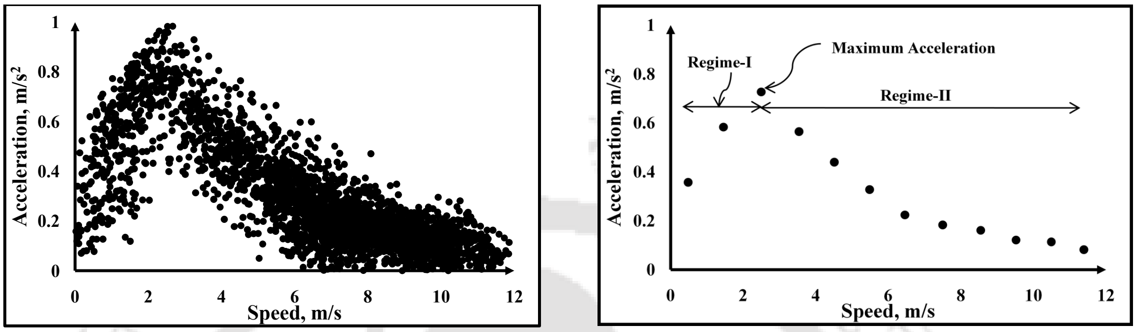
Figure 4.16: Scatter and idealized acceleration-time plots for motorized three wheeler during acceleration manoeuver

manoeuver monotonically (refer Figure 4.16a). This observation is concurrent to Akcelik and Biggs (1987) who suggested zero acceleration at the beginning and end of acceleration manoeuver. This behaviour is not captured in trucks as they quickly achieve their maximum acceleration because of their higher acceleration capability than motorized three wheeler. This makes it difficult to capture the regime of lower acceleration before achieving their maximum acceleration with 1 hz data logging frequency of GPS device. However, vehicles with poor acceleration capability like motorized three-wheeler achieve maximum acceleration bit late and hence the regime before maximum acceleration can be captured. Few such points are seen in Figure 4.16b. However, for trucks this regime is not visible (refer Figure 4.5b). In case of motorized three-wheeler this regime exists for 2-3 s time interval.

After attaining maximum value, acceleration gradually decreases with time. As such acceleration-time plot shows two distinct regimes, one before attaining maximum value and other after attaining maximum value of acceleration. This observation matches with the observation made by various researchers such as Akcelik and Biggs (1987); Akelik and Besley (2001); Bham and Benekohal (2002); Wang et al. (2004) but contradicts the observations, that the acceleration is maximum at the beginning of trip and decreases linearly with time as trip advances, made by Samuels and Jarvis (1978) and Rakha et al. (2001).

2. The maximum acceleration rate observed in this study varies from 0.50 m/s^2 to 1.009 m/s^2 with average maximum acceleration values as 0.76 m/s^2. The corresponding time taken by the trip to reach maximum acceleration is 3 s to 6 s with an average time is 4 s. The maximum acceleration rate reported for motorized three-wheeler by Arasan and Koshy (2005) and Arasan and K.Krishnamurthy (2008) is 1.01 m/s^2 which is slightly higher the acceleration rates observed in this study.

The acceleration is then compared with speed and the resulting acceleration-speed scatter is presented in Figure4.17a. Afterwards acceleration and speed values are averaged over every 1 m/s speed to get an idealized plot which is presented in Figure4.17b. Following observations are made from acceleration-speed plots:



(a) Scatter plot (b) Idealized plot

Figure 4.17: Scatter and idealized acceleration-speed plots for motorized three wheeler during acceleration maneouver

- Similar to acceleration-time scatter plot, acceleration initially increases with speed till it attains its maximum value. With further increase in speed, the acceleration decreases monotonously.
- According to Figure 4.17b, acceleration-speed idealized plot can be divided in two distinct regimes. Speed corresponding to maximum acceleration can act as a point of divide between two regimes. *Regime-I* can be defined as before attaining maximum acceleration and *regime-II* as after attaining maximum acceleration. The speed corresponding to maximum acceleration (which acts as a point of divide) is termed as *critical speed*. The idealized acceleration-speed plot (i.e Figure 4.17b) indicates that **critical speed** is 2.34 m/s.
- These two regimes can be modeled separately, since they have opposite slopes and are of different spans. A similar dual regime modelling philosophy was also reported by Bham and Benekohal (2002). Akcelik and Biggs (1987) too insisted that since the acceleration regime is divided by the point of maximum acceleration, the acceleration-speed should be modeled as dual regime, unlike single regime model reported by Samuels and Jarvis (1978) and Rakha et al. (2001). In single regime model the acceleration profile is in the form of a step function causing vehicle behaviour discontinuous from previous step. In dual regime model, however, there is only one point of discontinuity at the maximum acceleration (separation of regimes). A similar acceleration-speed plot is observed by some other researchers (Akcelik and Biggs, 1987; Akelik and Besley, 2001; Wang et al., 2004; Hong, 2007).

- The speed profile presented in Figure 4.15b also indicates that rate of change of speed over time is less in initial few second depicting lower acceleration and afterwards it increases indicating higher acceleration. Acceleration values again decreases towards the end of trip depicting condition of minimum acceleration.

- This changing acceleration behaviour of motorized three-wheeler can well be described using two different regimes (dual regime) for different acceleration. The point of divide between two regimes is the speed corresponding to point of maximum acceleration. Similar observation is also reported by Bham and Benekohal (2002).

4.4.1 Evaluation of existing model

Some of the existing models are evaluated in Section 4.3.2 on acceleration study for mid size truck. In case of motorized three wheeler, following models are evaluated to describe the observed acceleration-speed relationship.

1. Wang's polynomial Model, (Wang et al., 2004)
2. Dey's linear Model, (Dey and Biswas, 2011)
3. Bham's dual Regime Linear Model, (Bham and Benekohal, 2002)

Akcelik's polynomial and linear models (Akcelik and Biggs (1987), Akelik and Besley (2001)), which are evaluated for truck (Section 4.3.2), are not evaluated for motorized three-wheeler, since computation of model parameters for both these models is complex, which is illustrated in case of trucks. Further, acceleration-speed relationship shows a dual regime behaviour. Therefore, Bham's dual regime linear model is considered here for evaluation.

All the three models mentioned above are calibrated for motorized three wheeler data set. Calibrated model parameters are used to compute predicted accelerations and compared with observed acceleration using Hypothesis tests like Kolmpogoroff-Smirnoff (K-S) two sample test and Student's t-test. The results are presented in Table 4.8.

Table 4.8: Results of Hypothesis Test for predicted and observed acceleration using existing models for motorized three wheeler

Model	$\|t\|$	$t_{\alpha/2}$	h-value	Remark
Wang's Polynomial Model	4.60	2.00	1	Null Hypothesis cannot be accepted
Dey's Linear Model	2.39	2.00	1	Null Hypothesis cannot be accepted
Bham's Dual Regime Linear Model				
Regime-I	0.04	2.77	0	Null Hypothesis cannot be rejected
Regime-II	0.36	2.008	0	Null Hypothesis cannot be rejected

The acceleration data yielded from Wang's model Dey's single regime linear model has a different probability distribution (indicated by $|t|$ values exceeding $t_{\alpha/2}$, refer Table 4.8) and continuous distribution function (indicated by $h = 1$, in K-S two sample test, refer Table 4.8) as compared to acceleration computed from observed speed data. Hence, null hypothesis cannot be accepted in this case. However, the computation of acceleration using Bham's dual regime linear model indicates that accelerations computed using this model match with acceleration computed from observed speed data (null hypothesis cannot be rejected, refer Table 4.8). Hence, the *dual regime linear* model is evaluated further in detail in acceleration-speed model section.

4.4.2 Acceleration-speed model

For the purpose of modelling, speed and acceleration are averaged (idealized) over 1 m/s speed interval. Resulting idealized acceleration-speed plot is presented in Figure 4.17b. Following observations are made from idealized plot of acceleration-speed.

- The shape of idealized acceleration-speed plot is similar to that of a scatter plot *i.e.* dual regime. Since the slope of plot before and after occurrence of maximum acceleration is opposite, the plot is divided in two distinct regimes. The speed corresponding to maximum acceleration (termed as **critical speed**) acts as a point of divider between two regimes. Hence a dual regime model is developed for motorized three wheeler to explain acceleration-speed behaviour. Regime-I is for speed$\leq$ critical speed and Regime-II is for speed$\geq$ critical speed.

- The idealized acceleration-speed plot indicates a critical speed value of 2.34 m/s. Arasan and Koshy (2005) reported a critical speed to lie between 0-5.5 m/s for three wheeler in India. A similar shape of acceleration-speed plot is observed by some other researchers (Akcelik and Biggs (1987); Akelik and Besley (2001); Wang et al. (2004); Hong (2007)).

The Pearson correlation value, $'r'$, is computed for both regimes using Equation 4.11 and found as $+0.92$ for Regime-I and -0.94 for Regime-II.

$$r = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2(y-\bar{y})^2}} \tag{4.11}$$

Values for both regimes are close to $+1$ and -1 which indicates that relationship between acceleration and speed is strong. Also the $+$ and $-$ values of $'r'$ for Regime-I and Regime-II respectively, indicate that slope of relationship is positive in Regime-I and negative in Regime-II.

To verify the exact form of relationship, Residual Sum of Squares (RSS) is calculated using Equation 4.7 for Regime-I and Regime-II for linear and non-linear forms and presented in Table 4.9. Non linear forms chosen are negative exponential and polynomial. Linear form is reported by RaiChowdhury and Rao (1989) and second order polynomial form is reported by Akcelik and Biggs (1987) and Wang et al. (2004). The appropriate model form is one which gives minimum RSS. Table 4.9 indicates the RSS values for various model forms for both regimes. The hypothesis tests presented in Table 4.8 indicated that acceleration predicted by dual regime linear model and computed using observed speed may give satisfactory results, same is tested using RSS.

Table 4.9: Residual Sum of Squares (RSS) for various model forms for regime-I and regime-II for motorized three wheeler

	Linear	Exponential	Polynomial
	$a = \alpha + \beta \times v$	$a = k_1 \times e^{\pm k_2 \times v}$	$a = k_3 \times v^2 + k_4 \times v + k_5$
Regime-I	0.014	0.023	**0.0004**
Regime-II	0.110	**0.020**	0.023

The values in Table 4.9 indicate that RSS values are minimum for polynomial form for Regime-I and for negative exponential form for Regime-II. Hence these model forms are evaluated and validated further in this text for motorized three wheelers.

Linear regression (ordinary least square) is used to formulate the model and following relationships (refer Equations 4.12) are obtained for Regime-I and Regime-II.

$$
\begin{aligned}
&a = k_1 \times v^2 + k_2 \times v + k_3 \quad \text{Regime-I} \qquad (a)\\
&a = k_4 \times e^{-k_5 \times v} \quad \text{Regime-II} \qquad (b)
\end{aligned}
\tag{4.12}
$$

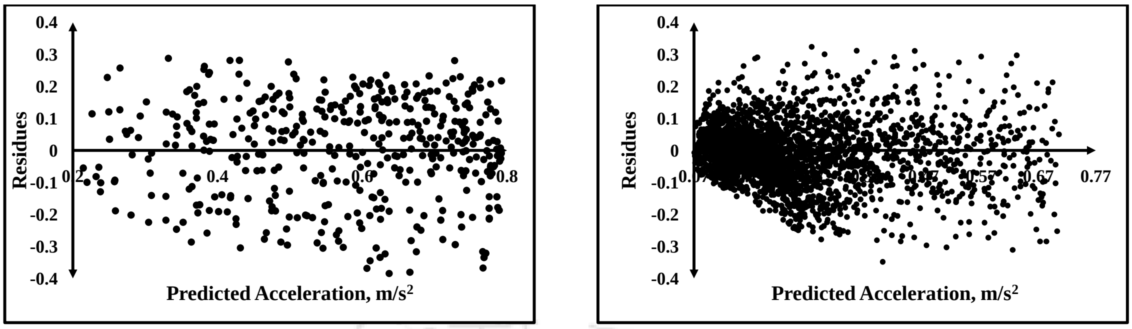
Collected field data is used to calibrate the model. Values of model parameters are presented in Table 4.10.

Table 4.10: Model parameters for Regime-I and Regime-II for motorized three wheeler

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
-0.23	+0.98	-0.295	0.99	1.471	-0.26	0.95

Model Diagnostic The theory relevant to model diagnostic is already presented in section 5.2 of this Chapter. Hence it is not repeated here. The acceleration-speed model of motorized three wheeler is tested similar to that of truck, using residual plots, quantile plots and box plots of residues and hypothesis testing and post hoc Least Significance Difference test.

Residual plots The residual plot (plot of residuals versus predicted values) for Regime-I and Regime-II are presented in Figure 4.18.

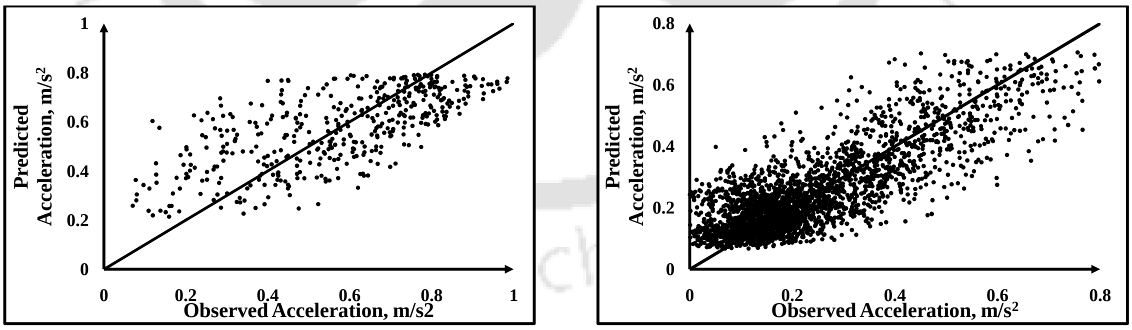


(a) Regime-I (b) Regime-II

Figure 4.18: Residual Plots of (a) acceleration residuals versus predicted acceleration values and (b) plot of acceleration residues versus time, for motorized three wheeler

The plot in Figure 4.18 indicates that the residues are not correlated to predicted values and also errors are not dependent on predicted values. This reinforces the compliance of assumptions of ordinary least square method.

Plot of observed versus predicted value The normality of error terms assumes that the random errors are normally distributed. The plot of observed versus predicted value indicates the normality of error terms. Figure 4.19 indicates that the points are clustered around a 45 ° straight line for a normally distributed variable(except for few data points), hence the assumption **'error terms are normally distributed'** is valid (refer Pg. 358 and 359, Freund and Wilson (2011)).



(a) Regime-I (b) Regime-II

Figure 4.19: Plot of observed versus predicted value of acceleration from field and proposed acceleration-speed model for motorized three wheeler

Box Plots of Residues The box plots indicating minimum and maximum values, first and third quartiles and medians of residues are presented in Figure 4.20. The plots indicate that the residues are fairly distributed around mean and that the distributions are fairly symmetric.

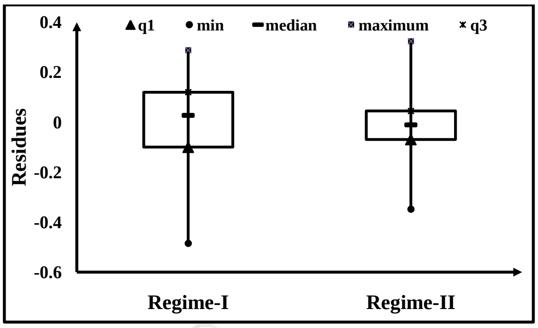


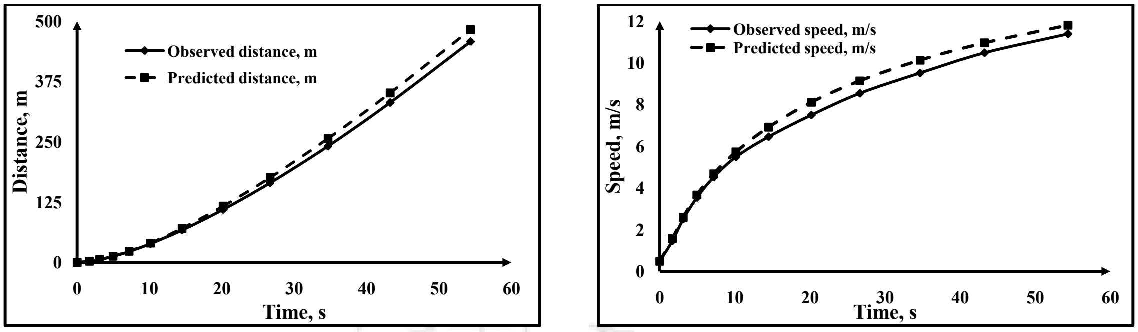
Figure 4.20: Box plots of residues of acceleration for Regime-I and Regime-II for motorized three wheeler

Hypothesis test Paired 't' test is used to test the means of observed acceleration and acceleration computed using exponential model in Equation 4.8. Two hypothesis are tested −(i) null hypothesis: $\mu = \mu_o - \mu_m = 0$, where μ_o and μ_m are mean of acceleration computed from observed speed and mean of acceleration obtained from model in Equation 4.8 and (ii) alternate hypothesis: $\mu \neq 0$. The test statistic is calculated using Equation 4.9. The t-statistics and critical t values are presented in Table 4.11 for Regime-I and Regime-II.

Table 4.11: t-test results for observed and predicted acceleration of Regime-I and Regime-II

Regime	$\|t\|$	$t_{0.025}$	Remark
Regime-I	0.03	1.96	$\|t\| < t0.025$
Regime-II	0.99	1.96	$\|t\| < t0.025$

Observed and predicted trajectories and speed Further, a comparison of observed and predicted trajectories and speed profiles are carried out and presented in Figure 4.21a and 4.21b. Observed trajectory of a vehicle is calculated from observed speed-time data. The modeled trajectory is calculated using modelled acceleration and modelled speed. A detailed derivation of speed and position from acceleration-speed relationship is appended to this thesis.



(a) Trajectory, observed and predicted (b) Speed, observed and predicted

Figure 4.21: Observed and predicted trajectories and speed of motorized three wheeler during acceleration manoeuver

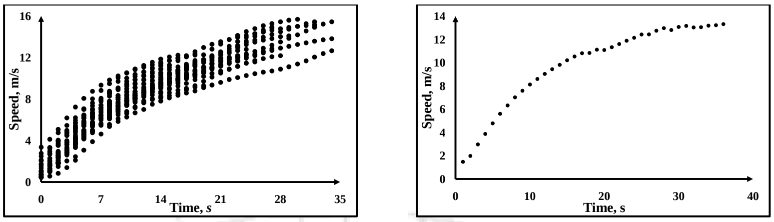
Paired t-test is used to compare the means of observed and modeled trajectories and speed profiles. Hypothesis is tested for 95% confidence interval ($\alpha = 0.05$)− (i) null hypothesis: $\mu = \mu_o - \mu_m = 0$, where μ_o and μ_m are mean of observed and modeled values and (ii) alternate hypothesis: $\mu \neq 0$. From the test results it is observed that the test statistic $|t| \leq t_{\alpha/2}(= t_{0.025})$. Hence the null hypothesis cannot be rejected. This indicates that proposed models for motorized three wheeler estimate the vehicle's trajectory and speed with fair accuracy.

Above discussion indicates that observed acceleration behaviour of motorized three wheeler can be described satisfactorily using dual regime model - polynomial model for Regime-I (Equation 4.12(a)) and negative exponential model for Regime-II (Equation 4.12(b)).

4.5 Study of Acceleration Behaviour of Motorized Two Wheelers

Literature reports that the composition of motorized two wheeler is 40.9% (Arasan and Koshy, 2005) and 32% (Jalihal et al., 2005) on urban arterial in India and it varies from 9% to 41% of total traffic composition on highways in India (Dey et al., 2008). The number of motorized two wheelers is fast increasing in India due to their slick design, speeding and accelerating capability and easy availability. Hence the proportion of fuel consumption and emission contributed by motorized two wheeler is increasing. Since the fuel consumption and emission of these vehicles is highly dependent on their acceleration (Ahn et al., 2002), it is necessary to understand acceleration behaviour of motorized two-wheeler.

As described in Section 4.2, acceleration data of 59 trips of motorized two wheelers have been collected and analyzed. Some of analysis results like speed profile, results of speed-time, acceleration-time and acceleration-speed relations, acceleration time and acceleration distance, critical speed, maximum acceleration rate, etc. are already discussed in Section 4.2. Some of figures like scatter and idealized plots of speed-time and acceleration -time are again presented here for their detailed analysis. Scatter and idealized plot of speed-time for motorized two wheeler trips is presented in Figure 4.22a and 4.22b).



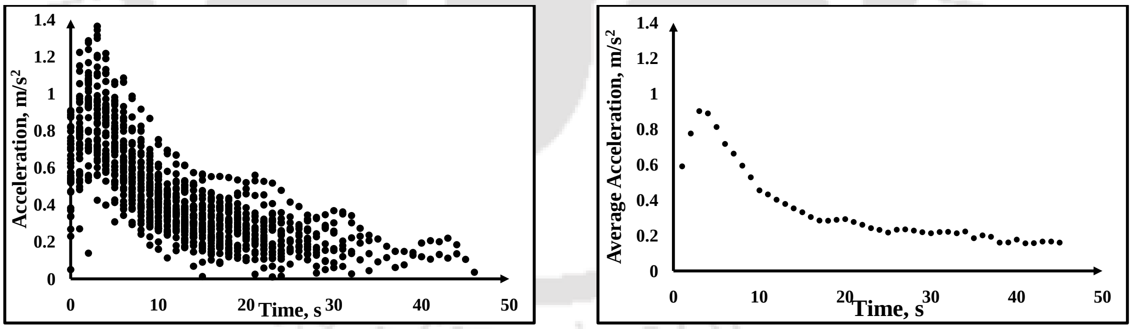
(a) Scatter plot (b) Idealized plot

Figure 4.22: Scatter and idealized plots of speed for motorized two wheeler during acceleration manoeuver

Following observations are made from the Figure 4.22.

1. Most of the trips start from rest (speed=0). The speed data of few trips at t=0 couldn't be logged due to 1 s data logging interval of GPS. Hence those trips are seen to start from higher speeds.
2. The maximum speed of motorized two wheeler trips varied from 12.45 m/s to 16.14 m/s. The maximum free speeds reported for motorized two wheeler is 12.5 m/s in India by Arasan and Koshy (2005).

Figure 4.23 presents scatter and idealized acceleration-time plots for motorized two wheelers.



(a) Scatter plot (b) Idealized plot

Figure 4.23: Scatter and idealized plots of acceleration for motorized two wheeler during acceleration manoeuver

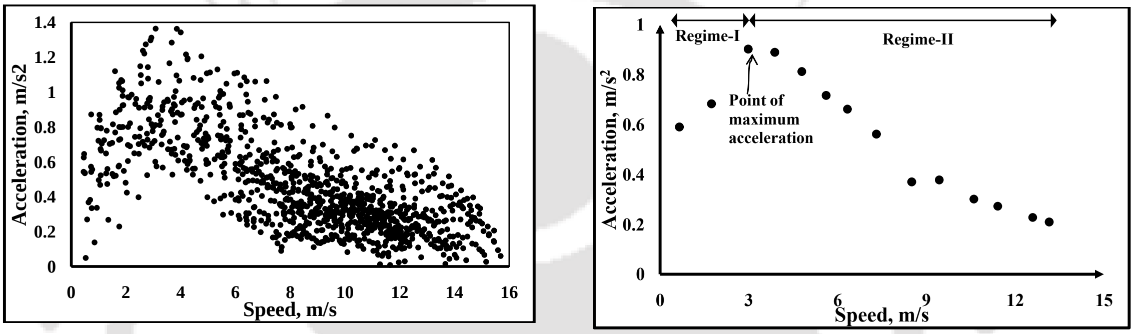
Following observations are made from scatter and idealized plot of acceleration (Figure 4.23).

1. Initial acceleration of motorized two-wheeler is low in start of acceleration manoeuver and it quickly increases to a maximum with passage of time value. Later it monotonically decreases till the end of acceleration manoeuver. This is similar to acceleration-time plot observed for motorized three wheeler.

2. Maximum acceleration rate of motorized two-wheeler observed in this study ranged from 0.53 m/s^2 to 1.36 m/s^2 with average maximum acceleration rate as 0.98 m/s^2. The maximum acceleration rate reported by Arasan and Koshy (2005) and Arasan and K.Krishnamurthy (2008) is 1.35 m/s^2.

3. It is seen from the acceleration-time idealized plot that motorized two-wheeler attain average maximum acceleration within 3 seconds from the beginning of trip.

The variation in acceleration over speed is evaluated using acceleration-speed scatter presented in Figure 4.24a. Idealized acceleration-speed plot is obtained by averaging the acceleration and speed values over every 1 m/s speed and presented in Figure 4.24b.



(a) Scatter plot (b) Idealized plot

Figure 4.24: Scatter and idealized acceleration-speed plots for motorized two wheeler during acceleration manoeuver

Following observations can be made from acceleration-speed plots:

1. The acceleration initially increases up to a maximum value with speed and later decreases monotonically with further increase in speed.

2. Therefore, similar to motorized three wheeler's case, acceleration-speed plot can be divided in two distinct regimes, Regime-I before achieving maximum acceleration and Regime-II after achieving maximum acceleration (refer Figure 4.24b). The speed corresponding to maximum acceleration is termed as **critical speed**. The Regime-I is for vehicle speed $\leq$ **critical speed** and Regime-II is for vehicle speed $\geq$ **critical speed**.

3. As such one point of discontinuity lies at the **critical speed** where acceleration-speed plot changes slope. as against several points of discontinuity in linear model proposed by Samuels and Jarvis (1978), as explained earlier.

4.5.1 Evaluation of existing models

Three existing models (like Wang's Polynomial Model, Dey's Linear Model and Bham's Dual Regime Linear Model) are evaluated (similar to those described in Section 4.4.1) to describe the observed acceleration-speed relationship. Models are evaluated using Hypothesis Test (Kolmogorov-Smirnov two sample test) and t-test (detail description about these tests are provided in Appendix B.3 and B.4. Evaluation results of these models are presented in Table 4.12.

Table 4.12: Results of t-test and Kolmogorov-Smirnov two sample test for predicted and observed acceleration using existing models for motorized two wheeler

Model	$\|t\|$	$t_{\alpha/2}$	Kolmogorov-Smirnov h-value	Remark
Wang's Polynomial Model	3.95	2.01	1	Null Hypothesis cannot be accepted
Dey's Linear Model	0.84	2.01	0	Null hypothesis cannot be rejected
Bham's Dual Regime Linear Model				
Regime-I	0.045	4.30	0	Null hypothesis cannot be rejected
Regime-II	4.16	2.2	0	Null hypothesis cannot be rejected

Table 4.12 indicates that the linear model can be used to describe the acceleration-speed behaviour if it is to be presented by single Regime model (indicated by $|t|$ values exceeding $t_{\alpha/2}$ and h value 0 for Kolmogoroff-Smirnoff two sample test in Table4.12). Though the single regime model may provide satisfactory fit but but it cannot be used to describe the acceleration-speed relationship in reality since the acceleration rates during acceleration manoeuver are not adequately presented by it. Bham and Benekohal (2002) opined that even if dual regime model does not give satisfactory fit, it will better represent acceleration in reality.

4.5.2 Acceleration-speed model

In order to decide the final form of acceleration-speed model, various model forms are tested for their suitability. Residual Sum of Squares (RSS[f]), is used to test the variability, that a particular model has from the observed data. The best model form is one which has minimum RSS values. Various forms that are tested are Linear, Exponential and Second Order Polynomial for both regimes. Values of RSS in Table 4.13 indicate that RSS values are minimum for polynomial form for Regime-I and exponential form for Regime-II. Hence these model forms are further evaluated and validated. Linear regression technic in used to formulate the models for Regime-I and Regime-II.

Values of RSS in Table 4.13 indicate that RSS values are minimum for polynomial form for Regime-I and exponential form for Regime-II. Hence these model forms are further evaluated and validated.

[f]refer Appendix B.6 for more details

Table 4.13: Residual Sum of Squares (RSS) for various model forms for Regime-I and Regime-II for motorized two wheeler

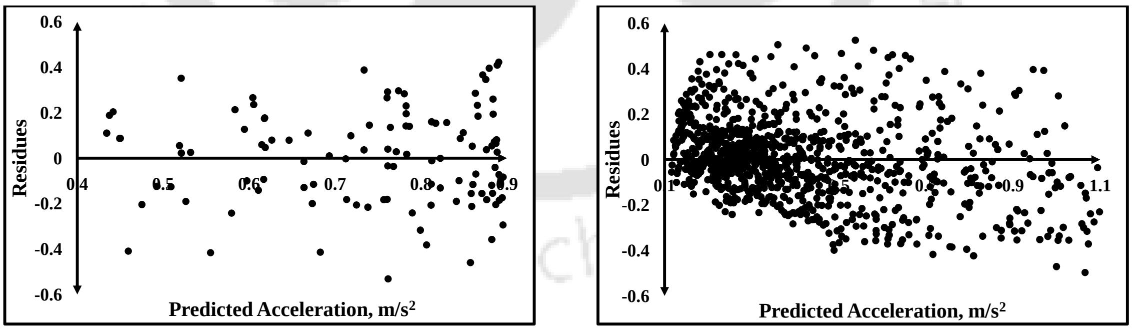
Regime	Linear	Exponential	Polynomial
	$a = \alpha + \beta \times v$	$a = k_1 \times e^{\pm k_2 \times v}$	$a = k_3 \times v^2 + k_4 \times v + k_5$
Regime-I	0.001	0.0018	$\mathbf{7.8 \times 10^{-7}}$
Regime-II	0.001	**0.0008**	0.05

Linear regression technic in used to formulate the models for Regime-I and Regime-II. The model forms are;

$$
\begin{aligned}
&a = -0.039 \times v^2 + 0.007 \times v + 0.578 \qquad r^2{=}1,\ \text{Regime-I} \\
&a = 1.628 \times e^{-0.15 \times v} \qquad r^2{=}0.98,\ \text{Regime-II}
\end{aligned} \tag{4.13}
$$

Model Diagnostic Similar to previous sections, acceleration-speed model for motorized two-wheeler is tested using residual plots, quantile plots and box plots of residues. The observed and predicted trajectories and speeds are also compared.

Residual plots Residual plots for Regime-I and Regime-II of acceleration-speed relationship for motorized two wheeler are presented in Figure 4.25a and 4.25b respectively. The residuals plots for both regimes indicate that residues are uniformly distributed around x-axis indicating uniform variance of errors. This satisfies one of the assumptions of linear regression. The residuals plots for both regimes



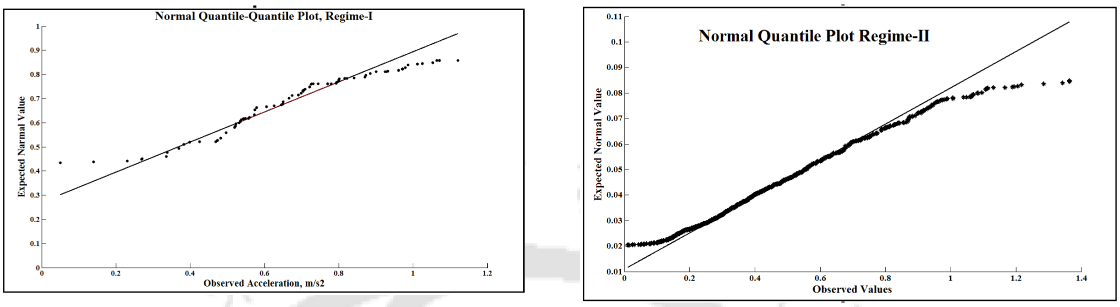
(a) Residues Regime-I

(b) Residues Regime-II

Figure 4.25: Residual plot for motorized two wheeler during acceleration manoeuver

indicate that residues are uniformly distributed around x-axis indicating uniform variance of errors. This satisfies one of the assumptions of linear regression.

Quantile plots The quantile plots for both regimes are presented in Figure 4.26a and 4.26b. The quantile plots indicate that the points have clustered around straight line depicting that variables are normally distributed fulfilling one more observation in linear regression. The quantile plots indicate that



(a) Quantile Plot, Regime-I (b) Quantile Plot, Regime-II

Figure 4.26: Quantile plot for motorized two wheeler

the points have clustered around straight line depicting that variables are normally distributed fulfilling one more observation in linear regression.

Box Plots of Residues The box plots of residues for both regimes are presented in Figure 4.27. The box plots indicate that the residues in Regime-I and Regime-II are symmetrically distributed around the median.

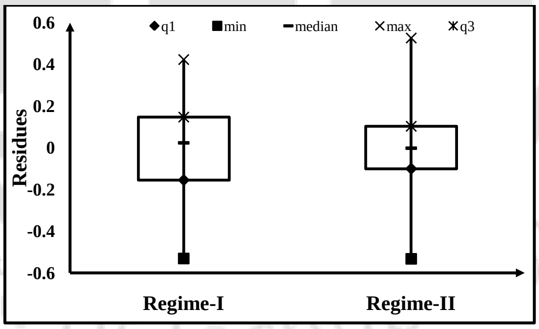
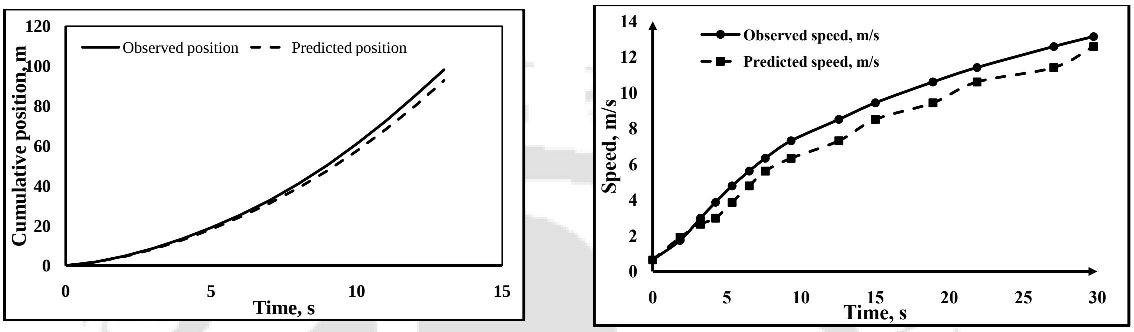


Figure 4.27: Box plots of residues for Regime-I and Regime-II for motorized two wheeler

The plots presented in Figure 4.25, 4.26 and 4.27 indicate no violation of assumptions in linear regression. The box plots of residues for Regime-I and Regime-II do not indicate presence of any outliers. Hence it can be concluded that proposed models are capable of predicting the accelerations of motorized two-wheelers with fair accuracy.

Trajectory and speed plots The models are further used to compute the position and speed of vehicle which are compared with observed position and speed values. The observed and predicted position and speed are presented in Figure 4.28a and 4.28b. The modeled and observed speed and trajectories indicate satisfactory prediction by model. Paired t-test is used to test null and alternate hypothesis as per the details described earlier in this chapter. The summary of $|t|$ values and $t_{\alpha/2}$ values for observed and predicted acceleration, position and speed data, are provided in Table 4.14. These values indicate that proposed model predicts acceleration, trajectory and speed of vehicle satisfactorily.



(a) Trajectory (b) Speed

Figure 4.28: Observed and Modeled, Speed and Trajectories for motorized two wheeler

Table 4.14: t-test results for motorized two wheeler

	$\|t\|$	$t_{\alpha/2}$	Remark
Acceleration	0.24	2.16	Null hypothesis cannot be rejected
Trajectory	0.001	2.16	Null hypothesis cannot be rejected
Speed	1.86×10^{-5}	2.16	Null hypothesis cannot be rejected

4.6 Study of Acceleration Behaviour of Cars

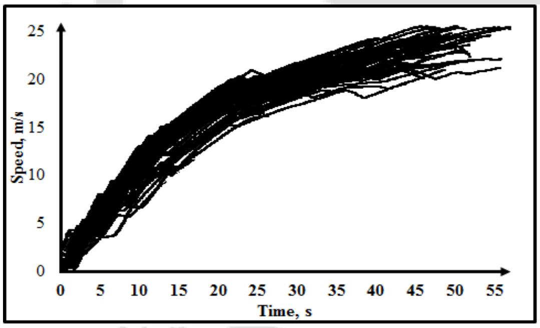
The vehicle traffic on Indian highways and urban arterial indicate that the cars form a sizeable proportion of traffic composition. Dey et al. (2008) reported that cars vary from 42% to 16% on Indian highways and Arasan and Koshy (2005) reported that cars are 27.8% on Indian urban arterial. This indicates that cars are in sizeable proportion on Indian roads hence it is necessary to understand the A/D behaviour of cars. These cars are run on two fuels; diesel and petrol (a very small proportion runs on gas). The engine undergoes some modifications with the change in fuel influencing their speeding and accelerating characteristics and tail pipe emission. This study therefore, emphasized on A/D behaviour of diesel and petrol car, separately. The scope of this study is limited to the cars having weight to horsepower ratio from 30 to 50 lb/hp (18-30 kg/kW).

Position and speed of cars are collected at second study stretch near IIT Guwahati (with similar road geometry) using V-Box with 10 Hz data logging capability. More detail about data collection procedure is provided in Chapter 3.

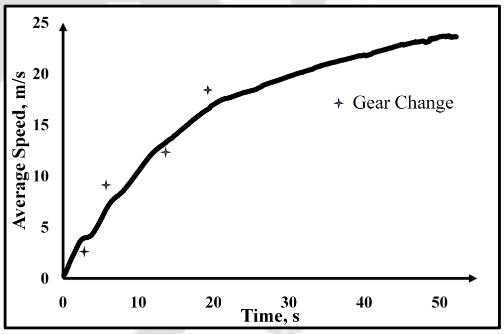
Subsequent sections will present the acceleration characteristics of diesel cars and petrol cars separately. The number of diesel car (Tata Indica V2 model with weight to horsepower ratio of 33) trips recorded during study are 110 whereas the petrol cars trips studied for the acceleration characteristics are 115.

4.6.1 Study of Acceleration Behaviour of Diesel Cars

Section 4.2 provides the data collection details for diesel cars. Analysis results like speed profile, results of speed-time, acceleration-time and acceleration-speed relations, acceleration time and acceleration distance, critical speed, maximum acceleration rate, etc. are already discussed in Section 4.2. Scatter and idealized plots of speed-time and acceleration-time are presented here again for detailed analysis. Scatter and idealized plot of speed-time for diesel car trips are presented in Figure 4.29a and Figure 4.29b. Scatter plot (refer Figure 4.29a) has more data points than similar plots for other vehicles as data is collected at 10 hz frequency using V-Box than 1 Hz frequency using GPS.



(a) Scatter plot



(b) Idealized plot

Figure 4.29: Scatter and idealized plot of speed for diesel car during acceleration manoeuver

Following observations are noted from speed profile presented in Figure 4.29.

- The scatter plot (refer Figure 4.29a) shows that maximum speed achieved by diesel car in different trips varies from 16.36 m/s to 25.58 m/s with an average maximum speed 21.96 m/s. The maximum speed of cars reported by other researchers are presented in Table 4.15. It can be seen that observed maximum speed of diesel cars matches with the findings of many researcher.

Table 4.15: Speed values of cars reported by various researchers

Sr. No.	Name of Researcher	Maximum Speed (m/s)
1	Wang et al. (2011)	28.08
2	Arasan and Koshy (2005)	25
3	Bham and Benekohal (2002)	17
4	Long (2000)	15.65
5	Hallmark (1999)	22.44
6	Aycin and Benekohal (2000)	23
7	Akcelik and Biggs (1987)	16.66
8	Samuels and Jarvis (1978)	22.36

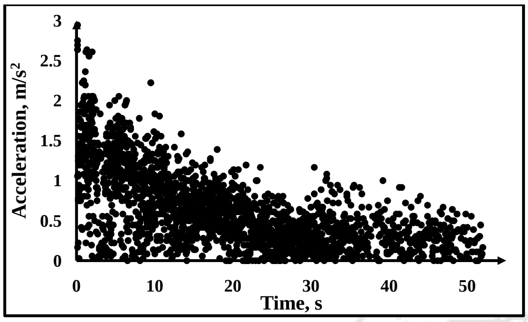
- The idealized speed plot indicate that rate of change of speed over time has become zero at certain points. This is seen by horizontal speed-time plot at some points marked by star (+). These are the points where driver has changes gears. At the time of gear change, drivers temporarily drive at constant speed and immediately after completing gear change, driver again resumes original acceleration. This effect is seen up to third gear only and fades thereafter.

- The shape of average speed profile indicates steep slope at the beginning of acceleration manoeuver. This indicates higher acceleration at the beginning of acceleration manoeuver. The average speed profile flattens at the end of acceleration manoeuver, indicating minimum (or zero) acceleration at the end of acceleration manoeuver (cruising). Similar shape of speed profile is also reported by other researchers like Akcelik and Biggs (1987); Akelik and Besley (2001); Wang et al. (2004) and Hong (2007).

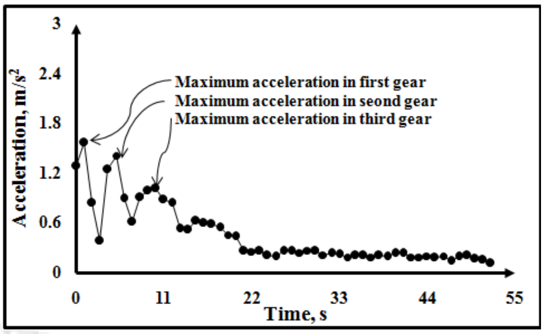
Acceleration of diesel cars is then computed using Equation 3.1 and scatter plot of acceleration-time (acceleration profile) is presented in Figure 4.30a. For understanding the average acceleration behaviour of diesel cars, the acceleration is averaged over 1 s and the average acceleration-time plot (*idealized acceleration plot*) is presented in Figure 4.30b. Following observations are made from acceleration-time scatter and acceleration-time idealized plot.

- It is seen from scatter plot of acceleration-time that maximum acceleration occurs soon after the trip begins. The vehicle trip begins with lower acceleration values and quickly attains maximum acceleration value. The maximum acceleration registered by the diesel car is 2.94 m/s^2.

- Maximum average acceleration of diesel car observed in this study is 1.90 m/s^2 achieved after 0.8 seconds after commencement of trip. It may be noted here that the point of maximum acceleration reaches so quickly after starting of trip that it is only possible to capture it using GPS device having 10 hz or more data logging frequency.



(a) Scatter plot

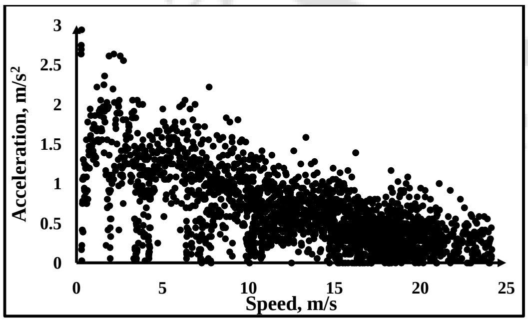


(b) Idealized plot

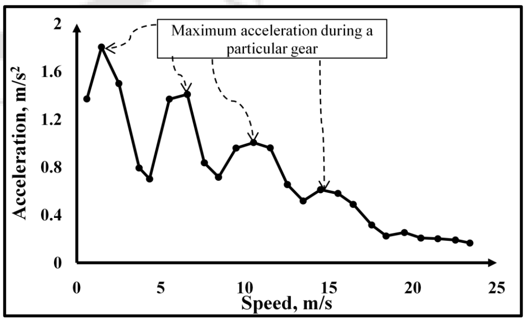
Figure 4.30: Scatter and idealized plot of acceleration-time for diesel cars during acceleration manoeuver

- The maximum acceleration is attained in first gear. The nature of scatter plot indicates that acceleration reduces as time increases. This observation is in agreement with other researchers, Akcelik and Biggs (1987); Akelik and Besley (2001) and Wang et al. (2004).
- The variation of acceleration over time is very well seen in idealized acceleration-time plot (refer Figure 4.30b). The acceleration increases initially in first gear up to a maximum value. During gear change acceleration decreases and again restores to higher value when gear change process is over. But this higher value of acceleration is less than what was achieved in previous gear. This phenomena continues up to third gear. After this the acceleration values do not undergo much of the change during gear change.

The acceleration is then compared with speed and the resulting acceleration-speed scatter plot is presented in Figure 4.31a. Acceleration and speed are averaged over every 1 m/s interval and the resulting idealized acceleration-speed plot is presented in Figure 4.31b. Following observations are made from



(a) Scatter plot



(b) Idealized plot

Figure 4.31: Scatter and idealized plots of acceleration-speed for diesel car during acceleration manoeuver

these acceleration-speed plots:

- 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. In each gear, acceleration attains maximum value from a lower value and then reduces to a minimum in a particular gear. In last gear i.e. in fifth gear acceleration monotonously decreases as speed increases.

- The maximum acceleration of all trips ranges from 1.52 m/s^2 at 1.47 m/s to 3.02 m/s^2 at 1.09 m/s (refer Figure 4.31a). The average maximum acceleration attained in every gear and speed at which maximum acceleration occurs is presented in Table 4.16. Values in Table 4.16 indicate that average maximum acceleration values decrease with increase in speed and vehicle gear.

Table 4.16: Maximum average acceleration attained in various gears

Gear	Average Maximum Acceleration, m/s^2	Speed at Maximum Acceleration, m/s
First	1.803	1.46
Second	1.408	6.57
Third	1.004	10.52
Fourth	0.610	14.50
Fifth	0.250	19.50

- The idealized acceleration-speed plot indicates that maximum average acceleration for diesel car is 1.803 m/s^2 at a speed of 1.46 m/s.

- It is also noted that at every gear change there is a maximum acceleration and associated speed. However, rate of average maximum acceleration is highest at first gear and lowest at higher gear.

- The idealized acceleration-speed plot for every gear can be divided in two distinct regimes, Regime-I for speed $\leq$ **critical speed** and Regime-II $\geq$ **critical speed**. But reporting separate models for every gear or reporting different model parameters for every gear is of less practical use. Therefore, a single regime model can be developed ignoring the effect of gears for most of the transportation engineering use.

Evaluation of existing models

Following two acceleration models are evaluated in the present study:

- Wang's Polynomial model, Wang et al. (2004)

- Dey's linear model, Dey and Biswas (2011)

These models are calibrated for diesel car data set. The resulting parameters are used to compute the acceleration predicted by models. Predicted and observed acceleration are compared using hypothesis test at 95% confidence level ($\alpha/2 = 0.025$). Kolmogoroff-Smirnoff two sample test and t-test are used to test the hypothesis. The results of hypothesis test are presented in Table4.17.

Table 4.17: Results of Hypothesis Test for predicted and observed acceleration using existing models for Diesel car

Model	Equation	r^2	$\|t\|$	$t_{\alpha/2}$	h-value	Remark
Wang's Polynomial Model Wang et al. (2004)	$a = (-7 \times 10^{-6} \times v^2)$ $-0.005 \times v + 1.292$	0.74	18.54	1.96	1	Null Hypothesis cannot be accepted
Dey's Linear Model Dey and Biswas (2011)	$a = -0.002 \times v + 0.986$	0.6	1.01	1.96	0	Null hypothesis can not be rejected

The absolute t-values ($|t|$), t-critical values ($t_{\alpha/2}$) values and h values for Kolmogoroff-Smirnoff test indicate that the Wang's polynomial model can not explain variation of acceleration with speed, properly. However, Dey's linear model can describe the dependence of acceleration on speed for diesel cars. However, the model that can best explain the acceleration-speed is one which yields lowest RSS. Hence, the linear model along with other model forms such as exponential and polynomial are evaluated for explanation of acceleration-speed relationship.

Acceleration-speed model

This section presents statistical modelling methodology and analysis results of modelling of acceleration-speed relationship for diesel cars. As mentioned earlier, acceleration-speed data reflect gear effect of vehicle. In every gear, acceleration initially increase with increase in speed up to a maximum value and then decreases with further increase in speed. It is felt that acceleration modelling of every gear level is not of much use in transportation engineering. Further it may add to complexity and points of discontinuity to the proposed model. Therefore, to keep model simple, yet reasonably accurate a single regime model is proposed neglecting the gear effect of cars.

Three single regime models (like Linear model, Polynomial model and exponential model) are evaluated for their suitability in describing the idealized acceleration-speed plot (refer Figure 4.31). Residual Sum of Squares (RSS) is used to test the variability, that a particular model exhibits from the observed data. The best model form is one which has minimum RSS values. Values of RSS are obtained as 0.59, 0.81 and 0.55 for models Linear model, Polynomial model and exponential model.

Linear regression (ordinary least square)is used to formulate the model and a relationship similar to Equation 4.8, ($\mathbf{a_1} = \mathbf{k_1 e^{(-k_2 v)}}$) is obtained.

The collected field data is used to calibrate the model. Values of parameters k_1 and k_2 are found to be 2.38 and 0.10 respectively. The coefficient of determination, r^2, is calculated by squaring results of Equation 4.6 and is found to be 0.88, indicating satisfactory fit.

Model Diagnostic The theory relevant to model diagnostic is already presented in section 5.2 of this Chapter. Hence it is not repeated here. The acceleration-speed model of diesel cars is tested similar to that of truck, using residual plots, quantile plot and hypothesis testing.

The residual plot (plot of residuals versus predicted values) is presented in Figure 4.32.

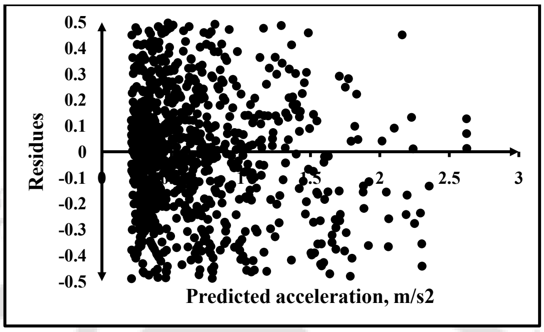


Figure 4.32: Residual plot for diesel car

The plot in Figure 4.32 indicates a band of approximately constant width around *x-axis* depicting fulfillment of assumptions made in regression analysis.

The normality of error terms assumes that the random errors are normally distributed. The plot of observed versus predicted values are used to check the normality assumption (Freund and Wilson, 2011). Figure 4.33 indicates that the points are clustered around a 45 ° straight line for a normally distributed variable(except for few data points), hence the assumption **'error terms are normally distributed'** is valid.

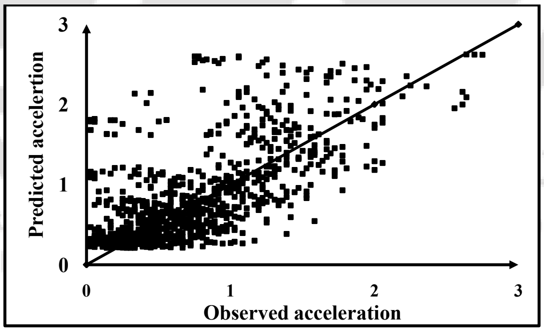
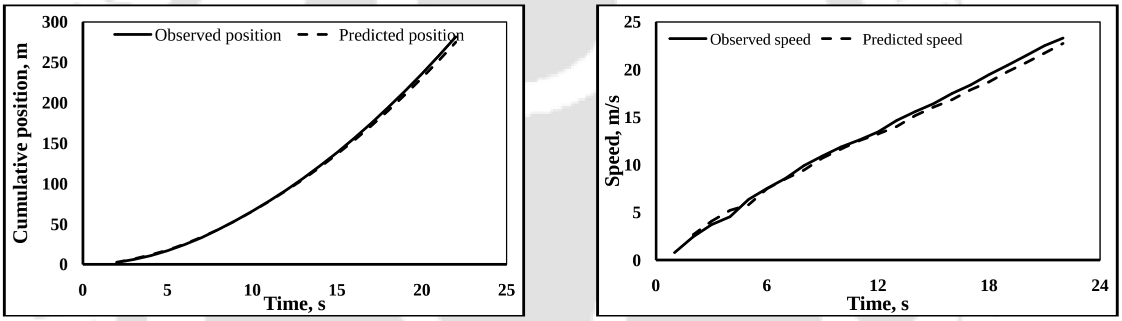


Figure 4.33: Observed vs. predicted plot for diesel car

Hypothesis test Paired 't' test is used to test the means of observed acceleration and acceleration computed using exponential model in Equation 4.8. t-statistic is found to be 0.735. Since, $|t|(= 0.735) < t_{\alpha/2}$, null hypothesis that $\mu = \mu_o - \mu_m = 0$ cannot be rejected. Therefore this diagnostic test shows that the proposed model is able represent the observed acceleration-speed relationship with fair accuracy.

Observed and predicted trajectories and speed Further, a comparison of observed and predicted trajectories and speed profiles are carried out and presented in Figure 4.34a and 4.34b. Observed trajectory of a vehicle type is the idealized plot where position values of car (obtained from their trajectories recorded using GPS) are averaged over every 1 second time interval. Similarly, observed speed profiles of car are also obtained by averaging speed of vehicles of truck over every 1 second time interval. Predicted position and speed profiles for car are obtained from the proposed models as given in Equation 4.8 and model parameters. Paired t-test is used to compare the means of observed and modeled trajectories and speed profiles. Two hypothesis are tested for 95% confidence interval ($\alpha = 0.05$)− (i) null hypothesis: $\mu = \mu_o - \mu_m = 0$, where μ_o and μ_m are mean of observed and modeled values and (ii) alternate hypothesis: $\mu \neq 0$. From the test results it is observed that for car the test statistic $|t| \leq t_{\alpha/2}(= t_{0.025})$. Hence the null hypothesis cannot be rejected. This indicates that proposed models for car estimate the vehicle's trajectory and speed with fair accuracy.



(a) Trajectory (b) Speed profile

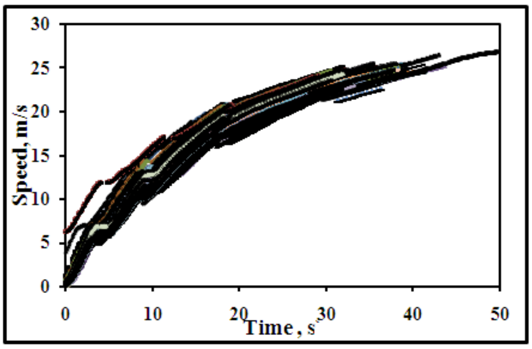
Figure 4.34: Observed and predicted trajectories and speed profile of diesel car

4.6.2 Study of Acceleration Behaviour of Petrol Cars

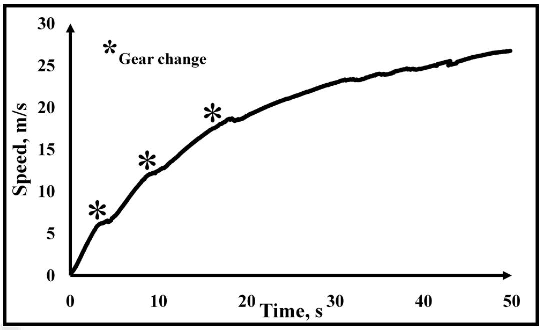
Section 4.2 provides the data collection details for petrol cars. Analysis results like speed profile, results of speed-time, acceleration-time and acceleration-speed relations, acceleration time and acceleration distance, critical speed, maximum acceleration rate, etc. are already discussed in Section 4.2. Scatter and idealized plots of speed-time and acceleration-time are presented here again for detailed analysis. Scatter and idealized plot of speed-time for diesel car trips are presented in Figure 4.35a and Figure 4.35b. Scatter plot (refer Figure 4.35a) has more data points than similar plots for other vehicles as data is collected at 10 hz frequency using V-Box than for other vehicles at 1 Hz frequency using GPS.

Following observations are noted from speed profile presented in Figure 4.35.

- The scatter plot (refer Figure 4.29a) shows that maximum speed achieved by petrol car in different trips varies from 22.24 m/s to 26.73 m/s with an average maximum speed 24.12 m/s. The maximum speed of cars reported by other researchers are presented in Table 4.15. It can be seen



(a) Scatter plot



(b) Idealized plot

Figure 4.35: Scatter and idealized plot of speed-time for petrol car during acceleration manoeuver

that observed maximum speed of petrol cars matches with the finding of many researcher.

- Similar to diesel car the idealized speed plot for petrol car also indicate that rate of change of speed over time has become zero at certain points (marked by *). These are the points where driver changes gear.

- The shape of average speed profile indicates steep slope at the beginning of acceleration manoeuver. This indicates higher acceleration at the beginning of acceleration manoeuver. The average speed profile flattens at the end of acceleration manoeuver, indicating minimum (or zero) acceleration at the end of acceleration manoeuver (cruising). Similar shape of speed profile is also reported by other researchers like Akcelik and Biggs (1987); Akelik and Besley (2001); Wang et al. (2004) and Hong (2007).

The acceleration was computed using Equation 3.1 and averaged over 1 second time interval for all trips. The idealized acceleration profile is presented in Figure 4.36.

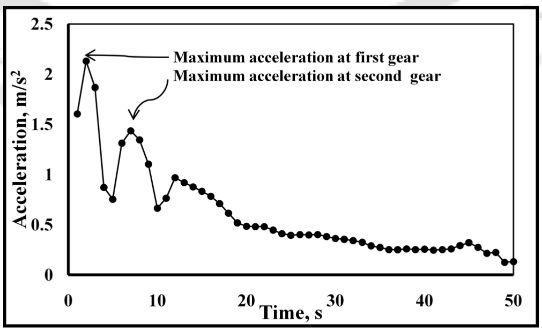


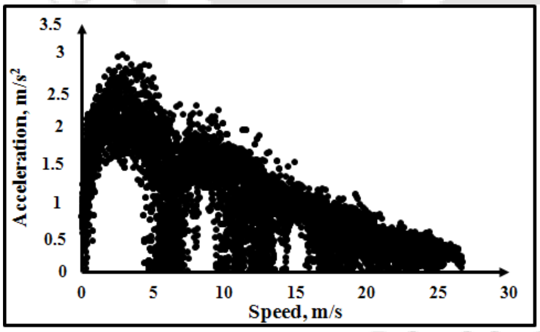
Figure 4.36: Idealized plot of acceleration-time for petrol car during acceleration manoeuver

Following observations can be made from Figure 4.36;

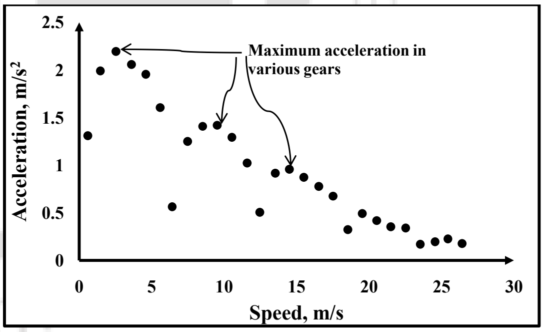
- Similar to diesel car, the average acceleration profile shows gear change phenomena (like speed profile scatter). The acceleration reduces at the time of gear change and again peaks up as vehicle speeds up in next gear. This phenomena is more prominent in petrol cars compared to diesel car. However, this phenomena is limited up to second gear and after that this phenomena is not prominently witnessed (though it exists, the reduction in acceleration is not as high as in gear 1 and 2). Unlike diesel cars (where this phenomena is observed up to third gear), the gear change phenomena in petrol cars is observed till second gear only. This indicates that the acceleration of petrol cars stabilize earlier than diesel car.

- The average maximum acceleration in first and second gear was observed to be 2.13 m/s^2 and 1.48 m/s^2 which is higher than acceleration in similar gear for diesel car (refer Table 4.16).
- The maximum acceleration is attained in first gear. The nature of scatter plot indicates that the acceleration reduces as time increases. This observation is in agreement with other researchers, Akcelik and Biggs (1987); Akelik and Besley (2001) and Wang et al. (2004).
- The variation of acceleration over time is very well seen in idealized acceleration-time plot (refer Figure 4.36). Like diesel cars, the acceleration increases initially in first gear up to a maximum value.

The acceleration is then compared with speed and the resulting acceleration-speed scatter plot is presented in Figure 4.37a. Acceleration and speed are averaged over every 1 m/s interval and the resulting idealized acceleration-speed plot is presented in Figure 4.37b.



(a) Scatter plot



(b) Idealized plot

Figure 4.37: Scatter and idealized plot of acceleration-speed plots for petrol car during acceleration manoeuver

Following observations are made from these acceleration-speed plots:

- Like diesel car, in petrol car also, 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.

- In each gear, acceleration attains maximum value and then reduces to a minimum in a particular gear. In last gear i.e. in fifth gear acceleration monotonously decreases as speed increases.

- The maximum acceleration of all trips ranges from 1.86 m/s^2 to 3.04 m/s^2 at around 2 m/s (refer Figure 4.37a).

- The idealized acceleration-speed plot indicates that maximum average acceleration for petrol car is 2.19 m/s^2 at a speed of 2.53 m/s. This indicates that the average maximum acceleration attained by petrol car is achieved at a speed higher than that in diesel car.

- It is also noted that at every gear change there is a maximum acceleration and associated speed. However, idealized maximum acceleration is highest at first gear and lowest at higher gear.

- The idealized acceleration-speed plot for every gear can be divided in two distinct regimes, Regime-I for speed $\leq$ **critical speed** and Regime-II $\geq$ **critical speed**. But reporting separate models for every gear or reporting different model parameters for every gear is of less practical use. Therefore, for diesel car a single regime model is proposed in this study.

Evaluation of existing and proposed models

Following two acceleration models are evaluated in the present study:

- Wang's Polynomial model, Wang et al. (2004)

- Dey's linear model, Dey and Biswas (2011)

These models are calibrated for petrol car data set. The resulting parameters are used to compute the acceleration predicted by models. Predicted and observed acceleration are compared using hypothesis test at 95% confidence level ($\alpha/2 = 0.025$). Kolmogoroff-Smirnoff two sample test and t-test are used to test the hypothesis. The results of hypothesis test are presented in Table 4.17.

Table 4.18: Results of Hypothesis Test for predicted and observed acceleration using existing models for Petrol car

Model	Equation	r^2	$\lvert t\rvert$	$t_{\alpha/2}$	h-value	Remark	RSS
Wang's Polynomial Model Wang et al. (2004)	$\sqrt{a} = 1.381 \times v + 0.011$	0.80	3.34	2.05	1	Null Hypothesis cannot be accepted	12.86
Dey's Linear Model Dey and Biswas (2011)	$a = -0.017 \times v + 1.907$	0.80	0.06	2.05	0	Null hypothesis can not be rejected	2.78
Exponential model	$a = 2.504 \times e^{-0.09 \times v}$	0.83	0.01	2.05	0	Null hypothesis can not be rejected	2.14

The absolute t-values ($|t|$), t-critical values ($t_{\alpha/2}$) values and h values for Kolmogoroff-Smirnoff test indicate that the Wang's polynomial model can not explain variation of acceleration with speed, properly. However, Dey's linear model can describe the dependence of acceleration on speed for petrol cars. However, the model that can best explain the acceleration-speed is one which yields lowest RSS. It is seen from Table 4.18 that the RSS values are lowest for exponential model. This has also resulted in higher r^2 values for exponential model.

The graphical presentation of these models is presented in Figure 4.38

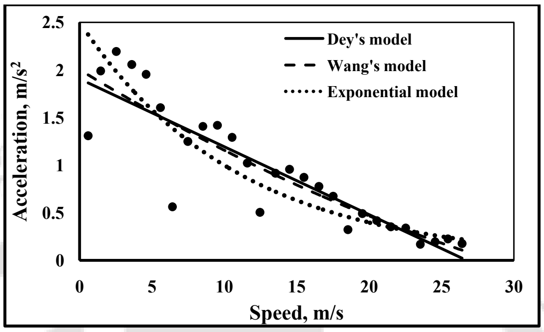
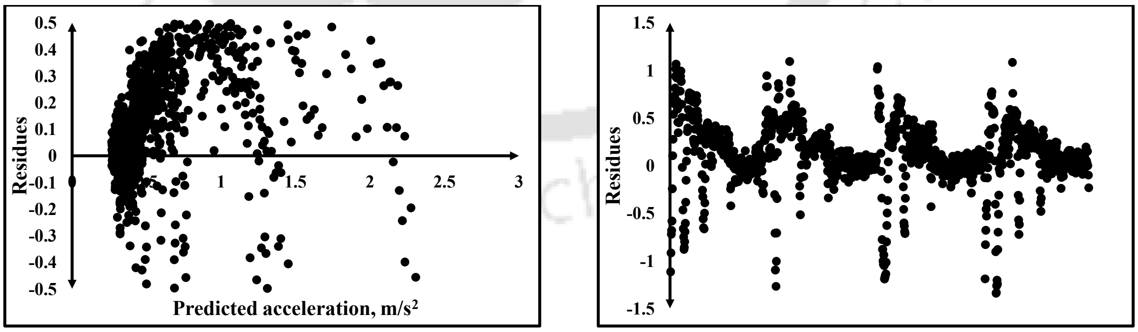


Figure 4.38: Various acceleration-speed models for petrol car

It is seen from Figure 4.38 that exponential model best fits data as compared to Wang's model and Dey's model. Therefore, exponential model form is proposed and evaluated further in this study.

Model Diagnostic The theory relevant to model diagnostic is already presented in Section B.8. Hence it is not repeated here. The acceleration-speed model of petrol cars is tested similar to that of truck, using residual plots, plots of observed and predicted acceleration and hypothesis testing.

The residual plot (plot of residuals versus predicted values) is presented in Figure 4.39a and 4.39b. The plot in Figure 4.39a and 4.39b indicates no correlation between predicted values and residues and



(a) Residues versus predicted

(b) Residues versus time

Figure 4.39: Residual plot of acceleration, petrol car

time and residues. However, the effect of gear is seen prominently in residual plots. Since the plot indicate no trend of it depicts that the errors are not dependent on each other. This reinforces the compliance of assumptions.

Figure 4.41 presents observed versus predicted plot indicating that the points are (more or less) clustered around a 45° straight line for a normally distributed variable. Hence the assumption **'error terms are normally distributed'** is valid (Freund and Wilson (2011)).

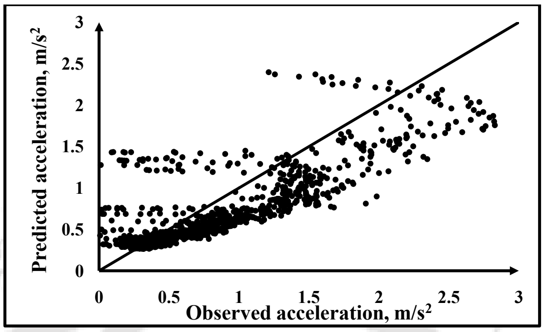


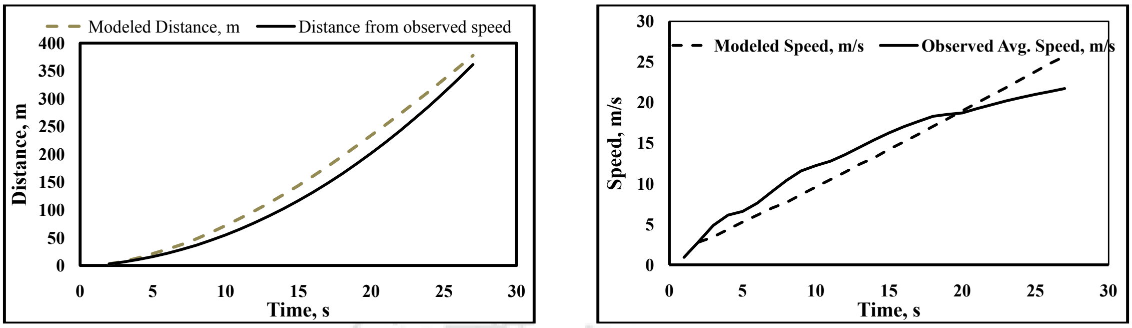
Figure 4.40: Observed versus predicted acceleration plot for petrol car

Hypothesis test Paired 't' test is used to test the means of observed acceleration and acceleration computed using exponential model in Equation 4.8 (refer section B.8 on page 197). The test statistic is calculated Equation 4.9. The hypothesis is tested for 95% confidence interval ($\alpha = 0.05$), where α is significance level. One can reject null hypothesis if $|t| \geq t_{\alpha/2}(= t_{0.025})$.

$$t = \frac{0.943 - 0.937}{0.327/\sqrt{26}} = 0.093, |t| = 0.093, t_{\alpha/2}(= t_{0.025}) = 1.7066, \text{hence}, |t| \leq t_{\alpha/2}$$

Since, $|t| \leq t_{\alpha/2}$, null hypothesis that $\mu = \mu_o - \mu_m = 0$ cannot be rejected.

Observed and predicted trajectories and speed Further, a comparison of observed and predicted trajectories and speed profiles (refer section B.8 on page 197) are carried out and presented in Figure 4.41a and 4.41b. Observed trajectory of a vehicle type is the idealized plot where position values of car (obtained from their trajectories recorded using GPS) are averaged over every 1 second time interval. Similarly, observed speed profiles of car are also obtained by averaging speed of vehicles of truck over every 1 second time interval. Predicted position and speed profiles for car are obtained from the proposed models as given in Equation 4.8 and model parameters. Paired t-test is used to compare the means of observed and modeled trajectories and speed profiles (refer B.8 on page 197). From the test results it is observed that for petrol car the test statistic $|t| \leq t_{\alpha/2}(= t_{0.025})$. Hence the null hypothesis cannot be rejected. This indicates that proposed models for car estimate the vehicle's trajectory and speed with fair accuracy.



(a) Trajectory

(b) Speed profile

Figure 4.41: Observed and predicted trajectories and speed profile of diesel car

4.7 Concluding Remarks

This chapter presents the acceleration behaviour of various vehicle types (mid size truck, motorized three wheeler, motorized two wheeler, diesel car and petrol car) at two stretches replicating the conditions of lead vehicle at signalized intersection. Studies in past emphasized on A/D behaviour of cars. Since, Indian traffic stream consists vehicle having different physical and engine characteristics, other vehicles are also included in this study. Following are the salient features of this study.

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 but 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 of various vehicle types are for truck 1.0 m/s^2, for motorized three-wheeler 0.64 m/s^2, for motorized two-wheeler 1.95 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 the rates observed in this study 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.

Chapter 5

Study of Deceleration Behaviour

Importance of acceleration/deceleration (A/D) characteristics of vehicles in transportation engineering is already discussed in previous chapters. Limited number of studies (in comparison to acceleration studies) have been carried out in past to understand the deceleration behaviour of vehicles. A details review of deceleration models developed in past are presented in literature review chapter of the thesis. Most of the old deceleration studies are either used old data set or used traditional methods/equipments (like radar gun, loop detector etc.) which may not lead to accurate results. Therefore, presents study aims to study the deceleration behaviour of different vehicles like trucks, motorized three wheelers, motorized two wheelers, petrol and diesel cars.

This chapter provides the details of deceleration behaviour data collected from field and discuss the observations on deceleration behaviour of different vehicle types. Existing acceleration models are evaluated for realistic description of observed deceleration behaviour. New deceleration models are proposed and evaluated, if existing models fails to explain the observed behaviour. Chapter is organized under following headings:

- Field data collection
- Analysis of field data
- Study of deceleration behaviour of mid size truck
- Study of deceleration behaviour of other vehicles

Data collection Chapter 3 presents the detail methodology for filed data collection. Data collection on acceleration and deceleration behaviour of vehicles is done together. Later acceleration and deceleration data is segregated as discussed in Chapter 3. A/D data were collected at two locations: (i) Nagpur-Aurangabad highway at Wardha and (ii) approach road of IIT Guwahati. The data for trucks, motorized two wheelers and motorized three wheelers were collected at Nagpur- Aurangabad highway (first study stretch) near Wardha while diesel and petrol cars data were recorded at approach road of IIT Guwahati (second study stretch). As mentioned in previous chapter, A/D data was collected on these selected stretches under controlled condition as data collected at Indian intersection generally results inconsistent data. Drivers were asked to accelerate to achieve their maximum acceleration in shortest possible time and later they were asked to decelerate quickly to the stopped condition after cruising for sometime at their maximum speed. Position and speed data of vehicles are collected using GPS (V-Box in case of cars) with 1 Hz (10 Hz in case of V-Box) frequency. Similar to acceleration behaviour study, Table 5.1 presents a 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.

Table 5.1: Number of trips and data points of various vehicle types

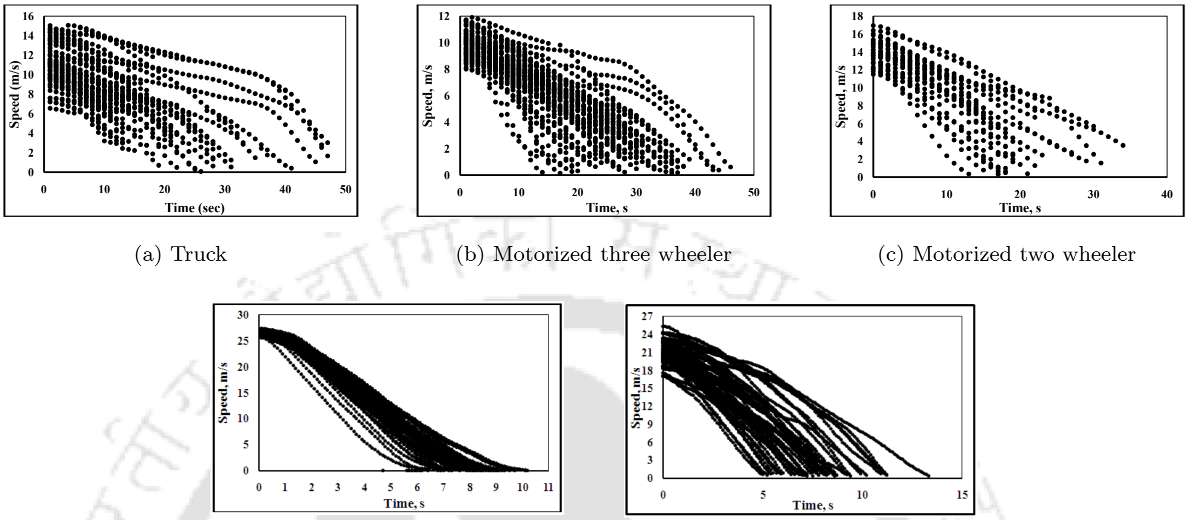
Serial No	Type of vehicle	Weight to Horsepower Ratio, lb/hp (kg/kW)	No. of trips	No.of data points
1	Trucks	300 (183.00)	42	902
2	Motorized three wheeler	100 (61.00)	67	1740
3	Motorized two wheeler	31 (18.91)	29	594
4	Cars			
	i)Diesel car	33 (20.13)	53	3982
	ii) Petrol car	30 (18.30)	75	5808

5.1 Analysis of Field Data

Speed and position data for different vehicle types were recorded using GPS (or V-Box) during the designed trips (acceleration, cruising and deceleration) under controlled condition. GPS data corresponding to deceleration manoeuver within each trip were segregated according to the criteria described in Chapter 3. These segregated deceleration manoeuver GPS data (in terms of position and speed vs time) of all trips of a particular vehicle type was grouped together. Thereafter, each deceleration trip GPS data was smoothed using exponential smoothing technique (or Kalman Filter smoothing algorithm for V-Box data) to minimize the effect of random errors. Corrected GPS/V-Box data of all vehicles trips are analyzed and presented in the following subsections.

5.1.1 Speed-time relationship

Speed profiles data for all deceleration manoeuvres are plotted together to get scatter speed-time plots (refer Figure 3.4) for each vehicle class separately. Figure 3.4 presents the scatter speed-time plot for all type of vehicles like mid sized truck, motorized three wheelers, motorized two wheeler, petrol and diesel cars.



(a) Truck (b) Motorized three wheeler (c) Motorized two wheeler

(d) Diesel Car (e) Petrol Car

Figure 5.1: Scatter, speed-time behaviour plot for truck, motorized three wheeler, motorized two wheeler, petrol and diesel car during deceleration manoeuver

Following observations can be made from Figure 5.1:

- Deceleration time of different vehicle trip is not constant but it varies with vehicle characteristics and driver attribute. The desired (or maximum) speed during deceleration manoeuver registered by petrol car is highest among all vehicle classes considered in this study while corresponding deceleration time is least. Similarly motorized three wheelers registered least desrired speed in deceleration manoeuvres while deceleration time is least. This contradicts the observation reported by Bennet and Dunn (1995), which states that deceleration time of vehicles remain constant irrespective of their deceleration speed.

- In this study, higher deceleration speed is associated with lower deceleration time and vice versa. This observation is endorsed by Wang et al. (2005). This indicates that vehicle trips with different maximum speed register different deceleration time. Cars lead to the lesser deceleration time while motorized three wheeler and truck require higher deceleration time.

- Within each vehicle type, variability in speed-time behaviour in deceleration manoeuver is much higher than the variation in speed-time behaviour in acceleration manoeuver (refer Figure 5.1 and 4.1). Large variability in deceleration behaviour may due to non-uniformity in gear change pattern w.r.t. acceleration manoeuver. During deceleration manoeuver, some drivers may switch their gears directly from highest to lowest gear of their vehicle in one step while others may do it in more than one steps (i.e. while switching from highest to lowest gear they may also choose intermediate gears in between).

Further, Table 5.2 presents deceleration time corresponding to different maximum speed of vehicles reported in previous studies. Most of these studies consider only passenger cars in their study. It can be observed from the Table 5.2, Figure 5.1d and 5.1e that observed deceleration time for a maximum speed of passenger car is lower than reported reported in previous studies.

Table 5.2: Deceleration time and maximum speed reported by researchers

Sr. No.	Researcher and Year	Vehicle studied	Deceleration time, (s)	Maximum speed (m/s)
1	Boonsiripant (2009)	Passenger car	15	17.95
2	Wang et al. (2005)	Passenger car	15	22.22
3	Bennet and Dunn (1995)[1]	Passenger car, LCV, MCV and HCV	14	20.1[1]
4	Samuels and Jarvis (1978)	Passenger car	Not mentioned	23.6

LCV, MCV and HCV-Light, Medium and Heavy Commercial Vehicle, respectively
[1]Average maximum speed for all vehicle class considered in study

Similar to acceleration calculation in previous chapter, deceleration is computed from second by second speed data obtained from GPS (or V-Box) during deceleration manoeuver using Equation 3.2 discussed in Section 3.3. Starting of deceleration process is defined from the time onwards where deceleration values calculated from Equation 3.2 are greater or equal to 0.1 m/s^2 for five consecutive seconds. At the end of deceleration process vehicle's speed become zero. This criteria is used to separate the deceleration manoeuver data from each trip GPS data. Next section discusses the effect of desired speed on vehicle's deceleration behaviour.

5.1.2 Speed and deceleration relationship with desired speed

Figure 5.1 shows that each trip of vehicle has different desired (maximum) speed as it is driven by different drivers. Speed and deceleration characteristics of trips depend on their maximum speed. Therefore, all collected deceleration speed profiles are grouped as per their maximum speed range of trips for all category of vehicles. The speed ranges are different with vehicle types since maximum speeding capacity of different vehicle types are different. The deceleration speed profile data are analyzed for various parameters like deceleration time and distance, maximum and mean deceleration rates and speed at maximum deceleration (referred hereafter as *critical speed*) at different desired speed levels of vehicle. Table 5.3 presents these parameters for all vehicle types. Observations made from this analysis of data presented in Table 5.3 are discussed in following subsections.

Table 5.3: 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

Deceleration time and deceleration distance Figure 5.2 and 5.3 presents the deceleration distance and deceleration time taken by different class of vehicles at different desired speed. It can be observed from Table 5.3 and Figure 5.2 and 5.3 that deceleration distance and time increases with increase in maximum (desired) speed 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).

The deceleration time of diesel and petrol car is more or less similar irrespective of desired speed of car. It can be seen from Figure 5.3 that the variation in deceleration time of petrol car is more with desired speed as compared to diesel car.

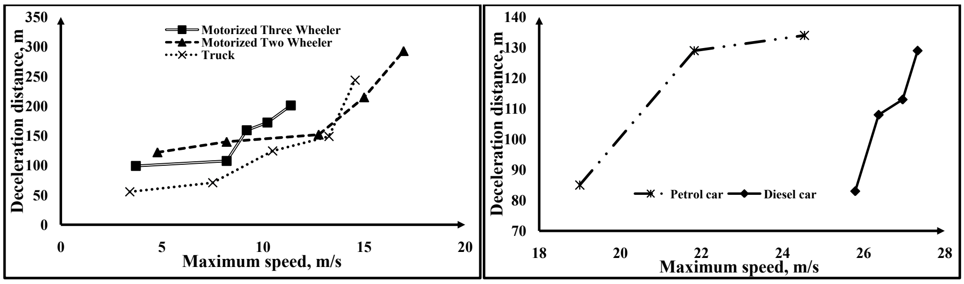


Figure 5.2: Variation of deceleration distance with maximum speed of vehicles

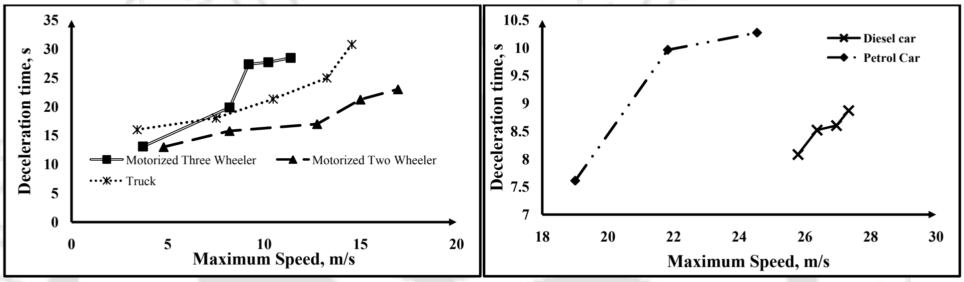


Figure 5.3: Variation of deceleration time with maximum speed of vehicles

Critical speed Critical speed is defined as the speed at which maximum deceleration rate occurs for a vehicle. For vehicle types which employ higher deceleration rates (like diesel car, petrol car and motorized two wheeler), critical speed increases with their maximum speed range. However, for other vehicle types, no such relationship could be observed.

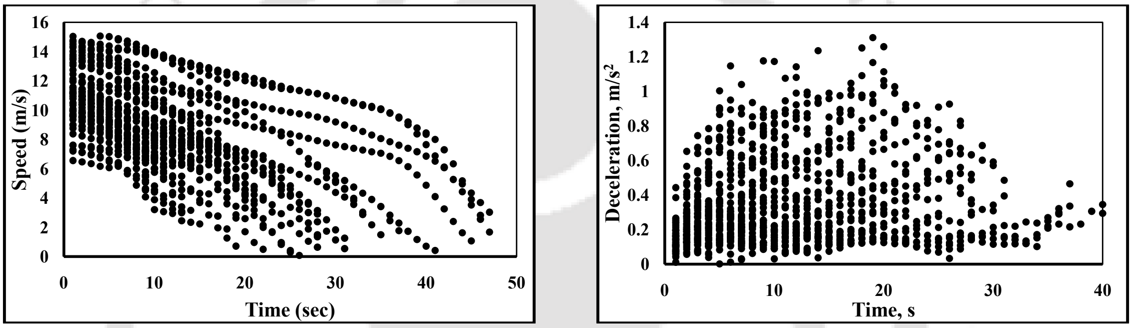
Maximum and mean deceleration rate Maximum deceleration rates generally increases with increase in maximum speed of all vehicle types observed in this study. This observation is in agreement with the observation reported by Wang et al. (2005) and Bennet and Dunn (1995). The average maximum deceleration rates recommended by ITE (2009) are 3.0 m/s^2 and by AASHTO (2004) are 3.40 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 (desired speed) 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 in most of the cases of approach speed.

Petrol car employ highest deceleration rates while truck use the lowest among the vehicle types considered in this study. Deceleration rates reported by Bennett 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.

5.2 Study of Deceleration Behaviour of Mid Size Trucks

Previous sections of this chapter presented the data collection and analysis for all type of vehicles. Scatter plots of speed-time and deceleration-time for all observed truck trips are again presented in Figure 5.4a and 5.4b respectively for detailed analysis. The deceleration of vehicles is computed for each trip using Equation 2.1. Scatter plot of speed-time and deceleration-time of all observed truck trips are shown in Figure 5.4(5.4a and 5.4b) respectively.



(a) Speed-time

(b) deceleration-time

Figure 5.4: Scatter plots of speed-time and acceleration-time for mid size truck

Following observations can made from these scattered plots:

- Speed of vehicle in each trip decreases monotonically with time of deceleration manoeuver. Speed at starting of deceleration manoeuver (i.e. desired speed) and time of stopping of each trip is different which me depend on driver behaviour.
- Deceleration-time scatter plot yields no relationship between deceleration and time in all trips. However, some researchers (ie.e Akcelik and Biggs (1987); Akelik and Besley (2001) and Wang et al. (2005)) have tried to model deceleration with time based on their observation.

The deceleration is then plotted against speed and resulting scatter is presented in Figure 5.5. This deceleration-speed scatter plot indicates that deceleration initially increases (till it attains maximum value) with decrease in speed and later deceleration decreases with further decrease in speed towards the end of deceleration manoeuver. This indicates that there is a strong relationship between deceleration-speed and hence the author has modeled deceleration with speed. This view is also supported by Bham and Benekohal (2002). One should remember that in deceleration manoeuver, vehicle speed reduce from maximum speed to zero (i.e. time counter runs opposite to speed axis as marked in Figure 5.5).

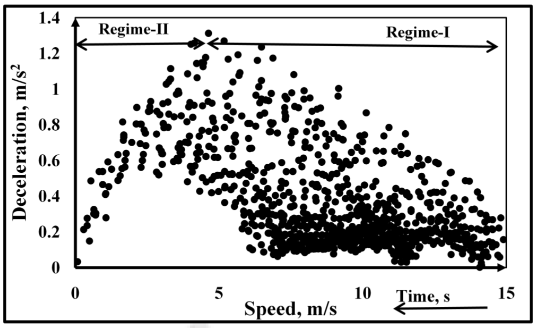


Figure 5.5: Deceleration-speed scatter for mid size truck

The speed and deceleration are then averaged over every $1m/s$ speed interval and obtained idealized plot of deceleration-speed is presented in Figure 5.6. The idealized plot in Figure 5.6 clearly indicates the relationship between deceleration-speed of vehicle in deceleration manoeuver. The *idealized* deceleration and speed are used to develop the deceleration models. Existing deceleration models are evaluated for their capability to explain the observed deceleration-speed relationship.

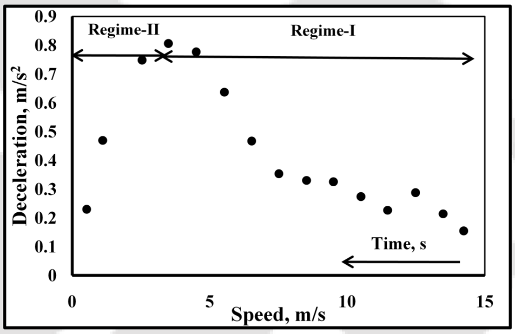


Figure 5.6: Idealized plot of deceleration-speed for mid size

5.2.1 Evaluation of existing deceleration models

Literature review yields very few deceleration models to describe the relationship between various parameters such as deceleration rate, deceleration distance, maximum (approach) speed, etc. A details description of existing deceleration models is provided in literature review chapter. Following two models are evaluated for their capability to described the observed deceleration-speed behaviour:

1. Wang et al. (2005)'s Model
2. Bennet and Dunn (1995)'s Model

Evaluation of Wang et al. (2005)'s Model Wang et al. (2005) proposed the deceleration model depicting relationship between deceleration and time (refer equation 5.1).

$$\sqrt{d} = 4.6899 + 0.0505v - 7.5835t^2, \quad R^2 = 0.95 \tag{5.1}$$

where, d is the deceleration (m/s^2) at time, t, (s).

Wang et al. (2005)'s model is calibrated from the present data and predicted speed from model is compared with observed speed. Kolmogoroff-Smirnoff test (K-S two sample test) is used to compare these predicted and observed speed of the vehicle during deceleration manoeuver. The result 'h' is '1' if the test rejects null hypothesis at 5% significance level ($\alpha = 0.05$); 0 otherwise. More detail about this test is provided in Appendix B.3 of this thesis.

Also t-test for paired sample of means is used to check the hypothesis (refer Appendix B.4 and Freund and Wilson (2011)). Two hypothesis are tested :(i) null hypothesis: $\mu = \mu_o - \mu_m = 0$, where μ_o and μ_m are mean of observed speeds of all trips of trucks during deceleration and mean of speed obtained from Wang's model respectively, and (ii) alternate hypothesis: $\mu \neq 0$. The hypothesis is tested for 95% confidence interval ($\alpha = 0.05$), where α is significance level. One can reject null hypothesis if $|t| \geq t_{\alpha/2}(= t_{0.025})$. Calculation yields values of $|t| = 15.35$ and $t_{\alpha/2} = 1.99$. Since $|t| > t_{\alpha/2}$, the null hypothesis can not be accepted. This implies that Wang et al. (2005)'s model is not sufficient to describe the observed deceleration-speed relationship.

Evaluation of Bennet and Dunn (1995)'s Model Bennet and Dunn (1995) proposed a polynomial model between speed and deceleration as given below,

$$S = a_0 - a_1 t - a_2 t^2 \tag{5.2}$$

where, S is speed (km/h), a_0, a_1 and a_2 are model coefficients and t is deceleration time in seconds.

This model depicts speed as a function of time during deceleration manoeuver (refer Equation 5.2). The model is calibrated for present data set and resulting model parameters a_0, a_1 and a_2 are obtained as 11.01, 0.262 and 0.003 respectively. The coefficient of regression for this model is 0.845. t-test for paired two samples for means is used to check the hypothesis (similar to evaluation of Wang et al. (2005)). In this case also, the null hypothesis can not be accepted since $|t| = 7.64 > t_{\alpha/2} = 2.009$. Therefore, Bennet and Dunn (1995)'s model also fails to describe the observed deceleration-speed behaviour.

Above discussion indicates that existing deceleration models proposed by Wang et al. (2005) and Bennet and Dunn (1995) fail to describe the present deceleration data set for mid size trucks and hence there is a need to formulate a new model.

5.2.2 Deceleration-speed model

Scatter and idealized plots of deceleration-speed data for truck are presented in Figure 5.5 and 5.6 respectively. These plots indicates a strong relationship between deceleration rate and speed. Initially deceleration increases with decrease in speed and after achieving a maximum value, deceleration starts decreasing with further decrease in vehicle's speed. Hence, it is more logical to model deceleration as a function of speed rather than as a function of time. This view is also supported by Bham and Benekohal (2002) and Long (2000). Therefore, in the present work, deceleration is modeled as a function of vehicle's speed.

The scatter plot in Figure 5.5 and idealized plot in Figure 5.6, both indicate that deceleration increases as speed decreases up to certain speed and then deceleration decreases as further decrease in speed. The speed at which maximum deceleration occurs (i.e. deceleration changes nature) is referred as *critical speed*. The variation of deceleration with speed (as observed from Figure 5.6) strongly suggest a duel regime model, as deceleration behaviour changes before and after the critical speed. The regime where speed> critical speed is termed as **Regime-I** and regime where the speed< critical speed is termed as **Regime-II**. Since the nature of deceleration-speed relationship is different in both regimes, both regimes are separately modeled. It is assumed that critical speed will act as divider between both regime. The only limitation with the dual regime model is that it has one point of discontinuity.

In order to test the strength of relationship between deceleration and speed in both regimes, Pearson Correlation is evaluated which is found as -0.92 for regime-I and $+0.95$ for regime-II. This suggests strong relationship between deceleration and speed in both regimes.

In order to describe the nature of deceleration-speed in both regime three different models like linear, second order polynomial and exponential are evaluated. Residual Sum of Squares (RSS) are calculated for all three model forms (like linear, second order polynomial and exponential) for both regimes separately and presented in Table 5.4, (refer Appendix B.6 for details on RSS). The appropriate model form is one which yields minimum value of RSS.

Table 5.4: Residual Sum of Squares (RSS) Values for proposed linear, second order polynomial and exponential model for Truck

Model form	General Form of Model	Regime-I	Regime-II
Linear	$d_1 = \alpha \pm \beta \times v$	0.066	**0.006**
Exponential	$d_1 = k_1 \times e^{\pm k_2 \times v}$	**0.031**	0.100
Second order polynomial	$d_1 = \pm k_3 \times v^2 + k_4 \times v + k_5$	0.038	0.036

Note: d_1-deceleration, (m/s^2) and k_1, k_2, k_3, k_4, k_5 are model parameters. $(\pm)$ indicates $+$ for Regime-II and $-$ for Regime-I

It is observed from Table 5.4 that for regime-I (i.e. speed > critical speed) the RSS value is minimum for exponential model and for regime-II RSS value is minimum for linear model. Hence general forms of the model for both regimes are as follows:

For Regime-I

$$\mathbf{d_1} = \mathbf{k_1}\mathbf{e}^{(-\mathbf{k_2}\mathbf{v})} \tag{5.3}$$

For Regime-II

$$\mathbf{d_2} = \alpha + \beta\mathbf{v} \tag{5.4}$$

where, d_1 and d_2 are deceleration rates (m/s^2) in Regime I and Regime II respectively, k_1 and k_2 are model parameters for Regime I, α is minimum deceleration rate (m/s^2) when speed is zero for Regime II and β is rate of change of deceleration with speed v (m/s) for Regime II.

Present data set is used to calibrate the model parameters and final forms of these models are as follows:

$$\mathbf{d_1 = 1.587e^{(-0.017v)}} \qquad r^2 = 0.86, \textbf{For Regime I}$$

$$\mathbf{d_2 = 0.104 + 0.225v} \qquad r^2 = 0.92, \textbf{For Regime II}$$

The model plot is presented in Figure 5.7.

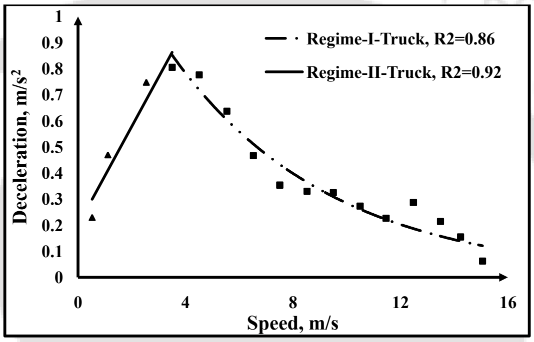


Figure 5.7: Model deceleration plots for Regime-I and Regime-II for mid size truck

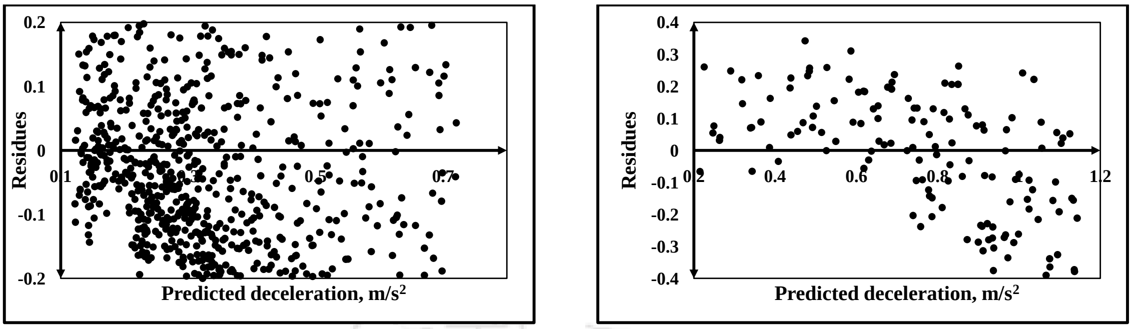
Model diagnostic

Proposed models for both regimes are statistically evaluated using following diagnostic tools:

- Residual plot
- Box plot of residues
- Quantile plots
- Hypothesis testing

In addition to this observed and predicted trajectory (vehicle position over time) and speed profiles are also presented and evaluated.

Residual plot: In residual analysis, residuals are plotted against predicted deceleration values for both regimes for deceleration-speed model of mid size trucks in Figure 5.8. This shows that residuals are uniformly distributed against predicted values depicting uniform variance of errors. At higher deceleration values of Regime-II, higher residues are associated with higher deceleration values. This indicates the weakness of proposed model in predicted deceleration-speed behaviour at higher deceleration rates in Regime-II.



(a) Regime-I (b) Regime-II

Figure 5.8: Residual plots of mid size truck deceleration

Box plot of residues: The box plot of redsidues plot for observed versus predicted values of deceleration in both regimes for trucks are obtained and presented in Figure 5.9. The plot shows that residuals are approximately normally distributed.

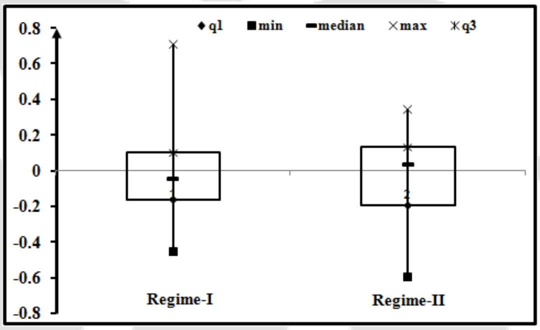
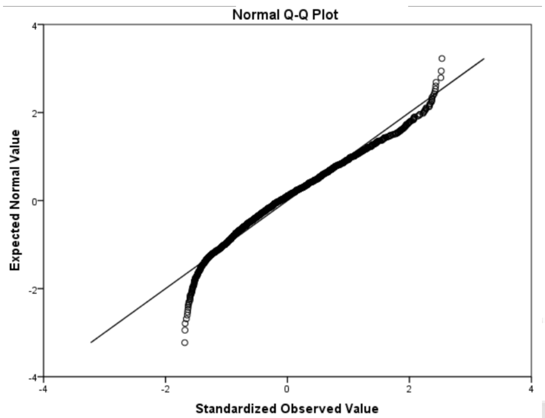
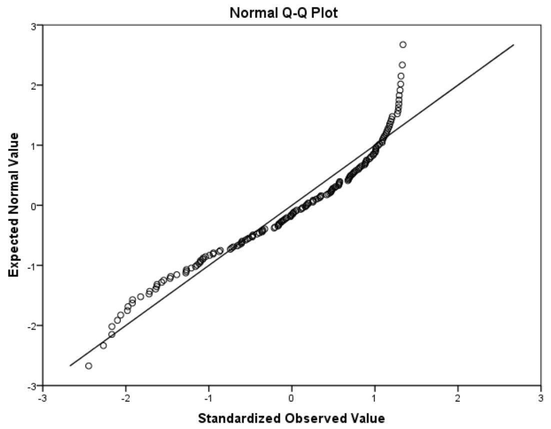


Figure 5.9: Box plots of residues for Regime-I and Regime-II for mid size truck

Quantile plot: The quantile-quantile plot for observed versus predicted values of deceleration in both regimes for trucks are obtained and presented in Figure 5.10. The plot shows that residuals are approximately normally distributed.



(a) Regime-I



(b) Regime-II

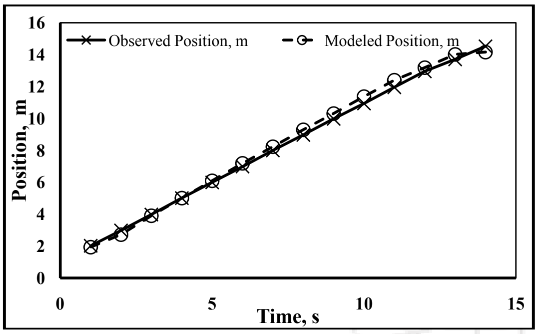
Figure 5.10: Quantile plots mid size truck deceleration

Hypothesis testing: Paired t-test is used to test the means of deceleration computed from observed speed and deceleration obtained from models for Regime I and Regime II in Equation 5.3 and 5.4 and results are presented in Table 5.5. 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.

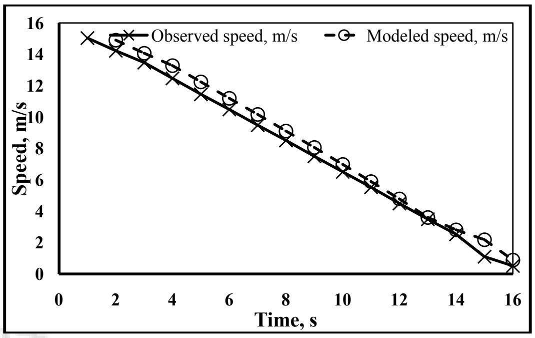
Table 5.5: t-test results for observed and predicted acceleration of Regime-I and Regime-II of deceleration-speed relationship of truck

Regime	$\|t\|$	$t_{0.025}$	Remark
Regime-I	0.45	2.17	$\|t\| < t0.025$ i.e. null hypothesis can not be rejected
Regime-II	0.03	2.17	$\|t\| < t0.025$ i.e. null hypothesis can not be rejected

Observed and predicted trajectories and speed Further, a comparison of observed and modeled trajectories and speed profiles is carried out and presented in Figure 5.11. Observed trajectory of a vehicle type is the idealized plot where position values of vehicle (obtained from its trajectories recorded using GPS) are averaged over every 1 second time interval. Similarly, observed speed profiles of vehicle is also obtained by averaging speed of vehicle over every 1 second time interval and presented in Figure 5.11. Modeled position and speed profiles are obtained from the proposed models (given in Equation 5.3, 5.4) and computed model parameters.



(a) Observed and modeled trajectories



(b) Observed and modeled speed

Figure 5.11: Observed and predicted trajectory and speed

Observed and predicted trajectories and speed are further tested using t-test. The values of t-statistics and t ratio are given in Table

Table 5.6: t-test results for observed and predicted trajectories and speed of Regime-I and Regime-II of deceleration-speed relationship of truck

Regime	$\|t\|$	$t_{0.025}$	Remark
Trajectory			
Regime-I	1.70	2.14	$\|t\| < t0.025$ i.e. null hypothesis can not be rejected
Regime-II	1.93	2.14	$\|t\| < t0.025$ i.e. null hypothesis can not be rejected
Speed			
Regime-I	0.81	2.14	$\|t\| < t0.025$ i.e. null hypothesis can not be rejected
Regime-II	2.01	2.14	$\|t\| < t0.025$ i.e. null hypothesis can not be rejected

It is seen from hypothesis testing that proposed models (in both regimes) satisfactorily replicate the observed values of speed, deceleration and position (trajectory). Hence it is concluded that the proposed models (negative exponential for regime-I and linear for regime-II) can be used as a surrogate to physical system.

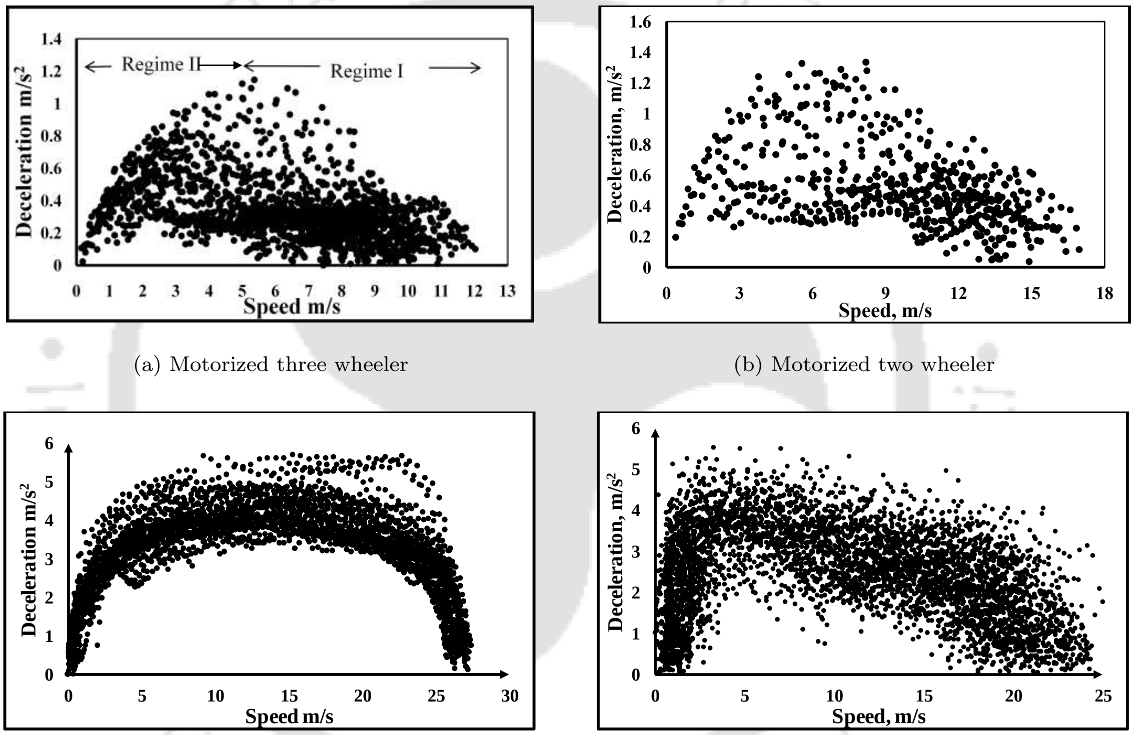
5.3 Study of Deceleration Behaviour of Other Vehicles

Previous section presents a detailed description regarding modelling methodology and evaluation of proposed models for truck. This section presents a concise modelling methodology and its evaluation for all other vehicle types (like motorized three wheeler, motorized two wheeler, petrol and diesel cars) to avoiding repetition of the contents. Only the important results/plots are presented in this section which are necessary for modelling works.

As observed in previous section that deceleration and speed parameter has strong relationship with each other for modelling of deceleration manoeuver of truck, the same is considered for other vehicles case.

5.3.1 Scatter and Idealized Deceleration-Speed Plots

The decelerations of motorized three wheeler, motorized two wheeler, petrol car and diesel car are calculated using Equation 3.2 from speed data of GPS (or V-Box). The scatter plots of deceleration-speed of these vehicles are presented in Figure 5.12.



(a) Motorized three wheeler

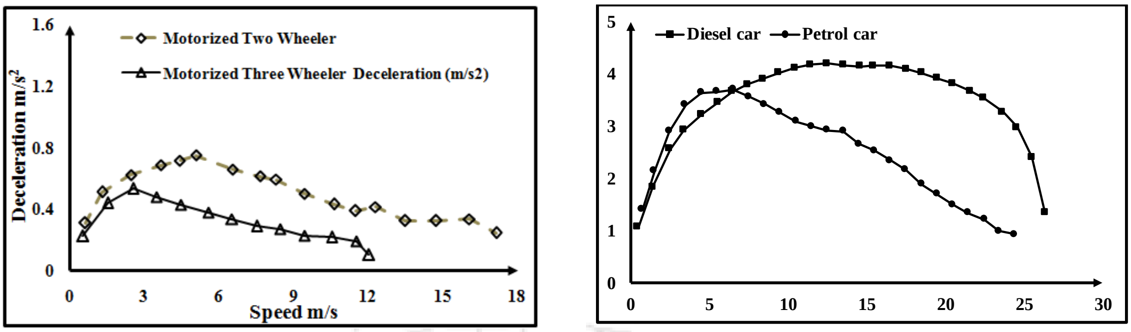
(b) Motorized two wheeler

(c) Diesel car

(d) Petrol car

Figure 5.12: Scatter plots of deceleration-speed (a) motorized three wheeler, (b)motorized two wheeler, (c) Diesel car and (d) Petrol car

It is observed from the deceleration-speed scatter plots that deceleration is strongly related to speed similar to that observed in case of trucks. To reinforce this observation, idealized deceleration and speed are plotted together in Figure 7.7.



(a) Motorized three wheeler and two wheeler (b) Diesel car and Petrol car

Figure 5.13: Idealized plots of deceleration-speed (a) motorized three wheeler and two wheeler, (b)Diesel car and Petrol car

It is observed from Figure 7.6 and 7.7 that critical 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. The nature of idealized deceleration-speed curve (more specifically slope) is opposite before and after the critical speed (similar to truck case), except in case of cars. For cars, the relationship seems to be curvilinear (as depicted in Figure 5.13). Therefore, single regime model is proposed for cars. In order to decide the form of model before and after a critical speed, Pearson Correlation and Residual Sum of Squares (RSS) are used. In case of cars, the Pearson Correlation is computed for single regime. Results of Pearson Correlation are presented in Table 5.7.

Table 5.7: Pearson correlation coefficients for deceleration-speed model for other vehicles

Vehicle Category	Regime I	Regime II
Motorized Three Wheeler	-0.97	+0.97
Motorized Two Wheeler	-0.97	+0.94
Petrol Car	0.12, single regime	
Diesel Car	0.14, single regime	

It is observed from Table 5.7 that Pearson correlation values are close to either ±1 for both regimes of all vehicle types except cars. This suggests strong linear relationship between deceleration-speed data in both regimes for all vehicle types except cars. Pearson correlation values for car suggest that linear relationship between deceleration-speed data is not strong. Therefore, a non linear relationship between deceleration-speed data for car can be explored for both regime.

Residual Sum of Squares for three proposed forms of model like linear, second order polynomial and exponential are evaluated and results are presented in Table 5.8.

Table 5.8: Residual Sum of Squares (RSS) Values for Different Model forms for deceleration-speed relationship of other vehicles

Vehicle Category	Regime I			Regime II		
	Linear	Exponential	Second order Polynomial	Linear	Exponential	Second order Polynomial
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

It is observed from Table 5.8 that for all vehicle types (except for car) negative exponential model for Regime I and linear model for Regime II are found suitable (minimum RSS values are shown by bold face). General forms of these models are as follows:

$$d_1 = -k_1 e^{-k_2 v} \quad \text{Negative Exponential For Regime I} \tag{5.5}$$

$$d_2 = \alpha + \beta \times v \quad \text{Linear For Regime II} \tag{5.6}$$

where, d_1 and d_2 are deceleration rates (m/s^2) in Regime I and Regime II respectively, k_1 and k_2 are model parameters for Regime I, α is minimum deceleration rate (m/s^2) when speed is zero for Regime II and β is rate of change of deceleration with speed v (m/s) for Regime II.

However, for diesel car, it is observed from Table 5.8 that RSS values are minimum for second order polynomial. Therefore, deceleration-speed relationship of diesel car is modeled using a single regime second order polynomial model with following general form:

$$\mathbf{d_c = -k_3 \times v^2 + k_4 \times v + k_5} \tag{5.7}$$

For petrol car third order polynomial model is found to be suited best for description of deceleration-speed relationship. Therefore, deceleration-speed relationship for petrol car is modeled using a single regime second order polynomial model with following general form:

$$\mathbf{d_c = k_6 \times v^3 - k_7 \times v^2 + k_8 \times v + k_9} \tag{5.8}$$

where, d_c is deceleration rate of car in m/s^2 at speed v m/s and k_3, k_4 and k_5 are model parameters to be determined from field data.

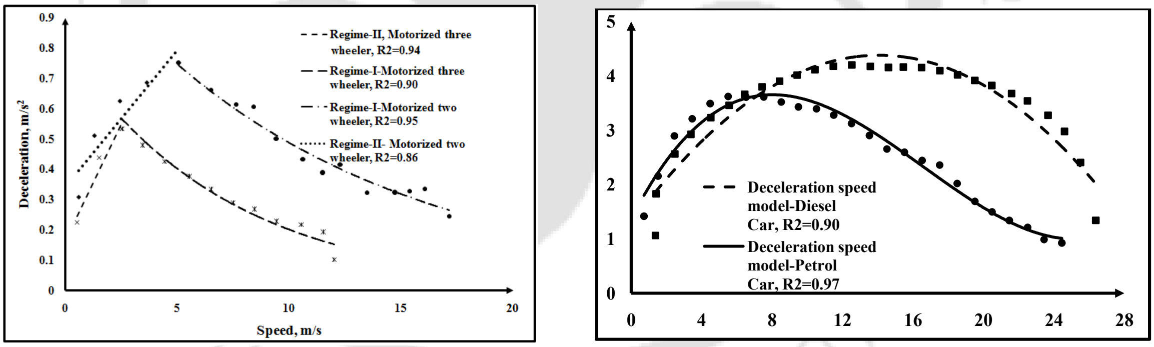
Model parameters Using linear regression, model parameters are obtained from the idealized deceleration and speed relationships of vehicles and presented in Table 5.9. Values of coefficient of regression corresponding to each models are also presented in the table.

Table 5.9: 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	
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

The calibrated model plots along with idealized deceleration-speed relationship for different vehicles are presented in Figure 5.14. It can be seen from Figure 5.14 that modelled deceleration-speed relationship can satisfactorily reproduces the idealized deceleration-speed relationship.



(a) Motorized three and two wheeler

(b) Diesel car and petrol car

Figure 5.14: Model deceleration plots of motorized three wheelers, motorized two wheelers, diesel car and petrol car

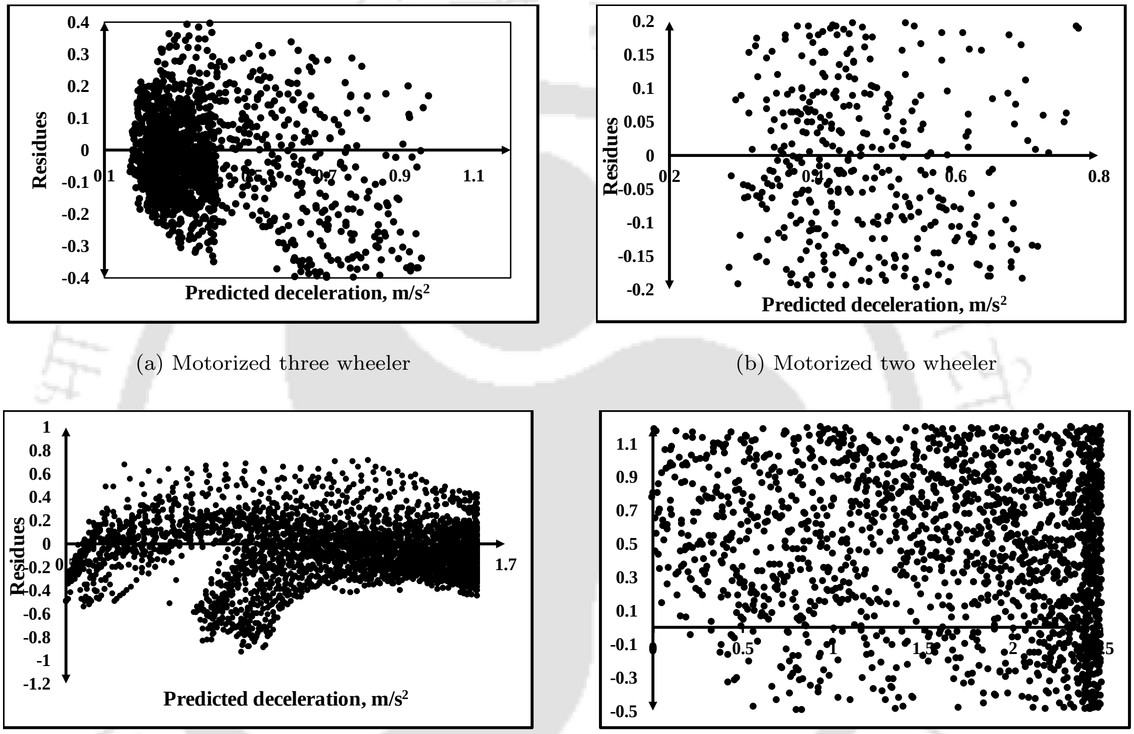
5.3.2 Model diagnostic

Similar to truck case, proposed models for both regimes (single regime in case of diesel and petrol car) are statistically evaluated using various diagnostic tools like residual plots, observed versus predicted deceleration plots, box plots of residues and hypothesis testing.

The detail theory of model diagnostic is presented earlier in the section of deceleration model diagnostics of trucks and also in Appendix B.8. Hence it is not repeated here.

Residual versus predicted plots

The residues are calculated using observed and predicted deceleration for both regimes (single regime in case of diesel and petrol cars). These residues are then plotted against predicted deceleration values. For satisfying the assumption of normality of residues (which is an important assumption in linear regression, the details can be seen in Appendix B.8). Figure 5.15 presents such residual plots of motorized three and two wheelers and diesel and petrol car.



(a) Motorized three wheeler

(b) Motorized two wheeler

(c) Diesel car

(d) Petrol car

Figure 5.15: Residual plots of deceleration for motorized three and two wheeler and diesel and petrol car

Residual plots of all vehicle types indicate that the residues are more or less uniformly distributed over the predicted values, depicting uniform variance. In case of motorized three wheeler the residues associated with lower deceleration values are densely located indicating that drivers use lower deceleration more often than higher deceleration. Also the residues associated with higher deceleration values are somewhat higher than that associated with lower deceleration values. This shows that the model performs well at the lower deceleration than at higher deceleration.

The residual plots for motorized two wheeler are somewhat nearer to null plot (refer Appendix B.8 for null plots) indicating satisfactory performance of model throughout deceleration manoeuver.

In case of diesel car the model has mixed performance at middle and lower deceleration values.

The model however performs well for higher deceleration values indicated by near null plot at higher deceleration values. Same argument can also be associated to petrol cars.

Box plots of residues

The box plot is an another important tool to examine the assumptions of linear regression. It indicates the presence of any outlier (lying at a distance of 1.5× IQR Interquartile Range, q3-q1 form q1 and q1, where q1 and q3 are first and third quartile respectively). Box plots for motorized three and two wheeler and diesel and petrol cars are presented in Figure 5.16.

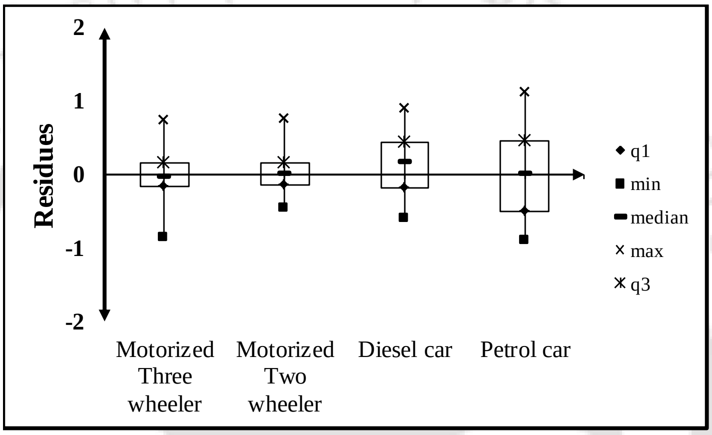
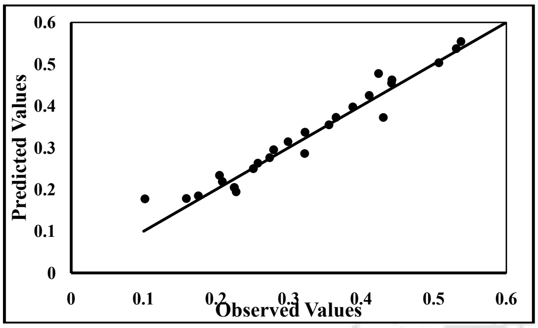


Figure 5.16: Box plots of residues of deceleration for motorized three and two wheeler and diesel and petrol car

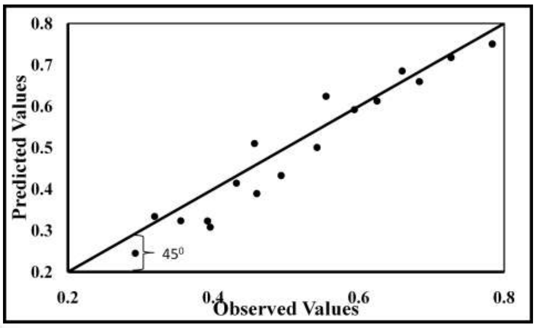
The box plots indicate no outlier. The length of upper and lower tails of an individual vehicle box plot for all vehicle types is approximately equal (except for petrol car) depicting symmetrically distributed residues. For petrol car the upper tail is longer than lower tail indicating higher residues associated with higher deceleration values. This more or less satisfies the assumption of constant variance.

Plot of observed and predicted deceleration

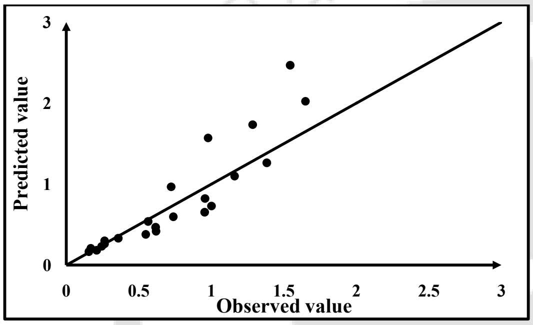
Figure 5.17 presents the plots of observed and predicted deceleration. Since the data points are clustered around the 45 degree line indicating that residuals are approximately normally distributed.



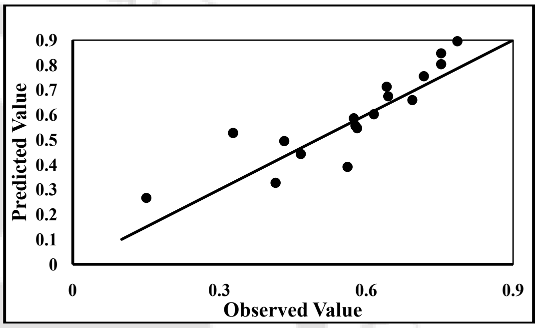
(a) Motorized three wheeler



(b) Motorized two wheeler



(c) Diesel car



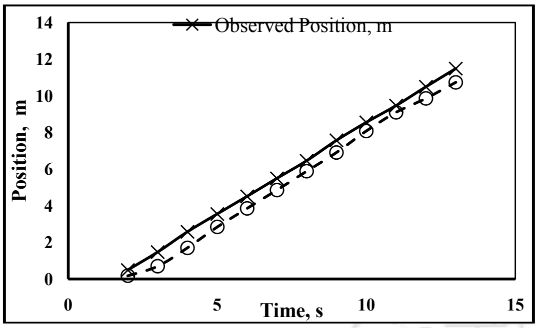
(d) Petrol car

Figure 5.17: Observed versus predicted deceleration for motorized three and two wheeler and diesel and petrol car

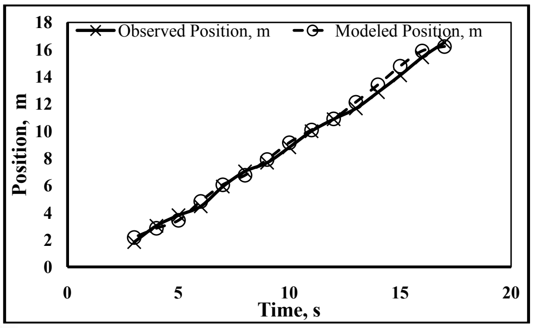
The plots indicates close clustering around 45○ line indicating that observed and predicted values of deceleration have good amount of agreement.

Plot of observed and predicted trajectories

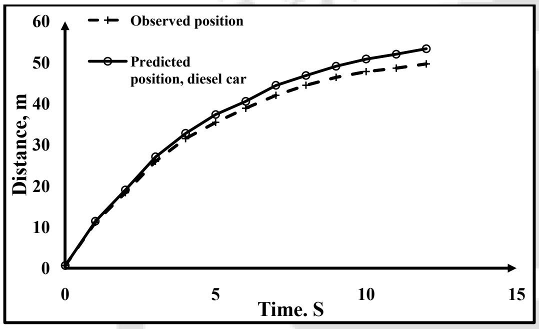
The observed and modeled trajectories are plotted and the resulting plots are presented in Figure 5.18. The plot shows satisfactory matching of observed and modeled trajectories in all vehicles.



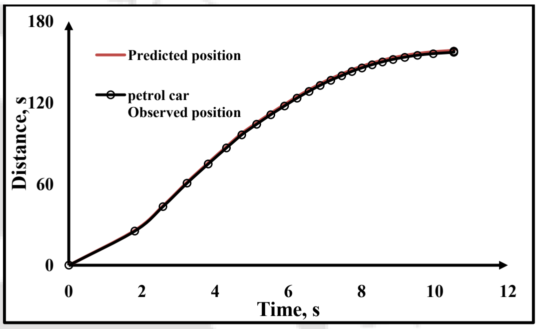
(a) Motorized three wheeler



(b) Motorized two wheeler



(c) Diesel car

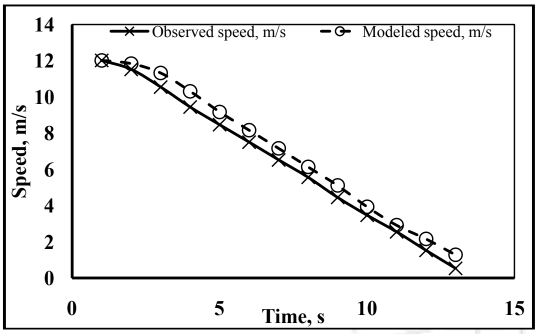


(d) Petrol car car

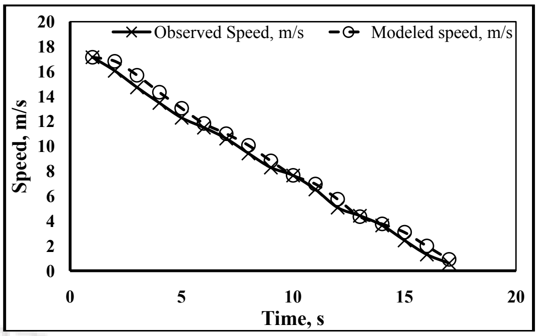
Figure 5.18: Observed versus predicted trajectories during deceleration for motorized three and two wheeler and diesel and petrol car

Plot of observed and predicted speed

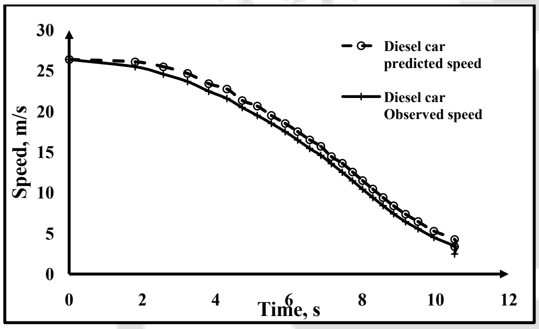
The observed and modeled speeds are plotted and the resulting plots are presented in Figure 5.19. The plot is indicative that the observed and modeled speed are matching each other sufficiently.



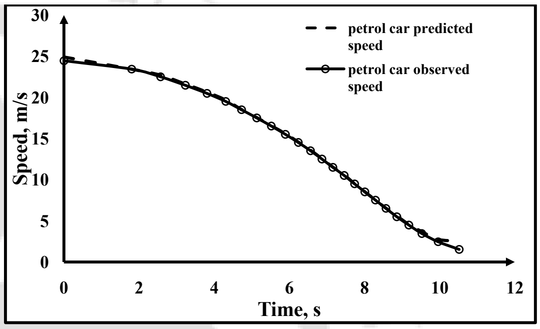
(a) Motorized three wheeler



(b) Motorized two wheeler



(c) Diesel car



(d) Petrol car car

Figure 5.19: Observed versus predicted speed plots during deceleration for motorized three and two wheeler and diesel and petrol car

It is seen from the above illustrations and discussions that the models (in both regimes) satisfactorily replicate the observed values of speed, deceleration and position (trajectory). Hence it is concluded that the proposed models (negative exponential for regime-I and linear for regime-II and second order polynomial) can be used as a surrogate to physical system.

5.4 Concluding Remarks

This chapter presented the deceleration behaviour of various vehicle types such as trucks, motorized three wheeler,motorized two wheeler and diesel and petrol car. Various analytical tools were applied to speed-deceleration and it was found that the deceleration behaviour of vehicles changes with vehicle type. Following salient features are observed from the above discussions.

1. The distance travelled 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. Similarly the deceleration time varied with vehicle type and more deceleration time was taken by

drivers to decelerate from higher approach speed.

3. 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 as the earliest.

4. The relation between observed deceleration-speed was evaluated using various existing models such as Wang's model and Bennett Dunn model. These models fail to describe the relation, hence the new models are proposed.

5. 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.

6. 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.

Chapter 6

Effect of Driver Attributes on Acceleration and Deceleration of Mid Size Truck

6.1 General

Advances in vehicle technology has boosted the confidence of drivers making them feel that they can decelerate fast enough before stop line of intersection or can accelerate adequately fast to clear the intersection within the green or amber timing. This altered acceleration-deceleration (A/D) behaviour of drivers has changed the delay at the signalized intersection, (Silcock D., 2000). Speed, acceleration and deceleration of vehicles depend on vehicle type and driver attributes such as age, driving experience, driver education, his social status and background etc. Driver attitude (which is a function of his attributes) towards speeding decides how the vehicle approaches and leaves signalized intersection. Therefore, study on effect of driver attributes on A/D behaviour may lead correct assessment of delay at signalized intersection, development of accurate simulation models and emission and fuel consumption models.

Most of the existing studies, however, report the effect of few of above mentioned driver attributes on speeding behaviour of drivers to understand the accidents due to violation of posted speed limits. These studies do not report the effect of driver attributes on vehicle A/D behaviour. These studies focus mainly on car following behaviour Wang et al. (2010); Rakha et al. (2007), which is not the case with lead vehicle at signalized intersection. Also earlier studies used devices with low data logging interval and involved human efforts giving scope to considerable errors,(Mehmood, 2009; Carcary and Murray, 2001).

Hence a look into effect of driver attributes on A/D behaviour of lead vehicles at signalized intersection is needed. Following sections present the results of study undertaken and further discuss the effect of driver attributes such as driver age, driving experience, driver education and driver monthly income on the A/D patterns of mid-sized trucks.

6.2 Assessment of Driver Attributes that Affect A/D Behaviour

This section presents the methodology that is used to determine the driver attributes that affect the A/D behaviour of vehicles. To choose suitable driver attributes that affect vehicle acceleration, authors conducted an opinion survey among transportation professionals present during an International conference on Transportation in India. Authors distributed questionnaire to all delegates (≈200 nos.) with various backgrounds (like academicians, practicing engineers, consultants, post graduate students) form India and abroad. They were asked to rate (on 100 point scale) the various drivers' attributes (like driver age, experience, education, monthly income and any other attribute they felt appropriate) which they felt can affect vehicle A/D. Table 6.1 presents the result of opinion of 55 delegate responses (out of 200), which were finally received.

Table 6.1: Results of opinion survey regarding effect of driver age, experience education and monthly income on A/D of truck

Sr. No Sr. No	Driver's Attribute	Mean Score on 100 point scale	Standard Deviation of Score
1	Age	80.58	13.23
2	Driving Experience	81.86	14
3	Driver Education	78.73	11.75
4	Monthly Income	31.41	24.30

The maximum standard deviation is observed in case of driver monthly income. Highest score was observed for driving experience and lowest for monthly income. To further verify these observations, single factor ANOVA[a] is used to compare the means of various responses regarding effect of driver attributes on driver A/D behaviour. ANOVA results indicate that F-ratio exceeded the F-critical value. This shows that mean of all driver attributes response are not equal. Hence to further quantify the difference between means of responses of effects for various driver attributes on A/D, Fisher's Post Hoc Least Significant Difference (F-LSD) test[b] is used to perform a 't' test for each pair of means using

[a]refer Appendix B.2
[b]refer Appendix B.9

Within Mean Square (MSW) as the estimate of variance. Critical LSD is computed as below;

$$LSD = 1.96\sqrt{\frac{2 \times 921.1}{55}}$$
$$= 11.34$$

So, any difference between the means of sample exceeding 11.34 is *statistically significant*. The difference between means of responses for driver age, driving experience and driver education (refer Table 6.1) is less than 11.34 and hence are statistically insignificant. Difference between means of responses on driver income and responses on other attributes is more than 11.34 (lowest difference is 47.32) which are statistically significant. Hence the driver income attribute is omitted from the analysis and effect of driver age, driving experience and driver education is presented.

6.3 Data Collection and Analysis

This section provides the salient features of A/D data collected for mid-sized truck, criteria for deciding various driver attributes considered in this study and preliminary assessment of differences in A/D posted by drivers of various attributes.

Owing to difficulty in getting consistent A/D data at actual signalized intersection (due to reasons already mentioned in Chapter 3), this study was conducted on 1.5 *km.* stretch of Nagpur-Aurangabad highway (on outskirts of Wardha city) 80 km. away from Nagpur, India. More details about study stretch are provided in Section 3.2. Truck drivers were interviewed for their personal and professional information. Their responses are recorded in a designed response chart (refer Appendix C), which presents sample copy of response chart). The speed and position data of mid-sized trucks are recorded using GPS device at 1 Hz frequency. The speed and position data were collected as mentioned in detail in Chapter 3. Also salient features of truck speed, acceleration and deceleration are presented in Chapter 3.

The trips during A/D manoeuver are then segregated as per driver attributes such as age, education and driving experience. Sample size (number of trips) pertaining to each attribute are presented in Table 6.2.

Table 6.2: Driver attributes and groups considered in this study

Driver attributes	**Groups**	Group designation	**Sample size**
Age	≤ 25 years	A1	35
	> 25 to ≤35 years	A2	43
	> 35 years	A3	36
Driving Experience	≤ 2 years	D1	26
	> 2 to ≤ 5 years	D2	32
	>5 to ≤ 10 years	D3	31
	> 10 years	D4	25
Education	≤ Std. 7th	E1	38
	> Std. 7th to ≤Std. 10th	E1	43
	> Std. 10th	E1	33

Further, the acceleration and deceleration posted by drivers of various attributes are tested for normality. This is done to decide the test (t-test or z-test) to be used for establishing the similarity or differences between acceleration or deceleration posted by drivers of different attributes.

6.3.1 Check for normality of acceleration and deceleration

To check whether the A/D posted by drivers with various attributes (as indicated in Table 6.2 above), come from population having normal distribution or not, the hypothesis is tested using one sample Kolmogorov-Smirnov test. This test compares the observed distribution with the distribution of the normal (Freund and Wilson, 2011). The null hypothesis is that observed distribution is normal and the alternative hypothesis is observed distribution is not normal. Result 'h' is 1 if test rejects null hypothesis, 0, otherwise. Matlab (2009) is used to conduct the test. The 'h' values for accelerations posted by drivers with different attributes are presented in Table 6.3

Table 6.3: Results of one sample Kolmogorov-Smirnov test on Cumulative Frequency Distribution of A/D posted by drivers with different attribute

Driver attributes	Driver Groups†	'h' value Acceleration	'h' value Deceleration
Age	A1	1	1
	A2	1	1
	A3	1	1
Driving Experience	D1	1	1
	D2	1	1
	D3	1	1
	D4	1	1
Education	E1	1	1
	E2	1	1
	E3	1	1

†-for driver groups refer Table 6.2

The null hypothesis is rejected for A/D posted by drivers of all attributes, indicating that the A/D are not normally distributed. Hence while testing hypothesis for difference or similarity between the A/D of drivers with different attributes 't' distribution should be used (since z-distribution pertains to the tests of normally distributed samples only, Freund and Wilson).

6.3.2 Verifying cumulative distribution function (CDF) of accelerations

Further the accelerations posted by drivers with different attributes are tested for similarity of cumulative distribution function (CDF). A two sample Kolmogorov-Smirnov test compares the distributions of two data vectors x_1 and x_2. The null hypothesis is that x_1 and x_2 are from the same continuous distribution. The alternative hypothesis is that they are from different continuous distributions. The result 'h' is 1 if the test rejects the null hypothesis at 5% significance level; 0 otherwise. The 'p' value is the Pearson Correlation indicating strength of relation between x_1 and x_2. The 'h' and 'p' values for accelerations posted by drivers with different attribute are presented in Table 6.4

Table 6.4: Results of two sample Kolmogorov-Smirnov test on comparison of Cumulative Distribution Function of A/D posted by drivers with different attribute

Driver attributes	Groups compared	For acceleration data		For deceleration data	
		'h'* value	'p' value	'h'* value	'p' value
Age	A1 & A2	0	0.396	1	4.18×10^{-7}
	A2 & A3	1	0.59×10^{-3}	0	0.64
	A1 & A3	1	0.21×10^{-3}	1	1.69×10^{-6}
Driving Experience	D1 & D2	1	1.6×10^{-3}	0	0.25
	D2 & D3	0	0.58	1	9.05×10^{-7}
	D3 & D4	0	0.31	0	0.61
	D1 & D4	1	8.8×10^{-3}	1	0.0069
Education	E1 & E2	1	17×10^{-3}	1	0.0016
	E2 & E3	0	0.14	0	0.67
	E1 & E3	1	60×10^{-3}	1	0.046

* - 'h' value 1 indicates null hypothesis cannot be accepted, 0, otherwise. [1]Experience, [2]Education

†-for driver groups refer Table 6.2

The results presented in Table 6.4 indicate that the A/D posted by drivers of some attributes have similar Cumulative Distribution Function (CDF), whereas A/D posted by drivers of some other attributes have different CDF. For example, h value of 0 indicates that drivers of Group A1 have similar CDF of acceleration as that of drivers in Group A2. Whereas, acceleration posted by drivers in age Group A2 have different CDF than acceleration posted by drivers having of Group A3 (indicated by h value 1). Similarly for decelerations, CDF is different in some cases and in some cases it is not. The Pearson Correlation value is poor in the cases where 'h' value is 1 and strong otherwise. This indicates that in some cases there is a strong correlation and in some it is not.

So, to further investigate the similarity and differences in A/D posted by drivers with various attributes, quantitative comparison is undertaken and presented in subsequent subsections. For this purpose speed, acceleration and deceleration of drivers with different attributes are averaged over 1 m/s speed range. Such plots, termed as *idealized plot* of acceleration-speed and deceleration-speed are used to quantify the similarity and differences in A/D.

6.4 Effect of Driver Attributes on Acceleration

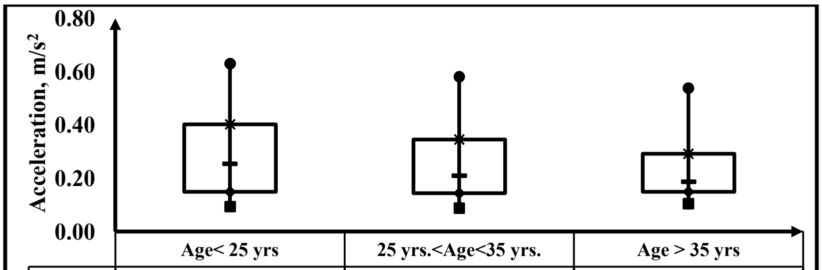
This section presents the effect of driver age, driving experience and driver education on mid-size truck acceleration. Drivers are grouped based on their classification in Table 6.2 to study the impact of different attributes of drivers on acceleration and deceleration of vehicles. Vehicle trips corresponding to each driver group are segregated and analyzed. Impact of different attributes of driver is analyzed using following steps;

1. The variability of A/D data in driver groups is studied using Box plot
2. Single factor ANOVA is used to compare the variance in acceleration and deceleration data of different driver groups, (refer Appendix B.2)
3. Fisher's Least Significance Test (Post Hoc Protected F-LSD test) is used to quantify the difference between means of acceleration and deceleration in various driver group, (refer Appendix B.9)
4. Idealized plots of acceleration-speed and column plots of average acceleration at different speed ranges are used to further quantify the difference graphically and numerically.
5. Average maximum and mean acceleration, kurtosis and skewness are used to demonstrate the effect on acceleration and the measures of actual distributions of acceleration.

Following subsections present the evaluation of effect of driver attributes in various groups (refer Table 6.2 for driver attributes groups) on mid size truck acceleration.

6.4.1 Effect of driver age on acceleration of truck

To asses the actual difference between the acceleration posted by drivers of different age groups, the average accelerations are plotted in a box plot in Figure 6.1.



	Age< 25 yrs	25 yrs.<Age<35 yrs.	Age > 35 yrs
◆q1	0.15	0.14	0.15
■min	0.09	0.09	0.10
−median	0.25	0.21	0.19
●max	0.63	0.58	0.54
✕q3	0.40	0.35	0.29

Figure 6.1: Box plot of accelerations posted by drivers of different age groups

The difference between maximum and minimum acceleration values (range) of trip acceleration is widest in age A1(0.54 m/s^2) and narrowest in older age group, A3. (0.44 m/s^2). This indicates that variability in acceleration is less for old driver than young drivers. Also the Inter Quartile Range, IQR, $(q_3 - q_1)$ is lower in old drivers (0.14 m/s^2) than young drivers (0.25 m/s^2) which substantiate the above observation. The variance for different age groups are 0.029, 0.020 and 0.017 for driver group A1, A2 and A3 respectively. It is evident from this statistics that there is difference in accelerations posted by drivers of different age groups.

Single factor ANOVA is carried out to check the equality of means of accelerations posted by drivers of different age groups. The results are presented in Table 6.5.

Table 6.5: Results of ANOVA for acceleration of drivers of different age groups.

Source of Variation	SS	df	MS	F	P-value	F critical
Between Groups	0.19	2	0.094	**4.44**	0.012	**3.01**
Within Groups	36.22	1712	0.022 (MSW)			
Total	36.40	1714				

Table 6.5 shows that null hypothesis is rejected (F> $F_{critical}$). This confirms the difference in acceleration employed by drivers of different age group. Rejection of null hypothesis alone does not convey the actual difference between the means of acceleration sample of drivers of different age groups.

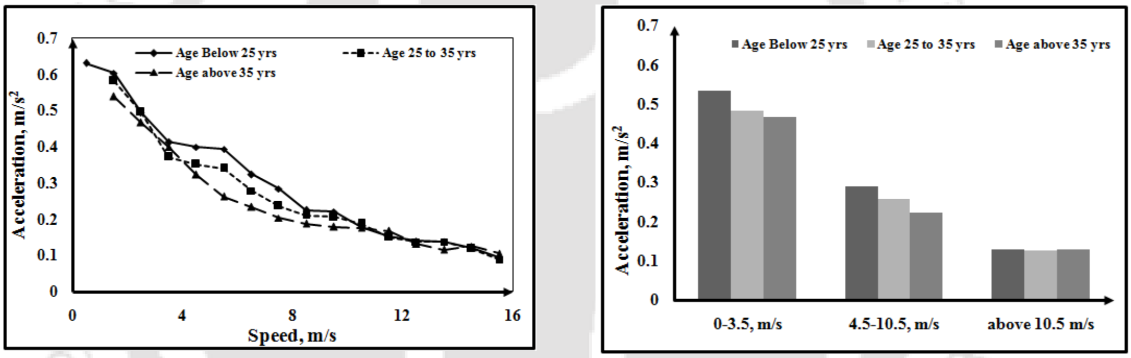
So, to further verify this, Fisher Least Significant Difference (LSD) procedure (refer Appendix B.9 and (Freund and Wilson, 2011)) is used. The LSD value for drivers of different age groups is 0.016.

So, any difference between the means of sample exceeding 0.016 is statistically significant. The mean of acceleration employed by drivers of group A1, A2 and A3 is 0.30 m/s2, 0.25 m/s2 and 0.22 m/s2 respectively. The difference between means of acceleration of drivers groups A1 and A2, A2 and A3 and A1 and A3 are 0.05, 0.03 and 0.08 respectively. All these differences exceeded critical LSD value (0.016) and hence are statistically significant.

After confirming that the trip accelerations employed by drivers of different age groups are different, the actual quantification of average mean accelerations is presented.

The idealized plot of acceleration-speed for different driver age groups are presented in Figure 6.2a. Figure 6.2b presents the bar plots of mean acceleration posted by drivers of various age group in various speed ranges. The mean acceleration values in different age groups in different speed ranges are presented in Table 6.6. The average maximum and average mean acceleration values, symmetry of acceleration distribution (kurtosis and skewness) and standard error of acceleration in different age groups are presented in Table 6.7.

Figure 6.2a indicates that at the beginning of acceleration manoeuver (speed range 0-3.5 m/s, refer Figure 6.2b) the mean acceleration values decrease as age increases. The acceleration used by young drivers below 25 yrs. is 9.43% more than drivers between age 25 to 35 yrs. and 13.20% more than used by drivers in age group above 35 yrs.



(a) Idealized acceleration for various age groups

(b) Mean acceleration values for various age groups in various speed ranges

Figure 6.2: Idealized acceleration and mean acceleration values employed by drivers of different age groups

Table 6.6: Mean acceleration values employed by drivers of different age groups in different speed ranges

	Age groups		
Speed range	Age below 25 yrs., A1	Age 25 to 35 yrs., A2	Age above 35 yrs., A3
0 to ≥3.5 m/s	0.53	0.48	0.46
>3.5 to ≤-10.5 m/s	0.28	0.25	0.22
>10.5 m/s.	0.128	0.125	0.128

Table 6.7: Maximum and mean acceleration, kurtosis and skewness and standard error values in various age groups.

Age group	Idealized Maximum acceleration, m/s^2	Average Mean acceleration, m/s^2	Kurtosis	Skewness	Standard error
Below 25 yrs., A1	0.63	0.3	-0.66	0.66	0.043
25 to 35 yrs., A2	0.58	0.25	0.35	0.99	0.037
Above 35 yrs., A3	0.53	0.24	0.42	1.17	0.034

Figure 6.2 shows that driver mean acceleration remains unaffected by age in higher speed group, (above 10.5 m/s, refer Figure 6.2a). This indicates that drivers accelerate in similar manner, irrespective of age, towards the end of acceleration manoeuver.

The kurtosis and skewness values are evaluated for different age groups (refer Table 6.6) to assess the symmetry of acceleration distribution. The acceleration distribution of younger drivers is found to have negative kurtosis, platykurtic distribution indicating that the acceleration distribution is flatter with heavy tail. However, the positive kurtosis, leptokurtic distribution, in older age group indicates more peaked distribution with lighter tail. This shows that acceleration values are more distributed (*i.e.* more variability) in younger age drivers than in old age drivers.

Positive skewness values in all age groups indicate that acceleration distribution is skewed towards right in all age groups. The skewness values go on increasing with age indicating a more skewed distribution in older drivers than in younger drivers. This shows that drivers use acceleration more than mean value more frequently than acceleration less than mean value. Since the right skewed distribution indicates that data is dense towards end, it is concluded that the older drivers use lower acceleration values more frequently than other driver age groups.

The standard error values (refer Table 6.6) of acceleration decreases with increase in age indicating that as age of driver increases the consistency in acceleration behaviour increases.

6.4.2 Effect of driving experience on acceleration of trucks

Figure 6.3 presents the box plots of trip accelerations employed by drivers having different driving experience.

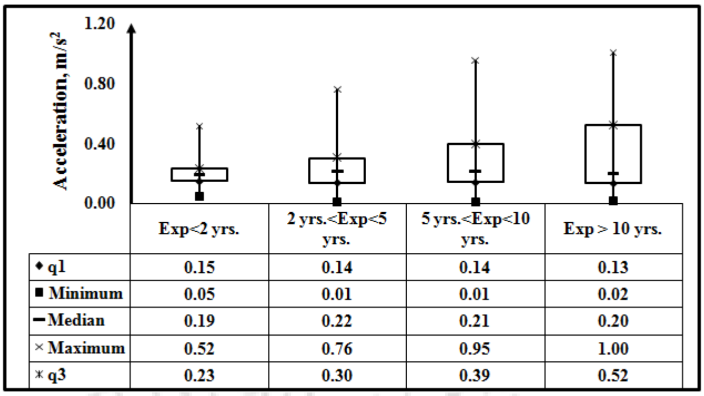


Figure 6.3: Box plots of trip accelerations employed by drivers of various driving experience.

The difference between minimum and maximum trip acceleration values (range) is widest in group D4 *i.e.* drivers having driving experience more than 10 yrs. (0.98 m/s^2) and narrowest in group D1 *i.e.* drivers with less than 2 yrs. driving experience (0.47 m/s2). This indicates that less experienced drivers apply lesser variation in acceleration (closely bunched) than more experienced drivers. Also the Inter Quartile Range, IQR, $(q_3 - q_1)$ is least in drivers with less than 2 yrs. driving experience (0.08 m/s^2) and maximum in drivers having driving experience more than 10 yrs. (0.39 m/s^2). This corroborate the previous result.

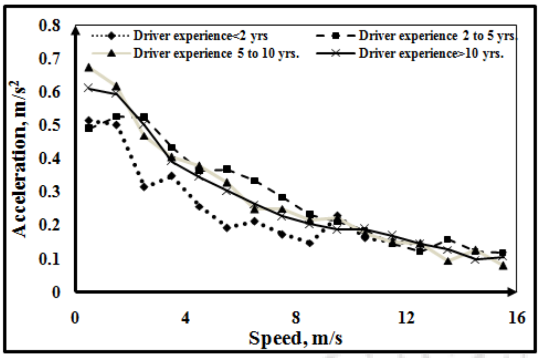
To verify this observation further, a single factor ANOVA is carried out and results are presented in Table 6.8.

Table 6.8: Results of ANOVA for acceleration of drivers with different driving experience.

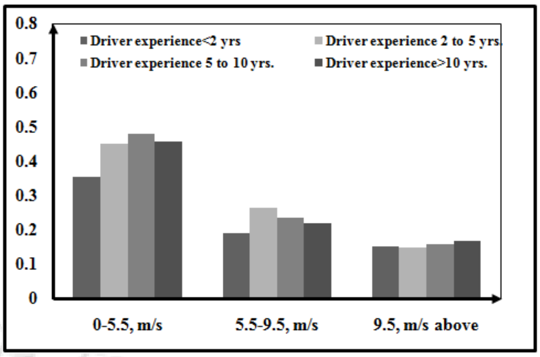
Source of Variation	SS	df	MS	F ratio	p value	F critical
Between groups	0.1	3	0.03	3.64	0.17	2.61
Within groups	35.08	1687	0.02 (MSW)			
Total	35.18	1690				

F ratio value exceeds F critical value, which indicates that it rejects the null hypothesis of equal means of average acceleration employed by drivers with different driving experience. Since null hypothesis cannot be accepted as per ANOVA, LSD value, (refer Appendix B.9) evaluated and found as 0.0131. So, any difference between the means of sample exceeding 0.0131 is statistically significant. The difference between means of acceleration employed by driver groups D1 and D2 is 0.03, D2 and D3 is 0.009 and D3 and D4 is 0.01. Therefore, there exists significant difference between group D1 and other groups, whereas there is no significant difference between D2 and D3.

After ascertaining these differences in means of accelerations of different driver experience groups, the quantification of acceleration is presented in following paragraphs. Figure 6.4a presents the idealized plot of acceleration-speed for drivers with different driving experience.



(a) Idealized acceleration for various driving experience groups



(b) Mean acceleration values for various experience groups in various speed ranges

Figure 6.4: Idealized acceleration and mean acceleration values for truck drivers with different driving experience

Idealized acceleration-speed plot shows that drivers with different driving experience accelerate their vehicles differently. In addition, acceleration behaviour of different drivers differs as acceleration manoeuvre advances. Drivers with least driving experience (group D1) drive vehicles cautiously (i.e. accelerate at lower rate) while driver with moderate experience (group D2) speed up their vehicles with higher acceleration rate. A small reduction in start-up acceleration is observed for highly experienced (group D4) drivers in comparison to the drivers with moderate experience. Highly experienced drivers are generally from older age group of drivers who reflect less aggressive behaviour. Difference in accelerating behaviour of drivers with different driving experience can be observed up to moderate speed of vehicles while at higher speed the difference vanishes.

Similar observation can be made from mean acceleration used during different speed ranges presented in Figure 6.4b and Table 6.9 by drivers varying in their driving experience.

Table 6.9: Mean acceleration values posted by drivers of various driving experience in different speed ranges

Speed Range	Driver experience			
	<2 yrs, D1	2 to 5 yrs., D2	5 to 10 yrs., D3	>10 yrs., D4
0-5.5, m/s	0.35	0.44	0.48	0.46
5.5-9.5, m/s	0.18	0.26	0.23	0.22
above 9.5, m/s	0.15	0.14	0.16	0.16

At start up (speed range 0-5.5 m/s), drivers in group D3 (5-10 yrs. driving experience use) highest rate of acceleration while drivers in group D1 (new drivers with experience $<$ 2yrs.) using the lowest. Average acceleration used by drivers in group D3 (5-10 yrs. experience) during start up is 25.9% higher than acceleration used by new drivers while other drivers in group D2 and D4 (with driving experience

2-5yrs. and >10 yrs.) use 21.26% and 22.4% higher acceleration rate than new drivers. At moderate speed (5.5 to 9.5 m/s), drivers in group D2 (drivers with 2-5 yrs.) driving experience use the highest acceleration rate (28.2% more than new drivers). At higher speed, all drivers used approximately similar acceleration rates.

Table 6.10 presents the maximum and mean acceleration, symmetry of acceleration distribution (kurtosis and skewness) for drivers of various driving experiences.

Table 6.10: Maximum and mean acceleration, kurtosis and skewness for drivers different driving experience.

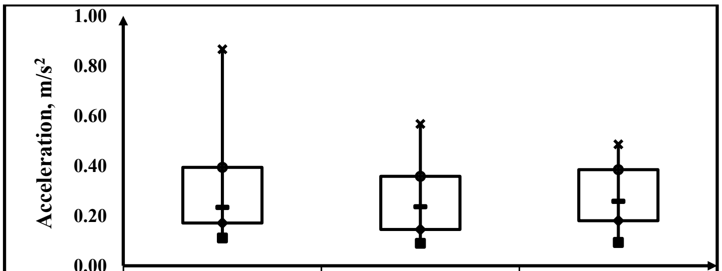
Driving Experience	Idealized Max. Range, (m/s^2)	Mean Accel., (m/s^2)	Kurtosis	Skewness
D1	0.51	0.25	3.49	1.63
D2	0.52	0.28	1.05	1.01
D3	0.67	0.28	2.17	1.31
D4	0.6	0.27	2.99	1.54

The idealized maximum acceleration and mean acceleration used by drivers increase with increase in driving experience except drivers with driving experience $>$ 10 yrs. The positive kurtosis represents leptokurtic distribution of acceleration for all drivers. Higher kurtosis values for driver groups D1 and D4 imply less variability in their acceleration behaviour. Being beginners, these drivers are more cautious and accelerate in certain manner. However, 2-5yrs. experience drivers are confident and young drivers and accelerate in their own manner. Therefore, they show highest variability in acceleration behaviour. Variability in acceleration behaviour reduces as driving experience (and age) increases that leads to wards common and matured acceleration behaviour.

The skewness of acceleration distribution is positive for all drivers, which implies that drivers use lower acceleration more often than higher accelerations from mean value. Higher skewness is observed for least and highest experience drivers. Mode of acceleration values lies between 0.10-0.15, 0.20-0.25, 0.15-0.20 and 0.10-0.15 m/s^2 for driver groups possessing least to highest driving experience respectively. It is observed from mode, least and highest experienced drivers use lower acceleration more often that ends higher skewness.

6.4.3 Effect of driver education on acceleration of trucks

In India, generally truck drivers are not highly educated. In this survey, truck driver education varied from 3^{rd} Std. to 12^{th} Std. Drivers' up to 3^{rd} standard education merely know reading and writing. The driver classification based on their education is already described in Table 6.2. The truck trips are segregated as per the driver education and disperse of acceleration data obtained is presented using box plots in Figure 6.5.



	Education < 7th std.	7th std. <Education<10th Std.	Education > 10th std.
◆q1	0.17	0.14	0.18
■Minimum	0.11	0.09	0.09
▬Median	0.23	0.24	0.26
×Maximum	0.87	0.57	0.49
○q3	0.39	0.36	0.38

Figure 6.5: Box plots of trip accelerations employed by truck drivers with different education level

The difference between minimum and maximum values (range) of trip acceleration is widest in drivers having least education, driver group E1 (less than 7^{th} Std.) (0.76 m/s^2) and narrowest in drivers with most education driver group E3 (more than 10^{th} Std.) (0.40 m/s^2). This indicates that less educated drivers acceleration behaviour has more variability (or inconsistency) than more educated drivers.

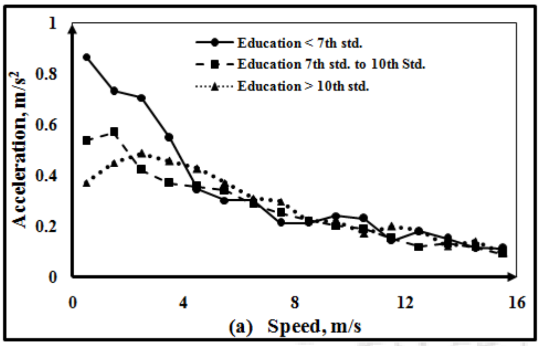
Further, a single factor ANOVA is carried out and results of ANOVA are presented in Table 6.11.

Table 6.11: Results of ANOVA for acceleration of drivers with different education levels

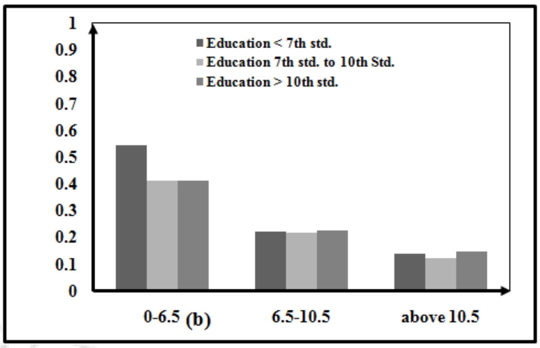
Source of Variation	SS	df	MS	F ratio	p value	F critical
Between groups	0.48	2	0.24	11	0.001	3
Within groups	33.2	1528	0.02			
Total	33.68	1530				

In results of ANOVA, F ratio value exceeding F critical value, which rejects the null hypothesis of equal means of acceleration employed by drivers with different education.

The LSD value, evaluated (refer Appendix B.9), is found to be 0.0051. So, any difference between the means of sample exceeding 0.0051 is statistically significant. The difference between means of acceleration employed by drivers, driver group E1 and E2 is 0.05, E2 and E3 is 0.01 and difference between driver group E1 and E3 is 0.06. Difference in all groups is more than LSD value and hence the acceleration employed by drivers in these groups are statistically significant. Figure 6.6 presents idealized plot of acceleration-speed relationship for drivers with different education levels. Effect of education on acceleration is evident in starting of acceleration manoeuvre. Least educated drivers, driver group E1, start their vehicles at much higher acceleration rate than more educated ones. Highest educated drivers driver group E3, start accelerating at lower rate, however, at moderate speed (4-8 m/s) educated drivers show slightly higher acceleration rate than others.



(a) Idealized acceleration for various driver education groups



(b) Mean acceleration values for various driver education groups in various speed ranges

Figure 6.6: Idealized acceleration and mean acceleration values for truck drivers with different education level

Figure 6.6b and Table 6.12 presents the mean acceleration used in different speed ranges by drivers with different education level. Up to speed of 6.5 m/s, differences in driver behaviour based on their education are evident. At higher speed, difference in acceleration behaviour of driver (with different education standard) vanishes.

Table 6.12: Mean acceleration in various driver education groups in various speed ranges

Speed range	Driver education		
	< 7th std., E1	7th std. to 10th Std., E2	> 10th std., E3
0-6.5	0.54	0.41	0.41
6.5-10.5	0.22	0.21	0.23
above 10.5	0.14	0.12	0.15

Maximum and mean acceleration, symmetry of acceleration distribution (kurtosis and skewness) for drivers with various education standards are presented in Table 6.13. Least educated drivers show aggressive behaviour than others i.e. use highest maximum and mean acceleration rates during their acceleration manoeuvre. However, highest educated drivers, driver group E3, use lowest maximum and mean acceleration rates. The positive kurtosis represents that variation in acceleration is less than normal distribution for all drivers.

Table 6.13: Maximum and mean acceleration, kurtosis and skewness for drivers with different education.

Driving Education	Idealized Max. Accel.	Mean Accel.	Kurtosis	Skewness
$< 7^{th}$ Std., E1	0.86	0.33	1.53	1.44
7^{th} Std. to 10^{th} Std., E2	0.56	0.27	2.08	1.21
$> 10^{th}$ Std., E3	0.48	0.28	0.58	0.89

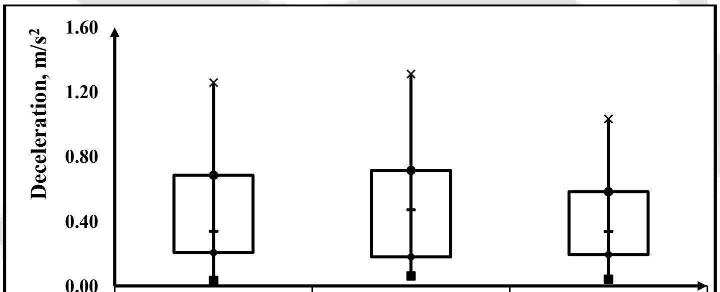
6.5 Effect of Driver Attributes on Deceleration

This section presents the effect of driver age, driving experience and driver education on mid-size truck deceleration. The methodology of ascertaining similarities and differences in deceleration posted by drivers of various attributes is similar to that used in case of acceleration study. Box plots, ANOVA, LSD, idealized plots of deceleration-speed, column plots of deceleration in different speed ranges and average maximum and mean deceleration are used to quantify the similarities or differences. Skewness and Kurtosis are used as the measure of symmetry of distribution of decelerations posted by drivers of different attributes.

6.5.1 Effect of driver age on deceleration of trucks

For the purpose of assessing effect of driver age on deceleration of mid-sized trucks, the drivers are grouped as A1, A2 and A3 similar to that in case of study of effect of driver attributes on acceleration of mid size truck. The detailed methodology is presented in Section 3.3.

The box plots showing various parameters of average deceleration is presented in Figure 6.7.



	Age<25 yrs.	25 yrs.<Age<35 yrs.	Age > 35 yrs.
◆q1	0.21	0.18	0.19
■Minimum	0.03	0.06	0.04
−Median	0.34	0.47	0.34
×Maximum	1.26	1.31	1.03
●q3	0.69	0.72	0.58

Figure 6.7: Box plots of deceleration posted by truck drivers of various age groups

The difference between maximum and minimum deceleration values (range) is widest in driver age group A2, (1.25 m/s^2) and narrowest in oldest age group, A3, (0.99 m/s^2). This indicates that the old driver apply lesser variation in deceleration (decelerations are closely bunched) than young drivers. Also the Inter Quartile Range, IQR, $(q_3 - q_1)$ is lower in old drivers (0.39 m/s^2) than young drivers (0.47 and 0.54 m/s^2 respectively for driver groups A1 and A2 which substantiate the above observation. The variance for different age groups are 0.087, 0.093 and 0.065 respectively for driver groups A1, A2 and A3. It is evident from these statistics that variability in deceleration of older drivers is less than younger drivers. This also indicates that there is difference in decelerations posted by drivers of different age groups. Further, the results of single factor ANOVA are presented in Table 6.14

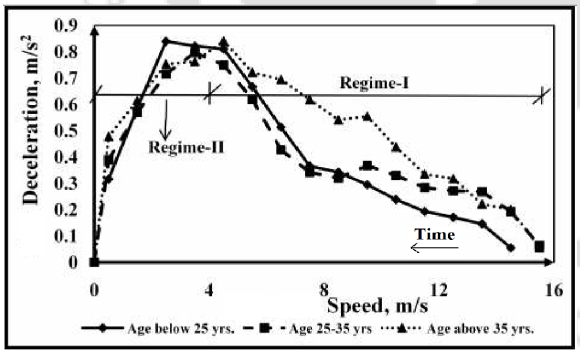
Table 6.14: Results of ANOVA for deceleration of drivers of different age groups.

Source of Variation	SS	df	MS	F ratio	P-value	F crit
Between Groups	0.74	2	0.37	**5.02**	0.01	**3.01**
Within Groups	87.15	1182	0.07			
Total	87.89	1184				

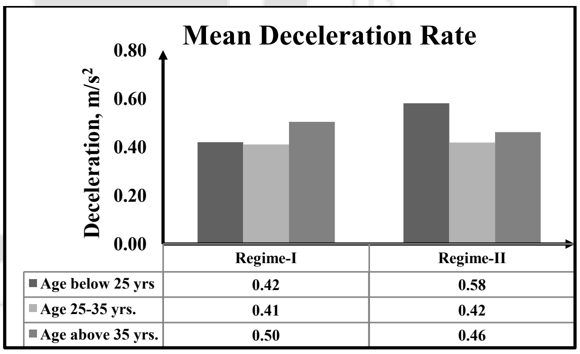
F critical value is less than F ratio (refer Table 6.14),which reject the null hypothesis of equal means. This shows that differences exist between the means of decelerations employed by drivers of different age group. But rejection of null hypothesis alone does not convey the actual difference between the means of deceleration sample of drivers of different age groups.

Hence the Fisher's Least Significant Difference (LSD) procedure is attempted to quantify the difference. The results of LSD are used to formulate the criteria for differences between means. Difference in means greater than LSD will conclude that the samples are different. The computed LSD is 0.037 (refer Appendix B.9). The differences between means are 0.06, 0.01 and 0.05 respectively for driver groups A1 and A2, A2 and A3 and A1 and A3. Since the difference in means between driver groups A2 and A3 is less than LSD, difference in deceleration behaviour is not significant for driver groups A2 and A3. In rest of the groups the difference is statistically significant.

The actual quantification of decelerations among different groups is done using idealized plot for deceleration-speed (deceleration averaged over speed 1 m/s) for different age groups which is presented in Figure 6.8.



(a) Idealized plot of deceleration-speed for different driver age



(b) Mean deceleration values of drivers with different driver age in Regime I and Regime II

Figure 6.8: Variation of mean deceleration with driver age

It is seen from Figure 6.8a that deceleration of trucks starts increasing till it attains maximum value afterwards deceleration decreases with time. The speed at which the deceleration is maximum is termed as **critical speed**. It is seen from Figure 6.8a that the slope of deceleration-speed plot is opposite before and after achieving **critical speed**. The deceleration manoeuver is, therefore, divided in two distinct regimes, before and after **critical speed**. The deceleration regime before **critical speed** is termed as Regime-I (since it occurs earlier) and after **critical speed** is termed as Regime-II (since it occurs later). This is presented in Figure 6.8a.

Following observations are made from Figure 6.8a.

- As presented in Figure 6.8a critical speed for all age group drivers is approximately 3.5 m/s.
- It is seen from idealized plots of deceleration that drivers with different age groups apply different decelerations in two regimes.

These differences in mean deceleration of drivers with different age groups in Regime-I and Regime-II are calculated and presented in Figure 6.8b

At the beginning of deceleration manoeuver (Regime-I), the mean deceleration used by driver group A3 is 18% more than deceleration used by drivers group A2 and 16% more than deceleration used by driver group A1. This indicates that old drivers use more deceleration in Regime-I as compared to young drivers. In Regime-II the young drivers used more mean deceleration rate as compared to older drivers. Drivers of group A1 use 27.5% and 20.7% higher deceleration than A2 and A3 respectively in Regime-II.

Table 6.16 presents average maximum decelerations posted by drivers of various age groups.

Table 6.15: Maximum deceleration rates and statistical measure of symmetry of distribution of deceleration

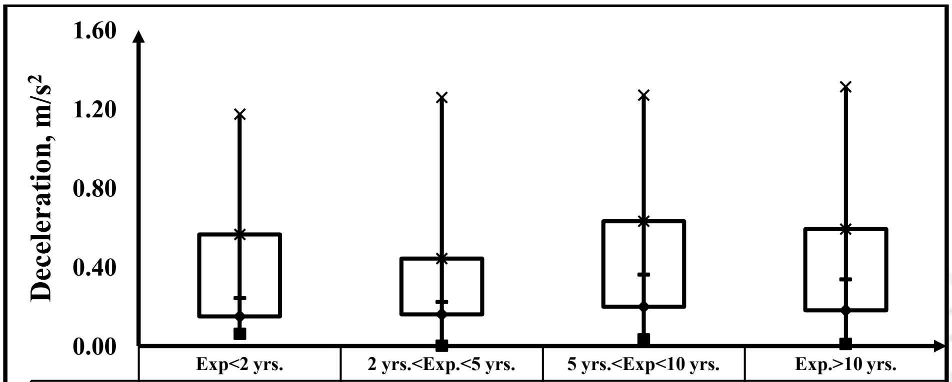
Driver age	**Maximum deceleration,** m/s^2	**Mean deceleration** m/s^2	**Kurtosis**	**Skewness**
<25 yrs., A1	0.84	0.49	-1.03	0.44
25yrs.<age<35yrs., A2	0.79	0.41	-0.49	0.28
>35 yrs., A3	0.77	0.38	-0.96	0.06

The average maximum deceleration rate (refer Table 6.16) employed by young drivers (driver group A1) is higher than older drivers (driver group A2 and A3.). The deceleration distribution is flatter in case of old drivers as compared to young drivers indicated by negative kurtosis values (refer Table 6.16).

The skewness values (refer Table 6.16) indicate that deceleration distribution is skewed to right in case of all age group drivers but in case of older drivers the skewness is minimum and is near to zero indicating near symmetric distribution. This indicates that, not only the magnitude of deceleration is affected by the driver age but the deceleration distribution is also different with different driver age.

6.5.2 Effect of driver experience on deceleration of trucks

To understand the effect of driver experience on deceleration of mid-sized truck , the drivers are classified in four categories viz; D1, experience<2 yrs., D2, 2 yrs.<experience<5 yrs., D3, 5 yrs.<experience<10 yrs. and D4, experience>10 yrs. The box plots showing various parameters of average deceleration is presented in Figure 6.9.



	Exp<2 yrs.	2 yrs.<Exp.<5 yrs.	5 yrs.<Exp<10 yrs.	Exp.>10 yrs.
◆q1	0.15	0.16	0.20	0.18
■minimum	0.06	0.00	0.03	0.01
−median	0.24	0.22	0.36	0.34
×maximum	1.17	1.26	1.27	1.31
✱q3	0.57	0.44	0.63	0.59

Figure 6.9: Box plots of deceleration posted by drivers having various driving experience

The difference between maximum and minimum deceleration values (range) is widest in highest experienced drivers D4 (1.30 m/s^2) and narrowest in least experienced driver, D1 (1.11 m/s^2). This indicates that variation in less experienced drivers (decelerations are closely bunched) is less than experienced drivers. Also the Inter Quartile Range, IQR, $(q_3 - q_1)$ is lowest in D2 group drivers (0.28 m/s^2) than other experience group drivers. However, in this case IQR cannot be considered as measure of difference since differences in IQR of different experience groups is not substantial. Similarly the variance of deceleration posted by various experience groups does not differ substantially (0.082, 0.070, 0.081 and 0.070 for D1, D2, D3 and D4 group drivers respectively).

Further, to verify the differences in decelerations posted by drivers of various experience groups, single factor ANOVA is carried out and the results are presented in Table 6.16

Table 6.16: Results of ANOVA for deceleration of truck drivers of different driving experience groups.

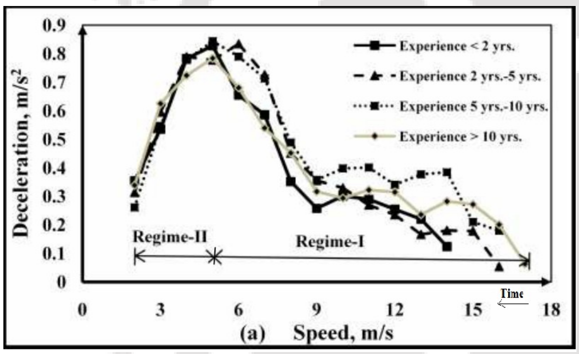
Source of Variation	*SS*	*df*	*MS*	*F-Ratio*	*P-value*	*F crit*
Between Groups	1.57	3.00	0.52	**7.12**	0.00	**2.61**
Within Groups	85.29	1162	0.07			
Total	86.86	1165				

F ratio values exceeds the F-critical values which indicates that differences exist between the means of decelerations employed by drivers of different experience groups.

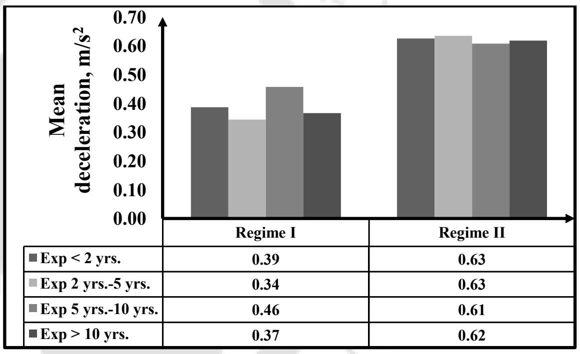
Fisher's Least Significant Difference (LSD) procedure is attempted to quantify the difference of mean deceleration employed by drivers of different groups, D1 to D4. The computed LSD is obtained as 0.021. The differences between means are 0.04, 0.09, 0.026 and 0.027 for D1 and D2, D2 and D3, D3 and D4 and D1 and D4 respectively. Since all differences are more than LSD it indicates that the differences between deceleration employed drivers of different groups are significant.

Idealized plot of deceleration-speed and effect of driver experience on deceleration of trucks are presented in Figure 6.10a and 6.10b respectively. The **critical speed** of drivers with different driving seems similar *i.e.* 4.5 m/s. The deceleration behaviour are different after and before critical speed (Regime-I and Regime-II).

The average maximum and average mean deceleration values, symmetry of deceleration distribution (kurtosis and skewness) and standard error of deceleration in different experience groups are presented in Table 6.17.



(a) Idealized plot of deceleration-speed for different driving experience



(b) Mean deceleration values of drivers in Regime I and Regime II

Figure 6.10: Variation of mean deceleration rate of truck driver with different driving experience

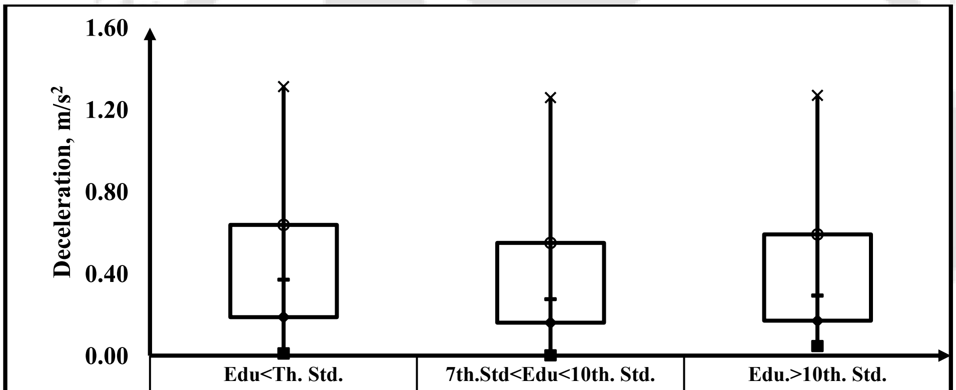
Table 6.17: Average Maximum deceleration values with driving experience and their statistics

Driving experience	**Maximum deceleration,** m/s^2	**Mean deceleration,**	**Kurtosis**	**Skewness**	**Standard error**
<2 yrs.	**0.82**	**0.43**	**-0.87**	**0.64**	**0.062**
2-5 yrs.	**0.83**	**0.41**	**-1.26**	**0.48**	**0.067**
5-10 yrs.	**0.84**	**0.47**	**-0.92**	**0.56**	**0.055**
>10 yrs.	**0.78**	**0.40**	**-0.67**	**0.44**	**0.052**

In regime-I, drivers with moderate experience (driver group D3) use higher mean deceleration among all driver groups. The mean deceleration (refer Figure6.8b) used by driver group D3 drivers is higher by 15.2%, 26% and 19.5% from driver groups D1, D2 and D4 respectively. In regime-II however, the deceleration behaviour of drivers with different driving experience is more or less similar. The kurtosis of driver deceleration (refer Table6.17) is negative indicating that deceleration distribution is flatter than normal distribution.Driver group D2, have the flattest distribution and D4 drivers have the highest peak distribution. The positive skewness values (refer Table 6.17) indicate that the distribution of deceleration is skewed to right and drivers with least experience have maximum skew.

6.5.3 Effect of driver education on deceleration

For understanding the effect of driver education on deceleration of mid-sized truck , the drivers are classified in three categories viz; education<7th. Std., E1, 7th. Std.<education<10th, E2 and Std., education>10th. Std., E3. The box plots showing various parameters of average deceleration is presented in Figure 6.11.



	Edu<Th. Std.	7th.Std<Edu<10th. Std.	Edu.>10th. Std.
◆ q1	0.19	0.16	0.17
■ Minimum	0.01	0.00	0.05
− Median	0.37	0.28	0.29
× Maximum	1.31	1.26	1.27
○ q3	0.64	0.55	0.59

Figure 6.11: Box plots of deceleration posted by drivers having various driving experience

The difference between maximum and minimum deceleration values (range) is widest in driver group E1 and narrowest in driver group E3. education<7th. Std. (1.30 m/s^2) and narrowest in education>10th. Std. (1.22 m/s^2). This indicates that the difference in deceleration variability among all driver groups, E1 to E3, is small *i.e.* 0.08 m/s^2. Also the Inter Quartile Range, IQR, $(q_3 - q_1)$ is lowest in 7th Std.<education<10th. Std.(0.39 m/s^2) than other education group drivers. However, in this case IQR cannot be considered as the measure of difference since the difference in IQR of different experience groups is not substantial. Similarly the variance of deceleration posted by various experience groups does not differ substantially (0.08, 0.070, 0.08 and for E1, E2 and E3 groups respectively).

Further, to verify the differences in decelerations posted by drivers of various education groups, single factor ANOVA is carried out and the results are presented in Table 6.18

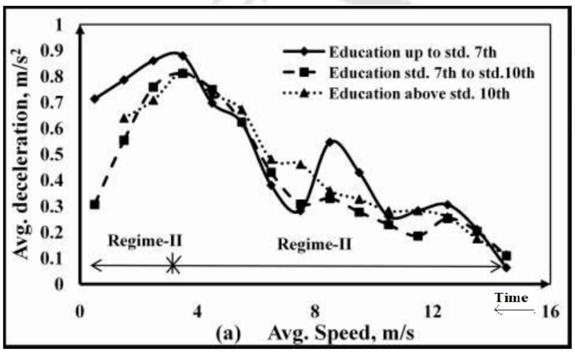
Table 6.18: Results of ANOVA for deceleration of truck drivers of different education groups.

Source of Variation	*SS*	*df*	*MS*	*F-Ratio*	*P-value*	*F crit*
Between Groups	0.69	2.00	0.35	**4.49**	0.01	**3.00**
Within Groups	78.42	1019	0.08			
Total	79.11	1021				

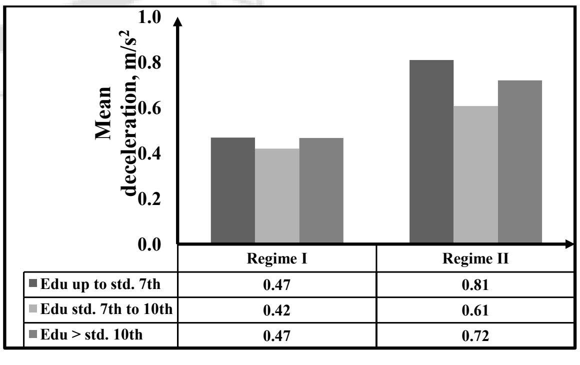
F ratio values exceeds the F-critical values indicating that null hypothesis that means of deceleration posted by drivers of different education groups are equal, cannot be accepted. This indicates that differences exist between the means of decelerations employed by drivers of different education group. But rejection of null hypothesis by ANOVA alone does not convey the actual difference between the means of deceleration sample of drivers of different experience groups.

Hence the Fisher's Least Significant Difference (LSD) procedure is attempted to quantify the difference. The results of LSD are used to formulate the criteria for differences between means. The computed LSD is 0.024. The differences between means are 0.068, 0.020 and 0.048 respectively between driver groups E1 and E2, E2 and E3 and E1 and E3 respectively. Since these differences are more than LSD (except between E2 and E3), deceleration posted by drivers with different education are different. These differences are further quantified using idealized plot of deceleration-speed and the column plots of mean deceleration in Regime-I and Regime-II.

Idealized plot of deceleration-speed and the effect of driver experience on deceleration of trucks is presented in Figure 6.12a and 6.12b respectively. The idealized maximum and average mean deceleration values and symmetry of deceleration distribution (kurtosis and skewness) in different experience groups are presented in Table 6.17.



(a) Idealized plot of deceleration-speed for different education



(b) Mean deceleration values of drivers with different education in Regime I and Regime II

Figure 6.12: Variation of mean deceleration for truck driver with different education level

Table 6.19: Idealized Maximum deceleration values with driving experience and their statistics

Driving education	**Maximum deceleration,** m/s^2	**Mean deceleration,** m/s^2	**Kurtosis**	**Skewness**
Edu<th. Std., E1	1.31	0.48	-0.41	0.61
7th.Std<Edu<10th. Std., E2	1.26	0.40	0.001	1.00
Edu.>10th. Std., E3	1.27	0.45	0.18	1.02

It is seen from idealized plot (refer Figure6.10a) that drivers with different educational level decelerate vehicle differently. The **critical speed** of drivers of various education groups is 3.5 m/s. Driver behaviour before and after critical, regime-I and Regime-II, are different. In regime-I the drivers in group E2 use 12% lower mean deceleration than driver group E1 and E3. In regime-II, however, drivers in group E2 use 32% and 14.75% lower mean deceleration than drivers in E2 and E1 group. This indicates that drivers with moderate education use lower deceleration as compared to higher education or lowest education drivers.

The kurtosis of driver deceleration (refer Table6.19) is negative in case of driver group E1 and positive in other cases. This indicates that deceleration distribution is flatter than normal distribution for less educated drivers whereas for drivers with more education, the distribution is peaked than normal distribution (*i.e.* variability in deceleration is less).

The positive skewness values (refer Table6.19) indicate that the distribution of deceleration is skewed to right and drivers with maximum education (driver group E3) have maximum skew.

6.6 Concluding Remarks

Drivers are divided in different categories depending on their attributes (like three groups A1, A2 and A3 based on age of drivers, four groups, D1 to D4 based on driving experience and three groups E1 to E3, based on driver education). Acceleration/deceleration trips, corresponding to each group of driver based attributes are segregated and analyzed. Following salient points can be observed towards attributes impacts on acceleration behaviour of drivers.

1. Younger drivers use highest rate of acceleration than old aged drivers. Thus difference in behaviour is more prominent up to moderate speed range ($\leq$ 10.5 m/s) of vehicle, however, at higher speed ($\geq$ 10.5 m/s) difference in acceleration vanishes.

2. Experienced drivers employ higher acceleration rate than new drivers. This difference in behaviour also reduces with increase in vehicle speed.

3. Less educate drivers reflect rough behaviour (higher acceleration) than other drivers towards of start up of acceleration manoeuver. At higher speed the differences in different driver behaviour are not prominent as employed acceleration values are quite low.

Following observations can be made from deceleration trip analysis regarding impact of driver attributes.

1. Old driver uses higher deceleration rate in regime-I while deceleration rate of young drivers are higher in regime-II. This implies that young drivers use hard breaking towards the end deceleration manoeuver while old drivers uses hard breaking start of deceleration manoeuver.
2. Effect of driver experience is visible in regime-I only (in starting of deceleration manoeuver). Moderate experienced driver (D3 group drivers) use relatively higher deceleration than less experienced drivers (D1 and D2 group drivers).
3. Least educated drivers decelerate vehicle roughly (*i.e.* uses higher deceleration rate than other drivers).

Chapter 7

Applications of Acceleration and Deceleration Study of Vehicles

Chapter 4 and 5 5 analyzed and modelled the acceleration/deceleration (A/D) behaviour of different vehicles. Real life A/D modelling is required for traffic engineering related works like microscopic traffic flow modelling, geometrical design of highways and intersection, estimation of control delay at signalized intersection, cycle time design of signals etc as discussed in Chapter 1. To verify the effect of A/D models, following two experiments are performed:

1. Study the effect of A/D on vehicular tail pipe emission, and
2. Study the effect of A/D behaviour on average delay per vehicle

Following subsections present the results of both the studies, one by one.

7.1 Effect of A/D on Vehicular Tailpipe Emission

Vehicular emissions contribute substantially to total environmental pollution for Carbon Monoxides(CO), Hydrocarbons (HC), Carbon Dioxides (CO_2) and Oxides of Nitrogen (NO_x). The emission of these gases contributes to global warming and greenhouse effect. The human health is adversely affected by these gases. Formation of Ozone and Smog are the results of NO_x and HC and formation of Carboxy-hemoglobin, inhibiting formation of oxygen carrying capacity of blood, is the result of CO, (Mudgal et al. (2011)).

Carbon Monoxide is the product of incomplete combustion of motor fuels and the Oxides of Nitrogen are the result of high temperature chemical process that occurs during combustion,(Rakha and Ding, 2003). In engines, the emissions are generated as a result of fuel combustion and are termed as engine out emissions. In petrol engines, these emissions are reduced using catalytic converter. However, in diesel engines, emissions cannot be reduced using catalytic converter due to presence of particulate matter.

Measurement of these emissions is typically done through driving cycle based models like MOBILE 5b, MOBILE 6, EMFAC etc. These driving cycles are developed by US Department of Environmental Protection Agency (EPA). The second by second data required for these models is taken from driving cycle based laboratory experiments using chassis dynamometer. The driving cycles consider average link speed without giving consideration to transient changes in vehicle speed and acceleration. The transient changes affecting tail pipe emissions include acceleration, cruise, breaking, deceleration and gear change. The emissions through such events is termed as *micro-scale emissions*, which are a substantial part of total emission inventory. Most of the existing models (like MOBILE 5b, MOBILE 6, EMFAC etc.) are based on aggregate modelling approach which do not consider effect of transient changes. A characteristic vehicle is used to represent dissimilar vehicles in these models. Such an approach is not suitable for environmental evaluation of individual vehicular tail pipe emissions (Ahn et al. (2002)). Therefore, the *micro-scale emission* models based on real world traffic data are needed. The traffic control strategies that will evolve through such models will reduce the real world emissions (Frey et al. (2001)).

This study aims at developing mathematical models that predict the *micro-scale emissions* like CO, HC and NO_x using average instantaneous speed, acceleration and deceleration as explanatory variables.

7.1.1 Data collection

Data required for investigating relationship between speed, acceleration and deceleration of cars and their tailpipe emission is;

1. Second by second speed data, and

2. Second by second emission data for CO, HC and NO_x

Hence study involved two different instruments to measure the speed profile and tailpipe emission of test vehicle. A GPS device capable of recording vehicle position and speed at 1 Hz frequency (1 Hz to 10 Hz frequency used in Chapter 4 and 5 for cars) is used for recording vehicle speed profile. Further, 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 1Hz rate. This device is capable of recording each second data of vehicular emissions such as CO, HC and NO_x . The device measures emitting pollutants by volume % for CO and by parts per million (*ppm*) by volume for HC and NOx.

Literature reveals that vehicle tailpipe emission depends on whether vehicle is fitted with catalytic converter or not. Accordingly two vehicle classes are selected in this study; one with catalytic converter and other without catalytic converter.

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 and then decelerate to stop after cruising at highest speed for 10 to 15 seconds time. This experiment is similar to previously described A/D pattern study of vehicles. This experiment is conducted near Indian Institute of Technology Guwahati (details are presented in Section 3.2.3). All trips were made during free flow traffic condition. A total of 70 such trips of each test car type of various weight to horse power ratio were recorded in sunny weather during November 2011. Both types of vehicles vehicles had similar kilometers of run on road and had similar engine and loading capacity. This has ensured that both the cars shall have similar characteristics except catalytic converter. All cars used in study were petrol cars with manual gear transmission facility. The details of instrumentation and data collection procedure is described in Chapter 3.

The speed-time data collected for few vehicle trips is presented in Figure 3.4 .

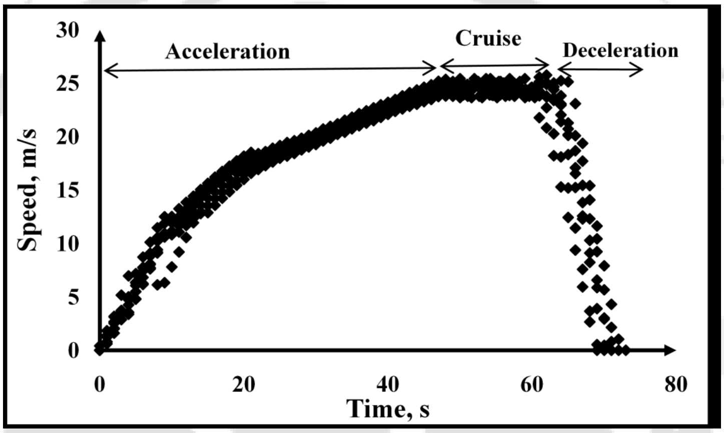


Figure 7.1: Scatter plot of speed-time of some trips during emission study

It is seen from the Figure 3.4 that the drivers accelerated very rapidly at the initial phase of acceleration manoeuver. The slope of speed time plot, which is very steep at the beginning, go on reducing as vehicle reaches to maximum speed. This supports the observation made by Bham and Benekohal (2002) that the acceleration is higher in the beginning and it reduces as vehicle reaches maximum speed. Rate of change of speed is very high during deceleration manoeuver. This variation in acceleration and deceleration is bound to have its influence on emission of vehicle. In each trip vehicle is allowed to run for 10-15 seconds to ensure that vehicular emission get stabilized before start of deceleration manoeuver. This cruising period data is not considered in A/D data.

The acceleration and deceleration are obtained from the observed data (similar to one described in Chapter 4 and 5).

The speed records obtained from all trips are then averaged over a speed range of 1 m/s to get an idealized value of speed. Similar averaging is 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 emission) is obtained for every 1 m/s speed range. This is done to examine aggregate behaviour of emission with speed, acceleration and deceleration. A similar procedure was adopted by Wang et al. (2005) for evaluation of deceleration behaviour of passenger cars at stop controlled intersections. The idealized plot of acceleration-speed and deceleration-speed are presented in Figure 7.2.

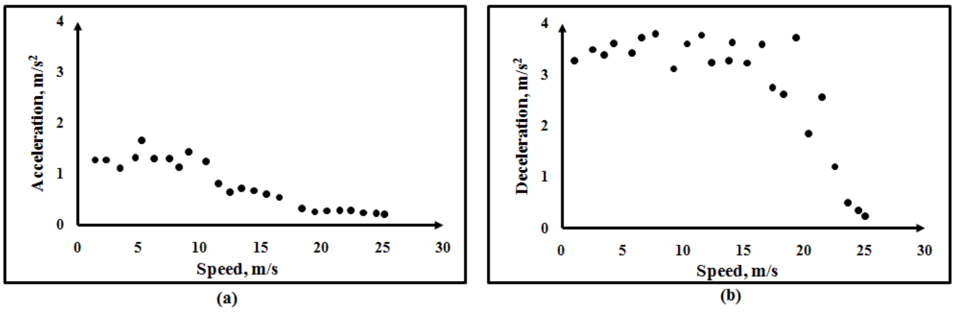


Figure 7.2: Idealized plots of (a) Acceleration-speed (b) Deceleration-speed, for car

It is observed from the plots in Figure7.2 that the acceleration and deceleration, both vary non-linearly with speed. The acceleration is more at the beginning of acceleration manoeuver and gradually decreases as the acceleration manoeuver advances (negative exponential form). Some local fluctuation in acceleration values is due to gear change of vehicles. Detailed discussion on effect of gear is already presented in Chapter 4.

The deceleration behaviour of vehicles is also nonlinear with speed (third order polynomial, refer Chapter 5) but is different as compared to acceleration behaviour. At the beginning of deceleration manoeuver (indicated by high speed), the decelerations are low. Afterwards deceleration increases to a maximum value and then decreases with further decrease in speed. A detailed discussion on this aspect if presented in Chapter 5.

7.2 Effect of Speed, Acceleration and Deceleration on Tailpipe Emission

This section presents effect of various modes of traffic like speeding, acceleration and deceleration on vehicular tail pipe emission. Initially, the direct relationship between speed (without giving any consideration to acceleration or deceleration) and tail pipe emission is probed. Then the relationship between speed and emission at a particular acceleration and deceleration level is investigated.

7.2.1 Effect of speed on tail pipe emission

In order to assess the effect of speed variation on tailpipe emission of test car idealized emissions are plotted against idealized speed as shown in Figure 7.3.

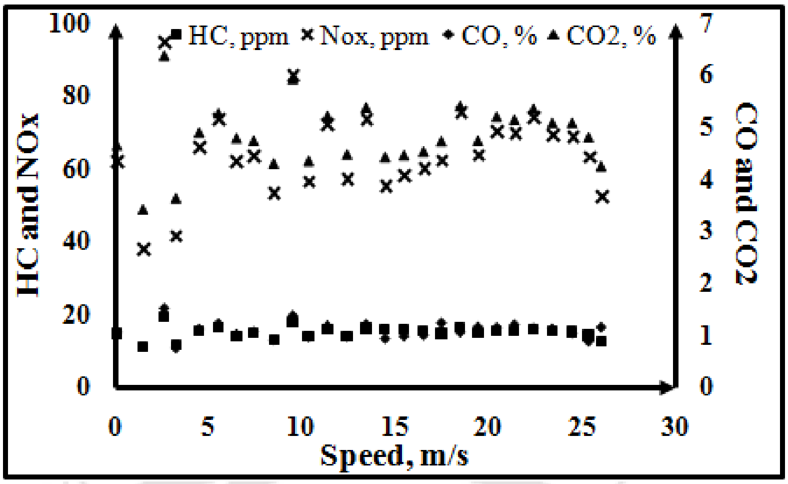


Figure 7.3: Effect of speed on tailpipe emission of vehicle fitted with catalytic converter

It is seen from Figure 7.3 that there is no consistent relationship or significant variation between car speed and tailpipe emission. Similar observation is also noted by other researchers (Ahn et al. (2002); Rakha et al. (2000)). One of the possible reason is that these speed records are mixed with acceleration records i.e. similar speed data but different acceleration levels. In Figure 7.3 emission were plotted against speed irrespective of acceleration levels. A similar attempt is made for the speed records and emission of car without catalytic converter. No consistent relationship between emission and vehicular speed was observed in this case also.

Therefore, it is felt that one should account A/D value also while developing speed-emission relationship *i.e.* tailpipe emission at a speed depends on the way in which the speed is attained.

So, for improved representations of emissions, vehicle operating conditions should also be taken into account. The important operating variable of vehicle is acceleration and deceleration, which are the measures of variation of speed. Also, it is reported by Joumard et al. (1995) that at the given engine input, the slow moving vehicle will accelerate at a higher rate than a fast moving vehicle. Hence it was decided to test the dependency of emissions on acceleration and deceleration.

7.2.2 Effect of acceleration on tail pipe emission

The speed records are then arranged as per the acceleration range and relation between speed and emission within a particular acceleration range is studied. For example, the speed and emissions data at an acceleration level ($\approx$1.0 m/s^2) are segregated and relationship between speed and emission is tested again. It is found that at similar acceleration range, speeds and tailpipe emissions manifest a prominent relationship. Therefore, the speed and emission relationships are developed for different acceleration ranges (like 0.8-1.0, m/s^2, 1.0-1.2 m/s^2, 1.2-1.4, m/s^2, 1.4-1.6, m/s^2, 1.6-1.8, m/s^2, 1.8-2.0, m/s^2 etc). Figure 7.4 (a; b and c) present the relationship of CO, HC and NO_x emission rate with speed at two different acceleration level (0.8-1.0, m/s^2, 1.4-1.6 m/s^2) for cars fitted with catalytic converter. Similarly, Figure 7.5, a,b, and c presents the emission relationship with speed at two different acceleration level (0.8-1.0 m/s^2 and 1.4-1.6 m/s^2) for car fitted without catalytic converter.

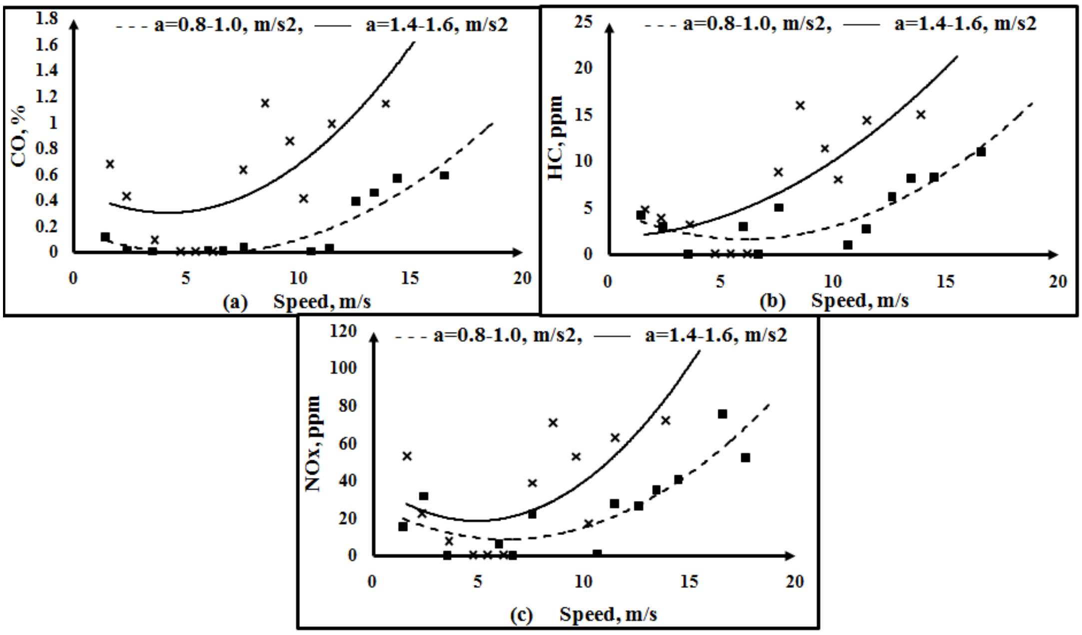


Figure 7.4: Effect of speed and acceleration on tailpipe emission of car fitted with catalytic converter (a) CO, (b) HC (c) NO_x

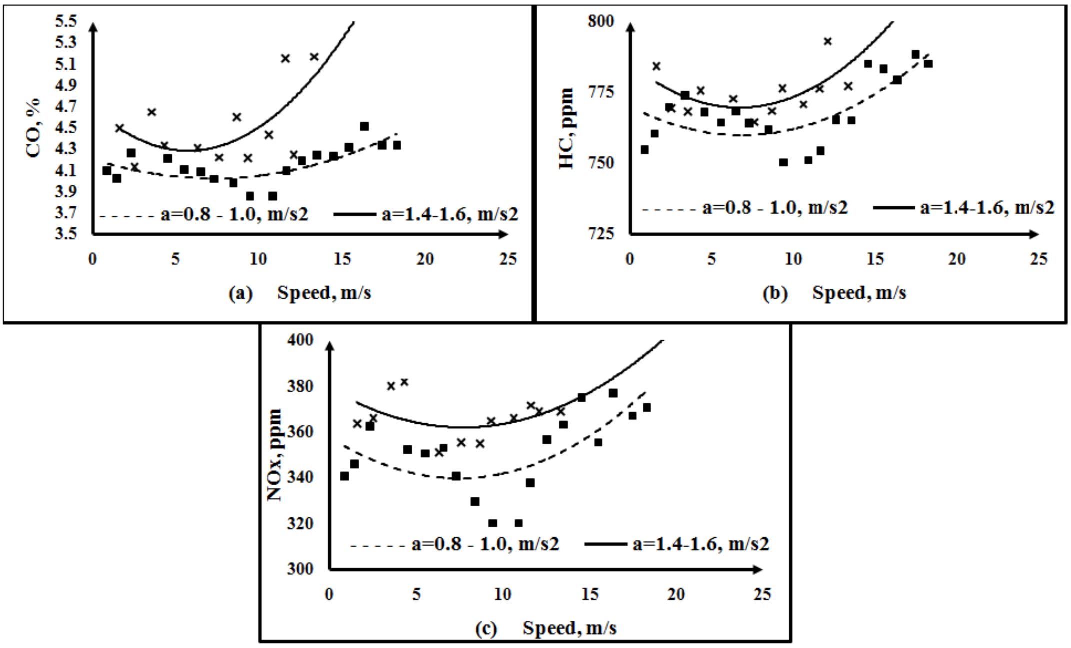


Figure 7.5: Effect of speed and acceleration on tailpipe emission of car without catalytic converter (a) CO, (b) HC (c) NO_x

It is seen from the Figure 7.4 and 7.5 that tailpipe emission rate is high at lower speed which gradually lowers with increase in speed. After attaining the lowest value, emission rate starts increasing with further increase in speed. Similar, trend is observed for all emissions such as CO, HC and NO_x. The reason is, at lower speed, the engine exerts more power (in first or second gear, speed 0-4 m/s) with more consumption of fuel. Since emission is directly proportional to fuel consumption (Ahn et al. (2002)), this results in high tailpipe emissions. As the vehicle speed advances (in second or third gear, speed 4 to 8 m/s) the power goes on reducing and hence the fuel requirement of engine goes on reducing. This results in reduced tailpipe emissions. However, with further increase in speed (in fourth or fifth gear, speed above 8 m/s) engine consumes more fuel for achieving higher speed resulting in increase in tailpipe emission. Similar behaviour is also reported by many researchers (Frey et al. (2001); Unal et al. (2004); Ahn et al. (2002) and Rakha et al. (2000)).

The lowest tailpipe emission rate is observed at the speed range of 4 to 8 m/s (refer Figure 7.4 and 7.5) at average acceleration rate of ≈ 0.8-1.0 m/s^2 for all tailpipe emissions (CO, HC and NOx). One should note that the optimal speed range (4-8 m/s) is found corresponding to minimum emission, does not represent the cruising speed (≈ 0 acceleration level) of vehicle for maximum fuel economy. Although Figure 7.4 and 7.5 show similar speed-emission pattern at an acceleration level, actual emission values are different for cars fitted with and without catalytic converter which is discussed in next section.

7.2.3 Effect of catalytic converter on tailpipe emission

The magnitude of emission is significantly more for all emissions in case of cars without catalytic converter than car fitted with catalytic converter. Joumard et al. (1995) reported that the CO and HC increased 20-30% when the catalytic converter is not used. However, they reported that NO_x emissions decreased by 2-5% when catalytic converter is not used. The results of present study contradict the observation noted by Joumard et al. (1995) in case of NO_x.

Table 3(a and b) presents average tailpipe emissions at different speed ranges and acceleration levels for car with and without catalytic converter.

Table 7.1: Average tailpipe emission rate at different speed ranges and acceleration levels

(b) For car with catalytic converter						
Speed range, (m/s)	CO, (%)		HC, (ppm)		NOx, (ppm)	
	a≈0.8-1.0 m/s^2	a≈1.4-1.6 m/s^2	a≈ 0.8-1.0 m/s^2	a≈ 1.4-1.6 m/s^2	a≈ 0.8-1.0 m/s^2	a≈1.4-1.6 m/s^2
0-4	0.043	0.4	2.4	3.92	15.66	27.53
4-8	0.006	0.008	1	1.06	2	2.46
above 8	0.29	0.865	5.29	10.49	31.08	44.77
(b) For car without catalytic converter						
Speed range, (m/s)	CO, (%)		HC, (ppm)		NOx, (ppm)	
	a≈0.8-1.0 m/s^2	a≈1.4-1.6 m/s^2	a≈ 0.8-1.0 m/s^2	a≈ 1.4-1.6 m/s^2	a≈ 0.8-1.0 m/s^2	a≈1.4-1.6 m/s^2
0-4	4.11	4.42	764	773	349	369
4-8	4.012	4.39	762	770	337	364
above 8	4.27	4.75	772	779	357	368
Note:a-acceleration						

It is seen from Table 7.1 that average emission rates for cars without catalytic converter are significantly more as compared to cars with catalytic converter.

It is also seen from Table 7.1, (a) and (b), 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 - 8 m/s at both acceleration levels. It can be observed that effect of acceleration on tailpipe emissions is more prominent at higher speeds. At higher speed range, all tailpipe emission rates (CO, %, HC, ppm and NO_x, 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 7.1 (a). This demonstrate the effect of speed and acceleration on tailpipe emission rates of test vehicle. Similar observation is also made from Table 7.1 (b), for car without catalytic converter. The emissions in car without catalytic converter are significantly high as compared to car with catalytic converter.

7.2.4 Effect of deceleration on tailpipe emission

This subsection analyzes the effect of vehicle deceleration on its tailpipe emission during deceleration manoeuver. Therefore, speed during deceleration are separated out from the complete speed data and corresponding decelerations are calculated. The speeds and emissions are then averaged over 1 m/s speed interval. Idealized speed and emission data are plotted and no consistent relationship is observed. Therefore, speed-emission data is re-plotted at different deceleration level.

However, any consistent relationship between speed and emission at a particular deceleration level couldn't be found. The reason is that during deceleration drivers apply break and clutch simultaneously. This detaches engine from vehicle. Hence in deceleration the role of engine is limited (engine may be playing role if the vehicle is decelerated using gears).

7.3 Emission Models

Linear regression technique is used to model the relationship between speed and various emissions at a particular acceleration level. Various model forms (such as, linear, second order and third order polynomial) were tested to assess the suitability of these model forms for explaining the dependence of emissions on speed at a particular acceleration level. The model form chosen was one yielding lowest Residual Sum of Squares (RSS). Following second order polynomial form was found suitable for explaining dependence of emission on speed;

$$e = k_1 \times v^2 - k_2 \times v + k_3 \tag{7.1}$$

where, where, e is emission (CO, %, HC, ppm and NO_x, ppm), v is instantaneous speed of vehicle in m/s and k_1, k_2 and k_3 are the model parameters. The observed average data is used to calibrate the model. The model parameters are presented in Table 7.2.

The second order polynomial model presented above satisfactorily fits with the emission data (indicated by r^2 values 0.84, 0.76 and 0.73 respectively for CO, HC and NOx, refer Table 7.2) for vehicles fitted with catalytic converter, at the acceleration rate ≈1 m/s2 for emissions like CO, HC and NOx. However, for acceleration rate, $a \approx 1.4 - 1.6m/s^2$ these emission rates show lesser satisfactory fit. Similarly for vehicles without catalytic converter, the fit is better at acceleration rate $a \approx 0.8 - 1.0m/s^2$ than at acceleration rate $a \approx 1.4 - 1.6m/s^2$. This indicates that the second order polynomial model is better at predicting emissions at lower acceleration levels than at higher acceleration levels.

7.3.1 Model Diagnostic

The model reported above is then applied to compare the predicted tail pipe emission data with observed tail pipe emission field data. The model diagnostic is presented in detail in Appendix B.8.

Table 7.2: Model parameters for various emissions at different acceleration levels for cars

(a) For car fitted with catalytic converter

Emission	Acceleration	Model parameters			r^2
	m/s^2	k_1	k_2	k_3	
CO	0.8-1.0	0.006	-0.067	0.172	0.84
	1.4-1.6	0.01	-0.091	0.486	0.49
HC	0.8-1.0	0.09	-1.094	4.901	0.76
	1.4-1.6	0.078	0.028	1.914	0.603
NOx	0.8-1.0	0.468	-5.91	26.87	0.73
	1.4-1.6	0.809	-7.985	38.243	0.44

(b) For car without catalytic converter

Emission	Acceleration	Model parameters			r^2
	m/s^2	k_1	k_2	k_3	
CO	0.8-1.0	0.003	-0.05	4.2	0.54
	1.4-1.6	0.012	-0.142	4.68	0.39
HC	0.8-1.0	0.21	-3.006	770.11	0.53
	1.4-1.6	0.349	-4.66	785.02	0.359
NOx	0.8-1.0	0.328	-4.91	357.63	0.45
	1.4-1.6	0.288	-4.47	379.23	0.15

Diagnostic plots in the form of plot of residues versus predicted values and normal quantile-quantile plots are developed. Residues are the difference between observed emission value and predicted emission value. The plots are presented in Figure 7.6 and 7.7 corresponding to car with and without catalytic converter respectively.

The residues versus predicted values (refer Figure 7.6(a); (b) and (c) for CO; HC and NOx for car with catalytic converter at 0.8-1.0 m/s2 acceleration level) show that residues are not correlated with predicted values. Also the assumption of constant variance is also satisfied. This indicates that the second order polynomial model is appropriate (no specification error) for describing the relationship between response and predictor. The assumption of constant variance is therefore fulfilled.

Similarly, for cars without catalytic converter, the model diagnostic indicates that (refer Figure 7.7(a); (b) and (c)) the assumptions of regression are not violated.

7.4 Effect of Acceleration and Deceleration on Delay of Car at Signalized Intersection

This section presents the second experiment to highlight the effect of A/D pattern on average delay at signalized intersection.

Performance of signalized intersection is primarily based on delay since it is associated with driver discomfort, frustration, fuel consumption, and lost travel time. The Highway Capacity Manual (HCM, 2000) recognizes delay as measure for determining level of service, (LOS) of signalized intersection. The intersection LOS defined by HCM is based on control delay, which includes deceleration and acceleration

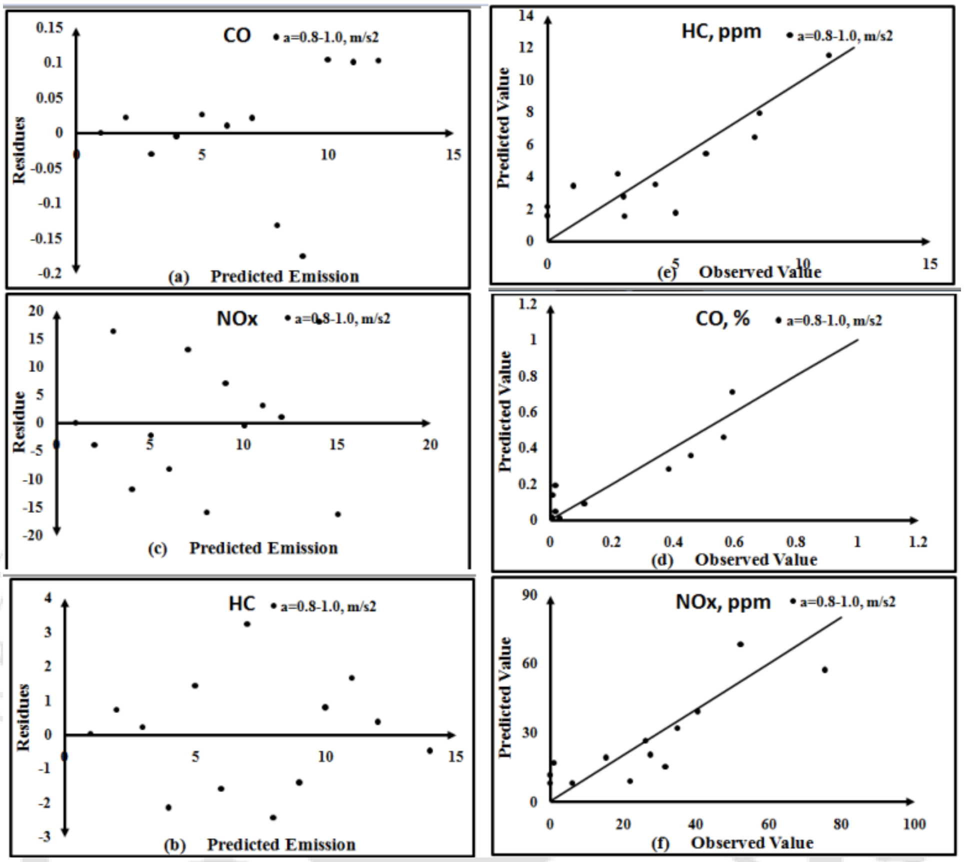


Figure 7.6: Diagnostic plots for cars fitted with catalytic converter

delay (along with stop delay and queue move up delay). Thus, identifying acceleration and deceleration delays at intersection is important for the analysis of performance of signalized intersection. This will also enhance the driver behaviour understanding around intersections, (Ko et al., 2008). It is however not easy to capture the deceleration and acceleration delay (control delay) in the absence of sophisticated devices. Hence the control delays have long been expressed as a portion of stopped delay.

This study aims at applying the pre-quantified acceleration and deceleration rates (refer Chapter 4 and Chapter 5) of car to measure average control delay (due to deceleration and acceleration) at signalized intersection on a single lane road stretch of 1 km length using simulation program VISSIM. Following sections present the results of analysis of simulation data for average control delay.

7.4.1 Details of simulation

In order to understand the effect of A/D pattern on average delay at signalized intersection, simulation of single lane 1 km road was carried out using VISSIM with a signalized intersection at 0.5 km distance. Traffic was considered homogeneous and flow was assumed as 800 $cars/hr$. Cycle time of signal was assumed as 60 s with 30 s Red, 27 s Green and 3 s Amber. Traffic was simulated for total 1200 s

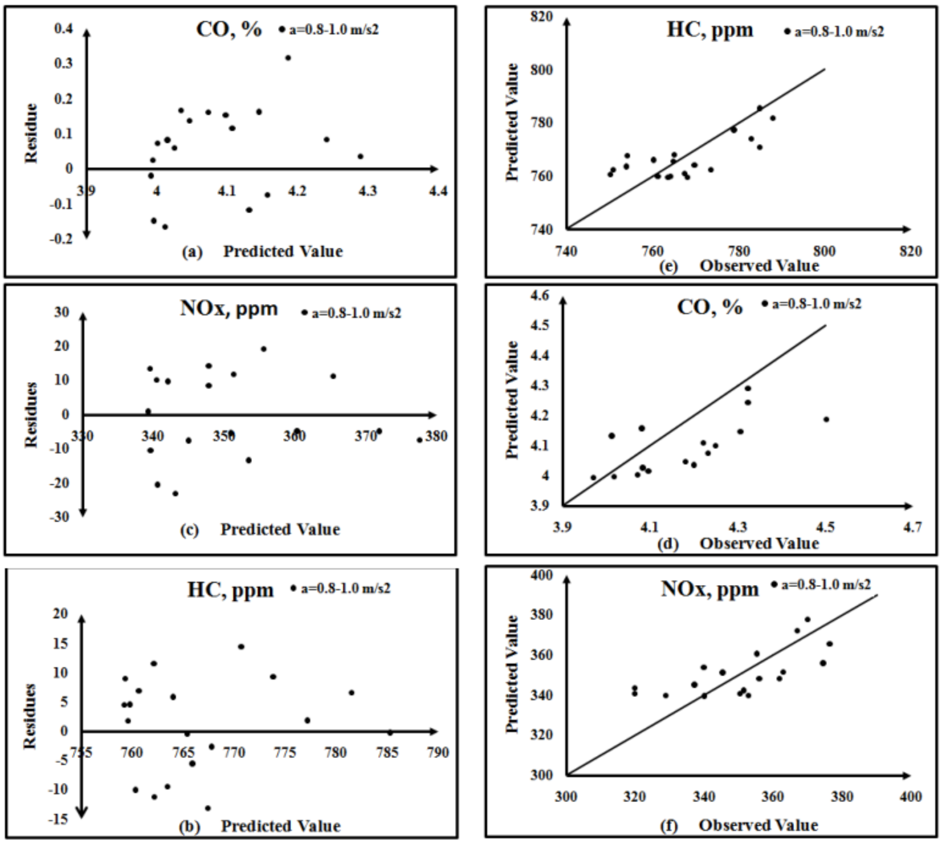


Figure 7.7: Diagnostic plots for cars without catalytic converter

and average delay was computed at signalized intersection for various combination of A/D patterns. Wiedemann's 99 model (with all default parameter values) was used for simulating the traffic stream. Model was not calibrated since author was interested only in relative change in delay corresponding to different A/D pattern. Desired speed of cars were assumed as normally distributed between 84 to 88 km/hr.

In order to see the effect of acceleration pattern on average delay, traffic streams with four linear decay acceleration models (i.e. zero acceleration at maximum speed and highest acceleration at zero speed) with one constant deceleration model (i.e. deceleration remains constant over speed) are simulated and average delay are recorded for each scenarios. Linear acceleration and constant deceleration models as author was interested only in relative change delay values instead of its comparison with field values. The maximum acceleration values were varied from 2 m/s^2 to 3.5 m/s^2 in the step of 0.5 m/s^2. The deceleration value was kept constant at 5.5 m/s^2. The results are presented in Table 7.3(a).

For assessing the effect of deceleration on average delay of cars, the values of selected deceleration were 3.5 m/s^2, 5.5 m/s^2 and 6.5 m/s^2 and the linear acceleration model adopted varied from 0 m/s^2 at highest seed and 2.5 m/s^2 at beginning of manoeuver. The results are presented in Table 7.3(b).

7.4.2 Effect of A/D Pattern on Average Delay at Signalized Intersection

To asses the effect of A/D pattern on delay of vehicles at signalized intersection, simulation is carried out with the parameters defined in previous section. It can be seen form the Table 7.3 that average delay increases for poor acceleration capabilities. Further, similar experiments are conducted to see the deceleration effect on average delay at signalized intersection. Traffic streams with three constant deceleration models and one linear decay acceleration model are simulated and average delay is recorded for all scenario (refer Table 7.3(b)). It is observed that average delay increases as deceleration capability of vehicle decreases.

These results corroborate the assumption that A/D pattern of vehicles affect the vehicle's behaviour/movement in traffic stream.

Table 7.3: Acceleration-Deceleration Delay of Car at Intersection

(a) Effect of Acceleration

Sr.No.	Acceleration range m/s^2	Deceleration m/s^2	Average Delay, s
1	3.5-0	5.5	9.16
2	3.0-0	5.5	9.87
3	2.5-0	5.5	11.36
4	2.0-0	5.5	15.01

(b) Effect of Deceleration

Sr.No.	Deceleration m/s^2	Acceleration range m/s^2	Average Delay, s
1	6.5	2.5-0	11.34
2	5.5	2.5-0	11.75
3	3.5	2.5-0	12.55

7.5 Concluding Remarks

Two different experiments were conducted to highlight the impact of A/D pattern on various traffic engineering applications (like vehicular emission models and delay at signalized intersection). It is observed that vehicular tailpipe emission is dependent on vehicle speed at particular acceleration level. Emission initially decreases, attains a minimum value and then increase monotonically with speed at a particular acceleration level. Tailpipe emission increases with increase in acceleration level at similar speed.

In second experiment, average delay at signalized intersection is calculated from a simulated stream using VISSIM. Traffic simulation was carried out for different combinations of A/D characteristics of vehicles. It was observed that average delay increases with reduction in vehicle A/D capability.

Chapter 8

Conclusions

Modelling of acceleration/deceleration (A/D) behaviour of vehicles are important for various traffic engineering related works like intersection design, deceleration lane design, ramp design, traffic simulation modelling, vehicular emission modelling, instantaneous fuel consumption rate modelling, etc. In this present study, A/D behaviour of various vehicle types (mid size truck, motorized three wheeler, motorized two wheeler, diesel car and petrol car) are analyzed. Further, it explores the impact of driver attributes (such as driver age, driving experience and driver education) on A/D characteristics. Vehicular tailpipe emissions and delays at signalized intersection have long been understood to have been affected by vehicle A/D. Hence the experiments are also conducted to understand the impact of A/D on vehicular tailpipe emission and average delay at signalized intersection. Brief summary of main findings of this study is presented in following section.

8.1 Summary of Results of This Study

This study is divided in four parts: (i) acceleration behaviour of vehicles, (ii) deceleration behaviour of vehicles, (iii) effect of driver attributes on acceleration/deceleration of mid size truck, and (iv) impact of A/D on vehicular tail pipe emission and average delay at signalized intersection. It was observed that different vehicle types have different A/D behaviour. It was also found that A/D behaviour also depends on the vehicle's desired (or maximum). The salient points that come out from each part of study are enumerated separately:

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 in 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 of various vehicle types are; 1.0 m/s^2 for truck, 0.64 m/s^2 for motorized three-wheeler, 1.95 m/s^2 for motorized two-wheeler, 2.23 m/s^2 for diesel car and 2.87 m/s^2 for petrol car. Petrol car posted highest maximum acceleration rate while motorized three wheelers posted the lowest. These rates are comparable with the rates reported by Wang et al. (2004); Bham and Benekohal (2002). Whereas the rates observed in this study 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. Proposed models are statistically evaluated and found fairly accurate in predicted the observed acceleration-speed behaviour.

5. In cars, at 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. Therefore every gear can be divided in two distinct regimes and modelled separately. However, reporting separate models for every gear or reporting different model parameters for every gear is of less practical use. Therefore, a single regime model (i.e negative exponential model) is developed ignoring the effect of gears for use in majority of applications in transportation engineering.

Deceleration behaviour

1. The distance traveled by various vehicle types during deceleration manoeuver is different and it varies with the speed at which driver start decelerating (*i.e.* approach speed). Driver requires longer decelerating distance for higher approach speed. Deceleration time also varies with vehicle type and approach speed similar to deceleration distance.

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 as the earliest.

3. The average maximum and mean deceleration rate observed in this study were found to be within the range specified by ITE (2009) and AASHTO (2004). However, these rates differ as compared to deceleration rates reported by Wang et al. (2005) and Bennet and Dunn (1995). This is because,

the vehicles in India have different vehicular characteristics as compared to vehicles in USA and New Zealand, where from these studies originate. No studies were found to report the deceleration rates of vehicles from India.

4. 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 (second order polynomial for diesel car and third order polynomial for petrol car) are proposed. 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.

Effect of driver attributes on A/D of mid size truck

1. Younger drivers use highest rate of acceleration than old aged drivers. Thus difference in behaviour is more prominent up to moderate speed range ($\leq$ 10.5 m/s) of vehicle, however, at higher speed ($\geq$ 10.5 m/s) difference in acceleration vanishes.
2. Experienced drivers employ higher acceleration rate than new drivers. This difference in behaviour also reduces with increase in vehicle speed.
3. Less educate drivers reflect rough behaviour (higher acceleration) than other drivers towards of start up of acceleration manoeuver. At higher speed the differences in different driver behaviour are not prominent as employed acceleration values are quite low.
4. Old driver uses higher deceleration rate in regime-I while deceleration rate of young drivers are higher in regime-II. This implies that young drivers use hard breaking towards the end deceleration manoeuver while old drivers uses hard breaking start of deceleration manoeuver.
5. Effect of driver experience on deceleration is visible in regime-I only (in starting of deceleration manoeuver). Moderate experienced driver use relatively higher deceleration than less experienced drivers .

Impact of A/D on vehicular tailpipe emission and average delay at signalized intersection
Two different experiments were conducted to highlight the impact of A/D pattern on various traffic engineering applications (like vehicular emission models and delay at signalized intersection). It is observed that vehicular tailpipe emission is dependent on vehicle speed at particular acceleration level. Emission initially decreases, attains a minimum value (in speed range 4-10 m/s) and then increase monotonically with speed at a particular acceleration level. Tailpipe emission increases with increase in acceleration level at similar speed.

In second experiment, average delay at signalized intersection is calculated from a simulated stream using VISSIM. Traffic simulation was carried out for different combinations of A/D characteristics of vehicles. It was observed that average delay increases with reduction in vehicle A/D capability.

8.2 Further scope of study

1. This study can be extended to observing the acceleration/deceleration behaviour of various vehicle types at actual signalized intersection. Conclusions of such study can be compared with the findings of present study.

2. The study can be conducted at more such locations to include more driver, vehicle and geometric variability in experimental results.

3. Various models of vehicles plying on Indian roads with different driver mix are needed to be quantified for their A/D characteristics. Assessment of driver attribute impact can lead to a robust A/D model which can be incorporated in simulation and other useful tools.

4. Effect of speed during particular A/D level on fuel consumption and tail pipe emission of various other vehicle types can be undertaken at signalized intersection which will help in building good emission and fuel consumption models.

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Chapter 9

List of Publications

International Journal, Published

1. Maurya, A.K. and Bokare, P.S. 'Study of Deceleration Behaviour of Different Vehicle Types', in *International Journal of Traffic and Transport Engineering*, 2012, 2(3), 253-270.

International Journal, Communicated

2. Bokare, P.S. and Maurya, A.K. 'Study of effect of Speed, Acceleration and Deceleration (A/D) Of Small Petrol Car on its Tailpipe Emission' in *International Journal of Traffic and Transport Engineering*

3. Maurya, A.K. and Bokare, P.S. 'Effect of Driver Age, Driving Experience and Education on Acceleration Pattern of Mid Sized Trucks', *Journal of Modern Transportation.*

4. Maurya, A.K. and Bokare, P.S.'Study of Acceleration Behaviour of Different Vehicle Types', *Journal of Advanced Transportation, Wily International.*

International Journal, In Preparation

5. Maurya, A.K. and Bokare, P.S., 'Effect of Speed, Acceleration and Deceleration of Cars on Their Tailpipe Emission', *Journal of the Air & Waste Management Association.*

6. Maurya, A.K. and Bokare, P.S.'Study of Acceleration-Deceleration of Various Vehicle Types', *Journal of Transportation Engineering, ASCE.*

International Conference

7. Maurya, A.K. and Bokare, P.S. 'Acceleration Modeling of Vehicles in Developing Countries',Published in 2^{nd} *International Conference on Models and Technologies for Intelligent Transportation Systems*, 22-24 June, 2011, Leuven, Belgium.

8. Maurya, A.K. and Bokare, P.S. 'Effect of Driver Behaviour on Vehicle Acceleration', 1^{st} *Conference of Transportation Research Group of India,* Banglore, India. December, 2011.

9. Maurya, A.K. and Bokare, P.S. 'Study of Effect of Speed, Acceleration and Deceleration on Vehicle's Tail Pipe Emission', *Transportation Planning Methodologies for Developing Countries-2012*, IIT Bombay, Bombay, India. 12-14 December, 2012.

International Conference, Communicated

10. Maurya, A.K. and Bokare, P.S. 'Speed-Time Models During Deceleration Manoeuver at Signalized Intersection in India for Various Vehicle Types' 16th IEEE Conference on ITS October, 2014, The Netherlands.

11. Maurya, A.K. and Bokare, P.S. 'Sample Size Requirements for Vehicles Speed Data Collection Using Global Positioning System' 2^{nd} *Conference of Transportation Research Group of India,* Agra, India. December, 2013.

National Journal (Review Received and Revised Paper Submitted)

12. Bokare, P.S. and Maurya, A.K. 'Acceleration and Deceleration Behaviour of Truck on Indian Highway' Indian Highways, Journal of Indian Roads Congress, New Delhi India.

National Conference

13. Maurya, A.K. and Bokare, P.S., 'Bus Driving Cycle on State Highway in Maharashtra, India.- A case Study', At *National Workshop on 'Understanding Real World Indian Driving Cycle'* at Central Road Research Institute, New Delhi, India. 4th December, 2012.

Appendices

Appendix A

Sample of Raw GPS Data

VEL:	_A__U:	19/08/2009	10:56:40.000am	2D:	0.03	3D:	0.089	227.735	70.521		
VEL:	_A__U:	19/08/2009	10:56:41.000am	2D:	0.054	3D:	0.079	171.239	46.578		
VEL:	_A__U:	19/08/2009	10:56:42.000am	2D:	0.171	3D:	0.216	316.744	-37.903		
VEL:	_A__U:	19/08/2009	10:56:43.000am	2D:	0.057	3D:	0.196	241.127	-73.231		
VEL:	_A__U:	19/08/2009	10:56:44.000am	2D:	0.024	3D:	0.097	315.137	-75.427		
VEL:	_A__U:	19/08/2009	10:56:45.000am	2D:	0.486	3D:	0.488	293.665	-4.708		
VEL:	_A__U:	19/08/2009	10:56:46.000am	2D:	0.996	3D:	1.457	290.967	-46.899		
VEL:	_A__U:	19/08/2009	10:56:47.000am	2D:	1.317	3D:	1.324	330.155	5.715		
VEL:	_A__U:	19/08/2009	10:56:48.000am	2D:	1.752	3D:	1.802	348.803	13.568		
VEL:	_A__U:	19/08/2009	10:56:49.000am	2D:	1.248	3D:	1.256	311.952	-6.284		
VEL:	_A__U:	19/08/2009	10:56:50.000am	2D:	1.246	3D:	1.249	321.776	3.649		
VEL:	_A__U:	19/08/2009	10:56:51.000am	2D:	1.087	3D:	1.087	319.04	1.452		
VEL:	_A__U:	19/08/2009	10:56:52.000am	2D:	1.048	3D:	1.049	301.255	-1.065		
VEL:	_A__U:	19/08/2009	10:56:53.000am	2D:	1.469	3D:	1.47	306.432	-1.818		
VEL:	_A__U:	19/08/2009	10:56:54.000am	2D:	1.322	3D:	1.335	299.605	-7.895		
VEL:	_A__U:	19/08/2009	10:56:55.000am	2D:	1.41	3D:	1.435	298.481	-10.628		
VEL:	_A__U:	19/08/2009	10:56:56.000am	2D:	1.142	3D:	1.174	307.284	-13.521		
VEL:	_A__U:	19/08/2009	10:56:57.000am	2D:	1.295	3D:	1.302	295.731	5.767		
VEL:	_A__U:	19/08/2009	10:56:58.000am	2D:	1.186	3D:	1.221	294.348	-13.708		
VEL:	_A__U:	19/08/2009	10:56:59.000am	2D:	1.047	3D:	1.898	286.879	56.512		
VEL:	_A__U:	19/08/2009	10:57:00.000am	2D:	1.067	3D:	1.728	285.069	51.851		
VEL:	_A__U:	19/08/2009	10:57:01.000am	2D:	0.363	3D:	0.364	307.274	2.069		
VEL:	_A__U:	19/08/2009	10:57:02.000am	2D:	1.011	3D:	1.511	237.3	47.975		
VEL:	_A__U:	19/08/2009	10:57:21.000am	2D:	0.138	3D:	0.201	89.558	-46.531		
VEL:	_A__U:	19/08/2009	10:57:26.000am	2D:	0.157	3D:	0.269	252.693	-54.37		
VEL:	_A__U:	19/08/2009	10:57:51.000am	2D:	0.017	3D:	0.185	245.809	84.643		
VEL:	_A__U:	19/08/2009	10:57:56.000am	2D:	0.249	3D:	0.334	244.086	41.677		
VEL:	_A__U:	19/08/2009	10:58:06.000am	2D:	3.473	3D:	3.473	315.073	0.323		
VEL:	_A__U:	19/08/2009	10:58:11.000am	2D:	4.48	3D:	4.48	308.578	-0.08		
VEL:	_A__U:	19/08/2009	10:58:16.000am	2D:	5.701	3D:	5.701	312.461	0.083		
VEL:	_A__U:	19/08/2009	10:58:21.000am	2D:	5.916	3D:	5.917	309.472	0.937		
VEL:	_A__U:	19/08/2009	10:58:26.000am	2D:	7.07	3D:	7.072	311.195	1.179		
VEL:	_A__U:	19/08/2009	10:58:31.000am	2D:	7.688	3D:	7.689	311.416	-0.938		
VEL:	_A__U:	19/08/2009	10:58:36.000am	2D:	7.998	3D:	7.999	310.578	-0.421		
VEL:	_A__U:	19/08/2009	10:58:41.000am	2D:	8.837	3D:	8.837	303.276	0.104		
VEL:	_A__U:	19/08/2009	10:58:46.000am	2D:	9.532	3D:	9.533	291.373	-0.76		
VEL:	_A__U:	19/08/2009	10:58:51.000am	2D:	10.193	3D:	10.19	4	283.1	12	0.493
VEL:	_A__U:	19/08/2009	10:58:56.000am	2D:	10.923	3D:	10.92	4	282.3	53	-0.713
VEL:	_A__U:	19/08/2009	10:59:01.000am	2D:	11.381	3D:	11.38	2	281.9	67	0.618
VEL:	_A__U:	19/08/2009	10:59:06.000am	2D:	11.405	3D:	11.40	5	282.1	45	0.640
VEL:	_A__U:	19/08/2009	10:59:11.000am	2D:	11.409	3D:	11.40	9	282.6	39	0.519
VEL:	_A__U:	19/08/2009	10:59:16.000am	2D:	11.368	3D:	11.36	8	282.0	90	0.312
VEL:	_A__U:	19/08/2009	10:59:21.000am	2D:	11.246	3D:	11.24	8	282.1	58	1.013
VEL:	_A__U:	19/08/2009	10:59:26.000am	2D:	10.361	3D:	10.36	2	282.5	64	0.468
VEL:	_A__U:	19/08/2009	10:59:31.000am	2D:	9.192	3D:	9.194	282.549	1.226		
VEL:	_A__U:	19/08/2009	10:59:36.000am	2D:	8.147	3D:	8.15	281.708	1.679		
VEL:	_A__U:	19/08/2009	10:59:41.000am	2D:	7.65	3D:	7.651	283.255	1.155		
VEL:	_A__U:	19/08/2009	10:59:46.000am	2D:	7.673	3D:	7.676	281.364	-1.534		
VEL:	_A__U:	19/08/2009	10:59:51.000am	2D:	7.751	3D:	7.751	280.089	0.171		
VEL:	_A__U:	19/08/2009	10:59:56.000am	2D:	7.814	3D:	7.815	280.664	-0.727		
VEL:	_A__U:	19/08/2009	11:00:01.000am	2D:	7.191	3D:	7.191	280.059	0.272		
VEL:	_A__U:	19/08/2009	11:00:06.000am	2D:	6.266	3D:	6.271	279.431	-2.137		
VEL:	_A__U:	19/08/2009	11:00:11.000am	2D:	4.988	3D:	4.988	280.763	-0.434		

Figure A.1: Raw GPS Data-1

Raw GPS Data (06-09-2009)

VEL: _A__U:	06/09/2009 10:35:16.000am	2D: 0.071	3D: 0.148	224.650	61.294
VEL: _A__U:	06/09/2009 10:35:21.000am	2D: 0.042	3D: 0.080	290.175	-58.279
VEL: _A__U:	06/09/2009 10:35:23.000am	2D: 0.013	3D: 0.043	261.504	71.948
VEL: _A__U:	06/09/2009 10:35:24.000am	2D: 0.012	3D: 0.079	21.999	81.563
VEL: _A__U:	06/09/2009 10:35:25.000am	2D: 0.033	3D: 0.034	126.328	-15.834
VEL: _A__U:	06/09/2009 10:35:26.000am	2D: 0.017	3D: 0.036	104.824	61.565
VEL: _A__U:	06/09/2009 10:35:27.000am	2D: 0.060	3D: 0.063	196.437	-18.723
VEL: _A__U:	06/09/2009 10:35:28.000am	2D: 0.025	3D: 0.039	349.583	50.833
VEL: _A__U:	06/09/2009 10:35:29.000am	2D: 0.018	3D: 0.023	314.109	39.078
VEL: _A__U:	06/09/2009 10:35:30.000am	2D: 0.068	3D: 0.087	271.739	39.035
VEL: _A__U:	06/09/2009 10:35:31.000am	2D: 0.079	3D: 0.147	33.076	-57.255
VEL: _A__U:	06/09/2009 10:35:32.000am	2D: 0.055	3D: 0.089	121.791	-51.194
VEL: _A__U:	06/09/2009 10:42:15.000am	2D: 1.750	3D: 1.752	100.619	2.409
VEL: _A__U:	06/09/2009 10:42:16.000am	2D: 2.267	3D: 2.270	102.544	-2.932
VEL: _A__U:	06/09/2009 10:42:17.000am	2D: 2.404	3D: 2.405	98.752	-1.060
VEL: _A__U:	06/09/2009 10:42:18.000am	2D: 2.696	3D: 2.697	97.574	-1.890
VEL: _A__U:	06/09/2009 10:42:19.000am	2D: 2.692	3D: 2.692	98.099	0.571
VEL: _A__U:	06/09/2009 10:42:20.000am	2D: 2.677	3D: 2.677	96.899	-0.290
VEL: _A__U:	06/09/2009 10:42:21.000am	2D: 3.270	3D: 3.272	92.720	-2.125
VEL: _A__U:	06/09/2009 10:42:22.000am	2D: 3.582	3D: 3.583	93.996	1.109
VEL: _A__U:	06/09/2009 10:42:23.000am	2D: 3.935	3D: 3.935	93.676	0.163
VEL: _A__U:	06/09/2009 10:42:24.000am	2D: 4.299	3D: 4.300	92.261	1.147
VEL: _A__U:	06/09/2009 10:42:25.000am	2D: 4.789	3D: 4.789	89.956	-0.429
VEL: _A__U:	06/09/2009 10:42:26.000am	2D: 5.353	3D: 5.355	87.335	1.511
VEL: _A__U:	06/09/2009 10:42:27.000am	2D: 6.120	3D: 6.120	88.731	0.317
VEL: _A__U:	06/09/2009 10:42:28.000am	2D: 6.319	3D: 6.320	91.306	0.559
VEL: _A__U:	06/09/2009 10:42:29.000am	2D: 6.785	3D: 6.785	92.218	-0.179
VEL: _A__U:	06/09/2009 10:42:30.000am	2D: 7.269	3D: 7.271	91.043	-1.385
VEL: _A__U:	06/09/2009 10:42:31.000am	2D: 7.751	3D: 7.751	90.543	0.143
VEL: _A__U:	06/09/2009 10:42:32.000am	2D: 8.265	3D: 8.265	90.660	0.598
VEL: _A__U:	06/09/2009 10:42:33.000am	2D: 8.722	3D: 8.723	89.878	-0.930
VEL: _A__U:	06/09/2009 10:42:34.000am	2D: 8.680	3D: 8.681	90.580	-0.406
VEL: _A__U:	06/09/2009 10:42:35.000am	2D: 8.301	3D: 8.301	91.228	0.218
VEL: _A__U:	06/09/2009 10:42:36.000am	2D: 7.947	3D: 7.947	90.526	0.021
VEL: _A__U:	06/09/2009 10:42:37.000am	2D: 7.370	3D: 7.371	91.162	-0.659
VEL: _A__U:	06/09/2009 10:42:38.000am	2D: 7.207	3D: 7.207	91.003	0.241
VEL: _A__U:	06/09/2009 10:42:39.000am	2D: 7.067	3D: 7.067	91.624	0.395
VEL: _A__U:	06/09/2009 10:42:40.000am	2D: 6.704	3D: 6.706	92.151	1.475
VEL: _A__U:	06/09/2009 10:42:41.000am	2D: 7.540	3D: 7.540	92.402	0.634
VEL: _A__U:	06/09/2009 10:42:42.000am	2D: 7.856	3D: 7.856	92.509	-0.042
VEL: _A__U:	06/09/2009 10:42:43.000am	2D: 8.187	3D: 8.187	92.376	0.443
VEL: _A__U:	06/09/2009 10:42:44.000am	2D: 8.162	3D: 8.162	92.236	-0.269
VEL: _A__U:	06/09/2009 10:42:45.000am	2D: 8.115	3D: 8.116	92.109	0.984
VEL: _A__U:	06/09/2009 10:42:47.000am	2D: 8.803	3D: 8.803	90.867	0.432
VEL: _A__U:	06/09/2009 10:42:49.000am	2D: 9.244	3D: 9.244	91.773	0.176
VEL: _A__U:	06/09/2009 10:42:50.000am	2D: 9.258	3D: 9.259	91.549	-0.656
VEL: _A__U:	06/09/2009 10:42:51.000am	2D: 9.126	3D: 9.127	90.134	-0.474
VEL: _A__U:	06/09/2009 10:42:52.000am	2D: 8.821	3D: 8.821	89.552	-0.651
VEL: _A__U:	06/09/2009 10:42:53.000am	2D: 8.609	3D: 8.609	90.321	0.444
VEL: _A__U:	06/09/2009 10:42:54.000am	2D: 8.587	3D: 8.587	90.496	-0.182
VEL: _A__U:	06/09/2009 10:42:55.000am	2D: 8.582	3D: 8.582	90.950	-0.249
VEL: _A__U:	06/09/2009 10:42:56.000am	2D: 8.866	3D: 8.867	91.765	-0.496
VEL: _A__U:	06/09/2009 10:42:57.000am	2D: 9.149	3D: 9.151	90.688	-1.025

Figure A.2: Raw GPS Data-2

Appendix B

Statistical Methods Used for Analysis of Data

This appendix presents in brief various statistical techniques that are used in this study. Though works of various past researchers have been referred (Wang et al., 2004; Maya et al., 2003; Mudgal et al., 2011; Nezamuddin et al., 2010; Shuo et al., 2002; Bham and Benekohal, 2002; Law and Kelton, 2007) to decide the type and nature of statistical tests to be carried out, Freund and Wilson (2011)'s book is a major source of reference for deciding the type, nature and method to apply a particular test. Some of the tests which are too complex to be done by hand calculator (for example Kolmogorov-Smirnov test), Matlab (2009) and Excel spreadsheet are used to arrive at the results of tests. Following sections present the brief overview of all such tests used in this work.

B.1 Hypothesis testing

A hypothesis usually results from speculation concerning the response resulting from observed behaviour and predicted (expected) behaviour. If the hypothesis is tested in terms of population parameters such as mean or variance, it is termed as *statistical hypothesis*. The procedures that enables us to agree or disagree with hypothesis is termed as *hypothesis testing*. Data from an experiment (sample) is used to test the hypothesis. Hypothesis testing starts from making two statements about the parameter in question. Two statements are mutually exclusive and exhaustive which means that one or the other statement must be true. The first statement is termed as *null hypothesis* denoted by H_0 and the other is termed as *alternative hypothesis* denoted by H_1.

Two statements are not treated equally. The null hypothesis which represents the status quo or the statement of "no effect", gets the benefit of doubt. The alternative hypothesis, which we are trying to establish, requires concrete mathematical evidence before we can conclude that it is correct.

B.1.1 Five step procedure for hypothesis testing

1. Specify H_0 and H_1 and an acceptable level of α, significance level, *i.e.* maximum acceptable probability of of rejecting a true null hypothesis.

2. Define a sample based test statistic and rejection region for specified H_0. Test statistic is a sample statistic whose sampling distribution can be specified for both the null and alternative case (though the sampling distribution when the alternative hypothesis is true can be quite complex). After specifying appropriate significance level α, the sampling distribution of this statistic is used to define the rejection region. It is computationally more convenient to express the rejection region in terms of a test statistic that can be computed directly to a table such as that of Normal Distribution. The test statistic can be;

$$Z = \frac{\bar{Y} - \mu}{\sigma/\sqrt{n}}$$

   This has standard normal distribution and can be compared with the values directly read from table.

3. Collect test data and calculate test statistic.

4. Make a decision to either reject or fail to reject the H_0. This decision will normally result in a recommendation for action.

5. Interpret the results in the language of a problem.

B.2 Analysis of Variance (ANOVA)

When we are interested in testing the statistical hypothesis of equality of mean of set of population, ANOVA can be used. The purpose of ANOVA is to compare sample means of t populations, $t \geq 2$ based on independently drawn random samples from these populations. We assume sample size on n are taken from population i, $i = 1, 2, ...t$. An observation from such set of data denoted by y_{ij}, $i = 1, 2, ...t$ and $j = 1, 2, ...n$. There are a total of $\sum n_i$ observations.

If we denote by μ_i the mean of the i_{th} population, then the hypothesis of interest are;

$H_0 : \mu_1 = \mu_2 = ... = \mu_t$

H_1 : at least one equality is not satisfied

The data set can be listed as presented in Table B.1.

Table B.1: Notation for one way ANOVA

Factor Levels	Observations	Totals	Means	Sums of Squares
1	$y_{11}\ y_{12}\ \cdots\ y_{1n_1}$	Y_1	$\bar{y_1}$	SS_1
2	$y_{21}\ y_{22}\ \cdots\ y_{2n_2}$	Y_2	$\bar{y_2}$	SS_2
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
t	$y_{t1}\ y_{t2}\ \cdots\ y_{tn_t}$	Y_t	$\bar{y_t}$	SS_t
Overall		$\sum_j Y_{ij}$		

The factor level sums are calculates as,

$Y_i = \sum_j y_{ij}$

and factor level means are calculated as,

$\bar{y_i} = \frac{Y_i}{n_i}$.

The overall total is,

$Y. = \sum Y_i = \sum_i \left[\sum_j (y_{ij})\right]$.

The overall mean is,

$\bar{y}. = \frac{Y.}{\sum_i (n_i)}$.

For calculating variance, we first calculate corrected Sum of Squares for each factor level,

$SS_i = \sum_j y_{ij} - {y_i}^2$ for i = 1,...,t

and pooled Sum of Squares is calculated as,

$SS_p = \sum_i SS_i$.

which is divided by pooled degrees of freedom to get Variance,

$s_p^2 = \frac{SS_p}{\sum n_i - t}$

where, s_p^2 is the variance of each sample.

The 'F' distribution describes the distribution of a ratio of two independent estimates of a common variance. The variance can be calculated using sample means as, $s^2_{means} = \sum (\bar{y}_i - \bar{y}.)^2/(t-1)$. This quantity is an estimate of $\frac{\sigma^2}{n}$. Hence, ns^2_{means} is an estimate of σ^2. Hence, $ns^2_{means} = n\sum (\bar{y}_i - \bar{y}.)^2/(t-1)$. Therefore, the ratio, $(\frac{ns^2_{means}}{s_p^2})$ has the 'F' distribution with degrees of freedom (t-1) and t(n-1).

The nature of sampling distribution of the statistic $(\frac{ns^2_{means}}{s_p^2})$, when H_0 is true forms the basis of hypothesis test. The test statistic is the ratio of two variance estimates, and the value of this ratio leads to the rejection of null hypothesis are those that are larger than the values of 'F' distribution for the desired significance level. That is the procedure for testing the hypothesis,

$H_0 : \mu_1 = \mu_2 = ... = \mu_t$

H_1 : at least one equality is not satisfied

is to reject H_0 if the calculated value of
$F = \frac{ns^2_{means}}{s^2_p}$
exceeds α right tail of 'F' distribution with (t-1) and t(n-1) degrees of freedom.

B.3 Kolmogorov-Smirnov test (K-S test)

There are formal tests for the null hypothesis that a set of values is from a specified distribution, usually normal. Such tests are known as **Goodness of Fit Tests**. One such test is Kolmogorov-Smirnov test. It compares the observed cumulative distribution with the cumulative distribution of normal, measuring the maximum difference between the two. This is a tedious calculation to be tried by hand. Hence in present work the K-S test is carried out using Matlab (2009).

Syntax

$h = kstest2(x_1, x_2)$

$h = kstest2(x_1, x_2, alpha, type)$

$[h, p] = kstest2(...)$

$[h, p, ks2stat] = kstest2(...)$

Description

$h = kstest2(x1, x2)$ performs a two-sample Kolmogorov-Smirnov test to compare the distributions of the values in the two data vectors x1 and x2. The null hypothesis is that x1 and x2 are from the same continuous distribution. The alternative hypothesis is that they are from different continuous distributions. The result h is 1 if the test rejects the null hypothesis at the 5% significance level; 0 otherwise.

The test statistic is:

$\max\left(|F1_{(x)} - F2_{(x)}|\right)$

where $F1_{(x)}$ is the proportion of x_1 values less than or equal to x and $F2_{(x)}$ is the proportion of x_2 values less than or equal to x.

h = kstest2(x1,x2,alpha) specifies the significance level alpha for the test. The default is 0.05.

h = kstest2(x1,x2,alpha,type) specifies the type of test using one of the following values for the string type:

- 'unequal' Tests the alternative hypothesis that the population cdfs are unequal. This is the default.
- 'larger' Tests the alternative hypothesis that the first population cdf is larger than the second population cdf. The test statistic does not use the absolute value.
- 'smaller' Tests the alternative hypothesis that the first population cdf is smaller than the second population cdf. The test statistic does not use the absolute value.

[h,p] = kstest2(...) also returns the asymptotic p-value p. The asymptotic p-value becomes very accurate for large sample sizes, and is believed to be reasonably accurate for sample sizes n1 and n2 such that $(n1 * n2)/(n1 + n2) \geq 4$.

$[h, p, ks2stat] = kstest2(...)$ also returns the p-value p and the test statistic ks2stat.

B.4 Student's t-test

The t-distribution with 'v' degrees of freedom takes form,

$$t(v) = \frac{Z}{\sqrt{\frac{\chi^2(v)}{v}}},$$

where, Z is the standard normal random variable and $\chi^2(v)$ is an independent χ^2 random variable with v degrees of freedom. Using this definition we can develop he sampling distribution of the sample mean when the population variance, σ^2 is unknown. The test statistic can be compared with standard t-distribution from table.

B.5 Test of normality

The for a sample, normal bell shaped distribution can be ensured as below;

- The interval $(\bar{y} \pm \sigma)$ contains 68% of observations.

- The interval $(\bar{y} \pm 2\sigma)$ contains 95% of observations.
- The interval $(\bar{y} \pm 3\sigma)$ contains virtually all the observations.

where, $\bar{y}$ is sample mean of average speed values and σ is standard deviation of average speed.

B.6 Residual Sum of Squares (RSS)

The estimated regression line is defined as;

$$\hat{\mu}_{y|x} = \hat{\beta}_0 + \hat{\beta}_1 x$$

where, $\hat{\mu}_{y|x}$ is an estimate of y for any given x. $\hat{\beta}_0$ and $\hat{\beta}_1$ are the model parameters estimated such that the difference between observed value and predicted value is minimum. The residues are the differences between observed and predicted responses. Minimizing the squares of these residues is the essence of **least square criteria**. Any proposed relationship can be weighted on the basis of minimum squared residuals, **Residual Sum of Squares (RSS)**. RSS can be calculated as;

$$RSS = \sum (y - \hat{\mu})^2$$

where, y is the observed value of response and $\hat{\mu}$ is the expected value of response.

B.7 Residual plots

The residues are the difference between observed response and predicted response. Residual plot is a scatter plot of residues on *y-axis* and predicted values of response on *x-axis*. If the data is collected over time, the residues are also plotted against time. A regression model that has no violations of errors, will have a residual plot that appears roughly as a horizontal band around *x-axis*.

B.8 Model diagnostic

The linear regression model is based on several assumptions. Regression diagnostic is looking for one or more of the following form of potential problems (Freund and Wilson (2011); Pruim (2010)).

1. Problems with the errors.

   The linear model assumes that the errors are,

   a. independent

   b. normally distributed, and

   c. homoscedastic (i.e., they have equal variance).

   Any or all these assumptions can be violated in a given situation.

2. Problems with the fit.

   Structural part of the model assumes that true relationship between response and predictor is linear but it can be otherwise.

3. Problems with unusual observations.

   It is possible that small number of data points have a disproportionately large influence on fit. This may result in mistaken strength of relationship.

4. Failure to include important variables.

   All variables required to obtain good model are not include.

Diagnostic procedures can be graphical as well as numerical. Graphical procedures are handy since they cover broader range of problems (Pruim, 2010). The graphical diagnostic procedures include:

- Residual plots,
- Observed and predicted value plots, and
- Box plots of residues.

The numerical procedures include

- Comparing the means of observed acceleration (calculated using observed speed data) and modeled acceleration, using paired t-test, and
- Post Hoc Fisher's Least Significant Difference (LSD) method.

B.9 Post Hoc Fisher's Least Significant Difference (LSD) method

The procedure for making all possible pairwise comparisons is attributed to Fisher (1933) and is known as **Least Significant Difference (LSD)** test. It performs **t-test** for each pair of means using **Within Mean Square, MSW** as estimate of σ^2. The **LSD** is calculated as;

$$LSD = t_{\alpha/2}\sqrt{\frac{2 \times MSW}{n}}$$

where, $t_{\alpha/2}$ is the $\alpha/2$ tail probability value from t-distribution, MSW is Within Mean Square, n is degree of freedom, same as associated with calculation of variance. The LSD procedures declares as significantly different any pair of means for which the difference between the sample means exceeds the computed LSD value.

It is found that since the experiment wise error tends to become higher than comparison wise error, some control over the application of test is required. Hence it is strongly recommended that the LSD procedure be implemented only if the hypothesis of equal means is rejected by ANOVA. This two step procedure is termed as **protected LSD test**.

Appendix C

Driver Response Sheet

Driver Reponse Sheet

Date	21/8/2009	Time	9:07 AM	Location	Highway-Exp
Surveyer Name:	Harish		Weather condition	Dry	
From no.	22				
Direction of flow	←				

Format for driver information

Name of driver	Kartar Singh	
Age	35 yrs	
Qualification	7th std.	
Driving Experience (yrs)	8 yrs	
Driving Lincense (Yes/No)		
Family background	married	Unmarried
	✓	
Financial status (monthly income)		10,000/-
Average driving hours (per day)		8 hours
No. of accidents in last 5 years		NIL
Capacity in case of goods carriage		10 t
Occupancy (no. of persons) (standard)		02
Occupancy (observed)		02

actual load= 12 t

Vehicle type	Truck ✓	Trailer	Car	Two wheeler	Tractor	Auto rickshaw	HCV	LCV	BUS	Minitruck	Tempo
Company	Tata										
Registration no	CG-04-JA 5866										
Model											

Figure C.1: Driver response sheet to collect driver and vehicle characteristics