Speed and Acceleration Characteristics of Different Types of Vehicles on Multi-Lane Highways

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Abstract

This paper presents speed and acceleration characteristics of different types of vehicles on four-lane and six-lane divided highways under mixed traffic conditions. These characteristics are very intrinsic to the particular vehicle category plying on a roadway. Speed and acceleration data were collected on six sections of four-lane divided inter-urban highways and two sections of six-lane divided highways in India. Mean speeds of standard cars and big utility cars are compared using two tailed t-test and are found to be different on four-lane highway with earthen shoulders and paved shoulders. Average mean speeds of standard car are also compared on two classes of highway. F-test indicates that the mean speed of standard cars on six-lane divided highway is significantly higher than that on four-lane highway. Acceleration data were collected using GPS based V-Box device, and speed-acceleration profiles are established for each type of vehicle. Average acceleration of a vehicle is related with speed through an exponential relationship. Average acceleration rate of standard car on six-lane highway is found significantly different from that on four-lane divided highway. Acceleration of heavy vehicle is examined in three different loading conditions and relations are established for calculating average and maximum acceleration of a vehicle type at the given operational speed.

Keywords: Speed, Acceleration, Highway, Heavy vehicles, Distribution.

1. Introduction

Speed of vehicles on a highway indicates the quality of service experienced by motorists. The speed is discriminated into different elements such as average mean speed, design speed, free-speed, operating speed, and upper and lower posted speeds. On a highway, design speed is the main criterion for setting the speed limits and posted speed is usually lower than the design speed because it is the driver's desired speed. Speed of vehicles on a highway is affected by various factors, but the most prominent are traffic volume and traffic composition. In a mixed traffic situation of the type prevailing in India, speed is considerably influenced by composition of traffic stream. Both free-flow and operating speeds play important part in assessment of highway capacity and level-of-service. The higher the speed variation, greater will be the

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interactions among vehicles, resulting bias in determining speed limits for design of highway facility. Along with speed, acceleration characteristics of vehicles are also important considerations for various highway design and construction aspects. Acceleration characteristics of vehicles vary with their average speed, power to weight ratio, type of gear transmission and loaded and unloaded states. Standard applications of acceleration characteristics are used in determining the length of acceleration lanes and in providing adequate sight distance for accelerating vehicle to pass on two-lane roads. Several acceleration models have been developed in the past to capture the driver behavior in different traffic flow conditions (Bham and Benekohal, 2002). Acceleration characteristics in standstill condition, during overtaking, lane-changing, car-following and under free-flow traffic condition are important in simulation studies also (Dey et al., 2008). When a vehicle starts from rest it takes medium to maximum acceleration rates due to the force available at rest to exceed the tractive effort by friction between tires and pavement. However, motorists rarely experience the maximum accelerations on multilane highways except in emergencies. Vehicle acceleration capability during overtaking is also important aspect to ascertain overtaking sight distance. Most of the drivers overtake and give pass to the vehicles at sub-maximal range of accelerations. The overtaking vehicle accelerates till the completion of overtaking operation. The average rate of acceleration during overtaking operations is also correlated with the overtaking time (Shukla and Chandra, 2011). This study presents the speed and acceleration characteristics of different types of vehicles on inter urban multilane highway under mixed traffic conditions. In the case of heavy commercial vehicle (trucks), the effect of load carried by the truck on its acceleration capability is also demonstrated.

2. Background Literature

Speed and acceleration characteristics are very intrinsic to the vehicle class and prevailing traffic conditions. Some empirical relationships are explained based on the experimental studies on free-speed and operating speed on highways. Dixon et al. (1999) applied Highway Capacity Manual (HCM) methodology to estimate posted speed limit on rural multilane highway in Georgia. Authors opined that the posted speed limits directly influence the free-flow speeds and operating speeds on highway. Further, speed limits for 89 and 105 km/h confirmed to the normal distribution and observed free flow speed in daylight was greater by 1% than in night. Fitzpatrick et al. (2002) found strong relationship between deign speed, operating speed and posted speed. Hunt et al. (2004) studied the effect on driver speeds after increasing the posted speed limit from 100 km/h to 110 km/h on rural four-lane highway in Saskatchewan. Tseng and Lin (2005) developed speed models to estimate harmonic mean and time-mean free-flow speed. They found a high correlation between time-mean speed and harmonic mean speed. Speed characteristics and equivalency unit for motorcycle traffic have been investigated by Minh et al. (2005) also to resolve the problem in speed and flow measurements due to high proportions of two-wheelers in traffic stream. Speed characteristics were found to be influenced by the presence of non-motorized vehicles under mixed traffic conditions. Dey et al. (2006) proposed unimodal (S-shape) and bimodal curves for speeds on two-lane roads in India. The speed data collected at 17 locations were analyzed to evaluate the distribution parameters. They introduced a parameter called spread ratio to predict the nature of bimodality in the speed data. Velmurugan et al. (2011) determined the free-speed for assessment of road users cost on

high-speed multilane carriageways in India. They observed that free-speed of heavy vehicles and autos were significantly higher on six-lane roads when compared with four-lane roads. However, the average speed on eight-lane roads was not different from that on six-lane roads. Shukla and Chandra (2011) analyzed the speed data collected on four-lane divided highways and estimated the speed parameters used to define variation in speed data on multilane highways.
Most of the studies on acceleration characteristics have been performed in developed countries. John and Kobett (1978) found the acceleration rates as linearly decreasing function of speed. The maximum and standstill acceleration was 3.36 m/s^2 and 5.19 m/s^2 for passenger car and heavy vehicle respectively. The rate of change of acceleration with respect to speed was higher for heavy vehicle than car. Wang et al. (2004) collected field data to analyze acceleration rates of different vehicles using Global Positioning System (GPS) and developed a quadratic relationship between acceleration and speed for straight and turning maneuvers. Kumar and Rao (1996) found a good relation between acceleration rates and overtaking time on two-lane roads. Long (2000) measured acceleration characteristics of starting vehicles in Florida and design accelerations were found to deviate substantially from observed accelerations. At start of the motion, observed accelerations were about 15% higher for passenger cars and 45% higher for trucks than design accelerations. Bham and Benekohal (2002) proposed a dual regime constant acceleration model which provides higher value of acceleration rate at lower speed and lower acceleration rate at higher speed. Dey et al. (2008) studied acceleration characteristics of vehicles on two-lane roads in India. Acceleration of vehicle starting from rest and during overtaking was estimated and relationships were developed between the rate of acceleration and overtaking time for different category of overtaking vehicles. Maximum, average and minimum acceleration rates were determined by fitting a third degree polynomial to the distance-time profile using least square technique. Bokare and Maurya (2011) presented the acceleration behavior through manual gear transmission (MGT) of a vehicle and fitted the data from first to fourth gear as polynomial. For fourth to fifth gear transmission, linear variation was found. Brooks (2012) determined acceleration characteristics of various vehicles at starting from rest, and during overtaking operations. All studies described above have taken car as subject vehicle for studying the variation in speed and acceleration on a highway. A few authors have considered heavy vehicle also and described speed and acceleration characteristics of both cars and heavy vehicles. In a mixed traffic situations prevailing in developing nations like India where other categories of vehicles are also present in the traffic stream, understanding of speed and acceleration characteristics of all vehicles types become important for proper design of a roadway. The present study demonstrates the effect of vehicle category on speed and acceleration on four-lane highways in India.

3. Field Data on Speed

Speed data for the present study were collected on six sections of four-lanes divided inter urban highways, three with earthen shoulders and three with paved shoulders, and two sections of six-lane highways with paved shoulders. The site for data collection was chosen such that there is no effect of access point, intersection or any other side friction. A longitudinal trap of 60 to 80 m was made on one side of carriageway and video recording was done on typical weekdays for 10-16 hours on each highway. The video film was later replayed on a wide screen monitor in laboratory and speed data with classified volume count was extracted. The speed of a vehicle was determined by noting the time taken by the vehicle to cross the longitudinal trap length using a stop watch of 0.01s accuracy. Extracted data were decoded into a spread sheet for further analysis. Traffic on Indian highways is mixed in nature and even within the same category of car, there are several models on the road with varying operating conditions. All vehicles were therefore, divided into four categories namely standard car (CS), big utility car (CB), heavy vehicle (HV) and motorized two-wheelers (TW). The standard car in the present study is defined as a passenger car having 3.6 m length and 1.5 m width, and engine power up to 1400 cc. The big utility car (CB) is the one having length 4.45 m and width 1.8 m, and the engine power up to 2500 cc. The dimensions of different vehicle types and their average proportions in the traffic stream are given in Table 1.

Table 1: Vehicle, categories and traffic composition observed in field

Vehicle type	*Vehicle designation*	*Length (m)*	*Width (m)*	*Average proportion in flow (%)*		
				Four-lane Shoulders		*Six-lane*
				Earthen	*Paved*	
Standard car	CS	3.60	1.50	40	42	55
Big utility car	CB	4.45	1.80	17	15	27
Motorized 2-wheeler	TW	1.87	0.64	05	13	13
Heavy vehicle	HV	10.10	2.50	38	30	05

Analysis of Speed Data

Speeds of individual categories of vehicles were analyzed and distribution profiles were created for each section. The parameters such as mean, standard deviation and percentile limits were estimated from these profiles on four-lane and six-lane highways. These speed parameters for four-lane highways as calculated from cumulative curves (Figure 1) are given in Table 2.

Table 2: Speed parameters for four-lane divided highways

Shoulder type	*Vehicle type*	*Speed parameters (km/h)*					
		Maximum	*Minimum*	*Average*	*σ*	*Percentile speed*	
						15th	*85th*
Earthen	CS	98.8	30.3	63.5	12.2	45.2	82.1
	CB	102.8	26.1	60.5	14.3	39.1	81.4
	TW	103.3	34.9	59.3	15.1	36.6	81.5
	HV	87.4	23.4	47.2	13.1	27.6	66.8
Paved	CS	103.0	32.2	67.7	11.7	50.1	85.2
	CB	102.2	34.4	66.0	11.5	48.3	82.9
	TW	100.3	36.8	68.7	7.8	47.0	80.3
	HV	80.1	18.5	50.4	8.6	37.6	63.3

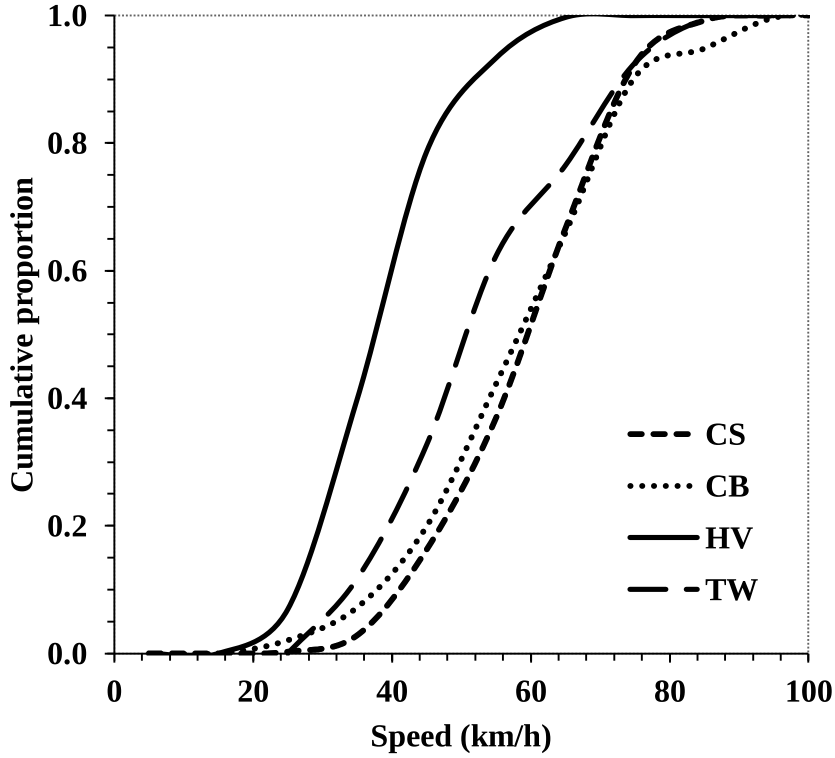

Figure 1: Speed curves on four-lane divided highway with earthen shoulders

Figure 1 shows that speed curves for CS and CB are quite close to each other and mean speeds (50^{th} percentile) for two types of vehicle are almost same, but their 15^{th} percentile speed are quite different. Speed curve for heavy vehicle is quite steep indicating less variation in their speed as compared to other categories of vehicles. Further, average speed of vehicles improved considerably when shoulders are paved (Table 2). Speed data collected on six lane sections were also analyzed in the same manner and results are shown in Figure 2.

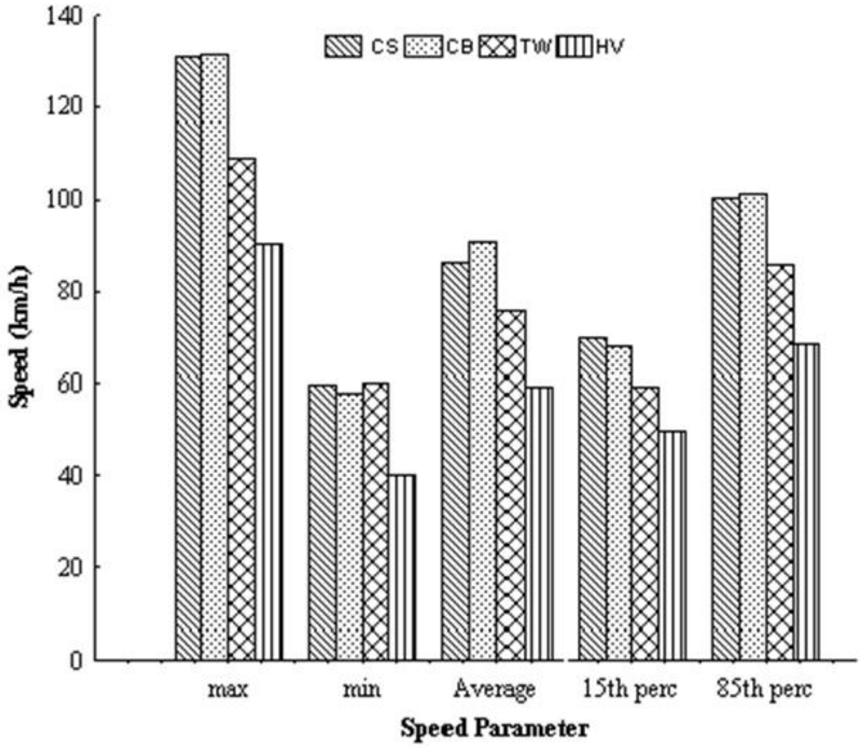

Figure 2: Speed parameters for different vehicle types on six-lane divided highway

Speeds of vehicles on four-lane and six-lane divided highway are compared to know if there is any significant improvement in speed on wider roadway or if provision of paved shoulders on a four lane road has any effect on speed of vehicles. Two-tailed t-test was conducted to compare the mean speed of cars on four-lane divided highways with earthen and paved shoulders. The null hypothesis is that mean speed is not influenced by the shoulder type. Table 3 shows the results of t-test performed for comparing mean speeds of standard, big utility cars and heavy vehicle. The calculated value of t statistics is 2.8 against the critical value of 1.96 at 95 % level of confidence. It implies that the speeds of cars are different on sections with earthen shoulders and paved shoulders, and hence the null hypothesis is rejected. But no significant difference is observed in average speed of heavy vehicle on highways with earthen or paved shoulders.

Table 3: Results of t-test for comparing mean speed of vehicles on four-lane highway

Vehicle type	*CS*		*CB*		*HV*	
Shoulder type	*Paved*	*Earthen*	*Paved*	*Earthen*	*Paved*	*Earthen*
Mean (km/h)	67.7	63.5	66.0	60.5	50.4	47.2
Variance	285.4	144.9	337.0	221.4	107.8	82.0
Observations	636	382	450	260	593	465
$t_{0.05}$	2.80		2.86		1.64	
$t_{critical}$ (two-tailed)	1.96		1.96		1.96	
Remarks	Significant		Significant		Not significant	

F-test was performed to compare the speed variance of standard car (CS) on two highway classes. The F hypothesis testing utilized to examine whether speed variance between two types of cars are equal on two different highways class. Each pair would have equal variance, if $F_{calculated} \leq F_{critical}$. The variances are compared between speed data of standard car that was observed on six-lane and four-lane highways paved shoulders a shown in Table 4. The comparative test of variance concludes a significant difference in speed of standard car on two class of highway at 95 % confident level. Similar analysis was done for other categories of vehicles also and two speeds were found to be different. It indicates that speed of vehicle is higher on six-lane road than on a four-lane road.

Table 4: Results of F-test for test on speed variance between four-lane and six-lane highways

Highway class	*Six-lane*	*Four-lane*
Shoulder type	Paved	Paved
Mean (km/h)	85.7	66.1
Variance	196.8	285.5
Observations	331	636
$F_{0.05}$	1.45	
$F_{critical}$	1.17	
Remarks	Difference is significant	

4. Acceleration Data

Acceleration data for this study were collected on selected sections of four-lane and six-lane divided highways using GPS based V-BOX device which is mounted on a vehicle. The important data pertaining to vehicles profile is related to the parameters that controls the vehicular longitudinal and lateral movements recorded at a small interval. The GPS receives constant information from satellite that measures the movement and position of the vehicle at every instance. Based on a range of high performance GPS receivers, V-box data loggers measure speed, distance, acceleration and braking distance with a high degree of accuracy. A number of runs were made on a highway and kinematic data were recorded at 0.1 s interval. Run reports were generated in the laboratory using V-BOX analysis software. The speed data of each vehicle type were generated at one second interval and maximum, average and minimum acceleration was obtained from these data. Average acceleration rates were analyzed to see its variation with speed. The attempt was made to capture the acceleration for whole range of speed for each type of vehicle. The acceleration behavior of vehicle types CS, CB and HV are considered for the analysis. Acceleration behavior of HV is expected to be different in loaded and unloaded conditions. Therefore, data for three conditions such as empty, half loaded and fully loaded HV were recorded to measure average acceleration.

Analysis of Acceleration Data

Vehicle acceleration characteristics are analyzed at different sections of four-lane and six-lane divided highways. For a vehicle type, maximum and average acceleration was measured at different speeds, from a standstill condition to the higher speed. Average acceleration profiles for the standard car (CS) on four-lane highway and six-lane are shown in Figure 3 and 4 respectively.

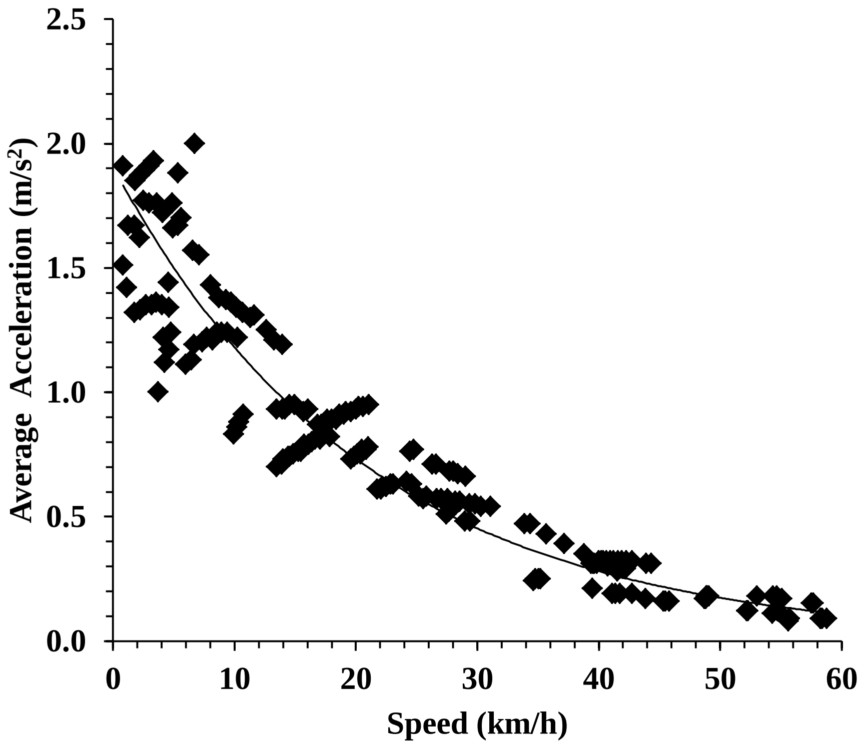

Figure 3 Acceleration profile for CS on four-lane divided highway

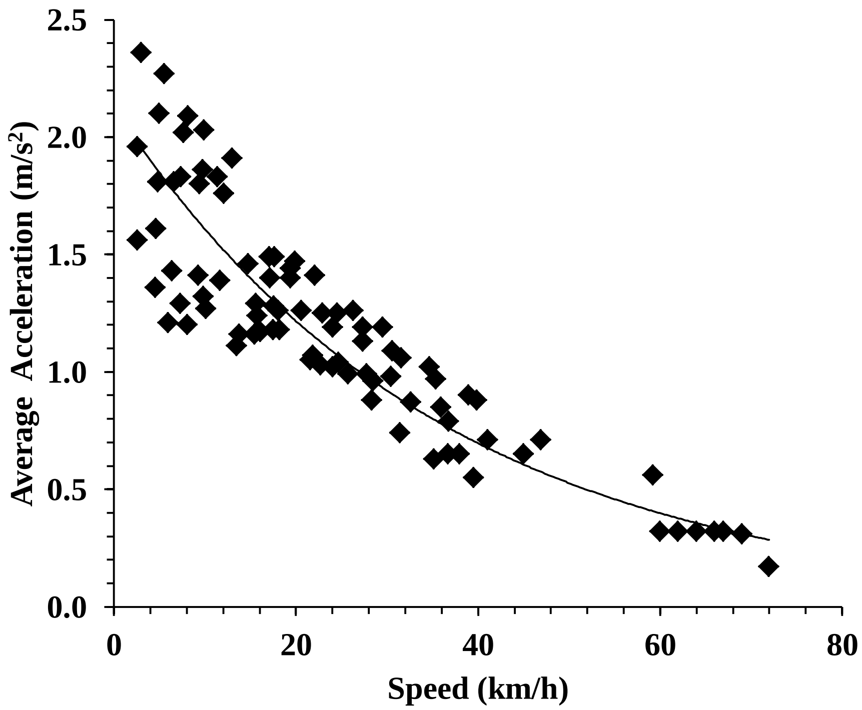

Figure 4 Acceleration profile for CS on six-lane divided highway

Acceleration of a vehicle is higher in initial gears (low speed) and it reduces as the speed increases. Average acceleration rate of a vehicle observed at six-lane highway is compared with that on four-lane highway using F-test of significance at 95 % confidence level. The two accelerations were found significantly different. The sample calculations are shown in Table 5 for vehicle type CS.

Table 5 F-test for comparing acceleration of standard car on two highway class

Highway class	*Six-lane*	*Four-lane*
Variance	0.23	0.24
Observations	87	55
Calculated $F_{0.05}$	0.98	
Critical $F_{0.05}$	0.67	
Remarks	Difference is significant	

The average acceleration is found to decrease exponentially with increase in speed whereas the maximum acceleration decreased linearly with speed. The equations for average acceleration and maximum acceleration are developed for different vehicle types at different speeds.

The general form of these models are given in Equation (1) and (2) respectively.

$$a_{av} = ae^{bv} \tag{1}$$

$$a_{max} = c + dv \tag{2}$$

where,
a_{av} = average acceleration, m/s^2
a_{max} = maximum acceleration, m/s^2
v = speed of vehicle, m/s
a,b,c and d = constant

The value of constants for two categories of vehicles viz. CS and CB are given in Table 6.

Table 6 Constants for maximum and average accelerations

Vehicle category	*Six-lane road*				*Four-lane road*			
	c	*d*	*a*	*b*	*c*	*d*	*a*	*b*
CS	3.68	-0.03	1.90	-0.04	3.80	-0.07	1.70	-0.04
CB	4.02	-0.05	2.03	-0.03	3.32	-0.06	2.03	-0.04

Maneuverability of heavy vehicles (truck) is different in loaded and unloaded state. Therefore, acceleration of heavy vehicles was examined in three different loading

conditions; empty, half loaded and full loaded. It is shown in Figure 5. The exponential line is fitted between average acceleration and speed of HV in three different loading states as shown in Figure 5.
The relations as given below developed from the fitted acceleration profiles of heavy vehicle in empty, half loaded and full loaded conditions, respectively.

For empty HV $a_{av}=2.19e^{-0.03v}$ (3)

For half loaded $a_{av}=1.65e^{-0.04v}$ (4)

Full loaded HV $a_{av}=0.98e^{-0.03v}$ (5)

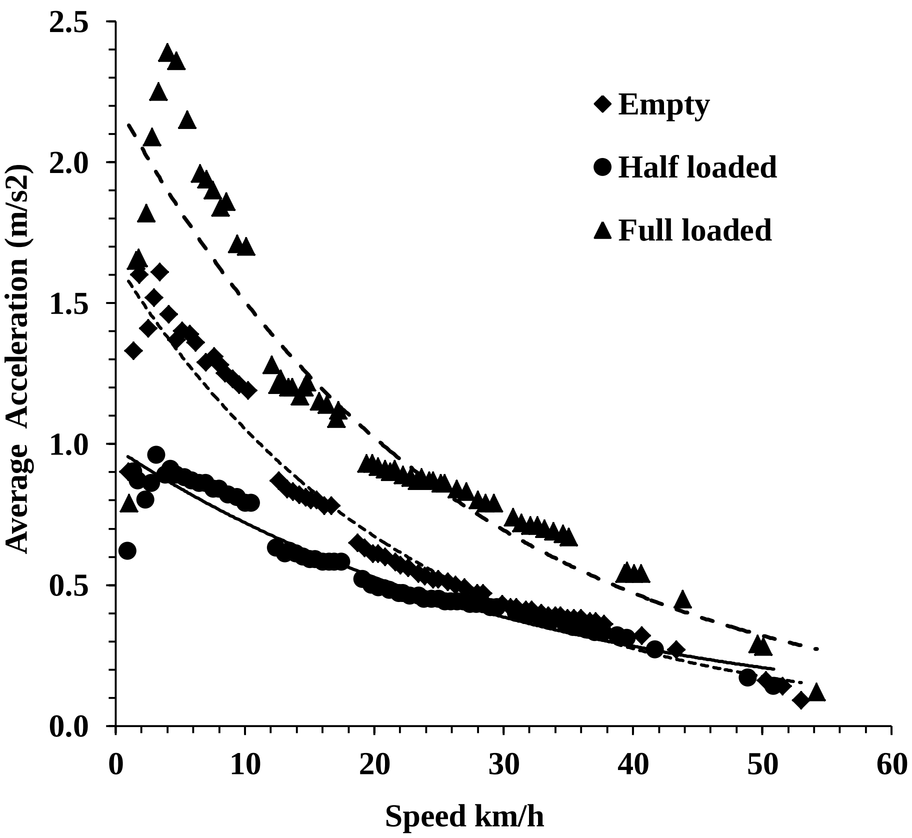

Figure 5 Acceleration of HV on four-lane divided highway

The acceleration profiles of trucks were also plotted on six-lane divided highway and no significant difference was observed between acceleration on four-lane and six-lane roads. Therefore, these results are not presented here.

5. Conclusions

The present paper demonstrates the speed and acceleration characteristics of vehicles on multilane highways in India. Speed and acceleration data were collected on four-lane and six-lane highways and are analyzed separately for each type of vehicle. Average

speeds of standard car (CS) are found marginally lower than those of big cars on four-lane highways. t-test was conducted to compare the mean speeds of these two vehicles on four-lane divided highway with paved and earthen shoulders. The results show that the mean speeds of standard car and big car on four-lane divided highways with earthen shoulders are significantly different from those on highway with paved shoulders at 95 % confidence level. Similarly, comparative test of variance resulted in a significant change in speed of standard car on six-lane highway and on four-lane highway at 95 % confidence level.
Acceleration characteristics of vehicles have also been examined at different speeds. Acceleration of a vehicle type is higher in initial gears and reduces as speed increases. Average acceleration of a vehicle on six-lane highway is found significantly different from that on four-lane divided highway. The average acceleration is related to speed by an exponential relation, whereas the measured maximum acceleration for the vehicle type is linear with respect to the speed. The new outcome of this study is the acceleration of heavy vehicles with speed under different conditions of their weight. Three cases are considered; empty, half loaded and full loaded, and acceleration rates are different in all three cases. Mathematical relations are developed for calculating acceleration of a vehicle at a given operating speed. Results of this study are very useful for development of simulation program of traffic flow under mixed traffic conditions on inter urban highways. Further study may include few sections of eight-lane highways to understand the effect of number of lanes on speed distribution curves and acceleration characteristics of different type of vehicles.

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