Development of free-speed equations for assessment of road-user cost on high-speed multi-lane carriageways of India on Plain Terrain

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The major factor affecting road-user costs (RUC) is the speed at which vehicles operate on roads which in turn determines fuel consumption and other cost components per unit distance travelled. Thus vehicular speed plays a significant role in highway economic evaluation. In the last decade, the Government of India has been involved in road capacity augmentation by building high-speed corridors to link major cities through the implementation of National Highway Development Programme (NHDP) projects such as Golden Quadrilateral, North–South, East–West, Expressway and Port Connectivity corridors. These recent radical changes in road network coupled with enhanced vehicle technology have resulted in huge variations in speed on these highways which has made it essential to evaluate the changing speed characteristics which are important inputs in estimation of RUC. An attempt is made in this article to study the speed characteristics on high-speed multi-lane corridors in plain terrain considering both straight and curved sections spread across the country. From the collected data, free-speed profiles of different vehicle types on high-speed corridors of India are developed and subsequently free-speed equations are developed considering the effect of roadway roughness.

Keywords: Free speed, free-speed equations, multi-lane high-speed corridors, roadway roughness, road-user cost.

Preamble

INDIA has one of the largest road networks in the world, covering around 3.5 million km at present. For the purpose of management and administration, roads in India are divided into five categories, viz. National Highways (NH), State Highways (SH), Major District Roads (MDR), Other District Roads (ODR) and Village Roads (VR). Basically, NHs are intended to facilitate medium- and long-distance inter-city passenger and freight traffic across the country. And they are also the main arterial roads which run through the length and breadth of the country connecting sea ports, state capitals, major industrial and tourist centres. NHs constitute less than 2% of the total road network, but carry nearly 40% of the total road traffic. The road infrastructure and available transport services in the country are highly inadequate for achieving fast movement of passenger and goods movement in comparison with the situation in the developed world. Many sections of the highways are in need of capacity augmentation, pavement strengthening, rehabilitation of bridges, improvement of riding quality, provision of traffic safety measures, etc. Further, the road sections passing through towns are congested where bypasses are essentially required and thus the above inadequacies of the transport systems continue to be a major impediment for economic growth. The gross inadequacies in the NH network are contributing to the high incidence of traffic congestion during peak hours caused by heterogeneity in traffic mix and thus resulting in huge economic losses in terms of high road-user cost (RUC) and also accounting for the high rate of road accidents as well.

Realizing the above-mentioned shortcomings in the transport sector, the Government of India has initiated a massive highway construction programme during the last decade termed as the National Highway Development Programme (NHDP) projects which encompass the Golden Quadrilateral, North–South, East–West corridors and in addition, the Port Connectivity and Expressway corridors linking major cities/activity centres. This has led to a gradual growth in the quantum of NH network which was around 22,255 km in 1951 and has risen to 70,934 km as on March 2010 (ref. 1). Moreover, the automobile industry and road design standards in India have also undergone tremendous changes during the last decade. These radical changes in vehicle technology coupled with road network capacity augmentation have resulted in huge variations in vehicular speeds on these highways. In 1982, free-speed studies were carried out on different carriageway widths covering varying geographical terrains (i.e. plain, rolling and hilly) as a part of the RUCS and they have been subsequently updated in 1992

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and 2001. These studies will be referred here onwards as RUCS-1982 (ref. 2), URUCS-1992 (ref. 3) and URUCS-2001 (ref. 4) respectively. As the condition of highways and vehicles have undergone tremendous changes, RUC models of the past studies[2–4] would not yield realistic results from economic evaluation of high-speed road network. In this article, an attempt has been made to study the free-speed characteristics on high-speed corridors of India in plain terrain covering both straight and curved sections. The term 'high-speed multi-lane corridors' used here implies four-lane, six-lane and eight-lane divided inter-city highways. In order to assess these characteristics, free-speed data was extensively collected spread over different regions of the country. From the collected data, free-speed profiles of different vehicle types on the above corridors are assessed and subsequently free-speed equations are developed considering road geometry.

RUC is an important and most significant input parameter for carrying out economic evaluation of highway projects and free-speed itself is a fundamental component to determine vehicle operating cost (VOC) and subsequently RUC. Hence, the outcome of the study, i.e. free-speed equations is expected to form an important input for developing RUC models exclusively for varying types of multi-lane highways. An overview of free-speed studies carried out at both international and national levels is presented in the next section emphasizing the influencing factors of free speed. The details about free-speed data collected at various sections are discussed in another section along with the adopted methodology. The estimated results from free-speed analysis are also dealt with. The development of free-speed equations for different vehicle types covering different multi-lane highways is summarized in the penultimate section. Finally, the conclusions of this study along with the study limitations are discussed in the last section.

Free speed

General

Speed is the main measure of performance of road segments, since it is easy to understand and measure, and is an essential input to RUC in economic analysis[5]. The free-speed of any vehicle can be defined as the speed adopted by the driver when not restricted by other vehicles in the stream under a given set of highway and environmental conditions[6]. Generally, free-speed conditions exist when traffic flow is very low (free-flow conditions) and drivers will have a fair degree of freedom in choosing the speed at which to drive. Thus, the volume of traffic is an important factor to determine the free-flow conditions. Theoretically, free speed should be the speed at zero flow, but it is not possible to attain zero flow condition on any highway. To overcome this difficulty, free speed is generally measured at a very low level of flow, i.e. about 200 to 300 vehicles per hour per lane.

Influencing factors of free speed

Free speed is influenced by many factors that can be categorized into five main groups including driver, road, vehicle, environment, traffic operations and control. These influencing factors of free speed in detail under the above-said categories are described in Figure 1. As shown in Figure 1, the driver characteristics such as age, gender, aggressiveness, condition of the driver (fatigue), etc. have significant influence on free speed. Road geometry facilities such as road width, number of lanes, width and position, curvature, gradient, roughness, lateral clearance, sight distance, etc. and surface type and condition, shoulder type and condition, service road presence, frequency of intersections, etc. will also play a vital role on free speeds[7]. Studies reveal that free speed of vehicles is significantly different for different types of highways as these geometric parameters vary based on functional classification of highways[8–10]. The vehicle travelling position on a highway (inner or outer lane) influences free speed significantly[10–12]. Vehicular factors that can have significant influence on free-speed characteristics include vehicle type, vehicle age, etc. and similarly, the traffic factors such as traffic volume, traffic density, trip distance, percentage of commercial vehicles, passing manoeuvres, opposing traffic, access control, etc. also affect the free speeds. Speed limits of a highway would also restrict free speeds of individual vehicles[12,13]. Apart from these factors, geographic location including the environmental variables such as time of the day and weather are among the other elements affecting vehicular free speeds[7]. Several studies have investigated the effects of day light, rain, snow and fog on both roadway capacity and speed[14–20] and found significant reductions in free speed under adverse weather conditions.

Free speed studies in India

Based on the review of studies in the developed world, it is obvious that the influencing parameters like roadway design and traffic control practices are country- or region-specific and hence the inferences drawn based on studies in any specific country cannot be translated for direct applications to another country through developing adjustment factors. Further, the speed studies on multi-lane highways conducted abroad are applicable only to the speed characteristics of homogeneous traffic conditions. This is because the roadway capacity and the conditions for adjustment are vastly different on Indian roadways as the local roadway design (i.e. lane width, curves, grades, etc.), vehicle size and more importantly, traffic mix and behaviour of a driver especially lane

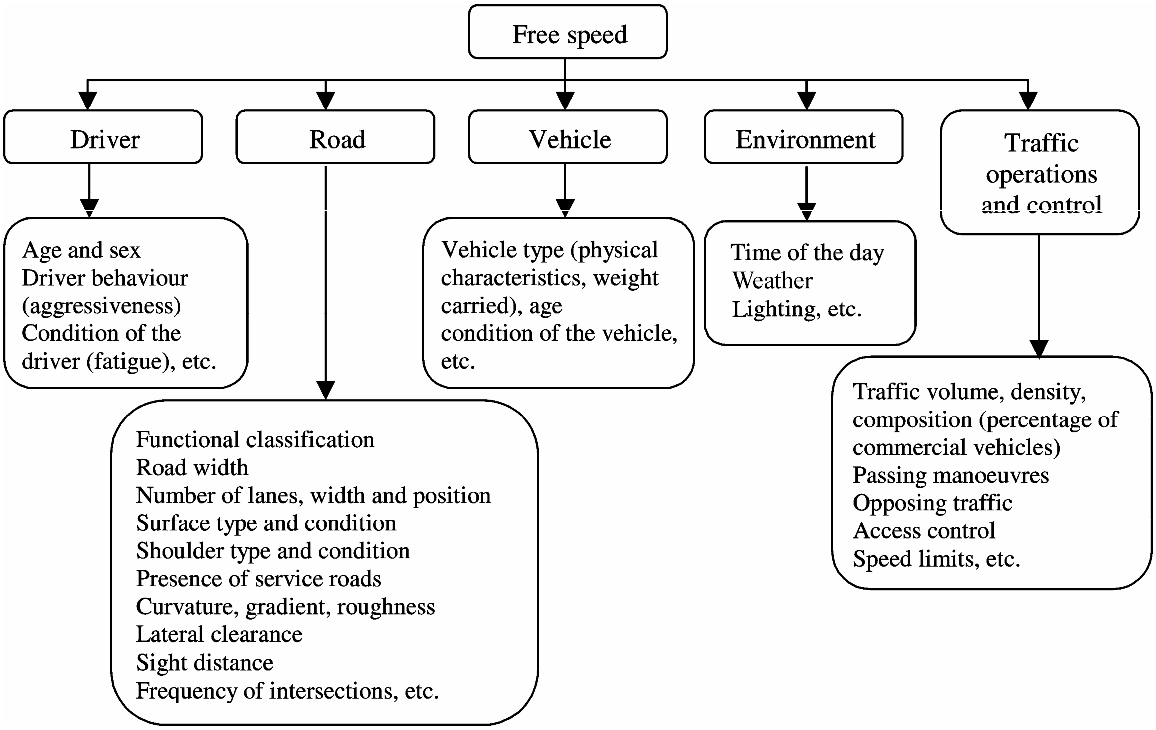

Figure 1. Influencing factors of free-speed of vehicles.

changing and lane discipline phenomenon are entirely different.

In India, studies have generally focussed on the free-speed characteristics on different multi-lane carriageways rather than the impact of influencing parameters. Kadiyali *et al.*[21] studied free-speed behaviour of vehicles on the Delhi–Faridabad section of NH-2, a four-lane divided carriageway with 2.5 m wide earthen shoulders and found that the speed distributions of vehicles were observed to follow the normal distribution pattern. Katti and Raghavachari[22] developed speed models based on traffic data collected on suburban sections of Hyderabad, Secunderabad and Surat cities in India. They found that speed dispersion was high for fast vehicles and low for bicycles and also speed data for fast vehicles followed normal distribution whereas log-normal distribution model defined the speed data for bicycles. Kadiyali *et al.*[23] carried out speed studies on Indian rural highways on single lane, intermediate lane, two-lane and four-lane (divided) rural highways. Speed data on a four-lane divided road followed normal distribution for each category of vehicles. The comparison of the findings with the earlier study[2] revealed an increase of 20–40% in speeds on four-lane roads and an increase of about 10% in speeds due to widening of two-lane bi-directional carriageways to four-lane divided carriageways.

The results obtained from the free-speed studies conducted as part of URUCS-2001 (ref. 4) illustrated that the free speeds had increased by about a maximum of 40% across the corresponding vehicle types and different types of carriageways. The speed increase with paved shoulders is only in the range of 1.5–3.5 on two-lane carriageways. The above increase in free speeds could be attributed to the improved road conditions and vehicle technology. Further, this study also revealed that the free speeds on curves are expected to decrease by about 7–14% on four-lane divided carriageways across different vehicle types[4,24]. Velmurugan *et al.*[25] studied the changes in operating speed characteristics on rural highways, based on the outcomes of RUCS-1982 (ref. 2) URUCS-1992 (ref. 3) and URUCS-2001 (ref. 4). The comparison of results showed statistically significant increase in speeds of all vehicle categories on roads of different widths between 1982 and 1992, and 1992 and 2001. However, there was no significant increment in free speed found from 1992 to 2001 in case of cars, two-wheelers, buses and two-axle trucks. Errampalli *et al.*[26] based on the data collected on different NHs covering 22 test sections on both straight and curved sections demonstrated the increase in free speeds especially cars, two-wheelers and buses and compared the same with the free-speed results of URUCS-2001 (ref. 4).

From the above discussions, it can be noted that many studies were carried out in India to understand the free-speed characteristics covering up to four-lane divided carriageways. However, these studies could not adequately explain current free-speed characteristics of high-speed corridors as massive construction of highways were undertaken by the government for expansion of NH network to multi-lane carriageways recently. At the same time, the automobile industry and road design standards in India have also undergone tremendous changes during the last decade. These recent radical changes in road network coupled with enhanced vehicle technology have caused significant increase in speeds on these highways. In the absence of any scientific study to address these issues and consider all the recent changes in road network and vehicle technology, the existing models would underestimate results which would finally lead to unrealistic economic evaluation through unrealistic RUC models. Therefore, we propose to study here speed characteristics exclusively on these high-speed corridors and develop free-speed models for different vehicle types accordingly.

Data collection and study methdology

As mentioned earlier, the primary objectives of the present study are to assess the free speeds of different vehicle types on multi-lane high-speed corridors and develop realistic free-speed equations for different vehicle types covering different widths of multi-lane highways. In order to achieve these objectives, a methodology has been developed for deriving free-speed profiles on different carriageway widths on multi-lane highways based on the free-speed studies.

Free-speed surveys

Free-speed data was collected on different NHs and expressways spread across the length and breadth of the country using pro-laser instrumentation system (laser speed measurement gun) and trap length method at 42 selected road sections (Table 1) covering different types of multi-lane divided highways (four-lane, six-lane and eight-lane), horizontal curvature and geometric conditions such as presence of service roads on multi-lane highways considering both directions of travel as a separate one-way road. The trap length method at some of the locations was adopted mainly to check the consistency of the laser speed measurement gun and also adopted at the situations of non-availability of laser gun. Trap length was taken as about 50 m to estimate spot speed of different types of vehicles measuring time to travel that distance. All these study sections possess good riding quality with roughness ranging from 2500 to 4000 mm/km. The test sections have been chosen as far as possible away from the urban influence so that free-flow conditions can be experienced.

As can be inferred from Table 1, the number of six-lane divided carriageway road sections considered is only 3 and also eight-lane divided carriageway considered is only 1. This may be due to the fact that relatively lesser number of road sections are presently available in these categories without having urban influence as compared to the four-lane divided carriageways on intercity corridors. As the test sections include four-lane, six-lane and eight-lane divided carriageways, separate analysis has been carried out. Further, it can also be noted from Table 1 that some of the selected test sections are lying in mild-curved sections. These sections are specifically selected to incorporate the influence of horizontal curvature on the vehicular speeds and determine free-speed characteristics on these multi-lane highways. The free-speed data was collected by classifying the vehicles into the following categories, viz. cars (which is further sub-classified into two categories, viz. small cars < 1400 cc engine capacity and big cars > 1400 cc engine capacity), two-wheeler (TW), bus, light commercial vehicle (LCV), two-axle heavy commercial vehicle (HCV) and multi-axle heavy commercial vehicle (MCV).

Methodology for free-speed analysis

Speed distribution: The observed free speeds of different vehicle types were classified into suitable intervals generally of 5 kmph to determine the frequency distribution of vehicles as per speed. The mean speed and standard deviation (SD) values were calculated from the frequency distributions. Further, these data were fitted to normal distribution using mean and SD of vehicle speeds. From these distributions, important parameters namely 15th percentile speed (V_{15}), 50th percentile speed (V_{50}), 85th percentile speed (V_{85}), 95th percentile speed (V_{95}) and spread ratio (SR) are calculated to check the validity of the data. The percentile speeds are helpful in determining the fit of the normal distribution through SR and moreover, they help in understanding characteristics of the vehicles in terms of their operating speeds. The design speed, fixation of maximum and minimum speed limits can be determined. Using these percentile speeds, the speed characteristics of the stream can be easily understood and regulation of the vehicles will be possible. V_{15} is generally used for posting minimum speed limit whereas V_{85} is for maximum speed limit. V_{95} is taken as design speed of the highway and V_{50} is the mean speed. The average speed and V_{85} can be used to check the consistency of speeds. SR is used to explain normality of the observed data and it is defined as

$$\mathrm{SR} = \frac{V_{85} - V_{50}}{V_{50} - V_{15}}. \tag{1}$$

The estimated frequency curve will be truly normal when SR is unity. It will tend to deviate from the normal distribution as SR deviates from the unity. As can be seen from the fitted normal distributions, the speed data follow the normal curve only when SR is ranging between 0.69 and 1.35 (ref. 27). In order to further ascertain the pattern distribution of data, chi-square test has been carried out.

Table 1. Selected study section for free-speed data collection

National highway (NH)/ expressway	Location (Chainage)	Direction	Number of lanes	Types of section
NH-2	km 98	Delhi–Mathura	Four	Straight
	km 98	Mathura–Delhi	Four	Straight
NH-2	km 629	Durgapur–Kolkata	Four	Curved
	km 629	Kolkata–Durgapur	Four	Curved
NH-2	km 643	Durgapur–Kolkata	Four	Straight
	km 643	Kolkata–Durgapur	Four	Straight
NH-4	km 1242	Bangalore–Chennai	Four	Straight
	km 1242	Chennai–Bangalore	Four	Straight
NH-5	km 1501	Chennai–Kolkata	Four	Curved
	km 1501	Kolkata–Chennai	Four	Curved
NH-6	km 44	Kharagpur–Kolkata	Four	Curved
	km 44	Kolkata–Kharagpur	Four	Curved
NH-6	km 47	Kharagpur–Kolkata	Four	Straight
	km 47	Kolkata–Kharagpur	Four	Straight
NH-45	km 29	Chenglepat–Chennai	Four	Straight
	km 29	Chennai–Chenglepat	Four	Straight
NH-45	km 58	Chennai–Villupuram	Four	Curved
	km 58	Villupuram–Chennai	Four	Curved
NH-45	km 98	Chennai–Villupuram	Four	Straight
	km 98	Villupuram–Chennai	Four	Straight
NH-5	km 5	Vijayawada–Kolkata	Four	Straight
	km 5	Kolkata–Vijayawada	Four	Straight
NH-5	km 1069	Vijayawada–Guntur	Four	Straight
	km 1069	Guntur–Vijayawada	Four	Straight
NH-202	km 15	Hyderabad–Warangal	Four	Straight
	km 15	Warangal–Hyderabad	Four	Straight
NH-7	km 25	Hyderabad–Bangalore	Four	Straight
	km 25	Bangalore–Hyderabad	Four	Straight
NH-7	km 462	Hyderabad–Nagpur	Four	Straight
	km 462	Nagpur–Hyderabad	Four	Straight
NH-9	km 499	Hyderabad–Mumbai	Four	Straight
	km 499	Mumbai–Hyderabad	Four	Straight
NH-9	km 30	Hyderabad–Vijayawada	Four	Straight
	km 30	Vijayawada–Hyderabad	Four	Straight
Greater Noida Expressway	Near Lotus Valley School	Delhi–Noida	Six	Straight
		Noida–Delhi	Six	Straight
Greater Noida Expressway	Near Panchsheel Bal College	Delhi–Greater Noida	Six	Curved
		Greater Noida–Delhi	Six	Curved
NH-1	km 38	Delhi–Sonepat	Six	Straight
	km 38	Sonepat–Delhi	Six	Straight
Delhi–Gurgaon Expressway	Near IFFCO Chowk	Delhi–Gurgaon	Eight	Straight
		Gurgaon–Delhi	Eight	Straight

Statistical tests: The significance of the difference in mean values of any two sets of data collected on the same type of carriageway observed in different time periods or different conditions can be examined by conducting normal approximation test[28]. Hence, it was proposed to assess significance level by conducting this statistical test whether the difference in mean speeds for different vehicle types on different time periods or different carriageways are statistically significant or not. While using the normal approximation test to evaluate the significance in difference in mean values, the initial assumption is that there is no significant difference in mean and thereafter the validity of this assumption is examined. This test is based on the hypothesis that the sample size (n) is sufficiently large (i.e. $n \geq 30$) and both μ_1 and μ_2 are mean values of samples from the population having the same distribution, then the value ($\mu_1 - \mu_2$) is asymptotically normal with a mean of 0 and a pooled standard deviation of σ_D i.e. $(\mu_1 - \mu_2) = N\ [0,\ \sigma_D]$ for $n \geq 30$ at 95% confidence level. The difference in mean is said to be significant if the following condition is satisfied:

$$(\mu_1 - \mu_2)/\sigma_D \geq 1.96. \tag{2}$$

The σ_D can be expressed as[28]

$$\sigma_D = \sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}}, \tag{3}$$

where n_1 and n_2 are number of observations of the two data sets; s_1 and s_2 are standard deviations of the two data sets.

Free-speed equation: Free speed of a vehicle depends upon roadway factors, travel distance, traffic characteristics, load carried, vehicle age, etc. The major factors considered in governing the free speed of vehicle are road surface in terms of roughness (in mm/km) and road gradient (in m/km). Even though the road gradient (i.e. rise and fall) plays an important role on the speed of the vehicles, it is to be borne in mind that in the present study, the test sections considered are falling mainly within 1–2% gradient (i.e. plain terrain). Therefore, rise and fall (RF) data was not found to be a major influential parameter for the development of speed equations in this study. The free-speed equations are developed for each vehicle type separately for four-lane and six-lane divided carriageways (except eight-lane divided carriageway as the data available consists of only one location as shown in Table 1) in the present study considering roughness (RG) as the influencing parameter. The free-speed study results and equations developed are explained in the subsequent sections.

Results of free-speed analysis

The collected free-speed data was analysed by fitting normal distribution curve according to the methodology explained in earlier. The data collected for all the 42 test sections were utilized. These sections include four-lane, six-lane and eight-lane divided carriageways, but separate analysis has been carried out for these carriageways. The observed free-speed data was fitted through normal distribution and relevant parameters, viz. average speed, SD, percentile speeds, SR and chi-square values were estimated. To demonstrate these parameters, typical normal distribution fitted curves for car and HCV for the speed-data collected on NH-45 at km 98 is shown in Figure 2.

Similar analysis was carried out on all the road sections and free-speed characteristics were derived for varying multi-lane carriageways. Because the free-speed analysis mainly focuses on free-flow conditions, the vehicles travelling with higher speeds are considered while arriving at the average free-speeds. For this purpose, the vehicle travelling below a specified speed range was ignored as they are considered as outliers based on the scatter plot of the free-speed data. Hence, the speed data considered for TW, autorickshaws, buses, cars, LCVs/HCV and MCV are more than 65, 50, 60, 80, 60 and 55 kmph respectively. The summary of results derived from free-speed analysis for different vehicles on four-lane, six-lane and eight-lane divided carriageways is presented in Tables 2–4 respectively.

From Tables 2–4, it can be inferred that the normal distribution curve described the speed distributions satisfactorily for most of the vehicle types since the SR value ranges from 0.950 to 1.157, indicating that SR is well within the limits. Moreover, the chi-square value is also more than the critical value at 95% confidence level for all the vehicle types except in the case of autorickshaws, HCV and MCV on eight-lane. This can be attributed to the fact that the sample size is rather small in the above vehicle types. Further, the SD values range from 5.12 to 10.12, 6.21 to 12.57 and 4.50 to 14.23 for four-lane, six-lane and eight-lane divided carriageways as there is a huge variation in sample sizes and speed characteristics. A comparison of average free speeds on four-lane, six-lane and eight-lane divided carriageways is presented in Figure 3. The growing trends of mean free speeds of different vehicle types across varying carriageway widths can be easily understood from Figure 3 and the following inferences are drawn.

- Generally, the mean free speeds of different vehicle types on eight-lane are higher when compared to four-lane and six-lane divided carriageways.
- Free-speeds of two wheelers and cars marginally increased from four- to six-lane while the increase is quite significant from six- to eight-lane. This is to say that the addition of one lane on either side of four-lane carriageway is actually not offering desired level of service (LOS), in the case of small cars and hence there is insignificant improvement of speeds on six-lane carriageway. However, the addition of one more lane on eight-lane divided carriageway offering higher freedom for vehicular movements might have aided in attaining substantial increase in desired speeds and thus resulting in enhanced free speeds.
- Free speeds of heavy vehicles and autos significantly increased from four- to six-lane while marginally increased from six- to eight-lane. This can be attributed to the above vehicle types not able to attain the desired speed levels on four-lanes whereas on six-lane divided carriageway, the presence of additional lane might have facilitated in achieving significant increase in free speed on a six-lane divided carriageway. However, there is insignificant improvement in free

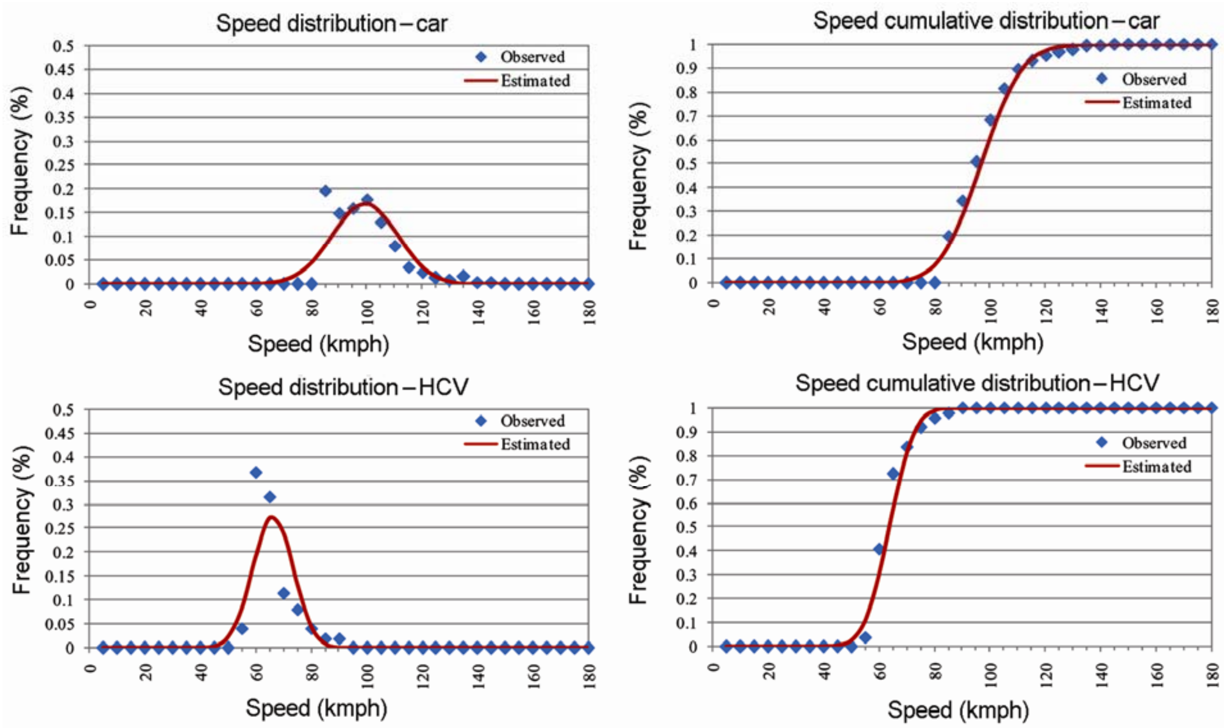

Figure 2. Typical distribution of free speed on four-lane divided carriageways (NH-45 at km 98).

Table 2. Free-speed statistics of different vehicles on four-lane divided carriageways

Vehicle type	Sample size	Average speed (kmph)	V_{15} (kmph)	V_{50} (kmph)	V_{85} (kmph)	V_{95} (kmph)	Maximum speed (kmph)	SD (kmph)	SR	Chi-square value
Big car	4137	93.0	79.7	90.1	100.4	106.3	149	9.76	1.000	1762.24
Small car	2688	92.4	80.7	89.9	100.6	106.7	161	10.12	1.157	1361.95
TW	1191	74.2	63.5	71.7	80.1	85.0	120	7.84	1.027	607.64
Auto	753	54.2	46.3	51.6	56.9	60.5	79	5.12	0.995	253.41
Bus	2138	71.1	59.8	68.6	77.1	82.1	108	8.25	0.961	859.20
LCV	1614	68.6	58.5	66.1	73.9	78.1	113	7.27	1.019	846.07
HCV	504	68.5	58.0	65.9	74.2	78.9	103	7.73	1.038	343.94
MCV	1924	64.0	58.2	64.6	71.2	75.2	97	6.18	1.019	856.80

Table 3. Free-speed statistics of different vehicles on six-lane divided carriageways

Vehicle type	Sample size	Average speed (kmph)	V_{15} (kmph)	V_{50} (kmph)	V_{85} (kmph)	V_{95} (kmph)	Maximum speed (kmph)	SD (kmph)	SR	Chi-square value
Big car	1132	95.5	82.1	93.0	104.0	110.6	135	10.49	1.014	309.92
Small car	749	93.1	80.2	90.6	100.9	106.8	136	9.79	0.998	118.08
TW	723	75.0	59.3	72.5	85.7	92.5	109	12.57	1.000	131.61
Auto	95	56.6	44.8	54.1	63.8	68.6	88	8.70	1.043	59.07
Bus	283	74.4	65.1	71.8	78.4	82.1	102	6.21	0.997	93.26
LCV	93	73.6	62.9	71.0	79.5	84.4	105	7.87	1.041	19.87
HCV	83	70.7	58.6	68.2	78.3	84.4	101	9.67	1.049	87.31
MCV	109	70.4	59.0	68.0	76.8	81.9	100	8.46	0.980	65.43

speeds on eight-lane as compared to six-lane carriageways for the above vehicle types. This phenomenon may be again attributed to the autos and heavy vehicles achieving their desired speed levels on six-lane itself and hence, there is no impact of eight-lane divided carriageway on speeds although it offers higher LOS and thus ensures enhanced safety for vehicle movements compared to six- and four-lane divided carriageways.

Table 4. Free speed statistics of different vehicles on eight-lane divided carriageways

Vehicle type	Sample size	Average speed (kmph)	V_{15} (kmph)	V_{50} (kmph)	V_{85} (kmph)	V_{95} (kmph)	Maximum speed (kmph)	SD (kmph)	SR	Chi-square value
Big car	180	101.4	84.7	98.9	113.7	122.5	158	11.81	0.977	186.22
Small car	165	98.0	83.2	95.5	107.5	115.2	163	14.23	1.049	90.04
TW	343	77.5	63.7	75.0	86.3	92.5	125	10.75	1.000	149.58
Auto	10	56.7	49.1	54.3	59.3	61.9	66	4.50	0.969	4.75
Bus	246	75.7	64.9	73.2	81.3	86.2	103	7.69	0.977	78.70
LCV	127	74.1	61.9	71.5	107.5	86.9	124	9.29	1.016	71.88
HCV	24	73.2	64.1	70.7	77.0	81.2	88	6.09	0.966	7.25
MCV	13	72.0	62.7	69.5	76.6	81.1	87	6.74	1.026	2.83

Table 5. Statistical tests results of different vehicles on four-lane, six-lane and eight-lane carriageways in plain terrain

	Between four-lane and six-lane		Between six-lane and eight-lane	
Vehicle type	Cal. value*	Result**	Cal. value*	Result**
Big car	7.20	Significant increase	5.35	Significant increase
Small car	1.72	Insignificant increase	4.97	Significant increase
TW	1.54	Insignificant increase	3.36	Significant increase
Auto	2.63	Significant increase	0.06	Insignificant increase
Bus	8.07	Significant increase	2.12	Significant increase
LCV	5.96	Significant increase	0.43	Insignificant increase
HCV	1.95	Insignificant increase	1.52	Insignificant increase
MCV	7.75	Significant increase	0.79	Insignificant increase

*Calculated values as per normal approximation test given in eq. (2); **Critical value at 95% confidence level = 1.96.

To establish the statistical validity of the above mentioned inferences, the statistical test namely normal approximation test described in the previous section has been carried out to assess the free speeds of different vehicle types on four-, six- and eight-lane divided carriageways. This test has been performed to assess whether mean free speed increase across varying carriageway widths is statistically significant or not by comparing the incremental increase in carriageway widths (i.e. four- and six-lane and similarly six- and eight-lane). The results of the normal approximation test are presented in Table 5. From Table 5, it can be noted that significant increase (calculated value is greater than critical value = 1.96 at 95% confidence level) in free speeds is found from four- to six-lane divided carriageways except in the case of small cars, TW and HCV. In the case of six- to eight-lane carriageways, statistically significant increase in free speeds is noted in the case of small cars, big cars and TW. These statistical results further reinforce the statement that the mean free speed of light vehicles except autos has registered significant increase from six- to eight-lane. In the case of heavy vehicles, the free-speed of heavy vehicles except HCV has gone up significantly when the road capacity is augmented from four- to six-lane divided carriageways which reinforces the fact that the effect of road capacity augmentation does not have a statistically significant influence on the free speeds of heavy vehicles beyond six-lane divided carriageways. To appreciate the changing speed characteristics of different vehicle types on high-speed corridors, a comparison was made with the past studies conducted as a part of RUCS-1982 (ref. 2), URUCS-1992 (ref. 3) and URUCS-2001 (ref. 4). A comparison of average free speeds on four-lane highways is presented in Figure 4. From Figure 4, it is clearly seen that the free speeds on four-lane high-speed corridors have rapidly increased especially in the case of cars and two-wheelers, whereas in the case of heavy vehicles it is comparatively less. This result confirms the fact that the benefits primarily accrued from improved road designs and advanced vehicle manufacturing technology over the years in India.

Free-speed equations

Using the collected free-speed data, the free-speed equations were initially proposed to be developed between free speed of the vehicle and road geometry features namely RG and RF. However, RF data is not taken as a major influential parameter for speed equation in the present study as the traffic data has been collected on plain terrain road sections spread across the country. Hence, the free-speed equations are eventually developed for each vehicle type separately for four- and six-lane divided carriageways considering RG alone as an influencing parameter in the article for obvious reasons. The developed free-speed equations are given in Table 6 for both four- and six-lane high-speed corridors. For comparison, the free-speed equations developed under URUCS-2001 (ref. 4) are also presented in Table 6.

From Table 6, it can be noticed that the free-speed equations possess reasonable R^2 values ranging from 0.27 to 0.88 in the case of four-lane divided carriageways across different vehicle types. However, in the case of six-lane divided carriageways, R^2 values range between 0.30 and 0.52, which is comparatively less and this can be due to the lesser number of test sections taken up under the six-lane divided category. From the developed equations, it can also be noted that the intercept (i.e. free speed of a vehicle) in the developed free-speed equations increases as the roadway width increases. Similarly, the coefficient of roughness in the equation has also increased as roadway width increases. This is due to the fact that the vehicles travel at higher speeds on six-lane compared to four-lane and the change in RG could result in rapid reduction in speeds as the RG coefficient is high in six-lane compared to four-lane. From this table, it can be further noted that the free speeds of all the vehicles have significantly increased compared with URUCS-2001 (ref. 4), which clearly demonstrates that there are substantial improvements in vehicle technology and road design as well. However, the slopes of the line are comparatively higher in the present study than URUCS-2001 (ref. 4), which implies that the impact of RG has increased compared to the results of URUCS-2001 study[4]. This is due to the fact that most of the vehicle ply at increased free speeds (statistically significant increase in mean free speeds already established in Table 5) and hence the influence of poor riding quality is quite pronounced on multi-lane highways for all the vehicle types on varying carriageway widths. To further demonstrate the suitability of developed speed equations (refer Table 6), the estimated free speed from the equations is compared with the observed free speeds (refer Tables 2 and 3) and the comparison is presented in Table 7. To estimate the free speed for different vehicle types, the average roughness of 2000 mm/km is assumed for both four- and six-lane divided carriageway.

From Table 7, it can be observed that the error between observed free speed and intercept of speed equations of different vehicle types on four-lane divided carriageway range from 0.3 to 2.8% whereas in the case of six-lane, the range is from 1.2 to 9.7%. From the above results, it can be concluded that the developed speed equations exhibit good statistical validity as the intercept derived through speed models has replicated the field conditions appropriately as the difference error between the observed free-speed and intercept of speed equations for different vehicle types is well within acceptable error limits. Therefore, it can be concluded that developed speed equations can be used for predicting vehicular free-speeds on both four- and six-lane divided carriageways.

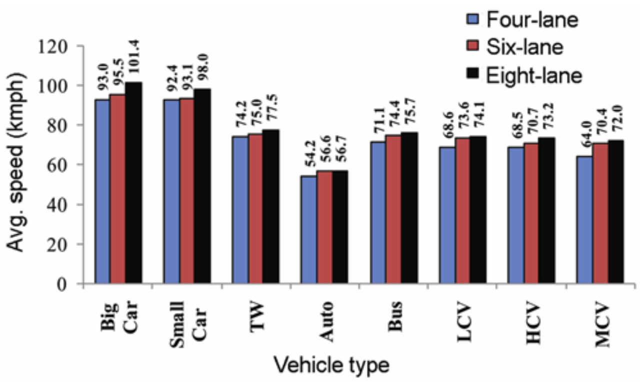

Figure 3. Comparison of average free speeds on different multi-lane high-speed carriageways.

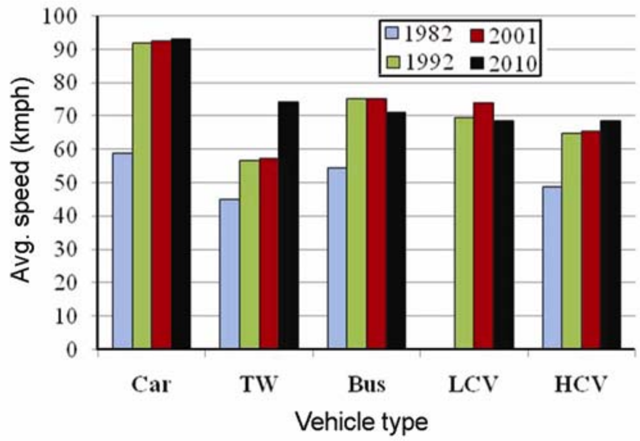

Figure 4. Trend of average free speeds on four-lane divided carriageway over the years.

Concluding remarks

As the high-speed corridors are rapidly increasing day-by-day along with improved quality in road design and advancements in vehicle technology, speeds on these highways have changed rapidly over the years. Because free-speed is an important input in the estimation of RUC and subsequent economic evaluation of the highway projects, extensive free-speed studies were carried out in the present study on selected corridors spread over the country to estimate changing free-speed characteristics of different vehicles covering varying widths of multi-lane carriageways for the first time in the country. The following conclusions are drawn from the present study:

- The mean free speeds of different vehicle types on eight-lane are higher than those on four- and six-lane divided carriageways.
- Free speeds of heavy vehicles and autos significantly increased from four- to six-lane while marginally increased from six- to eight-lane. This can be attributed to the above vehicle types not being able to attain their desired speed levels on four-lane divided whereas on six-

Table 6. Free-speed equations of different vehicles on different types of multi-lane highways

Vehicle type	Four-lane	Six-lane	Four-lane (URUCS-2001 (ref. 4))
Big car	V_{BC}^{4L} = 106.000 – 0.00521*RG (R^2 = 0.33) (18.109*, –2.233#, 7.369$)	V_{BC}^{6L} = 112.000 – 0.00569*RG (R^2 = 0.45) (22.764*, –2.25#, 16.333$)	V_{CAR}^{4L} = 78.58 – 0.7640* RF – 0.00183* (RG – 2000)
Small car	V_{SC}^{4L} = 102.746 – 0.00438*RG (R^2 = 0.27) (15.867*, –1.726#, 2.98$)	V_{SC}^{6L} = 107.000 – 0.00534**RG* (R^2 = 0.30) (3.546*, –0.344#, 0.78$)	
TW	V_{TW}^{4L} = 79.191 – 0.00262*RG (R^2 = 0.25) (22.543*, –1.814#, 3.289$)	V_{TW}^{6L} = 90.000 – 0.00505*RG (R^2 = 0.31) (2.88*, –0.303#, 1.215$)	V_{TW}^{4L} = 48.65 – 0.4729* RF – 0.00113* (RG – 2000)
Bus	V_{BUS}^{4L} = 76.487 – 0.00245*RG (R^2 = 0.58) (20.453*, –2.046#, 4.185$)	V_{BUS}^{6L} = 79.511 – 0.00316*RG (R^2 = 0.37) (14.682*, –1.083#, 1.174$)	V_{BUS}^{4L} = 60.32 – 0.4573* RF – 0.00109* (RG – 2000)
LCV	V_{LCV}^{4L} = 74.963 – 0.00235*RG (R^2 = 0.88) (78.591*, –7.74#, 59.914$)	V_{LCV}^{6L} = 80.000 – 0.00366*RG (R^2 = 0.52) (6.801*, –0.592#, 2.37$)	V_{LCV}^{4L} = 62.85 – 0.5604* *RF* – 0.00111* (RG – 2000)
HCV	V_{HCV}^{4L} = 76.000 – 0.00285*RG (R^2 = 0.52) (7.123*, –0.661#, 38.679$)	V_{HCV}^{6L} = 77.000 – 0.00659*RG (R^2 = 0.35) (3.11*, –0.498#, 9.374$)	V_{HCV}^{4L} = 55.53 – 0.4952* RF – 0.00098* (RG – 2000)
MCV	V_{MCV}^{4L} = 65.552 – 0.00118*RG (R^2 = 0.46) (60.664*, –2.923#, 8.547$)	V_{MCV}^{6L} = 70.000 – 0.00295*RG (R^2 = 0.37) (3.452*, –0.268#, 98.138$)	V_{MCV}^{4L} = 46.65 – 0.4159* RF – 0.00083* (RG – 2000)

V, Average free speed in kmph; RG, Roughness in mm/km; Subscripts BC and SC represent big cars and small cars respectively; superscript 4L and 6L represent four-lane and six-lane divided carriageways, respectively; **t*-Value for constant, #, *t*-value for coefficient and $, *F*-value.

Table 7. Comparison of observed free speed with intercept on speed-flow equation

	Four-lane			Six-lane		
Vehicle type	Observed mean free speed (kmph)	Estimated from speed equation (kmph)	Error (%)	Observed mean free speed (kmph)	Estimated from speed equation (kmph)	Error (%)
Big car	93.0	95.6	2.8	95.5	100.6	5.4
Small car	92.4	94.0	1.7	93.1	96.3	3.5
TW	74.2	73.9	0.3	75.0	79.9	6.5
Bus	71.1	71.6	0.7	74.4	73.2	1.6
LCV	68.6	70.3	2.4	73.6	72.7	1.2
HCV	68.5	70.3	2.6	70.7	63.8	9.7
MCV	64.0	63.2	1.3	70.4	64.1	9.0

lane divided carriageways, the presence of additional lane has helped in achieving significant increase in free speed from four- to six-lane. However, increase in free speeds is negligible on eight-lane as compared to six-lane carriageways. As autos and heavy vehicles have achieved their desired speed levels on six-lane itself, there is no impact of eight-lane divided carriageways though it offers higher LOS for vehicle movements compared to six- and four-lane divided carriageways.

- Further, it can be noted that statistically significant increase in free speeds is found from four- to six-lane divided carriageways except in the case of small cars, TW and HCV. In the case of six- to eight-lane carriageways, statistically significant increase in free speeds is noted in the case of small cars, big cars and TW. These statistical results further reinforce the statement that the mean free speed of light vehicles except auto has registered significant increase from six- to eight-lane. In the case of heavy vehicles, the free speed of heavy vehicles except HCV has gone up significantly when the road capacity is augmented from four- to six-lane divided carriageways which reinforces the fact that the effect of road capacity augmentation does not have statistically significant influence on the free speeds of heavy vehicles beyond six-lane divided carriageways.
- The developed free-speed equations possess reasonable R^2 values ranging from 0.27 to 0.88 in the case of four-lane divided carriageways across different vehicle types. However, in the case of six-lane divided carriageways, R^2 values range between 0.30 and 0.52, which is comparatively less and this can be due to lesser number of test sections taken up under the six-lane divided category.
- The validation of developed free-speed equations confers that the error between observed free speed and intercept of speed equations of different vehicle types on four-lane divided carriageway ranges from 0.3 to 2.8% whereas in the case of six-lane, the range is from 1.2 to 9.7%. From the above results, it can be concluded that the developed speed equations exhibit good statistical validity as the intercept derived through speed models has replicated the field conditions appropriately and the

difference error between the observed free speed and intercept of speed equations for different vehicle types is well within acceptable error limits. Therefore, it can be concluded that the developed speed equations can be used for predicting vehicular free speeds on both four- and six-lane divided carriageways.

In the present study, free-speed analysis was carried out covering four-, six- and eight-lane divided carriageways and however, due to paucity of the eight-lane divided carriageways on inter-city corridors, speed equations could not be exclusively developed for the above type of carriageways. As the study sections considered are less in the case of six-lane divided carriageways, the R^2 values obtained are also comparatively less. These limitations can be addressed by conducting free-speed studies by selecting more such test sections in future.

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