Spatio-Temporal Traffic Characteristics Analysis on Multi-lane Highways Under Varying Traffic Flow and Density Levels

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Abstract The study of traffic flow characteristics is essential for designing highway systems for which different traffic influencing variables are of primary importance. The study aims to assess the impact of a range of traffic flow and density levels on the spatio-temporal (lateral placement and time headway) traffic characteristics of highways. A substantial amount of traffic data like speed, time headway (TH), and lateral placement (LP) of vehicles was collected continuously for 12 h on six Indian highway sections. The DPCU for different vehicles with different flow and density rates were calculated. The speed and TH descriptive statistics and probability distribution functions at varying flow and density levels were also analyzed. To determine the most appropriate probability distribution function, the goodness of fit test was used. Furthermore, the impact of traffic speed, flow, and density on the LP of vehicles under different traffic conditions was assessed using descriptive statistics. It was observed that the traffic flow and density levels had an unusual effect on the DPCUs of vehicles. The mean traffic speed under high flow and density decreased by 33.3 and 18.3%, while the mean TH under high flow and density decreased by 28.4 and 29.9%. Also, the results indicated that traffic speed and TH data exhibit a different distribution of probability functions depending on the traffic flow and density. The descriptive statistics on the LP of vehicles show the existence of a significant difference of the same concerning the different ranges of traffic speed, flow, and density.

Keywords Speed · Flow · Density · Time headway · Lateral placement · Mixed traffic

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1 Introduction

Traffic data is essential for solving complex traffic engineering problems, especially under mixed traffic conditions [1]. Under ubiquitous heterogeneous traffic situations, different vehicles have varying maneuverability characteristics. These characteristics allow them to operate at different speed levels by maintaining different time headways and occupying any lateral space available in the roadway for a given traffic condition. These parameters are used to evaluate the changes in driver behavior on highways. Because speed, flow, and density are the necessary measures essential to understand the interaction among them collectively rather than independently, specifically on multi-lane rural highways.

Time headway (TH) is the elapsed time between the fronts of the previous vehicle to the front of the present vehicle crossing the IR sensor beams. The lateral placement (LP) is the distance between the center of the vehicle and the edge of the roadway on the curbside when the vehicle is moving. The poor lane discipline and heterogeneous traffic nature in Indian traffic conditions make it necessary to analyze the TH (temporal parameter) and LP (spatial parameter) of vehicles under mixed traffic conditions to understand traffic behavior better. Further, accurate acquisition of vehicular traffic information in real-time is necessary [2].

The majority of research conducted in developing nations with mixed traffic is confined to examining the traffic efficiency using the temporal and longitudinal parameters like speed and TH. Very few studies have been made to explore the spatial and lateral characteristics like LP of vehicles in the past. Speed and TH are critical performance measures to be examined under different traffic conditions such as flow and density. Furthermore, there is no doubt that it is worth researching the sensitivity of flow and density on dynamic passenger car units (DPCU) to assess traffic characteristics. Also, the LP of vehicles is one of the most vital operational characteristics of the highways, which needs to be extensively analyzed at a different speed, flow, and density levels.

For a clear understanding of vehicle dynamics and the development of traffic flow models, more observational studies using huge traffic data are needed. Besides, precise modeling with comprehensive research analysis representing the real-field conditions is essential to regulate, manage, and control traffic. Hence this research is undertaken to assess the impact of traffic flow and density on vehicle speed and TH. Also, the DPCU factors for different vehicle types with varying traffic flow and density were evaluated. The analyses of the probability distributions on the speed and TH at different flow rates and density levels were conducted to determine the best-fitted distribution. Besides, this study aims to examine the LP characteristics of vehicles at the varying speed, flow, and density of the traffic stream using the (Infra-red) IR sensor-based traffic data obtained from Indian highways.

2 Literature Review

Zhang et al. [3] obtained headway data from urban areas and analyzed the probability distributions. Similarly, Jang et al. [4] collected headway data on Korean multi-lane highways carrying homogenous traffic using loop detectors and researched theoretical progress models by categorizing the traffic flow into five different rates. The study found that Gamma distribution fits well at light to medium flows, and the Pearson VI distribution fits well at all flow rates.

Gunay and Erdemir [5] conducted a lateral analysis of longitudinal TH between the interacting vehicles. The authors observed that most of the vehicles chose either to pass by or lag instead of making a side-by-side movement. Araghi et al. [6] presented how to use GPS loggers to capture the travel time data. Bhaskar and Chung [7] provided a basic understanding of the use of Bluetooth scanner data. Brennan et al. [8] studied the efficiency of data collected from Bluetooth using the lateral distance of vehicles. Li et al. [9] used Bluetooth sensors to calculate the travel time of vehicles.

Goodall [10] analyzed the nature of Wi-Fi re-identification technology and suggested using Wi-Fi sensors for low-speed and low-volume traffic. Gore et al. [2] investigated the performance of Wi-Fi sensors in vertical and horizontal positions for evaluating the efficiency of traffic data under Indian traffic conditions. The study revealed that the sensor location significantly influences the stream speed, time headway, and time-to-detection. Jang [11] used laser-sensor data to investigate the time headway characteristics on an interrupted traffic stream at various levels of traffic flow to model many stochastic distributions. Mahapatra and Maurya [12] used V-Box equipment and analyzed the lateral and longitudinal vehicle behavior of the mixed traffic on the highways in India. The study explored the effect of vehicle speed in the longitudinal direction on the yaw rate of the vehicles and studied the relationships with the longitudinal speed of different vehicle types. All these studies have attempted to analyze traffic characteristics using different technologies.

Another piece of a study by Isaac [13] reported that speed has a linear relation with lateral clearance at different speed levels. However, a later study by Pal and Chunchu [14] concluded that lateral clearance/gaps are a direct consequence of several other aspects other than the speed of the passing/overtaking vehicle, and it depends upon the vehicle type. Furthermore, increasing the degree of the model improves the fitting of the regression curve showing higher sensitivity to speed. Budhkar and Maurya [15] determined the lateral clearance for vehicles during overtaking in mixed traffic using an instrumented vehicle with ultrasonic sensors and GPS devices with cameras. The analysis findings indicated that the lateral clearance preserved by similar vehicle pairs is less than dissimilar vehicle pairs. Mallikarjuna et al. [16] elaborated image processing-based vehicle detection techniques using computer software for computing the lateral interaction between vehicles. However, this technique lack accuracy in detection due to heterogeneous traffic condition on Indian roads.

In India, due to the presence of abreast driving behavior and mixed traffic driving conditions, vehicles interact longitudinally and laterally with other vehicles [17].

Modeling traffic characteristics under non-lane-based and mixed traffic is a daunting task. Considerable research efforts have been directed toward analyzing traffic characteristics on different types of roadway facilities using various technologies. A little amount of research has been concentrated on analyzing traffic parameters such as speed, flow, density, TH, and LP of vehicles on multi-lane rural highways using IR sensor-based technologies. Also, it is understandable from past research works that the use of advanced data collection techniques for acquiring mixed traffic characteristics is limited, mainly in developing countries like India.

3   Study Framework

The field data on traffic characteristics was collected using the IR sensor-based device. Initially, the data were classified at flow increments of 500 Veh/h, ranging from 0–500 up to 1500–2000 Veh/h and at a density rate of 25 Veh/km increments, ranging from 25–50 up to 100–125 Veh/km. The DPCU was estimated using the speed-area ratio method for each vehicle category at varying traffic flow and density levels. The descriptive statistics were carried out, and several speed and TH distribution functions concerning the traffic flow and density rates were determined. The goodness of fit of the probability distributions was measured using the Kolmogorov–Smirnov (K–S) statistical test at a 5% level of significance for finding the best-fit distribution.

Besides, the association of LP of vehicles with respect to the speed, flow, and density was analyzed to evaluate their influence. The traffic speeds are classified into four groups with the size of the bin as 20 km/h, ranging from 20–40 up to 80–100 km/h. Similarly, the flow and density were also classified into four groups with the size of the bin as 500 Veh/h and 25 Veh/km, respectively. The range of flow adopted was from 0–500 up to 1500–2000 Veh/h, and the range of density adopted was from 25–50 to 100–125 Veh/km. The impact of increasing magnitude of speed, flow, and density on the vehicular LP was analyzed.

4   Data Collection

4.1   Study Section Details

The national highways (NH) in the southern part of India were chosen as the study sections based on the criteria that the test sections did not have any pedestrian cross-walks, median openings for making U-turning movement and were free from any other such side frictions. The data was collected for 12 h by setting up the IR sensors device on the four-lane divided highway sections. Extraction of the speed and volume data at every 15-min interval was carried because "the aggregation of vehicle count provides the realistic estimation of hourly traffic volume in heterogeneous traffic
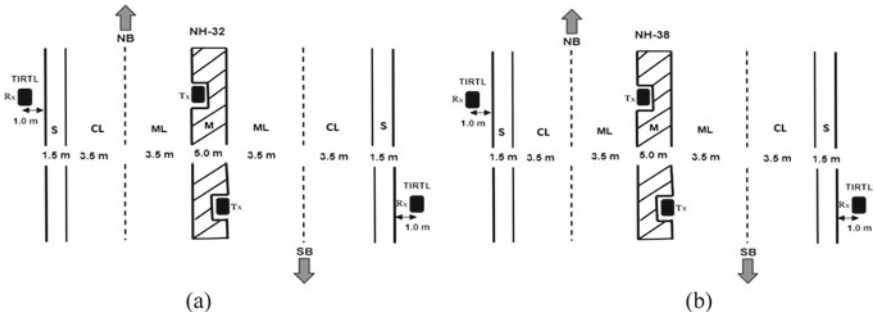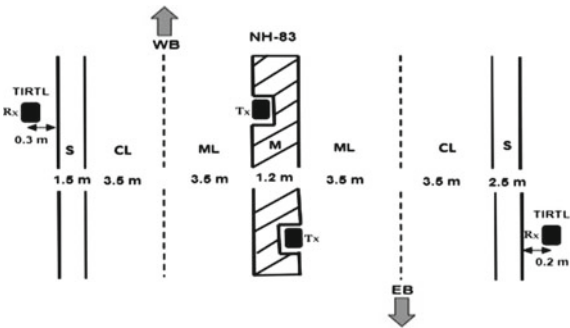
Fig. 1 Geometric features **a** NH-32. **b** NH-38

Fig. 2 Geometric features (NH-83)

flow conditions" [18]. Figures 1a, b and 2 depict the geometric features of NH-32, and NH-38, and NH-83, respectively.

4.2 Traffic Data Acquisition Using IR Sensor Device and Its Working Principle

The conventional traffic data collection methods, such as the video-graphic, pneumatic tubes, inductive loop detectors, etc., possess many limitations in their use by demanding various prerequisites. Also, these techniques are invasive and do not adapt to the mixed traffic scenarios peculiar to India. This difficulty can be overcome by using Intelligent Transportation Systems (ITS)-based new technological devices, such as the IR sensor devices. The IR sensor device, Transportable Infra-Red Traffic Logger (TIRTL), works on IR sensor-based technology to record traffic-related parameters such as speed, TH, LP, spacing, clearance, gap, CVC, volume, vehicle dimensions.

Both transmitter (TX) and receiver (RX), as shown in Fig. 3, are aligned so that they are less than 150 mm above the road surface, ensuring that the IR beams do
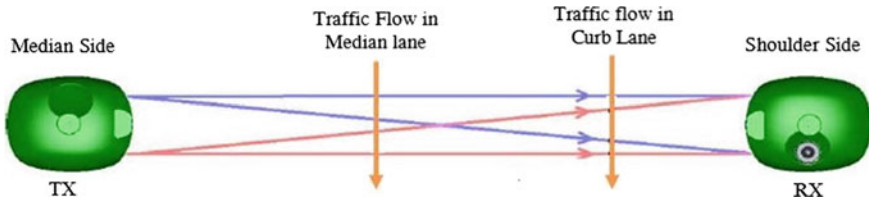
Fig. 3 IR lights transmission for traffic detection

not clip the vehicle bodies. The 12.0 V batteries are the power source for TX and RX. The TX is the IR beam source for traffic detection. On the other hand, the RX detects the disturbance caused by the passing vehicle wheels. The RX is connected to a laptop device through an RS232 serial port to access the system interface and store the data file in .csv format.

For any detection, the four beam events generate eight timestamps, and the vehicle travel direction is determined by the order of occurrence of beam events. The use of the "free-flowing" condition option optimizes vehicle detection for different traffic conditions. The make and break beam events are measured as time intervals to determine vehicle positions. Hence the LP of the vehicles is recorded. The field snapshot of the IR sensor device setup is shown in Fig. 4.

Accuracy of the IR sensor device. The traffic during the data collection was videotaped using a video camera for 1 h. It covered a 50 m trap length to capture the actual traffic movement. The speed, vehicle classification, TH, and LP of vehicles were extracted manually from the recorded videos and compared with the IR sensor device recorded data. An accuracy match of 96% for vehicle speed and 94% for CVC was obtained. The TH of vehicles was manually extracted at microscopic levels from the recorded

Fig. 4 Field snapshot of IR sensor device set up across the highway segment

Table 1 Average dimensions of the vehicle

Class of vehicle	Length (m)	Width (m)	Area (m^2)
2-wheeler (2W)	1.65	0.76	1.25
3-wheeler (3W)	2.74	1.25	3.43
Small car (SC)	3.84	1.45	5.57
Big car (BC)	4.60	1.80	8.28
Light commercial vehicle (LCV)	5.62	1.52	8.54
Medium commercial vehicle (MCV)	8.28	2.20	18.22
Heavy commercial vehicle (HCV)	9.10	2.30	20.93
Multi-axle vehicle (MAV)	12.62	2.42	30.54

videos, and the match percentage with the IR sensor device recorded TH was found to be 96%. As far as the LP of the vehicles is concerned, the collected IR sensor device data revealed a 95% accuracy match with the videotaped data. Other studies achieved up to an accuracy of 99% for the vehicle's speed [19] and 94–97% for classified vehicle count [20].

4.3 Vehicular Dimensions

The vehicles detected by the IR sensor are compared with the pre-loaded vehicle type scheme (up to 21 standard classes specific to Indian road conditions) for describing the vehicle class. The recorded classification is displayed in the user interface once all the axles of the vehicles cross the IR detection zone. Table 1 shows the average physical dimensions of the vehicle classes.

4.4 Traffic Composition at the Study Sections

The mainstream traffic is composed of eight different vehicle categories. The large-sized new generation cars of more than 5.57 m^2 area were categorized as BC, and the others were categorized as SC. LCV included light and small commercial vehicles. MCV included the two-axle buses/trucks, while the HCV included three-axle buses/trucks. The vehicles with four-axles, five-axles, and six-axles are categorized as one vehicle type as MAV. Figure 5 illustrates the vehicle composition of different vehicle classes.
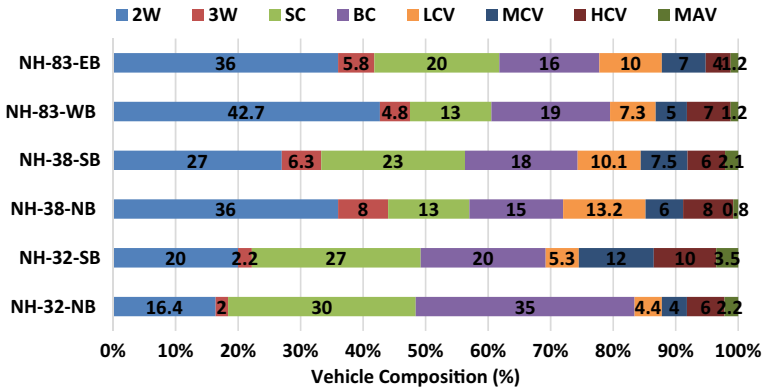
Fig. 5 Traffic composition for the subject study sections

4.5 Traffic Flow Variation at the Study Sections

The traffic flow variation on an hourly basis at the highway sections was examined to measure the peak and off-peak hours of vehicle traffic. It can be observed from Fig. 6 that the recorded volume of traffic is nearly the same at all sites except in the NH-32-NB section, which has the highest volume of traffic almost every hour. The hourly variation of traffic at all the subject study sections is depicted in Fig. 6.
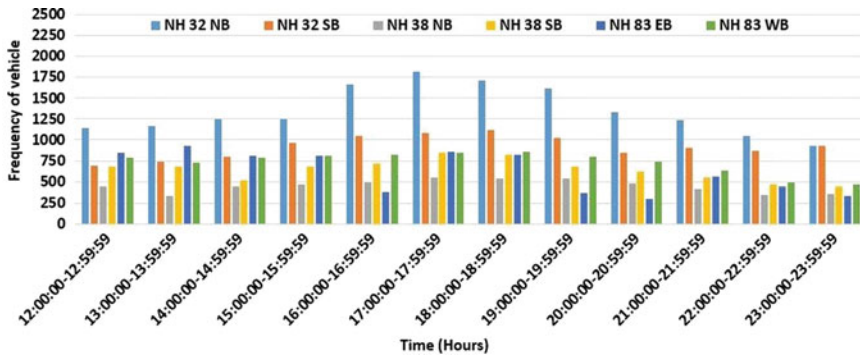
Fig. 6 Traffic variation at the subject study sections

5 Dynamic Passenger Car Unit (DPCU) Determination

The PCU values are typically assigned to homogenize the traffic [21]. The conventional PCE values suggested by HCMs cannot be used at different traffic flow conditions [22]. Additionally, the Indian Roads Congress-IRC:64 [23], the standard code provides single and static PCU values for the different ranges of traffic flow and density. Hence, the DPCU factors have been evaluated by the speed-area ratio model suggested Indo-HCM: 2017 [24], which is shown in Eq. (1).

$$DPCU_i = (V_c/V_i)/(A_c/A_i) \tag{1}$$

The DPCU values estimated for different traffic flow and density levels, as presented in Tables 2 and 3, respectively.

Tables 2 and 3 indicate that the DPCU of 2Ws, 3Ws, and BI decrease with the traffic flow and density increase. Conversely, the DPCU increases for BC, LCV, MCV, HCV, and MAV when the traffic flow and density increase. This was due to

Table 2 DPCU at different traffic flow levels

Traffic flow level (Veh/h)					
Class of vehicle	0–500	500–1200	1000–1500	1500–2000	Average DPCU
2W	0.35	0.33	0.28	0.25	0.30
3W	1.18	1.12	1.05	1.00	1.09
SC	1.00	1.00	1.00	1.00	1.00
BC	1.48	1.55	1.59	1.63	1.56
LCV	2.75	3.08	3.36	3.50	3.17
MCV	3.51	3.82	4.01	4.46	3.95
HCV	3.65	3.91	4.22	4.76	4.14
MAV	6.11	6.30	6.65	6.91	6.49

Table 3 DPCU at different traffic density levels

Traffic density level (Veh/km)					
Class of vehicle	25–50	50–75	75–100	100–125	Average DPCU
2W	0.38	0.35	0.29	0.25	0.32
3W	1.15	1.13	1.12	1.05	1.11
SC	1.00	1.00	1.00	1.00	1.00
BC	1.44	1.52	1.54	1.59	1.52
LCV	2.47	2.82	3.57	3.49	3.09
MCV	3.28	3.77	4.18	4.44	3.92
HCV	3.78	3.99	4.47	4.61	4.21
MAV	6.2	6.38	6.59	6.75	6.48

Table 4 DPCU values for the different types of vehicles as per Indo-HCM [24]

Class of vehicle	Indo-HCM [24] DPCU value	
	Range	Median
2W	0.3–0.5	0.4
3W	1.1–1.3	1.2
SC	1.00	1.00
BC	1.4–1.5	1.45
LCV	2.7–3.3	3.1
MCV	3.5–4.6	4.4
HCV	3.5–4.6	4.4
MAV	6.3–7.0	6.6

the inferior operation of these vehicles compared to an SC, 3W, and 2W, which have higher speeds. In both cases, the average DPCU for each type of vehicle was found to be logical and reasonably acceptable compared to the Indo-HCM [24] DPCU values, as presented in Table 4.

6 Analysis of Speed Data

The use of speed data without considering traffic composition, traffic flow, and density may yield skewed and inconsistent outcomes [25]. Further vehicle speed is affected by overall density, which includes individual vehicle densities [26] that are required for the development of macroscopic traffic models, microscopic traffic characteristics evaluation, capacity determination, and level of service analysis. Concerning this aspect, the study considers conducting the descriptive statistical analysis and finding the best-fitted distribution function for the traffic speed at varying flow and density levels.

6.1 Descriptive Statistics of Speed

The descriptive statistic of speed provides an understanding of the vehicle's quality of service. Table 5 summarizes the descriptive statistics on the speed at different traffic flow and density levels.

From Table 5, it can be observed that the vehicles have different minimum speed, maximum speed, mean speed, range value, mode value, standard deviation (SD), coefficient of variation (CV), standard error (SE), skewness, kurtosis, and percentile speeds over the varying range of traffic flow and density. The mean value of traffic speed under high traffic flow decreased from 57 to 38 km/h, which represents a reduction of 33.3%. The mean value of traffic speed under high traffic density decreased

Table 5 Descriptive statistics for speed data

Traffic characteristics	Flow range (Veh/h)				Density range (Veh/km)			
Statistical parameters	0–500	500–1000	1000–1500	1500–2000	25–50	50–75	75–100	100–125
Minimum	35	30	25	23	35	30	29	28
Maximum	81	78	72	73	82	76	72	70
Range	46	48	47	50	47	46	43	42
Mean	57	44	40	38	60	56	52	49
Mode	50	49	45	32	55	52	50	48
SD	12.4	12.6	13.1	14.4	13.6	14.5	15.4	16.1
CV	0.28	0.30	0.38	0.46	0.23	0.39	0.48	0.56
SE	0.20	0.16	0.14	0.21	0.27	0.24	0.21	0.14
Skewness	4.28	5.19	6.02	6.91	3.57	3.86	4.25	4.53
Kurtosis	3.14	3.25	4.65	4.97	4.58	4.95	5.89	6.41
15th percentile	40	36	28	26	38	32	30	27
50th percentile	56	42	38	36	58	54	51	47
85th percentile	75	73	68	67	78	74	70	67

from 60 to 49 km/h, which represents a reduction of 18.3%. It is observed that the speed gets affected because of the interaction of different classes of vehicles using the same road space. The higher the traffic flow and density, the lower is the speed value.

6.2 Probability Distributions for Speed Data

Conventionally, normal distribution defines the vehicle speed under homogeneous traffic conditions, but the distributions differ considerably under heterogeneous traffic conditions [22]. To assess the best-fitted distribution, the Kolmogorov–Smirnov (K–S) test was used with a 5% significance level. The distribution functions for speed are represented in Table 6.

The speed at a low traffic flow of 0–500 Veh/h exhibits Log-normal distribution, whereas, at high traffic flow of 1500–2000 Veh/h, the speed follows the Erlang distribution. Further, Table 6 shows that at a low traffic density of 25–50 Veh/km, the vehicle speed follows the Log-logistic distribution, whereas at a high traffic density of 100–125 Veh/km, the speed follows the Inverse-Gaussian distribution. The distribution functions varied for the vehicle speeds at several traffic flow rates and density levels because of variation in vehicles' static and dynamic characteristics

Table 6 Probability distribution functions for speed data

Traffic flow (Veh/h)	Type of distribution	K–S value	p-value	Best-fitted distribution	Traffic density (Veh/km)	Type of distribution	K–S value	p-value	Best-fitted distribution
0–500	Log-normal	0.032	0.941	Log-normal	25–50	Log-logistic	0.224	0.959	Log-logistic
	Beta	0.042	0.934			Beta	0.334	0.942	
	Log-logistic	0.054	0.920			Burr	0.568	0.912	
500–1200	Log-logistic	0.124	0.965	Log-logistic	50–75	Burr	0.347	0.954	Burr
	Gamma	0.322	0.953			Pearson 5	0.468	0.941	
	Weibull	0.392	0.941			Weibull	0.689	0.902	
1000–1500	Beta	0.155	0.941	Beta	75–100	Weibull	0.754	0.933	Weibull
	Weibull	0.184	0.883			Exponential	0.896	0.915	
	Log-Pearson III	0.210	0.875			Inverse-Gaussian	0.922	0.902	
1500–2000	Erlang	0.147	0.988	Erlang	100–125	Inverse-Gaussian	0.154	0.927	Inverse-Gaussian
	Log-logistic	0.171	0.972			Beta	0.247	0.910	
	Burr	0.189	0.966			Erlang	0.368	0.894	

and abreast driving behavior under prevailing traffic conditions. This has confirmed that speeds do not follow a particular distribution under different traffic conditions.

7 Analysis of Time Headway Data

7.1 Descriptive Statistics for TH Data

The TH data is the basis for building and analyzing the microscopic traffic simulation models. Table 7 summarizes the descriptive statistics on TH at different traffic flows and densities.

From Table 7, it can be observed that the TH varies with changes in traffic flow and density. Hence proving that TH is not a constant value. In general, the TH of vehicles typically decreased as the traffic flow and density values increased. From Table 7, it can be observed that because of the difference in the dynamic features of the vehicles, the TH has a different minimum speed, maximum speed, mean speed, range value, mode value, SD, CV, SE, skewness, kurtosis, and 15th, 50th, and 85th percentile speeds over the varying traffic flows and densities. The mean value of TH under high traffic flow decreased from 8.1 to 5.8 s, which represents a reduction of

Table 7 Descriptive statistics for TH data

Traffic characteristics	Flow range (Veh/h)				Density range (Veh/km)			
Statistical parameters	0–500	500–1000	1000–1500	1500–2000	25–50	50–75	75–100	100–125
Minimum	5.7	4.0	3.5	2.9	5.8	5.5	4.6	3.9
Maximum	16.4	14.5	13.2	12.8	12.6	10.2	8.6	7.1
Range	10.7	10.5	9.7	9.9	6.8	4.7	4.0	3.2
Mean	8.1	7.5	6.6	5.8	6.7	6.1	5.6	4.7
Mode	7.5	6.9	6.2	5.6	6.2	5.8	5.4	4.2
SD	7.21	8.48	9.02	9.77	5.68	6.52	7.41	8.47
CV	1.12	2.04	2.96	3.84	1.25	2.11	2.45	2.97
SE	0.11	0.11	0.10	0.15	0.11	0.11	0.10	0.13
Skewness	4.35	5.19	5.62	5.94	3.47	3.89	4.12	4.55
Kurtosis	2.20	3.14	3.78	4.12	2.78	2.99	3.47	3.79
15th percentile	6.2	4.8	3.9	3.6	6.0	5.8	4.9	4.1
50th percentile	7.8	7.2	6.3	5.7	6.5	6.2	5.7	4.8
85th percentile	12.2	10.5	9.8	8.6	9.4	8.5	7.7	5.9

28.4%. Meanwhile, the mean value of TH under high traffic density decreased from 6.7 to 4.7 s, which represents a reduction of 29.9%. It can be inferred that the TH is significantly influenced by the variation in the flow and density from a low level to a high level.

7.2 Probability Distributions for TH Data

The TH probability distributions were identified from the vehicle arrival pattern recorded in the field data. The K–S test results showed various probability distribution functions as the best-fitted distribution for TH at different traffic flow and density levels, which is represented in Table 8. It shows that the TH of vehicles follows the Exponential distribution when the traffic flow is as low as 0–500 Veh/h, whereas the TH of vehicles follows the Gumbel-max distribution when the traffic flow is as high as 1500–2000 Veh/h.

During high traffic flows, the repeated platoon formations on the highway by slow-moving vehicles increase the composition of following vehicles, thereby forming shorter headways [27]. This eventually identifies the form of distribution for this degree of traffic flow. Further, it can be observed that the TH of vehicles follows the Weibull distribution when the density is as low as 25–50 Veh/km, whereas the TH of vehicles follows the Log-logistic distribution when the density is as high as 100–125 Veh/km. Finally, it can be seen from the non-parametric test results of the distribution that the TH varies for every density level based on the traffic conditions.

8   Analysis of Lateral Placement of Vehicles

Lateral movements of vehicles in the traffic streams have a major effect on the traffic flow [28]. The vehicle's lateral interaction is influenced by the vehicle type, the speed of the vehicle, the behavior of the driver [29], and area-occupancy [30]. In this study, the LP of a vehicle is the distance between the center of the vehicle and the edge of the roadway on the curbside. The edge of the curbside of the roadway was chosen as a common reference point for the measurement of the LP of vehicles.

8.1 Frequency Distribution Analysis

The lane position of the vehicles on the carriageway is influenced by traffic characteristics [31]. The analysis of the frequency of LP of vehicles shows that many vehicles travel on the center of the road (between 2 and 7 m of the carriageway) as the vehicles try to maintain a safer longitudinal and lateral distance with the other

Table 8 Probability distribution functions for TH data

Traffic flow (Veh/h)	Type of distribution	K–S value	p-value	Best-fitted distribution	Traffic density (Veh/km)	Type of distribution	K–S value	p-value	Best-fitted distribution
0–500	Exponential	0.478	0.991	Exponential	25–50	Weibull	0.114	0.992	Weibull
	Log-normal	0.322	0.984			Erlang	0.176	0.974	
	Log-Pearson III	0.305	0.981			Burr	0.198	0.961	
500–1000	Gamma	0.216	0.964	Gamma	50–75	Beta	0.151	0.984	Beta
	Erlang	0.255	0.948			Erlang	0.186	0.977	
	Log-normal	0.277	0.934			Log-logistic	0.194	0.971	
1000–1500	Log-Pearson III	0.147	0.909	Log-Pearson III	75–100	Pearson 5	1.887	0.987	Pearson 5
	Log-logistic	0.161	0.891			Erlang	1.964	0.942	
	Pearson 5	0.188	0.872			Burr	1.992	0.968	
1500–2000	Gumbel-Max	0.115	0.974	Gumbel-Max	100–125	Log-logistic	1.511	0.991	Log-logistic
	Beta	0.126	0.955			Pearson 5	1.644	0.984	
	Weibull	0.145	0.950			Gamma	1.667	0.979	

interacting vehicles [32]. The frequency distribution of the LP of vehicles is shown in Fig. 7.

The analysis of the frequency of speed of vehicles shows that most of the vehicles travel, maintaining a moderate speed (30–40 km/h) to high speeds (60–80 km/h) and very high speeds (90–110 km/h) because of their maneuverability at nearly free-flow conditions. The frequency distribution for the speed of vehicles is shown in Fig. 8.

The speed and the LP of the vehicles have been found to follow the increasing nature of the relationship. Figure 9 indicates that the speed of vehicles increases as the vehicles shift toward the center of the highway sections. This may be reasoned to be because of the high speed vehicles wanted to have ease of maneuverability and lesser interaction with other vehicles.

As seen in Fig. 9, it can also be said in another way that the LP of vehicles increases as the speed of vehicles increases. Additionally, it can be noted that the observed LP maintained by the vehicles depends on the speed of the vehicles. Therefore, variation in traffic speed causes variation in the LP of vehicles and vice-versa.
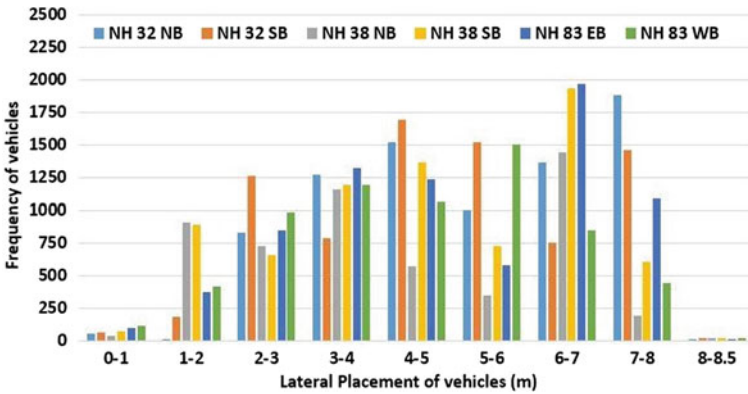

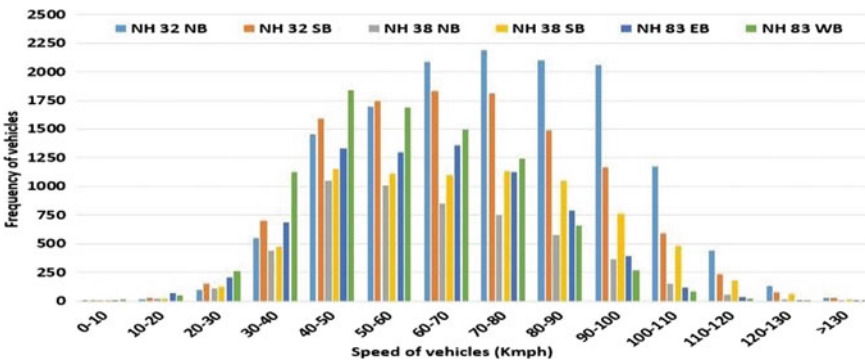Fig. 7 Frequency distribution of the LP of vehicles

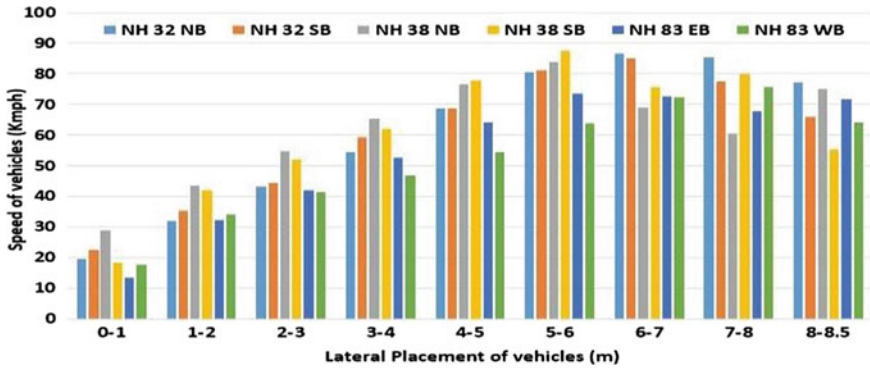Fig. 8 Frequency distribution of the speed of vehicles

Fig. 9 Variation of speed with respect to the LP of vehicles

8.2 Descriptive Statistical Analysis of LP of Vehicles

The observed vehicle speeds were classified at an increment of 20 km/h to determine the frequency distribution of the LP of vehicles. Speeds were assumed as 20–40, 40–60, 60–80, and 80–100 km/h. Similarly, the observed traffic flows were classified at 500 Veh/h increments as 0–500, 500–1000, 1200–1500, and 1500–2000 Veh/h. Also, the traffic density levels were classified at an increment of 25 Veh/km, ranging from 25–50 to 100–125 Veh/km. To comprehend the effect of speed, flow, and density on the LP of vehicles, descriptive statistics have been carried out, which are provided in Table 9.

From Table 9, it was interpreted that the mean vehicle LP at the lowest speed level is 2.2 m, and at the highest speed level is 4.6 m. Similarly, the mean vehicle LP at the lowest flow level is 1.2 m, and at the highest flow level is 4.2 m, while the mean LP of vehicles at the lowest density level is 1.4 m and at the highest density level is 4.6 m. The LP of vehicles was skewed toward the curbside of the road at low traffic speed, flow, and density range. As the speed, flow, and density of traffic increase, the LP of vehicles shifts from the curbside of the road to the median side. Because under free-flowing traffic conditions, the speed, flow, and density increase, and the lane occupancy of the vehicles in the median lane increases. The slow-moving vehicles alone are forced to occupy the curbside of the roadway. It can, therefore, be said that as the mean speed, flow, and density increase, the LP of vehicles increases.

From Table 9, it was interpreted that at the lowest speed range of 20–40 km/h, the minimum and maximum vehicle LP lies between 1.5 m and 2.7 m, respectively. While at the highest speed range of 80–100 km/h, the minimum and maximum vehicle LP lies between 2.7 m and 5.4 m, respectively. Similarly, at the lowest and highest flow ranges, the minimum and maximum LP of vehicles are 0.5 m and 4.8 m, respectively, while at the lowest and highest density ranges, the minimum and maximum LP of vehicles are 0.8 m and 5.1 m, respectively. Table 9 shows that as the speed, flow, and density range increases, the mean LP of the vehicles also increases. As the

Table 9 Descriptive statistics for LP of vehicles

Traffic characteristics	Speed range (km/h)				Flow range (Veh/h)				Density range (Veh/km)			
Statistical parameters	20–40	40–60	60–80	80–100	0–500	500–1000	1000–1500	1500–2000	25–50	50–75	75–100	100–125
Minimum	1.5	1.8	2.5	2.7	0.5	1.7	2.5	2.8	0.8	1.8	2.8	3.2
Maximum	2.7	3.9	5.0	5.4	1.7	3.1	4.2	4.8	1.6	3.2	4.6	5.1
Range	1.2	2.1	2.5	2.7	1.2	1.4	1.7	2.0	0.8	1.4	1.8	1.9
Mean	2.2	3.4	4.2	4.6	1.2	2.5	3.4	4.2	1.4	2.6	3.8	4.6
Mode	2.0	2.2	3.2	4.0	1.0	2.1	2.3	2.4	1.1	2.2	2.6	3.3
SD	1.01	2.18	3.56	3.87	0.82	1.57	2.42	4.45	1.86	2.84	3.57	3.80
CV	0.46	0.64	0.85	0.84	0.68	0.63	0.71	1.06	1.33	1.89	2.94	3.83
SE	0.02	0.03	0.04	0.05	0.01	0.02	0.03	0.07	0.04	0.05	0.05	0.06
Skewness	−0.24	0.49	0.72	0.95	0.48	0.69	1.62	1.94	−0.88	−1.58	1.73	2.34
Kurtosis	−1.15	1.24	1.65	1.76	1.10	−1.46	1.75	2.17	1.62	−1.90	2.43	3.11
15th percentile	1.6	2.0	2.6	3.2	0.7	1.9	2.2	3.0	0.9	2.1	3.0	3.4
50th percentile	1.9	3.3	3.8	4.1	1.1	1.8	2.8	3.9	1.2	2.4	3.5	4.2
85th percentile	2.5	3.7	4.7	5.1	1.3	2.8	3.8	4.4	1.5	2.8	4.4	4.7

highway's speed, flow, and density increase, the vehicles keep a more considerable distance from the edge of the road to avoid road crashes.

The SD and CV of the LP of vehicles were less for reduced speed, flow, and density ranges, while the SD and CV of the LP of vehicles were high for increased speed, flow, and density ranges. The SE, skewness, and kurtosis are seen to increase as traffic speed, flow, and density increase. Therefore, it can be said that stream speed, flow, and density influence the LP of vehicles. Moreover, the observed variation in the 15th, 50th, and 85th percentile for the LP of vehicles shows an increment with the increase in speed, flow, and density. Hence for safety reasons, vehicles maintain a more considerable distance from the interacting vehicles. This can be attributed to the drivers' propensity to travel at the optimal road speed for safety purposes, retaining relatively high speed limits.

9   Results and Discussion

The analyzed statistical data indicates that the distribution of the likelihood, followed by vehicle speed and TH, varies with changes in traffic flow and density rates. The study indicated distinct and significant variations, even with respect to the LP of vehicles. These results support the argument that the speed and TH analysis should consider traffic characteristics separately at the different flow and density levels. Therefore, it is important to explicitly consider the variations in the speed and TH distribution functions across the different flow and density levels when the microscopic simulation models are developed for analysis. More specifically, in calibration and validation of the generation of vehicle car-following models and lane changing algorithms. The LP of the vehicles increased with the increase in stream speed, flow, and density. It was found that at different traffic rates, the LP of the vehicles changes according to the traffic condition. Finally, the movement of the vehicle by maintaining a steady speed and desired TH, and optimal LP, is observed to be solely reliant on the traffic conditions.

The present study contributes to the existing literature by analyzing the traffic parameters under different mixed traffic conditions. The authors foresee that the researched traffic data from the study will aid in developing microscopic simulation models for various traffic conditions and can be used to calibrate and validate the build models. The results from this research provide significant insights into the extensive analysis of traffic variables for developing realistic simulation tools and human-like self-driving vehicles under varying traffic conditions on non-lane-based and heterogeneous highways.

Further, the study has explored and provided the working and technological usefulness of IR sensor devices for collecting traffic data under the different traffic conditions prevailing in India. Previous research used different methods for gathering traffic data; however, as per the authors' knowledge, no study has reported using IR sensor devices to capture the spatio-temporal characteristics of the traffic effectively and efficiently under mixed traffic environments. Additionally, the present findings

can assist in managing and controlling traffic to improve the efficiency of the highway traffic system, particularly in developing countries such as India, where ITS-based solutions are currently being looked upon.

10   Conclusion

This study uses a huge amount of traffic data collected to estimate the DPCU values for vehicle types at different traffic flow and density levels. This research has studied the variations in the speed and TH distribution functions at various traffic flow and density rates and has analyzed them. The study also seeks to identify and evaluate the impact of traffic parameters, such as speed, flow, and density, on the LP of vehicles. The distribution of speed and TH computed for different traffic flow and density levels shows a difference in the probability distribution patterns. Some noteworthy variations with regard to the speed and TH distributions were also observed. Furthermore, the LP of vehicles was also found to be significantly affected by variations in speed, flow, and density. This study could benefit traffic engineers and highway researchers to operate, control, and manage the NH in the future paradigm. The different traffic characteristics regarding similar and dissimilar specific-vehicle-type leader–follower pairs were not considered in this study, which could be examined extensively in future research.

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