Examining the Lane-Wise Time Headway and Speed Characteristics at Curb-Side Bus Stop on Four-Lane Divided Urban Arterials

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Abstract Increase in traffic flow demand on urban roads invites significant challenges in evaluation of operational performance measures and design of traffic flow facility. The complexity in design, analysis and modelling further increases due to presence of side friction in a form of curb-side bus stop. Present study is an effort on finding the impact of a curb-side bus stop on time headway and speed characteristics of traffic stream on individual lanes of four-lane divided urban roads. The field data are collected for study at four locations in two cities in India. Lane distribution analysis result indicates, more than 50% of vehicles tend to travel in inner lanes at bus stop resulting lower mean time headway in inner lane. Statistical analysis of time headway and speed data carried out to understand the vehicular behaviour by developing frequency distribution profiles. The relationship between mean time headway on inner lane and bus dwell time established to know the impact and duration of bus occupancy at curb side. The field data analysis performed at various locations showed a signification reduction in the mean speed of vehicles up to 22% due to bus stop. The present study also defined zone of influence at bus stop sections taking average speed of vehicular stream as measure of effectiveness. It is observed for every 20 m increase in zone of influence the percentage reduction in speed has been increased by 54.3%. The findings of the present study help engineers to design proper layout of bus stop facility and provide insight to manage the traffic operations on urban roads.

Introduction

India has the second largest roadway network in the world with almost 11% of total global urban population living in Indian cities (as per reforms in urban planning capacity in India, final edition, September 2021, [1]). As roadway transportation acts as an essential back bone to all economic activities, a significant increase in vehicular traffic flow demand is observed in the recent past over the world. The phenomenon results in recurrent traffic congestion in roadway network due to increase in the population of privately owned vehicles in cities. For accurate estimation of traffic performance measures, a detailed study is needed that involve vehicle interaction and its effect on traffic flow characteristics. Time headway is a microscopic parameter which can be used to relate with traffic flow at aggregate level for modeling and simulation of traffic flow behavior. It is defined as a time interval between two consecutive vehicles past a reference line in a travel lane or carriageway, measured in seconds. Speed is an important fundamental parameter plays a key role in regulating and controlling of traffic operations. In India, many studies on time headway and speed are considered for entire carriageway width in the analysis of an uninterrupted traffic flow facility. However, the smooth flow of traffic on an urban arterial road is commonly interrupted by various side-friction factors like curb-side bus stops, on-street parking,

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pedestrians, frontage access as they significantly contribute to reduce mobility and safety on the urban roads. Curb-side bus stop, which do not have a separate bus bay reduces the width of carriageway due to halting of a bus in outer travel lane. Vehicle stream characteristics are greatly influenced by the bus deceleration while approaching to a bus stop. A zone of influence where speed reduces, created mostly in the inner lanes due to bus manoeuvring. The traffic flow characteristics also get deteriorated that has an effect on overall service and efficiency of bus stop facility. Hence, the present study aims at investigating characteristics of time headway and speed of vehicles lane-wise at curb-side bus stop facility on four-lane divided urban roads.

Literature Review

Most of the researchers investigated the effect of endogenous factors-like flow, speed and density on time headway under homogenous and heterogeneous traffic conditions. Maximum authors worked on single headway distributions to avoid complexity. A negative exponential distribution fitting time headway data are generally observed in previous studies conducted for low and medium traffic volume conditions [2–12]. Many studies done in abroad suggested different statistical distributions combined distributions like double displaced negative exponential distribution under specified roadway and traffic conditions [13–16]. Al Ghamdi [4] attempted to determine the boundaries of flow for proposing models to determine average headway under prevailing traffic conditions [4, 17]. Jang [18] divided the traffic flow into different states based on flow ranged for, performing time headway analysis and suggested that Johnson SU was fitted best for low to medium flows and Johnson SB was suited best for further higher flows. Riccardo and Massimilano [19] conducted a study on time headway at different flow ranges on two-lane two-way roads showed that Inverse Weibull is the best fit for high flow ranges. Mohammed [20] studied the suitability of Weibull distribution on six-lane divided urban arterials under heterogeneous traffic conditions. Few more studies on urban arterials, proposed Gamma distribution model to be the best fit for medium traffic flow conditions [2, 21, 22]. Some studies conducted under higher volume conditions suggested log-logistic distribution model [18, 19, 23, 24].The log-logistic and Pearson (V) distributions were well fitted for the headway data under the higher volume ranges and Log-normal distribution is preferred under steady state and free flow conditions [6, 21, 25–27]. Many studies performed the headway data analysis by observing vehicle arrivals with Poisson distribution on single lane urban streets [3, 28] and Semi-Poisson distribution under vehicle platooning [16, 29, 30]. Some recent studies on mixed traffic

conditions suggested Generalized Extreme Value (GEV) distribution fits better at flows greater than 1500 vph [31, 32] and Generalized Pareto distribution fits well for the volume less than 1500 vph. One of the detailed studies on headway characteristics near bus stops as side friction was prepared by Nehir [33]. Pallela and Mehar [34] examined the time headway at curb-side bus stop on a four-lane divided urban arterial and found that the mean time headway on the inner lane is always lower than the outer lane under medium to heavy traffic volume [34]

A large number of literatures described speed distribution patterns in uninterrupted flow under homogeneous traffic conditions and few under heterogeneous traffic with interrupted flow conditions encounter by side friction. Most of the authors suggested normal distribution of speed data under free flow traffic state on rural and urban roads [35–38]. Dhamaniya [39] estimated speed spread ratio (SSR) ranging from 0.86 to 1.11 for multilane urban arterials define normal distribution. Gaussian mixture model was proposed by Jun [40] for congested flow condition and found the percentage reduction in speeds at a curb-side bus stop in a range of 23–30% in all working days [41].

As it is seen from the literature many studies carried out to examine the statistical distributions of time headway and vehicular speed on homogenous and heterogeneous traffic conditions for an entire roadway. However, time headway and speed characteristics of heterogeneous vehicular traffic stream are not explored lane wise which may alter the results under side friction like curb-side bus stop. Hence, the present study aimed at studying the lane-wise time headway and speed characteristics under the influence of side-friction for improving the operational conditions at bus stop facility. This study also analyses the influence of bus dwell time on time headway of vehicular traffic stream and examine traffic operational performance by defining zone of influence at bus stop.

Field Data Collection and Extraction

Field data was collected at four locations with bus stop section (BS1, BS2, BS3, and BS4) and upstream road mid-block sections (MS1, MS2, MS3 and MS4) located about 250 m apart without access points in between. A line diagram representing the location is shown in Fig. 1. Traffic inventory surveys are carried out manually to collect field data such as roadway width (RW), shoulder width (SW), median width (MW), number of lanes, and presence/absence of lane markings. Bus stop shelter length is measured using the measuring tape noted as bus stop length (BSL) at each bus stop sections. Traffic flow surveys were conducted parallelly at both sections (bus stop and mid-block) by using videography technique. This method is used to record traffic
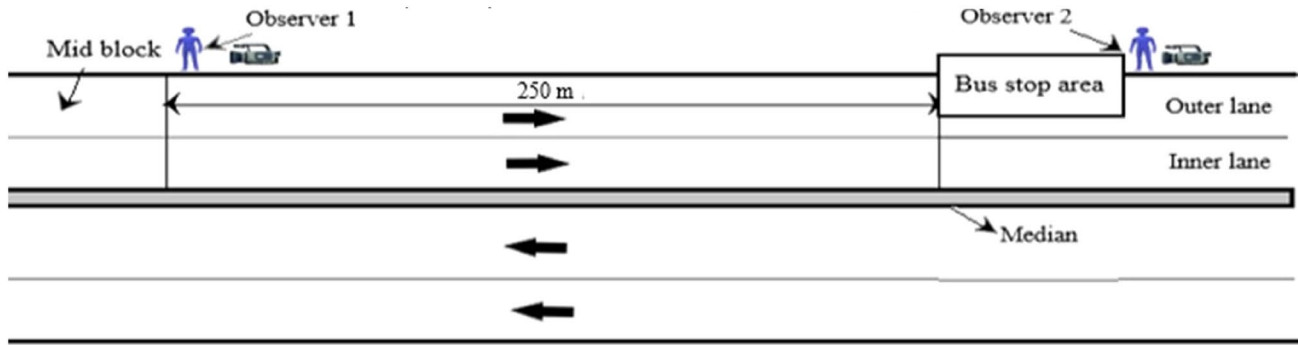
Fig. 1 Line diagram representing the two sections at a location

(a) Wadepally lake bus stop (BS1)

(b) Naimnagar bus stop (BS2)

(c) Ramanthapur bus stop (BS3)

(d) Medipally bus stop (BS4)

Fig. 2 Snapshot of curb-side bus stop locations

Table 1 Field Inventory data collected at selected study locations

No.	City	Study area	No of lanes	RW (m)	SW (m)	MW (m)	BSL (m)	Lane markings
I	Warangal	Wadepally	2	7.00	0.50	0.50	7.70	Yes
II		Naim Nagar	2	7.10	1.00	0.50	7.00	No
III	Hyderabad	Ramanthapur	2	8.50	1.50	1.50	6.50	No
IV		Medipally	2	6.70	2.00	1.25	6.34	Yes

operations for duration of 6 h (7AM to 1PM) covering both peak and off-peak hours. Snapshots of selected bus stop locations are presented in Fig. 2. Inventory survey details for each section are mentioned in Table 1.

In India, lane-wise extraction is difficult to carry out due to weak lane discipline of vehicles. However, stopping of bus at curb-side bus stop are observed mostly in the outer lanes thereby influencing the vehicular movement in the
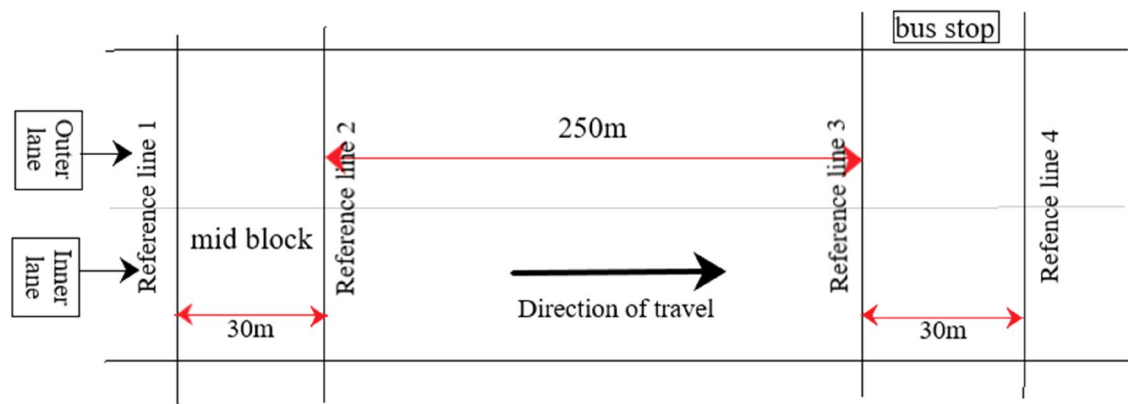
Fig. 3 A detailed Line diagram to explain the field data extraction procedure

inner lane. Hence, an attempt is made to perform lane-wise measurement of time headway and speed using 50–50 rule considering the position of a vehicle on reference lines across the roadway. If a vehicle occupies more than 50% in a lane, then it is assumed to be moving in that lane and vice-versa. A detailed line diagram explained the field data collection and extraction representing inner and outer lanes are shown in Fig. 3.

Two reference lines are marked at each section with a trap length of 30 m based on posted speed limit. Video cameras were mounted at each section covering both reference lines i.e. reference lines 1, and 2 at upstream road mid-block section and reference lines 3, and 4 at bus stop section. The recorded videos are played on a computer display and time of entry at each reference lines are noted. Classified traffic volume and continuous time headway data were extracted for each lane using the entry times at reference line 1 and reference line 3 for mid-block and bus stop sections, respectively. Time headway data are obtained based on the time difference between the entry times of two successive vehicles. For speed measurement, time difference between two reference lines at a section is estimated and speed is computed accordingly from a known distance of 30 m. Additionally, instantaneous spot speeds are also measured at every 20 m interval using radar gun for calculating the zone of influence. At bus stop sections additional factors such

as bus dwell time (BDT) and Bus Frequency (BF) are extracted. Bus dwell time is the amount of time when bus is stopped to serve passenger boarding and alighting, and BF is obtained by counting the number of buses arrive at bus stop in one hour (bus/hour).

Field Data Analysis

Volume Data Analysis

The vehicle types in the traffic stream observed at various locations are classified as: Two-wheeler (2w), Three-wheeler (3w), Car, Bus, LCV (light commercial vehicle), HCV (heavy commercial vehicle), and SMV (slow-moving vehicles-like Bicycle and Tractor). Corresponding traffic volume observed at different sections is converted to PCU (passenger car unit) according to the procedure given in Indo-HCM (2017) [42]. Traffic volume and vehicle composition observed at study sections are presented in Table 2.

Percentage of vehicle types manoeuvring in each lane are also analysed, and lane distribution (LD) percentage is calculated for entire traffic stream and for each vehicle type. Lane distribution describes the distribution of vehicular traffic across the roadway lanes. It is observed that the lane distribution varies differently at roadway mid-block and bus

Table 2 Traffic volume and vehicle composition on selected location

Location	Minimum Volume (PCU/h)	Maximum volume (PCU/h)	Vehicle composition (%)						
			Two-wheeler	Three-wheeler	Car	Bus	LCV	HCV	SMV
I	1169	1301	64.3	15.4	13.1	1.3	2.8	1.2	1.9
II	1508	2063	66.7	19.7	9.9	1.0	2.0	0.0	0.7
III	2730	3117	64.5	11.5	15.3	1.6	5.8	0.9	0.4
IV	2460	3044	64.8	5.8	18.6	2.9	6.1	1.5	0.4

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Table 3 Lane distribution of vehicle types at selected study locations

Location	Section	Lane type	LD	Lane distribution of each vehicle type (%)						
				Two-wheeler	Three-wheeler	Car	Bus	LCV	HCV	SMV
I	BS1	Inner	59.0	59.0	35.2	82.1	4.9	71.4	92.5	24.6
		Outer	41.0	41.0	64.8	17.9	95.1	28.6	7.50	75.4
	MS1	Inner	52.0	51.0	38.3	64.3	80.2	75.1	95.0	16.0
		Outer	48.0	49.0	61.7	35.7	19.8	24.9	5.00	84.0
II	BS2	Inner	56.0	53.2	48.9	81.4	47.8	74.6	0.0	0.0
		Outer	44.0	46.8	51.1	18.6	52.2	25.4	0.0	100
	MS2	Inner	52.0	49.0	50.5	60.8	82.7	76.2	0.00	0.00
		Outer	48.0	51.0	49.5	39.2	17.3	23.8	0.00	100
III	BS3	Inner	55.0	51.9	47.3	81.4	41.3	71.5	81.3	20.0
		Outer	45.0	48.9	52.7	18.6	58.7	28.5	18.8	80.0
	MS3	Inner	51.0	45.0	48.1	65.8	73.5	60.5	81.3	10.0
		Outer	49.0	55.0	51.9	34.2	26.5	39.5	18.8	90.0
IV	BS4	Inner	61.0	56.2	39.8	84.2	56.2	62.5	90.3	16.7
		Outer	39.0	43.8	60.2	15.8	43.8	37.5	9.7	83.3
	MS4	Inner	49.0	48.2	47.5	64.2	76.2	59.5	85.3	16.7
		Outer	51.0	51.8	52.5	35.5	23.8	40.5	14.7	83.3

stop sections. The lane distribution of vehicles at each location is presented in Table 3.

At the bus stop sections, the percentage share of two-wheeler, Car, LCV and HCV is more in the inner lane. The percentage share of public transport vehicle types, such as three-wheeler and bus is more in outer lane at bus stop. However, lane-wise distribution of traffic stream at bus stop section indicates more than 50% of vehicles tend to travel in inner lane due to stopping of buses in the outer lane.

Time Headway Analysis

The time headway characteristics of vehicular stream are analysed based on data collected at roadway sections with and without curb-side bus stop. Statistical parameters of time headway data estimated for each lane are presented in Table 4.

It may be observed that the mean time headway values obtained in the inner lane is less than the outer lane at bus

Table 4 Results of descriptive analysis of time headway data

Location	Section	Type	Sample size (N)	Mean TH (s)	Median TH (s)	Maximum TH (s)	Minimum TH (s)	Standard deviation (s)
I	BS1	Inner	1930	3.72	2.80	9.96	0.55	3.44
		Outer	1345	5.35	4.16	10.2	0.70	4.71
	MS1	Inner	1693	5.20	4.54	8.01	0.42	5.10
		Outer	1582	4.86	4.31	7.86	0.81	4.62
II	BS2	Inner	3704	2.08	1.36	5.68	0.35	1.94
		Outer	2946	2.59	1.84	6.60	0.32	2.38
	MS2	Inner	3426	2.30	2.06	4.12	0.41	2.10
		Outer	3225	1.84	1.53	3.94	0.56	1.48
III	BS3	Inner	4042	1.74	1.36	4.68	0.21	1.51
		Outer	3363	2.10	1.40	6.34	0.16	2.30
	MS3	Inner	3751	2.02	1.84	4.20	0.38	1.90
		Outer	3653	1.58	1.10	3.86	0.25	1.29
IV	BS4	Inner	3790	1.87	1.50	5.63	0.24	2.3
		Outer	2400	2.90	1.64	8.43	0.15	5.39
	MS4	Inner	2900	2.00	1.30	4.78	0.37	2.20
		Outer	3290	1.72	1.34	3.99	0.24	1.49

stop section. But at section without bus stop, mean time headway in inner lane is more than the outer lane. It shows that the lane utilization for traffic stream is non-uniformed at sections with and without bus stop. Hence, traffic behaviour at bus stop is impacted by the stopping of bus on outer lane as there is no separate bus bay. Non-uniform lane utilization led to uneven lane distribution and it results in increase in mean time headway values mainly under lane-wise analysis compared to full carriageway width.

Distribution of Time Headway Data

Distribution fitting helps to develop valid models considering a random process. Statistical distribution of headway data is carried out at 5% level of significance and best fit distribution types are identified based on goodness-of-fit test [43]. Three goodness-of-fit tests are popularly used in data analysis such as Kolmogorov–Smirnov, Anderson–Darling test and Chi-square tests. The goodness-of-fit test adopted in the present study is based on nonparametric Kolmogorov–Smirnov (K–S) test which is more reliable to validate predictive models for continuous data. The K–S test is defined by a null hypothesis (H_o: The data follow a specific distribution) and an alternate hypothesis (H_a: The data do not follow a specific distribution). The K–S static value quantifies the difference between the theoretical distribution function of the data and its reference cumulative distribution function as given in Eq. 1.

$$D = \max_{1 < i < N} \left(F(Y_i) - \frac{i-1}{N}, \frac{i}{N} - F(Y_i) \right) \quad (1)$$

where F is the theoretical cumulative distribution of the continuous distribution being tested at a level of significance of α. The hypothesis regarding the distributional form is rejected if the static value D is greater than critical value. The critical values for D are found in K–S test P-value table. The parameters like location, scale and shape of best fitted distributions are estimated by using maximum likelihood estimation (MLE) method. Location parameter shifts the distribution to left or right, shape parameter changes the shape of distribution and scale parameter stretches or compresses the distribution. Mean value of accepted best fitted distribution is noted.

Frequency distribution profiles are plotted to analyse the pattern of the best fit distribution at different bus stop sections. Time headway statistical distributions estimated for individual lane are validated by using K–S test at 95% confidence intervals. Table 5 presents the results of goodness-of-fit of individual lanes at curb-side bus stop. A brief description of statistical distributions observed for time headway in present study is given as follows:

- Generalized Gamma distribution

The Generalized gamma distribution is a continuous probability distribution with two shape parameters, and one scale parameter. It is generalization of the Gamma distribution and presents a flexible family of distributions used to model duration or time. It is suitable for modelling data with different forms of hazard rates. The probability density function and cumulative distribution function of Generalized Gamma distribution on the interval of $\gamma \leq x < +\infty$, are given by Eqs. (2) and (3). Probability density function

$$f(x) = \frac{kx^{k\alpha-1}}{\beta^{k\alpha}\Gamma(\alpha)}\exp\left(-\left(\frac{x}{\beta}\right)^k\right) \quad (2)$$

Cumulative distribution function

$$F(x) = \frac{\Gamma_{\left(\frac{x}{\beta}\right)^k}(\alpha)}{\Gamma(\alpha)} \quad (3)$$

where k Continuous shape parameter ($k > 0$), α Continuous shape parameter ($\alpha > 0$), β Continuous scale parameter ($\beta > 0$)

At section BS1 in inner lane, the shape parameter $\alpha < 1$, hence the density is unbounded with $\lim_{x \to 0+} f(x) = +\infty$ and increase in scale parameter, stretches the density, but does not influence the overall shape of the distribution.

- Weibull distribution

Table 5 Results of goodness-of-fit test on time headway for individual lane at bus stop

Section	Lane	Distribution	Static value	Critical value	Mean TH (s)	Distribution parameters
BS1	Inner	Gen. Gamma	0.0254	0.0309	3.72	$k = 0.733, \alpha = 2.276, \beta = 1.459$
	Outer	Weibull	0.0169	0.0370	5.35	$\alpha = 1.157, \beta = 6.970$
BS2	Inner	Log-Logistic	0.0290	0.0330	2.08	$\alpha = 2.092, \beta = 1.367$
	Outer	GEV	0.0216	0.0250	2.59	$k = 0.248, \sigma = 1.175, \mu = 1.398$
BS3	Inner	GEV	0.0187	0.0213	1.74	$k = 0.227, \sigma = 0.809, \mu = 1.047$
	Outer	GEV	0.0306	0.0318	2.10	$k = 0.318, \sigma = 0.998, \mu = 1.071$
BS4	Inner	GEV	0.0347	0.0430	1.87	$k = 0.281, \sigma = 0.888, \mu = 1.064$
	Outer	GEV	0.0324	0.0550	2.90	$k = 0.495, \sigma = 1.116, \mu = 1.186$

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The Weibull distribution is a continuous probability distribution and it is one of the most widely used distribution in reliability engineering. Weibull distribution has a shape parameter and a scale parameter and it can take into the form of other distributions based on the value of its shape parameter. The probability density function and cumulative distribution function of Weibull distribution on the interval of $\gamma \leq x < +\infty$ are given by Eqs. (4) and (5).

Probability density function

$$f(x) = \frac{\alpha}{\beta}\left(\frac{x}{\beta}\right)^{\alpha-1} \exp\left(-\left(\frac{x}{\beta}\right)^{\alpha}\right) \tag{4}$$

Cumulative distribution function

$$F(x) = 1 - \exp\left(-\left(\frac{x}{\beta}\right)^{\alpha}\right) \tag{5}$$

where α Continuous shape parameter ($\alpha > 0$), β Continuous scale parameter ($\beta > 0$). At section BS1 in outer lane, the data is more clustered around the left tail while the right tail of distribution is longer, with the shape parameter $\alpha < 2.6$, and scale parameter $\beta < 10$, the data is positively skewed (has a right tail) and the data gets pushed towards the left with increase in height.

- Log-logistic distribution

The Log-logistic is a continuous probability distribution for modelling a non-negative random variable and it is one of the most widely used distribution when hazard rate increases initially and decreases till end by taking a hump-shape. It can be a suitable substitute for Weibull distribution. Log-logistic model can be used to model the service times hence, it is applied for modelling time headways. As there is a heavy data at tails in inner lanes of BS2 section, Log-logistic model is observed to fit well. It has a shape parameter and a scale parameter. The probability density function and cumulative distribution function of Weibull distribution on the interval of $\gamma \leq x < +\infty$ are given by Eqs. (6) and (7).

Probability density function

$$f(x) = \frac{\alpha}{\beta}\left(\frac{x}{\beta}\right)^{\alpha-1}\left(1 + \left(\frac{x}{\beta}\right)^{\alpha}\right)^{-2} \tag{6}$$

Cumulative distribution function

$$F(x) = \left(1 + \left(\frac{\beta}{x}\right)^{\alpha}\right)^{-1} \tag{7}$$

where α Continuous shape parameter ($\alpha > 0$), β Continuous scale parameter ($\beta > 0$)

- Generalized extreme value (GEV) distribution

GEV distribution is developed with extreme value theory of continuous probability distributions. It is a probability of occurrence of extreme events. The GEV distribution is used to estimate the maxima of finite series of random variables. The parameters of GEV distribution are κ-shape parameter, σ-shape parameter ($\sigma > 0$), and μ-scale parameter. The probability density function and cumulative distribution function of Generalized Extreme Value (GEV) distribution on the interval of $1 + \kappa\frac{(x-\mu)}{\sigma} > 0$ for $\kappa \neq 0$ and $-\infty \leq x < +\infty$ for $\kappa = 0$ are given by Eqs. (8) and (9) respectively.

Probability density function

$$f(x) = \begin{cases} \frac{1}{\sigma}\exp-\left((1+z)^{-\frac{1}{\kappa}}\right)(1+z)^{-1-\frac{1}{\kappa}}\kappa \neq 0 \\ \frac{1}{\sigma}\exp(-z\exp(-z))\kappa = 0 \end{cases} \tag{8}$$

Cumulative distribution function

$$F(x) = \begin{cases} \exp(-(1+z)^{-\frac{1}{\kappa}}\kappa \neq 0 \\ \exp(-\exp(-z))\kappa = 0 \end{cases} \tag{9}$$

where $z = \frac{x-\mu}{\sigma}$, z is standard normal variate, k Continuous shape parameter ($k > 0$), σ Continuous shape parameter ($\sigma > 0$), μ Continuous scale parameter ($\mu > 0$)

The generalized extreme value distribution is often used to model the smallest or largest value among a large set of independent data, identically distributed random values representing measurements or observations. As the traffic volume is larger for BS3 and BS4 sections, GEV is observed to fit well both in inner and outer lanes.

It can be emphasized that the time headway of all vehicles fitted well with Generalized Gamma distribution in inner lane with traffic volume as 770 PCU/hr/lane and Weibull type distribution in outer lane with a little lower volume of 530 PCU/hr/lane. Log-logistic is the best fit for the inner lane headways under medium traffic volume as 1155 PCU/hr and GEV fits better at higher traffic flow in both inner and outer lanes. For example, at section BS2 the time headway distribution profile established for inner and outer lanes are shown in Fig. 4. Similarly, time headway distributions are also evaluated at upstream mid-block sections, and mean time headways are determined. It is observed that at low flow levels as lane position changes the type of distribution also changes which clearly shows the arrival patterns is affected at curb-side bus stop.

Effect of Dwell Time on Inner Lane Time Headway

The bus dwell time and bus frequency values are measured at selected locations. Table 6 provides the mean values
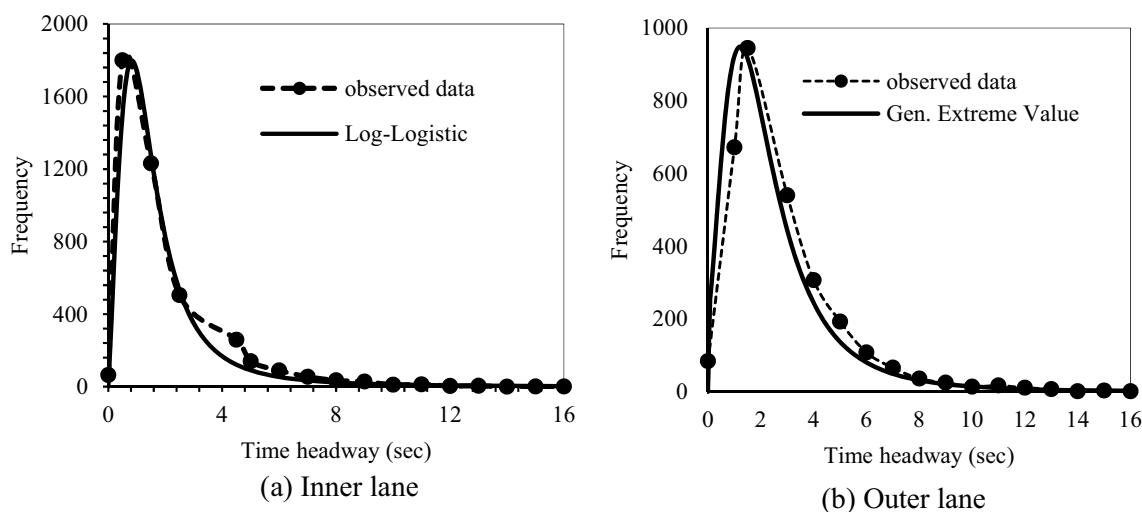
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Fig. 4 Lane-wise frequency distribution profiles of time headway at BS2 bus stop

Table 6 Mean Dwell time calculated at each bus stop section

Section	Location	BF (Bus/h)	Mean BDT (s)
BS1	Wadepally Lake	05	6.00
BS2	Naim Nagar	18	12.48
BS3	Ramanthapur	26	20.91
BS4	Medipally kaman	32	29.37
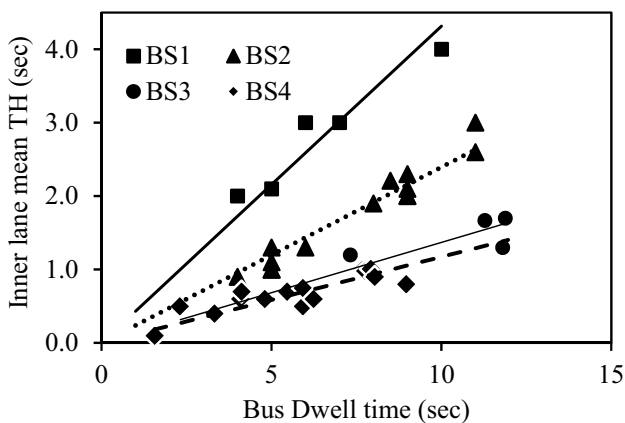
Fig. 5 Bus dwell time and inner lane mean time headway

these variables estimated for each location. The relationship between mean time headway of vehicles in inner lane and mean dwell time of bus arrived at bus stop is evaluated for each location. The bus frequency and mean dwell time are given in Fig. 5.

It is clear from the results that the mean time headway of vehicles in the inner lane increases with the increase in the dwell time of a bus. It is due to the fact that the vehicles maintain longer gap for increasing their

manoeuvrability and safety while moving through bus stop.

Speed Data Analysis

The statistical analysis of speed data is performed and parameters of speed charecteristics are estimated. Speed distribution curves are fitted at 95% confidence interval on all sections using K–S goodness-of-fit test. The result of speed distribution characteristics is provided in Table 7.

The reduction in the mean stream speed measured at bus stop locations is found as low as 6% at location I to as high as 22% at location IV. Reduction in the mean stream speed showed that the presence of a bus at bus stop highly affects the traffic stream performance. The speed distribution analysis confirms that the speed of mixed traffic stream follows Beta (4) distribution unlike normal distribution which fits well under low traffic volumes. Under mixed traffic conditions, platooning of vehicles increases behind a stopped bus under heavy traffic flow conditions deviating to skewed distributions from the traditional normal distribution. For example, speed frequency distribution graphs at Location 4 (Medipally) at both sections follow Fisher-Tippett (2) distribution but its parameters differ from other locations as shown in Fig. 6. It shows a change in the mean arrival rate at bus stop location to location. It also shows the curb-side bus stop interrupts the smooth flow of traffic and acts as a side-friction element.

A brief description of statistical distributions that observed for speeds data is given as follows.

• Beta (4P)

The four-parameter beta distribution is highly flexible in shape and bounded, and it is quite popular for attempting to fit to a

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Table 7 Speed characteristics measured at study locations

Location	Section	Speed characteristics (Kmph)				Distribution fitted
		Mean	Min	Max	V_{85}	
I	MS1	38.8	31.4	54.1	44.2	Beta (4)
	BS1	36.5	29.0	46.0	40.6	Beta (4)
II	MS2	31.5	20.1	44.1	35.4	Beta (4)
	BS2	28.8	19.9	34.8	31.5	Beta (4)
III	MS3	37.1	20.5	65.9	41.8	Dagum (4P)
	BS3	32.2	16.4	51.9	34.6	Dagum (4P)
IV	MS4	32.0	21.2	72.5	38.2	Fisher-Tippett (2)
	BS4	25.0	17.5	62.0	30.6	Fisher-Tippett (2)
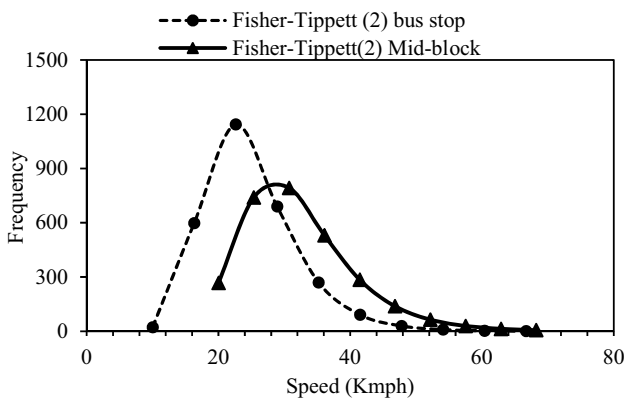
Fig. 6 Speed distribution patterns at BS4 mid-block and curb-side bus stop section

data set for a bounded variable. Beta (4P) has two continuous shape parameters and continuous boundary parameters. The probability density function and cumulative distribution function of Weibull distribution on the interval of $a \leq x \leq b$ are given by Eqs. (10) and (11).

Probability density function

$$f(x) = \frac{1}{B(\alpha_1 \alpha_2)} \frac{(x-a)^{\alpha_1-1}(b-x)^{\alpha_2-1}}{(b-a)^{\alpha_1+\alpha_2-1}} \qquad (10)$$

Cumulative distribution function

$$F(x) = I_Z(\alpha_1, \alpha_2) \qquad (11)$$

where $z = \frac{x-a}{b-a}$, B Beta function, I_Z Regularized incomplete beta function, α_1 Continuous shape parameter ($\alpha_1 > 0$), α_2 Continuous scale parameter ($\alpha_2 > 0$), a, b Continuous boundary parameters ($a < b$)

- Dagum (4P)

Dagum distribution is called as inverse Burr distribution and it can be used as an alternative to Pareto and Lognormal distribution to model a heavy tailed data. Dagum (4P) has four parameters namely, κ—shape parameter ($\kappa > 0$), α—shape parameter ($\alpha > 0$), β—scale parameter ($\beta > 0$) and γ—location parameter ($\gamma = 0$ yields the three parameter Burr Distribution). The probability density function and cumulative distribution function of four parameter Dagum distribution (4P) on the interval of $\gamma \leq x < +\infty$ are given by Eqs. (12) and (13).

Probability density function

$$f(x) = \frac{\alpha\kappa\left(\frac{x}{\beta}\right)^{\alpha\kappa-1}}{\beta\left(1 + \left(\frac{x}{\beta}\right)\right)^{\alpha\kappa+1}} \qquad (12)$$

Probability density function

$$F(x) = \left(1 + \left(\frac{x}{\beta}\right)^{-\alpha}\right)^{-\kappa} \qquad (13)$$

where κ shape parameter ($\kappa > 0$), α shape parameter ($\alpha > 0$), β scale parameter ($\beta > 0$) and, γ Location parameter

- Fisher-Tippett(2P)

The Generalized Extreme Value distribution (GEV) is also known as the Fisher–Tippett distribution, named after Ronald Fisher and L. H. C. Tippett. A detailed explanation about the distribution is covered in "Distribution of time headway data" section.

In order to understand which vehicle type highly suffered speed reduction at curb-side bus stop, mean speeds of individual vehicle type are evaluated for each lane. Table 8 presents the mean speed statistics for each vehicle type.

The vehicle type bus is found to have maximum reduction in speed i.e. about 30–52%. This reduction in due to lane changing manoeuvres of bus that forces other vehicles to reduce their speeds. Similarly, two-wheeler has maximum reduction in speed (19–27%) followed by three-wheeler (18–23%) and car (16–22%). This reduction in average speed of vehicles shows interference to the uninterrupted traffic

Table 8 Mean speed statistics for different vehicle type in study locations

Vehicle type	Condition	Average Speed (Kmph) at locations							
		I		II		III		IV	
		MS1	BS1	MS2	BS2	MS3	BS3	MS4	BS4
Two-wheeler	Inner	40.2	35.8	35.8	29.7	40.8	30.8	36.9	28.8
	Outer	38.1	30.9	28.5	26.3	31.2	28.1	30.8	27.9
Three-wheeler	Inner	36.7	32	32.8	26.4	38.9	29.8	29.9	23.9
	Outer	35.5	29.8	25.7	22.2	26.7	25.1	24.7	21.7
Car	Inner	43.9	38.1	35.6	28.1	39.3	29.1	34.4	26.7
	Outer	42.1	34.9	27.9	24.3	30.1	26.2	28.9	25.6
Bus	Inner	30.4	14.7	28.4	24.7	29.1	28.2	30.4	24.3
	Outer	20.9	13.8	15.6	9.3	16.4	10	12.4	9.9
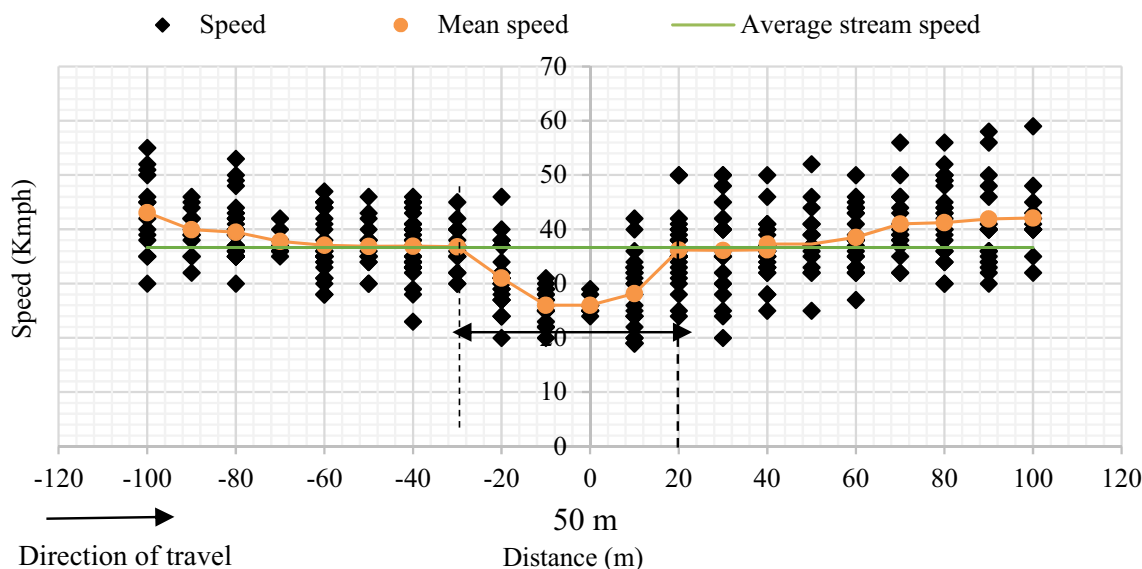
Fig. 7 Zone of influence at Wadepally (BS1) bus stop

flow. It is also observed that the vehicle types two-wheeler and car are having maximum reduction of speed in the inner lane whereas three-wheeler and bus have the same in outer lanes.

Analysing the Zone of Influence

The average speed of vehicles reduces significantly due to bus stop. The distance within which the deterioration to the vehicular speed may be observed is defined as zone of influence (ZI). To identify a zone of influence, a stretch of total 200m was selected (100 m downstream side and 100 m upstream side from bus stop). The spot speed data measured using radar gun on inner lane was aggregated at definite intervals. Average speed of all vehicles is calculated for every 20 m interval and ZI is determined as length

of section where vehicular stream speed reduces. Average speed measured across the bus stop zone is compared with the average speed at every 20 m. Figures 7, 8 and 9 represent the bus stop sections where average speed of vehicles was measured and determined the zone of influence. The variation in the length of ZI is observed in a range of 50 to 110 m across all selected bus stop sections. The variation of speed is found to be lower nearer to the bus stop in the influencing zone. For example, the ZI was found to be 50 m as bus stops on the outer lane nearby curb at Wadepally bus stop. Other vehicles start decelerating while approaching bus stop zone and need 50 m to regain its speed above average speed at down stream. It has been also found that at BS1 when a bus halts average speed of vehicles is observe to decrease at upstream point 30 m before approaching bus stop and increase at downstream beyond 20 m from bus stop centre. At section BS2, BS3 and BS4, the all vehicles start to
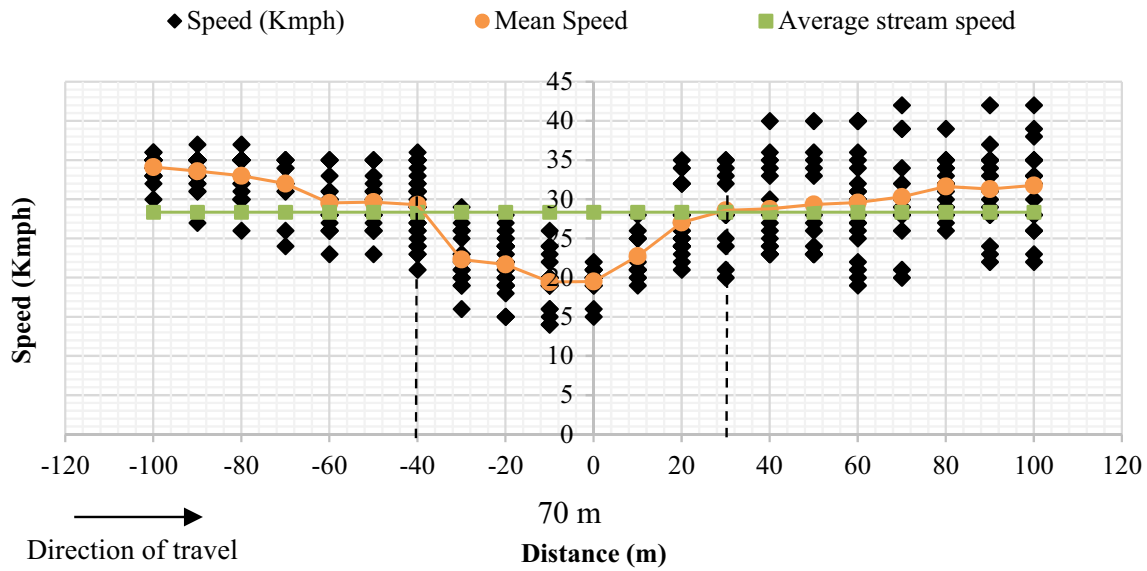
Fig. 8 Zone of influence at Naimnagar (BS2) bus stop
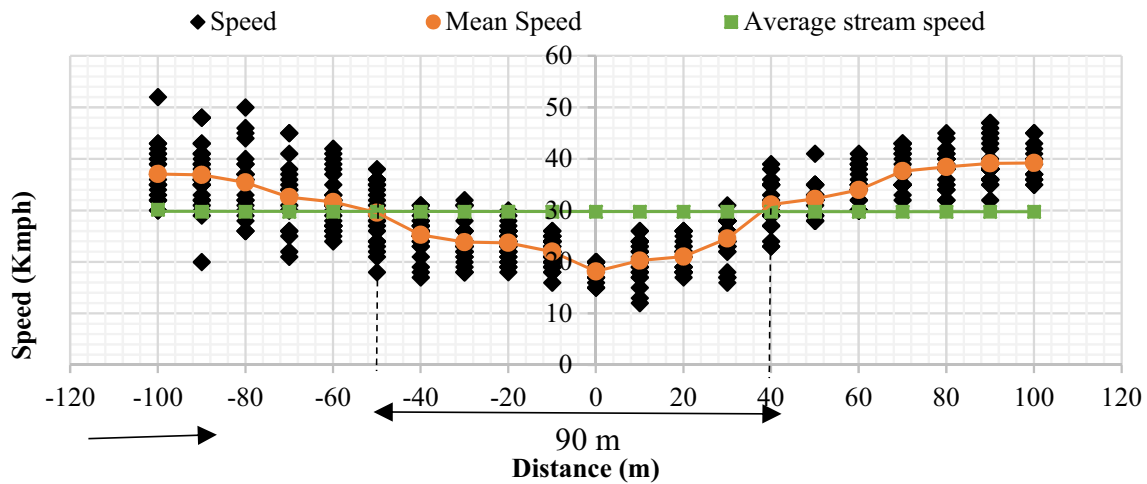

Fig. 9 Zone of influence at Ramanthapur (BS3) bus stop

decrease speeds at an upstream distance of 40 m, 50 m and 65 m, respectively, before approaching to the bus stop. After crossing the BS2, BS3 and BS4 bus stops, vehicles regain their speeds above the average speed at 30 m, 40 m and 45 m, respectively. The variation of speed measured nearer to bus stop is found to be lesser than the speed measured beyond the influencing zone of bus stop. Within the zone of influence, upstream influencing distances are observed to be larger than downstream distances. This shows that the presence of bus in outer lane of curb-side bus stop influence the upstream vehicles in traffic stream to reduce speeds for undergoing lane changing manoeuvre.

The length of influencing zone (ZI) determined at each bus stop location is plotted against percentage reduction in speed (PRS) (Fig. 10). It shows that the PRS at bus stop is increasing exponentially with the increase in the length of influencing zone. The relationship between PRS and ZI is plotted in Fig. 11. For every 20 m increase in zone of influence, percentage reduction in speed is increased at a rate of 54.3%.

The quantifying the rate of reduction of road speed for variable roadway and traffic conditions by considering all influencing parameters is essential for traffic planner to take policy decisions in establishing curb-side bus stop in urban areas. The above presented study helps planners to fulfil this need.
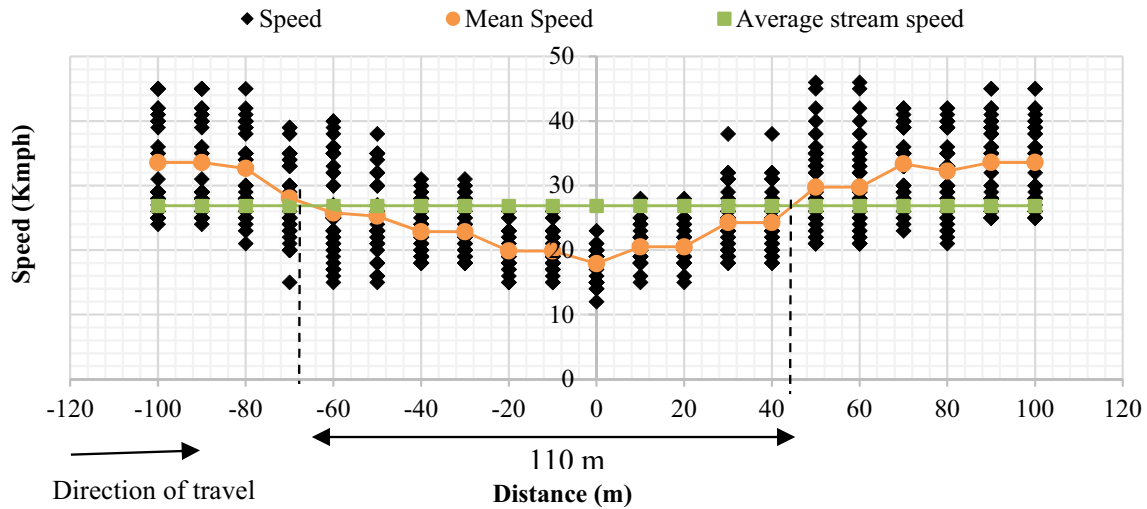
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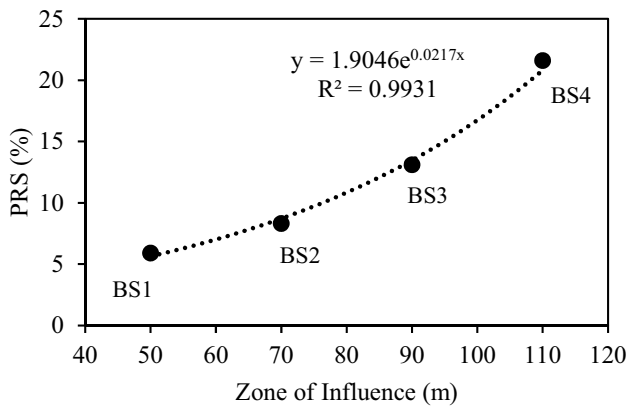**Fig. 10** Zone of influence at Medipally (BS4) bus stop

Fig. 11 Variation of PRS with zone of influence (ZI)

Results and Discussions

The present study attempts to find the impact of curb-side bus stop on time headway and speed characteristics of traffic flow stream on four-lane divided urban arterial roads in two different cities. The time headway and speed characteristics of vehicular traffic are analysed on individual lanes by performing lane distribution analysis. The results of lane distribution analysis indicates that there are more than 50% of vehicles tend to travel in inner lane at curb-side bus stop resulted in lower mean time headway values. The average time headway on inner lane is found to be less than the outer lane headway at curb-side bus stop locations due to increase in the percentage of slower moving vehicles in platoons due to stopping of bus in outer lane. At locations with a higher flow level, mean time headways are observed to be lower than that obtained at low flow sections. In statistical distribution analysis, distribution fit with lowest K–S static

value is considered as best-fitted distribution. It confirms that the presence of side-friction have affected the headway distribution on each lane. Flow wise analysis concluded that as traffic volume and lane position changes, time headway distribution profile of vehicle also changes. In order to study the effect of stopped bus on time headway, dwell time is analysed. Effect of dwell time of bus on inner lane mean time headway is analysed at each section to observe the effect of stopping of bus. Though the dwell time increases with increase in mean time headway values, the rate of increase or the slope is observed to be different for each sections.

The statistical analysis of speed data is performed and Speed distribution curves are fitted at 95% confidence interval on all sections using K–S goodness–of-fit test. The vehicular mean speed observed at various locations showed signification reduction at bus stop area of influence as smooth flow of traffic is interrupted. This resulted in deviation of speed distribution from the conventionally adopted normal distribution (Dey and Chandra 2006). The present study defined zone of influence (ZI) at bus stop sections based on average speed of vehicular stream measured at various points at upstream and downstream side on bus stop section. The variation of speed measured nearer to bus stop is found to be less than the speed measured beyond the influencing zone of bus stop. This shows that the presence of bus in outer lane of curb-side bus stop influence the upstream vehicles in traffic stream to reduced their speeds for undergoing lane changing manoeuvre. The results of the present study helps to examine the vehicular traffic flow performance at bus stop facility for improving level of service on four lane divided urban roads.

This study considered only single side-friction i.e. curb-side bus stop on four-lane divided sections. Further this study can be extended to multi-lane divided locations to

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understand the driving behaviour considering the influence of multiple side-frictions and varying geometric conditions.

Conclusions

The following major conclusions can be drawn from the above study:

- Lane distribution analysis concludes that the 68% of vehicles tend to travel in inner lane due to a presence of bus at bus stop therefore vehicles maintain less time than safe limit.
- A statistical distribution of time headway data describes poor operating conditions of traffic at bus stop. GEV fits well for traffic volumes greater than 1500 PCU/hr either in inner or outer lanes. However, without any interruptions to traffic stream, previous study showed log-Normal distribution fits better to describe headways for similar traffic conditions [26]. It confirms that the presence of side-friction affects the headway distribution on each lane.
- Time headway distribution is observed to change with the traffic volume and lane position of traffic stream
- The vehicular mean speed reduction is observed up to 22% at bus stop area of influence. Significant reduction in speed (PRS) is estimated with the increase in the length of zone of influence.
- The maximum reduction in the speed at bus stop section is observed for vehicle type two-wheeler (19–27%), followed by three-wheeler (18–23%) and Car (16–22%).
- The zone of influence (ZI) is varying in a range of 50 to 110 m on selected bus stop sections. Within the zone of influence, upstream distances are observed to be larger than downstream distances. This shows that the presence of bus in outer lane of curb-side bus stop influence the upstream vehicles in traffic stream to reduced their speeds for undergoing lane changing manoeuvre. It is observed that the percentage reduction in speed is increasing exponentially with increase in the length of bus stop influencing zone.
- Increase in the length of bus stop influencing zone contributed to increase in the time headways and decrease in average speed of vehicles.
- It is observed that for every 20 m increase in zone of influence, percentage reduction in speed is increased at a rate 54.3%.

The present study is involving future scope of development of headway models to be incorporated in computer simulation of traffic flow behaviour by incorporating curb-side bus stop effects suited under mixed traffic condition. The study also helps engineers to design the bus stop points appropriately for maintaining best operational performance on urban roads.

Declarations

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