European Transport Research Review (2018) 10: 3
https://doi.org/10.1007/s12544-017-0276-2

ORIGINAL PAPER

Headway distribution models of two-lane roads under mixed traffic conditions: a case study from India

Rupali Roy [1] · Pritam Saha [1]

Received: 26 April 2017 / Accepted: 28 November 2017 / Published online: 12 December 2017
© The Author(s) 2017. This article is an open access publication

Abstract

Introduction The time headway of vehicles is of fundamental importance in traffic engineering applications like capacity, level-of-service and safety studies. Further, the performance of traffic simulation depends on inputs into the simulation process and 'accurate vehicle generation' is critical in this context. Thus, it is important to define headway distribution pattern for the purpose of analyzing traffic and subsequently, taking infrastructure related decisions. In so far, majority of the researches on this subject are based on homogeneous traffic and effects of mixed traffic especially on two-lane roads are yet to be culminated. The present study, thus, aimed at investigating headway distributions on such roads under mixed traffic situation.

Methods Field study was conducted on two-lane highways in India that exhibits heterogeneity in its traffic composition. Contestant headway distribution models were evaluated and four distribution functions namely, log-logistic, lognormal, Pearson 5 and Pearson 6 were considered while modeling the headway data. The appropriate models were selected using a methodology based on K-S test and subsequent field validation.

Results Log-logistic distribution was found appropriate at moderate flow whereas, at congested state of flow it was Pearson 5. However, at unstable flow nearing capacity, both, following and non-following components of headways were observed to follow different distributional characteristics. Nomographs are developed for calculating the headway probabilities at different flow levels considering the appropriate distribution models. 'Probability of headway less than't's' increases with the flow rate and rate of such increase is considerably high for headways 7.5 s or more. This attributes to the fact that at heavy flow more vehicles are entrapped inside platoons and they move in following with shorter headways. Further, a comparison was made between the headway probabilities obtained in the current study and road segments that exhibit more or less homogeneous traffic. It was found that at moderate flow level proportion of shorter headways are considerably high under mixed traffic.

Conclusions The present paper demonstrates the effect of mixed traffic on distribution of time headways of two-lane roads. Presence of slower vehicles in such traffic leads to frequent formation of platoons, thereby, increases the risk taking behavior of drivers' while overtaking. As a result, proportion of shorter headways increases resulting in highly skewed observations. Thus, the study proposed Log-logistic distribution under medium flow since it can model events which have 'increased initial rate' and Pearson 5 under heavy flow to model 'highly skewed data'. The model outputs were accordingly compared with other studies and were found to explain the mixed traffic characteristics satisfactorily. The present study, thus, creates a starting point of further initiatives aimed at establishing a robust method of modeling headways on two-lane roads with mixed traffic.

Keywords Two-lane roads · Mixed traffic · Time headway · Distributions · Goodness-of-fit

✉ Rupali Roy
rupaliroy.nit@gmail.com

Pritam Saha
saha.pritam@gmail.com

[1] Civil Engineering Department, Indian Institute of Engineering Science and Technology, Shibpur, Howrah 711103, West Bengal, India

1 Introduction

Time headway is an important microscopic traffic flow parameter and defined as the time interval, usually measured in seconds, between successive vehicles in the traffic stream. Study on this parameter is important particularly in context to capacity analysis, safety studies, car following and lane changing behavior modelling and level of service evaluation [1]. Capacity of a roadway and saturation flow rate of an intersection is the reciprocal of minimum time headway; in a way that rear end collision does not occur even in the event of sudden stop of leading vehicles. Further, assessment of LOS on highways is predominantly based on the percentage of vehicles that move in following with shorter headways [2]. Defining headway distribution function is, therefore, considered as fundamental in traffic flow study and its' simulation issues. A key component of determining the performance of a simulation model is the generation of inter-arrival times as an input into the simulation process. However, most of the previous studies on this subject are based on homogeneous traffic and considered low and medium flow of traffic. In context to mixed traffic, there have been a very few research that focused on modeling headways under congested or heavy traffic flow in so far. Accordingly, there is a need to develop an appropriate headway model especially under mixed traffic situation while taking decisions on transportation infrastructure development [3]. At the same time, traffic congestion in many western countries has been a critical issue and transportation researchers have been trying to address it effectively. They are, therefore, in search of having a unified method of describing headways for the purpose of traffic characterization and modeling at congested state of flow; this is due to the fact that the conventional approach does not exhibit compatibility under such flow even if the traffic is homogeneous in character.

The negative exponential distribution is conventionally applied in describing the headway data. However, there have been a number of researchers who reported the use of several other models in order to explain the headway distribution pattern more explicitly if the prevailing traffic is heterogeneous in character and car-following interaction is frequent at increased flow level. This is more acute on two-lane roads where such interaction is reasonably frequent due to the presence of opposing flow and aggravates further especially under mixed traffic composed of a wide variety of vehicles in terms of static and dynamic characteristics. Statistically, the headway data can be described as exponential if the co-efficient of variation is unity resulting in an exact 45^0 plot of mean and standard deviation [4, 5]. However, research on heterogeneity effect into traffic flows indicates that co-efficient of variation is likely to deviate under such traffic mostly because of complicated traffic flow dynamics, thereby, making exponential model inappropriate in describing headways.

Over the past few decades, significant researches have been conducted while suggesting alternative distribution functions compatible to mixed traffic. The log-logistic and lognormal distributions were observed to describe headway data well at flow levels that corresponds to peak hour's traffic than off-peak hours, indicating a better approximation of congested traffic [6, 7]. By the same token, Pearson 5 and Pearson 6 distributions also exhibit their aptness at heavy flow and they provide a fairly decent fit under such flow while describing the headways [8]. After almost a century, this search is not yet over. In fact, transportation researchers are still working on reliable and practical descriptions of headways particularly if the prevalent traffic is extremely heterogeneous in character and composed of a wide variety of vehicles including the non-motorized ones.

There have been a number of studies that investigated headway distributions at low and medium traffic flow rates. However, studies that have been devoted to headway modelling at high flow, in which all vehicles are in the car-following state, are still insignificant [4]. Thus, the premise on which the present study is situated considers the effect of heterogeneity on headway distribution models and accordingly encompasses traffic flow ranging from moderate to congested, wherein such effect usually aggravates owing to frequent interaction between vehicles. Accordingly, an attempt was made to find the theoretical distribution models which fit well to headway data: log-logistic, lognormal, Pearson 5 and Pearson 6 distributions were considered in the present study. Appropriate models of headway distributions were selected using a methodology based on goodness-of-fit test (K-S test) considering 5% level-of- significance.

2 Research motivations

Over the past few decades, there have been a number of researchers who suggested several theoretical models for describing headways. Couple of experiences in urban settings with Indian traffic indicates that hyperlang distribution is best to describe the headway characteristics under mixed traffic conditions [9] whereas negative exponential distribution exhibits its compatibility over a wide range of traffic flow levels if the traffic consists of substantial percentage of smaller vehicles such as motorized two-wheelers [5]. Khasnabis and Heimbach [10] studied headway distribution models for two-lane rural highway under varying traffic flow levels in North Carolina. They applied six headway distribution models, namely, Erlang, negative exponential, Pearson Type III, Schuhl models, and their combinations and found Schuhl model appropriate for the headway distributions. Panichpapiboon [11] investigated and characterized the time-headway distributions of vehicles travelling on an urban expressway in Bangkok, Thailand and concluded that GEV distribution is most effective in modelling time headways. On the other hand, the exponential distribution was found to be the least effective distribution. Al-Ghamdi [4] studied time headways to establish boundaries in terms of traffic flow rate for each flow level. The negative exponential distribution was found to reasonably fit at the low flow state (less than 400 vph) whereas shifted exponential and gamma distributions were found to fit for medium flow (400–1200 vph). The Erlang distribution gave a decent fit for high flow state (more than 1200 vph). Based on a study in Finland, Luttinen [12] concluded that the gamma distribution is effective under low-to-moderate traffic volumes where probability for shorter headways is low and suggested that lognormal distribution could be considered as a model for the follower headway distribution. Riccardo and Massimiliano [8] analyzed headway distribution on rural two-lane two-way roads and suggested that the inverse Weibull distribution fits the headway data well. Abtahi et al. [13] studied different headway distribution models in the passing and middle lanes in urban highways under heavy traffic condition and concluded that lognormal and gamma models with 0.24 s and 0.69 s shifts exhibit their aptness in passing and middle lane respectively. Ren and Qu [14] studied headway distribution type analysis selecting three distributions namely, exponential, inverse gaussian and lognormal distribution. They found that the majority of headway samples follow an inverse Gaussian distribution.

The mixed models are more flexible to represent headways considering them into following and free-following components. Griffiths and Hunt [15] opined that double displayed negative exponential distribution is appropriate to model the vehicular headways. Zhang et al. [16] made an attempt to calibrate and examine the performance of various headway mixed models. The goodness-of-fit was checked by K-S test and also, visualized by Q-Q plot. The test result showed that the double displaced negative exponential distribution model provided the best fit to the urban freeway headway data and shifted lognormal distribution fits the general purpose lane headways very well. Besides, there are several other mixed models that have been developed and tested over the years in predicting headway distributions; they are respectively combined normal distribution and shifted negative exponential distribution, combined negative exponential distribution and shifted negative exponential distribution [1], generalized queuing model (GQM) [16] and semi Poisson distribution etc. Some mixed distributions were developed based on the assumption that headway consists of two components; following and free. Quite a few important models have been derived in accordance with this concept; they are Cowan M1–M4 [17], the generalized queuing model [18], and the semi-poisson model. Cowan's M3 model is, however, extensively investigated and applied because of its simplicity and easy approximation of describing longer headways [19].

Further, several studies investigated car-following interactions to identify free-moving vehicles in the traffic stream. An experience on Swedish roads reveals that vehicles could be considered free beyond 6 s headway when interaction of vehicles is usually observed to be nonexistent [20]. Similar results were also obtained by couple of studies conducted on two-lane roads [21, 22]. Dey and Chandra [23] proposed two continuous statistical distribution models, gamma and lognormal for desired time gap and time headway of drivers in a steady car-following state on two-lane roads under mixed traffic conditions. Mei and Bullen [24] reported that in a car-following situation time headways are log normally distributed and converge to the shifted lognormal distribution with a shift of 0.3–0.4 s at higher traffic volumes. Kumar and Rao [25] proposed that negative exponential distribution adequately describes the headways at low to moderate flow levels. A relationship was developed between the proportions of vehicles in platoons and mean headways with an assumption that the vehicles travelling at headways less than 2.0 s are in platoons. A study on mixed traffic, however, indicates that at car-following state headway between two vehicles depends on the length of the lead vehicle [26].

Above studies demonstrate various statistical distributions that could be applied in modelling the time headways. However, most of them are based on homogeneous traffic, thereby, making it intrinsic to investigate the effect of heterogeneity in the distribution models. Further, such effect aggravates in the event of heavy flow when interaction between vehicles is considerably high. This has been the motives of the present study wherein an attempt was made to develop accurate models considering a systematic analysis of headway data under mixed traffic.

3 Field data collection

Field studies were carried out to observe time headways on a National Highway (two-lane highway) in the north-east India, popularly known as the Assam-Agartala road. A highway section of about 20 km length, close to the capital city Agartala of the state of Tripura, was selected for conducting the study. Since road side development is typical in nature on highway section that connects an important, but small or medium-sized city, the study section exhibits different traffic characteristics than those in rural highways and urban arterials; in a way that it produces traffic ranging from bicycles to heavy trucks with the average speeds varying between 100 and 10 km/h. Despite the fact, vehicles other than two-wheelers were observed to follow lane discipline since they have only one lane for each direction of flow. Traffic data was captured covering a wide range of traffic flow: moderate to heavy flow situation which typically correspond to a volume to capacity ratio of 0.6 to 1.0. Further, study sites were selected in such a way so that they are free from the effect of intersection, curvature, ribbon development and also pavement conditions are good and uniform (see Fig. 1).

Video photographic survey technique was adopted while collecting field data. A reference line was marked on the pavement and two observation points were chosen for installing the video cameras; one in each direction, for recording the time when front and rear end of a vehicle cross the reference line. Heavy flow situation was investigated next to a bottleneck created by closing one lane of the two-lane carriageway and also, by stopping traffic movements for about two minutes to examine the discharged flow on the study section. Several

Fig. 1 Camera view at study section (image by author)

such trials were made in order to ensure adequate sample size for the purpose of analysis. Traffic police help was taken for conducting the study.

The video files were then played on a computer to extract the traffic data. The necessary readings i.e. vehicle type, entry and exit time of front and rear ends of the vehicles were noted down independently for the specified locations. Accordingly, headways between successive vehicles were determined as illustrated in Table 1 and histograms that contemplate the distributions of observed headways were subsequently plotted (see Fig. 2). The plot indicates a large proportion of shorter headways at moderate and heavy flow. Speeds of vehicles were also determined based on their category wise average length [27] and the time that they have taken while covering it. The possible capacity of the highway section was observed to be around 2300 pc/h for the prevailing mixed traffic [28] and it was used in computing volume to capacity ratio in subsequence; values that range between 0.6–0.7 and above 0.7 were used to approximate the moderate and heavy flow respectively. At almost all flow ranges, proportion of two-wheeler and car was observed to be significant; in the range of about 25–40 and 15–35% respectively. Further, presence non-motorized vehicles were sizable with city bound traffic; in a way that they share around 20% of total traffic.

4 Headway distribution modelling

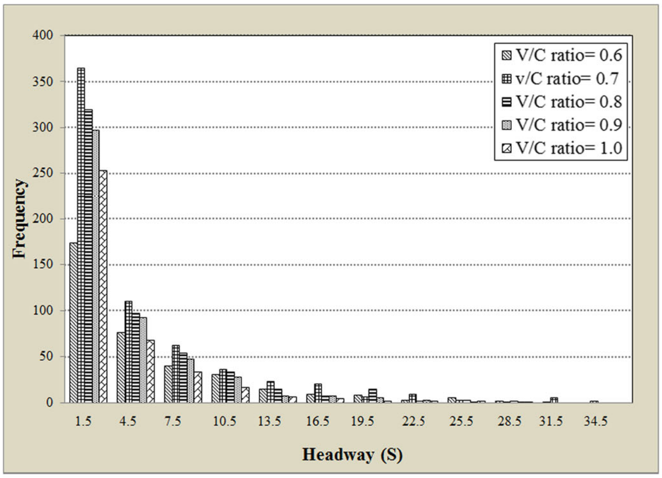
In an attempt to find an appropriate distribution function for describing headway data, the compatible statistical models have been critically reviewed and compared. Adams, as early as 1936, established that Poisson distribution could be applied to vehicle arrivals [29] and since then it has been extensively employed in many theories of traffic flow. Statistically, inter-arrival time i.e. headway between successive arrivals would follow negative exponential distribution in the event of Poisson arrivals. Therefore, negative exponential distribution is commonly used for headway modelling. However, the assumption of Poisson arrival could be well applied if traffic volume is considerably low and also, there are two factors that limit the application of negative exponential distribution to the headways.

Firstly, negative exponential distribution spreads over the entire range of headways from zero to infinity and the probability density is maximum at $h(t) = 0$. This seems to be impractical since a vehicle has a finite length and finite speed resulting in an existence of a minimum finite headway.

Secondly, at increased traffic flow levels formation of platoons is frequent resulting in an increase of shorter headways. Majority of them cluster within a certain short range thereby,

Table 1 Sample data collected on the selected highway section

Type of vehicles	Time in (Front axle)	Time out (Rear axle)	Lapsed time (Sec)	Speed, kmph	Headway (sec)
Car	00:15:49.000	00:15:49.850	0.850	21.18	
Two wheeler	00:15:50.000	00:15:50.270	0.270	26.67	00:00:01
Car	00:15:51.000	00:15:50.875	0.875	20.57	00:00:01
Two wheeler	00:15:55.000	00:15:51.310	0.310	23.23	00:00:04
Car	00:15:57.000	00:15:55.825	0.825	21.82	00:00:02
Three wheeler	00:16:01.000	00:16:01.450	0.450	24.00	00:00:04
Two wheeler	00:16:03.000	00:16:03.290	0.290	24.83	00:00:02
Two wheeler	00:16:04.000	00:16:04.320	0.320	22.50	00:00:01
Two wheeler	00:16:06.000	00:16:06.290	0.290	24.83	00:00:02
-	-	-	-	-	-
-	-	-	-	-	-



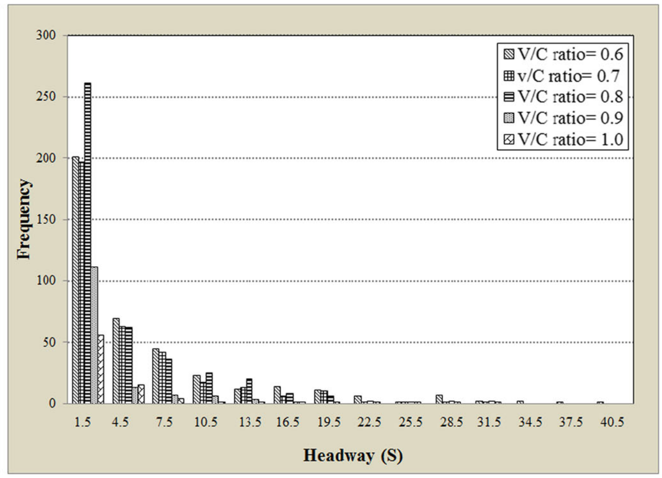


Fig. 2 Histograms of observed headways at different flow level: **a** west bound and **b** East bound traffic

hypothesizing of negative exponential distribution over the entire range becomes inaccurate.

Over the years, various modifications on the basic Poisson distribution have been proposed to compensate these disagreements [30]. Moreover, empirical investigations with mixed traffic indicate that the heterogeneity effect of traffic stream makes exponential model inappropriate in describing headways [7, 9, 11]. The premise on which the present study is based considers moderate and heavy flow of traffic wherein frequent car following interaction is apparent. This calls for a systematic investigation aimed at determining alternative models that would capture the characteristics of such traffic. Table 2 exhibits the contestant headway distribution models that could be applied at different traffic operating conditions and indicates that Pearson 5 (2P), Pearson 6 (3P), log-logistic and lognormal models could be appropriate in describing headways at moderate and heavy flow [6–8].

Besides, studies indicate that distribution of headways varies with the rate of traffic flow [2, 4].Such variation could be classified as random, intermediate and constant state respectively for low, medium and heavy flow of traffic: at random state there is no interaction between successive vehicles and their arrival is independent to each other, whereas, a constant state reflects following state of flow with constant headways near to capacity [31]. Since past few decades, significant efforts have been made in developing suitable distribution models for headways at low and medium traffic flow levels. However, attempts in describing them at heavy flow, in which all vehicles are in the car-following state, is still insignificant [4]. This has been the motives of taking initiatives for proposing distribution functions that exhibit aptness in modelling headways at moderate to heavy flow.

Several researchers have reported that the log-logistic distribution model is better for fitting headway data of peak hours

Table 2 Contestant headway distribution models

Author (Year)	Name of the distribution function	Comments
Adams (1936)	Poisson distribution	Vehicle arrival in short periods
Greenberg (1966) Mei and Bullen (1993) Luttinen (1996) Dey& Chandra (2009)	Log normal distribution	Car-following models
Kumar and Rao (1998) Al-Ghamdi (2001) Arasan and Koshy (2003)	Negative exponential distribution	Modelling of headways at low flow ; headways of smaller vehicles such as two-wheelers
Luttinen (1996)	Gamma distribution	Low to moderate flow level
Yin et al. (2007) Jang (2012)	Log-logistic distribution	Congestion status / Heavy flow at peak hours
Riccardo and Massimiliano (2012)	Pearson 5, Pearson 6	Meet all the traits at heavy flow
Griffiths and Hunt (1991) Zhang (2007)	Double displayed negative exponential distribution	Appropriate for mixed traffic in urban scenario

than off-peak hours i.e. at congestion state [6]. In fact, the logistic distribution affords a good approximation to the normal distribution and the log-logistic distribution in the same way approximates well the lognormal distribution which, apparently seems to be appropriate in car following state. Pearson 3 distribution, which is basically a very general case of negative exponential distribution and normal distribution as well, could be used for headway modelling at moderate flow levels [32, 33]; this is perhaps the most general function that traffic engineers use under such traffic. Similarly, Pearson 5 and Pearson 6 distributions reveal their appropriateness in time headway modelling under heavy flow of traffic [8].

Thus, the present study considers four distributions namely, log-logistic, lognormal, Pearson 5 and Pearson 6 for headway modelling at moderate and heavy flow of traffic. Eqs. 1–4 demonstrates the probability density function of the log-logistic, lognormal, Pearson 5 and Pearson 6 distributions and investigations were accordingly made with these functions.

Log-logistic distribution,

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

Lognormal distribution,

$$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} \times \exp\left(-\frac{(ln\, x-\mu)^2}{2\sigma^2}\right) \tag{2}$$

Pearson 5 distribution,

$$f(h) = \frac{exp\,(-\beta/h)}{\left\{\beta\mathrm{r}(\alpha)\left(\frac{h}{\beta}\right)^{\alpha+1}\right\}} \tag{3}$$

Pearson 6 distribution,

$$f(h) = \frac{\left(\frac{h}{\beta}\right)^{(\alpha_1-1)}}{\beta B\,(\alpha_1,\alpha_2)\left(1+\frac{h}{\beta}\right)^{(\alpha 1+\alpha 2)}} \tag{4}$$

Where, h = time headway; α = Shape parameter >0; β = Scale parameter >0; μ = Mean; σ= Standard deviation; Γ = Gamma function; B = Beta function

5 Empirical investigations

5.1 Descriptive statistics of the headway data

The fundamental statistical properties of the headway data such as mean, median, standard deviation, co-efficient of variation were examined at different volume to capacity ratio and presented in Table 3. A comparison of mean and median values indicates that at all flow scopes the median is less than mean. It indicates concentration of short headways; in a way that most of the drivers choose headways less than mean. This attributes to high risk-ability of driver population which results reduction in safety as a consequence. Similar results were also obtained in a study on time headway distributions under heavy traffic flow conditions in urban highways of Isfahan [13]. A careful examination of Table 3 reveals that with the increase of flow rate the mean and standard deviation of headways at all flow scopes decrease; this is somewhat expected because of the change in headways from random to constant state.

Further, in the event of negative exponential distribution, the mean and standard deviation should have equal value resulting in a 45^0 plot. Thus, statistically the headway data can be described as exponential if the co-efficient of variation is unity. However, Table 3 indicates that it exceeds unity at all the flow scopes pertaining to moderate and heavy flow. A study on urban roads of Riyadh reported that usually such co-efficient of variation falls in the range of 0.5 to less than 1.5 corresponding to the flows that range between 500 and 2000 vph [4]. However, the present investigation elucidates a higher range, from about 1.05 to 1.35, even when the observed flow is in the range of 900–1000 vph. This is evidently attributable to the effect of wide variety of vehicles in the traffic composition.

Figure 3 displays the scatter plot of the mean and standard deviation of the observed data set and makes it apparent that the data points do not exhibit satisfactory agreement with the 45^0 plot signifying inappropriateness of the negative exponential distribution in describing headways. The present study accordingly explicates the applicability of four distribution functions that seem to be compatible to such traffic while modelling headways; they are respectively log-logistic, lognormal, Pearson 5 and Pearson 6.

5.2 Statistical modelling of time headways

The statistical models should be used to fit the observed headway data in an attempt to find an appropriate model of headway distribution. Negative exponential distribution is normally used to describe the distribution pattern of highways. However, there have been a number of researchers who reported the use of several other models in order to explain the headway distribution pattern more explicitly. The extent of fit of the selected distributions to the data points is examined based on goodness-of-fit tests. In traffic engineering two such tests are commonly used: the chi-square test and the Kolmogorov–Smirnov (K-S) test.

In the present study, K-S test is chosen to measure goodness-of-fit of the selected headway models to the

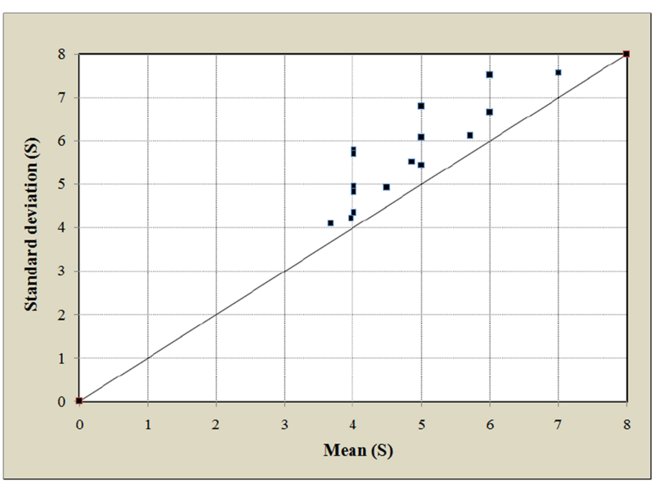
Table 3 Descriptive statistics of the headways

	v/c ratio	Mean (sec)	Median (sec)	Standard deviation (sec)	Co-efficient of variation	Skewness	Kurtosis	Sample Size (Nos.)
West bound traffic	0.6	5.70	4.50	6.11	1.07	2.05	4.63	744
	0.7	4.86	1.50	5.54	1.14	2.23	5.48	1302
	0.8	4.49	1.50	4.92	1.09	2.16	4.89	1110
	0.9	3.97	1.50	4.21	1.06	2.41	6.92	990
	1.0	3.66	1.50	4.10	1.12	2.84	9.97	782
East bound traffic	0.6	6.00	1.50	7.05	1.17	2.14	4.77	812
	0.7	4.69	1.50	5.05	1.08	2.12	5.04	738
	0.8	4.50	1.50	5.17	1.15	2.30	6.12	852
	0.9	3.60	1.50	5.12	1.43	3.29	11.71	314
	1.0	3.55	1.50	4.78	1.34	2.89	9.82	356

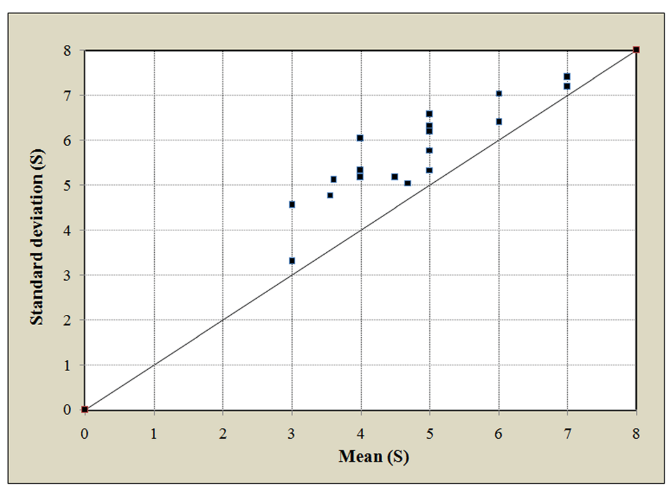
observed headways. The reason behind this decision was due to certain advantages that the K-S test offers over the chi-square test; K-S test can use data with a continuous distribution and there is no minimum frequency per test interval [1]. The K-S test statistic is calculated by determining the difference between the cumulative percentage of the measured frequency and the cumulative percentage of the expected frequency. The K-S test statistic, "D" was computed at the desired significance level for the selected distributions and the distribution which is expected to give the smallest "D" value was considered as the best fitted model.

The null hypotheses for each test were as follows: 'the compatibility hypothesis of headway distribution with fitted model was rejected (P-value < α) or not rejected (P-value > α)'. The '*p-value*' is defined as the probability of obtaining a result equal to or "more extreme" than what was actually observed, when the null hypothesis is true [13, 34]. A critical value is the point on the scale of the test statistic beyond which the null hypothesis is rejected, and is derived from the level of significance (α) of the test. If the test statistic exceeds the critical value for the predefined significance level then the null hypothesis is rejected. The null hypothesis cannot be rejected when the hypothesized distribution passes the K-S test [31]. However, if the hypothesized distribution is rejected by the K-S test, it signifies that the distribution is not good enough to model the empirical distribution.

Table 4 provides the estimated parameters for the selected distribution models and their goodness-of-fit test details. For both direction flows, west and east bound traffic, log-logistic distribution exhibits acceptable statistical validity in terms of K-S test at moderate flow levels that correspond to volume to capacity ratio of 0.6–0.7, while Pearson 5 demonstrates its strength in describing headways under congested traffic condition; they are represented in Fig. 4. However, at unstable flow nearing capacity, acceptability of Pearson 5 was rejected on the basis of Hypothesis test for both directional traffic flows. Virtually, both following and non-following headways are significant at such flow level and perhaps the trends in



(a)



(b)

Fig. 3 Scatter diagram for standard deviation vs. mean of headways: **a** west bound and **b** East bound traffic

Table 4 Goodness-of-fit test details and the estimated parameters of the fitted distribution model

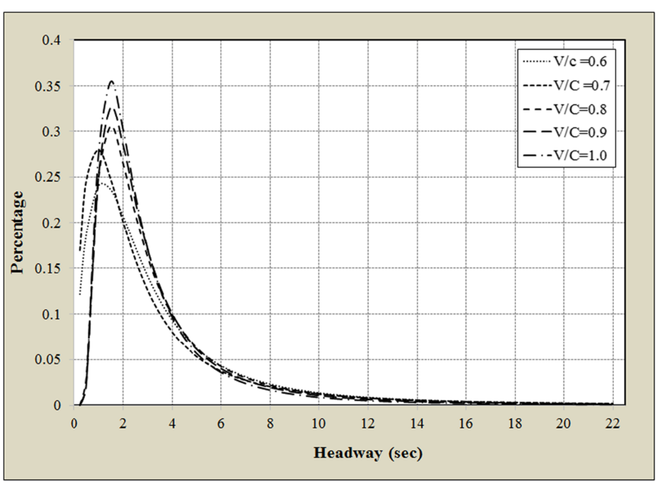
	v/c ratio	K-S test statistic (D-value)				Estimated Parameters (α [1], β [2])	P – Value[3]	Significance level	Critical value[3]	Hypothesis test
		Log logistic (2P)	Pearson 5 (2P)	Pearson 6 (3P)	Lognormal					
West bound traffic	0.6	0.26467$^{(1)}$	0.33164$^{(2)}$	0.33281$^{(3)}$	0.3420$^{(4)}$	1.7277; 2.5374	0.22670	0.05	0.37543	Accept
	0.7	0.33262$^{(1)}$	0.36204$^{(3)}$	0.36038$^{(2)}$	0.3643$^{(4)}$	1.6063; 1.9653	0.08819	0.05	0.39122	Accept
	0.8	0.41250$^{(4)}$	0.36275$^{(1)}$	0.39565$^{(3)}$	0.3652$^{(2)}$	1.9385; 4.2904	0.09016	0.05	0.39256	Accept
	0.9	0.65284$^{(4)}$	0.35135$^{(1)}$	0.49904$^{(3)}$	0.3805$^{(2)}$	2.2151; 4.7249	0.07057	0.05	0.38925	Accept
	1.0	0.69634$^{(4)}$	0.44933$^{(1)}$	0.44968$^{(2)}$	0.5168$^{(3)}$	2.4433; 4.9689	0.04634	0.05	0.40925	Reject
East bound traffic	0.6	0.28394$^{(1)}$	0.33164$^{(2)}$	0.33831$^{(3)}$	0.3492$^{(4)}$	1.7301; 2.7077	0.23508	0.05	0.34890	Accept
	0.7	0.33563$^{(1)}$	0.36242$^{(3)}$	0.35428$^{(2)}$	0.3686$^{(4)}$	1.8991; 2.1644	0.13807	0.05	0.39122	Accept
	0.8	0.41250$^{(4)}$	0.36484$^{(1)}$	0.39565$^{(3)}$	0.3829$^{(2)}$	1.9199; 4.1315	0.09857	0.05	0.38431	Accept
	0.9	0.62579$^{(4)}$	0.37341$^{(1)}$	0.49904$^{(3)}$	0.4596$^{(2)}$	2.6198; 4.8490	0.09186	0.05	0.39122	Accept
	1.0	0.69634$^{(4)}$	0.43762$^{(1)}$	0.46675$^{(2)}$	0.4964$^{(3)}$	3.4817; 6.5551	0.03644	0.05	0.41926	Reject

[1] Shape parameter > 0; [2] Scale parameter >0; [3] Corresponds to the lowest K-S test statistic

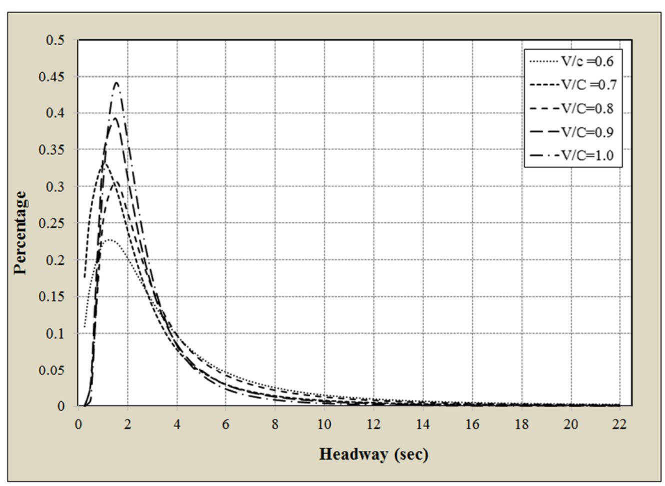
distributional characteristics are different for them. Accordingly, the present study creates a starting point of further initiatives aimed at developing an approach that would effectively describe headways at such flow by decomposing them into following and free components.

Experiences with the mixed traffic on two-lane roads indicate that such traffic mostly contains two groups: restrained and unrestrained. The restrained group is composed of those drivers who are travelling at or below their desired speed in a platoon by choice; they do not take any attempt to overtake even if there is an opportunity. The unrestrained group, on the other hand, includes those drivers, who are either not in a platoon and travelling at their desired speed or trapped inside a platoon and travelling below their desired speed with a continuous search in finding an acceptable gap to pass. The present study, therefore, made an attempt to develop nomographs considering the appropriate distribution models (see Table 4 and Fig. 4) for calculating the headway probabilities (probability of headway less than‘t’s) at different flow levels (see Fig. 5). As expected, probability of headway less than‘t’s increases with the flow rate and rate of such increase is considerably high for headways 7.5 s or more. This, accordingly, signifies that at heavy flow levels, the proportion of the unrestrained group tends to be higher because of large proportion of shorter headways in the traffic.

However, it is imperative to test the validity of model outcomes while representing the existing traffic system; in a way that it reproduces the system behaviour with good amount of accuracy. A further attempt was, therefore, made to assess the validity of the proposed model on the basis of a pilot study conducted on a different highway section (SH-13, a state highway that passes through the state of West Bengal, India)



(a)



(b)

Fig. 4 Probability density functions of headways at different flow levels: **a** west bound traffic and **b** East bound traffic which exhibits similar traffic characteristics. Theoretically calculated probabilities of headways were plotted against those observed at field in order to compare how rational the outcomes are with respect to field observations. The variability of predictions was determined based on the nomographs (see Fig. 5) developed for both directional traffic and field data obtained from the pilot study section; they are expressed in terms of 'standard error of the estimate (SEE)'. SEE values were found to be about 0.052 (Fig. 6a), 0.041 (Fig. 6b), 0.054 (Fig. 6c) and 0.059 (Fig. 6d) respectively indicating satisfactory agreement between the probability of headways of field data and model outcomes.

Ideally, the modelling paradigm will have some bearing on the system behaviour if expected probabilities are approximately equal to empirical probabilities. However, since 'traffic composition' and also, 'drivers' behaviour' in the pilot study segment are different to some extent, the data points do not lie on the same line and deviate from the anticipated line of agreement. The 'deviation' is shown by the 'blue zone' which explicates that the model may be valid in the sense that it represents the system behaviour with reasonable amount of accuracy.

6 Discussion

Developing an appropriate headway distribution model is an important step in traffic modelling and simulation. Thus, it is imperative to characterise the vehicle time headways statistically using a distribution function. Conventionally, negative exponential distribution function is used; however, several studies on mixed traffic have shown that it does not capture the characteristics of mixed traffic especially on two-lane roads where interaction takes place in both the directions. Besides, arrival pattern of vehicles changes considerably with the flow which may consequence different distributions to work better at different flow conditions. The lookout of the current study was, therefore, to investigate the appropriate headway distribution model on such roads under mixed traffic.

The present paper has proposed a statistical framework for modelling headways and determined the probabilities of headways at different flow levels. As anticipated, 'probability of headway less than't' sec' was observed to increase with flow rate; this is attributed to the fact that vehicles are entrapped inside platoons and they start moving in following (see Fig. 5). This is particularly true when the proportion of slower vehicles in the traffic stream is significant. In an attempt to investigate this fact, the current study made a comparison between headway probabilities obtained in the current study and road segments that exhibit more or less homogeneous traffic (see Table 5). Two flow levels, 600 and 700 veh/h were randomly chosen and two international experiences respectively in North Carolina [10] and Ohio [31] were considered for comparison.

Impedance to faster vehicles and availability of passing opportunities, effect of which is manifested in the amount of platooning, have significant impact on headway distribution pattern and thus, affects traffic modelling and

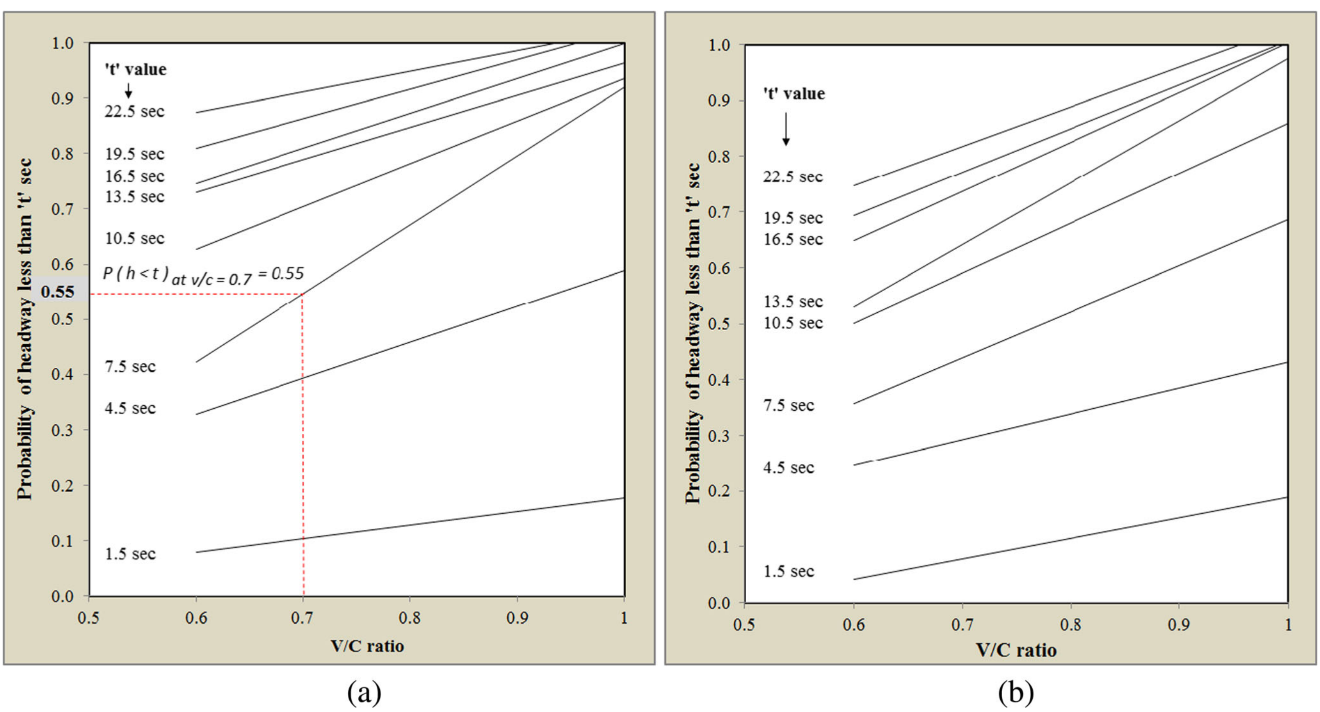


Fig. 5 Probability distribution nomograph developed based on the selected models: **a** west bound traffic and **b** East bound traffic

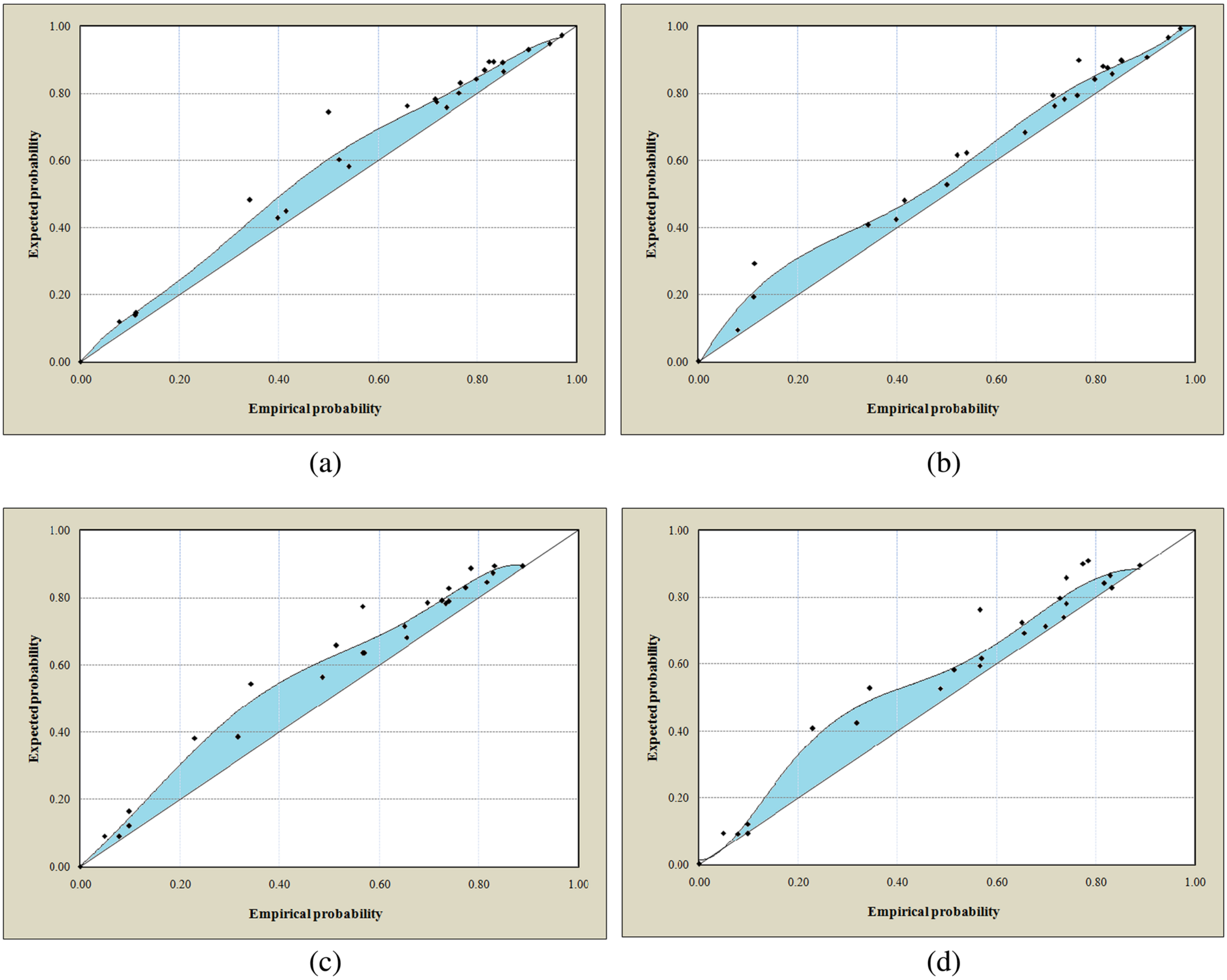


Fig. 6 Agreement between the probabilities of headways obtained from the 'nomograph' and field data obtained from a 'pilot study': **a** West (nomograph) and North (pilot study) bound traffic; **b** West (nomograph) and South (pilot study) bound traffic; **c** East (nomograph) and North (pilot study) bound traffic and **d** East (nomograph) and South (pilot study) bound traffic

Table 5 Comparison of headway probabilities [probability of headways less than't' sec] at different lane volumes: current study and case studies with homogeneous traffic

Headway (sec)	Probability at lane volume of 600 veh/h			Probability at lane volume of 700 veh/h		
	Current study	Zwahlen et al. 2007 [31]	Khasnabis and Heimbach 1980 [10]	Current study	Zwahlen et al. 2007 [31]	Khasnabis and Heimbach 1980 [10]
<1.5	0.0638	0.0000	0.1714	0.0952	0.0000	0.2046
<4.5	0.2853	0.0812	0.6348	0.3574	0.0968	0.7222
<7.5	0.4215	0.1853	0.7827	0.4808	0.1926	0.8772
<10.5	0.5718	0.2134	0.8464	0.6423	0.2190	0.9358
<13.5	0.6256	0.2871	0.8896	0.7271	0.2881	0.9634
<16.5	0.7065	0.3256	0.9187	0.7499	0.3384	0.9784
<19.5	0.7565	0.4012	0.9383	0.7995	0.4285	0.9870
<22.5	0.7893	0.4115	-	0.8426	0.4369	-

simulation. Usually, platoon formation is infrequent under homogeneous traffic and, thus, small proportion of shorter headways is observed in the traffic stream. However, once the proportion of slower vehicles starts increasing, formation of platoons is quite evident resulting in an increase of shorter headways. A look into the table (see Table 5) indicates that at moderate flow levels it is about 10% when the traffic is more or less homogeneous, which however, increases upto 30–35 in case of mixed traffic. This fact was further compared with a study wherein road segment exhibits more or less homogeneous traffic but carries truck traffic upto 20%. Since they usually travel at a speed that is much lower than the posted speed, a large proportion of faster vehicles are compelled to move with platoons resulting in a simultaneous increase of shorter headways (see Table 5). However, the car-following behaviours are quite different under mixed traffic; a large number of drivers adopt headways which are less than safe headway and a few drivers even take considerable amount of risk to overtake.

7 Conclusions

Over the past few years, road traffic has tremendously increased across the globe and as a result of it traffic congestion has been a critical issue in many countries worldwide. At times, traffic analysts face difficulties in characterizing and modeling such congested flow of traffic, thereby, addressing this issue effectively. Since a key component of determining the performance of a simulation model is the generation of inter-arrival times or headways as an input into the simulation process, it is imperative to have reliable and practical descriptions of headways. At congested state of flow, the conventional approach is, however, found ineffective due to large proportion of shorter headways. Further, modelling of time headways under mixed traffic is still vague even after decades because of inherent complexities of analysing such traffic and no significant efforts have been made so far in regard to this. This was the motives for taking up a systematic investigation of some intriguing characteristics of time headway distributions under such traffic particularly at moderate and heavy flow.

Empirical investigations with the headway data reveal that at all flow scopes' pertaining to moderate and heavy flow, median is less than mean, signifying concentration of shorter headways. This is attributable to high risk-ability of driver population which results in safety reduction. Further, it was observed that effect of heterogeneity results in a deviation from the conventional model and accordingly, makes exponential model inappropriate in describing headways. Assessment of contestant headway distribution models elucidates that at heavy flow under such traffic four distribution functions namely, log-logistic, lognormal, Pearson 5 and Pearson 6 exhibit their aptness is describing headways. Subsequently, the appropriate models were selected using a methodology based on K-S test and also, compatibility hypothesis of empirical distribution; log-logistic distribution fits well to the observed data at moderate flow whereas, Pearson 5 distribution provides a decent fit particularly at congested state of flow.

While Pearson 5 distribution indicates acceptable statistical validity in describing headways at heavy flow, its acceptability was rejected on the basis of hypothesis test at unstable flow nearing capacity. Field experiences with the mixed traffic on two-lane roads indicate that at such flow level existence of both following and non-following headways are significant, thereby, displaying different trends in distributional characteristics. This was further investigated by plotting the nomographs wherein probability of headway less than 7.5 s or more was observed to increase almost sharply with the flow; this attributes to frequent formation of platoons and higher amount of car following interaction.

In order to further validate the results, a pilot study was conducted and it was observed that the difference between the calculated probabilities of field data and the theoretical probabilities obtained from nomograph was very marginal. The present study, thus, creates a starting point of further initiatives aimed at establishing a robust method of modeling headways on two-lane rural highways with mixed traffic.

Acknowledgements The part of the analysis presented in the paper has used the data collected in the CSIR-CRRI, New Delhi sponsored project "Development of Indian Highway Capacity Manual (INDO-HCM)". The authors sincerely acknowledge CSIR-CRRI. The authors are grateful to the anonymous referees for their suggestions to improve the paper.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

References

1. Ye F, Zhang Y (2009) Vehicle type-specific headway analysis using freeway traffic data. Transportation Research Record: Journal of the Transportation Research Board 2124:222–230. https://doi.org/10.3141/2124-22
2. National Academics (2010) Highway capacity manual. TRB, Washington D.C
3. Gerlough D L, Huber M J (1976) Traffic flow theory: a monograph. Transp. Res. Board, Special Rept
4. Al-Ghamdi AS (2001) Analysis of time headways on urban roads: case study from Riyadh. J Transp Eng 127(4):289–294. https://doi.org/10.1061/(ASCE)0733-947X(2001)127:4(289)

5. Arasan VT, Koshy RZ (2003) Headway distribution of heterogeneous traffic on urban arterials. J Inst Eng 84:210–215 http://cat.inist.fr/?aModele=afficheN&cpsidt=15411224
6. Yin S, Li Z, Zhang Y, Yao D, Su Y, Li L (2009) Headway distribution modeling with regard to traffic status. Intelligent Vehicles Symposium, IEEE:1057–1062. https://doi.org/10.1109/IVS.2009.5164427
7. Jang J (2012) Analysis of time headway distribution on suburban arterial. KSCE J Civ Eng 16(4):644–649. https://doi.org/10.1007/s12205-012-1214-4
8. Riccardo R, Massimiliano G (2012) An empirical analysis of vehicle time headways on rural two-lane two-way roads. Proc Soc Behav Sci 54:865–874. https://doi.org/10.1016/j.sbspro.2012.09.802
9. Chandra S, Kumar R (2001) Headway modelling under mixed traffic on urban roads. Road Transp Res 10(1):61–79 https://trid.trb.org/view.aspx?id=732752
10. Khasnabis S, Heimbach C (1980) Headway distribution models for two-lane rural highways. J. Transp Res Rec 772:44–51
11. Panichpapiboon S (2014) Time-headway distributions on an expressway: case of Bangkok. J Transp Eng-ASCE 141(1): 05014007. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000731
12. Luttinen R T (1996) Statistical Analysis of Vehicle Time Headways [PhD thesis]. Finland, Helsinki University of Technology
13. Abtahi SM, Tamannaei M, Haghshenash H (2011) Analysis and modelling time headway distributions under heavy traffic flow conditions in the urban highways: case of Isfahan. Transport 26(4): 375–382. https://doi.org/10.3846/16484142.2011.635694
14. Ren L, Qu X (2016) Impact analysis of headway distributions on single-lane roundabout entry capacity. J Eng Proj Prod Manag 6(1): 2 http://www.ppml.url.tw/EPPM_Journal/volumns/06_01_January_2016/ID_132_06_01_2_12.pdf
15. Griffiths J D, Hunt J G (1991) Vehicle headways in urban areas. Traffic Eng Control 32(10):458–462. http://www.safetylit.org/citations/index.php?fuseaction=citations.viewdetails&citationIds%5B%5D=citjournalarticle_63466_34
16. Zhang G, Wang Y, Wei H, Chen Y (2007) Examining headway distribution model with urban freeway loop event data. Transp Res Rec J Transp Res Board:141–149. https://doi.org/10.3141/1999-15
17. Cowan RJ (1975) Useful headway models. Transp Res 9(6):371–375. https://doi.org/10.1016/0041-1647(75)90008-8
18. Branston D (1976) Models of single lane time headway distributions. Transp Sci 10(2):125–148. https://doi.org/10.1287/trsc.10.2.125
19. Zhang G, Wang YA (2013) Gaussian kernel-based approach for modelling vehicle headway distributions. Transp Sci 48(2):206–216. https://doi.org/10.1287/trsc.1120.0451
20. Katja V (2002) What characterizes a free vehicle in an urban area? Transp Res F 5(1):15–29 http://www.sciencedirect.com/science/article/pii/S1369847802000037
21. Al-Kaisy A, Karjala S (2010) Car-following interaction and the definition of free- moving vehicles on two-lane rural highways. J Transp Eng 136(10):925–931. https://doi.org/10.1061/ (ASCE) TE.1943-5436.0000148
22. Saha P, Roy R, Sarkar AK, Pal M (2017) Preferred time headway of drivers on two-lane highways with heterogeneous traffic. Transportation Letters: The International Journal of Transportation Research. https://doi.org/10.1080/19427867.2017.1312859
23. Dey PP, Chandra S (2009) Desired time gap and time headway in steady-state car-following on two-lane roads. J Transp Eng-ASCE 135(10):687–693. https://doi.org/10.1061/(ASCE)0733-947X(2009)135:10(687)
24. Mei M, Bullen GR (1993) Lognormal distribution for high traffic flows. Transp res. Theatr Rec 1398 https://trid.trb.org/view.aspx?id=383214
25. Kumar M, Rao S K (1998) Headway and speed studies on two-lane highways. Indian Road Congress 1998; 5: 23–36 http://www.safetylit.org/citations/index.php?fuseaction=citations.viewdetails&citationIds%5B%5D=citjournalarticle_239754_38
26. Penmetsa P, Ghosh I, Chandra S (2015) Evaluation of performance measures for two-lane intercity highways under mixed traffic condition. J Transp Eng-ASCE 141(10):04015021–04015028. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000787
27. Sai Kiran M, Verrma A (2016) Review of studies on mixed traffic flow: perspective of developing economies. Transp in Dev Econ 2(1):1–16. https://doi.org/10.1007/s40890-016-0010-0
28. Saha P, Sarkar AK, Pal M (2015) Evaluation of speed-flow characteristics on two-lane highways with mixed traffic. Transport. https://doi.org/10.3846/16484142.2015.1004369
29. Adams WF (1936) Road traffic considered as a random series. Inst. Civ Eng 4(1):121–130. https://doi.org/10.1680/ijoti.1936.14802
30. Katakura M (1971) Time headway distribution of traffic flow. Proc Jpn Soc Civ Eng (189):107–115. https://doi.org/10.2208/jscej1969.1971.189_107
31. Zwahlen HT, Oner E, Suravaram KR (2007) Approximated headway distributions of free-flowing traffic on ohio freeways for work zone traffic simulations. Transp Res Rec: J Transp Res Board 1999: 131–140. https://doi.org/10.3141/1999-14
32. Zala L B, Desai T A, Modi K B, Roghelia A N (2011) Headway distribution for NH-8 traffic at vagasi village location. Nat Conf on recent trends in Engg & Tech, BVM Engineering College, Gujrat, India
33. Krbalek M, Seba P, Wagner P (2001) Headways in traffic flow: remarks from a physical perspective. Phys Rev E 64(6):1–7. https://doi.org/10.1103/PhysRevE.64.066119
34. Singpurwalla D.A (2013) Handbook of statistics: an overview of statistical methods. Book boon: Denmark