

MODELLING VEHICULAR BEHAVIOUR USING TRAJECTORY DATA UNDER NON-LANE BASED HETEROGENEOUS TRAFFIC CONDITIONS

Hari Krishna GADDAM¹, K. Ramachandra RAO²

¹ Velagapudi Ramakrishna Siddhartha Engineering College, Vijayawada, Andhra Pradesh, India

² Indian Institute of Technology Delhi, Department of Civil Engineering, Hauz Khas, New Delhi, India

Abstract:

The present study aims to understand the interaction between different vehicle classes using various vehicle attributes and thereby obtain useful parameters for modelling traffic flow under non-lane based heterogeneous traffic conditions. To achieve this, a separate coordinate system has been developed to extract relevant data from vehicle trajectories. Statistical analysis results show that bi-modal and multi-modal distributions are accurate in representing vehicle lateral placement behaviour. These distributions help in improving the accuracy of microscopic simulation models in predicting vehicle lateral placement on carriageway. Vehicles off-centeredness behaviour with their leaders have significant impact on safe longitudinal headways which results in increasing vehicular density and capacity of roadway. Another interesting finding is that frictional clearance distance between vehicles influence their passing speed. Analysis revealed that the passing speeds of the fast moving vehicles such as cars are greatly affected by the presence of slow moving vehicles. However, slow moving vehicles does not reduce their speeds in the presence of fast moving vehicles. It is also found that gap sizes accepted by different vehicle classes are distributed according to Weibull, lognormal and 3 parameter log logistic distributions. Based on empirical observations, the study proposed a modified lateral separation distance factor and frictional resistance factor to model the non-lane heterogeneous traffic flow at macro level. It is anticipated that the outcomes of this study would help in developing a new methodology for modelling non-lane based heterogeneous traffic.

Keywords: Non-lane discipline, heterogeneous traffic, vehicle trajectories, lateral separation distance, frictional clearance

To cite this article:

Gaddam, H. K., Rao, K.R., 2019. Modelling vehicular behaviour using trajectory data under non-lane based heterogeneous traffic conditions. Archives of Transport, 52(4), 95-108. DOI: <https://doi.org/10.5604/01.3001.0014.0211>



Contact:

1) harikrishnagaddam@gmail.com [<https://orcid.org/0000-0002-8878-713X>], 2) rkalaga@civil.iitd.ac.in [<https://orcid.org/0000-0002-7229-519X>]- corresponding author

1. Introduction

In developing countries such as India, vehicles do not follow lane discipline and they always deviate from center-line positions. In addition disruptive lane changing can also be observed. In addition, the complexity in traffic flow also increases due to heterogeneous vehicle-driver units and their complex interactions. Contemporary macroscopic continuum models (Aw and Rasche 2000; Zhang 2002; Jiang et al. 2002; Wong and Wong 2002; Logghe and Immers 2003; Chanut and Buisson 2003; Gupta and Katiyar, 2006; Gupta and Katiyar, 2007; Tang et al. 2009; Ngoduy 2011) are developed to model lane based traffic movement. These models have some limitations to completely capture the complexities arise due to non-lane based heterogeneous traffic movement. Recently, Nair et al. (2011) proposed porous flow approach to model the behaviour of motorised two wheeler in heterogeneous traffic environment using static speed – pore size density relationship. Collecting pore size distribution of vehicles in dynamically changing environment is cumbersome and moreover it is difficult to implement the model for system with more than two vehicle classes. In another study, Mohan and Ramadurai (2013) addressed two main behavioural aspects of heterogeneous traffic: dissimilar vehicle types and non-lane discipline using extended Aw-Rasche (2000) model. They used Area-Occupancy parameter instead of linear density parameter. However the model does not consider the vehicles off-centeredness and the frictional effects of slow moving vehicles in the traffic stream. In another approach, Gupta and Dhiman (2014) proposed a non-lane continuum model using lateral separation distance factor. However, the model can only describe the vehicle movement on a single lane road and it does not taken in to account the interaction between slow moving and fast moving vehicles, viscosity effects. To this end, it is necessary to develop a second order macroscopic model which explicitly describes the heterogeneous traffic movement in non-lane based traffic system in multi-lane environment. One of the objectives of this study is to empirically derive some information (suitable parameters) from vehicle trajectories to build such models.

Several studies have been conducted to determine the characteristics of non-lane based heterogeneous traffic using empirical data. According to Dey et al.

(2006) study, speed distribution curves may be uni-modal or bi-modal based on the speed variation amongst different class of vehicles. This study revealed that the proportion of slow moving vehicles is not a true representative factor for bi-modality in the speed data. In another study, Chunchu et al. (2010) explored several traffic characteristics such as the lateral placement of vehicles on the carriage-way, lateral and longitudinal gaps between the vehicles. They examined the relationship between lateral gaps and area occupancy for various vehicle combinations and they found consistent correlation between these two variables. Modelling headways in non-lane based heterogeneous traffic condition is critical and it is useful in developing simulation models. Sharma et al. (2011) have done the exploratory data analysis to capture various parameters on two-way undivided roadways. Traffic flow characteristics such as arrival headways and speed distributions have been studied in a systematic way. Dubey et al. (2012) proposed Generalized Pareto (GP) and Generalized Extreme Value (GEV) distributions to model time gaps over a wide range of flows from 550 veh/h to 4100 veh/h. These models are successful in considering the problem of simultaneous arrival of vehicles in wide roads. In another approach, Ambarwati et al. (2014) developed a class specific pore size –density distribution, class specific speed-density and flow-density diagrams using trajectory data in Surabaya city, Indonesia. The analysis revealed that motor cycles and other vehicles exhibit significant difference in critical pore size distribution and traffic flow relationships. Kanagaraj et al. (2015) investigated some of the microscopic flow characteristics such as speed, acceleration and deceleration, selection of lateral spacing and longitudinal distances of various vehicle classes for the data collected on urban roads located in Chennai, India. The results are found to be useful in development of driver behaviour models for heterogeneous traffic conditions. Dehghani and Tafti (2018) studied the effect of different factors such as driver behaviour, vehicle characteristics and environmental conditions on saturation flow rates and capacity of signalised intersection under weak lane heterogeneous traffic conditions in Iran. The objective of this study is to identify the suitable method to estimate the saturation flow rates at the signalised intersections by comparing empirical observations and estimated values from different analytical models. In few other

studies such as Koshy and Arasan (2005), Dey et al.(2008) and Asaithambi et al. (2012), several problems of non-lane heterogeneous traffic for instances influence of composition, variability in physical and dynamical characteristics and the presence of bus stops on the capacity of the road are studied using simulation models. The desired microscopic data to develop these models such as speed, placement, arrival and overtaking is obtained through field studies. To this end, it is understood that use of the parameters developed from the empirical data have relevance in developing simulation models and modelling traffic flow characteristics.

Due to the complexity of Non-Lane based Heterogeneous Traffic system (NLHT), a detailed examination of vehicle interaction is required. Further it is necessary to identify suitable parameters to build macroscopic continuum models for non-lane system. In this paper, an exploratory and confirmatory data analysis is performed to examine the vehicle trajectory data. Important vehicle characteristics such as lateral placement on carriage way, effective gap size distribution, relationship between longitudinal headways and lateral separation distance, moreover the dependency between vehicle passing speed and lateral clearance of vehicles are studied. Further, based on the observations, the study also introduced new macroscopic parameters to model non-lane systems using continuum theories. This study helps in understanding the vehicle interactions in mixed traffic and can be used for developing new macroscopic continuum methodology for modelling heterogeneous traffic in non-lane based systems.

2. Definition of heterogeneity and vehicle attributes in non-lane based system

Vehicle behaviour in non-lane based heterogeneous traffic stream significantly deviates from homogeneous traffic stream. The typical behaviour of vehicles in NLHT can be best explained by staggered vehicle movement, lane sharing, varying physical dimensions and diverse dynamical characteristics. Due to their distinct behaviour, they may increase or decrease the capacity of the traffic facility. One of the unique features of the NLHT stream is that they utilise the road width very effectively without compromising their desired speed (Khan and Maini, 1999; Mallikarjuna and Rao, 2006).

In this study, exploratory data analysis was done to understand the behaviour of heterogeneous traffic using the following attributes:

- (i) Selection of lateral lane position (LP) by different vehicle classes across the carriage way (Fig. 1(a)).
- (ii) Relationship between longitudinal headways (LH) and lateral separation distances (LSD) (Fig. 1(b), 1(c)).
- (iii) Relationship between vehicle passing speed and lateral clearance (Fig. 1(d)).
- (iv) Finally, the distributions of effective roadway width (sum of vehicle width and frictional clearance on both sides) required for the vehicle classes to move downstream (Fig. 1(e)).

The coordinate system and the method of data collection used in this study are shown at the bottom of each sub plot in Fig.1. The analysis has been done for the data collected at or near-capacity condition where vehicles start interacting each other and sufficient deviation in speeds can also be observed. Terminologies such as non-lane based traffic and mixed traffic are interchangeably used in this paper to represent the traffic streams in NLHT.

3. Location details and data collection

A straight section (100 m length \times 10.5 m width) on an urban arterial (Fig. 2) without any interruption from bus bays and roadside facilities was chosen to collect the traffic data and the section is located on Panchsheel Marg, Outer Ring Road, Delhi, India. Two hours video graphic survey was conducted to obtain traffic and vehicular characteristics. In order to obtain the data, camera was mounted on a foot over bridge at 45° to 60° angle and at a height of 10 meters. Vehicle trajectories were obtained using MATLAB[®] based video image processing tool developed in Traffic and Transportation Laboratory at IIT Delhi for which proper calibration and validation has been done before using the tool (Singh et al., 2016). A separate coordinate system (as shown in Fig. 1) is used to identify the vehicle position in each time step, i.e. one second. In this study, vehicles are grouped into four distinct types such as Cars, Motorised Two Wheelers (MTW), Motorised Three Wheelers (MThW) and Heavy Vehicles (HV) based on their physical and dynamic characteristics. Physical and dynamical characteristics of different vehicle classes are mentioned in Table 1 and the composition of these vehicle classes are given in Fig. 2.

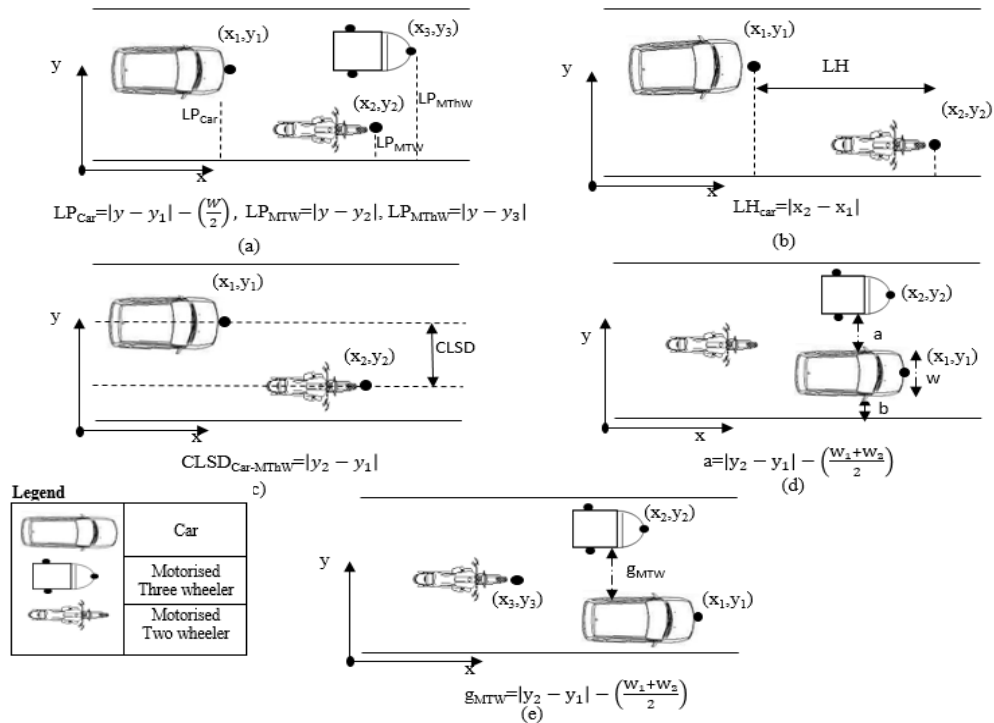


Fig. 1. Studying heterogeneous vehicle behaviour under non-lane discipline (a) lateral placement (b) longitudinal headway in meters (c) lateral separation distance and (d) a = frictional clearance between car and three wheeler, b = frictional clearance between car and median (e) Effective carriageway width. Here w = width of the vehicle, x = longitudinal co-ordinate, y = lateral co-ordinate.

Table 1. Vehicle classes and dimensions

Vehicle Class	Vehicles included	Vehicle average dimensions (m)	Speed characteristics* (km/h)			
			v_{free}	v_{cong}	v_{mean}	v_{σ}
Car	Small Car, SUV*, Van	5.0 x 2.0	73.4	4.7	47	14.8
Motorised Two Wheeler	Scooter, Moped	1.8 x 0.6	65.2	7.4	46.5	12.8
Motorised Three Wheeler	Auto – Rickshaw, Tuk-Tuk, LCV*	2.6 x 1.4	55.5	4.5	31	8.2
Heavy vehicles	Bus, Truck	10.3 x 2.5	52.3	3.5	29	9.0

*SUV=sports utility vehicle, LCV = light commercial vehicle, v_{free} =maximum free flow speed, v_{cong} =minimum congested speed, v_{mean} =mean speed, v_{σ} = standard deviation of speeds

Empirical traffic data and fundamental diagrams derived from the trajectories have been used to check the temporal variation of traffic flow, composition of traffic, and free flow or congested conditions. Trajectory data was used to obtain vehicle behavioural attributes such as lateral placement, longitudinal headways, lateral separation distances and effective lane width etc.

4. Data Analysis

The data extracted from vehicle trajectories pertaining to different vehicle characteristics (as discussed under section 2.0) are analysed using several statistical methods. The analysis was done using statistical packages R (R Core Team, 2015) and Minitab (Minitab, 2003).

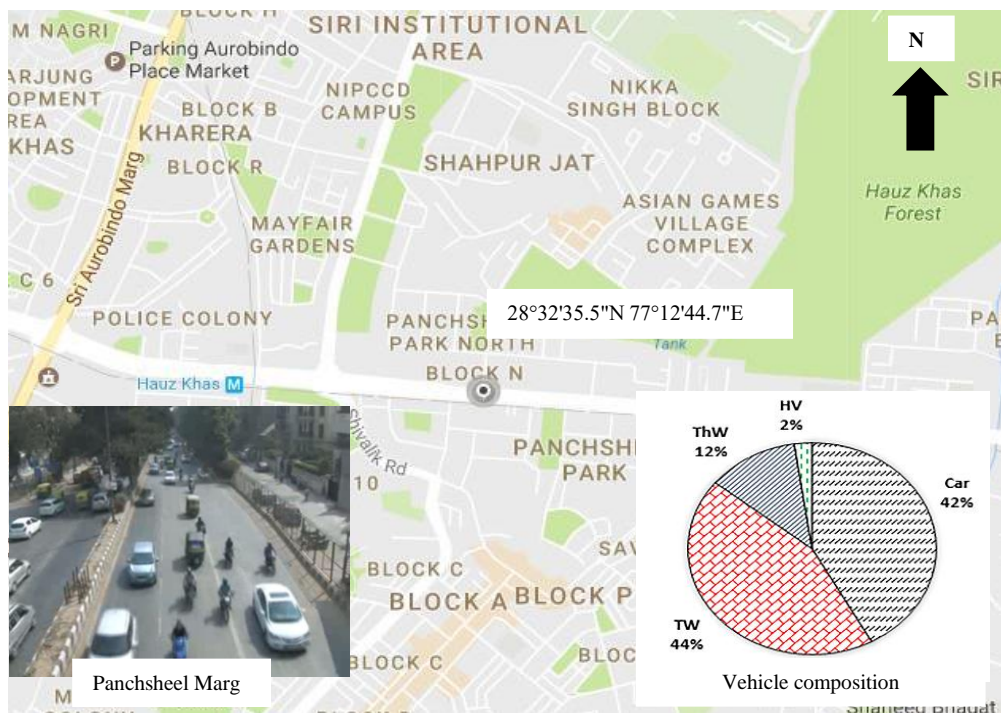


Fig. 2. Location details and composition of vehicles

4.1. Lateral placement of vehicles on carriage-way

To understand the driver’s choice in selecting the lateral position on carriageway, data has been collected regarding lateral placement of vehicles, by measuring the distance of right wheel from the median of the carriageway. Vehicles lateral placement data for the Cars and MTW’s has multiple peaks and it is only fitted by multi-modal distributions such as

normal, lognormal, and gamma mixture distributions (Fig. 3, Table 2). The distributions are fitted using “mixdist” package in R (Macdonald and Du, 2011).The distributions and its goodness-of-fit measures are presented in Table 2. Following inferences can be drawn from the analysis.

- Vehicle lateral placement data (Table 2 and Fig. 3) in mixed traffic conditions revealed that vehicles do not restrict their movement to the center of the lanes and they distribute across the carriageway.

Table 2. Statistical description about vehicles lateral placement and fitted distributions

Vehicle type	Mean ± SD* (m)	Median (m)	Min* (m)	Max* (m)	Inference: ANOVA* statistics	Games-Howell Multiple comparison	Distribution fitted (chi-square value)
Car	3.74 ± 2.44	3.24	0.68	10.76	p < 0.00	Except MTW-HV (p -value = 0.98), MThW-HV (p -value = 0.19) all other are significantly different in mean lateral positions	Lognormal Mixture (0.15)
MTW	6.11 ± 2.29	6.04	1.11	10.95			Gamma Mixture (0.04)
MThW	5.35 ± 1.91	5.03	1.44	9.87			Gamma (0.70)
HV	6.17 ± 1.51	6.05	4.00	8.03			Lognormal (0.92)
ALL	4.95 ± 2.52	4.86	0.69	10.95			Lognormal Mixture (0.01)

*SD = standard Deviation, Min = minimum, Max = maximum, ANOVA = analysis of variance

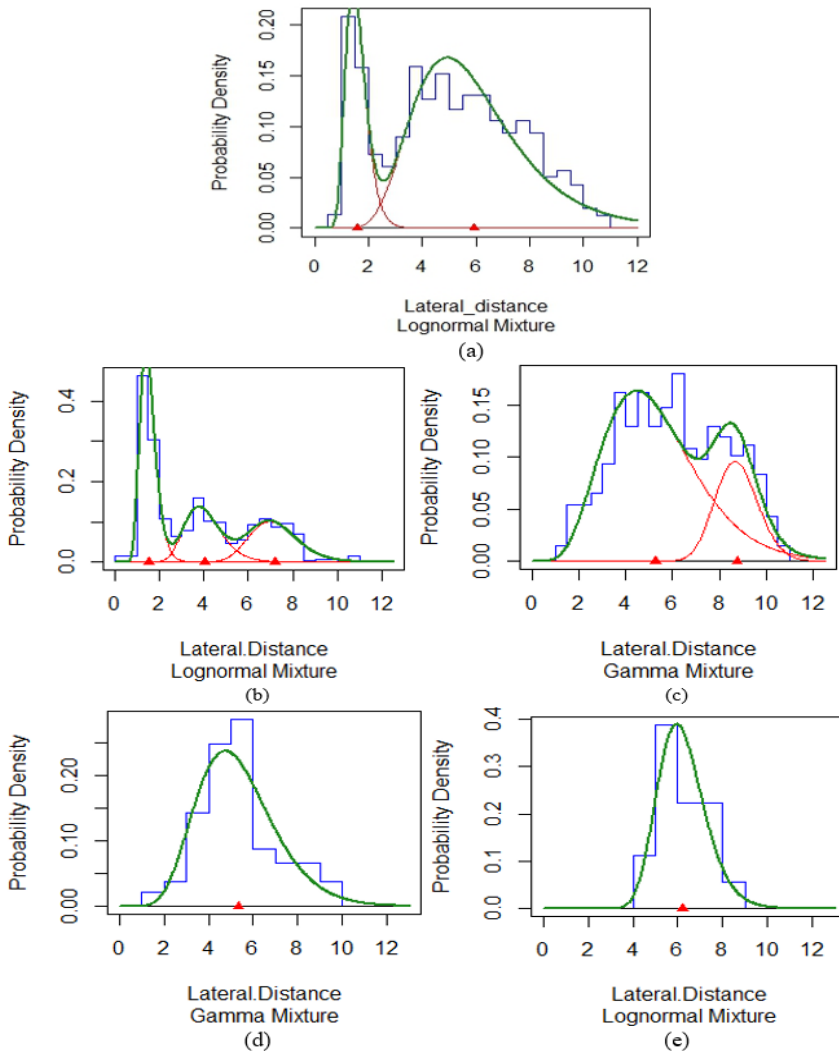


Fig. 3. Lateral distribution of vehicles across the carriageway under non-lane discipline
(a) Total vehicles (b) Car (c) MTW (d) MThW (e) HV (Red triangle shows the mean value)

– The statistical analysis (Table 2 and Fig. 4) shows that vehicles are choosing their respective positions based on their physical and dynamical characteristics, ease of movement etc. Heavy vehicles mostly occupy left most part of the carriageway to give way to the fast moving vehicles whereas cars mostly travel in the right most lanes to avoid hindrance from slow moving vehicles. On the other hand, due to the smaller cross sectional area and

high maneuverability, MTW’s are able to occupy anywhere on the carriageway and high percentage of MThW chose to travel at middle of the carriageway.

– Vehicle lateral placement data seems to follow multi-modal distributions. These distributions help in improving the accuracy of microscopic simulation models in predicting vehicle lateral placement on carriageway.

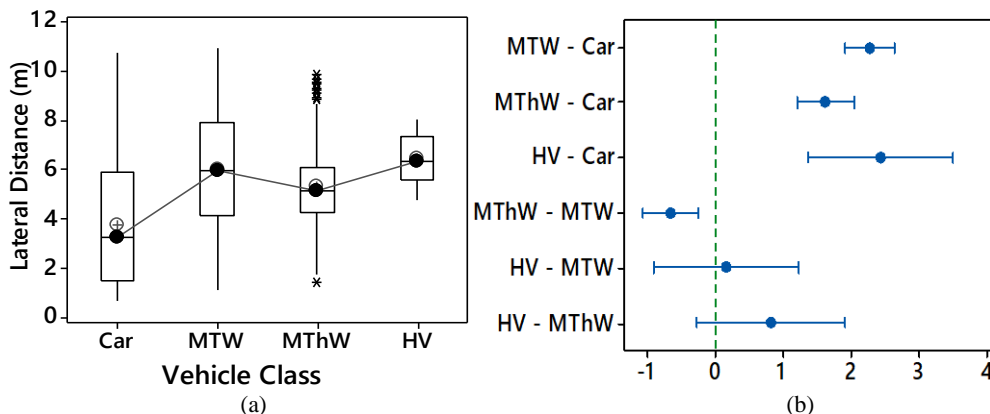


Fig. 4. (a) Box plot (b) Games –Howell comparison of mean lateral positioning of vehicles (In Figure 4(b) Blue line represents that, if the interval does not contain zero, the corresponding means are significantly different)

4.2. Lateral separation distance and longitudinal headways for different vehicle classes

In heterogeneous traffic conditions, vehicles deviate from their center-line position as shown in Fig. 1(c). It happens due to the presence of different vehicle sizes and the driver behaviour. Due to the off-centeredness of the vehicles, following vehicle does not assign full leadership to the front vehicle. In this case, the selection of safe headway by any vehicle depends on the amount of vehicles off-centeredness and the type of vehicle present ahead. This characteristic influences the number of vehicles present in a roadway section and the highway capacity. To this end, this section explores the relationship between longitudinal headways and lateral separation distance between different classes of vehicles. The section also presents lateral separation distance parameter estimation procedure and its usefulness in macroscopic modelling methodology.

Table 3 shows that there is a large variation amongst the vehicle classes in selecting longitudinal headways and lateral separation distances while following the leader vehicle. It was observed that vehicles maintained larger headways while following heavy vehicles and those values are ranging from 20 m to 52 m. Maximum LSD values observed while vehicles following heavy vehicles are from 1.6 m to 4.2 m. In contrast, vehicles maintain smaller headways and lateral separation distances with MTW's. For example, in case of Car-MTW combination, LH was 9.30 m and LSD was 0.77 m. Further, ANOVA statistics (Table 3) also

prove that at peak traffic flow condition, mean longitudinal distance and mean lateral separation distances maintained by different follower and leader combinations are significantly different ($p < 0.00$). However, the Tukey - pairwise comparison shows that vehicles maintained larger headways and larger lateral separation distances with slow moving vehicles such as MThW's and heavy vehicles. From the analysis, it can be inferred that presence of slow moving vehicles reduce the density and capacity of the traffic stream. Following interpretations can be drawn from the scatter plots (Fig. 5) and from Tab.3. It can be seen that the spatial headways are highly correlated (-ve) with the lateral separation distances. Further, it is also observed that the critical headways decreases with increasing lateral separation between the vehicles. Longitudinal headways of the following vehicles do not get affected by the presence of MTW as a leader. Following vehicles such as cars and MThW maintain close proximity with MTW at all conditions. Moreover, MTW drivers maintain close distances to other vehicles and tend to overtake whenever sufficient gaps are available. Maximum longitudinal headways maintained by any class of vehicle with MTW at zero LSD is 12 m and it indicates that, the presence of MTW *increases the capacity* of the stream. Analysis also shows that heavy vehicles barely follow any other vehicle in mixed traffic stream. They *create vacuum in front* due to their slow acceleration characteristics and it further reduces the capacity.

Table 3. Statistics analysis between different vehicle groups and lateral separation distance factor

Follower-leader vehicle types	LH Description					LSD Description					Correlation between LSD and LH	LSD factor for vehicle combinations (δ_{ij})	LSD factor for each vehicle class (δ_i)
	μ^* (SD*)	median	min*	max*	ANOVA*	μ (SD)	median	min	max	ANOVA*			
Car-Car	17.84(5.95)	16.63	8.05	35.35	Welch test - p < 0.00	0.84(0.65)	0.71	0.03	2.40	Welch test - p < 0.00	y = -6.1x + 23 R ² = 0.44	0.24	0.25
Car-MTW	9.62(4.12)	9.30	0.39	21.88		0.77(0.55)	0.68	0.01	2.12		y = -3.3x + 12 R ² = 0.20	0.22	
Car-MThW	11.14(4.85)	10.89	0.74	23.78		1.17(0.73)	1.19	0.03	2.99		y = -4.3x + 16 R ² = 0.43	0.33	
Car-HV	25.52(12.97)	26.43	3.4	38.69		1.99(1.69)	1.57	0.50	4.17		y = -6.2x + 38 R ² = 0.7	0.57	
MTW-Car	17.19(5.92)	16.85	5.89	32.55		0.99(0.52)	0.96	0.03	2.01		y = -5.8x + 23 R ² = 0.26	0.28	0.24
MTW-MTW	7.65(3.50)	7.33	0.41	20.53		0.64(0.39)	0.59	0.01	1.56		y = -3.5x + 10 R ² = 0.15	0.18	
MTW-MThW	10.08(5.09)	10.67	0.26	23.5		1.04(0.55)	1.02	0.03	2.46		y = -6.3x + 17 R ² = 0.46	0.30	
MTW-HV	25.62(14.89)	25.40	3.62	52.12		1.80(0.77)	1.85	0.36	3.53		y = -14.7x + 52 R ² = 0.58	0.51	
MThW-Car	15.05(5.09)	15.90	6.07	25.22		1.22(0.73)	1.31	0.10	2.38		y = -5.6x + 22 R ² = 0.64	0.35	0.30
MThW-MTW	8.06(3.49)	7.85	2.62	18.04		0.66(0.51)	0.55	0.01	1.76		y = -4.1x + 11 R ² = 0.36	0.19	
MThW-MThW	11.02(4.99)	11.87	1.20	22.14		1.17(0.61)	1.27	0.04	2.14		y = -5.3x + 17 R ² = 0.40	0.33	
MThW-HV	28.70 (7.68)	28.95	13.4	30.51		2.58(0.95)	2.11	1.47	4.12		y = -4.2x + 40 R ² = 0.30	0.74	
HV-All	21.22(8.19)	20.79	9.76	40.5	0.92(0.71)	0.72	0.04	2.33	y [#] = -4.0 x + 25, R ² = 0.12	0.26	0.26		

* μ = mean (m), SD = Standard Deviation(m), min = minimum(m), max = maximum(m), ANOVA = analysis of variance, y = longitudinal Headway (LH), x = lateral separation distance (LSD), # with respect to all vehicles

Lateral separation distance factor (δ)

Recently, Jin et al. (2010) and Li et al. (2015) have proposed two different non-lane based full velocity difference (NLBCF) car following models by considering lateral separation distances for single lane and multilane traffic flow facilities respectively. These models assume that the following vehicle movement is governed by the lateral separation effects of its leader. Lateral effects of lane width helps in improving the stability of traffic flow and explains the traffic congestion pattern and its evolutions. Even though the findings of these studies provide some insights in analysing performance of non-lane traffic system they lack in empirical understanding of heterogeneous vehicle behaviour in non-lane based traffic conditions. Therefore, this study modi-

fied the estimation procedure for finding lane separation distance factor for heterogeneous traffic. The modified lane separation distance factors for heterogeneous traffic stream given in Table 3 are derived using Eq. (1).

$$\delta_{ij} = \frac{LSD_{ij}}{W} \text{ and } \delta_i = \sum_{j=1}^N P_{ij} \delta_{ij} \tag{1}$$

where δ_{ij} is the lateral separation distance factor between vehicle i and j, LSD_{ij} is the lane separation distance (m) between vehicle i and j and 'W' in denominator represents the standard lane width (for example 3.5 m is the standard lane width for Indian traffic condition). P_{ij} represents the number of times vehicle i follow vehicle j.

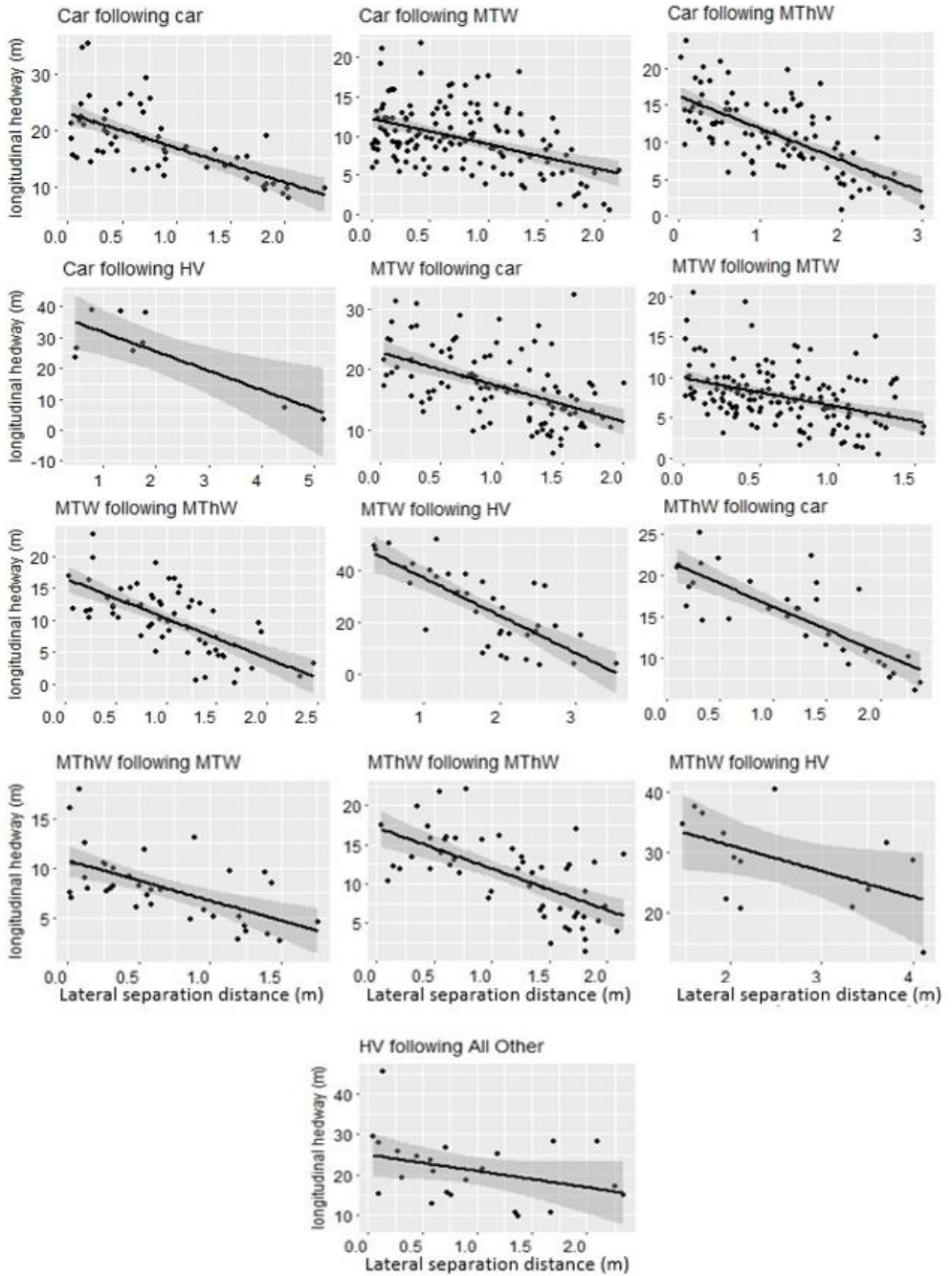


Fig. 5. Relationship between longitudinal headway and lateral separation distance for different types of vehicle interactions

4.3. Vehicle passing speed vs lateral clearance

In this section, lateral clearance between the vehicles and its effect on speeds are analyzed. Regression analysis (Fig. 6 and Table 4) shows that speed of the cars is significantly affected by lateral clearance between the vehicles (p-value of L is 0.00, $R^2 = 0.63$). In contrast, the speeds of vehicles such as MTW, MThW and HV are not influenced by the presence of other vehicles (p-value of L > 0.2 with $R^2 < 0.05$). Analysis further revealed that passing speeds of the fast moving vehicles such as cars are greatly affected

by the presence of slow moving vehicles. However, slow moving vehicles such as HV's do not reduce their speeds in the presence of fast moving vehicles. Vehicles such as MTW's and MThW's managed to travel at their desired speeds because of their ability to seep through small gaps in the stream. These inputs help in framing new methodology in modelling traffic flow. The governing equation for modelling dynamic behaviour of vehicles is presented in the next section.

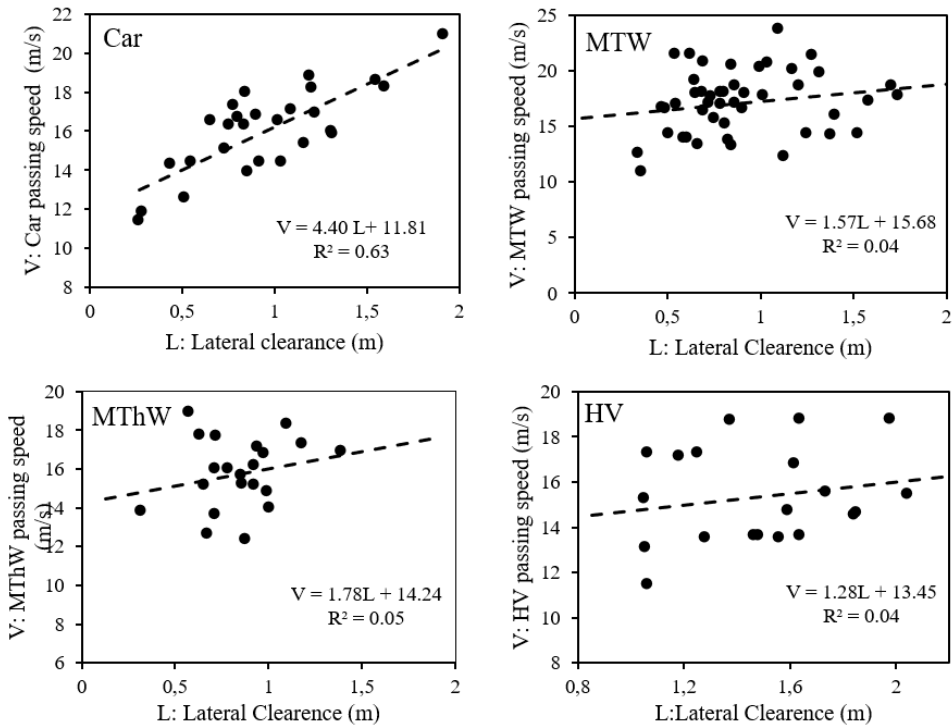


Fig. 6. Correlation between passing speed (V) of the vehicle and lateral clearance (L)

Table 4. Regression statistics

Response variable	Predictor variables	Coefficients	t-statistics	p-value	R ² -value
Car speed	Intercept	11.81	16.18	0.00	0.63
	Lateral Clearance	4.40	6.14	0.00	
MTW speed	Intercept	15.68	12.86	0.00	0.04
	Lateral Clearance	1.57	1.19	0.24	
MThW speed	Intercept	14.24	8.80	0.00	0.05
	Lateral Clearance	1.78	1.31	0.21	
HV speed	Intercept	13.45	5.60	0.00	0.04
	Lateral Clearance	1.28	0.74	0.47	

Frictional clearance factor

In existing higher order continuum modelling methodology (Aw and Rascle 2000; Zhang 2002; Jiang et al. 2002; Gupta and Katiyar, 2006; Gupta and Katiyar, 2007) the longitudinal acceleration of the vehicle is governed by relaxation term, anticipation term and convection term in the equation. However, in non-lane system, one additional term is also required to capture the effect of frictional resistance offered by sideways movement of vehicles. This section discuss the introduction of frictional resistance term in to the macroscopic model, which is as follows:

The vehicle acceleration in non-lane heterogeneous traffic stream is governed by spatial headway and velocity difference between different vehicle classes. Therefore, acceleration of i^{th} class vehicle (Tang et al., 2009) is a function of:

$$\frac{dv_{i,n}(t)}{dt} = f(V_{i,n}^i(t), \Delta V_{n,n+1}^i(t), \Delta x_{n,n+1}^i(t)) \quad (2)$$

$$\frac{dv_{i,n}(t)}{dt} = \kappa_i [V_{i,n}(\Delta x_{i,n}) - v_{i,n}] + \sum_{j=1}^N \lambda_{ij} P_{ij} [v_{j,n+1} - v_{i,n}] \quad (3)$$

$\forall j = 1, 2 \dots N$

where:

$$\Delta x_{n,n+1}^i(t) = \sum_{j=1}^N P_{ij} (x_{n+1}^j(t) - x_n^i(t)),$$

$$\Delta V_{n,n+1}^i(t) = \sum_{j=1}^N P_{ij} (V_{n+1}^j(t) - V_n^i(t))$$

are space headway and speed of vehicle class i respectively. N is the number of vehicle classes; P_{ij} is the number of times vehicle class i followed vehicle class j ; $\alpha_i = 1/T_i$ and $\kappa_i = 1/\tau_i$ are the driver reactive coefficients of vehicle class i .

In order to develop macroscopic continuum model, suitable transformation technique must be used to convert discrete variables into the continuous variables. The method suggested by (Jiang et al., 2002) is applied to transfer the variables from microscopic to macroscopic ones. After applying Taylor expansion series and neglecting the higher order terms, the final form of the model is:

$$\frac{\partial V_i}{\partial t} + V_i \frac{\partial V_i}{\partial x} = \frac{1}{T_i} [V_{ie}(k) - V_i] + \sum_{j=1}^N \frac{P_{ij}}{\tau_{ij}} \Delta x \frac{\partial V_j}{\partial x} - \sum_{j=1}^N \frac{P_{ij}}{\tau_{ij}} (V_j(x, t) - V_i(x, t)) \quad (4)$$

The first term in the right hand side of the equation represents the relaxation term, second term represents the driver reactions to sudden change in the downstream velocity. Third term is the velocity difference between two different vehicle classes present in the same cell.

Even though the macroscopic continuum model present in Equation (4) is logically sound, some engineering corrections need to be applied to capture complex driving behaviour present in Indian driving environment. As discussed in section 4.3, only cars are significantly affected by the presence of other vehicle classes present in the same section. Based on the empirical observations, a new term called *friction factor* (μ_{ij}) is introduced to modify the last term in the equation.

$$\mu_{ij} a_{ij} \text{ where } a_{ij} = \sum_{j(\neq i)}^N \frac{P_{ij}}{\tau_{ij}} (V_j(x, t) - V_i(x, t)) \quad (5)$$

where μ_{ij} is the friction factor and the value is 1 if $V_i > V_j$ otherwise zero. P_{ij} is the percentage of times vehicle i followed j , τ_{ij} is the reaction time and V_j and V_i are speeds of vehicle j and i respectively. It is expected that the proposed equation will improve the model capability in capturing non-lane behaviour.

4.4. Effective gap size

Effective gap size is the minimum width of the road required for the vehicle to move downstream without reducing its current speed significantly. It is estimated to be the width plus frictional clearance on both sides of the vehicle (Fig.1 (e)). Gap size accepted by different vehicle classes have been estimated using the method suggested in section two. It is found that, vehicles effective gap sizes are distributed according to Weibull, lognormal and 3 parameter log logistic distributions with mean effective sizes ranging from 1.83 m to 4.99 m. The widespread in effective gap size data of Cars and MThW's shows that drivers are selecting different gap sizes. Interestingly, MTW and HV data is skewed to the right and distributed around the mean value. Descriptive statistics and gap size distributions are given in Table 5 and Fig. 7. These results will be used in estimating traffic density and modelling vehicle behaviour.

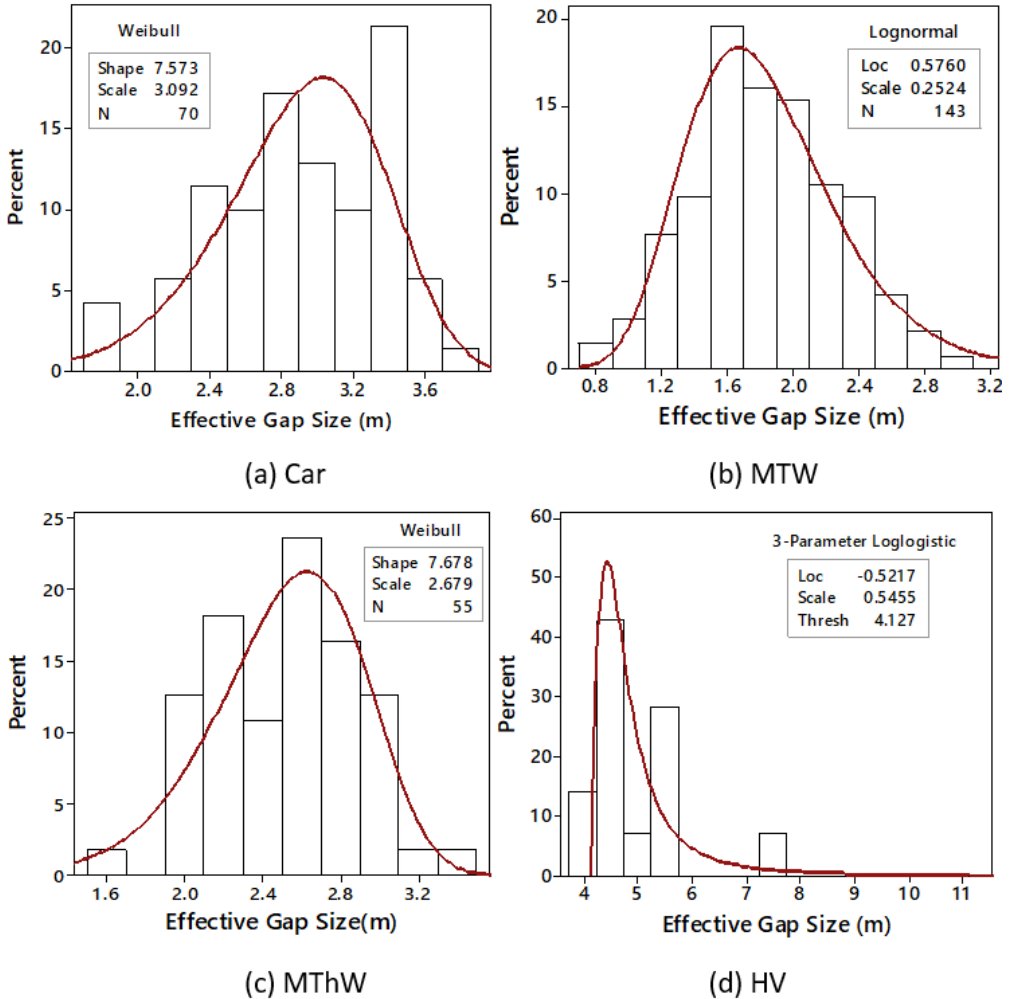


Fig. 7. Gap size distribution for different vehicles classes

Table 5. Descriptive statistics and distribution of effective gap sizes

Vehicle type (sample size)	Mean (m)	Median (m)	Minimum (m)	Maximum (m)	Standard Deviation (m)	Skewness	Kurtosis	Distribution fitted (p-value)	P-value
Car (70)	2.90	2.91	1.80	3.78	0.46	-0.44	-0.26	Weibull	0.24
MTW (143)	1.83	1.79	0.75	2.91	0.44	+0.11	-0.32	Log Normal	0.31
MThW (55)	2.52	2.57	1.69	3.32	0.38	-0.09	-0.75	Weibull	0.25
HV (20)	4.99	4.67	4.21	7.60	0.87	+2.32	+6.58	3 parameter log logistic	0.02*

*Likelihood Ratio P-Value

5. Conclusions

Following are the conclusions from this study:

- In non-lane environment, vehicles lateral positions on carriageway depend on their ease of movement, physical and dynamical characteristics. The study suggests that the use of bi-modal and multi-modal distributions in representing lateral placement characteristics of vehicles will improve the modelling accuracy.
- Safe longitudinal headways maintained by vehicles decrease due to their off-centered behaviour. This behaviour leads to reduction in the critical gaps maintained by vehicles. In other words, it increases the density of the road way section. Car following models suggested by Jin et al. (2010) and Li et al. (2015) can be taken as basis to incorporate off-centered behaviour of the vehicles into macroscopic continuum model.
- Another interesting outcome of this study is that frictional clearance distance between vehicles influence their passing speed. Based on empirical observations, parameters such as lateral separation distance factor and frictional clearance factor were introduced to study the behaviour of non-lane heterogeneous traffic flow at macro level.
- It is interesting to note that vehicles maintain closer headways with MTW's. Hence, high proportion of MTW's increases the density and capacity of the traffic stream. However, heavy vehicles such as buses act like a moving bottlenecks, thereby reducing the critical density, jam density and capacity of the traffic stream.
- The two new concepts proposed in this study such as modified lateral separation distance factor and frictional clearance factor can be used in the development of non-lane based heterogeneous continuum models.

References

[1] AMBARWATI, L; ADAM J. P; ROBERT, V; & BART VAN A., 2014. Empirical analysis of heterogeneous traffic flow and calibration of porous flow model. *Transportation Research Part C: Emerging Technologies*, 48, 418–436. doi:<https://doi.org/10.1016/j.trc.2014.09.017>

[2] ASAITHAMBI, G; VENKATESAN, K; KARTHIK S; & SIVANANDAN, R., 2012. Mixed Traffic Characteristics on Urban Arterials with Significant Motorized Two-Wheeler Volumes: Role of Composition, Intra-

Class Variability, and Lack of Lane Discipline. *Transportation Research Record*, 2317: 51–59.

[3] AW, A; & RASCLE, M., 2000. Resurrection of Second Order Models of Traffic Flow. *SIAM Journal on Applied Mathematics*, 60(3): 916–938. doi:
<https://doi.org/10.1137/S0036139997332099>.

[4] DEY, P.P., CHANDRA, S; & GANGOPADHYAY, S., 2008. Simulation of mixed traffic flow on two-lane roads. *Journal of Transportation Engineering*, 134(9): 361–369.

[5] CHANUT, S; & BUISSON, C., 2003. Macroscopic Model and Its Numerical Solution for Two-Flow Mixed Traffic with Different Speeds and Lengths. *Transportation Research Record*; 1852(1): 209–219.

[6] CHUNCHU, M., KALAGA, R.R. & SEETHEPALLI, N.V.S.K., 2010. Analysis of microscopic data under heterogeneous traffic conditions. *Transport*, 25(3): 262–268. doi:
<https://doi.org/10.3846/transport.2010.32>.

[7] DEGHANI-ZADEH, M., & TAFTI, M.F., 2018. Estimating saturation flow under weak discipline traffic conditions, case study: Iran. *Archives of Transport*; 46(2):47–60.

[8] DEY, P.P., CHANDRA, S;& GANGOPADHAYA, S., 2006. Speed Distribution Curves under Mixed Traffic Conditions. *Journal of Transportation Engineering*, 132(6):475–481.

[9] DUBEY, S.K., PONNU, B; & ARKATKAR, S.S., 2012. Time Gap Modeling under Mixed Traffic Condition: A Statistical Analysis. *Journal of Transportation Systems Engineering and Information Technology*, 12(6): 72–84.

[10] GUPTA, A.K; & DHIMAN, I., 2014. Analyses of a continuum traffic flow model for a nonlane-based system. *International Journal of Modern Physics C*, 25(10):1450045. doi:
<http://dx.doi.org/10.1142/S0129183114500454>

[11] GUPTA, A.K; & KATIYAR, V.K., 2006. A new anisotropic continuum model for traffic flow. *Physica A: Statistical Mechanics and its Applications*, 368(2): 551–559. doi:
<https://doi.org/10.1016/j.physa.2005.12.036>.

[12] GUPTA, A. K; & KATIYAR, V.K., 2007. A New Multi-Class Continuum Model for Traffic Flow. *Transportmetrica*, 3(1): 73–85.

[13] JIANG, R., WU, Q.-S; & ZHU, Z.-J. 2002. A new continuum model for traffic flow and

- numerical tests. *Transportation Research Part B: Methodological*, 36(5): 405–419. doi: [https://doi.org/10.1016/S0191-2615\(01\)00010-8](https://doi.org/10.1016/S0191-2615(01)00010-8).
- [14] JIN, S; DIANHAI, W; PENGFEI, T; & PING-FAN, L., 2010. Non-lane-based full velocity difference car following model. *Physica A: Statistical Mechanics and its Applications*, 389(21):4654–4662.
- [15] KANAGARAJ, V; GOWRI A; TOMER T; & TZU-CHANG L., 2015. Trajectory Data and Flow Characteristics of Mixed Traffic. *Transportation Research Record: Journal of the Transportation Research Board*, 2491:1–11. doi: <http://dx.doi.org/10.3141/2491-01>.
- [16] KHAN, S; & MAINI, P., 1999. Modeling Heterogeneous Traffic Flow. *Transportation Research Record: Journal of the Transportation Research Board*, 1678(1): 234–241. doi: <http://dx.doi.org/10.3141/1678-28>.
- [17] KOSHY, R.Z; & ARASAN, V.T., 2005. Influence of Bus Stops on Flow Characteristics of Mixed Traffic. *Journal of Transportation Engineering*, 131(8): 640–643.
- [18] LI, Y; LI Z; SRINIVAS P; HONGGUANG P; TAIXIONG Z; LI,Y; & HE, X., 2015. Non-lane-discipline-based car-following model considering the effects of two-sided lateral gaps. *Nonlinear Dynamics*, 80(1-2): 227-238. doi: <http://dx.doi.org/10.1007/s11071-014-1863-6>.
- [19] LOGGHE, S; & IMMERS, L., 2003. Heterogeneous traffic flow modelling with the lwr-model using passenger-car equivalents. *Proceedings of the 10th World congress on ITS, Madrid (Spain)*.1–15. Available at: <http://www.kuleuven.be/traffic/dwn/P2003E.pdf>.
- [20] MACDONALD P; & DU, J., 2011. Package “MIXDIST” for R. Finite mixture distribution models; vol.5–4. Canada: McMaster University. R-CRAN.
- [21] MALLIKARJUNA, C; & RAO, K.R., 2006. Area Occupancy Characteristics of Heterogeneous Traffic. *Transportmetrica*, 2(3): 223–236.
- [22] MINITAB, I.N.C., 2003. *MINITAB User's Guide 2: data analysis and quality tools*.
- [23] MOHAN, R; & RAMADURAI, G., 2013. Heterogeneous traffic flow modelling using macroscopic continuum model. *2nd Conference of Transportation Research Group of India (2nd CTRG)* 381(3):115–123. doi: <http://dx.doi.org/10.1016/j.physleta.2016.10.042>.
- [24] NAIR, R., MAHMASSANI, H.S; & MILLER-HOOKS, E., 2011. A porous flow approach to modeling heterogeneous traffic in disordered systems. *Transportation Research Part B: Methodological*, 45(9): 1331–1345.
- [25] NGODUY, D., 2011. Multiclass first-order traffic model using stochastic fundamental diagrams. *Transportmetrica*, 7(2): 111–125.
- [26] SHARMA, N., ARKATKAR, S.S; & SARKAR, A.K., 2011. Study on Heterogeneous Traffic Flow characteristics of a Two-Lane Road. *Transport*, 26(2): 185–196.
- [27] SINGH, M. K., GADDAM, H., VANUMU, L. D. & RAO, K. R., 2016. Traffic Data Extraction Using MATLAB® Based Tool. *TPMDC-2016, International Conference, IIT Bombay*.
- [28] R CORE TEAM., 2015. *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria. URL <https://www.R-project.org/>.
- [29] TANG, T. Q., HUANG, H. J., ZHAO, S. G; & SHANG, H. Y., 2009. A new dynamic model for heterogeneous traffic flow. *Physics Letters A*, 373(29):2461–2466. doi: <http://dx.doi.org/10.1016/j.physleta.2009.05.006>.
- [30] WONG, G.C.K; & WONG, S.C., 2002. A multi-class traffic flow model - An extension of LWR model with heterogeneous drivers. *Transportation Research Part A: Policy and Practice*, 36(9):827–841.
- [31] ZHANG, H.M., 2002. A non-equilibrium traffic model devoid of gas-like behavior. *Transportation Research Part B Methodological*, 36(3): 275–290.