Following Behaviour in Mixed Traffic: Effects of Vehicular Interactions, Local Area Concentration and Driving Regimes

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Abstract

This paper models the following behaviour of vehicles in mixed traffic using trajectory data. New models for the longitudinal acceleration of following vehicles are developed based on vehicle type differences and their asymmetric interactions. Two new variables capture the effect of lack of lane-discipline: lateral offset and local area concentration. These variables not only affect the follower's acceleration but also the spacing and relative speed. The following behaviour also varies across gap-narrowing and gap-widening regimes. The proposed models considerably improve the goodness-of-fit measures compared to the base models. Such models are believed to add value to microscopic simulation models of mixed traffic by enhancing their realism.

Keywords: Heterogeneous traffic, weak lane-disciplined condition, influence area, vehicle following characteristics, vehicular interactions, driving regime models.

I. INTRODUCTION

The precision and realism of microscopic modelling is influenced by the identification, investigation and analysis of complex interactions between the traffic components, viz., road, road user, and vehicles. Among these, vehicle-to-vehicle interaction plays a dominant role. In mixed traffic condition, different types of vehicles share the same road space with dissimilar static and dynamic characteristics, where vehicles attempt to manoeuvre through the gaps available between the vehicles ahead. Thus, the application of conventional car-following models developed for lane-based homogeneous conditions are inadequate and inappropriate for usage in mixed traffic conditions.

The following behaviour of a vehicle in the traffic stream is greatly influenced by the static and dynamic characteristics of the leader and the following vehicle. The reaction of a two-wheeler when following a truck is vastly different from the same two-wheeler following another two-wheeler. Also, the responsiveness of a car to a specific leader will significantly vary from that of a truck or an auto-rickshaw (motorized three-wheeler) under the same circumstances. This offers a potential research gap for analysing and modelling the following behaviour for different vehicle pair combinations. Even though the response of a follower differs for different leader-subject

vehicle pair combinations, these variations can be grouped based on size-differential interactions. Therefore, the vehicle heterogeneity that exists in mixed traffic condition is addressed through the parameter called size-differential interaction. The present study groups the leader-subject vehicle pair interaction into three segments, namely, symmetric interaction, positive asymmetric interaction, and negative asymmetric interaction.

Due to varying dimensions of vehicles that exist in mixed traffic condition, the vehicles can find gaps between the leading entities to move forward. Thus, the drivers mostly consider area-based arrangement of vehicles as an optimum way of utilising the road space than linear based arrangement in heterogeneous non-lane-based traffic condition. This area-based arrangement of vehicles thus constitutes the research gap and the research question that originates is how to incorporate these characteristics into driving behaviour models and whether there exists substantial implication of these parameters. Thus, in the present study, the area-based arrangement of vehicles is captured through two variables namely local area concentration and lateral offset. In weak lane disciplined condition, the driving decision and manoeuvres performed by any vehicle in the traffic stream is not only influenced by the leader but by a group of vehicles surrounding it. This instigates the need to study the influence of surrounding vehicles on the following behaviour of subject vehicle, which indeed is addressed through the parameter called local area concentration (LAC) and is incorporated in modelling the response of the subject vehicle. The same attributes discussed above also lead to staggered following of vehicles along with strict following. The off-centeredness thus created between the leader and follower is addressed through the variable called lateral offset.

If the leader-subject vehicle pair and surrounding vehicle conditions are fixed, then the response of the follower to the leader will be varying for different driving conditions. These driving conditions can be called as regimes, and the sensitivity of a vehicle to these may differ significantly depending on leader-follower pair. The sensitivity of a follower to a leader present far ahead with a gap widening relative speed can be substantially different from the condition when the same leader is present at a closer spacing with a negative relative speed. The former condition may lead to a free driving or acceleration regime, while the latter may lead to deceleration or emergency braking situation. So, the role of size differential interactions, along with LAC and driving regimes are combined together in

the present study to capture the time-varying response of the subject vehicle under heterogeneous non-lane-based traffic condition.

II. LITERATURE REVIEW

Traffic flow models can be classified into microscopic, mesoscopic and macroscopic, depending on the level of detail. Macroscopic models deal with the aggregate traffic stream parameters like speed, density, volume, travel time, etc. and the interrelationships between them were derived by considering the traffic flow to be analogous to liquid or fluid flow. Whereas, microscopic models consider the disaggregate units of traffic stream and analyse the complex interactions between them. However, in mesoscopic models, the interaction at the disaggregate level is studied, but the results are represented at the aggregate level.

Microscopic modelling deals with capturing the action and reaction of vehicles under different situations, like car-following, lane changing, gap acceptance etc. [1]. Car-following models describe the acceleration characteristics of the following vehicle in reaction to the actions of its leader [1]. Several theories have been proposed to model car-following behaviour, which can be divided into five classes based on behavioural assumptions, namely, stimulus-response models, safety distance/ collision avoidance models, action point / psycho-physical models, optimal velocity models and cellular automata model [2]. All these models are developed for homogeneous lane-based conditions and transferability to mixed traffic conditions are questionable.

Gunay [3] has modified the Gipps basic car-following equation to incorporate the non-lane-based following by incorporating off-centred positions of vehicles. Later, the developed theoretical aspect was applied in the simulation model for a link where various types of vehicular interactions, including vehicle-following and lane changing, are studied. Kanagaraj et al. [4] studied the influence of composition, intra-class variability, and lack of lane discipline on traffic flow characteristics in mixed traffic with significant motorised two-wheeler volumes. Mallikarjuna et al. [5] explain a microscopic data collection methodology for heterogeneous traffic conditions and the traffic parameters for heterogeneous traffic, such as vehicle composition, lateral distribution of vehicles, lateral gaps and longitudinal gaps were analysed. Ravishankar and Mathew [6] have developed a model that incorporates vehicle-type dependent behaviour by modifying the widely used Gipps model. Three vehicle classes, namely, car, autorickshaw and bus, were considered, and the Gipps parameters were evaluated for each vehicle-type pair. Naveen [7] found that the models such as Gipps, IDM and Das-Asundi following models seem to be reasonable under steady-state and mixed traffic conditions and Krauss model performs well under non-steady state conditions. Metkari et al. [8] developed a traffic simulation model accounting for both heterogeneity and non-lane discipline condition together by incorporating the modified Gipps model [6] and the off centred car-following state [3]. The measures like traffic concentration and area occupancy have also been used to model the heterogeneous traffic conditions with no lane discipline [9].

In the various studies highlighted above, the theoretical car-following model was either directly applied or modified concepts were used for modelling mixed traffic condition. The response of subject vehicle and the various influencing factors have not been formulated from the empirical data yet. Effect of leader-subject vehicle pair and surrounding vehicle types on driving decisions have not been analysed from trajectory data. The variation in the following characteristics under different driving regimes also needs to be investigated. The research work presented in this paper studies the time-varying response of subject vehicle from trajectory data by considering the effect of leader-subject vehicle pair, surrounding vehicles and driving regimes.

III. DATA DESCRIPTION AND EXPLORATORY ANALYSIS

The methodology employed for data collection and extraction, along with exploratory analysis, has been discussed in this section. Driving behaviour models depict the response of vehicles to different static and dynamic circumstances on the road [1]. In this context, traffic data at the microscopic level is essential for the modelling and analysis of various complex vehicular interactions. Theoretical models were built to characterise the driving behaviours, but the calibration and validation of these models using actual field data are found to be limited at the microscopic level [10]. For homogeneous condition, FHWA's next-generation traffic simulation project has gathered and integrated trajectory data from major roads, and the data was made available to the public [11]. But the availability of such data for the heterogeneous condition is limited in extent due to extensive labour and time involved in the process of data collection [10].

III. I. Methodology for Trajectory Data Collection and Extraction

The current study developed a methodology for extracting trajectory data of mixed traffic condition using Python's graphical user interface. The data was collected from a straight section of urban mid-block in Chennai, India. The stretch selected is a six-lane divided road with three lanes in each direction on Mount Poonamalle Road, Chennai. The stretch was chosen such that it was devoid of influence of intersections, pedestrian crossings, median gaps and bus stops. A nearby eleven-storey building was selected as the vantage point for placing the video camera. Fig.1. shows the details of the study location marked on Google map.

Fig. 1. Details of Study Stretch Indicated on Google Maps

The chosen midblock stretch is 250 m long with a carriageway width of 10.5 m (in the direction of flow). The green arrow mark shows the direction of traffic flow. Peak and off-peak hour data were collected on a typical weekday, from which forty-five minutes of data was extracted using Python Graphical User Interface (GUI). The basic step involved in trajectory data collection is image calibration and perspective transformation. The entire road space is divided into blocks in the longitudinal and lateral directions, as shown in Fig. 2(a). The dimensions of each block are 10 m in the longitudinal direction and 1 m in the lateral direction. The actual measurements of each block should be known to transform the image coordinates into ground coordinates, and the corners of each block are marked, and video-graphed during the morning off-peak hour when the traffic flow is sparse. The video is then played in Irfan-view software to ascertain the pixel coordinates of each block. Both ground and pixel coordinates were together used to determine the correction factors of each block in the longitudinal and lateral direction. The traffic video so collected is converted into frames at a resolution of one frame for every second. These frames are opened in Python's GUI, where a vehicle can be tracked by clicking at a distinguishable point on it across the frames. Screenshot of a frame opened in GUI of python is shown in Fig. 2(b).

a) Screen Shot of Study Corridor with Gridlines Overlaid

b) Screen Shot of GUI for Semi-Automated Vehicle Tracking

Fig. 2. Trajectory Data Extraction

Every vehicle in the traffic stream is allotted a unique identification number, and the vehicle is continuously tracked from entry to exit point. Every time a new vehicle gets tracked, GUI asks for the vehicle ID and vehicle type, which gets stored along with its x- and y-position coordinates across different frames from entry to exit point of the study section. Five classes of vehicles are being considered: TW (motorised Two-Wheeler), car (passenger car and SUV), HCV (Heavy Commercial Vehicle, both trucks and buses together), LCV (Light Commercial Vehicle) and Auto (Autorickshaw). The extracted data at the microscopic level can be used for classifying the vehicle at each time step into the subject and surrounding vehicles.

III. II. Definition of Terms and Exploratory Analysis

The various terms used in the study is explained in this section:

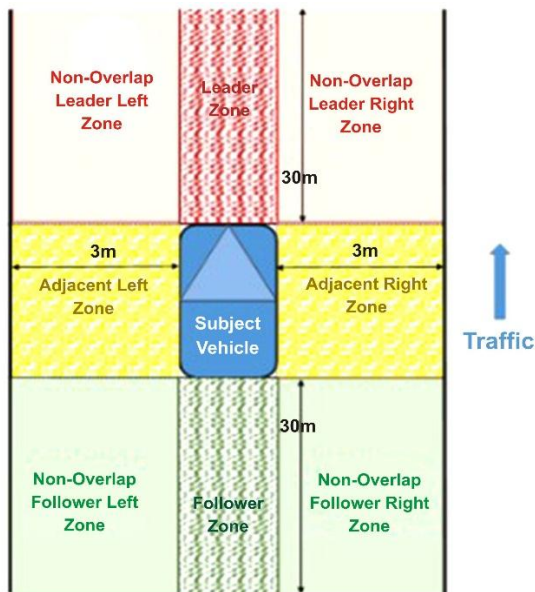### III. II. I. Influence Area, Subject Vehicles and Surrounding Vehicles

Each vehicle in the traffic stream is identified as the subject vehicle from entry to exit point in the study stretch. The position, speed and acceleration of the subject vehicle in both longitudinal and lateral direction is tracked continuously. Once the subject vehicle is recognised, then surrounding vehicles are identified depending on the concept of influence area. Influence area is defined as the region of influence around the subject vehicle where the surrounding vehicles are present, and which can influence the driving behaviour of the subject vehicle. Any vehicle which is wholly or partly contained in the influence area is considered as the influencing surrounding vehicle. At each instant of time, the subject vehicle's choice of speed, position and shift is assumed to be controlled by these surrounding vehicles. Influence area is demarcated depending on the composition and arrangement of vehicles around the subject vehicle in the surrounding zone of influence.

In the present study, the region surrounding the subject vehicle is partitioned into eight zones of influence, namely, leader zone, follower zone, adjacent zone - right and left, non-overlapping leader zone - right and left, and non-overlapping follower zone - right and left, as indicated in Fig. 3(a). Leader zone is an area where the leader of the subject vehicle is expected to be present and is delimited as a region whose width is same as that of subject vehicle's width and having a length of 30 m. The same concept is being used to demarcate the follower zone at the rear end of the subject vehicle. Adjacent vehicle zones are regions present on either side of the subject vehicle with length equal to subject vehicle length and having a width of 3 m each on both right and left sides. The remaining area on all the four corners of the subject vehicle, with a length of 30 m and width of 3 m are considered as the non-overlapping zones. The non-overlapping zone positions on the front end of the subject vehicle is named as non-overlapping leader zone right and left, where the non-overlapping leaders are expected to be present. Corresponding areas on the rear side are demarcated as non-overlapping follower zones - right and left side, respectively. All these area boundaries are shown in Fig. 3(a). The surrounding vehicles present in the above delineated zones of influence are categorised into eight positions of neighbouring vehicles, as shown in Fig. 3(b) and are named as follows:

- Position 1 – Leaders
- Position 2 - Left side non-overlapping vehicle ahead
- Position 3 - Right side non-overlapping vehicles ahead
- Position 4 - Left side adjacent vehicles
- Position 5 - Right side adjacent vehicles

- Position 6 – Follower
- Position 7 - Left side non-overlapping vehicle behind
- Position 8 - Right side non-overlapping vehicle behind

a) Zones of Influence around Subject Vehicle
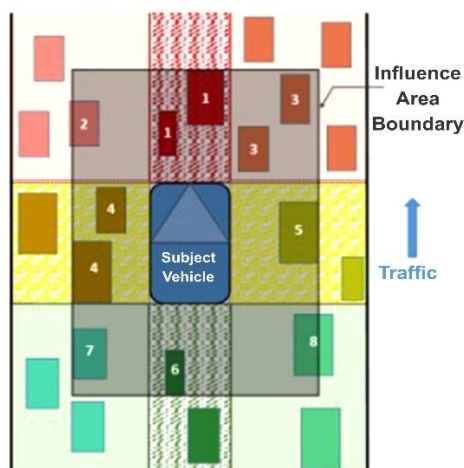
b) Demarcation of Influence Area Based
on Surrounding Vehicle Layout

Fig. 3. Influence Zones and Demarcation of Influence Area

IV.III. II. Delineation of Influence Area and Identification of Surrounding Vehicles

Overlapping and Non-Overlapping Leaders:

The front longitudinal boundary of the influence area is fixed at 30 m from the front bumper of the subject vehicle. The presence of overlapping front vehicles within this boundary is checked. If only one front vehicle has been present, then the front bumper of that overlapping vehicle is fixed as the front longitudinal boundary of influence area. If more than one overlapping front vehicles are present within 30 m from the subject vehicle, then two conditions have been checked. The first condition is whether these front vehicles' longitudinal dimensions are overlapping with each other, and if so, then the

farthest front bumper of these vehicles is fixed as the front longitudinal boundary of the influence area. The second condition is when the longitudinal dimensions of the front vehicles are not overlapping with each other. Under this condition, the front bumper of the nearest front vehicle is considered as the front longitudinal boundary of the influence area. Once the front longitudinal limit of influence area is fixed, then any vehicle present in front of the subject vehicle and positioned within this boundary is identified as a leader. The leaders are of two types, namely, overlapping leader and non-overlapping leader, depending on whether they are laterally overlapping with subject vehicle's width. The most influencing leader is then identified from the set of leaders based on the closest gap with the subject vehicle, which is determined based on the longitudinal gap for overlapping leader and diagonal gap for non-overlapping leaders, as shown in Fig. 4.
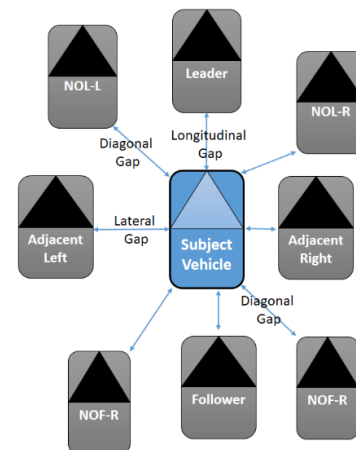

Fig. 4. Most Influencing Vehicles and their Corresponding Gaps with Subject Vehicle

If overlapping front vehicles are absent for subject vehicle, then the front longitudinal boundary of influence area is fixed based on the position and arrangement of non-overlapping front vehicles. The front longitudinal limit is initially assumed to be 30 m from the front bumper of the subject vehicle. The presence of a non-overlapping front vehicle within this region has been checked, and if vehicles are absent, then 30 m is fixed as the boundary. Otherwise, the presence of more than one non-overlapping vehicle in front is reviewed and if only one vehicle is present, then the front bumper of the vehicle which is present is demarcated as the front longitudinal boundary of influence area. If more than one non-overlapping front vehicles are present, then the condition of longitudinal overlap between them is checked. Then, the front bumper of laterally closer one to the subject vehicle is selected as the front longitudinal boundary of influence area. There can be situations where the non-overlap front vehicles laterally overlap with each other instead of longitudinal overlap between them. In that condition, the front bumper of the non-overlapping front vehicle which is longitudinally closer to the subject vehicle is selected as the front longitudinal boundary of influence area. After demarcating the front boundary, the non-overlapping leaders within this boundary are divided into non-overlapping leader right (NOL-R) or non-overlapping leader left (NOL-L) based on their position with respect to the subject vehicle. From the set of non-overlapping leaders, the most influencing one is

selected which has the minimum diagonal gap with the subject vehicle.

Overlapping and Non-Overlapping Followers:

Following vehicles are the ones which are present at the rear side of the subject vehicle and are present within the back end longitudinal boundary of influence area. The longitudinal limit at the rear end of the subject vehicle is fixed based on the constitution of followers, and similar concept as that discussed in the previous section is employed for demarcating it. If vehicles on the rear side of the subject vehicle are absent, then 30 m from the rear bumper of the subject vehicle is fixed as the rear longitudinal boundary of influence area. Otherwise, the back longitudinal edge of the influence area is set based on the presence or absence of overlapping rear side vehicle. First, the number of overlapping rear side vehicles is checked. If only one overlapping rear side vehicle is present, then the farther end of the nearest vehicle is selected as the rear longitudinal boundary of influence area. If more than one overlapping rear side vehicles are present, then the condition of longitudinal overlap among them is tested. Then the farthest rear boundary among the overlapping rear vehicle is selected as the back end longitudinal boundary of influence area. If overlapping rear side vehicles are absent, then the above condition is checked for non-overlapping rear side vehicles on the right and left sides. In the absence of both overlapping and non-overlapping rear side vehicles, 30 m from the rear bumper of the subject vehicle is fixed as the rear side longitudinal boundary of influence area. Once the influence area longitudinal rear boundary is demarcated, all the rear end vehicles present within the delineated boundary and which are non-overlapping with subject vehicle is considered as non-overlapping follower right (NOF-R) or non-overlapping follower left (NOF-L) based on their position with respect to the subject vehicle. Most influencing non-overlapping follower right and left is selected based on minimum diagonal gap with the subject vehicle on right and left sides, respectively.

Adjacent Vehicles:

The lateral boundary of the influence area has been fixed based on the positioning of the adjacent vehicles. Adjacent vehicles are surrounding vehicles whose longitudinal dimensions overlap with the length of the subject vehicle. All the vehicles which satisfy the above condition and within 3 m lateral boundary are considered as the adjacent vehicles to the left or right of subject vehicle based on their relative positions. If adjacent vehicles are absent, then the lateral boundary of the influence area is fixed at 3 m from both sides of the subject vehicle. If only one adjoining vehicle is present on one side, then the farther lateral side of the adjoining vehicle is considered as the lateral boundary of influence area. If more than one adjacent vehicle is present on one side of the subject vehicle, then the condition of whether these adjoining vehicles are laterally overlapping with each other is checked. If the above said requirement had been satisfied, then the farthest lateral side among all adjoining vehicles is traced as the lateral

boundary of influence area on one side. If adjoining vehicles identified are not laterally overlapping with each other, then the laterally nearest adjoining vehicle's farther lateral side from the subject vehicle is delineated as the lateral boundary of influence area. The same concept can be applied on the other side of the subject vehicle for fixing the opposite side lateral edge. All adjoining vehicles present within the above said lateral boundary are considered as the adjacent vehicles - right or left, based on their corresponding positions with respect to the subject vehicle. The most influencing adjacent vehicle is the one which is having the minimum lateral gap with the subject vehicle.
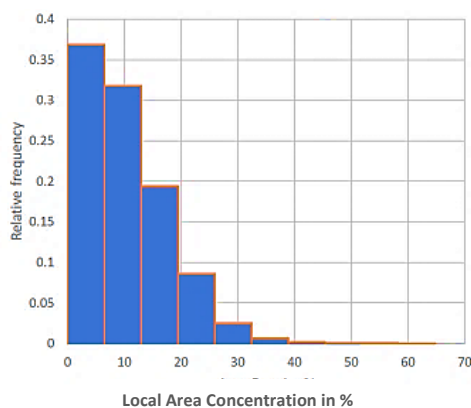
III. II. III Local Area Concentration (LAC)

In mixed traffic conditions, due to varying dimensions and weak lane discipline, vehicles can position themselves anywhere in the traffic stream depending on the availability of gaps, resulting in area-based arrangement of vehicles, rather than linear arrangement. The driving decisions of the subject vehicle under weak lane disciplined condition is not only influenced by the leader, but also by a group of vehicles surrounding it. The area encompassing the subject vehicle where the surrounding vehicles are expected to be present is termed as influence area. The concentration of vehicles in this influence area can significantly control the driving behaviour of the subject vehicle, and this study focuses on modelling its longitudinal response as a function of surrounding vehicles. Thus, the current study introduces the term Local Area Concentration (LAC), which is a measure of density of vehicles around the subject vehicle and depends on the type and composition of surrounding vehicles in the influence area. It is defined as the ratio of the sum of areas of surrounding vehicles to the total area of influence of the subject vehicle. Any vehicle which is wholly or partly contained in the influence area is considered as the surrounding vehicle. LAC is calculated using the expression given in Equation. 1.

$$LAC = \frac{\Sigma_{i=1}^{N} n_i a_i}{A} \times 100 \qquad (1)$$

Where, LAC is the Local Area Concentration in percentage, N is the total number of vehicles present in the vicinity of the subject vehicle in the influence area, n_i and a_i are the number and area of different vehicle classes i present in the influence area (i =1 for TW, i=2 for car, i=3 for HCV, i=4 for LCV and i=5 for autorickshaw),A is the total area of influence region surrounding the subject vehicle.

The frequency distribution of LAC and the box plot is shown in Fig. 5. From the histogram, the range of local area concentration is classified into three groups, namely, Low LAC (values less than 10%), Medium LAC (range of 10% to 20%) and High LAC (more than 20%). By considering the composition of vehicles in each range of LAC, as illustrated in Fig. 6., it is found that the LAC increases as the car composition increases concomitantly with a decrease in TW volume.
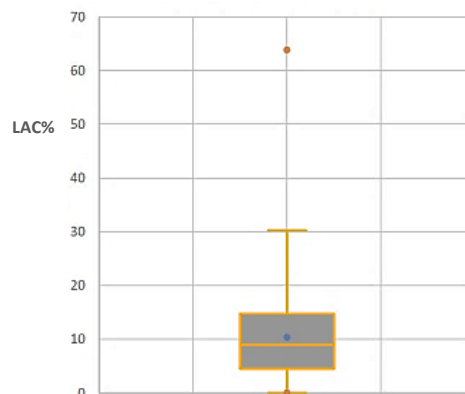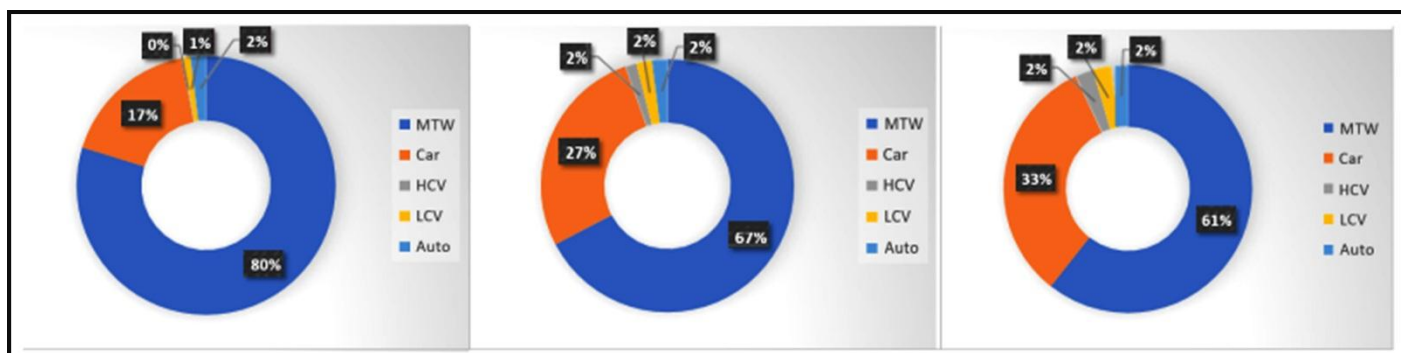
| (a) Histogram: LAC | (b) Box Plot: LAC |

Fig. 5 Frequency Histogram and Box Plot of the Observed Local Area Concentration (LAC)

| (a) Low LAC | (b) Medium LAC | (c) High LAC |

Fig. 6 Variation in Composition Across Different Local Area Concentration (LAC) Levels

III. II. IV Lateral Separation

Lateral separation is another variable which has been used to capture the effect of weak lane-disciplined condition. Due to lack of enforcement of lane discipline and vehicle heterogeneity, the vehicles in the mixed traffic condition follow their leaders mostly in a staggered manner, which gives better freedom for the followers to manoeuvre. Lateral separation is defined as the centre-to-centre separation between the leader and the subject vehicle (follower) as shown in Fig.7.
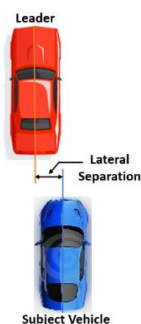
Fig. 7. Lateral Separation: Leader and Subject Vehicle

III. II. V Size Differential Interaction Between Leader and Subject Vehicle

In mixed traffic condition, the driving behaviour decisions are to be modelled by considering the vehicle heterogeneity and non-lane discipline conditions together in a meaningful and

realistic way. The driving behaviour of a vehicle is largely influenced by the vehicle it is following. For example, the response of a passenger car when following a bus or truck is significantly different from the same vehicle following a motorised two-wheeler. Present study models and analyses the effect of interaction between the leader and follower by considering the effect of size differential effect between the leader and subject vehicle (follower) pair as depicted in Fig. 8.

| (a) Symmetric Interaction | (b) Positive Asymmetric Interaction | (c) Negative Asymmetric Interaction |
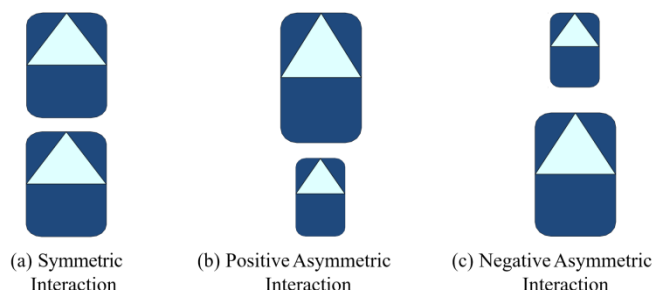
Fig. 8. Classification of Interactions Based on Width Difference Between Leader and Subject Vehicle

The key aspect of mixed traffic is vehicle heterogeneity which is precisely captured by size differential interaction parameter. The difference in size between leader and subject vehicle leads to three types of interactions, namely, symmetric interaction, positive asymmetric interaction and negative asymmetric interaction. Symmetric interaction refers to the interaction between leader-subject vehicle pairs of similar physical dimensions and asymmetric interactions refer to those between

dissimilar vehicle pairs. Asymmetry can be experienced in two ways: when the leader vehicle size is larger than the follower vehicle size, which is regarded as positive asymmetry and the vice-versa is considered as negative asymmetry. At each instance of time, the vehicle in the leading position of the subject vehicle is identified from the influence area concept.

leader and follower. Positive relative speed results in widening of gaps between the leader and follower, thus named as gap-widening regime and the vice-versa as gap-narrowing regime. These regimes are determined at every instant of time, and the derived driving regimes are used as a categorical independent variable in estimating acceleration of the subject vehicle.

III. II. VI Driving Regimes

The response of vehicle while driving is erratic and depends on time-varying perceptions based on thresholds [12,13]. The erratic driving response can be captured using gap widening or narrowing driving regimes. The driver switches from one regime to another based on the difference in speed between the

III. II. VII Description of Variables and Notations Used

The description of variables used in the study and the corresponding notations are listed in Table 1.

**Table 1.** Variable Description and Notations

Notation	Variable Description
s	Subject Vehicle: The vehicle under consideration at every time step is called as subject vehicle (follower).
l	Leader: The influence area concept is used to identify the leader. The present study considers only the overlapping leader with the subject vehicle
$a_s(t + \tau)$	Acceleration or Deceleration: The response of subject vehicle s in the longitudinal direction at a time $(t + \tau)$ .Unit: m/s^2
t	Time: Given instant of time in seconds
τ	Reaction time: The reaction time of subject vehicle which is considered as 1 sec in the present study
$v_{rel}(t)$	Relative speed: The relative speed between the leader and the subject vehicle at time t,. Unit: m/s^2 $v_{rel}(t) = v_l(t) - v_s(t)$
$S_{long}(t)$	Longitudinal gap: Bumper to bumper gap between the leader and the subject vehicle in the longitudinal direction in metres at time t
$LAC(t)$	Local area concentration (LAC): The ratio of sum of horizontal projected area of surrounding vehicles to the total influence area at time t
$S_{lat}(t)$	Lateral Offset: The centre-to-centre separation between the leader and the subject vehicle in the lateral direction (Absolute value). Unit: m
$\delta_{gap\_widening}$	Gap-Widening or Gap-Narrowing: Dummy variable for gap opening and gap closing, which is an indicator variable for positive or negative relative speed, • $\delta_{gap\_widening} = 0$ if the relative speed is negative indicating that the leader is slower than the subject vehicle • $\delta_{gap\_widening} = 1$ if the relative speed is positive indicating that the leader is faster than the subject vehicle
β_x	Coefficient: Parameter associated with variable x
ε	Error term that is assumed to be normally distributed

III. II. VIII Model Structure

The longitudinal response of the subject vehicle is modelled against relative speed and spacing with the leader. The dependent variable considered is the acceleration or deceleration of the subject vehicle in the longitudinal direction. Unsegmented (aggregate) and segmented (disaggregate) acceleration models for subject vehicles are formulated for different size-differential interaction between the leader-subject vehicle pair. The independent variables considered are as follows:

1. Relative speed of the leader with the subject vehicle

2. Longitudinal gap between the leader and the subject vehicle

3. Local area concentration and its interaction with relative speed and spacing

4. Lateral separation between leader and subject vehicle

5. Gap- widening/narrowing between leader and subject vehicle and its interaction with relative speed

6. Driving regimes and their interaction with relative speed

The acceleration model of the subject vehicle is built incrementally by introducing the dependent variable at three different stages formulating three different models incrementally as shown in Fig. 9.
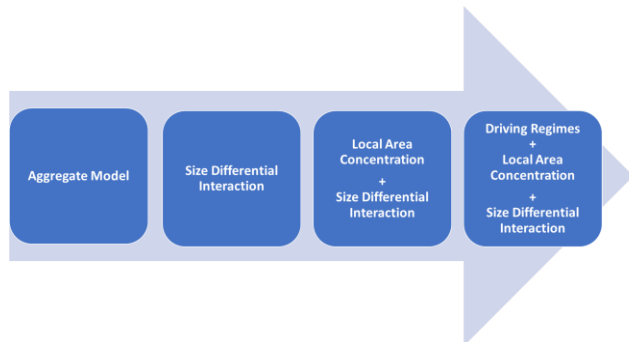
Fig. 9. Model Building Stages

The base structure of the model considered is the multiple linear regression equation with the dependent variable as the longitudinal response of the subject vehicle (acceleration/deceleration of subject vehicle at each instant of time). The independent variables considered for the base model are relative speed and spacing with the leader. The model structure is represented in Equation.2, and the terms are defined in Table 1.

$$a_s(t + \tau) = \beta_0 + \beta_1 v_{rel}(t) + \beta_2 S_{long}(t) + \varepsilon \quad (2)$$

Unsegmented Vs Segmented Aggregate Models:

Empirical data is used to estimate the multiple linear regression model parameters. The data were classified into three segments: symmetric interaction, positive asymmetric interaction, and negative asymmetric interaction, based on size differential interaction portrayed in Fig. 8. Chow's test was performed to test whether there is a statistically significant difference in the following behaviour across the three segments. Chow test is commonly used to test for structural change in some or all of the parameters of a model in cases where the disturbance term is assumed to be same in both periods or segments [14]. The test statistics for the Chow test is shown in Equation 3.

$$F_{obs} = \frac{(RSS - RSS_1 - RSS_2 - RSS_3)/2k}{(RSS_1 + RSS_2 + RSS_3)/(n_1 + n_2 + n_3 - 2k)}$$
$$\sim F(2k, n_1 + n_2 + n_3 - 2k) \quad (3)$$

where, F_{obs} is the test statistics of Chow-test, RSS is the restricted sum of squares, RSS_i is the sum of squares residual for segment i, (i=1 denotes symmetric interaction segment, i=2 denotes positive asymmetric interaction segment, and i=3 denotes negative asymmetric interaction segment). RSS_1 + RSS_2 + RSS_3 is the unrestricted sum of squares of residuals. k is the number of linear restrictions, and $n_1 + n_2 + n_3 - 2k$ is the number of parameters in the unrestricted regression model.

Table 2. shows a comparison between the unsegmented aggregate models and the aggregate models that are segmented based on symmetric and asymmetric interactions. The R^2 has nearly doubled from the unsegmented to segmented models, and the mean absolute error also decreases. The Chow test results (F_{obs} = 82.629 vs F_{crit} = 3.783) conclusively reject the unsegmented model in favour of the segmented model at 1% level of significance. Thus, segmenting the models based on the size difference between leader and follower yields coefficients which are statistically different from the aggregate models. The magnitudes of coefficients also vary across segments indicating significant differences in the following behaviour depending on the size difference between leader and follower

Table 2. Comparison of Aggregate Model with Size Differential Interaction Models

Aggregate and Disaggregate Leader-Follower Interaction Models	Sample Size	Coefficients for			R^2	MAE
		Constant b_0	Relative Speed b_1	Longitudinal Gap b_2		
Aggregate Model	49899	0.053	0.244	0.003	0.078	1.606
Symmetric Interaction Case	28714	*0.000*	0.268	0.003	0.149	1.520
Positive Asymmetric Interaction	8525	0.111	0.318	0.013	0.160	1.650
Negative Asymmetric Interaction	12660	-0.140	0.185	0.006	0.136	1.570

* represents coefficient not statistically significant at 5%. Sample sizes are n, n₁, n₂, n₃ for the aggregate, symmetric, positive asymmetric and negative interaction cases respectively.

Although the coefficients of relative speed and spacing are significant for the aggregate as well as disaggregate models, the magnitudes of coefficients vary depending on the size difference between leader and follower. The relative speed coefficient is the largest when size difference is positive (the leading vehicle is larger), followed by symmetric interaction, and is smallest when the size differential is negative (leading vehicle is smaller in width). The sensitivity to relative speed reduces by nearly 15% (0.318 to 0.268) for the symmetric case and drops by almost 40% for the negative asymmetric case (to 0.185). In comparison, the aggregate model (where size difference is ignored), yields a coefficient of 0.244, which is comparable and marginally smaller than the symmetric case. This implies that for a given spacing and relative speed difference, the following vehicle will decelerate more when the leading vehicle is bigger than otherwise. In this case, the follower will be in a more constrained condition, as compared to the negatively asymmetric situation.

With regard to the coefficient for longitudinal spacing also, significant differences in magnitudes are observed based on the size difference. The coefficients are much larger for longitudinal spacing (by four times, coefficient = 0.013) when the leading vehicle is bigger and twice as big for the negative symmetric case (coefficient = 0.006) than the symmetric cases (coefficient = 0.003). The aggregate model coefficient is the same as the symmetric case and hence smaller than the asymmetric cases. Thus, drivers display a more cautious response when following a larger vehicle than another vehicle of the same size. Interestingly, the larger sensitivity to spacing for negative interaction also implies that larger vehicles like cars and heavy vehicles are also more sensitive to longitudinal gaps while following smaller vehicles such as two-wheelers and autos than while following another vehicle of its own type. This behaviour may be interpreted as to allow for and avoid conflicts for the larger vehicles due to the tendency of such smaller vehicles to filter through narrow gaps within the heterogeneous traffic stream.

The coefficient for the intercept also varies between the segments. The intercept is positive for the asymmetric case suggesting a tendency to accelerate when relative speed difference is zero for a given longitudinal spacing. Thus, the smaller following vehicle will try to seek lateral gaps and avoid following the larger vehicle as soon as such an opportunity arises. In contrast, the intercept is negative for the case when bigger vehicle follows a smaller one, indicating a tendency to decelerate when relative speed difference is zero as there might not be sufficient lateral gap for the larger vehicle to overtake the smaller lead vehicle. The symmetric case intercept is not significant, implying the tendency to maintain current speed when the leading and following vehicles are of the same size. In contrast, the aggregate model coefficient is positive and significant, which can lead to an unrealistic conclusion that all vehicles will accelerate when relative speed difference tends to zero for a given longitudinal spacing, regardless of the size and type of leading and following vehicles.

IV. ACCELERATION MODELS FOR SUBJECT VEHICLE

Every driver, while driving evaluates the current speed and position with respect to his/her desired speed and/or position that is suitable in relation to the surrounding traffic. Accordingly, the driver decides to modify either speed or position as needed. This study focuses on the following behaviour, and hence attention is restricted to longitudinal response in the form of acceleration or deceleration of the following (subject) vehicle which can lead to a change in speed. The models shown in Table 2, in the previous section have established that two primary stimuli that affect the acceleration of the subject vehicle are the relative speed between the leading and following vehicles, and the longitudinal gap or spacing between them. Besides, the model results indicate that the effect of size difference also influences the role of these variables in mixed traffic.

In this section, the effect of following mixed traffic characteristics on the longitudinal acceleration of the subject vehicle is investigated:

1. Effect of vehicle type heterogeneity in the following behaviour

2. Effect of lack of lane discipline

3. Asymmetric variation in following behaviours across different driving regimes

IV.I. Model 1: Effect of vehicle type heterogeneity in the following behaviour

The results from the previous section indicate apparent differences in the following behaviour depending on the size difference between the leader and follower in mixed traffic. Thus, the differences in interaction between the leader and follower can lead to considerable differences in longitudinal gaps and deceleration behaviours, which in turn has implications on flow rate in the stream and traffic safety aspects. The research issues in this regard include: does the size difference effect vary depending on the exact types of leading and following vehicles? In other words, is there heterogeneity in behaviour even within a given type of asymmetric or symmetric interaction? For e.g., how is the response of a car following a bus different from a motorised two-wheeler following a bus even though both of them involve positive asymmetry (size difference). Similarly, are there differences in driving response when a two-wheeler follows another one, compared to a car-car following scenario?

In this section, in addition to the size differential interaction, the effect of vehicle type heterogeneity in the following response is also studied. This is done by classifying leader-follower pairs based on vehicle types. The vehicle types are classified into four categories as: motorised two-wheeler (TW), car and SUV (Car), autorickshaws (Auto), bus and Heavy Commercial Vehicles (HCV). Accordingly, leader-follower vehicle pairs are extracted based on the combination of vehicle types. The vehicle pair combinations with adequate sample size are selected to build a model for each case and are listed as follows:

1. Symmetric Interaction:

    a. TW-TW

    b. Car-Car

2. Positive Asymmetric Interaction

    a. Car-TW

    b. HCV-TW

    c. Auto-TW

    d. HCV-Car

    e. Car - Auto

3. Negative Asymmetric Interaction

    a. TW-Car

    b. TW-HCV

    c. TW-Auto

    d. Car-HCV

    e. Auto-Car

The vehicle following model shown in Equation 2 is estimated separately for each of the leader-follower types above, and the results are summarised in Table 3. In the table, * represents the coefficients that are not statistically significant at 5% significance level.

IV.I. I. Model 1 Results

Three sets of size-differential interactions were considered, namely, symmetric interaction, positively asymmetric interaction and negatively asymmetric interaction. Table 3 shows the parameters of the acceleration/deceleration model for the subject vehicle for these three sets of interactions. Including the effect of heterogeneity increases the goodness-of-fit compared to size difference models presented in Table 2. The coefficient of multiple determination R^2 improves considerably. It nearly doubles from 0.14-0.16 to $0.23 - 0.40$ and the mean absolute error decreases by a factor of two from 1.52-1.65 to 0.72-0.89). Further, a Chow test was conducted to test whether there are statistically significant differences across vehicle pair types with each size difference class (symmetric, positive asymmetric and negative asymmetric cases). The results indicate that the coefficients within each interaction class are considerably different at a significance level of 1%.

For the different vehicle pair combinations, the coefficients of relative speed and effective longitudinal gap are found to be realistic—the acceleration of subject vehicle increases as relative speed increases and vice-versa. Similarly, the sign for the longitudinal gap is also positive and intuitive, indicating that as the longitudinal gap between the leader and follower increases, the following vehicle shows a greater tendency to accelerate.

The key difference in symmetric and asymmetric interaction lies in the sensitivity of the dependent variable on relative speed and gap. The sensitivity is highest for positive symmetric interaction compared to the other two types. This is due to the fact that when vehicles are contained within the width of a slow-moving leader of wider dimension, then the freedom to manoeuvre or to shift its position is limited and the responsiveness to the changes in leader speed and gap influence the follower's decision to a higher degree. For example, consider the car as a follower in different interaction conditions shown in Table 3. Responsiveness (as seen from the magnitude of slope coefficients) is higher for a car following an HCV (under positively asymmetric interaction) than a car following a TW (under negatively asymmetric interaction) or a car following another car (symmetric interaction). Even under the same negative asymmetric interaction, the responsiveness of the car to relative speed is more when the leader is an auto-rickshaw than when the leader is a TW.

The sensitivity to the longitudinal gap is significant for most pairs (except car-auto) in the positive asymmetry case. In contrast, it is insignificant for most pairs (except auto-car) in the negative asymmetric interactions. Among symmetric interactions, though the spacing effect for car-car and TW-TW are nearly equal in magnitude. However, car-car is significant at 5% level, but the TW-TW spacing variable is significant only at the 10% level. The magnitudes of longitudinal spacing coefficients (among those significant at 10% level) also vary substantially across vehicle pairs. The largest sensitivity to spacing is for a two-wheeler following an HCV and car (0.122 and 0.101), followed by car-car and TW-TW (0.006, and 0.005), and much smaller for auto-car, auto-TW, HCV-car (0.02, 0.016, and 0.010).

Unlike longitudinal gap above, the coefficient for relative speed is significant for all leader-follower pairs. However, the magnitudes show a wide range of variation across symmetric, positive asymmetric and negative asymmetric interactions. The most considerable magnitude and range are seen for the positive interaction cases (0.301 to 0.478). The symmetric cases have the next largest sensitivity (0.295 to 0.315). On the other hand, the sensitivity to relative speed drops substantially in the negative asymmetric interaction cases (0.16 to 0.223). Significant variations, even within positive and negative asymmetric situations, are also observed as explained in the following paragraphs.

When two-wheeler is the subject vehicle, it is more responsive when following an HCV than a car or an autorickshaw. Its sensitivity to the independent variables of relative speed and longitudinal spacing is the smallest when it another TW. For auto-rickshaw as the subject vehicle, the sensitivity to relative speed and gap is more when it is following a car than when following a TW. On the other hand, if HCV is considered as a subject vehicle (which is being the most significant vehicle type in the study), its responsiveness is more when following a car than a TW. All these findings are consistent with results from the previous section that show the highest sensitivity towards the independent variable in the case of positive asymmetric interaction. The minimum sensitivity corresponds to the negative asymmetric interaction, whereas the sensitivity to stimuli for the symmetric cases lie between these extremes.

Table 3. Model 1: Effect of Size Differential (Vehicle Pair Wise) on Subject Vehicle's Acceleration

Leader-follower Interaction Models	Sample Size	Coefficients for			R^2	MAE
		Constant b_0	Relative Speed b_1	Longitudinal Gap b_2		
Symmetric Interaction						
TW-TW	21879	0.002*	0.295	0.005*	0.278	0.89
Car-Car	6755	0.003*	0.315	0.006	0.306	0.75
Positive Asymmetric						
Car-TW	9344	0.117	0.457	0.101	0.320	0.75
HCV-TW	710	0.115*	0.478	0.122	0.347	0.72
Auto-TW	869	0.085*	0.379	0.010	0.239	0.84
HCV-Car	263	-0.041*	0.386	0.016	0.310	0.78
Car -Auto	273	0.02*	0.301	0.009*	0.276	0.79
Negative Asymmetric						
TW-Car	6198	-0.089	0.196	0.009*	0.398	0.71
TW-HCV	373	-0.096	0.156	0.008*	0.318	0.76
TW-Auto	678	-0.149*	0.201	-0.007*	0.298	0.85
Car-HCV	133	-0.156*	0.225	0.017*	0.365	0.74
Auto-Car	266	-0.121*	0.228	0.002	0.282	0.88

* represents coefficient not statistically significant at 5%.

Within positive symmetric interaction, specific pairs have almost similar coefficients for relative speed. The coefficient for relative speed is comparable for car-TW (leader-follower) and HCV-TW pairs (0.48 and 0.46). This suggests that the following behaviour of two-wheeler is similar across different leader types. However, when a TW follows an auto, it is much less sensitive to speed difference (coefficient is 0.38). Thus, the following behaviour not only depends on the following vehicle type but also the leading vehicle type.

Interestingly, the coefficient for relative speed is similar when a car is following a heavy commercial vehicle (0.39). This is despite the bigger dimensions of HCV-car pair than auto-TW pair. This may be the result of similar differences in dynamic characteristics between leader and follower pair, where the leading vehicle has significantly inferior speed and acceleration characteristics than the following vehicles. An interesting finding is that the least sensitivity for the positive asymmetry (size difference) is found for the car-auto pair. The coefficient for relative speed is only 0.301, which is considerably smaller than other pairs in this class. In all the other cases of positive asymmetry, the following vehicle is smaller and has superior dynamic characteristics (maximum speed and acceleration) than the leader. Only in the case of car-auto, the following vehicle has more manoeuvrability but inferior dynamic features which may lead to lower sensitivity to relative speed. Thus, in addition to the size difference, leader type and dynamic characteristic differences also influence the following vehicle's response.

With regard to the negatively asymmetric case, the longitudinal gap is significant for only the auto-car pair. This is believed to be due to the smaller width difference in this vehicle pair. This causes limitations in movement as compared to the larger width difference. But more importantly, the role of the longitudinal gap effect for this pair is still much smaller than both symmetric (by a factor of 3), and positive asymmetric case (by a factor of 4 to 6). Thus, longitudinal gap plays a more critical role when

the leading vehicle is bigger or of the same size as the following vehicle.

Differences across vehicle pairs are also observed in the coefficients of relative speed for negative asymmetric interaction. Within this class, the range of coefficients is much smaller than the positive interaction case. For example, in the negative asymmetric interaction case, a unit change in relative speed produces the most substantial change in acceleration for auto-car and car-HCV pairs (0.228 and 0.225). The TW-car and TW-auto pair have nearly equal and slightly smaller coefficients of 0.20 and 0.196 respectively. The behaviour when an HCV follows a two-wheeler shows a much lower sensitivity to speed difference (0.156) indicating a more cautious following behaviour of HCVs which may be due to the largest size differential and weaker dynamic characteristics of HCVs.

IV.I. II. Model 1 Inference and Significance

The responsiveness to relative speed and spacing is found to be more for positive asymmetric interaction, followed by symmetric interaction and then by negative asymmetric interaction. Further, there are variations even within a given size difference class. The above results imply that for a given subject vehicle, the responsiveness is more for a large leader and sensitivity declines as the size of the leader reduce. Furthermore, the sensitivity towards relative speed is different for positive and negative asymmetry depending on the width difference. For positive asymmetry, sensitivity reduces as the width difference reduces, whereas for negative asymmetry, the sensitivity increases as the width difference decrease.

The differences in following behaviour noted above due to heterogeneity and asymmetry of vehicle types across leader-follower pairs have practical significance concerning safety and capacity of mixed traffic streams. Considering the safety aspect, the longitudinal gap affects positive asymmetric pairs, but there is no significant effect of this gap for negative

asymmetric pair (leader is smaller). Thus, the closer following behaviour may be expected with negative asymmetric pairs which can be confirmed through the measure of central tendency and the respective values for negative asymmetric, symmetric and positive asymmetric vehicle pairs are 10.875, 11.055 and 11.835, respectively. Further, the gap maintained between the leader-subject vehicle pair also influences the capacity of the system. The capacity will be affected not only by the vehicle composition, but also by the gap maintaining behaviour which depends on the composition or fraction of different leader-follower vehicle types that make up the mixed traffic stream. In the case of a vehicle following a TW or a TW following another vehicle, the sensitivity towards the longitudinal gap is less compared to other vehicle types. Therefore, there is a need to study how the difference in gap maintaining behaviours will affect capacity and safety of mixed traffic in future.

IV.II. Model 2: Effect of Local Area Concentration, Lateral Offset and Gap-Widening Regime on Acceleration of Subject Vehicle

As already discussed, vehicle heterogeneity and weak lane disciplined conditions are the peculiarities of mixed traffic condition. The effect of heterogeneity in vehicle types was captured through size-differential variables in the previous section.

Along with heterogeneity, the weak-lane discipline condition is another factor that needs to be accounted for in mixed traffic. Two related issues arise in this regard: As vehicles are distributed laterally over the entire road width without regard to lane discipline, how can this area based arrangement of vehicles be captured (unlike the linear and lane-based arrangement in homogeneous traffic streams)? Second, to what extent do these weak-lane discipline related factors influence the driving behaviour of subject vehicle? This study proposes two new variables to address these questions as defined below:

1. Local Area Concentration (LAC)

2. Lateral offset

Under medium to heavy traffic flow condition, at every instant of time, the vehicles are surrounded by adjoining vehicles which are assumed to influence the driving decisions of the subject vehicle. The influence is expected to diminish when the longitudinal and / or lateral distance of a given vehicle increases from the subject vehicle. The area within which adjoining vehicles have a significant influence on the subject vehicle is referred to as the area of influence. Because of the non-lane disciplined nature of traffic stream, the number and composition of vehicles in the influence area could vary over time and space. Consequently, the influence of these vehicles on subject vehicle response needs to be quantified systematically. For this purpose, a new variable is defined as local area concentration. It is defined as the ratio of sum of areas of surrounding vehicles to the influence area encompassing the subject vehicle. Thus, LAC measures the effect of different types of vehicles that are in the vicinity of the subject vehicle but also how many and how closely the surrounding vehicles are placed around the subject vehicle.

To study the effect of local area concentration, alternative models of subject vehicle acceleration were built based on equation 3 from previous section by adding different function representation of the LAC variable. Linear, polynomial, and log-linear forms of models were estimated (Table 4). The results showed that the linear form of the variable provides the best fit with observed data. Hence, this form is retained for the rest of this analysis in equation 4. Another parameter which is concurrently used with LAC to model the non-lane-based arrangement of vehicles is the lateral offset. Lateral offset is defined as the lateral separation between the centre line of the lead vehicle and the centre line of the following vehicle. The lateral offset value is small (close to zero) under strict following. In contrast, this offset may be much larger (up to a maximum of sum of half the width of the leader and half the width of the follower) in the case of staggered following. Beyond this limit, the following vehicle does not overlap with the leader, and such manoeuvres are not considered within the following cases in this study. Greater values of lateral offset and staggered following can lead to greater visibility of downstream conditions, improved manoeuvrability, and lower potential for severe collision with the lead vehicle and thus is expected to lead to significantly different response compared to strict following.

Table 4. Functional Forms of Subject Vehicle Acceleration with Local Area Concentration for CAR-TW Vehicle Pair

Functional Forms	Coefficients			
	b_0	b_1	b_2	b_3
$a_s(t + \tau) = \beta_0 + \beta_1 v_{rel}(t) + \beta_2 S_{long}(t) + \beta_3 L_{AC}(t) + \varepsilon$	0.029*	0.380	0.024	0.218
$a_s(t + \tau) = \beta_0 + \beta_1 v_{rel}(t) + \beta_2 S_{long}(t) + \beta_3 L_{AC}^2(t) + \varepsilon$	0.091	0.384	0.023	0.717*
$a_s(t + \tau) = \beta_0 + \beta_1 v_{rel}(t) + \beta_2 S_{long}(t) + \beta_3 \ln(L_{AC}(t)) + \varepsilon$	0.291	0.385	0.024	0.226*

* represents coefficient not statistically significant at 5%

Another improvement in this model 2 compared to model 1 is to account for asymmetric response of the subject vehicle under gap-widening versus gap-narrowing regimes. Gap narrowing occurs when the follower is travelling faster than the leader and widening occurs when the leader is faster. The gap remains stationary if the relative speed difference is zero. If the gap widens over time, the subject vehicle may have greater freedom and manoeuvrability. In contrast, gap narrowing creates constrained conditions for subject vehicle movement. Thus, the effect of a given gap or other variables such as leader's speed are likely to vary depending on gap-widening or gap-narrowing conditions. Specifically, the responsiveness of subject vehicle to surrounding vehicles is assumed to be more during gap-narrowing compared to gap-widening as the opportunity to manoeuvre is restricted in the first case. To capture this asymmetry, a gap-widening binary indicator variable is included in equation 4 below to differentiate the response from gap narrowing cases. In addition, this variable is also interacted with relative speed, thus capturing heterogeneity in driving behaviour response to relative speed and spacing between the widening and narrowing cases. Thus, the improved model for predicting acceleration of the subject vehicle is synthesised as given in Equation. 4 and the variables are defined in Table 1.

$$
\begin{aligned}
a_s(t + \tau) = {} & \beta_0 + \beta_1 v_{rel}(t) + \beta_2 S_{long}(t) + \beta_3 S_{lat}(t) \\
& + \beta_4 LAC(t) + \beta_5 LAC(t)v_{rel}(t) \\
& + \beta_6 LAC(t)S_{long}(t) + \beta_7 \delta_{gap\_widening} \\
& + \beta_8 \delta_{gap\_widening} v_{rel}(t) + \varepsilon \qquad (4)
\end{aligned}
$$

IV.II.I. Model 2 Results

The parameters of model 2 (Equation.4) are presented in Table 5, which describes the responsiveness of subject vehicle acceleration to relative speed and longitudinal gap along with lateral offset, local area concentration, gap-widening for different classes of symmetric and asymmetric interactions. This upgraded model has considerably improved from the base segmented and unsegmented models, both statistically and realistically. The coefficient of determination, R^2 value for different vehicle pairs have increased by 1.5 times from previous model (with R^2 range of $0.23 - 0.40$) to present model (with R^2 range of $0.41 - 0.59$). Besides, the mean absolute error value has also reduced considerably due to the inclusion of non-lane-based variables and asymmetry between gap narrowing and gap widening situations.

The results from this model are discussed in detail below. As expected, the coefficient of relative speed and longitudinal gaps for all vehicle pair groupings is positive and consistent with model 1 as discussed previously. Once again it is found that the effect of these variables vary depending on size differential interaction as well as specific vehicle pairs: the sensitivity to relative speed and longitudinal gap is more for positive asymmetric interaction followed by symmetric interaction and is lowest for negative asymmetric interaction. A notable difference from model 1 is that the coefficient of longitudinal gap (which was insignificant earlier) assumes significance in this model after accounting for non-lane-based variables (LAC, lateral offset) and gap widening indicator. Thus, not accounting for these could lead to biased and erroneous inferences about the effect of key variables influencing following behaviours.

The results show that the coefficients of relative speed and longitudinal gap increase with increasing size of the leader. Also, the type of subject vehicle also matters with regard to the effect of these two conventional variables. The largest influence is seen for cars when it follows an HCV, whereas the smallest influence is for a car following a two-wheeler. Within the same size difference class (symmetry, positive or negative asymmetry) also, the magnitudes vary depending on leader-follower pair type. For e.g., the coefficients (sensitivity to relative speed and spacing) are smaller for TW-HCV pair than car-HCV pair, suggesting a greater influence of the variables for smaller size differential. Similar trends are observed with greater coefficients for auto-car pair than TW-HCV pair. In the latter case, the longitudinal gap is not statistically significant.

Local area concentration (LAC) which is an indicator of density and composition of surrounding vehicles, is found to be significant at 5% significance level for all the vehicle pairs except HCV-TW (which is significant at 10% significance level). The interesting finding is that the coefficient of LAC is negatively correlated with acceleration for all subject vehicles except TW. An increase in local area concentration in the influence area leads to deceleration of the subject vehicle for all vehicles (other than two-wheelers). This may be logically explained by the higher degree of confinement provided by surrounding vehicles as LAC increases, thereby affecting the freedom to manoeuvre which forces the subject vehicles to decelerate under the growing values of LAC. But motorised two-wheelers have a smaller size and dynamic characteristic advantages, and hence can utilise the small gaps available in the surrounding area to 'escape' from the influence of neighbouring vehicle. So, even within the high density of vehicles in the surrounding area, the two-wheelers can seep through the gaps, thus creating a positive correlation between the longitudinal response and LAC.

The effect of LAC is highest for positive asymmetric interaction (leader is bigger), followed by symmetric interaction and minimum for negative asymmetric interaction (leader is smaller). The same trend is observed with coefficients of interaction term of LAC with relative speed and longitudinal gap. Comparing between the subject vehicles, for a constant value of relative speed and longitudinal gap, the sensitivity to LAC is highest for the car, followed by HCV, autorickshaw and much lower for TW. For the same subject vehicle, the coefficient for LAC is also found to vary depending on the type of leading vehicle. The magnitude of LAC coefficient is more for larger vehicles. For e.g., the coefficients are in decreasing order for HCV-car, car-car, auto-car, and TW-car pairs. Interestingly, for the car and auto pair, the coefficient for auto-car is 32% more than car-auto pair due to the difference in driving behaviours across these vehicle types. This suggests that car drivers behave more conservatively and are more sensitive to the surrounding vehicle characteristics in the influence area compared to autos. A similar trend is observed where the coefficient of HCV-car pair is more than 2.6 times the coefficient for car-HCV pair. Within negative asymmetric interaction, the magnitude of LAC is more for heavy vehicles when compared to other vehicles.

Local area concentration not only affects the response (acceleration of the subject vehicle) directly as an explanatory

variable noted above, but it also plays a mediating role on the subject vehicle's acceleration response by modifying the effect of relative speed and spacing on acceleration. The coefficient of interaction of LAC with relative speed is negative for all the subject vehicle types except TW. However, when a smaller vehicle follows a larger leader (positive asymmetric interactions), the parameter is insignificant for TW and auto, but significant for cars. This implies that for a given speed difference, cars tend to decelerate more at higher local concentration when following a larger vehicle (HCV) than at lower concentrations, whereas such an effect is not noticeable for two-wheelers and autos (due to their smaller size and propensity to filter through smaller gaps).

Among symmetric pairs, the interaction term of LAC with relative speed has a significant and positive effect for TW-TW pair, but a negative effect for car-car pairs. This shows how the following behaviour of TW is distinctly different with respect to car. With increasing levels of local traffic concentration in its vicinity, a car decelerates while following another car, whereas, a two-wheeler tends to accelerate in order to filter through gaps to avoid this increased concentration.

When a larger vehicle follows a smaller vehicle (negative asymmetry), the interaction parameter of LAC with relative speed is significant and negative for all vehicle pairs considered. However, there are notable differences in magnitude across some pairs. The effect is maximum for the car-HCV pair followed by auto-car pair, whereas the coefficient is much smaller for TW-HCV and TW-car pairs. With increasing local concentration, larger vehicles tend to display more cautious behaviour while following a smaller vehicle for a given relative speed difference, but the extent of deceleration is smaller when an HCV or car follow a two-wheeler. This suggests that the larger vehicles anticipate the possibility and tendency of two-wheelers to manoeuvre out of areas of higher local concentration noted earlier.

Unlike the interaction of relative speed and local area concentration, higher levels of concentration do not significantly influence the effect of longitudinal spacing for almost all leader-follower pairs with one exception. Only for the HCV-car pair, the effect of spacing decreases with increasing area concentration. This may be attributable to the larger contribution of HCV as the leader to local area concentration, and the superior dynamic characteristics (acceleration/braking) of car relative to the heavy commercial vehicle.

The above discussion shows that under mixed traffic, the response of following vehicle to a leader depends not only on their respective vehicle types, but also on the local area concentration, which represents the types of vehicles in the neighbourhood of subject vehicle as well as their spatial arrangement. The significance of the interaction terms above implies that it is able to capture non-linear interactions between leader and follower due to the presence of surrounding vehicles of various types under non-lane-based conditions, thus improving the realism of the model.

The second variable capturing lack of lane discipline is lateral offset. The results indicate that this variable is insignificant for all pairs except TW-car pair. For this pair, the coefficient is positive. This implies that an increase in the lateral separation between the leader and follower results in greater freedom to manoeuvre for subject vehicle, thereby leading to acceleration. The reason for insignificance for most other pairs is that the lateral spacing between just leader and follower does not adequately characterise following behaviours in mixed traffic because of constraints imposed by other vehicles in the vicinity of the follower.

Next, the effect of gap-widening/gap-narrowing (categorical variable with values 1/0) and its interaction with relative speed on longitudinal response of subject vehicle is studied. Both these parameters are positively correlated with response variable, stating that the subject vehicle accelerates when gap widens and decelerates when the gap is narrowing. Asymmetric behaviour in the rate of deceleration and acceleration is observed during the gap-widening and gap-narrowing cases. When all other variables are kept fixed during the two cases, the difference arises due to coefficients b_0, b_1, b_7 and b_8. For the gap-narrowing case, the mean deceleration rate at small relative speeds (close to zero) is given by b_0 (ranges from -0.055 to -0.28 m/s^2). In contrast, the mean acceleration rate at small relative speeds when gap is widening is given by b_0+b_7 (0.03 to 0.33 m/s^2). A vehicle pairwise comparison of the average acceleration vs deceleration rate for small relative speed difference during gap-widening and narrowing cases reveals that the acceleration rate is nearly 1.5-2 times larger for all but TW-TW and car-HCV pairs. For e.g., for the car-car pairs, the mean acceleration rate is (0.545-0.208 = 0.337) whereas the deceleration rate during gap narrowing is -0.208 for small relative speeds. When car follows a two-wheeler (with small relative speed difference near zero), the average acceleration and decelerations are 0.227 m/s^2 and -0.137 m/s^2. Thus, magnitude of response is larger when gap is increasing than when it is decreasing in most cases when the leader and follower are travelling at almost the same speed. The more cautious (smaller) deceleration rate may be intended to avoid rear-end collisions from vehicles that are behind the subject vehicle. In contrast, for the TW-TW pair, these rates are 0.039 m/s^2 and -0.217 m/s^2, respectively. The car-HCV pair also exhibits a similar trend with 0.14 m/s^2 and -0.28 m/s^2 during the gap-widening and narrowing conditions.

In contrast to the above analysis for small relative speed difference, for larger speed differences, the terms b_1 and b_8 will dominate as they are multiplied by relative speed (v_{rel}). The coefficient of interaction term between gap-widening and relative speed captures this effect. This coefficient is positive for all and significant for most pairs at 5% level, but the magnitude of increase (b_8 for gap widening case) is small compared to b_1. The coefficient b_1 indicates the effect of relative speed for the gap narrowing case. On the other hand, b_8 represents the increase in effect of relative speed for the gap widening case. Thus, for the TW-TW pair, the coefficient is 0.189 for the gap-narrowing case, whereas it is b_1+b_8 = 0.189+0.0112=0.2 for the gap-widening case. The range of increase in magnitude of longitudinal response for widening versus narrowing scenarios ranges from 0.012 to 0.082 m/s^2 across different leader-follower pairs for unit increase in relative speed difference. No significant difference of the effect

of relative speed variable is observed for car-TW, auto-car, and car-auto pairs between gap-widening and gap-narrowing cases.

The sensitivity of the dependent variable on gap-widening varies with subject vehicle type and also the lead vehicle. The coefficient for gap-widening for different subject vehicle types for b_7 vary as follows: car has the largest magnitude (ranging from 0.339 to 0.545), followed by HCV (0.349 to 0.421), autorickshaw (0.289) and lowest for TW (0.256 to 0.365). This shows that car and HCV adjust the longitudinal response more aggressively in the gap-widening case than in the gap-narrowing case when compared to autorickshaw and TW.

For a given subject vehicle, the effect varies with the type and size of the leader. For instance, when car is the subject vehicle, the sensitivity to gap-widening (b_7) is largest when following a car or a larger vehicle and lowest when following smaller vehicles. For the first two interactions, the follower is contained within the leader width, thus increasing the sensitivity of the dependent variable on the attribute of relative speed being positive (gap widening). When the car follows an HCV, the coefficient is nearly twice as large than when it follows a two-wheeler. Similarly, the sensitivity towards gap-widening is more for an HCV when following a car (0.421) than a TW (0.349). However, TW has an almost similar sensitivity to gap-widening when the lead vehicle is either a TW or a car (0.256 and 0.287), but the sensitivity increases by nearly 40% when following an HCV. These differences may be attributed to manoeuvrability of the subject vehicle, size difference with the leader as well as dynamic characteristics of the lead vehicle.

IV.II.I. Model 2 Inference and Significance

For a given subject vehicle, the responsiveness of acceleration to relative speed and the longitudinal gap is high when it is following a larger sized leader and the sensitivity declines as the size of the leader reduce. For the same vehicle pair combination, the responsiveness to relative speed and spacing is more for positive symmetric interaction, followed by symmetric interaction and negative symmetric interaction as seen in the previous model. For all vehicle types except TW, the increase in local area concentration results in the reduction in speed as the acceleration and LAC are negatively correlated. Therefore, because of the confinement offered by the surrounding vehicles, the subject vehicles decelerate and adapt to the speed of leader as LAC increases. Whereas, for motorised two-wheeler being the subject vehicle, the influence of surrounding vehicle is minimum, which is due to its ability to filter through the gaps available between the surrounding vehicles. The gap-widening/narrowing parameter in the acceleration model explains the asymmetric response of subject vehicle towards positive and negative relative speed. Thus, the longitudinal response in mixed traffic is complex as the same subject vehicle behaves differently depending on the leader type, the narrowing or widening regime, and whether relative speed difference is small or large, local area concentration and lateral offset.

V. CONCLUSIONS

The present study developed driving behaviour models considering the combined effect of size differential, local area concentration and driving regimes. The base model was built

considering the time-varying response of subject vehicle acceleration about relative speed and the gap at the aggregate level. The model was further segmented based on size differential, and the local area concentration and driving regimes are introduced to improve the realism of modelling.

The study found that the size differential has a significant influence on the following behaviour of a vehicle. The sensitivity to relative speed and spacing with the leader for a smaller vehicle when following a larger vehicle is more compared to a leader of equal or lower dimension. This indicates that there is variation in the following behaviour of subject vehicle concerning symmetric or asymmetric interaction with the leader. The local area concentration also has an impact on the decisions made by the subject vehicle. As the local area concentration increases, the sensitivity to relative speed and gap increases. Higher local area concentration results in the deceleration of the subject vehicle, whereas low values of LAC have a positive coefficient for relative speed. The responsiveness of subject vehicle varies with gap widening and gap-narrowing situation. These findings could be used for improving existing driving behaviour models and can enhance the realism of the microscopic modelling scheme for mixed traffic condition.

The findings of the research work presented in this study have potential applications in several areas of traffic engineering and management. The idea on following gap maintained by different vehicle types and local area concentration gives an insight into the capacity and level of service of the system. The safety aspect of driving is also absorbed in these models where the sensitivity of vehicle types in gap maintaining behaviour has been discussed. The sensitivity of vehicle types to local area concentration, lateral offset and narrowing or widening regime could be incorporated into the automated highways and driverless vehicle concept to enhance safety. Integrating size differential interaction, local area concentration and driving regimes into microsimulation algorithms for mixed traffic condition could capture the naturalistic driving behaviour, thereby resulting in more realistic models.

REFERENCES

[1] Toledo, T., 2007, "Driving Behaviour: Models and Challenges," Transport Reviews, 27(1), 65–84.

[2] Brackstone, M., and McDonald, M., 1992, "Car-following: A Historical Review," Transportation Research Part F: Traffic Psychology and Behaviour, 2(4), 181–196.

[3] Gunay, B., 2007, "Car Following Theory with Lateral Discomfort," Transportation Research Part B: Methodological, 41(7), 722-735.

[4] Kanagaraj, V., Asaithambi, G., Srinivasan, K.K., and Sivanandan, R., 2011, "Vehicle Classwise Analysis of Time Gaps and Headways under Heterogeneous Traffic," Transportation Research Board 90th Annual Meeting, Washington, DC.

[5] Mallikarjuna, C., Ramachandra, R., Kalaga, and Seethepalli, N.V.S.K., 2011, "Analysis of Microscopic

Data under Heterogeneous Traffic Conditions," Transport, 25(3), 262-268.

[6] Ravishankar, K.V.R., and Mathew, T.V., 2011, "Vehicle-Type Dependent Car-Following Model for Heterogeneous Traffic Conditions," Journal of Transportation Engineering, 137(11), 775-781.

[7] Naveen, C.H., 2013, "Microscopic Analysis of Vehicle Behaviour in Mixed Traffic," MTech Thesis, Indian Institute of Technology Madras, Chennai.

[8] Metkari, M., Budhkar, A., and Maurya, A.K., 2013, "Development of Simulation Model for Heterogeneous Traffic with No Lane Discipline," Procedia - Social and Behavioral Sciences, 104, 360-369.

[9] Arasan, V., and Dhivya, G., 2010, "Methodology for Determination of Concentration of Heterogeneous Traffic," Journal of Transportation Systems Engineering and Information Technology, 10(4), 50-61.

[10] Kanagaraj, V., Asaithambi, G., Toledo, T., and Lee, T.C., 2015, "Trajectory Data and Flow Characteristics of Mixed Traffic," In Transportation Research Board 94th Annual Meeting, Washington, DC.

[11] Kovvali, V., Systematics, C., Alexiadis, V., Zhang, L., and Length, P., 2007, "Video-Based Vehicle Trajectory Data Collection," In Transportation Research Board 86th Annual Meeting, Washington, DC.

[12] Leutzbach, W., and Wiedemann, R., 1986, "Development and Applications of Traffic Simulation Models at the Karlsruhe Institut fur Verkehrwesen," Traffic Engineering and Control, 27(5), 270-278.

[13] Raju, N.P., Kumar, A., Jain, Arkatkar, S.S., and Joshi, G., 2018, "Application of Trajectory Data for Investigating Vehicle Behavior in Mixed Traffic Environment," Transportation Research Record, 2672(43), 122-133.

[14] Fisher, F.M., 2006, "Tests of Equality Between Sets of Coefficients in Two Linear Regressions. An Expository Note," Econometrica, 38(2), 361-371.

Table 5. Model 5: Effect of Size Differential Interaction, Lateral Separation, Gap-Widening and Gap-Narrowing and Local area concentration on Subject Vehicle's Acceleration

Disaggregate Leader-Follower Interaction Models	Sample Size	Coefficients									R^2	MAE
		b_0 (Intercept)	b_1 (v_{rel})	b_2 (S_{long})	b_3 (S_{lat})	b_4 (L_{AC})	b_5 ($L_{AC} * v_{rel}$)	b_6 ($L_{AC} * S_{long}$)	b_7 ($\delta_{gap\_widening}$)	b_8 ($\delta_{gap\_widening} * v_{rel}$)		
Symmetric Interaction												
TW-TW	6690	-0.217	0.189	0.017*	0.037*	0.159	0.120	-0.041*	0.256	0.0119	0.542	0.61
Car-Car	2465	-0.208	0.356	0.041	0.055*	-0.599	-0.256	-0.216*	0.545	0.0179	0.589	0.52
Positive Asymmetric Interaction												
Car- TW	2715	-0.083*	0.218	0.019	0.005*	0.109	0.121*	0.001*	0.287	0.011*	0.568	0.50
HCV-TW	166	-0.093*	0.487	0.031	0.003*	0.098*	0.078*	0.003*	0.365	0.015	0.548	0.53
HCV-Car	71	-0.099*	0.558	0.152	0.015*	-1.084	-0.162	-0.225	0.489	0.082	0.551	0.54
Car-Auto	108	-0.055*	0.331	0.027	0.004*	-0.182	-0.095*	-0.009*	0.289	0.027*	0.434	0.71
Negative Asymmetric Interaction												
TW-Car	2287	-0.137	0.155	0.012	0.011	-0.121	-0.120	-0.031*	0.364	0.018	0.536	0.57
TW-HCV	218	-0.156	0.128	0.011*	0.003*	-0.188	-0.135	-0.212*	0.349	0.015	0.487	0.69
Car-HCV	77	-0.280	0.239	0.015	0.004*	-0.278	-0.285	-0.251*	0.421	0.017	0.409	0.70
Auto-Car	117	-0.129*	0.299	0.019	0.007*	-0.182	-0.186	-0.054*	0.339	0.016*	0.510	0.58

❖ represents coefficient not statistically significant at 5%