# STUDY OF VEHICULAR INTERACTION IN HETEROGENEOUS TRAFFIC FLOW ON INTERCITY HIGHWAYS USING MICROSCOPIC SIMULATION

**V. Thamizh Arasan [a] & Shriniwas S. Arkatkar [b]**

[a] Professor, Transportation Engineering Division, Department of Civil Engineering,
Indian Institute of Technology Madras, Chennai - 600 036, India
[b] Ph.D. scholar, Transportation Engineering Division, Department of Civil Engineering,
Indian Institute of Technology Madras, Chennai - 600 036, India

[a] arasan@iitm.ac.in, [b] s_arkatkar@yahoo.co.in

## ABSTRACT
Study of the basic traffic flow characteristics and comprehensive understanding of vehicular interaction are the pre-requisites for highway capacity and level of service analyses and formulation of effective traffic regulation and control measures. This is better done by modeling the system, which will enable the study of the influencing factors over a wide range. Computer simulation has emerged as an effective technique for modelling traffic flow due to its capability to account for the randomness related to traffic. This paper is concerned with application of a simulation model of heterogeneous traffic flow, named HETEROSIM, to study the relationships between traffic flow variables such as traffic volume and speed. Further, the model is also applied to quantify the vehicular interaction in terms of Passenger Car Equivalent (PCE) or Passenger Car Unit (PCU), taking a stretch of an intercity road in India as the case for the study. The results of the study, provides an insight into the complexity of the vehicular interaction in heterogeneous traffic.

Keywords: Heterogeneous Traffic, Micro-Simulation, Passenger Car Unit and Highway Capacity.

## 1. INTRODUCTION
The road traffic in the developing countries like India is highly heterogeneous comprising vehicles of wide ranging static and dynamic characteristics. The different types of vehicles present in the traffic can be broadly grouped into eight different categories as follows: 1. Motorized two-wheelers, which include motor cycles, scooters and mopeds, 2. Motorized three-wheelers, which include Auto-rickshaws – three wheeled motorized transit vehicles to carry a maximum of three passengers and tempos – three wheeled motorized vehicles to carry small quantities of goods, 3.Cars including jeeps and small vans, 4. Light commercial vehicles comprising large passenger vans and small four wheeled goods vehicles, 5. Buses, 6. Trucks, 7. Bicycles and 8.Tricycles, which include cycle-rickshaws- three wheeled pedal type transit vehicles to carry a maximum of two passengers and three wheeled pedal type vehicles to carry small amount of goods over short distance. These motorised and non-motorised vehicles share the same road space without any physical segregation. The speeds of these vehicles vary from just 5 to over 100 km/h. Due to the highly varying physical dimensions and speeds; it becomes difficult to make the vehicles to follow traffic lanes. For manoeuvre, the vehicles take any lateral position along the width of roadway, based on space availability. When such different types of vehicles having varying static and dynamic characteristics mix and move on the same roadway facility, a variable set of longitudinal and transverse distribution of vehicles are noticed from time to time.

The study of vehicular interaction is intended to quantify the relative impact of the presence of each of the different types of vehicles on traffic flow. This can be achieved by estimating Passenger Car Unit (PCU) values for the different categories of vehicle in the traffic. Under heterogeneous traffic conditions, in India, expressing traffic volume as number of vehicles per hour per lane is irrelevant and the volume of traffic has to be expressed taking the whole of the width of roadway as the basis. Also, the volume of such heterogeneous traffic needs to be expressed as PCU per hour by converting the different types of vehicles into equivalent passenger cars. Hence, estimation of PCU values of different categories of vehicles at various traffic volume levels is necessary for planning, design, and operational analysis of roadway facilities, in addition to regulation and control of traffic.

To arrive at an estimate of the PCU values, it is necessary to study the influence of roadway and traffic characteristics and the other relevant aspects, on vehicular movement, accurately. Study of these by observing various aspects of traffic flow in the field is difficult and time consuming. Also, it is not possible to carry out such experiments in the field covering a wide range of traffic volume and composition on a given roadway due to practical difficulties. Hence, it is necessary to model road–traffic flow for in depth understanding of the related aspects. The study of these complex characteristics, that may not be sufficiently simplified using analytical solution, requires alternative tools like computer simulation (Banks et al. 2004). Simulation, from microscopic through macroscopic, is increasingly becoming a popular traffic-flow modeling tool for analyzing traffic operations and highway capacity. Helbing et al. (2002), have shown that all the presently known macroscopic phenomena of freeway traffic, including (i) the fundamental diagrams, (ii) the characteristic parameters of congested traffic and (iii) the transitions between free traffic and other congested traffic states can be reproduced and explained by microscopic and macroscopic traffic models based on plausible assumptions and realistic parameters.

This paper is focused on the conceptual traffic simulation framework of highly heterogeneous traffic flow and application of the microscopic simulation model to study the relationship between traffic volume and speed. The model is also applied to study vehicular interaction by quantifying the relative impact of the presence of each of the different types of vehicles on traffic flow, under homogeneous (cars-only) and heterogeneous traffic conditions, at various traffic volume levels taking all the influencing factors into account.

## 2. OBJECTIVE AND SCOPE OF THE STUDY

Most traffic and transportation system simulation applications today are based on the simulation of vehicle-vehicle interactions and are microscopic in nature. The interaction between moving vehicles under heterogeneous traffic condition is highly complex. Microscopic simulation is a very powerful technique and has been applied to study the complex nature of the vehicular interactions in traffic stream. The knowledge of traffic volume is an important basic input required for planning, analysis and operation of roadway systems. Expressing traffic volume as number of vehicles passing a given section of road or traffic lane per unit time will be inappropriate when several types of vehicles with widely varying static and dynamic characteristics are comprised in the traffic. The problem of measuring volume of such heterogeneous traffic has been addressed by converting the different types of vehicles into equivalent passenger cars and expressing the volume in terms of Passenger Car Unit (PCU) per hour. Hence, the objective of the research work reported here is to quantify the vehicular interaction, in terms of Passenger Car Unit (PCU) values, of different categories of vehicles at various traffic volume levels, under heterogeneous traffic conditions prevailing on intercity roads, in plain terrain, in India. A recently developed heterogeneous traffic-flow simulation model, named, HETEROSIM is used to study the vehicular interactions, at micro-level, over a wide range of traffic flow conditions. Field data collected on traffic flow characteristics such as free speed, acceleration, lateral clearance between vehicles, etc. are used for validation of the simulation model. The validated model is then applied to develop the relationship between traffic volume and speed and derive Passenger Car Unit (PCU) values for different types of vehicles. Finally, check for the accuracy of the estimated PCU values is also made.

## 3. THE SIMUALTION FRAMEWORK

Simulation models may be classified as being static or dynamic, deterministic or stochastic, and discrete or continuous. A simulation model, which does not require any random values as input, is generally called *deterministic*, whereas a *stochastic* simulation model has one or more random variables as inputs. Random inputs lead to random outputs and these can only be considered as estimates of the true characteristics of the system being modeled. Discrete and continuous models are defined in an analogous manner. The choice of whether to use a discrete or continuous simulation model is a function of the characteristics of the system and the objectives of the study (Banks et al. 2004). For this study, a dynamic stochastic type discrete event simulation is adopted in which the aspects of interest are analysed numerically with the aid of a computer program.

The applications of traffic simulation programs can be classified in several ways. According to the problem area one can separate intersection, mid-block road section and network simulations. For traffic and transportation system applications, the available traffic-simulation-program packages have been used by the researchers all over the world. Bloomberg and Dale (2000) have given the detailed information about the use of two popular traffic simulation models (CORSIM and VISSIM) for traffic analysis on a congested network. Ben-Akiva et al. (1997), developed a simulation laboratory for performance evaluation and design refinement of dynamic traffic management systems. The simulation laboratory has been implemented in C++ using object-oriented programming and a distributed environment. Elefteriadou et al. (1997), used simulation as a tool to develop a methodology for calculating passenger car equivalents for freeways, two-lane highways, and arterials. Ahn et al. (2002), estimated vehicle fuel consumption and emissions based on instantaneous speed and acceleration using INTEGRATION microscopic simulation model. AIMSUN, DRACULA, PARAMICS and VISSIM are the main micro-simulation tools that have been used to model traffic on UK roads (Barcelo 1996).

As this research work pertains to the heterogeneous traffic conditions prevailing in India, the available traffic-simulation-program packages mentioned above such as CORSIM, AIMSUN, VISSIM, etc. cannot be directly used to study the characteristics of the traffic flow as these are based on homogeneous traffic-flow conditions. Also, the research attempts made earlier (Khan and Maini 2000; Marwah and Singh 2000; Kumar and Rao 1996; and Ramanayya 1988) to simulate heterogeneous traffic flow on Indian roads were limited in scope as they were location and traffic-condition specific. Moreover, these studies did not truly represent the absence of lane and queue discipline in heterogeneous traffic. Hence, an appropriate traffic simulation model, named, HETEROSIM has been developed (Arasan and Koshy 2005) to replicate heterogeneous traffic flow conditions accurately.

The modelling framework is explained briefly here to provide the background for the study. For the purpose of simulation, the entire road space is considered as single unit and the vehicles are represented as rectangular blocks on the road space, the length and breadth of the blocks representing respectively, the overall length and the overall breadth of the vehicles. The entire road space is considered to be a surface made of small imaginary squares (cells of convenient size 100 mm in this case); thus, transforming the entire space into a matrix. The vehicles will occupy a specified number of cells whose co-ordinates would be defined before hand. The front left corner of the rectangular block is taken as the reference point, and the position of vehicles on the road space is identified based on the coordinates of the reference point with respect to an origin chosen at a convenient location on the space. This technique will facilitate identification of the type and location of vehicles on the road stretch at any instant of time during the simulation process (Fig. 1).

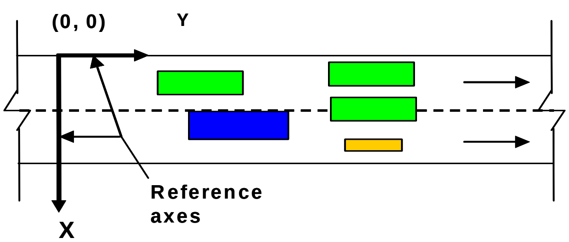



Figure 1: Reference Axes for Representing Vehicle Positions

The simulation model uses the interval scanning technique with fixed increment of time. For the purpose of simulation, the length of road stretch as well as the road width can be varied as per user specification. The model was implemented in *C++* programming language with modular software design. The flow diagram illustrating the basic logical aspects involved in the program is shown as Figure 2. The simulation process consists of the following major sequential steps: (1) vehicle generation, (2) vehicle placement, and (3) vehicle movement.

**3.1. Vehicle Generation**

In a stochastic traffic simulation process, the vehicles arrive randomly, and they may have varying characteristics (e.g. speed and vehicle type). Traffic-simulation models therefore, require randomness to be incorporated to take care of the stochasticity. This is easily done by generating a sequence of random numbers. For generation of headways, free speed, etc., of vehicles, the model uses several random number streams, which are generated by specifying separate seed values. Whenever a vehicle is generated, the associated headway is added to the sum of all the previous headways generated to obtain the cumulative headway. The arrival of a generated vehicle occurs at the start of the warm-up road stretch when the cumulative headway equals the simulation clock time. At this point of time, after updating the positions of all the vehicles on the road stretch, the vehicle-placement logic is invoked.

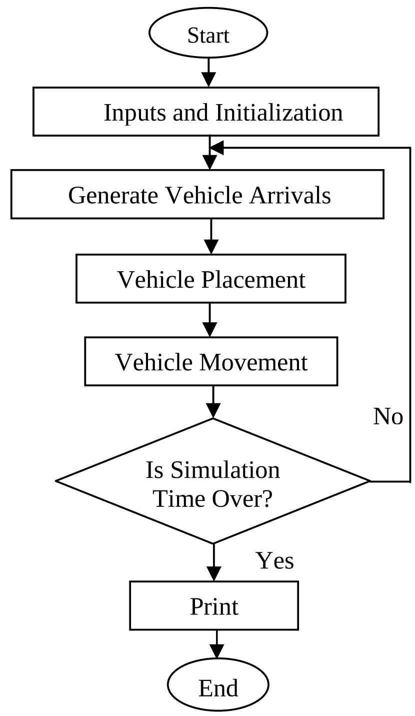



Figure 2: Flow Diagram of the Simulation Model

**3.2. Vehicle Placement**

Any generated vehicle is placed at the beginning of the simulation stretch, considering the safe headway (which is based on the free speed assigned to the entering vehicle), lateral gap and the overall width of the vehicle with lateral clearances. If the longitudinal gap in front is less than the minimum required safe gap, the entering vehicle is assigned the speed of the leading vehicle, and once again the check for safe gap is made. If the gap is still insufficient to match the reduced speed of the entering vehicle, it is kept as backlog, and its entry is shifted to the next scan interval. During every scan interval, the vehicles remaining in the backlog will be admitted first, before allowing the entry of a newly generated vehicle.

**3.3. Vehicle Movement**

This module of the program deals with updating the positions of all the vehicles in the study road stretch sequentially, beginning with the exit end, using the formulated movement logic. Each vehicle is assumed to accelerate to its free speed or to the speed limit specified for the road stretch, whichever is minimum, if there is no slow vehicle immediately ahead. If there is a slow vehicle in front, the possibility for overtaking the slow vehicle is explored. During this phase, the free longitudinal and transverse spacing available for the subject vehicle (fast moving vehicle), on the right and left sides of the vehicle in front (slow vehicle), are calculated. If the spacing is found to be adequate (at least equal to the movable distance of the vehicle intending to overtake plus the corresponding minimum spacing in the longitudinal direction and the minimum required lateral spacing in the transverse direction), an overtaking maneuver is performed. If overtaking is not possible, the fast vehicle decelerates to the speed of the slow vehicle in front and follows it. Thus, the various maneuvers for a vehicle moving on the simulation road stretch include free forward movement with desired speed, acceleration maneuver, movements leading to lateral shifting and overtaking of slower vehicles, movements involving deceleration and following of the front vehicle for want of sufficient gaps for overtaking, etc. The model is also capable of displaying the animation of simulated traffic flow through mid block sections. The animation module of the simulation model displays the model's operational behavior graphically during the simulation runs. The snapshot of animation of heterogeneous traffic flow, obtained using the animation module of HETEROSIM, is shown in Figure 3. The model has been applied for a wide range of traffic conditions (free flow to congested flow conditions) and has been found to replicate the field observed traffic flow to a satisfactory extent through an earlier study (Arasan and Koshy, 2005).

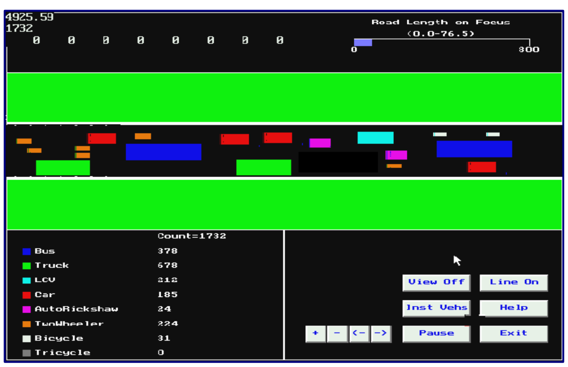



Figure 3: Snapshot of Animation of Simulated Heterogeneous Traffic Flow

For the purpose of simulation, the time scan procedure is adopted. The scan interval chosen for the simulation is 0.5 second. The arrival of vehicles on the road stretch will be checked for every 0.5 second and the arrived vehicles will be put on to the entry point of the study stretch of the road, on first-come-first-served basis. In the vehicle-generation module, the first vehicle is generated after initialization of the various parameters required to simulate heterogeneous traffic flow. Then, the generated vehicle is added to the system when the current time (clock time) becomes equal to the cumulative headway. At this stage, the module for adding vehicles named 'Add Vehicle' will be activated to facilitate the process. At higher traffic flow levels, there is a chance of more than one vehicle arriving during each scan interval (0.5s). To address this issue, an additional clock for scanning with a precision of 0.05 s is provided, so that a maximum of 20 vehicles can be added in one second. The precision of 0.05 s, decided based on field studies, is intended to account for the maximum possible number of smaller vehicles, like motorised two wheelers, auto-rickshaw, etc. that may arrive in large numbers in short periods on multilane highways. Thus, the logic formulated for the model also permit admission of vehicles in parallel across the road width, since it is common for smaller vehicles such as Motorised two-wheelers to move in parallel in the traffic stream without lane discipline. Vehicles admitted to the simulation road stretch are then allowed to move based on the various movement logics formulated. When the cumulative precision time is equal to the scan interval, the module for vehicle movement 'Move All Vehicles' will be activated to move all the vehicles in the simulation road stretch, with their current parameter values. The above process will be continued until the clock time matches with the assigned total simulation time. The model is also capable of simulating homogeneous traffic (cars-only traffic stream, comprising of 100 percentage of car). The snapshot of animation of homogeneous traffic flow, obtained using the animation module of HETEROSIM, is shown in Figure 4.


Figure 4: Snapshot of Animation of Simulated Homogeneous (Cars-only) Traffic Flow

## 4. DATA COLLECTION

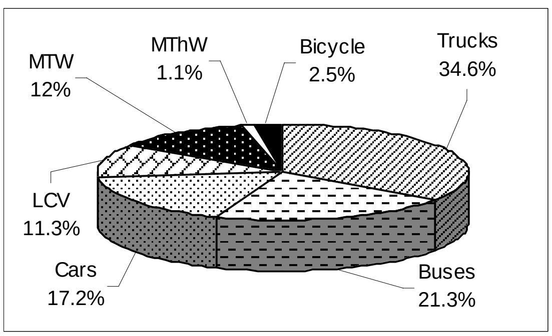
### 4.1. Study Stretch

The stretch of intercity roadway between km 77.2 and km 77.4, of National Highway No. 45 between the cities, Chennai and Chengalpet, in the southern part of India, was selected for collection of traffic data for the study. The study stretch is a four-lane divided road with 7.5 m wide main carriageway and 1.25 m of paved shoulder for each direction of movement. The stretch is straight and level with no side road connections. Also, the traffic flow on the study stretch was unhindered by the road side land uses.

### 4.2. Traffic Characteristics

Collection and analysis of data play a pivotal role in the development of successful simulation models. The field data inputs required for the model were collected at the selected stretch, which had a total carriageway width (including shoulder) of 8.75 m for each direction. A digital video camera was used to capture the traffic flow for a total duration of 1h. The video captured traffic data was then transferred to a Work station (computer) for detailed analysis.

The inputs required for the model to simulate the heterogeneous traffic flow are: road geometry, traffic volume, and composition, vehicle dimensions, minimum and maximum lateral spacing between vehicles, minimum longitudinal spacing between vehicles, free speeds of different types of vehicles, acceleration and deceleration characteristics of vehicles, the type of headway distribution and the simulation period. The required input traffic data for the simulation was obtained by running the video of the traffic flow at a slower speed ( $\frac{1}{8}^{th}$ of the actual speed) to enable one person to record the data by observing the details displayed on the monitor of the computer. The composition of the measured traffic volume on the study stretch is as depicted in Figure 5. It may be noted that Animal drawn vehicles and Tricycles, which may be present in small numbers on certain intercity roads, are not present on the study stretch.




L.C.V. - Light Commercial Vehicles, M.Th.W. – Motorised Three-Wheelers, M.T.W. - Motorised Two-Wheelers

Figure 5: Traffic Composition at the Study Road Stretch

The free speeds of the different categories of vehicles were also estimated by video capturing the traffic under free-flow conditions. The speeds of the different categories of vehicles were measured by noting the time taken by the vehicles to traverse a trap length of 30 m. The observed mean, minimum and maximum free speeds of various classes of vehicles and their corresponding standard deviations are shown in columns (2), (3) ,(4) and (5) respectively of Table 1. The overall dimensions of all categories of vehicles, adopted from literature (Arasan and Koshy 2005), are shown in columns (2) and (3) of Table 2. Any vehicle moving in a traffic stream has to maintain sufficient lateral clearance on the left and right sides with respect to other vehicles/curb/ median to avoid side friction. These lateral clearances depend upon the speed of the vehicle being considered, speed of the adjacent vehicle in the transverse direction, and their respective types.

Table 1: Free Speed Parameters of Different Types of Vehicles

| Vehicle type | Free speed parameters in km/h | | | |
|---|---|---|---|---|
| | Mean | Min. | Max. | Std. Deviation |
| (1) | (2) | (3) | (4) | (5) |
| Trucks | 62 | 53 | 90 | 8 |
| Buses | 70 | 45 | 90 | 10 |
| Cars | 86 | 60 | 110 | 15 |
| L.C.V. | 67 | 50 | 90 | 6 |
| M.T.W | 57 | 35 | 75 | 11 |
| M.Th.W | 52 | 45 | 55 | 3 |
| Bicycles | 14 | 10 | 20 | 4.5 |

L.C.V. - Light Commercial Vehicles, M.Th.W. – Motorised Three-Wheelers, M.T.W. - Motorised Two-Wheelers

Table 2: Observed Vehicle Dimensions

| Vehicle type (1) | Average overall dimension (m) | |
|---|---|---|
| | Length (2) | Width (3) |
| Trucks | 7.5 | 2.5 |
| Buses | 10.3 | 2.5 |
| Cars | 4.0 | 1.6 |
| L.C.V. | 5.0 | 2.0 |
| M.T.W | 2.0 | 0.75 |
| M.Th.W | 3.0 | 1.5 |
| Bicycles | 1.9 | 0.5 |

L.C.V. - Light Commercial Vehicles, M.Th.W. – Motorised Three-Wheelers, M.T.W. - Motorised Two-Wheelers

The minimum and maximum values of lateral-clearance share adopted from an earlier study (Arasan and Koshy 2005), are given in columns (2) and (3), respectively, of Table 3. The minimum and the maximum clearance- share values correspond to, respectively, zero speed and free speed conditions of respective vehicles. The lateral-clearance-share values are used to calculate the actual lateral clearance between vehicles based on the type of the subject vehicle and the vehicle by the side of it. For example, at zero speed, if a motorized two-wheeler is beside a car, then, the clearance between the two vehicles will be 0.2 + 0.3 = 0.5m. The data on, acceleration values of different vehicle categories, at various speed ranges, taken from available literature (Arasan and Koshy 2005), are shown in Table 4.

The observed traffic volume and composition was given as input to the simulation process. The simulation runs were made with different random number seeds and the averages of the values were taken as the final model output. The model output includes the number of each category of vehicle generated, values of all the associated headways generated, number of vehicles present over a given road length at any point of time, number of overtaking maneuvers made by each vehicle, speed profile of vehicles, etc.

Table 3: Minimum and Maximum Lateral Clearances

| Vehicle type (1) | Lateral-clearance share (m) At zero speed (2) | At a speed of 60 km/h (3) |
|---|---|---|
| Trucks | 0.3 | 0.6 |
| Buses | 0.3 | 0.6 |
| Cars | 0.3 | 0.5 |
| L.C.V. | 0.3 | 0.5 |
| M.T.W | 0.1 | 0.3 |
| M.Th.W | 0.2 | 0.4 |
| Bicycles | 0.1 | 0.3* |

L.C.V. - Light Commercial Vehicles, M.Th.W. – Motorised Three-Wheelers, M.T.W. - Motorised Two-Wheelers

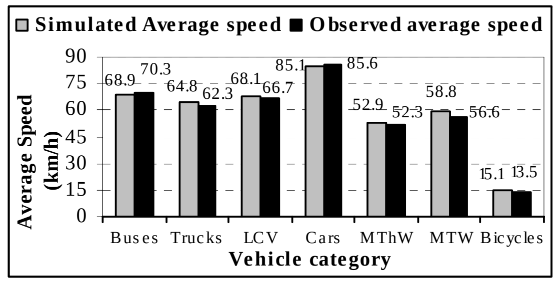
Table 4: Acceleration Rates of Different Categories of Vehicles

| Vehicle type | Rate of acceleration at various speed ranges ($m/s^2$) | | |
|---|---|---|---|
| (1) | 0-20 km/h (2) | 20- 40 km/h (3) | Above 40 km/h (4) |
| Trucks | 0.80 | 0.6 | 0.50 |
| Buses | 0.90 | 0.75 | 0.60 |
| Cars | 1.40 | 1.10 | 0.95 |
| L.C.V. | 1.00 | 0.55 | 0.45 |
| MTW | 1.40 | 0.80 | 0.65 |
| MThW | 1.00 | 0.55 | 0.45 |
| Bicycle | 0.10 | - | - |

*- Maximum speed of these vehicles is 20 km/h

## 5. MODEL VALIDATION

A developed model needs to be validated to check whether the model is capable of replicating the real life situations (Field conditions) accurately or not. The most definitive test of a simulation model's operational validity is establishing that its output data closely resemble the output data that would be expected from the actual system using identical inputs (Law and Kelton 1991). For the purpose of validation, the simulation model was used to replicate the heterogeneous traffic flow on a stretch of road. The total length of road stretch, for simulation purpose, was taken as 1,400 m. The initial 200 m length, at the entry point, was used as a warm-up zone. To avoid unstable traffic flow condition at the exit end, a 200 m long road stretch at the exit end was also excluded from the analysis. Thus, the middle 1000 m length of the simulation stretch was used to collect the data of the simulated traffic flow characteristics. To eliminate the initial transient nature of traffic flow, the simulation clock was set to start only after the first 50 vehicles reached the exit end of the road stretch. The simulation model was run with three random number seeds, and the average of the three runs was taken as the final output of the model. The observed roadway condition, traffic volume and composition were given as input to the simulation process. The inter arrival time (headway) of vehicles was found to fit into negative exponential distribution and the free speeds of different categories of vehicles, based on the results of an earlier study (Arasan and Koshy 2005), was assumed to follow Normal distribution. These distributions, then, formed the basis for input of the two parameters for the purpose of simulation. To check for the validity of the model, the vehicle speeds simulated by the model were compared with the field observed speed values for each category of vehicles. The results of the experiment, for the observed traffic volume of 482 vehicles per hour, are shown in figure 6. It can be seen that the simulated speed values significantly replicate the field observed speeds for all vehicle types.




L.C.V. - Light Commercial Vehicles, M.Th.W. – Motorised Three-Wheelers, M.T.W. - Motorised Two-Wheelers

Figure 6: Model Validation by Comparison of Speeds

A statistical validation of the model, based on observed and simulated speeds of different categories of vehicles, was also done through t-test. The value of t-statistic, calculated based on the observed data ($t_0$), is 1.39. The critical value of t statistic for level of significance of 0.05 (95% confidence limit), at 6 degrees of freedom, obtained from standard t-distribution table is 2.45. Thus, it can be seen that the value of t statistic, calculated based on the observed data, is less than the corresponding table value. This implies that there is no significant difference between the simulated and observed means speeds.

## 6. MODEL APPLICATION

The 'HETEROSIM' model can be applied to study various heterogeneous traffic scenarios for varying traffic and roadway conditions. Here, the application of the model is specific to develop relationship between traffic volume and speed and then to quantify the relative impact of the presence of each of the different types of vehicles on traffic flow by estimating PCU value under heterogeneous traffic conditions.

### 6.1. Speed-Volume Relationship

One of the basic studies in traffic flow research is pertaining to the relationship between speed and volume of traffic. The highway capacity for different roadway and traffic conditions can be estimated using speed-volume relationship. Hence, the speed-flow relationship was developed for the heterogeneous traffic flow, the composition of traffic and roadway conditions being the same as observed in the field, by running the simulation for various volumes, starting from near zero to the capacity of the road. Also, speed-volume relationship for cars-only traffic (traffic stream comprising of 100 percentage cars) was developed by simulating the homogeneous traffic flow from the minimum to the maximum possible volumes.

The total length of road stretch considered for the experiments is 1400 m, with 200 m sections at the entry and exit excluded from output data collection as warm-up and stabilizing section. The central 1000 m stretch was considered as the observation stretch, the various traffic flow parameters were recorded while vehicles were moving through it. To account for the variation due to randomness, the simulation runs were repeated using three different-random number streams to check for the consistency of the results. Both the speed-volume relationships pertaining to 8.75 m wide road are depicted, on the same set of axes, in figure 7. It can be seen that, in both the cases, the speed-volume curves follow the established trend. Also, it can be seen from the speed-volume curves, the capacity of the considered road stretch is about 2700 vehicles per hour under the heterogeneous traffic condition and it is about 4500 cars per hour under cars-only traffic condition.

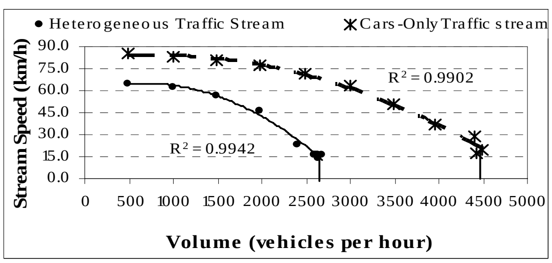



Figure 7: Speed – Volume Relationship

### 6.2. Estimation of PCU Values

Expressing highway-capacity (volume) as number of vehicles passing a given section of road per hour will be inappropriate when two or more than two types of vehicles with widely varying static and dynamic characteristics are present in the road traffic. The capacity-volume of such heterogeneous traffic can be expressed more precisely as Passenger Car Unit (PCU) per hour by converting the different types of vehicles into equivalent passenger cars. Therefore, it is very important to estimate these PCU values accurately. After a careful study of the various approaches adopted for estimation of PCU of vehicles, it was found that the methodology of approach of Transport and Road Research Laboratory (TRRL), London, UK may be appropriate for the heterogeneous traffic being dealt with. The PCU has been defined by TRRL (1965) as follows: "*on any particular section of road under particular traffic condition, if the addition of one vehicle of a particular type per hour will reduce the average speed of the remaining vehicles by the same amount as the addition of, say x cars of average size per hour, then one vehicle of this type is equivalent to x PCU.* This definition has been taken as the basis for derivation of PCU values, in this study. Hence, the PCU values for the different types of vehicles, at various volume levels, were estimated by taking the average stream speed as the measure of performance.

#### 6.2.1. Estimating PCU Values in Cars-Only Traffic

Though the prime objective of this study is to quantify the vehicular interactions, in terms of Passenger Car Unit (PCU) under heterogeneous traffic, it will be appropriate to estimate the Passenger Car Unit (PCU), values of different vehicle types while moving with cars-only traffic stream to provide a set of basic PCU values of the different types of vehicles for the purpose of comparison. This will provide information on the absolute amount of impedance caused by a vehicle type while moving in the traffic stream, which comprises of cars and the subject vehicles only.

Since, speed is the performance measure identified to estimate the PCU values, average speed of cars-only traffic for a set of selected volume levels corresponding to volume-to-capacity ratios of 0.13, 0.25, 0.38, 0.50, 0.63, 0.75, 0.88 and 1.0 (taking the capacity value from the speed-flow curve corresponding to cars only traffic shown in figure 7) were estimated by simulating the homogeneous traffic flow (100 % passenger cars) in one direction, on four-lane, divided intercity road. The impedance caused by a vehicle type, in terms of PCU, for a chosen volume level was estimated by replacing a certain percentage (the observed percentage composition of the subject-vehicle in the field - Fig. 5) of cars in the homogeneous traffic stream with the subject-vehicle type, such that, the average speed of cars remained the same as before the replacement of the cars. The number of subject vehicle can be adjusted on trial basis by observing the average speed of cars in each trial. If the average car speed is more, after replacement, than the average car speed under homogeneous traffic, it is to be inferred that, the introduced number of subject vehicles is inadequate to compensate for the removed cars. Similarly, if the average speed of cars, after replacement, is less than the average car speed under homogeneous traffic, it is to be inferred that the introduced subject-vehicle volume is more than the equivalent volume of cars. After regaining the original speed of cars by adjusting the number of subject vehicles, the PCU value of the vehicle type can be estimated using the relation,

$$PCU\ Value\ of\ subject-vehicle\ type = \frac{Number\ of\ cars\ removed}{Number\ of\ subject-vehicle\ type\ added} \quad (1)$$

The logic behind the above approach is that, as stated in the definition of PCU, the introduced subject vehicle type creates more or less the same effect on the traffic stream that is equivalent to that of the cars removed from the stream. The PCU value of the subject-vehicle was determined, following the said procedure, for the same set of traffic volume levels selected for cars-only traffic. To account for the variation due to randomness, the simulation runs were made with three random number seeds and the average of the three values was taken as the final value. The variation of PCU values of the different types of vehicles over traffic volume, in homogeneous (Cars-only) traffic condition has been shown in Table 5.

Table 5: Variation of PCU Value over Volume for Different Vehicles Types in Cars-only Traffic

| V/C ratio | PCU value | | | | | |
|---|---|---|---|---|---|---|
| | Buses | Trucks | LCV | MThW | MTW | Bicycle |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) |
| 0.13 | 3.00 | 3.26 | 2.16 | 1.10 | 0.90 | 0.85 |
| 0.25 | 2.87 | 3.11 | 2.04 | 1.60 | 1.50 | 1.35 |
| 0.38 | 2.75 | 2.95 | 1.93 | 1.75 | 1.60 | 1.48 |
| 0.50 | 2.63 | 2.83 | 1.85 | 1.80 | 1.65 | 1.53 |
| 0.63 | 3.10 | 3.25 | 1.97 | 1.40 | 1.28 | 1.13 |
| 0.75 | 3.66 | 3.62 | 2.35 | 1.20 | 1.10 | 0.92 |
| 0.88 | 4.50 | 4.28 | 2.74 | 1.00 | 0.90 | 0.82 |
| 1.00 | 5.57 | 5.33 | 3.45 | 0.90 | 0.78 | 0.75 |

L.C.V. - Light Commercial Vehicles, M.Th.W. – Motorised Three-Wheelers, M.T.W. - Motorised Two-Wheelers

From table 5, it can be seen that at low volume levels, in the case of vehicles that are larger in size than car (columns (2), (3) and (4)), the PCU decreases with increase in traffic volume (when V/C ratio is less than 0.63) and the PCU increases with the increase in traffic volume at high volume levels (When V/C ratio is 0.63 and more). Whereas, in the case of vehicles that are smaller than car (columns (5), (6) and (7)), at low volume levels, the PCU increases with increase in traffic volume and the PCU decreases with increase in traffic volume at high volume levels. The attempt to find the possible reason for these trends revealed that the relative changes, caused by the overall traffic environment, (because of the factors such as manoeuvrability and physical size of the subject vehicle type) in the speeds of the reference vehicle (car) and the subject vehicle (for which the PCU value is to be estimated), at various traffic volume levels, are the main contributors to the trend.

### 6.2.2. Estimating PCU Values in Heterogeneous Traffic

The PCU values for the different types of vehicles, at various volume levels, were estimated using simulation. For the purpose of simulation, eight traffic volume levels corresponding to volume to capacity (V/C) ratios of 0.13, 0.25, 0.38, 0.50, 0.63, 0.75, 0.88 and 1.0 (taking the capacity value from the speed-flow curve corresponding to heterogeneous traffic shown in figure 7) were considered. At each volume level, first, heterogeneous traffic flow of field observed composition (figure 5) was simulated for an hour and the traffic stream speed was obtained as the weighted average of the speeds of the different categories of vehicles. Then, a certain percentage of cars were replaced by the subject vehicle type (for which the PCU value is to be estimated) in the mixed traffic stream, such that the average stream speed obtained by simulation (figure 7), remained the same as the earlier stream speed. Then, for each flow level, the number of cars removed divided by the number of subject vehicle type introduced will give the PCU value of that vehicle type. The variation of PCU values of the different types of vehicles over traffic volume, in heterogeneous traffic condition, for the purpose of comparison, has been presented in Table 6. It can be seen that the general trend of variation of the PCU values of vehicles over volume is the same as in the case of cars-only traffic. Hence, the explanation provided for the trend in the case of cars-only traffic is valid for heterogeneous traffic condition also.

Table 6: Variation of PCU Value over Volume for Different Vehicles Types in Heterogeneous Traffic

| V/C ratio | PCU value | | | | | |
|---|---|---|---|---|---|---|
| | Buses | Trucks | LCV | MThW | MTW | Bicycle |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) |
| 0.13 | 2.00 | 2.25 | 1.42 | 0.50 | 0.34 | 0.30 |
| 0.25 | 1.95 | 2.20 | 1.38 | 0.72 | 0.43 | 0.42 |
| 0.38 | 1.90 | 2.15 | 1.32 | 0.85 | 0.52 | 0.54 |
| 0.50 | 1.80 | 2.10 | 1.28 | 0.90 | 0.66 | 0.66 |
| 0.63 | 1.70 | 1.90 | 1.24 | 0.85 | 0.74 | 0.72 |
| 0.75 | 1.80 | 1.95 | 1.28 | 0.80 | 0.72 | 0.70 |
| 0.88 | 2.20 | 2.10 | 1.32 | 0.72 | 0.62 | 0.63 |
| 1.00 | 2.70 | 2.50 | 1.48 | 0.60 | 0.49 | 0.50 |

L.C.V. - Light Commercial Vehicles, M.Th.W. – Motorised Three-Wheelers, M.T.W. - Motorised Two-Wheelers

### 6.3. Effect of Heterogeneity on PCU values

It is clear that the degree of heterogeneity of traffic stream affects the speed and other traffic flow parameters, and influences the magnitude of interaction between the moving vehicles significantly. The presence of a vehicle type, other than car, in the cars-only traffic stream, creates a traffic condition, which is totally different from the cars-only traffic condition. The change in the traffic condition make the vehicles to offer varying amount of impedance to the movement of adjacent vehicles in the traffic stream, depending upon the extent of variation of traffic stream from cars-only (homogeneous) traffic condition. In the light of the said fact, a comparison of the interactions of different vehicle types in cars-only traffic and in heterogeneous traffic, the amount of interaction having been measured in terms of PCU, will be useful. Figures 8 through 13 illustrate the comparison of PCU values of different vehicle type and their variations over traffic volume, in cars-only traffic and heterogeneous traffic flow conditions. It may be noted that, to facilitate plotting of the variation of PCU in homogeneous and heterogeneous traffic conditions using the same set of axes, the traffic volume has been represented using V/C ratio.

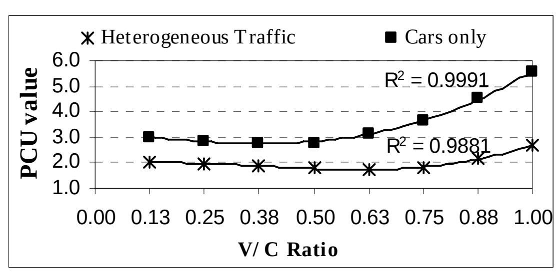



Figure 8: Variation of PCU Values of Buses on 8.75 m Wide Road

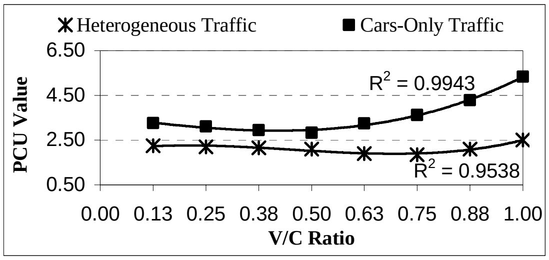



Figure 9: Variation of PCU Values of Trucks on 8.75 m Wide Road

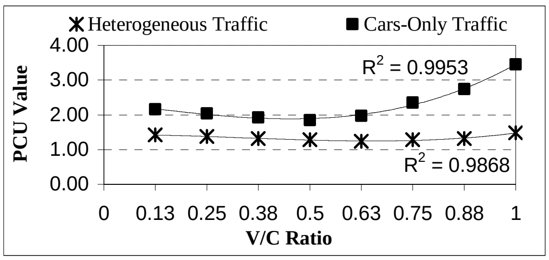



Figure 10: Variation of PCU Values of Light Commercial Vehicles on 8.75 m Wide Road

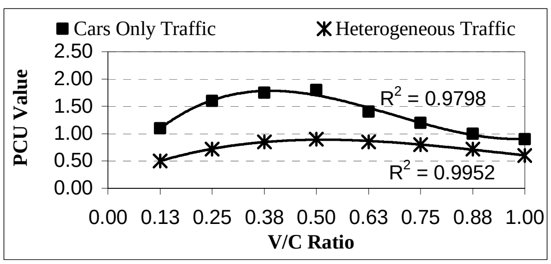



Figure 11: Variation of PCU Values of Motorised Three-Wheelers on 8.75 m Wide Road

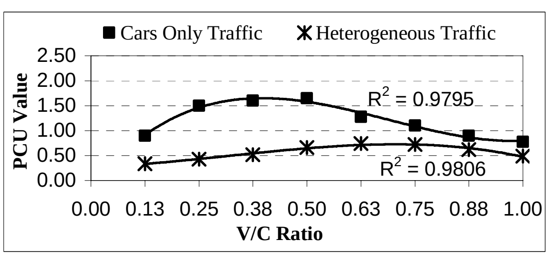



Figure 12: Variation of PCU Values of Motorised Two-Wheelers on 8.75 m Wide Road

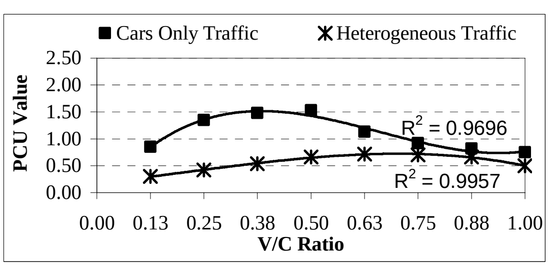



Figure 13: Variation of PCU Values of Bicycles on 8.75 m Wide Road

It can be seen that, the magnitude of vehicular interactions measured in terms of Passenger Car Units (PCU), under cars-only traffic condition, are significantly higher for all the vehicle types, when compared to their corresponding values under heterogeneous traffic condition. Higher PCU values under cars-only traffic condition may be attributed to the higher speed difference between the cars and the subject-vehicle speed in cars-only traffic than the difference between car speed and subject-vehicle speed under heterogeneous traffic condition. For example, at volume-to-capacity ratio value of 0.63, under cars-only traffic condition, through the simulation experiments it has been found that the average speed of cars is 74.19 km/h and buses is 58.76 km/h, with a speed difference of 15.43 km/h. Whereas under heterogeneous traffic condition, the average car speed for the same volume-to-capacity ratio is 58.01 km/h and the average bus speed is 51.23 km/h, resulting in a speed difference of 6.78 km/h. The PCU values of buses at this level of traffic flow under cars-only traffic and heterogeneous traffic conditions are 3.1 and 1.7 respectively.

## 7. CHECK FOR ACCURACY OF PCU VALUES

For the purpose of checking the accuracy of the PCU estimates for the different categories of vehicles, first, the heterogeneous traffic flow of field observed composition was simulated for one hour period for selected values of V/C ratios and the number of vehicles in each category, for each case, was noted. Then, the vehicles of the different categories were converted into equivalent PCUs by multiplying the number of vehicles in each category, obtained for the selected V/C ratios, by the corresponding PCU values (Table:6). The products, thus, obtained were summed up to get the total traffic flow in PCU/h. Then, 'cars-only' traffic was simulated for one hour for the same set of V/C ratio values (taking the capacity value from the speed-flow curve corresponding to cars only traffic shown in Figure 7). Thus, the traffic volume, in terms of number of cars, was obtained for the set of selected V/C ratios. A comparison of the traffic flow in terms of PCU and in terms of number of passenger cars, for the set of the selected V/C ratios, is shown in Figure 14. It can be seen that the heterogeneous traffic flow in PCU/h and the cars-only flow in cars/h match to a greater extent at each V/ C ratio, indicating the accuracy of the estimated PCU values.

A paired t-test, based on the passenger cars equivalent (PCU/h) and passenger cars-only (cars/h) traffic volumes was also done. The value of t statistic calculated ($t_0$) is 0.82. The critical value of t statistic for a level of significance of 0.05 for 7 degrees of freedom, obtained from standard t-distribution table is 2.37. This implies that, there is no significant difference between the traffic volumes measured in terms of passenger cars and in PCU.

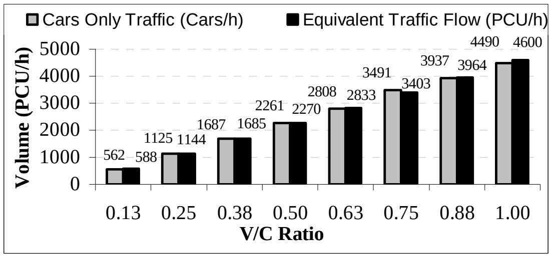



Figure 14: Comparison of Heterogeneous Traffic and Cars-only Traffic Flows

## 8. CONCLUSIONS

The following are the important conclusions of the study:

1. The simulation model of heterogeneous traffic flow named, HETEROSIM is found to be valid for simulating heterogeneous traffic flow on intercity roads to a satisfactory extent. The validity of the model is further confirmed by the speed-flow relationships developed, using the simulation model, which are found to follow the well established trend of the speed-volume curve.
2. From the speed-volume curve, developed using the simulation model, it is found that, for the observed traffic composition, the capacity of a four lane divided road with 7.5 m wide main carriageway and 1.25 m wide paved shoulder, for one direction of traffic flow, in plain terrain, is about 4600 PCU per hour.
3. It is found that, the estimated PCU values of the different categories of vehicles of the heterogeneous traffic are accurate at 5% level of significance.
4. It is found that, by virtue of the complex nature of interaction between vehicles under the heterogeneous traffic condition, the PCU estimates, made through simulation, for the different types of vehicles of heterogeneous traffic, for a wide range of traffic volume levels significantly changes with change in traffic volume.

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#### AUTHORS BIOGRAPHIES

**Prof. Dr. V. Thamizh Arasan** is currently a full Professor in the Transportation Engineering Division of the Department of Civil Engineering of Indian Institute of Technology Madras, Chennai, India, which is one of the seven national level higher technological institutions in the country. He has a professional experience of about 30 years in teaching research and consultancy in the area of Transportation Engineering. Travel demand modeling and traffic flow modeling are his areas of research interest. He has guided a number of doctoral degree students and has published more than eighty research papers in international and national journals and conference proceedings. Three of his papers published in journals have received awards for excellence in research. Prof. Arasan has successfully completed several sponsored research projects both at national and international levels. The international projects are: (i) Development of Transportation Planning Techniques for Indian conditions in collaboration with the Technical University of Braunschweig, Germany and (ii) Enhancing the Level of Safety at Traffic Signals in collaboration with the Technical University of Darmstadt, Germany.

**Mr. Shriniwas S. Arkatkar** is a Ph.D. Scholar in Transportation Engineering Division, Department of Civil Engineering, Indian Institute of Technology Madras, Chennai, India. His doctoral research work is in the area of 'Heterogeneous Traffic Flow Modeling'. Mr. Shriniwas S. Arkatkar obtained his undergraduate degree in the area of Civil Engineering in the year 1999 and post graduate degree in the area of Urban Planning in the year 2001 from Visvesvaraya National Institute of Technology, Nagpur, India. He has served as Lecturer in Department of Civil Engineering, Nirma University, Ahmedabad, India for the duration of three and half years.