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Microsimulation study of vehicular interactions in heterogeneous traffic flow on intercity roads

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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 modeling 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 roadway capacity.

1. Introduction

The road traffic in developing countries like India is highly heterogeneous comprising vehicles of wide ranging static and dynamic characteristics. The 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

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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 distributions 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 estimate 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 validated model is 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. Review of earlier studies

In the past, various approaches have been adopted for estimation of Passenger Car Unit (PCU) or Passenger Car Equivalent (PCE) values of vehicles. The bases used for the estimation process are (i) delay (e.g. Craus et al., 1980), (ii) speed (e.g. Linzer et al.1979; Aerde and Yagar 1984; and Elefteriadou et al., 1997), (iii) density (e.g. Huber, 1982; and Webster and Elefteriadou, 1999), (iv) headway (e.g. Krammes and Crowley, 1986) and (v) queue discharge (e.g. Al-Kaisy et al., 2005). Peeta et al. (2003) modelled the car-truck interactions on freeway sections using microscopic traffic flow models. The car-truck interactions were modelled by associating a “discomfort level” for every non-truck driver in the vicinity of trucks. It was observed that this discomfort is affected by the driver socioeconomic characteristics, and situational factors such as time-of-day, weather, and ambient traffic congestion levels. All these studies, however, are mainly related to estimation of PCE for heavy vehicles (Trucks and Buses) under fairly homogeneous traffic conditions and hence, the results of these studies are not applicable for Indian conditions. Fan (1990) estimated the PCU values for various vehicle categories, for the congested traffic flow conditions prevailing on the Pan Island Expressway, Singapore. The study also revealed that the PCU values recommended by the highway capacity manuals of U.S.A., U.K., etc. may not be directly suitable for capacity analysis in Asian countries. Terdsak and Charong (2005) studied the effect of motor cycles on traffic operations on arterial streets of Bangkok. They found that the derived PCU of motor cycles showed a decreasing trend with increase in share of motor cycles in the traffic stream. In India, Indian Roads Congress, the professional organization responsible for development of codes and guidelines related to road transportation, has provided a set of constant PCU values for different vehicle categories, (IRC: 64-1990) which are based on limited field observed data. It is found from the review of Indian studies related to PCU estimation that there had been only a few studies on the subject matter. Chandra (2004) estimated PCU values for vehicles on two-lane undivided rural roads (intercity roads) using two variables: (i) speed ratio of car to the subject vehicle (for which PCU value is to be calculated), and (ii) space-occupancy ratio of car to the subject vehicle. However, these values are empirical and are based on limited traffic data. Mallikarjuna and Rao (2006) used area occupancy in place of density, as equivalency criteria to estimate the PCU values for buses, trucks and motorized two-wheelers using a simulation model based on cellular automata. The estimated PCU values, for all the considered vehicle categories are found to decrease with increase in their respective proportions. The study has considered only two vehicle categories at a time (cars, as the reference vehicle and the subject category vehicle for which the PCU values are to be estimated) for the mixed traffic stream. Therefore, the effect of a combination of all other vehicle categories in addition to cars is not considered in this study. Justo and Tuladhar (1984) developed mathematical models to derive PCU values for vehicles on urban roads based on empirical data under mixed traffic flow. Ramanayya (1988) estimated PCU factors for different vehicle types at different levels of services taking the Western car as the Design Vehicle Unit (DVU). The review of literature on the subject matter reveals that the studies conducted are mostly related to fairly homogeneous traffic conditions, and the few studies conducted under heterogeneous traffic conditions are not comprehensive enough to replicate the field conditions accurately. Hence, it was decided to make an attempt to study the vehicular interaction in heterogeneous traffic in a comprehensive manner and derive PCU values for different vehicle types through the research work reported here.

3. Objective and scope of the study

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 the highly heterogeneous traffic conditions prevailing on intercity roads, in plain terrain, in India. A recently developed micro-simulation model of heterogeneous traffic-flow, 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. The effect of heterogeneity on PCU values is studied using the simulation model for a level four-lane divided road stretch on intercity road. For this purpose, the PCU values are estimated under two different traffic conditions, namely, cars-only traffic (100% cars) and heterogeneous traffic conditions prevailing on intercity roads.

4. The simulation model

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 areas, 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. 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, etc. cannot be directly used to study the characteristics of the traffic flow as these are based on homogeneous traffic-flow conditions. Also, the models developed through research attempts made earlier to simulate heterogeneous traffic flow Indian roads (Khan and Maini 1999; Marwah and Singh 2000; Kumar and Rao 1996; and Ramanayya 1988) are limited in scope as they are 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 at IIT Madras, India (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 (Figure 1).

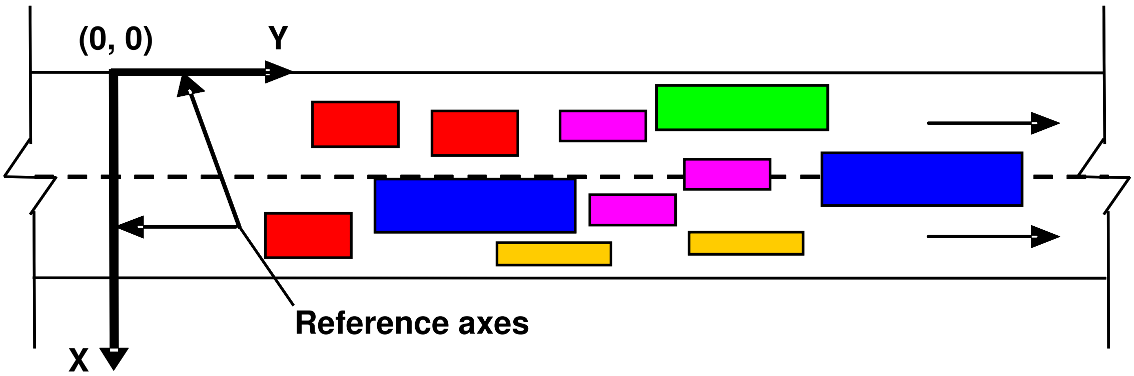

Figure 1: Reference axes for representing vehicle positions.

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.

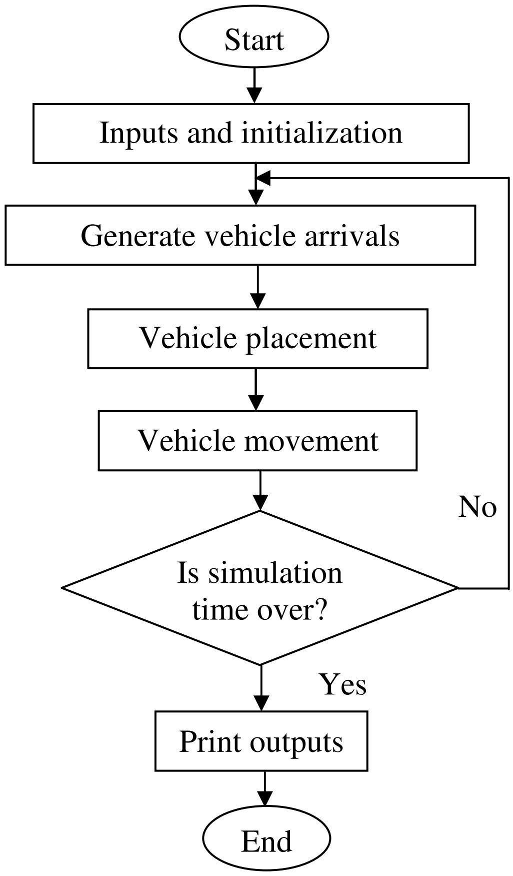

Figure 2: Flow diagram of the simulation model.

4.1 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.

4.2 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.

4.3 Vehicle movement

This module of the program deals with updating of the positions of all the vehicles in the simulation 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.

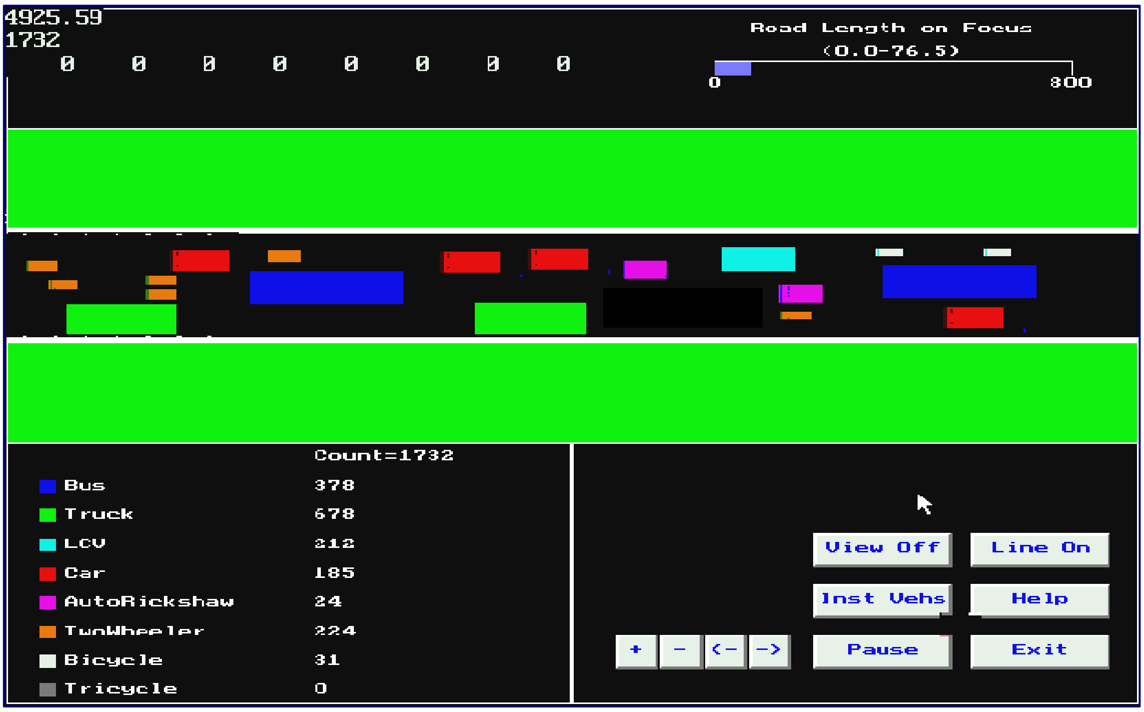

Figure 3: Snapshot of animation of simulated heterogeneous traffic flow.

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).

4.4 Simulation logic and scan interval

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 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 various quantitative results of the simulation process (model outputs), obtained over the specified length of the simulation stretch are: category-wise average speeds of vehicles, speed profiles of all the vehicles, time headways of all the vehicles generated, number of overtaking (passing) maneuvers executed by each vehicle.

5. Model validation

The process of checking for the effectiveness of a model to replicate reality is termed as model validation. Thus, there is a need to collect the data of the characteristics of the system being simulated. For collection of traffic data to validate the simulation model, 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 7.25 m wide main carriageway and 1.5 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.

5.1 Data collection

Collection and analysis of data play a pivotal role in the development of successful simulation models. The field data inputs required for the model, as mentioned earlier, was collected at the selected stretch. 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 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 4. 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.

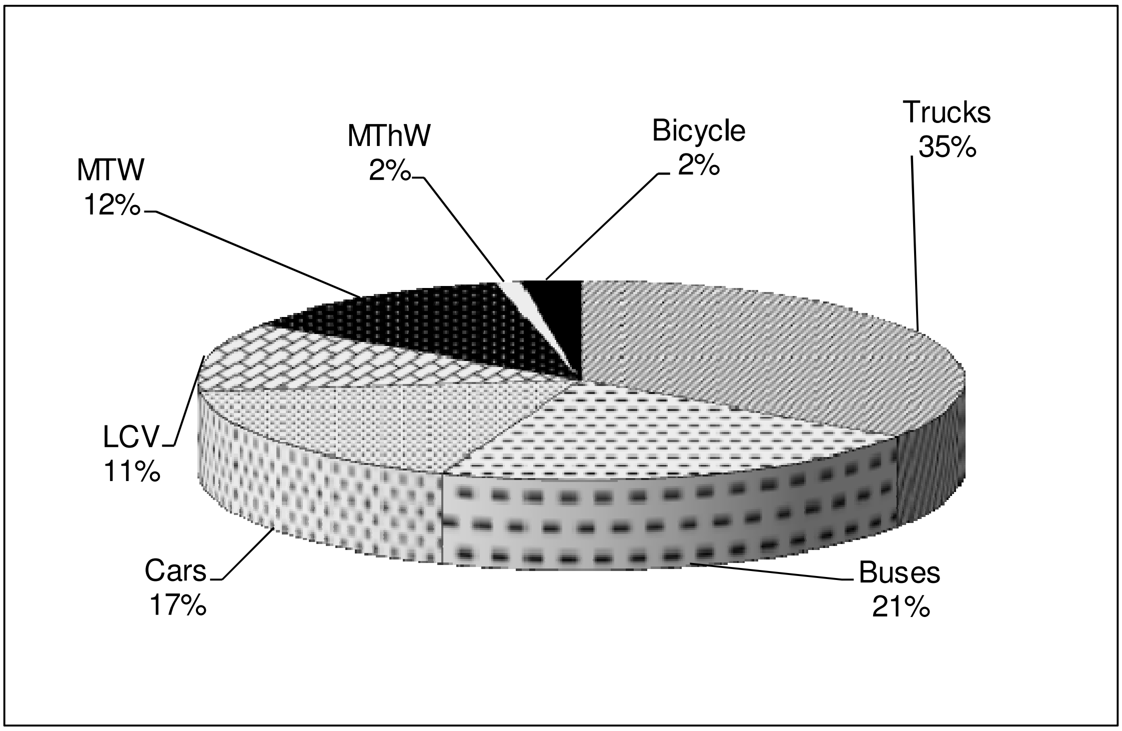

Figure 4: Traffic composition at the study road stretch.
Note: *L.C.V. - Light Commercial Vehicles*; *M.Th.W. - Motorised Three-Wheelers*; *M.T.W. - Motorised Two-Wheelers*.

The free speeds of the different categories of vehicles were measured under free-flow conditions and this time period is different from the 1 hour period of data collection. The speeds of the different categories of vehicles were measured by noting the time taken by the vehicles to traverse a trap length of 50 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.

Table 1: Free speed parameters of different types of vehicles.

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

Note: *L.C.V. - Light Commercial Vehicles*; *M.Th.W. - Motorised Three-Wheelers*; *M.T.W. - Motorised Two-Wheelers*.

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 2: Observed vehicle dimensions.

Vehicle type	*Average overall dimension (m)*	
	Length	*Width*
(1)	*(2)*	*(3)*
Buses	10.3	2.5
Trucks	7.5	2.5
L.C.V.	5.0	2.0
Cars	4.0	1.6
M.Th.W	2.6	1.4
M.T.W	1.8	0.6
Bicycles	1.9	0.5

Note: *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.

Table 3: Minimum and maximum lateral clearances.

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

Note: * - *Maximum speed of these vehicles is 20 km/h*; *L.C.V. - Light Commercial Vehicles*; *M.Th.W. - Motorised Three-Wheelers*; *M.T.W. - Motorised Two-Wheelers.*

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 0.1 + 0.3 = 0.4 m. 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.

Table 4: Acceleration rates of different categories of vehicles.

Vehicle type	*Rate of acceleration at various speed ranges (m/s^2)*		
	0-20 km/h	*20- 40 km/h*	*Above 40 km/h*
(1)	*(2)*	*(3)*	*(4)*
Buses	0.89	0.75	0.67
Trucks	0.79	0.50	0.43
L.C.V.	0.82	0.45	0.35
Cars	1.50	1.10	0.95
MThW	1.01	0.45	0.30
MTW	1.35	0.80	0.60
Bicycle	0.10	-	-

Note: * - *Maximum speed of these vehicles is 20 km/h*; *L.C.V. - Light Commercial Vehicles*; *M.Th.W. - Motorised Three-Wheelers*; *M.T.W. - Motorised Two-Wheelers.*

5.2 Distribution of input variables

5.2.1 Arrival pattern

Some of the input variables to the simulation model are random in nature and hence are to be represented using appropriate probability distributions. The required traffic data for this purpose were obtained by running the video of the traffic flow at a slower speed (⅛th of the actual speed) to enable one person to record all the vehicle arrivals by observing the details displayed on the monitor of the computer. Fixing the time interval as 5 seconds (real time), the number of vehicle arrivals, in each successive five seconds interval, covering the whole of the hourly volume of traffic, was recorded. The data, thus obtained, after grouping into different classes was fitted into statistical distributions. In this case, Poisson distribution was found to fit well the vehicle-arrival pattern. The Chi-square goodness-of-fit test shows that the observed frequencies have significant fit with Poisson distribution for vehicle arrival pattern. The goodness of fit of the vehicle arrival pattern into poission distribution is depicted in Figure 5. It can be seen that there is a good match of observed and the theoretical values.

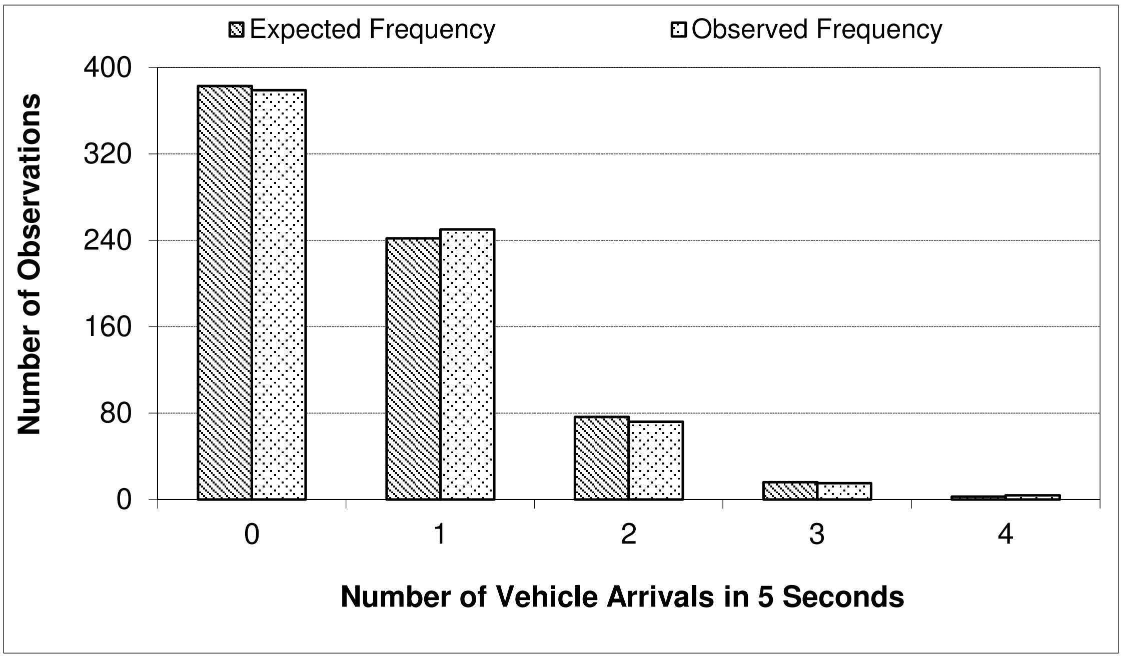

Figure 5: Theoretical and observed arrival patterns.

5.2.2 Headway distribution

The inter arrival time (headway) between successive vehicles was measured by noting down the time gap between successive vehicle arrivals by playing the video of the traffic flow at ⅛th of the original speed to enable data recording easier. The details of the observed headway are shown in Table 5.

Table 5: Chi-square goodness-of-fit test for headway distribution.

Class interval (1)	*Lower class limit 't'* (2)	$e^{-\lambda t}$ (3)	*Theoretical % frequency of headway > Lower class limit* (4)	*Theoretical frequency in the class (E)* (5)	*Observed frequency in the class (O)* (6)	$\chi^2 = \frac{(O-E)^2}{E}$ (7)
0-5	0	1.000	100.0	226	236	0.484
5-10	5	0.532	53.2	120	112	0.534
10-15	10	0.283	28.3	63	62	0.016
15-20	15	0.151	15.1	34	35	0.031
20-25	20	0.080	8.0	18	18	0.000
25-30	25	0.043	4.3	10	7	0.712
30-35	30	0.023	2.3	5	6	0.152
>35	35	0.012	1.2	6	6	0.000
χ2 value from table at 5% level of significance for 6 degrees of freedom is 12.59.						χ2 value = 1.930

The data, classified over a time interval of 5.0 s, was fitted into the negative exponential distribution, as per the details given in Table 5 and the goodness of fit was tested using a chi-squared distribution. It can be seen that the observed chi-square value is 1.930 against the critical value from chi-squared table, for 6 degrees of freedom at 5% level of significance, of 12.59. Hence, the observed headway distribution fits well into the assumed negative exponential distribution. To depict the goodness of fit, the cumulative frequency distribution of the observed and theoretical headways (inter arrival time) were plotted on the same set of axes, as shown in Figure 6. It can be seen that the distribution of observed and theoretical headways match with each other to a large extent corroborating the inference obtained through the chi-square test.

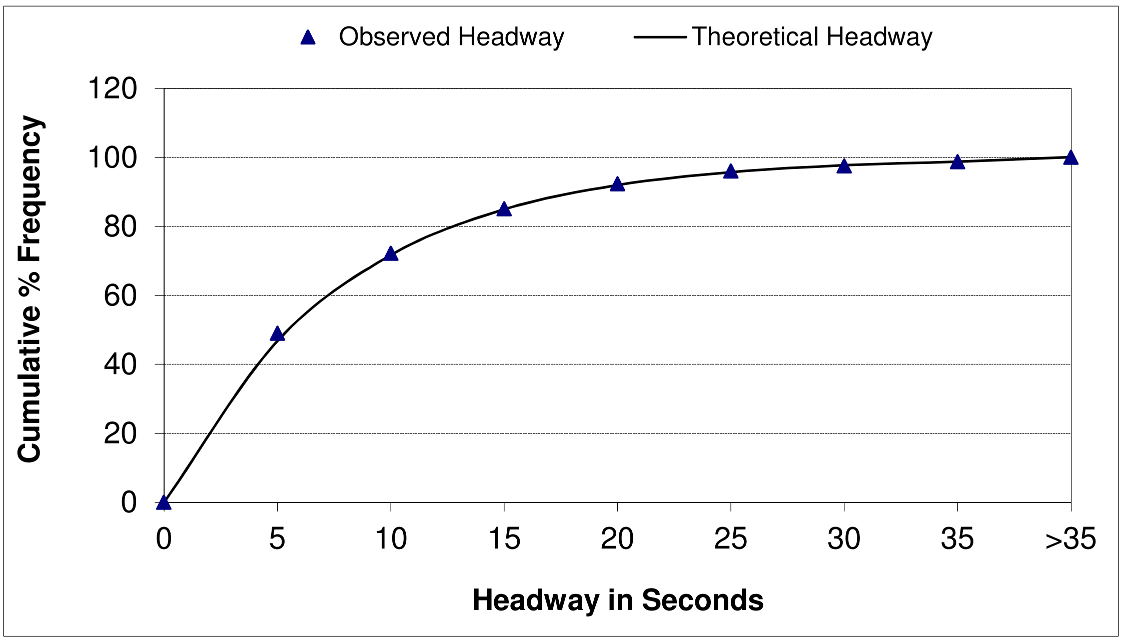

Figure 6: Goodness of fit of observed and theoretical headways.

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.

For the purpose of validation, the simulation model was used to replicate the field observed 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 (Kadiyali et al. 1981)), 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 comparison of the observed and simulated speeds, for the observed traffic volume of 482 vehicles per hour, is shown in Figure 7. It can be seen that the simulated speed values significantly replicate the field observed speeds for all vehicle types.

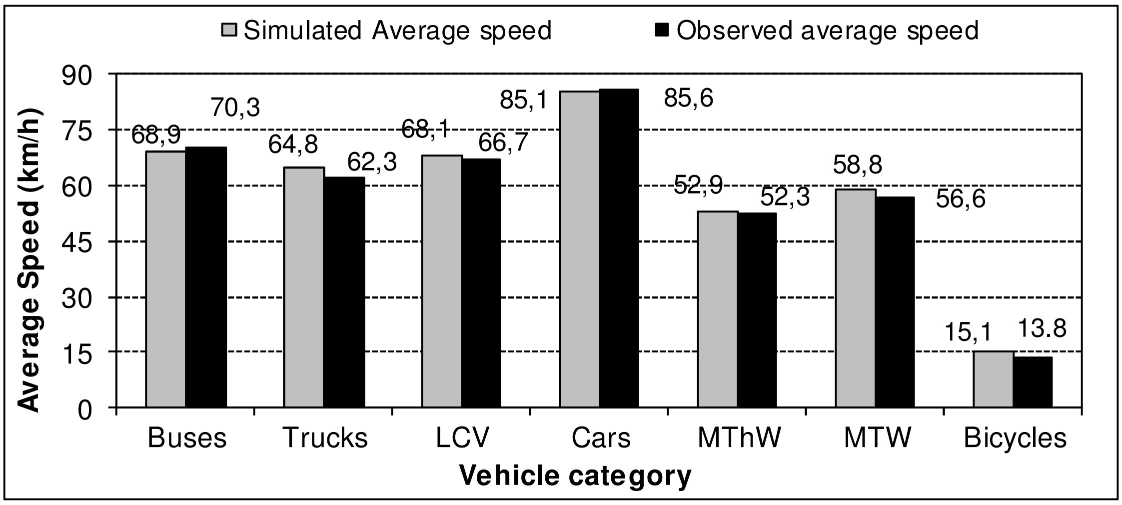

Figure 7: Model validation by comparison of speeds.
Note: *L.C.V. - Light Commercial Vehicles*; *M.Th.W. - Motorised Three-Wheelers*; *M.T.W. - Motorised Two-Wheelers.*

A statistical validation of the match of the observed and simulated speeds of different categories of vehicles was also done through a paired t-test. The details of the comparison of the simulated and observed speeds of different categories of vehicles on statistical basis are shown in Table 6. It can be seen that the simulated speed values significantly replicate the field observed speeds of the different categories of vehicles.

Table 6: Details of comparison of the observed and simulated speeds on statistical basis.

Vehicle type (1)	*Observed average speed in km/h* (2)	*Simulated average speed in km/h* (3)	*Difference (deviation)* (4)	*Square of deviation minus mean* (5)
Buses	68.87	70.26	-1.39	5.35
Trucks	64.84	62.30	2.54	2.61
Light Commercial Vehicles	68.09	66.70	1.39	0.22
Cars	85.11	85.64	-0.53	2.11
Motorised Three-Wheelers	52.92	52.29	0.63	0.09
Motorized Two-Wheelers	58.84	56.58	2.26	1.79
Bicycles	15.09	13.83	1.26	0.41
Total			6.16	12.28

d_{mean} = Mean of observed difference =6.16/7 = 0.88
t statistic, $t_o = d_{mean}/(S_d/\sqrt{K})$, where K = Number of data sets =7
$S_d^2 = 12.28/(k-1) = 12.28/6 = 2.05$, where S_d is the Standard deviation; S_d =1.430
$t_o = 0.88/(1.430/\sqrt{7}) = 1.628$

The critical value of t statistical for 0.05 level of significance and 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 (t_o) is less than the corresponding Table value. This implies that the simulated speeds significantly represent the observed 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 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 values under homogeneous and heterogeneous traffic conditions, for the different categories of vehicles.

6.1 Speed-volume relationship

One of the basic studies in traffic flow research pertains to the relationship between speed and volume of traffic. The highway capacity for different roadway and traffic conditions can be estimated using speed-volume relationships. Hence, the speed-flow relationship was developed for the heterogeneous traffic flow, taking 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, in one direction, 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 tail end sections, respectively. The central 1000 m stretch was considered as the observation stretch and 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. Giving the relevant data as input, the traffic flow was simulated for volume levels ranging from a very low level to the maximum possible value (capacity) and the speeds corresponding to each of the volume levels were obtained as output. In this regard, it may be noted that when simulation runs are made with successive increments in traffic volume (input), there will be commensurate increase in the exit volume at the end of simulation stretch. When the simulated volume reaches the capacity level, the increments in the input traffic volumes will not result in the same amounts of increase in the exit volume, and will result in a decrease in the rate of traffic flow. A few successive decreases in the exit volume (in spite of increase in the input) indicate that the roadway has reached its capacity. The speed-volume relationships, pertaining to 8.75 m wide road, are depicted, on the same set of axes, in Figure 8. It can be seen that, in both the cases, the speed-volume curves follow the established trend. Also, it can be seen from the curves that the capacity of the considered road stretch, having width of 8.75 m (two lanes plus 1.5 m wide paved shoulder) for one direction of traffic flow, is about 2700 vehicles per hour under the heterogeneous traffic condition and it is about 4500 cars per hour under cars-only traffic condition.

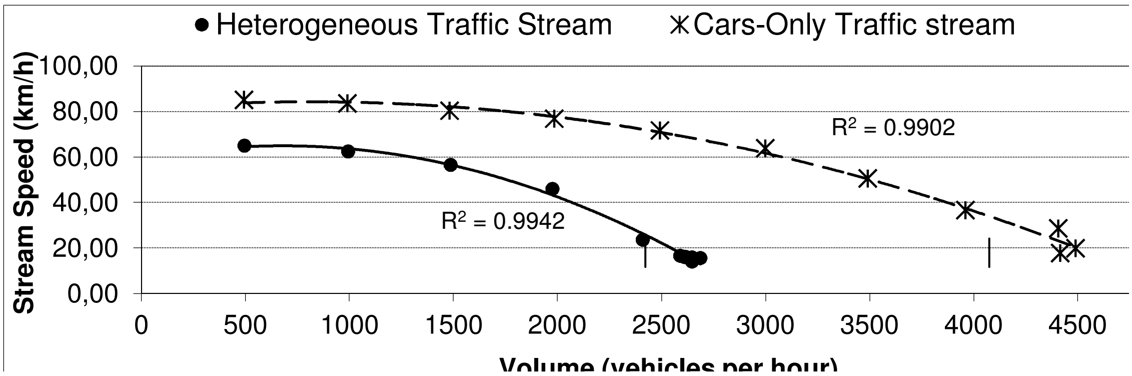

Figure 8: Speed - Volume relationship.

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 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.

6.3 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 useful 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, 0.375, 0.50, 0.625, 0.75, 0.875 and 1.0 (taking the capacity value from the speed-flow curve corresponding to cars only traffic shown in Figure 8) 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. 4) 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 following equation.

$$PCU\ \ value\ \ of\ \ subject\ \ vehicle\,type = \frac{Number\ \ of\ \ cars\ \ removed}{Number\,of\ \ subject\ \ vehicle\ \ type\ \ added} \tag{1}$$

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.

At low traffic volume levels, if the speed of cars corresponds to their free-flow speed for a selected V/C ratio, to estimate PCU value of vehicles, however, the maximum number of cars that will not change the speed of the cars, when added to the traffic stream corresponding to the selected V/C ratio; is first determined. Then, the number of cars added is to be removed and the maximum number of subject vehicle that will not alter the speed of cars, when added, needs to be determined by trial and error. Then, the maximum number of cars divided by the maximum number of subject-vehicle will give the PCU value of the subject vehicle. The said procedure was adopted in the present study as and when required.

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 7.

Table 7: Variation of PCU value over volume for different vehicles types in cars-only traffic.

	PCU value					
V/C ratio (1)	*Buses (2)*	*Trucks (3)*	*L.C.V. (4)*	*M.Th.W (5)*	*M.T.W. (6)*	*Bicycle (7)*
0.125	3.00	3.26	2.16	1.10	0.90	0.85
0.250	2.87	3.11	2.04	1.60	1.50	1.35
0.375	2.75	2.95	1.93	1.75	1.60	1.48
0.500	2.63	2.83	1.85	1.80	1.65	1.53
0.625	3.10	3.25	1.97	1.40	1.28	1.13
0.750	3.66	3.62	2.35	1.20	1.10	0.92
0.875	4.50	4.28	2.74	1.00	0.90	0.82
1.000	5.57	5.33	3.45	0.90	0.78	0.75

Note: *L.C.V. - Light Commercial Vehicles*; *M.Th.W. - Motorised Three-Wheelers*; *M.T.W. - Motorised Two-Wheelers*.

From Table 7, 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 0.5) and the PCU increases with the increase in traffic volume at high volume levels (When V/C ratio is more than 0.5). 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.

6.4 Estimating PCU values in heterogeneous traffic

The PCU values for the different types of vehicles, under heterogeneous traffic conditions, 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 0.125, 0.25, 0.375, 0.50, 0.625, 0.75, 0.875 and 1.0 (taking the capacity value from the speed-flow curve corresponding to heterogeneous traffic shown in Figure 8) were considered. At each volume level, first, heterogeneous traffic flow of field observed composition (Figure 4) 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 8), 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 8. 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 8: Variation of PCU value over volume for different vehicles types in heterogeneous traffic.

	PCU value					
V/C ratio (1)	*Buses (2)*	*Trucks (3)*	*L.C.V. (4)*	*M.Th.W (5)*	*M.T.W (6)*	*Bicycle (7)*
0.125	2.00	2.25	1.42	0.50	0.34	0.30
0.250	1.95	2.20	1.38	0.72	0.43	0.42
0.375	1.90	2.15	1.32	0.85	0.52	0.54
0.500	1.80	2.10	1.28	0.90	0.66	0.66
0.625	1.70	1.90	1.24	0.85	0.74	0.72
0.750	1.80	1.95	1.28	0.80	0.72	0.70
0.875	2.20	2.10	1.32	0.72	0.62	0.66
1.000	2.70	2.50	1.48	0.60	0.49	0.50

Note: *L.C.V. - Light Commercial Vehicles*; *M.Th.W. - Motorised Three-Wheelers*; *M.T.W. - Motorised Two-Wheelers.*

The variation of the PCU value of Buses, over V/C ratio, as example, has been depicted in Figure 9. It can be seen that the PCU value of buses is high at very low volume levels and the value decreases with increase in volume up to certain volume level (V/C = 0.625) beyond which there is increase in the PCU value. The attempt to find the possible reason for that trend revealed that the relative changes, caused by the overall traffic environment, in the speeds of the reference vehicle (car) and the subject vehicle (bus), at various traffic volume levels are the main contributors to the trend. The change in speed difference, in respect of the cars and buses, can be calculated as the percentage change in the speed of cars minus the percentage change in the speed of buses. The trend of the change in speed difference between cars and buses is also shown in Figure 9. It can be seen that both the trend lines exhibit the same pattern.

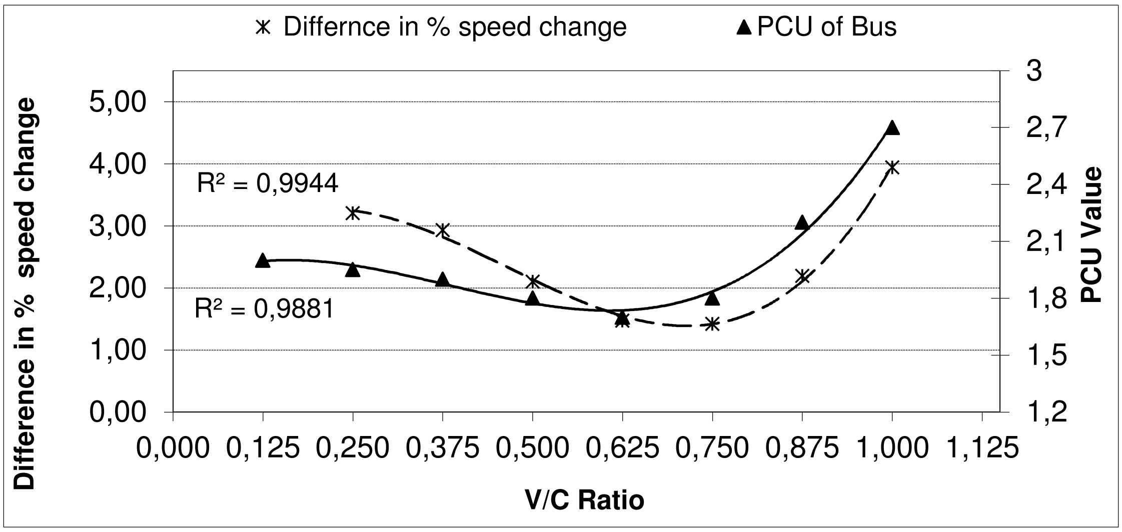

Figure 9: Variation of PCU value of buses.

The variation of PCU value of a smaller vehicle (motorised two-wheeler), over traffic volume, as example, is depicted in Figure 10. It can be seen that the PCU value of motorised two-wheelers is low at very low traffic volume level and then, it increases with increase in traffic volume. This trend continues up to certain volume level (V/C ratio = 0.625) beyond which the PCU value decreases with further increase in traffic volume. The trend line depicting the change in speed difference between cars and motorised two-wheelers is also shown in Figure 10. It can be seen that the trends of change in PCU and the change in speed difference have similar pattern.

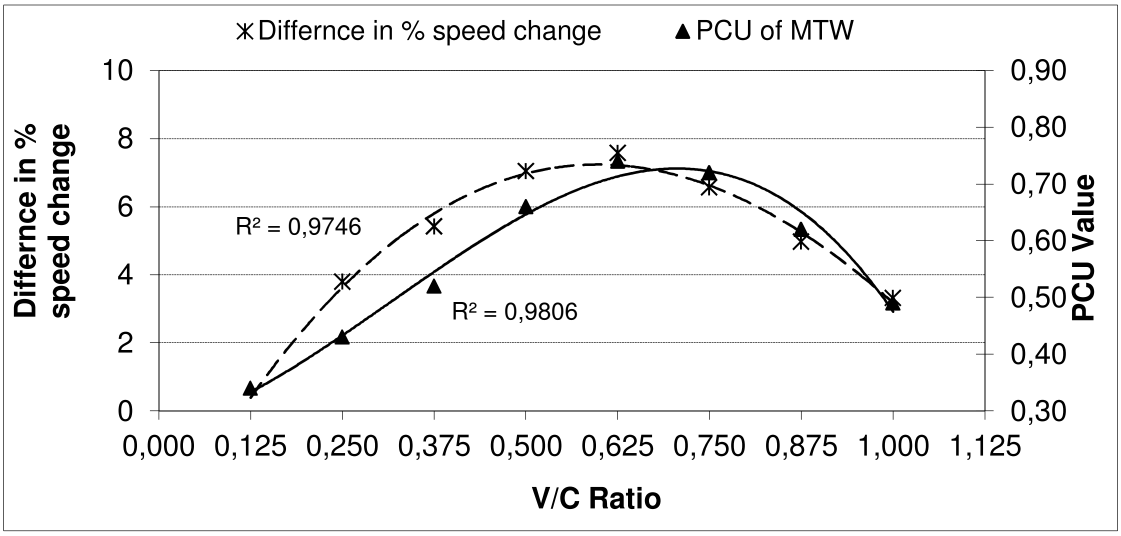

Figure 10: Variation of PCU value of motorized two-wheelers.

6.5 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 11 and 12, for example, illustrate the comparison of variation of PCU values of buses and motorised two-wheelers, 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.

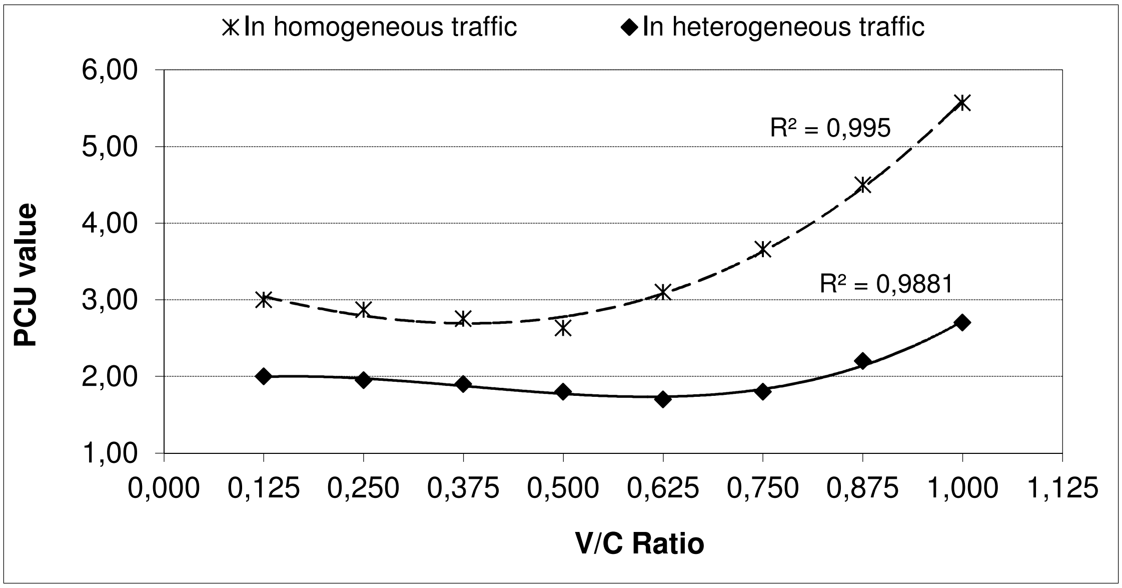

Figure 11: Comparison of variation of PCU values of buses.

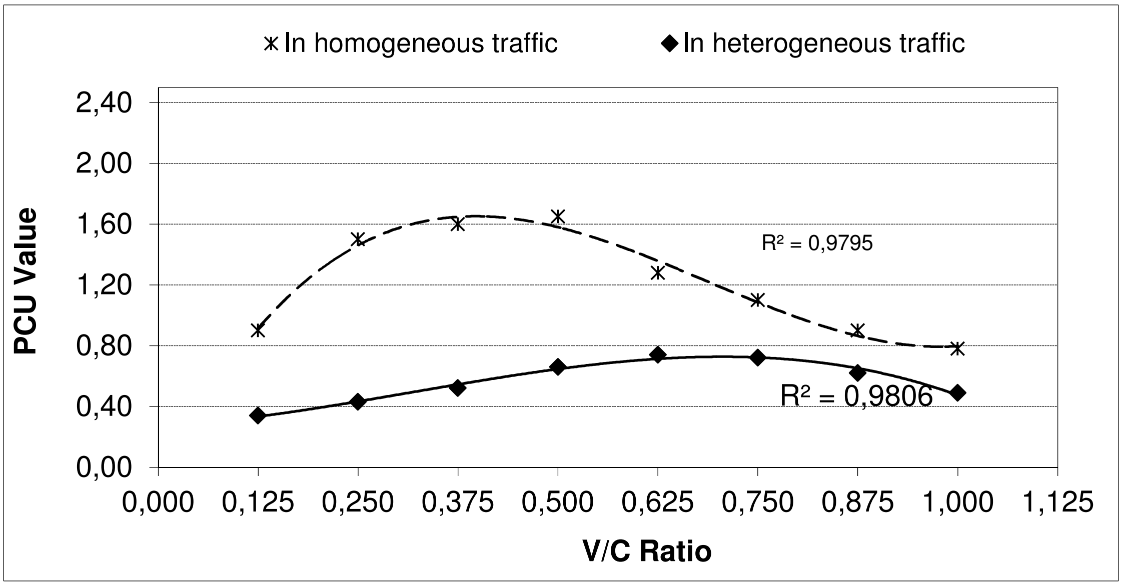

Figure 12: Comparison of variation of PCU values of motorised two-wheelers.

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 in cars-only traffic, than the difference between car speed and subject-vehicle speed under heterogeneous traffic condition, as shown in Table 9. For example, at volume-to-capacity ratio value of 0.50, under cars-only traffic condition, through the simulation experiments, it has been found that the average speed of cars is 74.35 km/h and that of buses is 60.65 km/h, resulting in a speed difference of 13.7 km/h. Whereas, under heterogeneous traffic condition, the average car speed for the same volume-to-capacity ratio is 66.83 km/h and the average bus speed is 57.16 km/h, resulting in a speed difference of 9.66 km/h. The PCU values of buses, at this level of traffic flow, under cars-only traffic and heterogeneous traffic conditions are 2.63 and 1.80 respectively. Similarly, the average speeds of cars and motorised two-wheelers, at V/C ratio of 0.5, in cars-only traffic, are 70.11 and 57.53 km/h respectively, resulting in a speed difference of 12.58 km/h. The average speeds of cars and motorised two-wheelers in heterogeneous traffic, at the same flow (V/C ratio) level are 66.83 and 56.17 km/h respectively, resulting in a speed difference of 10.66 km/h. The PCU values of motorised two-wheelers at V/C ratio level of 0.5, with cars-only traffic and heterogeneous traffic, are 1.65 and 0.66 respectively.

Table 9: Comparison of speeds of the vehicles in cars-only and heterogeneous traffic conditions.

Volume-to-Capacity (V/C) ratio	*Cars-only traffic condition (vehicle speed in km/h)*			*Heterogeneous traffic condition (vehicle speed in km/h)*		
	Cars	*Subject vehicle*	*Speed difference*	*Cars*	*Subject vehicle*	*Speed difference*
	Subject vehicle: Buses					
0.25	81.05	65.95	15.1	78.55	64.34	14.2
0.50	74.35	60.65	13.7	66.83	57.16	9.66
0.75	52.66	46.15	6.51	47.82	42.86	4.96
	Subject vehicle: Trucks					
0.25	81.38	63.15	18.23	78.55	61.04	17.51
0.50	76.00	59.80	16.20	66.83	56.79	10.04
0.75	52.35	46.45	5.90	47.82	43.68	4.14
	Subject vehicle: L.C.V.					
0.25	81.62	66.84	14.78	78.55	66.12	12.43
0.50	75.80	62.25	13.55	66.83	60.48	6.35
0.75	54.98	49.53	5.45	47.82	46.52	1.30
	Subject vehicle: M.Th.W.					
0.25	81.29	52.86	28.43	78.55	51.78	26.76
0.50	69.54	52.65	16.89	66.83	50.76	16.06
0.75	54.39	44.76	9.63	47.82	43.32	4.50
.	Subject vehicle: M.T.W					
0.25	81.11	57.64	23.47	78.55	57.15	21.40
0.50	70.11	57.53	12.58	66.83	56.17	10.66
0.75	57.12	50.53	6.59	47.82	47.74	0.08

Note: *L.C.V. - Light Commercial Vehicles*; *M.Th.W. - Motorised Three-Wheelers*; *M.T.W. - Motorised Two-Wheelers.*

For studying, the effect of heterogeneity of traffic on PCU values of vehicles, plots showing the variation of difference in speed change over traffic volume under cars-only and heterogeneous traffic conditions on 8.75 m wide road, were also made for each of the different vehicle types. The plots depicting the variation of difference in speed change over traffic volume under cars-only and heterogeneous traffic conditions on 8.75 m wide road for buses and motorised two-wheelers, as examples, are given in Figures 13 and 14. The difference in speed change, in respect of cars and the subject vehicle, is calculated as the percentage change in speed of cars minus the percentage change in speed of subject vehicle for the successive V/C ratios.

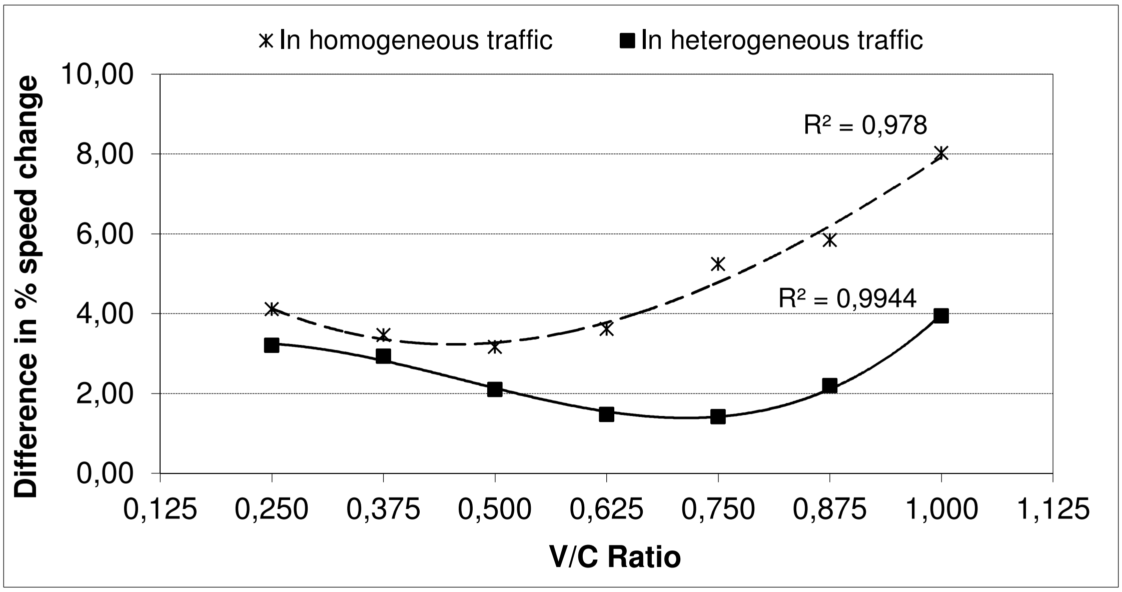

Figure 13: Comparison of difference in speed change between cars and buses under homogeneous and heterogeneous traffic condition.

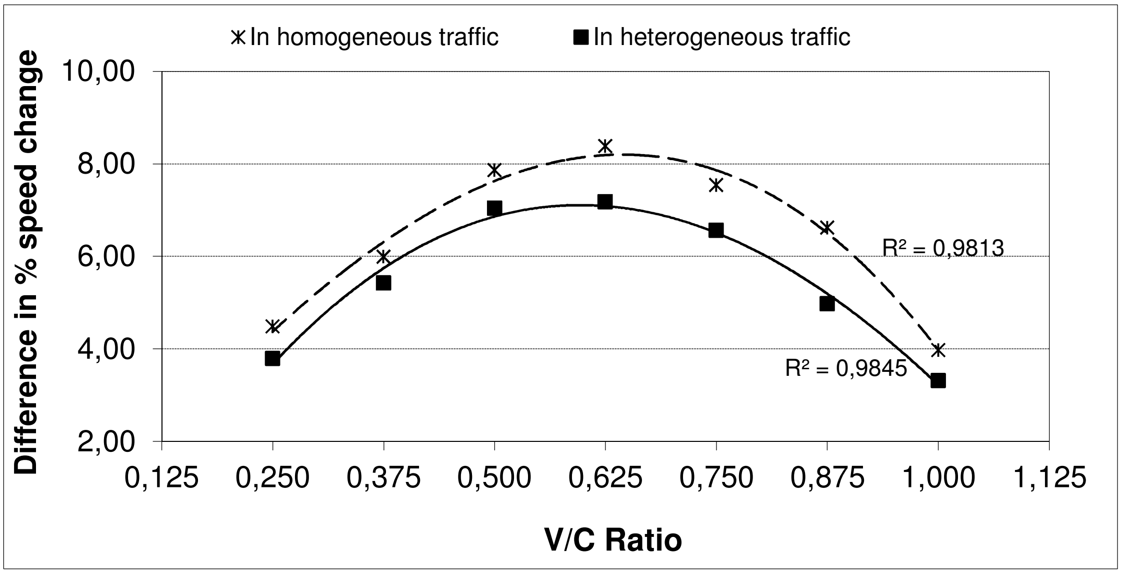

Figure 14: Comparison of difference in speed change between cars and buses under homogeneous and heterogeneous traffic condition.

From the Figures (13 and 14), it can be seen that both the trend lines (pertaining to the variation of difference in speed change over volume under cars-only and heterogeneous traffic conditions) exhibit the same pattern as the trends of variation of PCU values of buses and motorised two-wheelers (Figures 11 and 12). Moreover, it can be noted that, at all the volume-to-capacity (V/C ratios) levels, the difference in percentage change is higher in the case of cars-only traffic conditions, when compared to the corresponding values under heterogeneous traffic conditions. Hence, it is clear that higher speed difference between cars and other categories of vehicles, in cars-only traffic, than the difference between car speed and subject-vehicle speed under heterogeneous traffic condition, has resulted in higher PCU values under cars-only traffic condition. Thus, in general, it is seen that, the impedance caused to traffic flow by a vehicle type in cars-only traffic is higher in magnitude than in heterogeneous traffic. The speed reduction to cars, in cars-only traffic, has been caused fully by the impedance offered by the subject-vehicle type. Whereas, under heterogeneous traffic, the speed reduction of cars, has been caused by the collective impedance offered by the vehicles, other than cars, along with the subject vehicle type.

7. Check for Accuracy of PCU Values

For the purpose of checking for 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, for selected values of V/C ratios and the number of vehicles passing the simulation stretch, 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, by the corresponding PCU values (Table 8). 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 8). Thus, the traffic volume, in terms of number of cars, was obtained for the set of selected V/C ratios. Comparison of the traffic flows measured 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 15. 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.

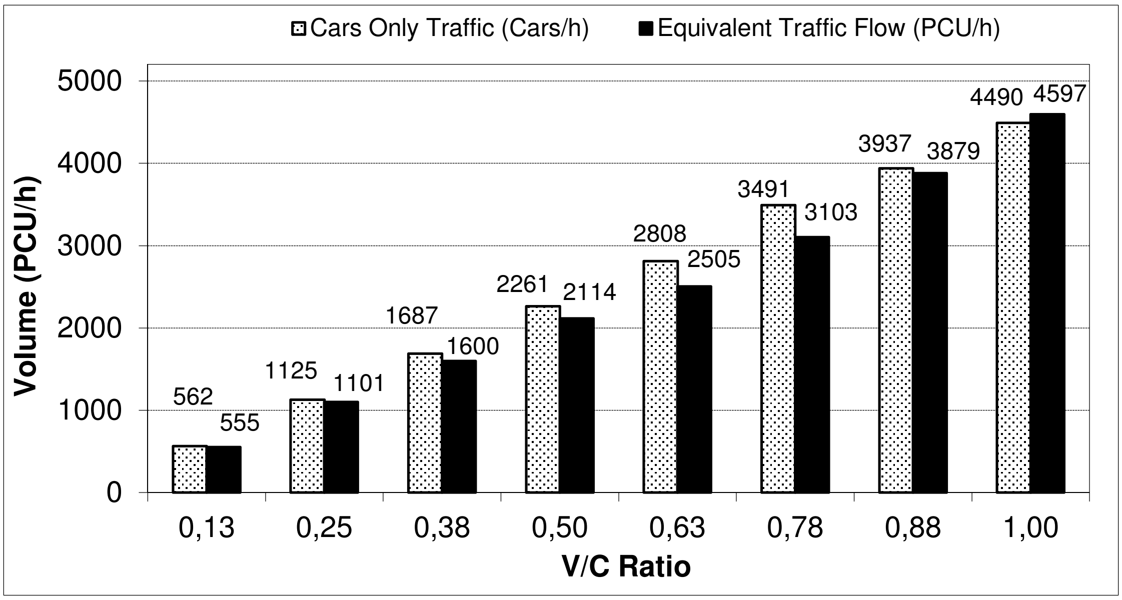

Figure 15: Comparison of heterogeneous traffic and cars-only traffic flows.

A paired t-test, based on the passenger car equivalent (PCU/h) and passenger cars-only (cars/h) traffic volumes was also done. The calculated value of t-statistic (t0) is 1.98. 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.

8. Findings

The following are the important findings 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.
2. From the speed-volume curve, developed using the simulation model, it is found that, for the observed traffic composition, the capacity of a level, four-lane divided road with 7.25 m wide main carriageway and 1.5 m wide paved shoulder for one direction of traffic flow, is about 4600 PCU/h.
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 seen that, the impedance caused to traffic flow by a vehicle type in cars-only traffic is higher in magnitude than in heterogeneous traffic.
5. 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.

6. Under heterogeneous traffic conditions, the trend of variation of the PCU value, over traffic volume, indicates that (i) in the case of vehicles that are larger than passenger cars, at low volume levels, the PCU value decreases with increase in traffic volume and at high traffic volume levels, the PCU value increases with increase in traffic volume and (ii) whereas, in the case of vehicles that are smaller than passenger cars, at low volume levels, the PCU value increases with increase in traffic volume and at high volume levels, the PCU value decreases with increase in traffic volume.
7. It is inferred that the change in the PCU value of the different categories of vehicles, due to change in traffic volume, under heterogeneous traffic condition, is directly influenced by the change in the speed difference between the reference vehicle (car) and the subject vehicle (a chosen vehicle type, other than car) under various volume levels.

References

Aerde, M.V. and Yagar, S. (1984) "Capacity, speed, and platooning vehicle equivalents for two-lane rural highways", *Transportation research record: Journal of the TRB*, National Research Council, Washington, D.C., 971: 58-67.

Ahn, K., Rakha, H., Trani, A. and Aerde, M.V. (2002) "Estimating vehicle fuel consumption and emissions based on instantaneous speed and acceleration", *Journal of transportation engineering*, ASCE, 128, 2: 182-190.

Al-Kaisy, A., Younghan, Jung and Hesham, Rakha (2005) "Developing passenger car equivalency factors for heavy vehicles during congestion", *Journal of transportation engineering*, ASCE, 131, 7: 514-523.

Arasan, V.T., and Koshy, R. (2005) "Methodology for modeling highly heterogeneous traffic flow", *Journal of transportation engineering*, ASCE, 131, 7: 544-551.

Banks, J., Carson, J.S., Barry, L.N. and David, M.N. (2004) *Discrete-event system simulation*, Pearson education, Singapore, Third edition: 12-14.

Barcelo (1996) *The parallelization of aimsun2 microscopic traffic simulator for its applications*, Available from: http://www.microsimulation.drfox. org.uk /tools [accessed 5 June 2008].

Ben-Akiva, Moshe, E., Koutsopoulos, H.N., Mishalani, R.G. and Yang, Q. (1997) "Simulation laboratory for evaluating dynamic traffic management systems", *Journal of transportation engineering*, ASCE, 123, 4: 283-289.

Bloomberg, L. and Dale, J. (2000) "A comparison of the VISSIM and CORSIM Traffic simulation models on a congested network", *TRR: Journal of the TRB*, National Research Council, Washington, D.C., 1721: 52-60.

Chandra, S. (2004) "Capacity estimation procedure for two lane roads under mixed traffic conditions", *Indian road congress journal*, New Delhi, India, 165, 1: 139-170.

Craus P. and Grinberg, I.A. (1980) "Revised method for the determination of passenger car equivalencies", *Transportation research*, Part A, 14A, 5: 241-246.

Elefteriadou L., Torbic, D. and Webster, N. (1997) "Development of passenger car equivalents for freeways, two-lane highways, and arterials", *Transportation research record: Journal of the TRB*, National Research Council, Washington, D.C., 1572: 51-58.

Fan Henry, S.L. (1990) "Passenger car equivalents for vehicles on Singapore expressways", *Transportation research*-A, 24A, 5: 391-396.

Helbing, D., Hennecke, A., Shvetsov, V. and Treiber, M. (2002) "Micro-and macro-simulation of freeway traffic", *Journal of mathematical and computer modelling*. 35, 5/6: 517-547.

Huber, M.J. (1982) "Estimation of passenger car equivalents of trucks in traffic stream", In *Transportation research record: Journal of TRB*, National Research Council, Washington, D.C., 869: 60-70.

Indian roads congress (1990) "Guidelines for capacity of roads in rural area", *IRC code of Practice*, IRC: 64, New Delhi, India.

Justo, C.E.G. and Tuladhar, S.B.S. (1984) "Passenger car unit values for urban roads", *Journal of Indian roads congress*, New Delhi, India 26, 12: 33-41.

Kadiyali, L.R., Viswanathan, E. and Gupta, R.K. (1981) "Free speeds of vehicles in indian roads", *Journal of Indian road congress journal*, New Delhi, India 165, 1: 387-457.

Khan, S.I. and Maini, P. (1999) "Modeling heterogeneous traffic flow", *Transportation. research record: journal of the transportation research board*, National Research Council, Washington, D.C., 1678: 234-241.

Krammes, R.A. and Crowley, K.W. (1986) "Passenger car equivalents for trucks on level freeway segments", *Transportation research record: Journal of the TRB*, National Research Council, Washington, D.C., 1091: 10-17.

Kumar, V.M. and Rao, S.K. (1996) "Simulation modeling of traffic operations on two lane highways", HRB, *Indian Roads Congress*, New Delhi, India, 54: 211-236.

Linzer, E., Roess, R. and McShane, W. (1979) "Effect of trucks, buses, and recreational vehicles on freeway capacity and service volume", In *TRR: Journal of the Transportation Research Board, TRB*, National Research Council, Washington, D.C., 699: 17-24.

Mallikarjuna, C. and Ramachandra Rao. K. (2006) "Modelling of passenger car equivalency under heterogeneous traffic conditions", *22nd Australian Road Research Board Conference*, Canberra, Australia.

Marwah, B.R. and Singh, B. (2000) "Level of service classification for urban heterogeneous traffic: a case study of kanpur metropolis", *Transportation research circular* E-C018: Proceedings of the 4th International Symposium on Highway Capacity, Maui, Hawaii.

Peeta, S., Weimin, Z. and Pengcheng, Z. (2004) "Modelling and mitigation of car-truck interactions on freeways", *Transportation research board annual meeting CD-ROM*.

Ramanayya, T.V. (1988) "Highway capacity under mixed traffic conditions", *Traffic engineering and control*, U.K., 29, 5: 284-287.

Terdsak, R. and Charong, S. (2005) "Effects of motorcycles on traffic operations on arterial streets", *Journal of Eastern Asia society for transportation studies*, 6: 137-146.

Transportation and Road Research Laboratory (1965) *Research on Road Traffic*, H.M.S.O, London.

Webster, N. and Elefteriadou, L. (1999) "A simulation study of truck passenger car equivalents (PCE) on basic freeway sections", *Transportation research*, Part B, 33B, 5: 323-336.