Bus Priority on Roads Carrying Heterogeneous Traffic: a Study using Computer Simulation

Venkatachalam Thamizh Arasan* and Perumal Vedagiri**
Transportation Engineering Division
Department of Civil Engineering
Indian Institute of Technology Madras
Chennai, 600 036
India
* tel: +91 44 2257 4270
fax: +91 44 2257 4252
e-mail: arasan@iitm.ac.in
** e-mail: transpoveda@gmail.com

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The desirable goal in passenger transportation is moving more people in fewer vehicles. This goal, in respect of road transport, can be attained by encouraging public transport modes like buses by assigning priority. This paper is concerned with application of micro simulation technique to study the impact of provision of reserved bus lanes on the flow of highly heterogeneous traffic on urban roads. The specific objectives of this paper are (i) to modify and validate a newly developed model of heterogeneous traffic flow using field observed data and (ii) to apply the validated simulation model to study the impact of exclusive bus lanes introduced on urban arterials for a wide range of traffic volume levels. The impact of introduction of an exclusive bus lane is measured in terms of the reduction in speed of other categories of motor vehicles, due to the consequent reduction in road space, over a wide range of traffic volume. The main finding of this paper is, that if an exclusive bus lane is provided under highly heterogeneous traffic conditions,(prevailing in Indian cities), then, the maximum permissible volume to capacity ratio that will ensure a level of service of C for the traffic stream comprising all the motor vehicles, except the buses, is about 0.53.

Keywords: Computer Simulation, Exclusive Bus Lane, Heterogeneous Traffic, Impact Assessment

1. Introduction

The traffic on the roads of Indian cities 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 includes 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. By virtue of the wide ranging static and dynamic characteristics, the vehicles occupy any lateral position on the road depending on the availability of road space at a given instant of time without any lane discipline and it is nearly impossible to impose lane discipline under such conditions. Under the said heterogeneous traffic flow conditions, the buses, being relatively larger vehicles, find it difficult to maneuver through the mixed traffic and are subjected to frequent acceleration and deceleration leading to lower speed and discomfort to both the driver and passengers. This also results in enormous delay and uncertainty to bus passengers and consequently, the level of service of buses gets reduced considerably making bus a less attractive mode of transport. The road traffic in Indian cities has grown at a very steep rate in the recent past making the available transport infrastructure inadequate. As augmentation of urban transport infrastructure is expensive, there is a need to find alternative solutions to the problem. One way is to devise methods for optimal utilization of the available infrastructure (road space) in such a way that the carrying capacity of the roadway, in terms of number of persons transported, is enhanced. This may be achieved by providing priority for buses, which will facilitate faster movement of more people in less number of vehicles resulting in reduced congestion and air pollution. This paper is concerned with the study of the impact of provision of exclusive bus lanes on the flow of heterogeneous traffic using a newly developed simulation model. The contents of the paper is organized sequentially in eight sections, namely, review of earlier studies, objectives, the simulation model, data collection, model validation, model application, results and discussions and conclusions.

2. Review of Earlier Studies

Bus priority schemes have been implemented in many urban areas around the world with the major objective underlying their implementation being to enhance bus attractiveness and improve its competitiveness with respect to other modes. One of the common bus preferential treatments is provision of exclusive bus lanes on major urban roads, to facilitate faster movement of buses, which will make the mode more attractive. Provision of exclusive bus lane is possible only in situations, where the carriageway is of adequate width and a lane can be easily spared for buses. This implies that there should be at least 3 lanes for each direction of movement (Kadiyali, 1997). Exclusive bus lanes can be provided either adjacent to the curb or by the side of the median depending on the operational strategies and road side land use. To be successful, the bus lanes should be created for a good length of the road instead of small bits. The major benefits of bus lanes are: reduced delay due to elimination of friction between buses and other traffic, improved reliability and regularity of bus service, improved bus utilization, reduced bus operating cost, effective utilization of available road space and reduced accident rates. A bus may carry twenty times as many passengers as a car, yet it only contributes three times as much to congestion (CCMS, TRRL, UK, 1976).

The review of literature indicates that several research works, related to the subject matter of the present study, have been done in the past. Feather et al. (1973) presented some of the experiences gained by the Greater London Council bus unit in the design of a wide variety of bus lanes. Cox (1975) studied the exclusive bus lanes that were implemented in the city of Dallas, Texas, USA. He concluded that the assignment of special lanes to buses had not adversely affected the level of service of the vehicular traffic, and there had been a reduction in travel time, a reduction in the number of stops, and an increase in speed of buses. Also, the improved level of service of bus transit, due to bus lane implementation, had attracted additional ridership. Tanaboriboon and Toonim (1983) determined the impact on bus movement and car traffic due to provision of with-flow bus lanes on selected streets in the central part of the city of Bangkok, Thailand. The results have shown that, in all selected streets, bus travel-time savings varied from 0.11 minutes to 1.66 minutes. Shalaby and Soberman (1994) studied the effect of an urban reserved bus lane on bus travel time on individual segments. The results of the study suggest opportunities for using reserved bus lanes on a more selective basis along a particular route and the need to reconsider whether taxies should be permitted to use these lanes. The analysis carried out in this study leads to the following conclusions: (i) the bus lane has little impact on bus performance during off-peak periods and when traffic is low (ii) Ridership generally increases after introducing the lane, even without improvements in travel time. Shalaby (1999) used the TRANSYT-7F simulator to examine changes in performance measures of through buses and adjacent traffic following the introduction of reserved lanes for buses in an urban arterial in downtown Toronto, Canada. Huanyu et al. (2003) described an effort to develop a decision model for determining whether a freeway preferential bus lane can be justified under the conditions prevailed. The CORSIM simulation model was used to simulate the different input conditions. Currie et al. (2004) defined a balanced framework for road space reallocation in relation to transit priority. The framework aims to clarify the trade-offs required in developing transit priority systems in a range of traffic circumstances and to provide a balanced allocation of road space based on the full range of impacts. In particular, the approach focuses on ‘people travel’ not ‘vehicle travel’. This approach utilizes advanced micro traffic simulation model for better understanding of operational implications of alternative transit priority measures. Currie et al. (2007) described the methodology developed to evaluate trade offs in the use of the limited road space in Melbourne, Australia for new bus and tram priority projects. The approach employs traffic micro simulation modeling to assess road space reallocation impacts, travel behaviour modeling to assess changes in travel patterns and a social cost benefit frame work to evaluate impacts.

It is clear from the review of literature that the reported studies have been conducted under fairly homogeneous traffic conditions and there are no ready-to-apply reference materials available to assist in exclusive bus lane planning and design under heterogeneous traffic conditions, in which different types of vehicles share the same road space without any physical segregation. Hence, there is a need to devise appropriate methodology to study the effect of exclusive bus lane on heterogeneous traffic flow. Introduction of exclusive bus lanes requires comprehensive study of the flow characteristics of the traffic as a whole, and this can be done by using appropriate modeling technique.

3. Objectives

This paper is concerned with validation of a newly developed micro simulation model of heterogeneous traffic flow and application of the model to study the impact of provision of reserved bus lanes on urban roads. The specific objectives of this study are as follows:

1. To study the flow characteristics of heterogeneous traffic on selected stretches of urban arterials with specific reference to bus movement.
2. To modify and validate the newly developed model of heterogeneous traffic flow using field observed data.
3. To apply the validated simulation model to study the impact of exclusive bus lanes introduced on urban arterials, for a wide range of traffic volume levels.

4. The Simulation Model

At a conceptual level, simulation is often defined as the representation of reality through the use of a model or other device which will react in the same manner as reality, under a given set of conditions. As such, simulation models predict how a system should behave without having the real system involved, thus, avoiding the need to use the system itself to conduct experiments. Input conditions can be carefully controlled and environments created where cause and effect relationships are easy to discern. In addition, variables can be treated as independent and experiments can be repeated many times. Stochastic variations that typically accompany real world experiments can either be removed or be introduced in a controlled manner. It is also possible to instrument the system in ways that would be difficult or impossible in the real world.

Simulation models may also 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.

As this study pertains to the heterogeneous traffic conditions prevailing in India, the available traffic simulation models, which are based on homogeneous traffic conditions, where clear lane and queue discipline exists, are not applicable to study the heterogeneous traffic flow characteristics. Also, the research attempts made to model heterogeneous traffic flow (e.g-Katti and Ragavachari, 1986; Marwah, 1995; Kumar and Rao, 1996; Khan and Maini, 2000) are limited in scope and do not address all the aspects comprehensively. Hence, there was a need to develop appropriate models to simulate heterogeneous traffic flow. Accordingly, a model of heterogeneous traffic flow, named, HETEROSIM was developed (Arasan and

Koshy, 2005). The modeling 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 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. 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 1.

The simulation process consists of the following major sequential steps related to traffic flow on mid-block section of roads: (1) vehicle generation, (2) vehicle placement, and (3) vehicle movement.

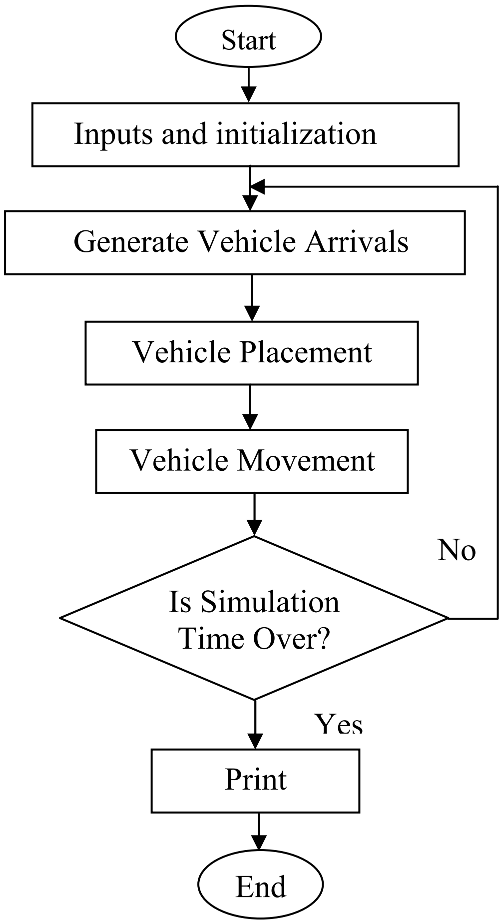

Figure 1. Flow diagram of the simulation model

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., 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 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. The model is also capable of displaying the animation of simulated traffic movements 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 traffic flow, obtained using the animation module of HETEROSIM, is shown in figure 2. 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).

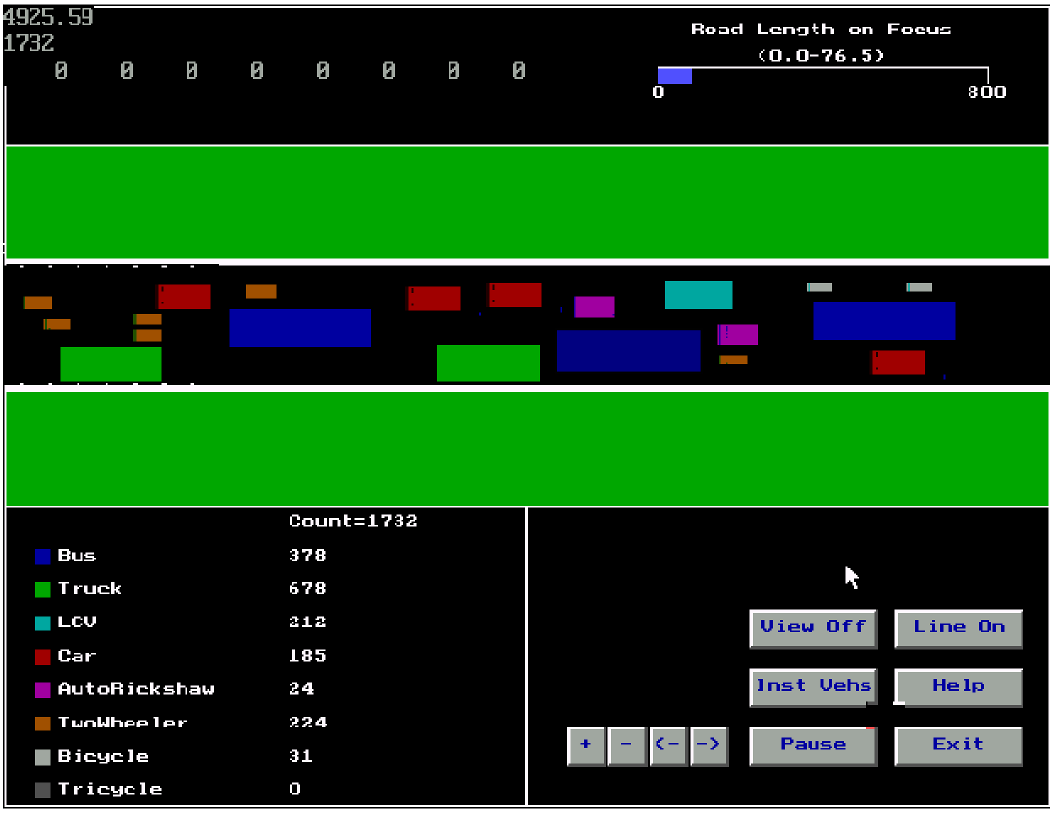

Figure 2. Snapshot of animation of simulated heterogeneous traffic flow

5. Data Collection

Collection and analysis of data play a pivotal role in the development of successful simulation models. Field data should be gathered covering the ranges of anticipated roadway and traffic flow conditions. The required traffic data were collected by observing traffic flow on the Maraimalai Adigalar Bridge, near Saidapet, which falls in the southern part of the metropolitan area of Chennai city, India. The bridge has a six lane divided road with raised curbs on both sides and it is 250 m long. Since, the study stretch is on the bridge, the road geometry is uniform and there is no interference to vehicular movement due to pedestrian traffic as the pedestrian walk-way is segregated by a barricade. The traffic flow from Guindy side to Saidapet side was considered for the study. The width of the carriageway is 12m for the traffic stream considered.

The traffic flow was recorded for one hour using a video camera mounted on the terrace of an adjacent building, which enabled recording of all the traffic flow characteristics at the same time. The video data was then transferred to computer for further processing. 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 relevant characteristics of the vehicles are given in table 1. The composition of the measured traffic volume on the study stretch is as depicted in figure 3.

Table 1. Characteristics of vehicles of the heterogeneous traffic

Vehicle Type	Dimensions in m		Lateral Clearance allowance in m		Free Speed in km/h	
	Length	Breadth	Minimum	Maximum	Mean	S.D.
(1)	(2)	(3)	(4)	(5)	(6)	(7)
Bus	10.3	2.5	0.3	0.6	67	7
Truck	7.5	2.5	0.3	0.6	62	9
LCV	5.0	2.0	0.3	0.5	61	7
Car	4.0	1.6	0.3	0.5	72	7
M.Th.W.	2.6	1.4	0.2	0.4	48	8
M.T.W.	1.8	0.6	0.1	0.3	61	10
Bicycle	1.9	0.5	0.1	0.3	15	2

LCV- light commercial vehicle, M.Th.W – Motorised Three Wheelers, M.T.W - Motorised Two Wheelers

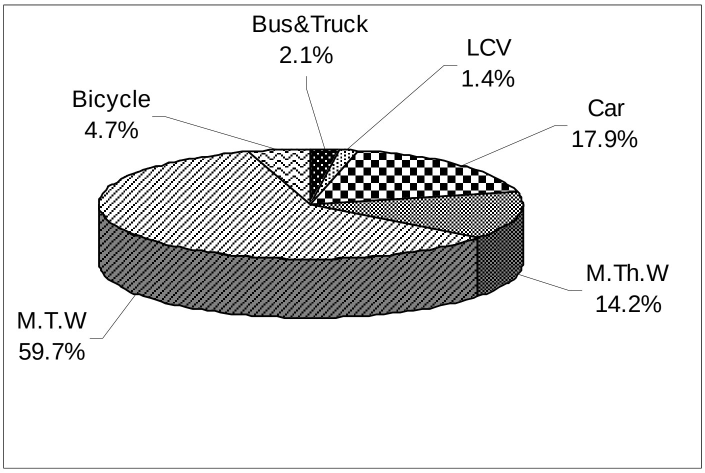

Figure 3. Traffic composition at the study road stretch

The overall dimensions of all categories of vehicles, adopted from literature (Arasan and Koshy, 2005) are shown in columns (2) and (3) of table 1. The Minimum Clearance value pertaining to zero speed condition and the maximum Clearance corresponding to a speed of 60 km/h and more adopted from literature (Arasan and Koshy, 2005) are shown respectively in columns (4) and (5) of table 1. Any vehicle moving in a traffic stream has to maintain sufficient transverse clearances on both sides with respect to other vehicles/curb/ median to avoid side friction. The clearance value is assumed to vary linearly from minimum to maximum depending upon the speed of Vehicles. Lateral clearance allowance is the clearance share pertaining to a vehicle type. For example, if a bus and M.Th.W. are placed side by side, the minimum lateral clearance between the two vehicles will be 0.3 + 0.2 = 0.5 m. Knowledge of speed characteristics of various categories of vehicles is essential for the calibration and validation of simulation models. Free speeds of different types of vehicles are important input parameters for any traffic flow simulation model. Free speed is defined as the speed adopted by the driver when not restricted by any other vehicle in the stream under a set of given road way and environmental conditions. Free speeds are affected by driver characteristics, vehicle factors, roadway factors, and environmental factors. The free speed of the different categories of vehicles were also noted by estimating the time taken by the vehicles to travel a trap length of 30 m on the study stretch of the road during lean traffic periods when the movement of vehicles are not hindered by the presence of other vehicles. The observed mean free speeds of various types of vehicles and the respective standard deviations are shown respectively, in columns (6) and (7) of table 1. 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.

5.1 Distribution of Input Variables

5.1.1 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 4. It can be seen that there is a good match of observed and the theoretical values.

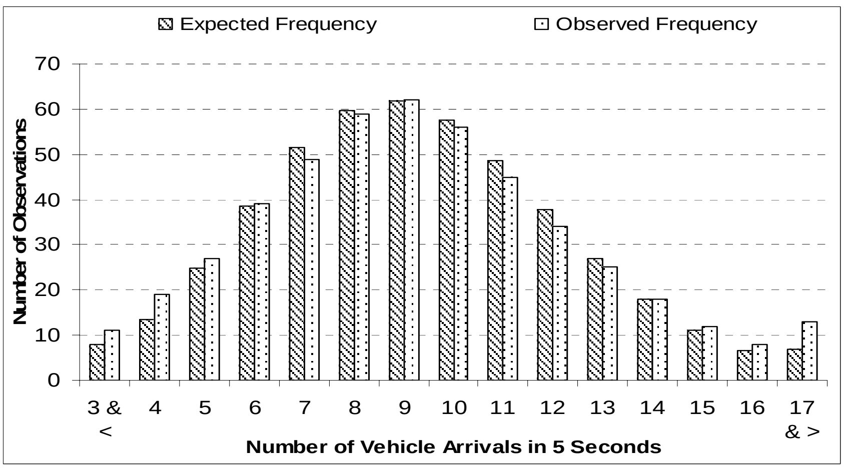

Figure 4. Theoretical and observed arrival pattern

5.1.2 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 2. The data, classified over a time interval of 0.3 s, was fitted into the negative exponential distribution, as per the details given in table 2 and the goodness of fit was tested using a chi-squared distribution. It can be seen that the observed chi-square value is 12.91 against the critical value from chi-squared table, for 11 degrees of freedom at 5% level of significance, of 19.68. 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 5. 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.

Table 2. 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)
0.0 – 0.3	0	1.000	100.0	2877	2967	2.797
0.3 – 0.6	0.3	0.574	57.4	1652	1674	0.291
0.6 – 0.9	0.6	0.330	33.0	949	906	1.940
0.9 – 1.2	0.9	0.189	18.9	545	506	2.790
1.2 – 1.5	1.2	0.109	10.9	313	308	0.080
1.5 – 1.8	1.5	0.062	6.2	180	158	2.689
1.8 – 2.1	1.8	0.036	3.6	103	94	0.786
2.1 – 2.4	2.1	0.021	2.1	59	60	0.017
2.4 – 2.7	2.4	0.012	1.2	34	32	0.118
2.7 – 3.0	2.7	0.007	0.7	20	22	0.200
3.0 – 3.3	3.0	0.004	0.4	11	12	0.090
3.3 – 3.6	3.3	0.002	0.2	6	8	0.666
3.6 – 3.9	3.6	0.001	0.1	9	11	0.444
3.9 – 4.2	3.9	0.001	0.1			
χ^2 Value at 5% level of Significance for 11 degrees of freedom is = 19.68					χ^2 Value =	12.91

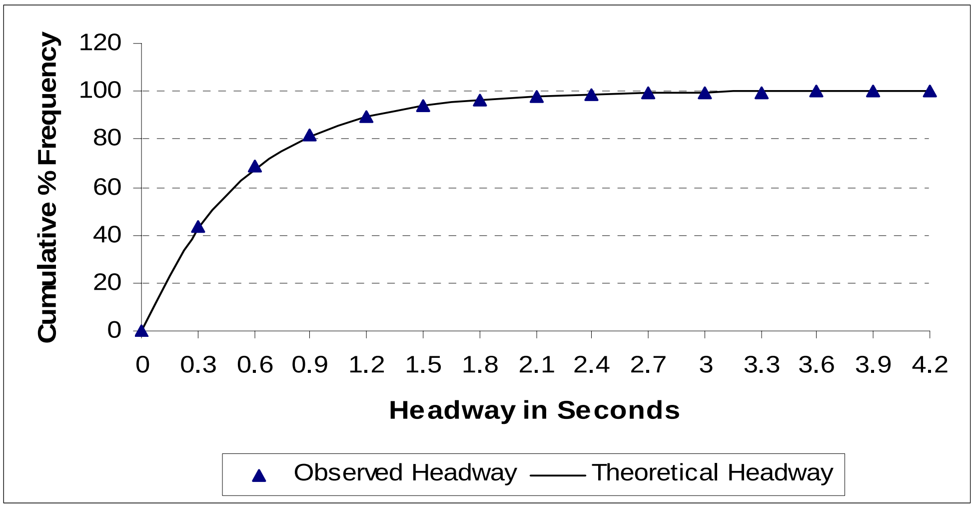

Figure 5. Goodness of fit of observed and theoretical headways

6. Model Validation

Model validation is the process of comparing model results with the corresponding field observed values to ensure that the simulated results realistically represent the real system (field conditions). Only measurable data from the field can be used to validate the model results. Though the available model is generally validated, it was decided to check for the appropriateness of the model for the specific requirements of this study. For validating the simulation model, the traffic flow through a length of 1400 m of the study stretch was simulated. 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. For the purpose of model validation, it was decided to consider the derived traffic flow characteristics at the micro level so that the validation is satisfactory. Accordingly, the field observed and simulated mean speeds of each of the categories of vehicles were compared to check for the validity of the model. For this purpose simulation runs with three random number seeds and the average of the three values was taken as the final result. A comparison of the observed and simulated average speeds of the different types of vehicles is shown in figure 6. It can be seen that the simulated speed values significantly replicate the field observed speeds for all vehicle types. The simulated speeds were also statistically compared with observed speed values. A paired *t*-test of null hypothesis of no mean difference was performed to check for the match between simulated and observed average speeds of vehicles. The calculated value of t (t_0) is 0.39 against the critical value (from 't' table) of 2.57. It was found that the observed and simulated average speeds agreed at a 5% level of significance (95% confidence limit).

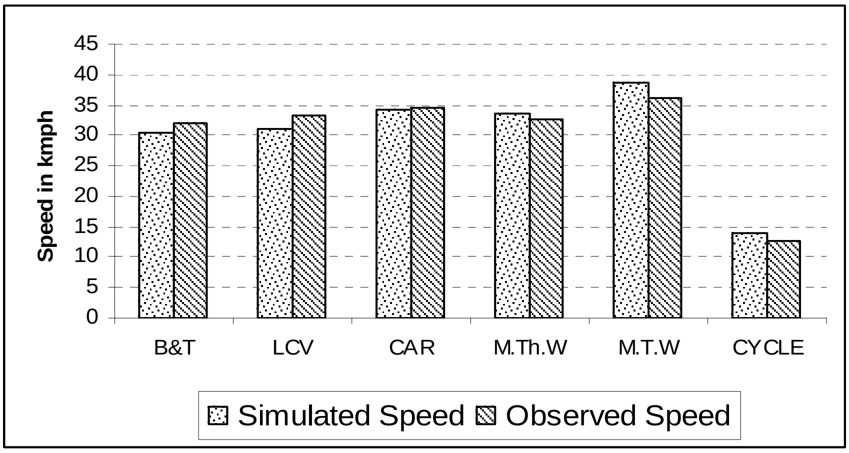

Figure 6. Comparison of observed and simulated speeds
LCV- Light Commercial Vehicles, M.Th.W. – Motorised Three-Wheelers, M.T.W. - Motorised Two-Wheelers

7. Model Application

The 'HETEROSIM' model can be applied to study a host of heterogeneous traffic scenarios on urban road links. Here, the application of the model is specific to study the impact of provision of an exclusive bus lane. For this purpose, a traffic composition representing the mean composition of traffic on the major roads of Chennai city was considered (figure 7).

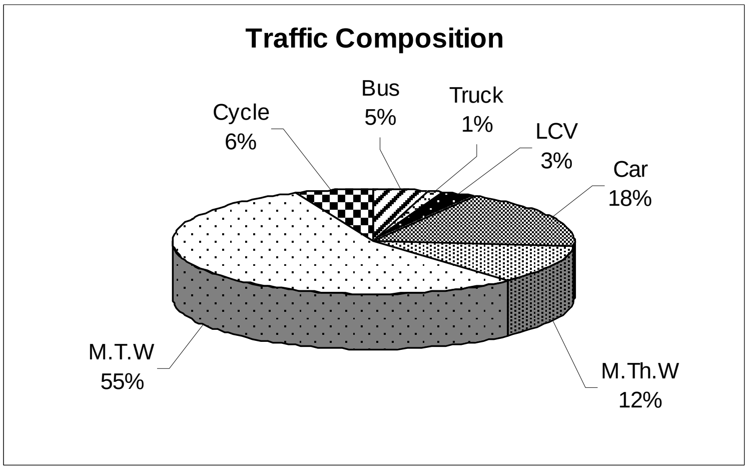

Figure 7. Representative traffic composition
LCV- Light Commercial Vehicles, M.Th.W. – Motorised Three-Wheelers, M.T.W. - Motorised Two-Wheelers

The roadway width for the simulation was fixed as 11 m (3 lanes) in each direction (most common type of urban arterial in Indian cities). Out of the total width of 11 m, a 1.5 m wide road space, adjacent to the curb, was reserved for bicycles (as is the normal practice in Indian cities). First, the traffic flow on the assumed arterial, without bus lane, was simulated and the output values were recordered. During validation of the model, it was found that three simulation runs (with three different random seeds) were sufficient to get consistent simulation output to replicate the field observed traffic flow. Hence, for model application also, the simulation runs were made with three random number seeds and the averages of the three values were taken as the final model output. The simulation was run with volumes varying from a low level to the capacity flow condition. The speed flow relationship developed, based on the results of the simulation runs, is depicted in figure 8.

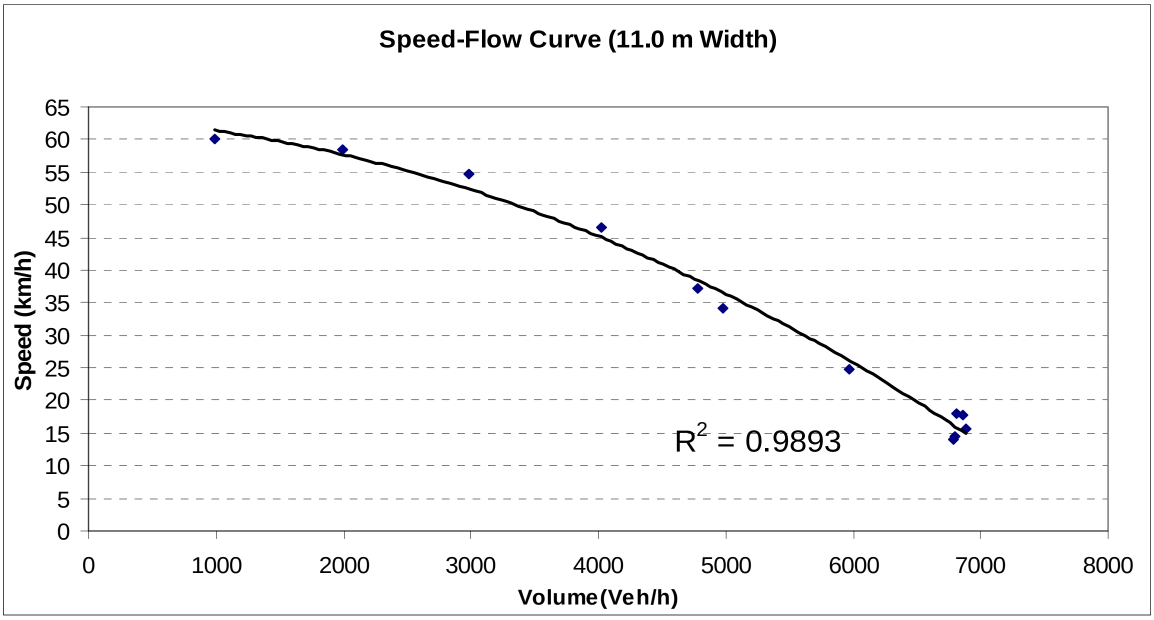

Figure 8. Speed flow curve for 11 m wide urban road

It can be inferred from the plot (figure 8) that the capacity of 11 m wide road space, when there is no exclusive bus lane (all vehicles mixed), is about 6900 vehicles per hour and the corresponding stream speed is about 16 km/h. As per the Indian Roads Congress-a statutory body responsible for development of codes and standards for road transport in India, guidelines (IRC, 106-1990), the acceptable level of service for urban roads is ‘C’ and the volume of traffic corresponding to this level of service can be taken as 0.7 times the capacity. Accordingly, here, the volume of traffic corresponding to level of service C is 0.7*6900=4830, say 4800 vehicles per hour. To study the impact of provision of exclusive bus lane under the assumed road condition, for the purpose of simulation, an exclusive bus lane was introduced by the side of the median on the stretch of road, which will be used by all the buses and this roadway condition was given as the input to the model by holding the traffic volume and composition to be the same as for the previous case. The assumed layout of the road stretch with the proposed with-flow bus lane is shown in figure 9. The simulation runs, after introducing the bus lane, were made similar to the previous case. For these (with bus lane) simulation runs, the traffic volume on the study stretch was varied, as in the case without bus lane, from 1000 to 7000 vehicles/h. A simulation run was also made for the traffic volume corresponding to level of service C, namely, 4800 vehicles/h. The speeds maintained by the different types of vehicles for different simulated traffic volume levels are shown in table 3.

Table 3. Speeds of different categories of vehicles on the roadway with and without bus lanes

Traffic Volume (Vehicles/h) (1)	Road-way Condition (2)	Speed Maintained by Vehicles in Km/h						
		Bus (3)	Truck (4)	LCV (5)	Car (6)	M.Th.W (7)	M.T.W (8)	Bicycle (9)
1000	WoBL	63.5	55.6	60.8	72.8	48.9	62.9	14.5
	WBL	66.2	52.9	58.5	70.4	48.3	62.9	13.9
2000	WoBL	58.8	53.7	58.4	68.9	48.0	62.2	14.5
	WBL	65.9	48.4	53.9	61.9	46.6	60.6	13.3
3000	WoBL	51.2	45.8	51.1	60.9	46.1	59.4	14.5
	WBL	65.5	41.4	45.3	49.9	42.7	53.3	13.1
4000	WoBL	40.3	37.6	41.2	47.6	41.6	51.9	14.5
	WBL	65.2	29.3	30.4	33.6	32.0	37.3	12.9
4800	WoBL	30.3	28.2	31.7	35.3	34.2	41.8	14.4
	WBL	65.1	19.9	19.5	20.4	20.9	22.9	12.9
5000	WoBL	28.3	26.8	28.9	32.7	32.0	37.9	14.4
	WBL	65.1	16.7	16.3	16.9	17.2	19.3	12.8
6000	WoBL	20.9	20.5	21.6	23.3	23.7	27.4	13.9
	WBL	65.4	14.3	13.9	13.9	14.5	15.5	12.2
7150	WoBL	14.7	14.6	14.9	15.2	15.3	16.5	12.5
	WBL	64.5	13.7	13.5	13.4	13.5	14.9	12.2

WoBL Without Bus Lane
WBL With Bus Lane
LCV Light Commercial Vehicles
M.Th.W. Motorised Three-Wheelers
M.T.W. Motorised Two-Wheelers

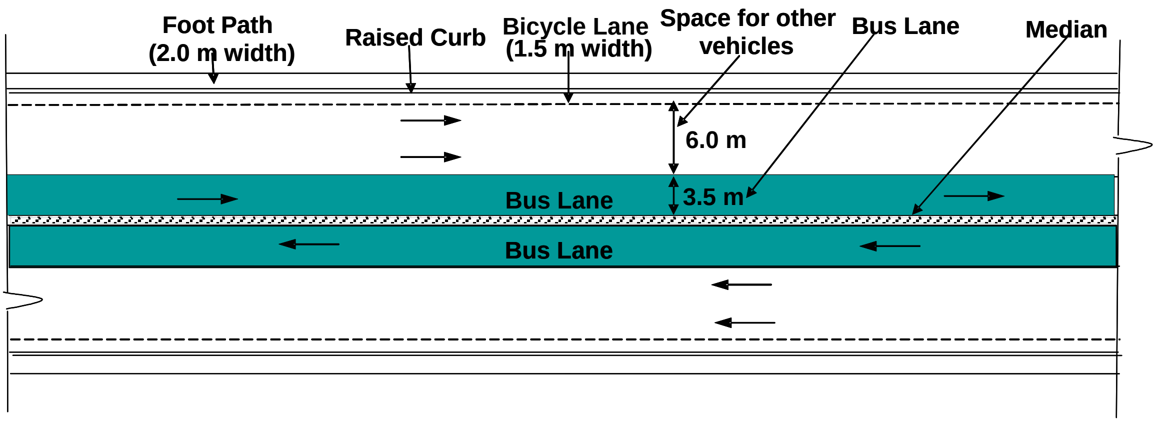

Figure 9. Schematic layout of the road stretch with exclusive bus lane

8. Results and Discussions

From table 3, it can be seen that there is increase in the speed of bus due to provision of exclusive bus lane, at all volume levels. It can be noted that at lower volume levels (1000 & 2000 vehicles/h), due to provision of bus lane, there is marginal increase in bus speeds and marginal speed reduction to other vehicles. This is mainly because of the near-free-flow condition enjoyed by all categories of vehicles at low volume levels. Also, it can be noted that at higher volume levels (3000 vehicles/h and above), there is a significant speed improvement for bus and a steep decline in the speeds of other categories of vehicles. This implies that at higher volumes, there is a complex interaction among the different categories of vehicles and this creates a negative impact of bus lane on the flow of all the other categories of vehicles. In the case of the other categories of motorised vehicles, the exact value of speed reduction varies between vehicle types.

The trend of possible percentage gain in the speed of the buses due to provision of exclusive bus lanes (obtained as speed of buses with bus lane minus speed of buses without bus lane and the whole multiplied by 100), at different traffic-volume levels, has been depicted in figure 10. It can be observed in figure 10, that at the volume level corresponding to level of service C (4800 vehicles per hour), the percentage gain in speed of bus, due to provision of exclusive bus lane, is about 115. It can also be seen that beyond the volume level, of 5000 vehicles per hour, the possible rate of increase in the gain in speed of buses is steep.

The trend of percentage reduction in the speeds of each of the other categories of vehicles - other than bus, (obtained as the speeds of other categories of vehicles without bus lane minus speeds of the categories of vehicles with bus lane and he whole multiplied by 100), plotted using the same set of axes, is depicted in figure 11. It can be seen that for all the other categories of motor vehicles, the percentage reduction in the speed, due to provision of exclusive bus lanes, is less at low volume levels and the rate of reduction in the speeds of all the motorized vehicles is steep from a volume level of about 3000 vehicles per hour up to a volume level of 5000 vehicles per hour. Also, it may be noted that from the volume level of 5000 vehicles per hour up to the capacity volume of 7000 vehicles per hour (near capacity), the rate of reduction in speed is relatively less. This is because of the reason that at high volume levels (more than 5000 vehicles per hour), due to high concentration, the speeds of all vehicles get reduced in both the cases (with and without bus lanes) and hence, the impact of bus lane on the speeds of the other vehicles become relatively less resulting in lesser percentage decrease in speed. The decrease in the speed of bicycle is marginal over the entire range of traffic volume. This can be attributed to the availability of exclusive road space of 1.5 m width for bicycles.

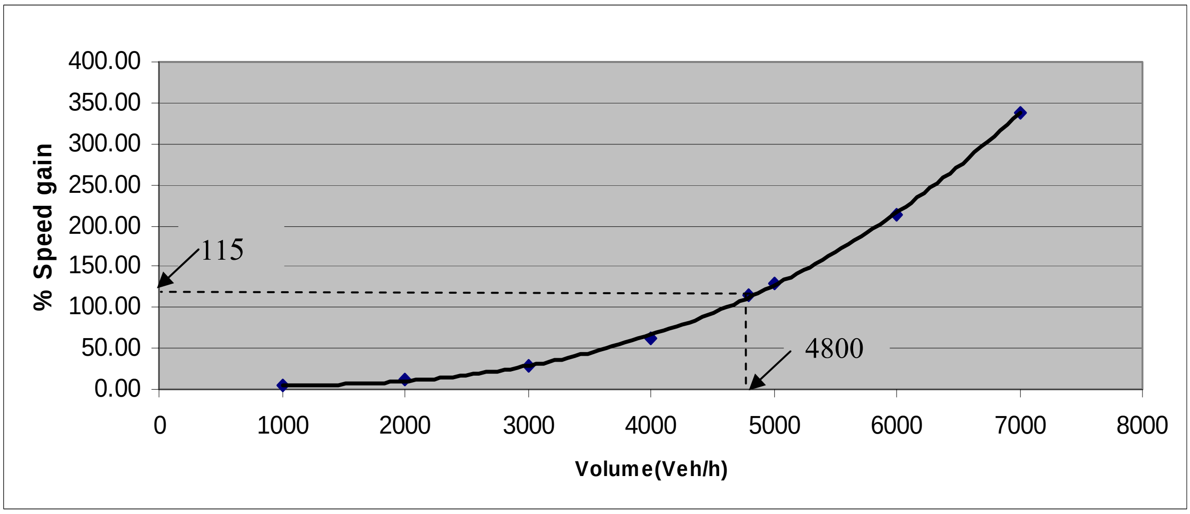

Figure 10. The rate of increase in speed of buses due to provision of exclusive bus lane

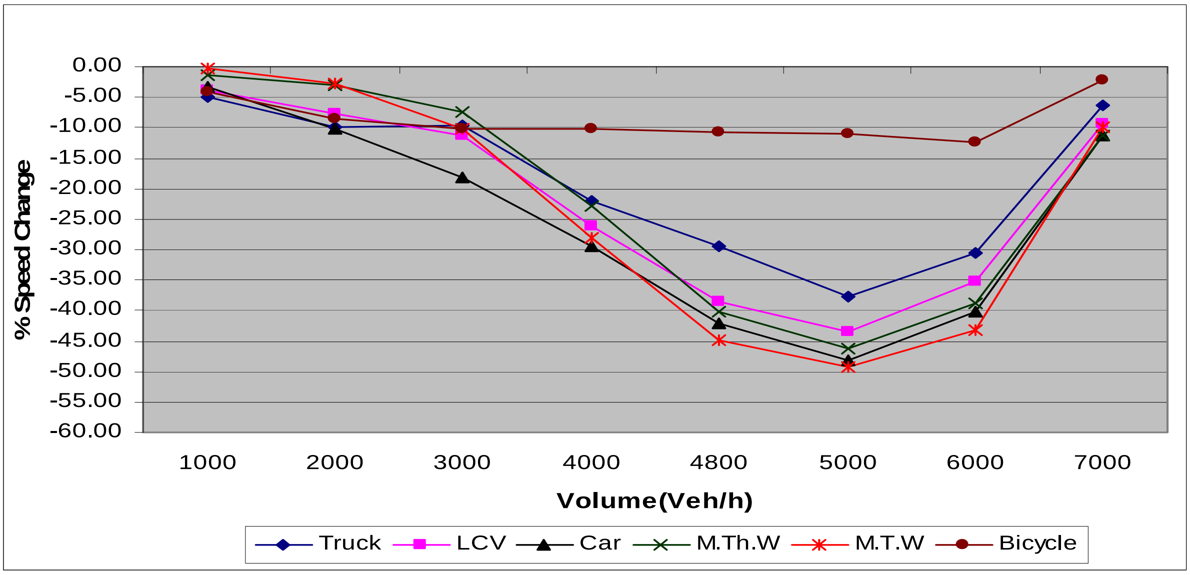

Figure 11. The rate of reduction in speeds of other categories vehicles due to provision of exclusive bus lane

It is important, while providing exclusive bus lanes, to see that the level of service enjoyed by the other categories of vehicles does not get deteriorated beyond the acceptable limit. In this context, it is reasonable to ensure level of service C (recommended as acceptable level of service on urban roads by Indian Roads Congress (IRC)) for the other categories of motor vehicles while providing an exclusive bus lane. Hence, there is a need to have information on the trend of speed difference of the stream of motorised traffic, excluding the buses, for roadway conditions, with and without bus lanes. Hence, two plots, on the same set of axes depicting the difference of the stream speed, over volume to capacity ratio, for the two conditions of the road, were made as shown in figure 12.

It can be seen that the speed of the stream involving the other motorised vehicles, when no bus lane is provided, at level of service C (corresponding volume/capacity ratio of 0.7) is 39 km/h. If it is desired to provide bus lanes without adversely affecting the level of service of the other categories of motor vehicles, the volume of traffic that will ensure the same speed for the other categories of motor vehicles corresponds to a V/C ratio of 0.53 as depicted in the figure. Thus, for the assumed road geometry and traffic composition, provision of exclusive bus lane may not adversely impact the minimum level of service required for the other categories of vehicles up to a traffic volume to capacity ratio of 0.53. The two plots also enable understanding of the traffic flow conditions, in terms of, speed over a range of volume-to-capacity ratios for the two roadway conditions (with and without bus lane). It can also be seen that at a traffic volume level near capacity, the stream speed of all the other categories of vehicles (other than bus), when no bus lane is provided, is about 16 km/h and the stream speed becomes about 14 km/h, when a bus lane is introduced.

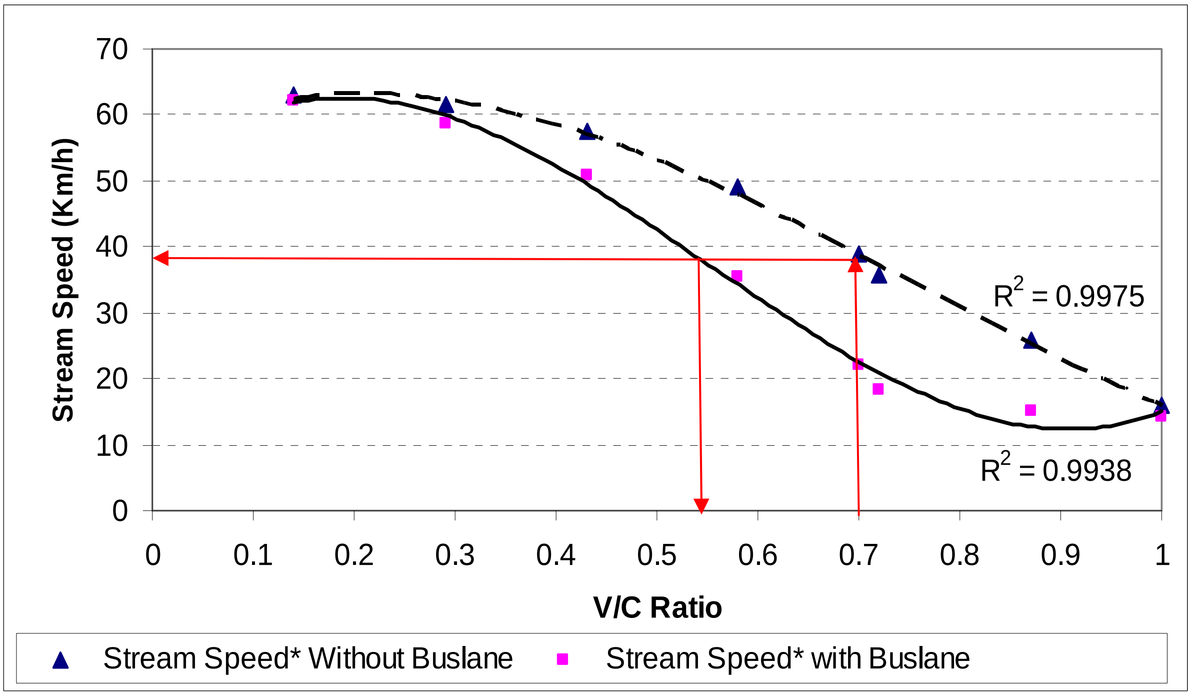

Figure 12. Traffic stream speed on the roadway with and without bus lane
* Stream of all motorised vehicles except buses

9. 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 for the specific purpose of this study.
2. It has been found through the study that for the assumed traffic composition, without any exclusive bus lane, the capacity of a 11 m wide road with 1.5 m wide bicycle track (included in the total width of 11 m), for one way movement of traffic, is about 6900 vehicles per hour.
3. If an exclusive bus lane is provided under the assumed roadway and traffic conditions, then, the maximum permissible volume to capacity ratio that will ensure a level of service of C for the traffic stream comprising all the other motor vehicles (except the buses), is about 0.53.
4. When an exclusive bus lane is provided, the mean running speed of buses can be up to 65 km/h and the mean running speed of the stream of traffic comprising all the other motor vehicles (other than buses) enjoying level of service C, will be 39 km/h.

9.1 Scientific Contribution of the Paper

In Indian cities, the roads are relatively narrow. Hence provision of exclusive bus lanes on these roads may adversely affect users of other modes like car, motorised three-wheeler, motorised two-wheeler, etc., resulting in congested conditions and reduced speed for these vehicles. Hence, there is a need to study the possible impact of provision of exclusive bus lanes (by taking a portion of the available road space exclusively for bus transit), the findings of which will serve as a very important base document for discussion with all concerned, to get their acceptance before implementing the bus priority scheme (provision of exclusive bus lanes). Through this study, a balanced framework for road space allocation, in relation to bus priority, has been defined. The framework aims to clarify the trade-offs required in developing bus priority systems in a range of traffic circumstances and to provide a balanced allocation of road space based on the full range of impacts. In particular, the approach focuses on ‘people travel’ not ‘vehicle travel’. The simulation model used here will be useful to develop such frameworks for a wide range of roadway and heterogeneous traffic conditions. Thus, the model will serve as an important decision making tool in managing the heterogeneous traffic on Indian roads and in several other developing countries where similar traffic scenarios exist.

9.2 Limitations of the Study

This paper is devoted mainly to study the impact of introducing bus lanes on running speed of vehicles. Hence, the effect of bus stops has need not been discussed. The level of impact of bus stops depends on the spacing of bus stops and the dwell time of buses at the stops. The authors are currently involved in the study of these aspects including the problem of passenger access to bus stops when the bus lane is provided at the middle of the roadway.

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