Micro-simulation Study of Vehicular Interactions on Upgrades of Intercity Roads under Heterogeneous Traffic Conditions in India

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Abstract

Purpose: Study of the basic traffic flow characteristics and clear understanding of vehicular interactions are the pre-requisites for highway capacity analysis and to formulate effective traffic management and control measures. The road traffic in India is highly heterogeneous comprising vehicles of wide ranging physical dimensions, weight, power and dynamic characteristics. The problem of measuring volume of such heterogeneous traffic has been addressed by converting the different types of vehicles into equivalent passenger cars and expressing the volume as Passenger Car Unit per hour (PCU/h).

Methods: 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 quantify the vehicular interaction, in terms of PCU, for the different categories of vehicles, by considering the traffic flow of representative composition, on upgrades of different magnitudes on intercity roads in India.

Results and Conclusions: The PCU estimates, made through microscopic simulation, for the different types of vehicles of heterogeneous traffic, for a wide range of grades and traffic volume, indicate that the PCU value of a vehicle significantly changes with change in traffic volume, magnitude of upgrade and its length. It is found that, the change in PCU value of vehicles is not significant beyond a length of 1600 m on grades. Also, it has been found that the PCU estimates are accurate at 5% level of significance.

Keywords: Upgrades, Power-to-weight ratio, Heterogeneous traffic, simulation, Passenger car unit, capacity

1.0 Introduction

The information on traffic volume is an important input required for planning, analysis, design and operation of roadway systems. Highway capacity values and speed-flow relationships used for planning, design and operation of highways, in most of the developed countries, pertain to fairly homogeneous traffic conditions comprising vehicles of more or less uniform static and dynamic characteristics. The road traffic in developing countries like India is highly heterogeneous comprising vehicles of wide ranging physical dimensions, weight and dynamic characteristics. The different types of vehicles in India, which generally present on intercity roads having uniform magnitude of upgrades may be broadly grouped

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into the following categories: 1. Buses, 2. Trucks, 3. Light commercial vehicles comprising large vans and small trucks, 4. Cars including jeeps and small vans, 5. Motorized three-wheelers, which include three-wheeled motorized vehicles to carry passengers and three wheeled motorized vehicles to carry small quantities of goods, and 6. Motorized two-wheelers, which include motorcycles, scooters and mopeds. These vehicles share the same road space without any physical segregation. Under these conditions, the vehicles, for maneuver, take any lateral position along the width of roadway, based on space availability. When such different types of vehicles, with varying static and dynamic characteristics, are allowed to mix and move on the same roadway facility, a variable set of longitudinal and transverse distributions of vehicles may be noticed from time to time. This results into very complex dynamic vehicular interactions. The interaction between the vehicles can be represented in terms of the amount of impedance caused to flow of traffic by a vehicle type (subject vehicle type, for which the dynamic PCU value is to be estimated) in comparison with that of passenger cars (reference vehicle category). The relative impedance can be quantified in terms of Passenger Car Units (PCU). Under such heterogeneous traffic conditions in India, expressing traffic volume as number of vehicles passing a given section of road per unit time will be inappropriate and some other suitable base needs to be adopted for the purpose. The problem of measuring volume of such heterogeneous traffic has been addressed by converting the different types of vehicles into equivalent passenger cars and expressing the volume in terms of Passenger Car Unit (PCU) per hour. On upgrades, heavy vehicles such as trucks, buses, etc. will experience significant reduction in their speeds, whereas, passenger cars and other smaller vehicles such as motorized-two-wheelers may experience relatively lesser speed reduction. This variation in speed reduction among the different vehicle categories can be attributed to their wide ranging physical characteristics such as dimensions, weight, etc. and dynamic characteristics such as engine power, acceleration rate, etc. The variation in the level of interaction between the vehicles on upgrades may result in different set of PCU values of the vehicle types. Hence, it is necessary to model the traffic flow on grades and study the change in traffic flow characteristics and vehicular interactions with variation in magnitude of upgrade and its length.

Traffic phenomena are complex and nonlinear, due to the interactions of a large number of vehicles. Moreover, vehicles do not interact simply following the laws of mechanics, but also due to the reactions of human drivers. Normally, solutions to traffic problems are evolved through empirical or analytical approaches by conducting on-site studies on traffic behavior. However, these conventional methods have certain limitations and drawbacks, particularly, while dealing with complex situations involving considerable amount of stochastic attributes. An empirical approach is based on extensive field data, which is neither easily available nor easily collectable. The analytical approach has the limitation of underlying assumptions of homogeneity, which are far from the high variations of driver-vehicle characteristics in heterogeneous traffic conditions. In view of this, researchers concentrated on appropriate modeling technique and the modeling approach through simulation, emerged as the most powerful, flexible and acceptable solution searching tool. A review of the literature shows that only limited studies have been done to develop an understanding of simulation of traffic flow under non-lane based heterogeneous traffic conditions. The prominent among them are briefly reviewed here. Several researchers (Chari and Badarinath, 1983; Palaniswamy et al., 1985; Ramanayya, 1988; Kumar, 1994; Singh, 1999; Oketch, 2000) have attempted to model the heterogeneous traffic and most of these models are microscopic in nature. Chandra and Pariah (2004) developed a heterogeneous-traffic-flow simulation model to analyze urban road traffic. The various input parameters required for the model such as classified volume count, free speed of different types of vehicles, headway distribution at different volume levels, and lateral clearances were collected through video recording technique. It was found that the free speed data of vehicles followed the normal distribution and hyperlang model was found to fit well for the headways on urban roads under mixed traffic condition. The analysis, through this simulation study, indicated that the interaction between the vehicles is the function of traffic volume and composition. Cho and Wu (2004) proposed a motorcycle traffic flow simulation model, which contains longitudinal and lateral movement models. The concept of the longitudinal model is to decide an appropriate speed under the repulsion and the thrust. The concept of the lateral model **is** to modify the lateral position to get the maximum lateral space.

Arasan and Koshy (2005) developed a heterogeneous-traffic-flow simulation model to study the various characteristics of the traffic flow at micro level under mixed traffic condition. The vehicles are represented, with dimensions, as rectangular blocks occupying a specified area of road space. The positions of vehicles are represented using coordinates with reference to an origin. 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 model is also capable of showing the animation of simulated traffic movements over the road stretch. Implementing the cellular automata (CA) concept for modeling the heterogeneous traffic has been suggested by some researchers (Lan and Chang 2005, Hsu et al. 2007, Mallikarjuna and Ramachandra Rao 2009). Bohang et al. (2009) developed a new simulation model based on safety distance model, and the mixed traffic advance model for the mixed traffic conditions in China. An angle between the direction of vehicle movement and the lane (θ) is introduced into the stimulation-action model after a great deal of actual investigation and study. The following acceleration and angle of the vehicle is expressed through the change of the angle. Motor vehicles adjust their speed and angle according to the movement of all the non-motorized vehicles in front of them. The model is the traditional stimulation-action model, if θ is 0 degrees; the maximum of θ is 45 degrees considering actual traffic and the behavior of the driver. The characteristics of the vehicle movement are accurately described by the process of recycle from 0 degree to the maximum. The improved model is proposed based on the stimulation-action model by analyzing the behavior of the driver under mixed traffic conditions in China. Lan and Chang (2005) developed an inhomogeneous cellular automata models to elucidate the interacting movements of cars and motorcycles in mixed traffic contexts. Based on the field survey, the authors established deterministic cellular automata (CA) rules to govern the particle movements in a two-dimensional space. The instantaneous positions and speeds for all particles are updated in parallel per second accordingly. The deterministic CA models have been validated by another set of field observed data. The unique behavior patterns of motorcycles were characterized by Lee (2007). Three models were developed to describe motorcycle movements, namely the longitudinal headway model, the oblique & lateral headway model and the path choice model. The longitudinal headway model focused on describing the phenomenon that a motorcycle will maintain a shorter headway when aligning to the edge of the preceding vehicle. The oblique & lateral headway model described the headway distribution of motorcycles when they are following the preceding vehicles obliquely. The path choice behavior was modeled by using a multinomial logit model which described the dynamic virtual lane-based movements of motorcycles. Further, an agent-based traffic simulator was built to represent the motorcycle behavior in mixed traffic flow. The mathematical models developed for describing the motorcycle behavior were implemented in this simulator. Through the verification process, this simulation system showed that it was able to work as intended and represent the characteristic behavior patterns of motorcycles. Three applications of this simulator were presented to show that this simulator was able to carry out policy tests and was a powerful tool for conducting a study on mixed traffic flow containing motorcycles.

A review of the literature on modeling movement of vehicles on upgrades have shown that in the past, researchers have used force balance equation and vehicle mechanics (weight-to-power ratio of the vehicle) for developing models that predicts truck speeds on upgrades of any percentage and length (Gillespie, 1985; Archilla and Fernandez De Cieza, 1996; Lan and Menendez, 2003). All these studies, however, are mainly related to characterization of truck performance on upgrades under homogeneous traffic conditions and hence, the results of these studies are not applicable for Indian conditions. The impact of road gradient on speed was analyzed by Yagar and Aerde (1983) and found that the operating speed at a location is expected to decrease by approximately 1.8 km/h for each 1% of grade when going uphill. Traffic flow characteristics on freeway upgrades in Germany, were analyzed by Brilon and Bressler (2004). A combination of measurements, analyses of continuous counting results and microscopic simulations were performed. Based on the study, it was found that road capacity depends solely on the degree of gradient. Speed, however, is determined not only by the degree of the gradient but also by the length of the upgrade as well.

The Highway Capacity manual (HCM, 2000), has given the passenger-car-equivalent (PCE) values for trucks and recreational vehicles for different grades. The variables pertaining to various roadway and traffic conditions, such as magnitude of upgrade and its length, number of lanes, pavement type and condition, flow rate and percentage composition of trucks were tested (through PCE estimation) for both single and multiple truck populations by Ingle (2001). The relationships for these variables were found to be the same for single truck populations as compared to multiple truck populations. Based on these results, it was recommended that the simplification of simulating a single truck population with an average weight to power ratio can confidently be used. 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. Huber, 1982; and Webster and Elefteriadou, 1999), (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). Elefteriadou et al. (1997) studied the impact of grade, and length of grade on PCE values using simulation model. The authors found that the PCE value of the vehicles increases significantly with increase in the magnitude of gradient and grade length. Al-Kaisy et al. (2005) also found a similar trend. The authors also found that the effect of trucks and other heavy vehicles on traffic stream during congestion is higher from their effect during free-flow conditions. All these studies, however, are mainly related to estimation of PCE for heavy vehicles (Trucks and Buses) under 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.

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. Indian Roads Congress has recommended that the same PCU values can be used for rolling/hilly sections since the effect of terrain has been accounted for in a consolidated manner in the recommended Design Service Volumes. Hence, it may be inferred that the PCU values are valid for a particular traffic and roadway condition. Tiwari *et al.* (2000) concluded that the modified density method can be used to determine passenger car units for various traffic entity groups on rural and suburban roads. It is found from the review of Indian studies related to PCU estimation that there is only one significant study of Chandra and Goyal (2001), on the subject matter. The researchers studied the effect of gradient on capacity of two-lane roads. The authors calculated the PCU values using two variables: (i) speed ratio of the car to the subject vehicle (for which PCU value is to be calculated), and (ii) space- occupancy ratio of the car to the subject vehicle. This study concluded that (i) the PCU for a vehicle type increases with increase in gradient, and (ii) the effect of grade on PCU is linear. However, these results are empirical and are based on limited traffic data. The review of literature on the subject matter of traffic flow modeling using simulation technique shows that the modeling approach through simulation emerged as the most powerful, flexible and acceptable solution searching tool. The review of literature on the subject matter of movement of vehicles on upgrades and PCU estimation reveals that 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.

The review clearly shows that, at present, there is no ready-to-use reference material available on estimation of PCU of vehicles traffic on upgrades under heterogeneous traffic conditions prevailing in India. The PCU value of a vehicle category may not be constant as given in (IRC: 64-1990), because it may vary, based on not only the vehicle factors but also with several other factors associated with roadway and traffic conditions. It may be appropriate to consider the PCU value of a vehicle type as a dynamic quantity instead of considering it as constant. Hence, there is a need to accurately estimate the PCU values, through a comprehensive study of the interaction between vehicles of the traffic, at the micro-level, over a wide range of roadway and traffic conditions. The derived PCU values, using microscopic technique, can be useful for enhancing the accuracy of capacity estimates under heterogeneous traffic conditions. Hence, the research work reported here, is aimed at quantification of the vehicular interaction under heterogeneous traffic conditions, in terms of PCU value of different vehicle types, due to changes in the magnitude of upgrade and its length, over a wide range of traffic volume levels. The procedure adopted for PCU estimation and the relevant results, along with the details of the simulation model used for this study, are presented in the following sections.

2.0 The simulation model

A recently developed micro simulation model, of heterogeneous traffic-flow named, HETEROSIM (Arasan and Koshy, 2005) is used to study the vehicular interactions, at micro-level, over a wide range of traffic flow conditions on upgrades of different magnitudes. Field data collected on traffic flow characteristics such as free speed, physical dimensions of different vehicle types, lateral clearance between vehicles, etc. are used in calibration and validation of the simulation model. The acceleration rates, over different speed ranges, required for simulation of heterogeneous traffic flow on grades, were estimated for different upgrades. The speed-distance profiles are developed for different vehicle categories, pertaining to grades of different magnitudes, using the validated simulation model. The simulation model is then used to estimate PCU values of different types of vehicles. Finally, a check for the accuracy of the estimated PCU values is also made.

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 models developed through research attempts made to model heterogeneous traffic flow by Khan and Maini (2000); Marwah and Singh (2000); Kumar and Rao (1996); and Ramanayya (1988), are limited in scope and do not address all the aspects comprehensively.

A recently developed model of heterogeneous traffic flow, named HETEROSIM Arasan and Koshy (2005), however, is comprehensive and is capable of replicating the heterogeneous traffic flow. 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 *Fig. 1*.

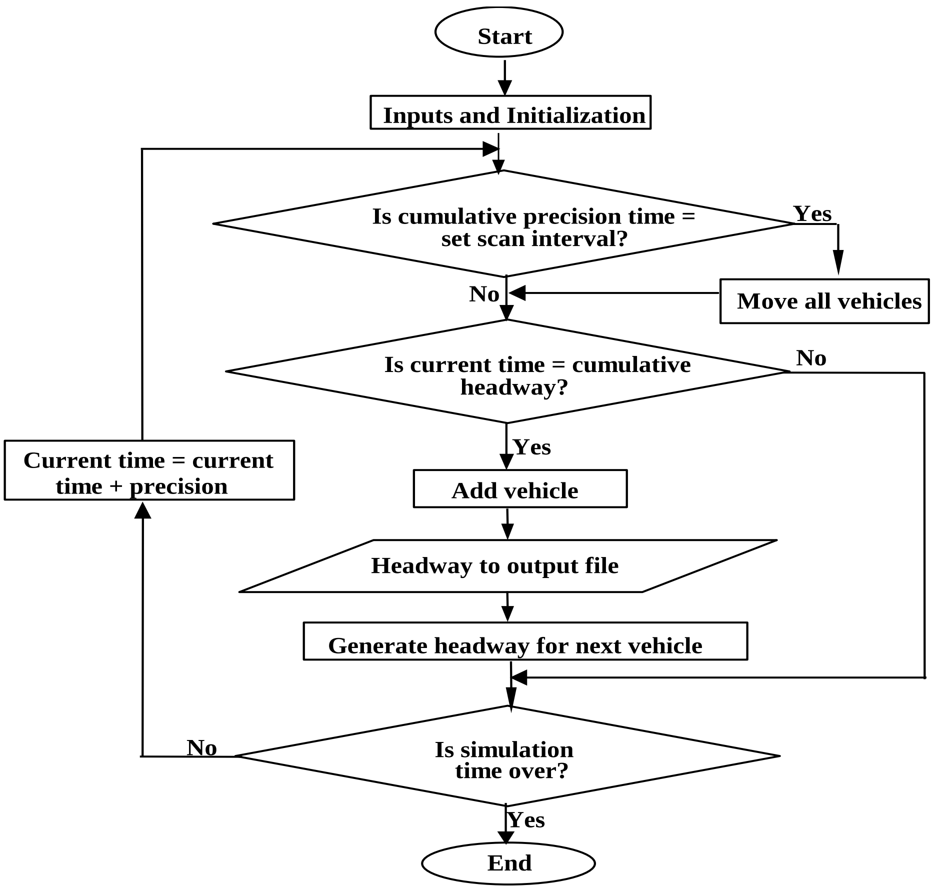

Figure 1: General Structure of Simulation Model

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 ("Add Vehicle") will be activated to facilitate the process. At higher traffic flow levels; there is a chance of more vehicle arrivals during each scan interval (1s). To address this aspect, an additional clock for scanning with a precision of 0.05 s was provided. Checking for the possibility of placing a generated vehicle during a scan interval (1s) on the simulation road stretch, as well as updating the status of the vehicles already in the system is done when the cumulative precision scan interval is equal to the set scan interval of 0.5s.The simulation is continued until the input simulation-run length is completed. 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. 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, a "snapshot" of which is shown in *Fig. 2*.

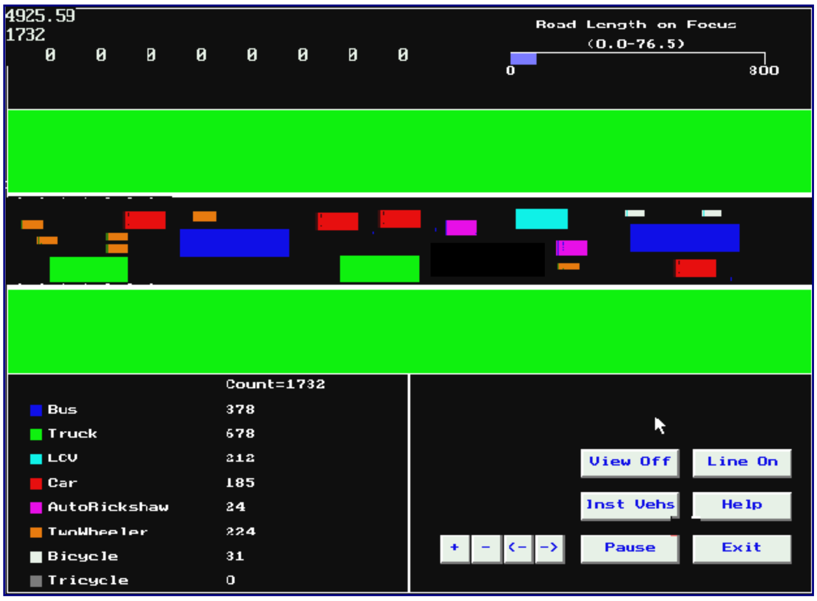

Figure 2: Snapshot of animation of simulated heterogeneous traffic flow

Vehicle Generation

In a stochastic traffic simulation process, the vehicles arrive randomly, and they may have varying characteristics (e.g., speed, vehicle type, etc.). Traffic-simulation models therefore, require randomness to be incorporated to take care of the stochiasticity. 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 value. 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.

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.

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. If possible, the fast vehicle will take the slow vehicle. If overtaking is not possible, the fast vehicle decelerates to the speed of the slow vehicle in front and follows it.

2.1 Model validation on roads with different upgrades

The simulation model, HETEROSIM (developed for non-lane based traffic conditions prevailing in India), when used for studying the effect of gradient, requires data, particularly on free-flow speeds of the different vehicle types at the start of the sections and acceleration rates of the different vehicle categories generally present on Indian intercity roads, while negotiating a particular gradient, in addition to the other relevant data pertaining to the observed roadway and traffic conditions.

2.2 Selection of study stretches

Out of the three study stretches, selected for data collection, one is on National Highway No. 4 (NH-4), near Pune, in Maharashtra (Western part of India) and its specific location is between km 31.2 and km 31.5 (length of 300 m), with 3% of gradient. The other two stretches are on Mumbai-Pune bypass road, connecting NH-4, near Pune, in Maharashtra. Their specific locations are between km 2.6 and km 3.0 (length of 400 m) with 3.78 % of gradient and between km 5.2 and km 5.9 (length of 700 m) with 5 % of gradient. The selected stretches are four lane divided roads with a total carriageway width of 8.75 m (including shoulder) for each direction of traffic flow. These study stretches were selected after conducting reconnaissance survey to satisfy the following conditions: (1) The stretch should be fairly straight and have uniform gradient for a considerable length, (2) Width of Roadway should be uniform and, (3) There should not be any direct access from the adjoining land uses on both sides. The simulation model was validated for all the upgrades, namely, 3%, 3.78%, 5%. In this paper, the validation results along with the relevant data collected, pertaining to two grades of magnitude 3.78% and 5% are presented.

2.3 Free speed on selected upgrades

In a traffic simulation model, there are two types of speeds that may be considered, these are, desired speed (free-speed) and actual speed. 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 drivers when not restricted by other vehicles in the stream under a set of given roadway and environmental conditions. The actual speed is the speed with which a vehicle moves at a given point of time in the simulation process, and this is subjected to change over time based on the traffic conditions. For the purpose of model validation, the free speed data was collected during lean traffic periods when the vehicles were freely moving without any hindrance from other vehicles present on the road. The free speed of the different categories of vehicles were measured by noting the time taken by the vehicles to travel a trap length of 30 m, on the study stretches, at the respective initial positions of the chosen sections of different grades (km 2.600 for 3.78% upgrade and km 5.500 for 5% upgrade). *Table 1* gives the details of the free speed data of various vehicle classes collected on the road stretches with magnitude of upgrade as 3.78% and 5%. The variation in the free speeds of different vehicles (mean, minimum, maximum and standard deviation values mentioned in Table 1) can be attributed to the magnitude of upgrade, make of the vehicle, loading (less loaded or heavily loaded), the age of the vehicle, level of maintenance, age, sex and the behavior of the driver. These factors fall over a wide range under Indian conditions. This variation in free speed data, for each of the vehicle categories has been represented very well using a probability distribution, named Normal distribution. This hypothesis has been proved very well in an Indian study performed by Kadiyali et. al, 198. Hence, to incorporate this random variable (free speed of a given vehicle category) into simulation process, the Box-Muller Transformation method is used to generate Normal deviates (S) using the equation,

$$S = (-2 \ln r_1)^{1/2} \cos (2\pi r_2) \tag{1}$$

where, r_1 and r_2 are two uniform random numbers, and S is a Normal random deviate. These random numbers r_1 and r_2 are sampled from two different random number streams. A sample u from any standardized Normal distribution, with specified mean (μ) and standard deviation (σ) can be obtained as,

$$u = \sigma S + \mu \tag{2}$$

This value of u is assigned as the free speed of the vehicle under consideration. However, truncated Normal distributions with extreme values as observed in the field were used for generation of free speeds in the simulation process. This enables drawing of data from Normal distribution, rejecting the values generated outside the speed range used for truncation and replacing the value by generating fresh free speed from within the range. The simulation program used for this study uses different random-number streams for the generation of vehicle arrivals, identification of vehicle type, assigning free speed, etc.

2.4 Estimation of acceleration rates

The acceleration ability of the vehicles on different upgrades will be significantly lower as compared to their acceleration ability on level roads. On level roads, different vehicles may maintain their speeds uniformly. However, on upgrades, heavy vehicles such as trucks, will experience significant reduction in their speeds, whereas, passenger cars and other smaller vehicles such as motorized-two-wheelers may experience relatively lesser speed reduction. This variation in speed reduction among the different vehicle categories on upgrades, in India under heterogeneous traffic conditions, can be attributed to their wide ranging physical characteristics such as dimensions, weight, etc. and dynamic characteristics such as engine power, acceleration rate, etc. Therefore, there is a need to estimate or calibrate the acceleration rates of different vehicle types for different grades in India. The procedure

Table 1: Free speed parameters of different types of vehicles on upgrades

Vehicle category (1)	*Free speed parameters on 3.78 % Upgrade (km/h)*				*Free speed parameters on 5 % Upgrade (km/h)*			
	Mean (2)	*Min. (3)*	*Max. (4)*	*Standard deviation (5)*	*Mean (6)*	*Min. (7)*	*Max. (8)*	*Standard deviation (9)*
Buses	52	45	74	11	44	36	70	11
Trucks	42	22	74	13	36	18	70	13
L.C.V.	54	34	74	11	47	33	70	9
Cars	72	48	100	14	67	42	96	13
M.Th.W	38	25	50	8	34	24	48	6
M.T.W	52	30	72	11	50	26	72	9

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

adopted for estimation acceleration rates for different speed ranges under traffic conditions prevailing in India, is explained in detail below.

The thrust required for the forward movement of a road vehicle is determined by the summation of forces acting on the vehicle in the longitudinal direction. The forces acting on the vehicle while negotiating an upgrade of magnitude *i* percent, are: (i) rolling resistance, (ii) air resistance, (iii) grade resistance, and (iv) inertial forces during acceleration and deceleration, as shown in *Fig. 3.*

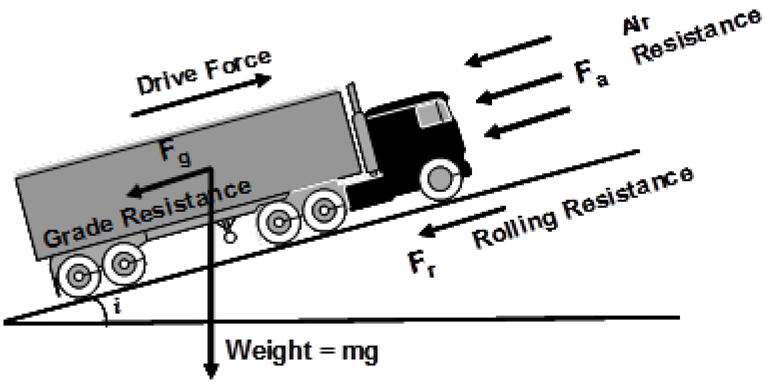

Fig. 3 Forces acting on a moving vehicle on upgrades

The governing equation for the forward movement of any vehicle, when it encounters a grade, is determined by the summation of the forces on the vehicle in the longitudinal direction. The following is the fundamental equation of motion for a vehicle (Bennett and Greenwood (2001); Highway Development and Management Manual (HDM-4)):

$$a = \frac{1000Pd}{M \times EMRAT}\frac{1}{v} - \frac{1}{M \times EMRAT}[Fa + Fr + Fg] \tag{3}$$

Where,
a is acceleration, in m/s^2;

P_d is the driving power delivered to the wheels, in kW,
M is the vehicle mass; EMRAT is effective mass ratio,
F_a is Aerodynamic drag resistance in N;
F_r is Rolling resistance in N,
F_g is Gradient resistance in N, and v is speed of the vehicle, in m/s.

The equation used for calculating aerodynamic drag resistance is as follows:

$$F_a = 0.5 * \rho * CD * CDmult * AF * v^2 \tag{4}$$

Where,
Fa is aerodynamic force opposing the motion of vehicle, in N,
ρ is mass density of air, in kg/m^3 (1.2 kg/m^3)
CD is aerodynamic drag coefficient
CDmult is aerodynamic drag coefficient multiplier
AF is projected frontal area of the vehicle in m^2 and
v is speed of the vehicle, in m/s

The values pertaining to different parameters such as CD, CDmult and AF, which are used to estimate the aerodynamic resistance, have been used separately for each of the vehicle categories considered for this case study.

The equation used for calculating rolling resistance is as follows:

$$F_r = Mfg \tag{5}$$

Where,
Fr is rolling resistance in N, M is mass of vehicle in kg, and
f is coefficient of rolling resistance.

It has been found that under traffic conditions exist in India, the value of coefficient of resistance (f) is approximately constant up to a speed of 50 km/h (Kadilyali *et al.* 1982). At higher speeds (more than 50 km/h), the values for Indian roads may be approximately calculated as,

$$f = f_o[1 + 0.01(v - 50)] \tag{6}$$

Where,
f is coefficient of rolling resistance at speed v,
v is speed in km/h, and f_o is coefficient of rolling resistance assumed constant up to a speed of 50 km/h
The equation used for calculating grade resistance is given as follows:

$$F_g = \frac{Mig}{100} \tag{7}$$

where,
Fg is gradient resistance in N,

M is mass of vehicle in kg, and
i is Magnitude of gradient in percentage.

Equation (1) indicates that the ability of a vehicle to accelerate on an upgrade is dependent on the used power-to-weight ratio, the mass and the various forces opposing the motion. Vehicles with low power-to-weight ratios such as trucks, while negotiating up grades, may decelerate to a crawl or terminal speed, where forces are in balance and the acceleration is equal to zero. This steady-state terminal speed can, thus, be obtained by solving the above equation for the velocity term. Thus, the limiting speed of a vehicle on a grade is a function of the power-to-weight ratio. Hence, the data pertaining to maximum power (kW) and gross vehicle weight (kg) of different makes for each vehicle category which exist in India was collected from different manufacturers of the country. Finally, the mean representative values of power and weight for each vehicle category were arrived at for calculating the acceleration rates at various speed ranges. The mean representative values of maximum power and gross vehicle weight, for each vehicle category considered for this case study, are given in columns (2) and (3) of Table 2 respectively. The values pertaining to the coefficient of drag (CD), CD multiplier (CDmult), and the projected frontal area in m^2 (AF), for each vehicle category, taken from the manual of Highway Development and Management (HDM-4) (Bennett and Greenwood, 2001), are given in columns (4), (5) and (6) of Table 2, respectively. The manual has provided these values for different vehicle categories exist in most of the Asian countries such as China, India, Indonesia, etc. The CD is a function of the direction of movement of vehicle relative to the wind direction. The apparent direction of the wind, which is the vector resultant of the vehicle-movement direction and the wind direction, is termed the yaw angle (Ψ). The values of CD reported in the literature are usually from wind tunnel tests conducted with a zero degree yaw (*i.e.* front on to the wind) and accordingly, are the minimum for the vehicle. Hence, to obtain typical values of CD, which would be found on roads, it is necessary to adjust for the variation in wind direction. This can be done using a "typical" wind angle which increases the zero degree-yaw CD, leading to wind averaged CD, or CD (Ψ). The ratio of CD (Ψ) divided by CD is termed the CD multiplier (CDmult). The Effective Mass RATIO (EMRAT) for each vehicle category is also calculated at various speeds as per the guidelines of HDM-4 manual. The coefficient of rolling resistance (f) is taken as 0.01 based on an Indian study (Kadiyali *et al.* 1982), for pavement surface of the study stretch is made of asphaltic concrete.

Table 2**:** Vehicular characteristics used for estimation of acceleration rates on upgrades

Vehicle Category	Gross Vehicle Weight (kg)	Max. Power (kW)	Aerodynamic Drag Coefficient (CD)	Aerodynamic Drag Coefficient Multiplier (CDmult)	Projected Frontal Area (AF) (m^2)
(1)	(2)	(3)	(4)	(5)	(6)
Buses	15200	103.00	0.55	1.22	5
Trucks	17000	104.00	0.6	1.19	5
LCV	6500	60.00	0.5	1.16	2.85
Cars	1500	47.00	0.42	1.12	1.9
M.T.W	250	6.80	0.7	1.12	0.8
M.Th.W	900	6.00	0.56	1.12	1.35

L.C.V–Light commercial vehicles, M.Th.W- Motorized Three- Wheelers, M.T.W- Motorized Two-Wheelers

For calibration of used driving power delivered to the wheels (P_d), the variable, 'power factor' introduced by Lucic (2001) is used. The calibration of the variable, 'power factor' involves finding the speed at which the vehicle power reaches its maximum. For this purpose, a terminal speed for each vehicle category, at which the vehicle power reaches its maximum, is calculated by considering acceleration, a = 0 in equation (1). Then, the ratio of vehicle speed under consideration and maximum speed at which vehicle power reaches its maximum is considered as variable power factor. The terminal speed for each of the vehicle category, which are used to calibrate the variable 'power factor' was determined separately, using respective vehicle values for the parameters required in equation (1). The used driving power (p_d), then, can be estimated by multiplying the average power value by this variable power factor. The acceleration rates for different vehicle categories existing In India, estimated over different speed ranges, which were used as the input to the simulation model, for model validation on both the grades of 3.78% and 5%, are given in *Table 3*. From the Table, peculiarly it can be seen that the acceleration rates of the vehicle types such as buses, trucks, light commercial vehicles and motorized three-wheelers, in the speed range of more than 40 km/h, are negative. The reason behind these negative values can be explained as follows. The force balance equation (1) consists of two components, namely, drive force, derived based on the engine power of the vehicle and resistances (air, rolling and grade) arising from the grade of the given magnitude. The propulsive effort (drive force) is derived from the engine (based on the power of the vehicle) to overcome these forces. Any reserve in drive force, if available, may be used either to accelerate the vehicle or to overcome the drag arising from up grades. When encountering a grade of certain magnitude, requiring thrust that is greater than the available drive force (magnitude of resistances is higher than the drive force generated from the engine of the vehicle), the deficiency is made up by deceleration of the vehicle.

Table 3: Estimated acceleration rates for different upgrades

Vehicle category	Estimated acceleration rates at various speed ranges (m/s^2) for Upgrade of Magnitude					
	3.78 %			5%		
(1)	0-20 Km/h (2)	20-40 Km/h (3)	Above 40 Km/h (4)	0-20 Km/h (5)	20-40 Km/h (6)	Above 40 Km/h (7)
Buses	0.09	0.09	- 0.10	0.08	0.05	- 0.21
Trucks	0.07	0.07	- 0.13	0.06	0.02	- 0.25
L.C.V.	0.08	0.08	- 0.02	0.07	0.06	- 0.07
Cars	0.41	0.41	0.38	0.38	0.38	0.35
M.T.W	0.75	0.64	0.38	0.70	0.60	0.35
M.Th.W	0.12	0.08	- 0.09	0.11	0.03	- 0.20

L.C.V–Light commercial vehicles, M.Th.W- Motorized Three- Wheelers, M.T.W- Motorized Two-Wheelers

2.5 Data Collection

On upgrades, the traffic flow characteristics (speed of the vehicles), will change as its length increases. So, in the case of upgrades, for the purpose of model validation, it is very important to compare the simulation-output values with the corresponding observed values at different sections of the gradient length. Therefore, it is required to collect the traffic flow data for a particular upgrade, at different intervals of the length of upgrade, selected for model validation. The required traffic data for the study were collected by video recording of the traffic flow on the selected locations. The traffic flow on identified upgrade sections in India was recorded for one hour using a video camera mounted on the surface of an adjoining elevated ground, which enabled recording of all the traffic flow characteristics continuously. The traffic flow was captured, at each of the chosen three different locations on 3.78% gradient at: km 2.600, km 2.800 and km 3.000 and four different locations on 5% gradient at: km 5.200, km 5.500, km 5.700 and km 5.900 along the grade. The video captured traffic data of the locations were then transferred to a Work Station (computer) for detailed analysis. The inputs required for the model to simulate the heterogeneous traffic flow are: road geometry, traffic volume, and composition, vehicle dimensions, minimum and maximum lateral spacing between vehicles, minimum longitudinal spacing between vehicles, free speeds of different types of vehicles, acceleration and deceleration characteristics of vehicles, the type of headway distribution and the simulation period. The required input traffic data was obtained by running the video of the traffic flow at a slower speed (⅛th of the actual speed) to enable one person to record the data by observing the details displayed on the monitor of the computer.

A total of 578 and 598 vehicles per hour were observed to pass through the section during the observation period at the respective initial positions of different gradients (km 2.600 for 3.78% and km 5.500 for 5%). The category-wise vehicle count was made conveniently by repeatedly playing the video recording in the computer. The observed traffic compositions, for the measured traffic volumes of 578 and 598 vehicles per hour, at the initial position of the study stretches (3.78% and 5%, respectively) were noted (Table 4). Similarly, using the same data extraction technique, the observed traffic volume and composition, at all other locations, for each of the grades, were also obtained. It was observed that, for each of the grades, there is no significant difference in the traffic volume and composition obtained from the traffic flows passing through various locations of a particular grade. It may be noted that the traffic compositions provided in Table 4, were used only for the purpose of model validation. These observed traffic compositions are found to be distinctly different from the traffic composition observed in the case of intercity roads (multilane roads) in developed countries. The percentage of heavy vehicles such as buses, trucks, and, light commercial vehicles on intercity roads is found to be on higher than the percentage of smaller vehicles such as cars, motorized two-wheelers and motorized three-wheelers. The vehicles, of heterogeneous traffic with widely varying physical and operational characteristics such as the one prevailing on Indian roads, as mentioned earlier occupy, any convenient lateral position on the road based on the availability of space without any lane discipline. Heavy vehicles like, trucks maintain lower speeds, as compared to cars, even at free flow conditions. Therefore, at low volume levels, the presence of heavy vehicles (trucks), with relatively low free speed, may obstruct the faster movement of the cars significantly. When the traffic volume becomes high, the magnitude of relative speed difference between motor vehicles is governed the physical dimensions (size) and the maneuvering ability of vehicles, which play a major role in determining their interactions. At this stage, all the vehicles move very close to each other resulting in frequent aacceleration and deceleration. This condition leads to relatively higher rate of reduction in the speeds of smaller vehicles like cars, due to even smaller rate of reduction in speed of heavy vehicles, like trucks. Hence, it is very interesting to study the level of interactions between the moving vehicles when the percentage of heavy vehicles is higher than the percentage of smaller vehicles, over a wide range of roadway and traffic conditions. The overall dimensions of all categories of vehicles and the minimum and maximum values of lateral-clearance share (correspond to, respectively, zero speed and free speed conditions of respective vehicles) were adopted from an earlier study by Arasan and

Koshy (2005).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. 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. The minimum and the maximum clearance-share values correspond to, respectively, zero speed and free speed conditions of respective vehicles.

Table 4: Observed traffic compositions on different upgrades

Vehicle category	Traffic composition (%) on upgrades of magnitude	
	3.78 %	5%
Buses	23	19
Trucks	33	38
L.C.V.	12	10
Cars	14	19
M.T.W	15	11
M.Th.W	3	3

L.C.V–Light commercial vehicles, M.Th.W- Motorized Three- Wheelers, M.T.W- Motorized Two-Wheelers

For the purpose of model validation, it was decided to compare the observed and simulated speeds maintained by the different categories of vehicles at regular intervals, when the vehicles negotiate a particular upgrade. The length of stretches with their grades of magnitude of 3.78% and 5% were respectively 400 m and 700 m. The total width of roadway available for one direction of movement on the divided highway, with bituminous surfacing was 8.75m for both the upgrades. For the purpose of validation, for both the grades, the simulation was run with three random number seeds, and the averages of the three runs were taken as the final output of the model. The observed roadway conditions, measured free speed parameters at the initial position (Table 1), observed traffic volume and composition (Table 4) and the acceleration rates (estimated at various speed ranges: (Table 3)) were given as input to the simulation process. The inter-arrival time (headway) of vehicles under heterogeneous traffic conditions in India, was found to fit well into negative exponential distribution and the free speeds of different categories of vehicles, based on the results of an earlier study by 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. The speeds maintained by the different categories of vehicles considered for this case study, at the selected sections on the study stretches were obtained as the simulation output.

The comparison of the observed and simulated speeds maintained by the different types of vehicles under heterogeneous traffic conditions in India, at the two selected sections on 3.78% upgrade (km 2.600 to km 2.800 (200 m) and km 2.600 to km 3.000 (400 m)), namely, sections I and II are shown in *Table 5*. Then, the comparison of the observed and simulated speeds maintained by the different types of vehicles under heterogeneous traffic conditions in India, at the three selected sections on 5% upgrade (km 5200 to km 5500(300 m), km 5200 to km 5700 (500 m) and km 5200 to km 5900 (700 m)), namely, sections I, II and III are shown in *Table 6*. From the *Tables 5 and 6*, it can be seen that the simulated speed values significantly match with the field observed speeds for all vehicle types for each of the distances of upgrades. A statistical validation of the model, based on observed and simulated speeds of different categories of vehicles on each of the upgrades (3.78% and 5%) for different lengths, was also done through paired t-test for 5 degrees of freedom at level of significance of 0.05. The calculated t-statistic values for sections I and II on 3.78% upgrade, are respectively 0.0166 and 1.27 against the table value of 2.57. The calculated t-statistic values for sections I, II and III on 5% upgrade, are respectively 1.23, 0.343 and 0.862 against the table value of 2.57. In all the cases (upgrades of magnitude 3.78% and 5%), it can be seen that the value of t statistic, calculated based on the observed data, is less than the corresponding table value. This implies that there is no significant difference between the simulated and observed mean speeds at all the sections. The validation results of the simulation model of heterogeneous traffic flow indicate that the model is capable of replicating the heterogeneous traffic flow on Indian intercity roads having upgrades of different magnitude to a highly satisfactory extent.

Table 5: Model validation by comparison of speeds on sections of 3.78% upgrade

Vehicle category (1)	Section I		Section II	
	Average Observed Speed (2)	Average Simulated Speed (3)	Average Observed Speed (4)	Average Simulated Speed (5)
Buses	48.12	47.38	45.64	45.03
Trucks	38.68	38.38	36.44	37.11
L.C.V.	51.18	53.35	49.69	52.38
Cars	70.79	69.68	68.95	68.33
M.Th.W	36.97	36.22	35.39	36.09
M.T.W	51.22	51.90	50.74	51.71

L.C.V–Light commercial vehicles, M.Th.W- Motorized Three- Wheelers, M.T.W- Motorized Two-Wheelers

Table 6: Model validation by comparison of speeds on sections of 5 % upgrade

Vehicle category (1)	Section I		Section II		Section III	
	Average Observed Speed (2)	Average Simulated Speed (3)	Average Observed Speed (4)	Average Simulated Speed (5)	Average Observed Speed (6)	Average Simulated Speed (7)
Buses	40.13	37.96	37.67	35.98	35.05	34.74
Trucks	34.37	33.22	31.38	31.87	30.05	30.52
L.C.V.	43.62	42.96	41.89	41.34	40.07	40.35
Cars	64.82	64.00	63.23	61.91	60.95	59.86
M.Th.W	33.09	33.40	32.35	33.12	31.86	33.06
M.T.W	48.78	49.85	48.16	49.45	47.49	48.93

L.C.V–Light commercial vehicles, M.Th.W- Motorized Three- Wheelers, M.T.W- Motorized Two-Wheelers

3.0 Model application

The 'HETEROSIM' model of traffic flow can be applied to study various heterogeneous traffic scenarios for varying traffic and roadway conditions in developing countries like India. In this paper, the application of the model is to develop relationship between traffic volume and speed for varying roadway conditions (four-lane divided roadways with upgrades having magnitude varying from 2% to 6%) and then to quantify the relative impact of the presence of each of the different types of vehicles on traffic flow by estimating the PCU values under heterogeneous traffic conditions in India, for different categories of vehicles.

3.1 Development of speed-flow relationships

Since the research work reported here is aimed at studying the effect of upgrade on PCU value of different vehicle categories under heterogeneous traffic for a set of traffic volume levels falling over a wide range, a four-lane divided roads with 8.75 m of road space (main roadway plus shoulder) available for each direction of movement with magnitude of upgrades of 2%, 3%, 4%, 5% and 6% were considered for the model application. For this purpose, a mean representative traffic composition (*Fig. 4*) was considered for simulating traffic flow on different upgrades. This mean traffic composition has been considered for the purpose of model application, calculated using traffic compositions observed on the identified stretches of upgrades of magnitude 3.78 and 5% (Table 4).

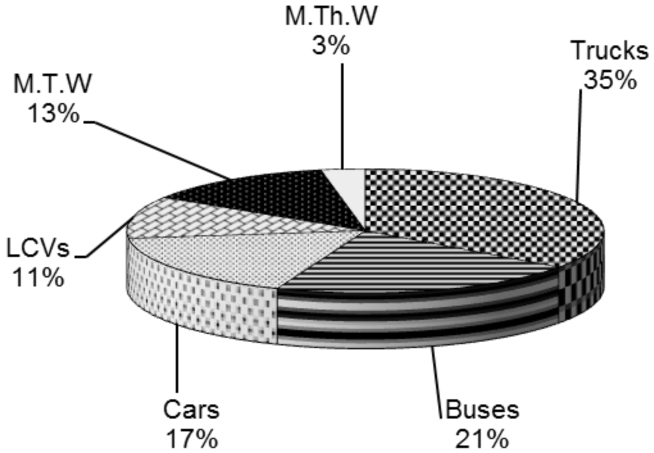

Figure 4: Representative traffic composition for model application
L.C.V. - Light Commercial Vehicles, M.Th.W. – Motorized Three-Wheelers, M.T.W. - Motorized Two-Wheelers

The input data on free speeds at the initial position, required for simulating the traffic flow on grades, was collected on a stretch between km 77.2 and km 77.4, of National Highway No. 45 near Chennai (Southern part of India), which is a four-lane divided road (total width for one direction: 8.75 m). 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. The field observed free speed data is given in *Table 7*. By giving free speeds (observed on 8.75 m wide level road), as input at the entry position of road stretch considered for simulating traffic flow on upgrades, it was possible to model the movement of vehicles approaching an upgrade of given magnitude from level roads. The acceleration rates, over different speed ranges, required for simulation of heterogeneous traffic flow on grades, were estimated for different upgrades of magnitude varying from 2% to 6%, using equation (1), as explained earlier. The length of observation stretch (used for noting outputs) for simulation was considered as 1600 m. Giving the other relevant data as input, for the traffic flow on the roadway and traffic conditions pertaining to the different upgrades were 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 volume reaches the capacity level, the increments in the input traffic volumes may not result in the same amount of increase in the exit volume resulting 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 roadway has reached its capacity. The plots made relating the speed and the flow, for all the upgrades (2% to 6%), on the same set of axes, is shown in *Fig. 5*.

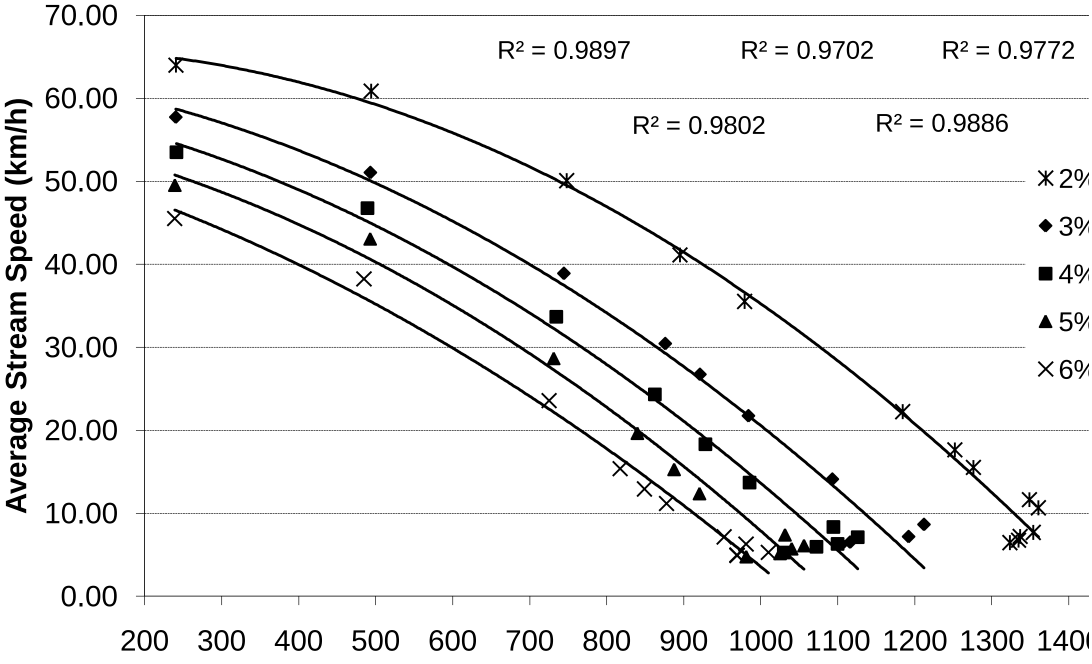

Figure 5: Speed–volume relationships on different upgrades

It can be seen that the developed speed-flow relationships follow the well established trend, indicating the validity of the model to simulate heterogeneous traffic flow on different upgrades of magnitudes varying from 2% to 6%. The capacity values of 8.75 m wide roads, having upgrades of magnitude 2%, 3%, 4%, 5% and 6%, for a length of 1600 m, under heterogeneous traffic for the traffic composition (*Fig. 4*) considered, are found to be 1360, 1210, 1120, 1050 and 1010 vehicles/h, respectively.

Table 7: Free speeds of different vehicle types on 8.75m wide level road

Vehicle type	Free speed parameters in km/h			
	Mean	Max.	Min.	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

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

It may be noted that the speed-volume relationships for the homogeneous traffic flow in developed countries like USA (HCM, 2000), Germany, etc. are generally flat up to certain volume level, beyond which speed drops down below free-flow speed as the curve goes towards capacity. Whereas, in the case of heterogeneous traffic conditions in India, speeds of different vehicle categories and hence the traffic stream speed drops down quickly whenever there is increase in traffic volume, as shown in Figure 5 . This is because of increasing level of interaction among different vehicle categories with increase in volume level. It may be noted in this regard that, homogeneous traffic has strict lane discipline and has traffic entity types whose characteristics do not vary much. On the contrary, heterogeneous traffic comprises of vehicles with wide ranging static and dynamic characteristics such as vehicle size, engine power, acceleration/deceleration, maneuvering capabilities, etc. Due to the highly varying physical dimensions and speeds, the vehicles do not follow traffic lane, and occupy any lateral position based on the space availability, on the whole of the road space available for the vehicular movement. Therefore, level of interaction among the vehicles in heterogeneous traffic may be relatively more even under free-flow conditions. Hence, the speed-volume relationships are entirely different under homogeneous and heterogeneous traffic conditions.

3.2 Speed-distance profile for different vehicle categories on upgrades

The speed-distance relationship can be developed by simulating heterogeneous traffic flow on the chosen roadway with a specified gradient and noting down the change in speed of vehicles at regular intervals over space, while the vehicles negotiate the upgrade. For the purpose of simulation, the volume level corresponding to Volume-to-capacity (V/C) ratio value of 0.5 (normally used as design service volume in India with respect to level of service B) was considered for developing speed-distance curves for different vehicle categories along different grades. The free speed values for different vehicle categories, traffic composition (as shown in figure 4) and the estimated acceleration rates for the different vehicle categories at different speed ranges, were given as input to the simulation model for simulating the traffic flow along the different grades ranging from 2% to 6% considered for this study under heterogeneous traffic conditions in India. The total length of road stretch, for simulation purpose, was taken as 3,400 m. The middle 3000 m length of the simulation stretch was used to collect the data of the simulated average speed for each vehicle category at every 200 m interval. 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 speed-distance relationships were thus developed, for different vehicle categories, for each of the different grades. The relationships thus, obtained, in respect of buses and cars are depicted in *Fig. 6 and 7*, respectively, as examples. From the Figures, it can be noted that vehicle performance (speed reduction) pertaining to the different grades, is different across different vehicle categories. In the case of heavy vehicles such as buses, having lower power-to-weight ratio, there is significant reduction in speed, whereas, for other smaller vehicles such as cars, having higher power-to-weight ratio, there is relatively lesser speed reduction. It can also be noted that for buses, there is a significant speed reduction, on all the upgrades, up to a distance of 1600 m, beyond which the speed-distance curve is relatively flatter indicating that there is no significant speed reduction beyond that point. This was also confirmed using statistical paired-t test, at 5% level of significance. In the case of heterogeneous traffic conditions in India, speeds of heavy vehicle categories were found to be decreasing sharply with increase in magnitude of upgrade and its length, as shown in Figure 6. Therefore, it may be concluded, that the rate of speed reduction for the vehicles on upgrades can vary based on the type of vehicle and is a function of power-to-weight ratio of the vehicle type. This can also be attributed to the increasing level of interaction among different vehicle categories with increase in length of upgrade and its magnitude.

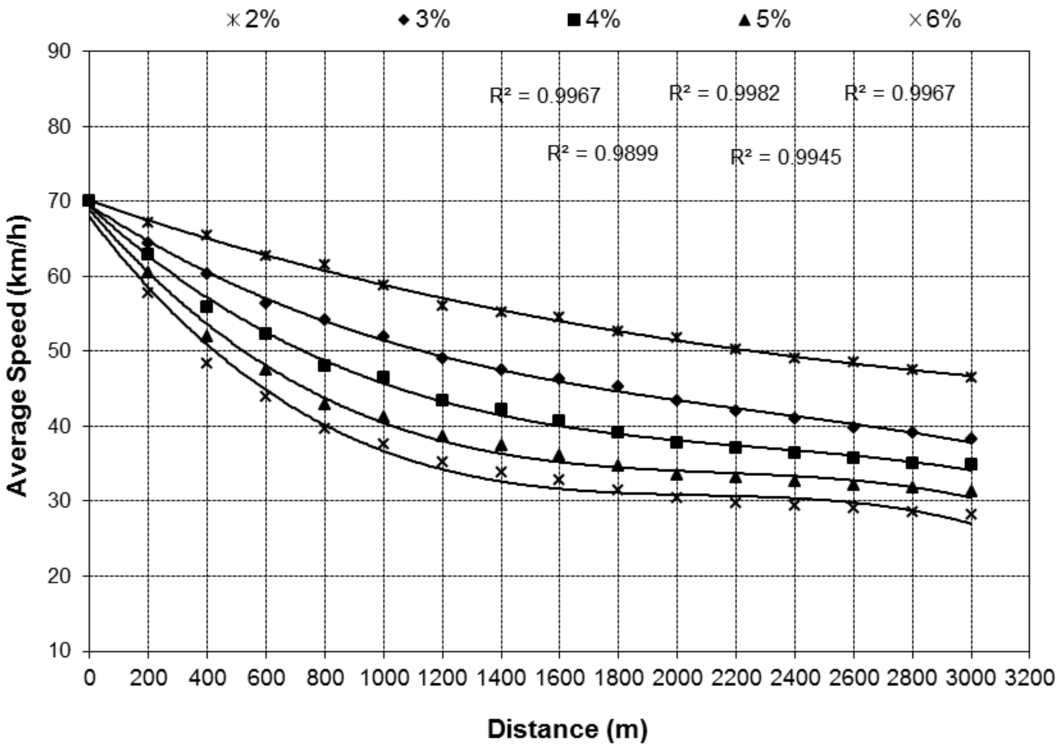

Figure 6: Speed-distance profile for buses on different upgrades

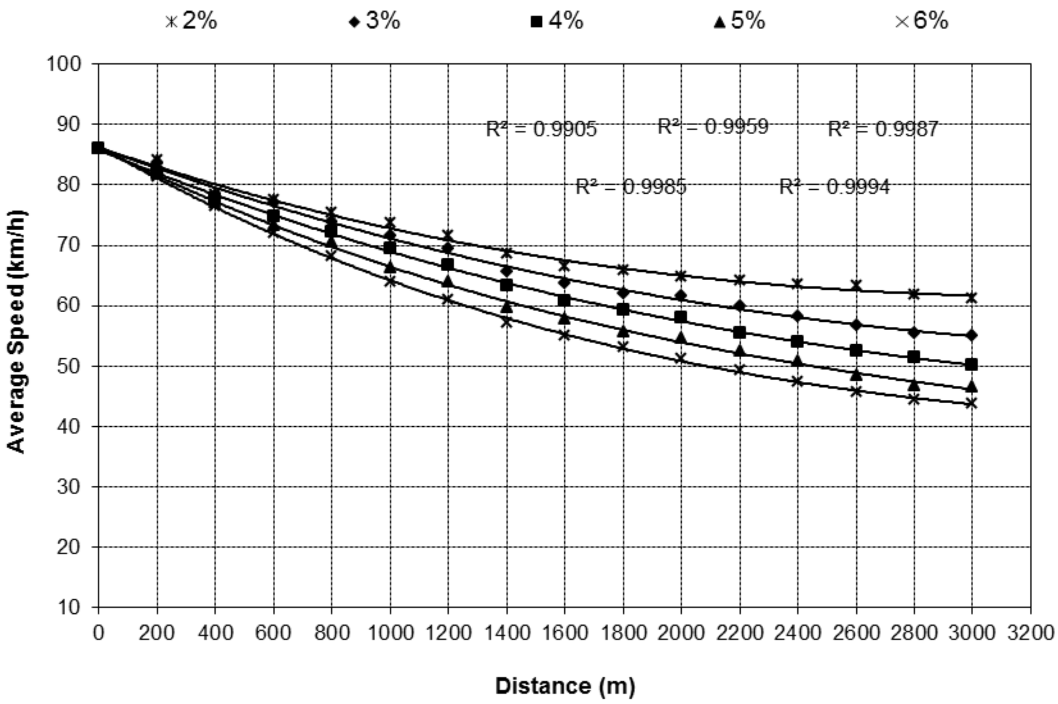

Figure 7: Speed-distance profile for cars on different upgrades

3.3 Estimation of PCU values

As one of the objectives of this research work is to study the effect of magnitude of upgrade and its length on PCU values of vehicles, the PCU values of the different categories of vehicles were estimated, by simulating traffic flow on different upgrades, varying from 2% to 6%, over different lengths, at intervals of 400 m, namely, 0 to 400 m, 400 to 800 m, 800 to 1200m, and 1200 to 1600 m (based on the guidelines given in HCM 2000, USA). The length of 1600 m, along the different upgrades, was fixed as the limiting value based on the finding that there is no significant change in the speed of vehicles (while negotiating upgrades) beyond 1600 m (*Fig. 6 and 7* depict the fact for buses and cars, respectively). Under heterogeneous traffic conditions prevailing in developing countries like India, quantification of change in vehicular interactions, over a wide range of roadway and traffic conditions, can be done better by taking speed as the measure of performance, since it may reflect the combination of factors contributing to the overall influence of the subject-vehicle type on the performance of the traffic stream. The simulation logic of the heterogeneous traffic-flow model (HETEROSIM), used for the study in India, accounts for the dimensions of vehicles, their free speeds, acceleration characteristics, vehicle-specific gap requirements in a heterogeneous traffic stream (longitudinal and transverse directions), etc. Hence, taking average speed of traffic stream as measure of performance, for finding the equivalent number of subject-vehicle type (for which PCU value is to be estimated), which would create the same impact on the heterogeneous traffic stream as that of the specified number of reference vehicle category (passenger cars), is a satisfactory basis for estimating the PCU value of a given vehicle type, interacting under the given traffic conditions in India.

The PCU has been defined by Transport and Road Research Laboratory (TRRL), London, UK in 1965 as follows: "*on any particular section of road under particular traffic conditions, 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, for the different types of vehicles, 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.

The method adopted for estimation of PCU values involves the following steps: (i) For the purpose, five traffic volume levels, corresponding to volume to capacity ratios of 0.30, 0.50, 0.60, 0.80 and 1.0 were considered. While simulating heterogeneous traffic flow corresponding to the V/C ratios, in each case, a certain percentage of cars was replaced by the subject vehicle type (for which the PCU value is to be estimated) in the heterogeneous traffic stream, such that the average stream speed, obtained by simulation, before and after replacement, remained the same. (ii) 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. To account for the variation due to randomness, the simulation runs with three random number seeds were found sufficient to get consistent PCU values and the average of the three values was taken as the final value. 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. For the purpose of estimating PCU values on upgrades, traffic of the same composition *(Fig. 4)* on roadway width of 8.75 m (equivalent to the width of road space for one direction of movement on four-lane divided roadway of intercity road) was considered. The PCU value of the subject-vehicles were determined, following the said procedure, for upgrades varying from 2% to 6%, for a set of traffic volume levels, corresponding to volume-to-capacity ratios of 0.30, 0.50, 0.60, 0.80, and 1.0. Since the capacity of a roadway section varies with magnitude of upgrade, the PCU values on these roads need to be compared based on some common traffic flow criterion. For this purpose, volume-to-capacity ratio (V/C ratio) was selected as the traffic flow criterion common to different upgrades. Though, it was observed that the average speed reduction for the vehicles beyond 1600 m along the upgrade, is relatively less, it was decided to additionally check for the change in PCU value also by simulating traffic flow beyond 1600 m. It was found that for all the vehicle categories, on all the upgrades, the change in PCU value beyond 1600 m is not significant. Hence, it was decided to have single estimate of PCU value, when the length of upgrade is more than 1600 m.

The variation of PCU values of heavy vehicles such as buses, trucks, light commercial vehicles and smaller vehicles such as motorized two-wheelers and motorized three-wheelers, for upgrades of 3%, 4% and 5% at selected road lengths of 0 to 400 m, 400 to 800 m, 800 to 1200 m, 1200 to 1600 m, and more than 1600 m, over traffic volume, obtained through simulation, are presented here as examples, in *Tables 8 and 9*, respectively. The magnitude of PCU values of heavy vehicles such as buses, trucks, and light commercial vehicles is found to be higher than the magnitude of the PCU value given by Highway capacity manual of USA (HCM, 2000). This may be attributed to the heterogeneous traffic nature and diverse static and dynamic characteristics of vehicles present in India. It can be seen from *Table 8*, that for a given magnitude of upgrade and its length, at low volume levels, in the case of vehicles that are larger in size than car such as buses, trucks and light commercial vehicles, the PCU value decreases with increase in traffic volume (value of V/C ratio) and at high volume levels (When V/C ratio is 0.6 and more), the PCU increases with the increase in traffic volume. Whereas, in the case of vehicles that are smaller than cars such as motorized three-wheelers and motorized two-wheelers *(Table 9)*, for a given magnitude of upgrade and its length, at low volume levels, the PCU value increases with increase in traffic volume and at high volume levels (When V/C ratio is 0.6 and more), the PCU decreases with increase in traffic volume. It was also found that, for all the vehicle categories, at all the chosen V/C ratios and given length, the PCU value (level of interaction among the vehicles) increases with increase in magnitude of upgrade from (3% to 5%). It was also found that the PCU value of all the vehicle categories, on all the upgrades, at any V/C ratio, increases with increase in its length. From *Tables 8 and 9*, it can be noted that the increase in PCU value (level of interaction among the vehicles) is relatively more in case of heavy vehicles such as trucks, buses and light commercial vehicles, whereas, the increase in PCU value is small for smaller vehicles like motorized two-wheelers and three-wheelers. This may be attributed to the inferior performance of heavy vehicles on grades in comparison with the smaller vehicles.

The variation of the PCU value of buses and motorized three-wheelers, on upgrades of magnitude 3%, 4% and 5%, for the stretch from 1200 to 1600 m, as examples, has been depicted in *Fig. 8 and 9*, respectively. Also, the variation of the PCU value of buses and motorized three-wheelers, on upgrades of magnitude 4% over different grade lengths, as examples, have been depicted in *Fig. 10 and 11*, respectively.

Table 8: Variation of PCU value of heavy vehicles over volume and road length for different upgrades of magnitude 3%, 4% and 5%

Description of Road Stretch (Length m)	V/C ratio = 0.30								
	PCU value of Buses			PCU value of Trucks			PCU Value of LCV		
	3%	4%	5%	3%	4%	5%	3%	4%	5%
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
0-400	4.12	4.33	4.49	4.32	4.48	4.61	2.71	2.89	3.00
400-800	4.50	4.70	4.80	4.66	4.79	4.95	2.92	3.12	3.22
800-1200	4.78	4.92	5.02	5.06	5.19	5.36	3.19	3.31	3.41
1200-1600	5.06	5.24	5.33	5.46	5.63	5.71	3.45	3.54	3.61
> 1600	5.23	5.39	5.50	5.67	5.82	5.92	3.61	3.71	3.78
Grade Length (m)	V/C ratio = 0.50								
	3%	4%	5%	3%	4%	5%	3%	4%	5%
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
0-400	3.49	3.75	3.95	3.80	3.95	4.17	2.30	2.55	2.75
400-800	3.79	4.05	4.25	4.12	4.26	4.49	2.52	2.76	2.93
800-1200	4.15	4.38	4.58	4.49	4.61	4.82	2.73	2.92	3.09
1200-1600	4.50	4.65	4.87	4.75	4.89	5.11	2.95	3.15	3.27
> 1600	4.66	4.82	5.02	4.95	5.05	5.29	3.08	3.3	3.41
Grade Length (m)	V/C ratio = 0.60								
	3%	4%	5%	3%	4%	5%	3%	4%	5%
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
0-400	3.41	3.67	3.85	3.74	3.87	4.05	2.25	2.45	2.65
400-800	3.71	3.95	4.15	4.02	4.18	4.40	2.45	2.65	2.81
800-1200	4.09	4.31	4.43	4.38	4.58	4.71	2.68	2.88	3.00
1200-1600	4.41	4.59	4.75	4.70	4.87	5.05	2.91	3.05	3.18
> 1600	4.59	4.73	4.90	4.89	5.01	5.19	3.04	3.14	3.32
Grade Length (m)	V/C ratio = 0.80								
	3%	4%	5%	3%	4%	5%	3%	4%	5%
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
0-400	3.97	4.15	4.29	4.15	4.30	4.42	2.55	2.73	2.86
400-800	4.31	4.45	4.58	4.45	4.61	4.71	2.80	2.95	3.02
800-1200	4.55	4.72	4.88	4.85	4.99	5.12	2.97	3.12	3.21
1200-1600	4.80	4.95	5.11	5.11	5.25	5.49	3.18	3.35	3.42
> 1600	4.89	5.06	5.23	5.22	5.34	5.61	3.27	3.43	3.52
Grade Length (m)	V/C ratio = 1.0								
	3%	4%	5%	3%	4%	5%	3%	4%	5%
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
0-400	4.22	4.52	4.88	4.40	4.65	4.95	2.80	3.11	3.28
400-800	4.60	4.89	5.26	4.75	5.05	5.35	3.05	3.33	3.48
800-1200	4.90	5.30	5.65	5.20	5.45	5.71	3.31	3.55	3.73
1200-1600	5.40	5.70	6.05	5.65	5.85	6.28	3.55	3.80	4.00
> 1600	5.49	5.79	6.14	5.75	5.94	6.37	3.63	3.87	4.08

Table 9**:** Variation of PCU value of smaller vehicles over volume and road length for different upgrades of magnitude 3%, 4% and 5%

Description of Road Stretch (Length m) (1)	V/C ratio = 0.30					
	PCU value of Motorized Three-Wheelers			PCU value of Motorized Two-Wheelers		
	3% (2)	4% (3)	5% (4)	3% (5)	4% (6)	5% (7)
0-400	1.02	1.05	1.07	0.56	0.63	0.68
400-800	1.08	1.12	1.14	0.64	0.70	0.75
800-1200	1.16	1.21	1.24	0.72	0.77	0.81
1200-1600	1.24	1.27	1.30	0.81	0.84	0.88
> 1600	1.29	1.31	1.35	0.86	0.88	0.92
Grade Length (m) (1)	V/C ratio = 0.50					
	3% (2)	4% (3)	5% (4)	3% (5)	4% (6)	5% (7)
0-400	1.22	1.29	1.33	0.63	0.69	0.74
400-800	1.32	1.37	1.40	0.70	0.76	0.81
800-1200	1.41	1.47	1.50	0.79	0.84	0.88
1200-1600	1.49	1.55	1.57	0.87	0.91	0.95
> 1600	1.54	1.59	1.61	0.91	0.94	0.97
Grade Length (m) (1)	V/C ratio = 0.60					
	3% (2)	4% (3)	5% (4)	3% (5)	4% (6)	5% (7)
0-400	1.30	1.35	1.40	0.65	0.71	0.75
400-800	1.39	1.45	1.48	0.72	0.78	0.82
800-1200	1.49	1.55	1.58	0.81	0.86	0.90
1200-1600	1.56	1.61	1.65	0.89	0.93	0.96
> 1600	1.61	1.65	1.69	0.93	0.96	0.98
Grade Length (m) (1)	V/C ratio = 0.80					
	3% (2)	4% (3)	5% (4)	3% (5)	4% (6)	5% (7)
0-400	1.26	1.30	1.35	0.63	0.67	0.73
400-800	1.35	1.39	1.43	0.70	0.74	0.79
800-1200	1.43	1.47	1.51	0.78	0.83	0.87
1200-1600	1.51	1.55	1.58	0.86	0.90	0.94
> 1600	1.55	1.58	1.61	0.91	0.94	0.96
Grade Length (m) (1)	V/C ratio = 1.0					
	3% (2)	4% (3)	5% (4)	3% (5)	4% (6)	5% (7)
0-400	1.15	1.20	1.24	0.59	0.63	0.68
400-800	1.22	1.27	1.31	0.65	0.69	0.75
800-1200	1.32	1.36	1.39	0.75	0.79	0.83
1200-1600	1.39	1.44	1.46	0.82	0.85	0.89
> 1600	1.43	1.47	1.49	0.86	0.88	0.92

In all the cases, the attempt to find the possible reason for the trend of variation of PCU value over volume (V/C ratio), magnitude of gradient and its length, revealed that the relative changes in the speeds of the reference vehicle (car) and the subject vehicle (such as buses, motorized three-wheelers) because of varying levels of interactions, at various traffic volume levels are the main contributors to the trend. The change in speed difference under heterogeneous traffic conditions, 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 for the successive V/C ratios, for a given magnitude of upgrade and its length. The trends of the change in speed difference between cars and buses and also cars and motorized three-wheelers, for upgrades of magnitude starting from 3% to 5%, for the stretch from 1200 to 1600 m, as examples, are shown in *Fig. 12 and 13*, respectively. It can be seen that in both the cases, the trend lines pertaining to the variation of speed difference over volume (V/C ratio) exhibit the same pattern as in the case of variation of PCU for buses and motorized three-wheelers *(Fig. 8 and 9)* . Moreover, it can be noted that at all the volume-to-capacity (V/C ratios) levels, the difference in percentage change, at a given length, increases with increase in magnitude of upgrade. Hence, it is clear that the increase in speed difference between cars and other categories of vehicles, with increase in magnitude of upgrade, has resulted in higher PCU values with increase in the magnitude of upgrade. The trends of the change in speed difference between cars and buses and cars and motorized three-wheelers, for the upgrades of magnitude 4%, over different lengths, are shown, as examples, in *Fig. 14 and 15*. It can be seen that in both the cases, the trend lines pertaining to the variation of speed difference over volume (V/C ratio) exhibit the same pattern as in the case of variation of PCU for buses and motorized three-wheelers *(*see *Fig. 10 and 11)* . It can also be noted (see *Fig. 14 and 15)* that at all the volume-to-capacity (V/C ratio) levels, at a given upgrade (4%), the difference in percentage speed change between cars and the subject vehicle categories (buses and motorized three-wheelers) is found to be increasing with increase in length of upgrade. Hence, it is clear that the increase in speed difference between cars and other categories of vehicles with increase in length of upgrade has resulted in increased PCU values.

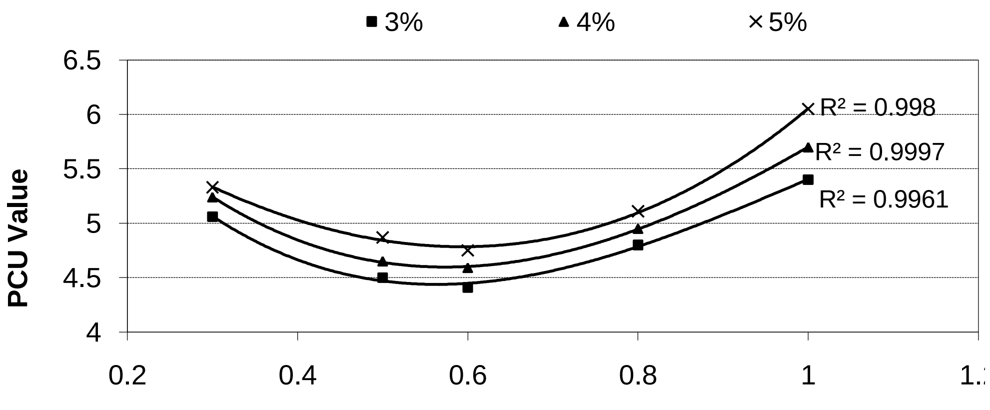

Figure 8: Comparison of PCU values of buses on upgrades of magnitude 3%, 4% and 5% for road stretch from 1200 to 1600 m

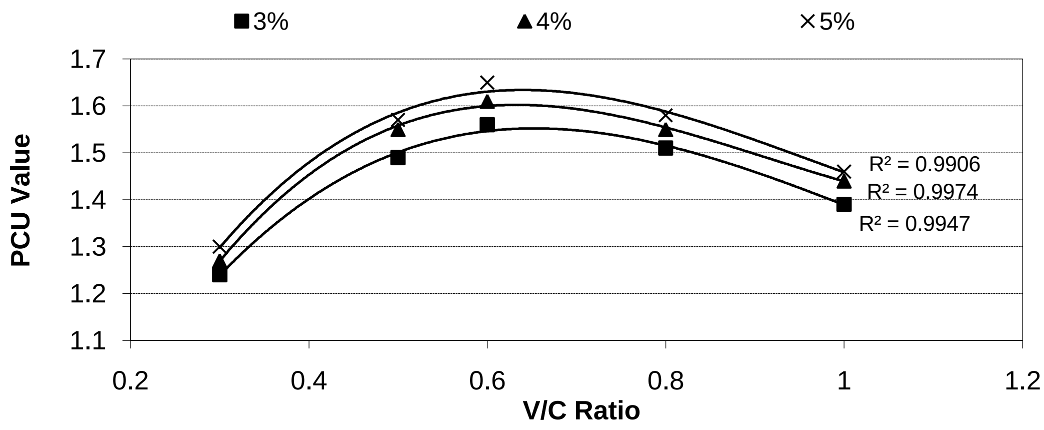

Figure 9: Comparison of PCU values of motorized three-wheelers on upgrades of magnitude 3%, 4% and 5% for road stretch from 1200 to 1600 m

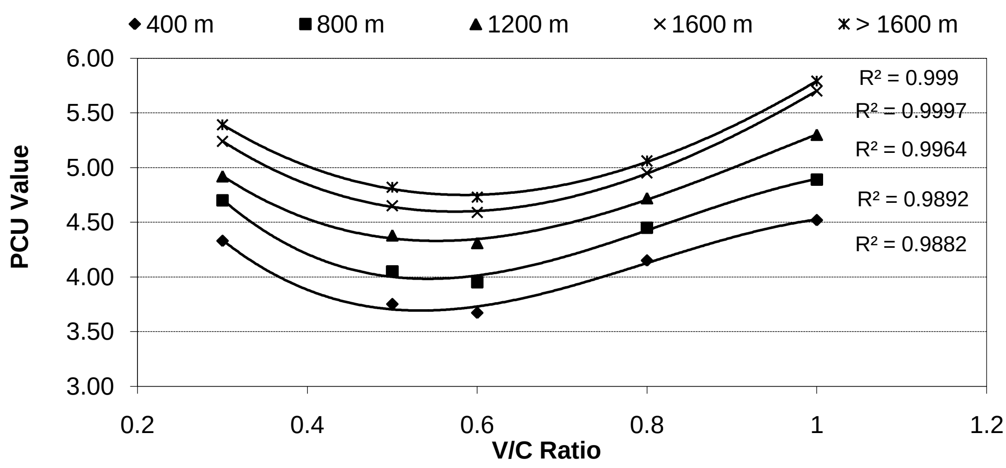

Figure 10: Comparison of PCU values of buses, along different lengths of upgrade of magnitude 4 %

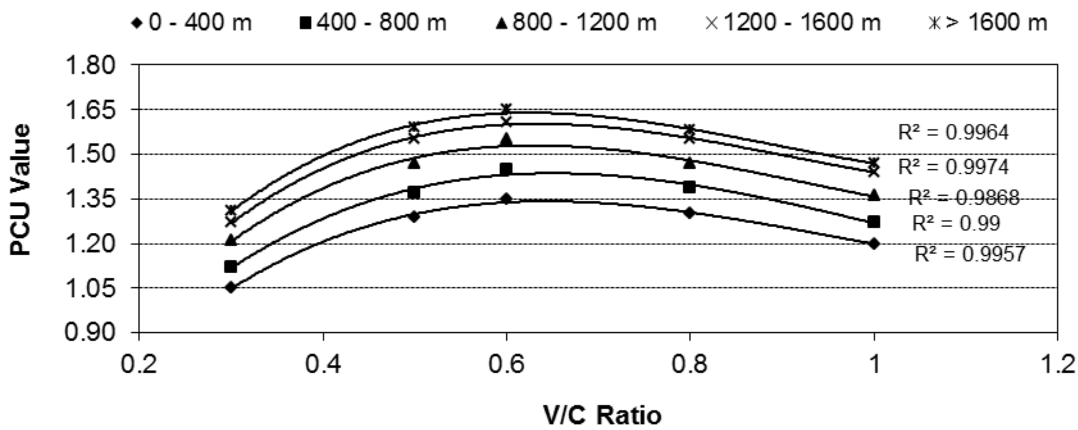

Figure 11: Comparison of PCU values of motorized three-wheelers, along different lengths of upgrade of magnitude 4 %

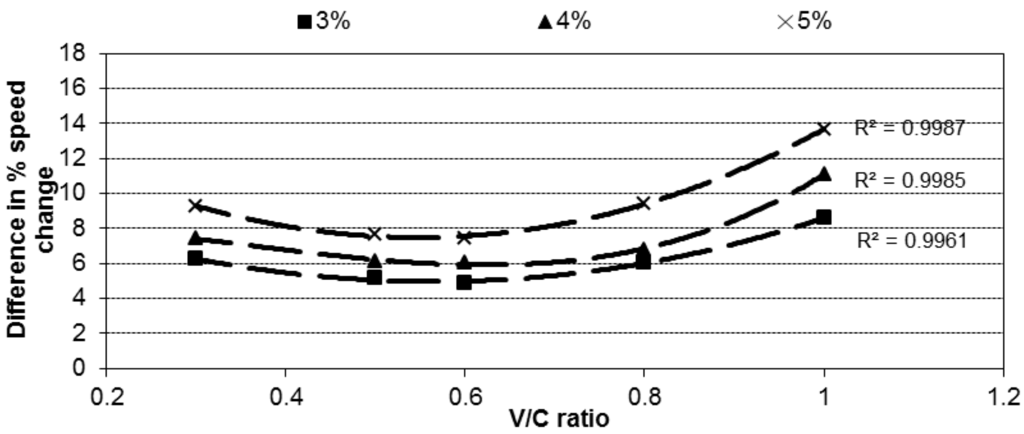

Figure 12: Comparison of difference in speed change between cars and buses on different upgrades for road stretch from 1200 to 1600 m

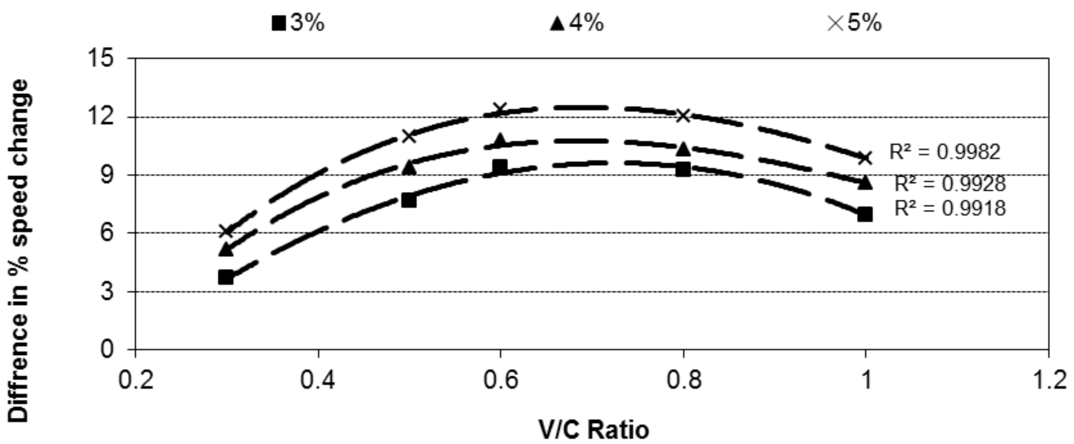

Figure 13: Comparison of difference in speed change between cars and motorized three-wheelers on different upgrades for road stretch from 1200 to 1600 m

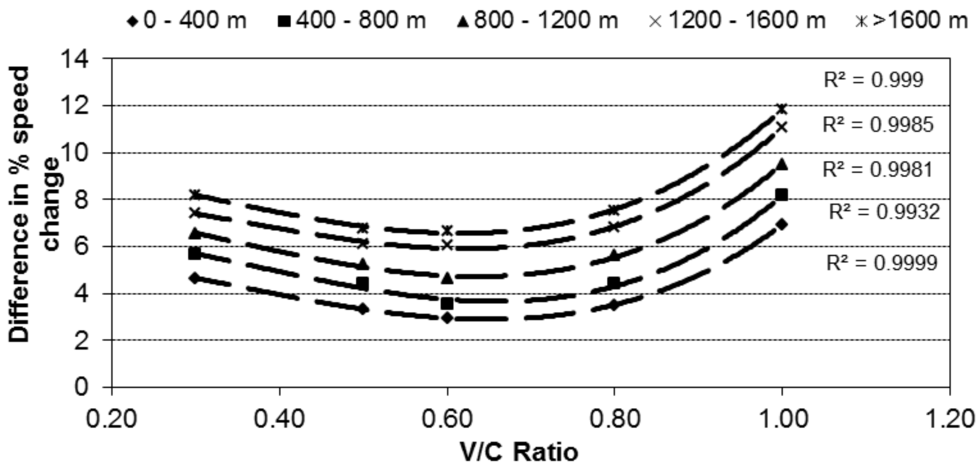

Figure 14: Comparison of difference in speed change between cars and buses, along different lengths of upgrade of magnitude 4 %

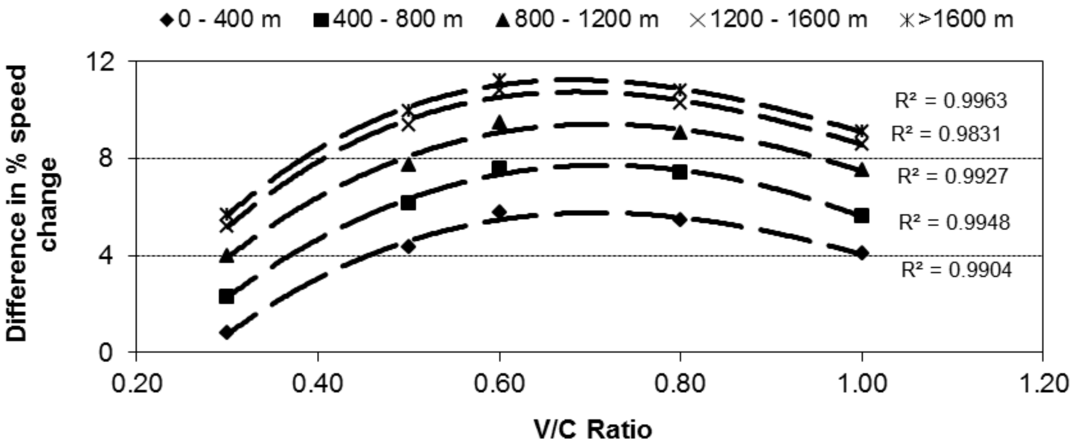

Figure 15: Comparison of difference in speed change between cars and motorized three-wheelers, along different lengths of upgrade of magnitude 4 %

3.4 Check for accuracy of estimated PCU values

For the purpose of checking for the accuracy of the PCU estimates for the different categories of vehicles on roads having grades of different magnitudes, first, the heterogeneous traffic flow of the same representative traffic composition *(Fig. 4)* was simulated for one hour period, for upgrades of magnitude varying from 3% to 5%, over different lengths (0- 400 m, 400 - 800 m, 800 -1200 m, 1200 -1600 m and more than 1600 m) 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 *(Tables 8 and 9)*. The products, thus obtained, were summed up to get the total traffic flow in PCU/h (equivalent traffic flow under heterogeneous traffic conditions in India), for each of the upgrades over different lengths. Then, the flows for cars-only traffic condition were obtained through simulation, for the same set of V/C ratio values (taking the capacity value from the speed-flow curve developed corresponding to cars-only traffic on each of the upgrades). Thus, the traffic volume, in terms of number of cars, was obtained for the set of selected V/C ratios for different upgrades. The comparison of the two traffic flows, in terms of PCU and passenger cars, was done for each of the upgrades in two ways: (i) over a range of V/C ratios at a given length of upgrade of certain magnitude and (ii) over different lengths of upgrade of certain magnitude for a given V/C ratio. A comparison of the two traffic flows, in terms of PCU and passenger cars, for a range of V/C ratios, on a stretch from 1200 to 1600 m, on upgrade of magnitude 4%, as example, is shown in *Fig.16*. Also, comparison of traffic flows in terms of PCU and passenger cars, for V/C ratio of 0.5, for different stretches on upgrades of 4%, as example, is shown in *Fig. 17*. It can be seen that, in both the cases, the two values match with one another to a satisfactory extent. Paired t-tests, based on the passenger cars equivalent (PCU/h) and passenger cars-only (cars/h) traffic volumes, for each of the upgrades (3% to 5%), were also done and it was found that there were no significant differences between the traffic volumes measured in terms of passenger cars and in PCU for 5% level of significance.

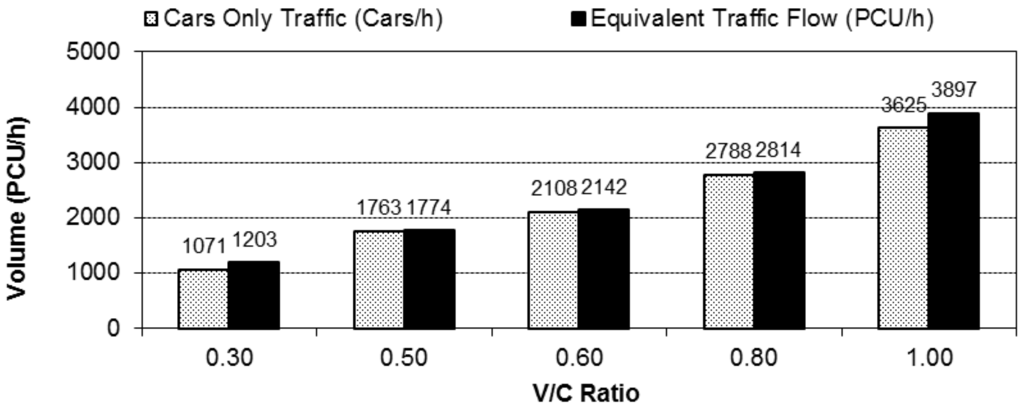

Figure 16: Comparison of heterogeneous traffic and cars-only traffic flows on 4% upgrade over different v/c ratios at grade length of 1200-1600 m

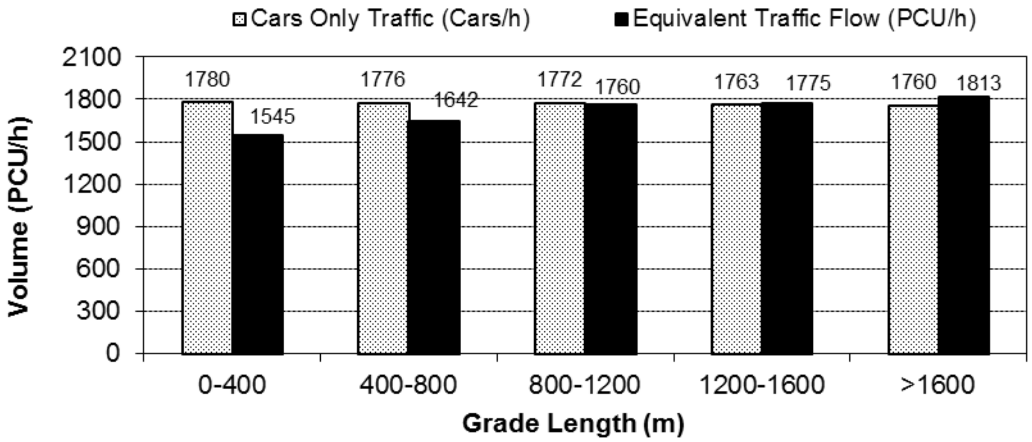

Figure 17: Comparison of heterogeneous traffic and cars-only traffic flows on 4% upgrade over different lengths at V/C ratio of 0.50.

4.0 Conclusions

In order to estimate the traffic volume or capacity of roadway sections under heterogeneous traffic conditions, it is required to quantify the interaction between the moving vehicles over a wide range of roadway and traffic conditions. The interaction between the vehicles can be represented in terms of the amount of impedance caused to flow of traffic by a vehicle type in comparison with that of passenger cars (reference vehicle). The relative impedance can be quantified in terms of Passenger Car Units (PCU). The Passenger Car Unit (PCU) or Passenger Car Equivalent (PCE) is the universally adopted unit of measure for traffic volume or capacity. Thus, the traffic flow with any vehicular composition can be expressed in its equivalent Passenger Car Units. Under heterogeneous traffic conditions prevailing in developing countries like India, due to the highly varying physical dimensions and speeds of the vehicles, it becomes difficult to enforce lane discipline. Consequently, for maneuver, the vehicles tend to take any lateral position along the width of roadway, based on the space availability. When such different types of vehicles with varying static and dynamic characteristics are allowed to mix and move on the same roadway facility, a variable set of longitudinal and transverse distribution of vehicles may be noticed from time to time. Under the said traffic conditions, quantification of change in vehicular interactions, over a wide range of roadway and traffic conditions, can be done better by taking speed as the measure of performance, since it reflects the combination of the factors contributing to the overall influence of the type of vehicle on the performance of the traffic stream. Speed is a performance measure which is accurately measurable and directly experienced by all users of a highway.

The Simulation model of the heterogeneous traffic-flow, named, HETEROSIM, used for the study, accounts for the dimensions of vehicles, their free speeds, acceleration characteristics, space gap requirements (longitudinal and transverse), etc. Hence, taking average speed of traffic stream as measure of performance, for finding the equivalent number of subject vehicle type (for which PCU value is to be estimated), which would create the same impact on the traffic stream as that of the specified number of reference vehicle category (passenger cars), is a satisfactory basis for estimating the PCU value of a vehicle type, under heterogeneous traffic conditions. The following are the important conclusions of this study:

1. The validation results of the simulation model of heterogeneous traffic flow indicate that the model is capable of replicating the heterogeneous traffic flow on intercity roads having upgrades of different magnitude to a highly satisfactory extent.
2. Expressing traffic volume as number of vehicles passing a given section of road or traffic lane per unit time will be inappropriate when several types of vehicles with widely varying static and dynamic characteristics are comprised in the traffic. The problem of measuring volume of such heterogeneous traffic has been addressed by converting the different types of vehicles into equivalent passenger cars using dynamic PCU values, estimated through this study and expressing the volume in terms of Passenger Car Unit (PCU) per hour.
3. From the speed-volume curves, developed using the simulation model, it is found that, for the representative traffic composition, the capacities of four-lane divided 8.75 m wide roads having upgrades of magnitudes 3%, 4%, and 5%, for one direction of traffic flow, for a grade length of 1600 m, are about 4100 PCU/h, 3900 PCU/h and 3700 PCU/h, respectively.
4. It is found that, under heterogeneous traffic conditions, for a given roadway condition and traffic composition, the PCU value of vehicles (interaction level among vehicles) vary significantly with change in traffic volume. Hence, it is desirable, to treat PCU as dynamic quantity.
5. The trend of variation of the PCU value, over traffic volume, under heterogeneous traffic conditions in India, 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.
6. It was found that the rate of speed reduction for the vehicles, on upgrades, will vary based on the type of vehicle and it is a function of power-to-weight ratio. In the case of heterogeneous traffic conditions in India, speeds of heavy vehicle categories were found to be decreasing sharply with increase in magnitude of upgrade and its length. This can also be attributed to the increasing level of interaction among different vehicle categories with increase in length of upgrade and its magnitude. Based on the simulation experiments conducted for developing speed-distance profiles for each of the vehicle types under heterogeneous traffic conditions in India, it was found that the effect of grade on the vehicle performance (speed reduction) may not be significant beyond a length of 1600 m.

7. The results of the simulation experiments conducted to study the effect of magnitude of upgrade and its length on PCU values indicate that for any vehicle type, in heterogeneous traffic, the PCU value increases significantly with increase in the magnitude of grade as well as its length. The magnitude of PCU values of heavy vehicles such as buses, trucks, and light commercial vehicles is found to be higher than the magnitude of the PCU value given by Highway capacity manual of USA (HCM, 2000). This may be attributed to the heterogeneous traffic nature and diverse static and dynamic characteristics of vehicles present in India.

Limitations of the Study

The following are the limitation of the study:

1. The driver behavior which depends on physical, mental, psychological and environmental factors could not be incorporated in the model due to difficulties in measurement and quantification of the influencing factors.
2. The model, in its present form, can simulate only one-way traffic movement which restricts its application to only divided roads.

Scope for Further Research

1. Through this study, the effects of change in traffic volume, magnitude of upgrade and its length on PCU values of different vehicle categories of heterogeneous traffic have been analyzed in detail. There is further scope for the study of the effect of variation in traffic composition on PCU values of different categories of vehicles in heterogeneous traffic. As there are several categories of vehicles in heterogeneous traffic, attempts to change the traffic composition may results in a number of traffic situations making the problem highly complex. However, it is worth attempting in spite of the anticipated complexities.
2. In future, the authors would like to study the effect of traffic volume and magnitude of downgrade on PCU values of different vehicle categories of heterogeneous traffic.
3. There is scope for further research towards improving the model capabilities. The model can be augmented to replicate two-way traffic flow on undivided roads by incorporating suitable simulation logic for movement of vehicles in opposing streams, so that the vehicular interactions can be quantified for two-way traffic conditions also.

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