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Derivation of Capacity Standards for Intercity Roads Carrying Heterogeneous Traffic using Computer Simulation

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Abstract

The knowledge of roadway capacity is an important basic input required for planning, analysis and operation of roadway systems. Expressing capacity as number of vehicles passing a given section of road or traffic lane per unit time will be inappropriate when several types of vehicles with widely varying static and dynamic characteristics are comprised in the traffic. The problem of measuring volume of such heterogeneous traffic has been addressed by converting the different types of vehicles into equivalent passenger cars and expressing the volume in terms of Passenger Car Unit (PCU) per hour. The effect of variation of traffic volume, road width, magnitude of upgrade and its length on PCU value is studied. A recently developed heterogeneous traffic-flow simulation model, named, HETEROSIM is used for this study. Field data collected on traffic flow characteristics are used in calibration and validation of the simulation model. The validated simulation model is then used to derive PCU values for different types of vehicles. The PCU estimates, made through microscopic simulation, for the different types of vehicles of heterogeneous traffic, for a wide range of traffic volume and roadway conditions indicate that the PCU value of a vehicle significantly changes with change in traffic volume, width of roadway, magnitude of upgrade and its length. Using the derived PCU values, capacity guidelines are also developed for typical roadway and traffic conditions.

Keywords: Traffic volume;Traffic speed;PCU;Traffic capacity;Heterogeneous traffic simulation model;

1. Introduction

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. But the traffic scenario in developing countries like India differs significantly from the conditions of developed countries in many respects. The road traffic in India is highly heterogeneous comprising vehicles of wide ranging physical dimensions, weight and dynamic characteristics. The different types of vehicles of the heterogeneous traffic on Indian roads may be grouped into the following

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categories: 1. Buses, 2. Trucks, 3. Light commercial vehicles comprising large vans and small trucks, 4. Cars including jeeps and small vans, 5. Motorised three-wheelers, which include three-wheeled motorised vehicles to carry passengers and three wheeled motorised vehicles to carry small quantities of goods, 6. Motorised two-wheelers, which include motorcycles, scooters and mopeds, 7. Bicycles, 8. Tricycles, to carry passengers or small quantities of goods and 9. Animal drawn vehicles. These motorised and non-motorised vehicles share the same road space without any physical segregation.The speeds of these vehicles vary from just 5 to over 100 km/h. Due to the highly varying physical dimensions and speeds, it becomes difficult to make the vehicles to follow traffic lanes and consequently, for manoeuvre, they tend to 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. Under the said traffic conditions, 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. One commonly adopted procedure in this regard is expressing the volume of such heterogeneous traffic as PCU per hour by converting the different types of vehicles into equivalent passenger cars.

For accurate estimation of PCU values, it is necessary to study, at micro level, the influence of roadway and traffic characteristics such as variation in traffic volume, road width, magnitude of upgrade and its length, etc. and the other relevant aspects on vehicular movement accurately. Simulation, from microscopic through macroscopic, is increasingly becoming a popular traffic-flow modeling tool for analyzing various traffic operations and vehicular interactions. This paper is focused on the study of the effect of variation in traffic volume, road width and magnitude of upgrade and its length, on PCU value of vehicles. Also, capacity guidelines are developed using the derived PCU values.

2. Review of the earlier studies

In the past, various approaches have been adopted for estimation of Passenger Car Unit (PCU) or Passenger Car Equivalent (PCE) values of vehicles. The bases used for the estimation process are (i) delay (e.g. Craus et al. 1980), (ii) speed (e.g. Elefteriadou et al. 1997), (iii) density (e.g. Webster and Elefteriadou, 1999), (iv) headway (e.g. Krammes and Crowley, 1986), and (v) queue discharge (e.g. Al-Kaisy et al. 2005). 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. In the past, researchers have used force-balance equation and vehicle mechanics (weight-to-power ratio of the vehicle) for developing models that predicted truck speeds on upgrades of any percentage and length (Gillespie, 1985; Archilla and Fernandez De Cieza, 1996; Lan and Menendez, 2003). It was 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 (Yagar and Aerde, 1983). All these studies, however, are mainly related to characterization of truck performance on upgrades under homogeneous traffic 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 single set of constant PCU values for different vehicle categories (IRC: 64-1990), which are based on limited field observed data. It is found from the review of Indian studies related to PCU estimation that there are only few studies conducted on the subject matter. Chandra & Goyal (2001) 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. Chandra and Kumar (2003) studied the effect of road width on PCU of vehicles on two-lane highways and found that the PCU value increased with increase in width of roadway. However, these values are empirical and are based on limited traffic data. In summary, the review of literature on the subject matter reveals that the studies conducted are mostly related to fairly homogeneous traffic conditions, and the few studies conducted under heterogeneous traffic conditions are not comprehensive enough to replicate the field conditions accurately. Hence, it was decided to make an attempt to study the vehicular interaction in heterogeneous traffic in a comprehensive manner and derive PCU values for different vehicle types through the research work reported here. Further, the estimated PCU values for the different types of vehicles, are used for developing capacity guidelines.

3. Objective and scope

The general objective of the research work reported here is to quantify the vehicular interaction in terms of Passenger Car Unit (PCU) values of different categories of vehicles and then deriving capacity guidelines, for different roadway conditions, under heterogeneous traffic conditions prevailing on intercity roads in India. A recently developed heterogeneous traffic-flow simulation model, named, HETEROSIM (Arasan and Koshy, 2005) is used to study the vehicular interactions, at micro-level, over a wide range of traffic flow conditions. Field data collected on traffic flow characteristics such as free speed, acceleration, lateral clearance between vehicles, etc. are used in calibration and validation of the simulation model. The validated simulation model is then used to derive Passenger Car Unit (PCU) values for different types of vehicles. The effect of variation of traffic volume, road width, magnitude of upgrade and its length on PCU value is studied by deriving PCU values for the different types of vehicles, for a set of traffic-volume levels falling over a wide range. Finally, a check for the accuracy of the estimated PCU values is also made.

4. The simulation model

Under 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 (Kumar and Rao, 1996; and Ramanayya, 1988, etc.) 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. Realising this need, a model of heterogeneous traffic flow, named, HETEROSIM was developed (Arasan and Koshy, 2005). The modelling framework is explained briefly here to provide the background for the study. For the purpose of simulation, the entire road space is considered as single unit and the vehicles are represented as rectangular blocks on the road space, the length and breadth of the blocks representing respectively, the overall length and the overall breadth of the vehicles. The 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 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. The snapshot of animation of heterogeneous traffic flow, obtained using the animation module of HETEROSIM, is shown in Figure 1. 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 1: Snapshot of animation of simulated heterogeneous traffic flow

5. Model validation

5.1 Traffic flow on level roads

The level stretch of intercity road between km 77.2 and km 77.4, of National Highway (NH)-45 near Chennai city, in south India, was selected for collection of traffic data for the purpose. The study stretch is a four-lane divided road with 7.25m wide main carriageway and 1.5m of paved shoulder for each direction of movement. The field data required for model validation were collected at the selected stretch, which had a total carriageway width (including shoulder) of 8.75 m for each direction. A digital video camera was used to capture the traffic flow for a total duration of 1 h. The video captured traffic-data was then transferred to a Work station (computer) for detailed analysis. The observed traffic composition and measured free-flow speeds for all the vehicle categories, and the data of the overall dimensions of all the categories of vehicles and the minimum and maximum values of lateral-clearance share, taken from an earlier study (Arasan & Koshy, 2005), are given in Table 1.

Table 1 Input data for simulation of heterogeneous traffic flow on level terrain

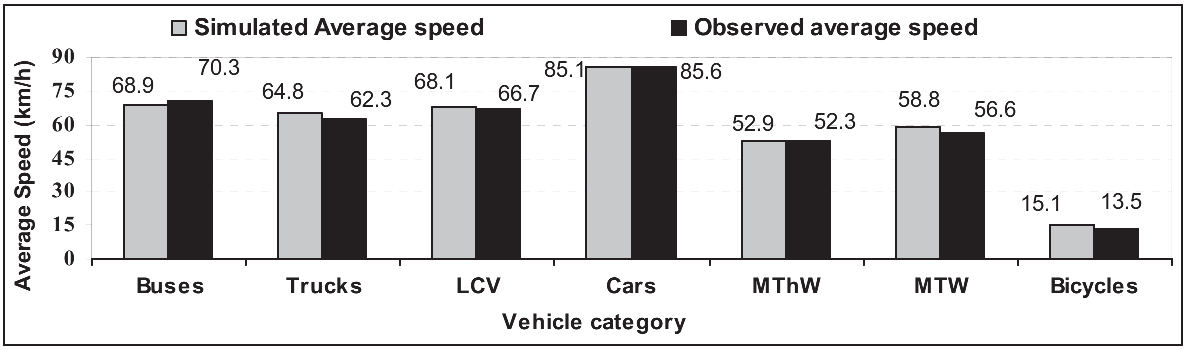
Vehicle category	Traffic composition %	Free-flow speed (km/h)				Average vehicle dimension (m)		Lateral-clearance share (m)	
		Mean Speed	Max. Speed	Min. Speed	Std. Deviation	Length	Width	Min.	Max.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Trucks	35	62	90	53	8	7.5	2.5	0.3	0.6
Buses	21	70	90	45	10	10.3	2.5	0.3	0.6
Cars	17	86	110	60	15	4.0	1.6	0.3	0.5
L.C.V.	11	67	90	50	6	5.0	2.0	0.3	0.5
M.T.W.	12	57	75	35	11	2.0	0.75	0.1	0.3
M.Th.W.	2	52	55	45	3	3.0	1.5	0.2	0.4
Bicycles	2	14	20	10	4.5	1.9	0.5	0.1	0.3

L.C.V. - Light commercial vehicles, M.Th.W. - Motorised Three-Wheelers, M.T.W. - Motorised Two-Wheelers
Note: Animal drawn vehicles and tricycles were not found on the study stretch.

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

For the purpose of validation, the total length of road stretch, for simulation purpose, was taken as 1,400 m. The initial 200 m length, at the entry point, was used as a warm-up zone. To avoid unstable traffic flow condition at the exit end, a 200 m long road stretch, at the exit end, was also excluded from the analysis. Thus, the middle 1000 m length of the simulation stretch was used to collect the data of the simulated traffic flow characteristics. The vehicular characteristics, observed roadway condition, traffic volume and composition were given as input to the simulation process. The inter arrival time of vehicles (headways) was found to fit into exponential distribution and the free speeds of different categories of vehicles, based on the results of an earlier study (Kadiyali et al.,1981) was assumed to follow Normal distribution. These distributions, then, formed the basis for input of the two parameters for the purpose of simulation. During validation of the model, it was found that three simulation runs (with three different random seeds) were sufficient to get consistent simulation output and hence, the simulated values of traffic flow characteristics represent the mean of the three values. A comparison of the observed and simulated average speeds of the different types of vehicles for the field observed traffic volume level of 482 vehicles per hour, is shown in Figure 2. It can be seen that the simulated speed significantly replicates the field observed speed for all the vehicle types. The validation of the model, based on observed and simulated speeds of different categories of vehicles, was also done by conducting a paired t-test. The value of t-statistic, calculated based on the observed data

(t_0), is 1.69. The critical value of t statistic for level of significance of 0.05, for 6 degrees of freedom, obtained from standard t-distribution table is 2.45. Thus, it can be seen that the value of t statistic, calculated based on the observed data, is less than the corresponding table value. This implies that there is no significant difference between the simulated and observed mean speeds.



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

Figure 2: Comparison of speeds of the different types of vehicles on 8.75 m wide road

5.2 Traffic flow on upgrades

On upgrades, heavy vehicles such as trucks and buses will experience significant reduction in their speeds, whereas, passenger cars and other smaller vehicles such as motorized-two-wheelers and three wheelers may experience relatively lesser speed reduction. This 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 simulation model (HETEROSIM), when used for studying the effect of gradient on PCU values, mainly requires data on free-flow speeds and acceleration rates of different vehicle categories while negotiating gradient. The study stretches were selected after conducting a reconnaissance survey to satisfy the following conditions: (1) The stretch should have uniform gradient for a considerable length, and (2) The stretch should be fairly straight and uniform with no direct access from the adjoining land uses on both sides. The three study stretches of National Highway No. 4 near Pune, in Maharashtra (Western part of India), that satisfied the said requirements are: (1) between km 31.2 and km 31.5 with 3% gradient, (2) between km 2.6 and km 3.0 with 3.78 % gradient, (3) between km 5.2 and km 5.9 with 5 % gradient. The free speeds of the different categories of vehicles were measured by noting the time taken by the vehicles to traverse a trap length of 30 m on the approaches to the selected road stretches.

The governing equation for the forward movement of any vehicle when it encounters a grade is determined by the summation of forces acting on the vehicle in the longitudinal direction. The following (Equation 1) is the fundamental equation of motion for a road vehicle (Bennett and Greenwood, 2001):

$$a = \frac{1000 \times P_d}{M \times EMRAT} \frac{1}{v} - \frac{1}{M \times EMRAT}[F_a + F_r + F_g] \qquad (1)$$

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 vehicle speed in m/s.

The data pertaining to power and gross vehicle weight of different makes for each vehicle category was collected from the manufacturers' websites, different automobile showrooms, users' manual, etc. Finally, the average representative values of power and weight for each vehicle category were considered for calculating its acceleration rates at various speed ranges. The values pertaining to aerodynamic drag coefficient (CD), CD multiplier (CDmult), the projected frontal area in m^2 (AF), for each vehicle category, were taken from the manual of Highway Development and Management (HDM-4). The effective mass ratio (EMRAT) for each vehicle category is also calculated at various speeds as per the HDM-4. The coefficient of rolling resistance (f) is taken as 0.01 (Kadiyali et al.,1982) for pavement surface of the study stretch (asphaltic concrete). For calibration of used driving power delivered to the wheels (Pd), the variable, 'power factor' was introduced by Lucic (2001). 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 the maximum speed at which vehicle-power reaches its maximum is considered as variable power factor. The used driving power (p_d), then, can be estimated by multiplying the average power value by this variable power factor. Hence, using all these parameters, the acceleration rates at various speed ranges with respect to each upgrade considered for the study, are calculated for different vehicle categories. These acceleration rates were given as input to the model, to simulate the traffic flow on upgrade.

For the purpose of validation, the observed roadway condition, measured free speed parameters at the initial point, traffic volume and composition and the acceleration rates (estimated at various speed ranges with respect to different upgrades, having magnitude 3%, 3.78% and 5%) were given as input to the simulation process. To check for the validity of the model, the vehicle speeds simulated by the model at different lengths along the grade were compared with the respective, length-wise, field observed speed values for each category of vehicles. A comparison of the observed and simulated speeds of the different types of vehicles, at the three selected sections on 5% upgrade, as example, is shown in Table 2. It can be seen that the simulated speed values significantly match with the field observed speeds for all vehicle types at all the sections. A statistical validation of the results, based on observed and simulated speeds of different categories of vehicles, was also done through paired t-test for each case. The validation results for the observed traffic volume, on upgrades with magnitude 3%, 3.78% and 5%, also showed that there were no significant differences between their respective simulated and observed mean speeds.

Table 2. Model validation by a comparison of observed and simulated speeds on different stretches of the road with 5 % upgrade

Vehicle category	Section I (km 5.2 to 5.5)		Section II (km 5.2 to 5.7)		Section III (km 5.2 to 5.9)	
	Average Observed Speed*	Average Simulated Speed*	Average Observed Speed*	Average Simulated Speed*	Average Observed Speed*	Average Simulated Speed*
(1)	(2)	(3)	(4)	(5)	(6)	(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. - Motorised Three-Wheelers, M.T.W. - Motorised Two-Wheelers. *Speed in km/h*

6. Model application

6.1 Speed-volume relationships

The speed-flow relationship was developed, for level stretches of 8.75 m and 12.25 m wide road spaces (width of road space for one direction of movement on four-lane divided and six-lane divided roads with 1.5 m wide paved shoulders) under heterogeneous traffic flow conditions, the composition of traffic being taken as the same for both the cases, by running the simulation for various volumes, starting from near zero to the capacity of the road. Also, traffic flow on 8.75 m wide road space with upgrades of magnitude 2%, 3%, 4%, 5% and 6%, for a length of 1600 m were simulated from very low to capacity flow level, and the relationship between speed and flow for these cases, made on the same set of axes, are developed. The developed speed-volume relationships level stretches of 8.75 m and 12.25 m wide road spaces are shown in Figure 3, as example. It can be seen that, the speed-volume curves follow the established trend. Also, it was found, from the speed-volume curves, that the capacity values of the considered level road stretches having widths, 8.75 m and 12.25 m, for the representative composition (column 2 of Table 1), are about 2700 vehicles per hour and 3700 vehicles per hour respectively. The capacity values of 8.75 m wide space, for one direction flow of traffic, having upgrades of magnitude 2%, 3%, 4%, 5% and 6%, at a section, 1600 m away from the starting point of the grade, are found to be 1360, 1210, 1120, 1050 and 1010 vehicles/h respectively.

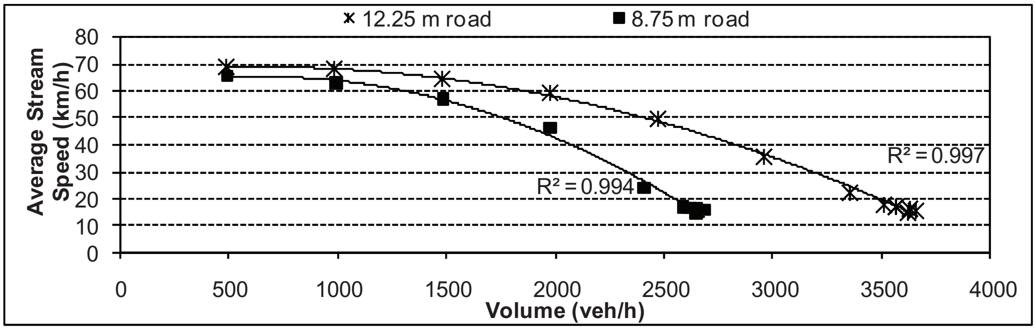


Figure 3: Speed–volume relationships for 8.75 and 12.25 m wide level road spaces

6.2 Speed-distance profile for different vehicle categories on upgrades

The speed-distance relationship for a vehicle type, while negotiating upgrades, was developed by simulating traffic flow on the chosen roadway with a specified gradient. 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) was considered for developing speed-distance curves for different vehicle categories for different grades. The free-flow speed values, for different vehicle categories, representative traffic composition 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%. 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 speed-distance relationships were thus developed, for the different vehicle categories, for each of the different grades. The relationships thus, obtained, in respect of trucks, as example, is depicted in Figure 4.

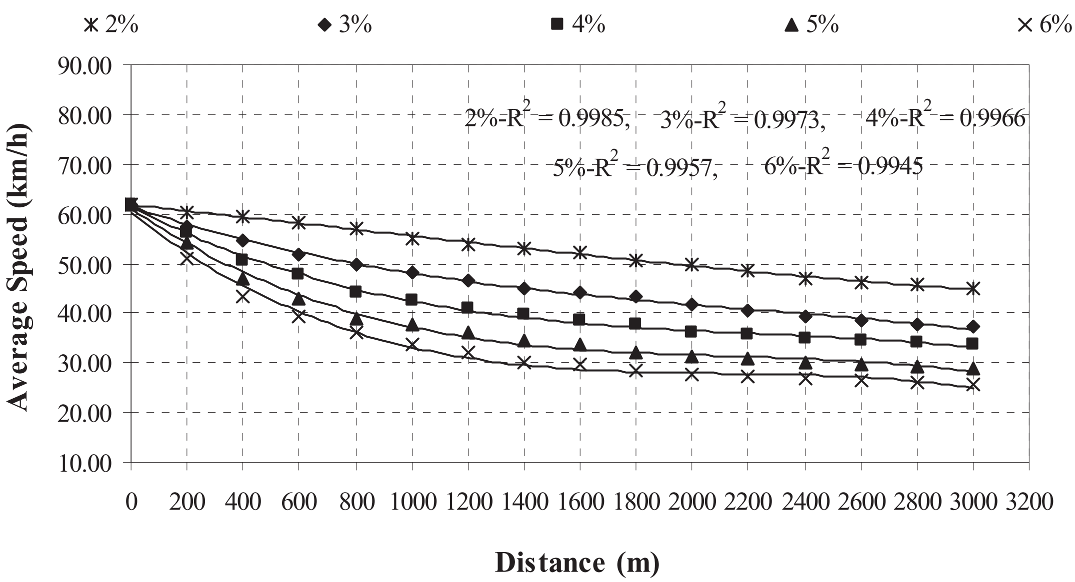


Figure 4: Speed-distance profile for trucks on different upgrades

From Figure 4, it can be noted that, 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 flat indicating that there is no significant speed reduction beyond that point. To check this null hypothesis paired t-tests were conducted between the simulated speeds, obtained across different sections, on each of the upgrades (2% to 6%), for each of the vehicle categories. The results of the t-tests have indicated that there is no significant speed reduction beyond a grade length of 1600 m.

6.3 Estimation of PCU values

The PCU has been defined by Transport and Road Research Laboratory *(TRRL)* London, UK, 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: (1) A set of traffic volume levels, corresponding to a chosen set of volume to capacity ratios, were considered. While simulating traffic flow corresponding to the V/C ratios, in each case, a certain percentage of cars were replaced by the subject vehicle type (for which the PCU value is to be estimated) in the mixed traffic stream, such that the average stream speed remained to be same, before and after the replacement. (2) 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 made 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 set of cars removed from the stream.

The PCU values of the different categories of vehicles were estimated, by simulating traffic flow on different widths of roads and on different upgrades. For this purpose, heterogeneous traffic flow of a representative composition (Column no. 2 of Table 1), was considered on two different widths of road, namely, 8.75 m, and 12.25 m (equivalent to the widths, for one direction of traffic flow of 4 and 6-lane divided roads) and five different upgrades, namely, 2%, 3%, 4%, 5% and 6%. The PCU value of a subject-vehicle was determined following the said procedure, both for 8.75 m and 12.25 m wide level roads. It was also decided to derive PCU values for different vehicle categories for the different upgrades (2% to 6% on 8.75 m wide road space) at every 400 m on 1600 m long road stretches, at selected traffic volume levels. The variation of PCU values of the different types of vehicles, over traffic volume, both on 8.75 m and 12.25 m wide roads has been presented in Table 3.

Table 3. Variation of PCU value for the different types of vehicles on 8.75 m and 12.25 m wide roads

V/C ratio	PCU value of vehicles on roadway widths of 8.75 and 12.25 m											
	Buses		Trucks		L.C.V.		M.Th.W.		M.T.W.		Bicycles	
	A	B	A	B	A	B	A	B	A	B	A	B
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
0.125	2.00	2.65	2.25	2.75	1.42	1.64	0.50	0.66	0.34	0.42	0.30	0.41
0.250	1.95	2.51	2.20	2.61	1.38	1.57	0.72	0.82	0.43	0.54	0.42	0.57
0.375	1.90	2.36	2.15	2.49	1.32	1.50	0.85	0.96	0.52	0.74	0.54	0.75
0.500	1.80	2.21	2.10	2.37	1.28	1.39	0.90	0.99	0.66	0.81	0.66	0.82
0.625	1.70	2.11	1.90	2.28	1.24	1.35	0.85	0.92	0.74	0.89	0.72	0.90
0.750	1.80	2.32	1.95	2.36	1.28	1.40	0.80	0.86	0.72	0.81	0.70	0.83
0.875	2.20	2.58	2.10	2.45	1.32	1.49	0.72	0.76	0.62	0.73	0.66	0.75
1.000	2.70	2.90	2.50	2.80	1.48	1.67	0.60	0.66	0.49	0.57	0.50	0.56

Note: L.C.V.–Light commercial vehicles, M.Th.W. - Motorised Three-Wheelers, M.T.W. - Motorised Two-Wheelers
A - 8.75 m wide road space, B - 12.25 m wide road space

It can be observed from Table 3, that there is a significant increase in magnitude of PCU values on 12.25 m wide road when compared to the corresponding values on 8.75 m wide road. For finding out the possible reason for this trend, it was decided to calculate the percentage increase in speeds of all types of vehicles, with increase in road width, so that the increase in car speed can be compared with the increase in the speed of other vehicles.

Accordingly, it was found that, at all the chosen volume-to-capacity ratio values; the percentage increase in speed of cars is higher than the percentage increase in speed of all the other categories of vehicles. The higher free speed, acceleration and other mechanical capabilities of cars facilitate the vehicles to gain more speed with increase in the road width when compared to other vehicle categories. Hence, it is clear that the increase in speed difference between cars and other categories of vehicles with increase in width of road space has resulted in increased PCU values with increase in the width of road space. The estimated PCU values of the different vehicle categories, for 3 % and 6% grades, as examples, for every 400 m, over a total grade length of 1600 m, at different volume levels, are shown in Table 4.

Table 4. Variation of PCU value of different vehicles types on 3% and 6% upgrades

Grade Length (m)	PCU value of the different types of vehicles									
	3 % Upgrade					6% Upgrade				
	V/C ratio = 0.30					V/C ratio = 0.30				
	Bus	Truck	L.C.V.	M.Th.W.	M.T.W.	Bus	Truck	L.C.V.	M.Th.W.	M.T.W.
0-400	4.12	4.32	2.71	1.02	0.56	4.63	4.72	3.09	1.10	0.73
400-800	4.50	4.66	2.92	1.08	0.64	4.93	5.13	3.30	1.16	0.80
800-1200	4.78	5.06	3.19	1.16	0.72	5.15	5.46	3.50	1.27	0.86
1200-1600	5.06	5.46	3.45	1.24	0.81	5.44	5.86	3.68	1.33	0.93
>1600	5.23	5.67	3.61	1.29	0.86	5.60	6.03	3.85	1.37	0.96
Grade Length (m)	V/C ratio = 0.50					V/C ratio = 0.50				
	Bus	Truck	L.C.V.	M.Th.W.	M.T.W.	Bus	Truck	L.C.V.	M.Th.W.	M.T.W.
0-400	3.49	3.80	2.30	1.22	0.63	4.18	4.30	2.90	1.37	0.78
400-800	3.79	4.12	2.52	1.32	0.70	4.45	4.65	3.07	1.43	0.85
800-1200	4.15	4.49	2.73	1.41	0.79	4.71	4.97	3.25	1.52	0.92
1200-1600	4.50	4.75	2.95	1.49	0.87	4.98	5.31	3.40	1.60	0.99
>1600	4.66	4.95	3.08	1.54	0.91	5.12	5.44	3.51	1.64	1.00
Grade Length (m)	V/C ratio = 0.60					V/C ratio = 0.60				
	Bus	Truck	L.C.V.	M.Th.W.	M.T.W.	Bus	Truck	L.C.V.	M.Th.W.	M.T.W.
0-400	3.41	3.74	2.25	1.30	0.65	4.00	4.17	2.80	1.44	0.79
400-800	3.71	4.02	2.45	1.39	0.72	4.30	4.58	2.96	1.52	0.86
800-1200	4.09	4.38	2.68	1.49	0.81	4.56	4.88	3.15	1.60	0.93
1200-1600	4.41	4.70	2.91	1.56	0.89	4.88	5.20	3.30	1.68	1.00
>1600	4.59	4.89	3.04	1.61	0.93	5.00	5.33	3.42	1.72	1.01
Grade Length (m)	V/C ratio = 0.80					V/C ratio = 0.80				
	Bus	Truck	L.C.V.	M.Th.W.	M.T.W.	Bus	Truck	L.C.V.	M.Th.W.	M.T.W.
0-400	3.97	4.15	2.55	1.26	0.63	4.45	4.55	2.98	1.39	0.77
400-800	4.31	4.45	2.80	1.35	0.70	4.74	4.82	3.11	1.47	0.84
800-1200	4.55	4.85	2.97	1.43	0.78	5.05	5.23	3.30	1.55	0.90
1200-1600	4.80	5.11	3.18	1.51	0.86	5.24	5.58	3.48	1.62	0.97
>1600	4.89	5.22	3.27	1.55	0.91	5.34	5.68	3.56	1.65	0.99
Grade Length (m)	V/C ratio = 1.0					V/C ratio = 1.0				
	Bus	Truck	L.C.V.	M.Th.W.	M.T.W.	Bus	Truck	L.C.V.	M.Th.W.	M.T.W.
0-400	4.22	4.40	2.80	1.15	0.59	5.20	5.29	3.41	1.28	0.74
400-800	4.60	4.75	3.05	1.22	0.65	5.58	5.64	3.63	1.35	0.82
800-1200	4.90	5.20	3.31	1.32	0.75	5.91	6.08	3.89	1.42	0.88
1200-1600	5.40	5.65	3.55	1.39	0.82	6.30	6.55	4.15	1.48	0.95
>1600	5.49	5.75	3.63	1.43	0.86	6.39	6.64	4.22	1.51	0.97

Note: L.C.V.- Light commercial vehicles, M.Th.W. - Motorised Three-Wheelers, M.T.W. - Motorised Two-Wheelers

From Table 4, it can be noted that PCU value of all the vehicle categories increases with increase in the magnitude of grade and its length. The increase in PCU value 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. It can be also seen from Tables (3 and 4), that at low volume levels, in the case of vehicles that are larger in size than cars, 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 value increases with the increase in traffic volume. Whereas, in the case of vehicles that are smaller than car, such as motorised three-wheelers and motorised two-wheelers, 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 value decreases with increase in traffic volume. In both the cases, the attempt to find the possible reason for the trend of variation of PCU value over volume (V/C ratio), revealed that the relative changes, caused by the overall traffic environment, in the speeds of the reference vehicle (car) and the subject vehicle (other than car, for which PCU value is to be estimated), at various traffic volume levels, are the main contributors to the trend. The change in speed difference, in respect of cars and trucks, for example, can be calculated as the percentage change in speed of cars minus the percentage change in speed of trucks for the successive V/C ratios.

7. Check for accuracy of PCU values

For the purpose of checking the accuracy of the PCU estimates for the different categories of vehicles on level roads having widths 8.75 m, 12.25 m and on 8.75 m wide road stretches having upgrades varying from 2% to 6%, first, the heterogeneous traffic flow of the chosen composition (Column 2 of Table 1) was simulated separately for one hour for selected values of V/C ratios and the number of vehicles in each category, for each case, was noted. Then, the vehicles of the different categories were converted into equivalent PCUs by multiplying the number of vehicles in each category, obtained for the selected V/C ratios, by the corresponding PCU values (Tables 3 and 4). The products, thus obtained, were summed up to get the total traffic flow in PCU/h separately for the roads of width 8.75 m, 12.25 m and for upgrades of 2% to 6% considered for this study. Then, 'cars-only' traffic flow was simulated for one hour, for each of the roadway conditions considered for this study, for the same set of V/C ratio values (taking the capacity value from the speed-flow curve developed corresponding to cars only traffic for each of the roadway condition separately). Thus, the traffic volume, in terms of number of cars, was obtained for the set of selected V/C ratios for both the road widths. A comparison of the traffic flow in terms of PCU and in terms of number of passenger cars, pertaining to the road widths of 8.75 m and 12.25 m, for the same set of the selected V/C ratios, was done. It was found that the two flow values were closely matching. A similar exercise, done for upgrades of magnitude 2% to 6% also resulted in a close match between the volumes of traffic measured in PCU and in passenger cars. The comparison of traffic flow in terms of PCU and in terms of number of passenger cars, pertaining to the 6% upgrade for 1600 m length, as example, has been depicted in Figure 5. A paired t-test, based on the passenger car equivalent (PCU/h) and passenger cars-only (cars/h) traffic volumes for both the road widths, was also done for each case. The results of the paired t-test, for each of the roadway considered for this study has indicated that there is no significant difference between the traffic volumes measured in terms of passenger cars and in PCU at 5% level of significance.

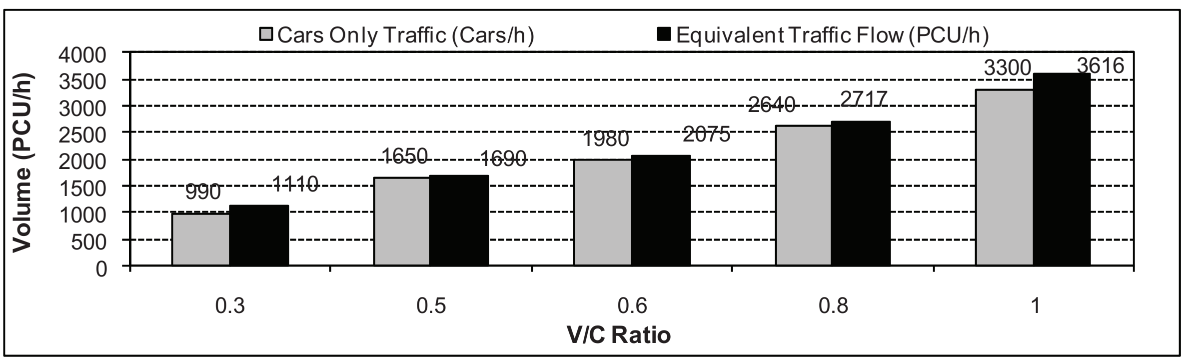


Figure 5: Comparison of heterogeneous traffic and cars-only traffic flows on 6% upgrade

8. Findings

The following are the important findings 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 mid block sections of intercity roads, for different roadway conditions, to a highly satisfactory extent.
2. It is found that, under heterogeneous traffic conditions, for a given roadway condition and traffic composition, the PCU value of vehicles vary significantly with change in traffic volume. Hence, it is desirable, to treat PCU as dynamic quantity instead of assigning fixed PCU values for the different vehicle categories.
3. The study of effect of variation in road width on PCU values indicate that for any vehicle type, in heterogeneous traffic, the PCU value increases significantly with increase in the width of road space.
4. 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.
5. From the speed-volume curves, developed using the simulation model, it is found that, for the representative traffic composition, the capacity for one direction of movement of a level four-lane divided road with 8.75 m wide road space is about 4600 PCU per hour and it is 7200 PCU per hour for a level six-lane divided road with 12.25 m wide road space, for one direction of traffic flow. It is also found that for the same traffic composition, the capacities for one direction of flow, of four-lane divided roads (width of road space: 8.75 m), having upgrades of magnitudes 2%, 3%, 4%, 5% and 6%, for a grade length of 1600 m, are about 4300 PCU/h, 4100 PCU/h, 3900 PCU/h, 3700 PCU/h and 3600 PCU/h respectively.

References

[1] Al-Kaisy A., Younghan Jung, and Hesham Rakha (2005). "Developing Passenger Car Equivalency Factors for Heavy Vehicles during Congestion." *ASCE, Journal of Transportation Engineering*, 131(7), 514-523.

[2] Arasan V. T. and Koshy R (2005). "Methodology for Modeling Highly Heterogeneous Traffic Flow." *ASCE, Journal of Transportation Engineering*, 131(7), 544-55.

[3] Archilla A. R., and Fernandez De Cieza, A. O (1996) "Truck performance on Argentinean highways. "*TRR No. 1555*, Transportation Research Board, Washington, D.C., 114–123.

[4] Bennett C.R. and Greenwood I.D (2001) "Manual on "Modeling Road User And Environmental Effects In Hdm-4" The *Highway Development and Management Series*.

[5] Chandra Satish and Goyal N. K. (2001) "Effect of Grade on Capacity of Two-Lane Road." HB No. 64, *IRC*, New Delhi, India, 77-86.

[6] Chandra S. and Kumar U. (2003) "Effect of lane width on capacity under mixed traffic conditions in India." Journal of Transportation Engineering, ASCE, 129(2), 155-160.

[7] Craus Polus and Grinberg, I. A. (1980) "Revised Method for the Determination of Passenger Car Equivalencies." Transportation Research, Part A, 14A (5), 241-246.

[8] Elefteriadou L, Torbic, D. and Webster, N. (1997) "Development of Passenger Car Equivalents for Freeways, Two-Lane Highways, and Arterials." In TRR: Journal of the TRB, No.1572, NRC, Washington, D.C., 51-58.

[9] Fan Henry, S. L. (1990) "Passenger car equivalents for vehicles on Singapore expressways." Transportation Research-A, Vol. 24A No. 5, 391-396.

[10] Gillespie T. D. (1985) "Methods for Predicting Truck Speed Loss on Grades", Report No. FHWA/RD-86/059, Federal Highway Administration.

[11] Indian Roads Congress. (1990) "Guidelines for capacity of roads in rural area", IRC code of Practice, IRC: 64, 1990, New Delhi, India.

[12] Kadiyali L. R., Viswanathan, E. Bajaj, J.C. and Bhandari N.K. (1982) "Rolling resistance and air resistance factors for Indian road and vehicle conditions, *HRB 19, Indian Roads Congress*, New Delhi.

[13] Kadiyali L.R., Viswanathan E., Gupta, R. K. (1981): "Free Speeds of Vehicles in Indian Roads." Indian Road congress Journal, New Delhi, India 165(1), 387-457.

[14] Krammes R. A. and Crowley K. W. (1986) "Passenger Car Equivalents for Trucks on Level Freeway Segments." In TRR: Journal of the TRB, No. 1091. TRB, Washington, D. C., 10-17.

[15] Kumar V. M. and Rao S. K. (1996) "Simulation Modeling of Traffic Operations on Two Lane Highways." HRB, No. 54, Indian Roads Congress, New Delhi, India, 211-236.

[16] Lan Chang-Jen and Menendez M. (2003) "Truck Speed Profile Models for Critical Length of Grade" *ASCE, Journal of Transportation Engineering*, Vol.129, No.4, 408-419.

[17] Lucic I. (2001) "Truck Modeling Along Grade Sections" *M.S. Thesis of Virginia Polytechnic State University*.

[18] Ramanayya T. V. (1988) "Highway capacity under mixed traffic conditions." Traffic Engineering and Control, U.K., 29(5), 284-287.
[19] Transportation and Road Research Laboratory (TRRL) *Research on Road Traffic*, H.M.S.O, London, (1965).
[20] Webster N. and Elefteriadou L. (1999) "A Simulation Study of Truck Passenger Car Equivalents (PCE) on Basic Freeway Sections." In Transportation Research, Part B, 33B (5), 323-336.
[21] Yagar S. and Aerde V. M. (1983) "Geometric and Environmental Effects on Speeds of Two-Lane Highways" Transportation Research Vol. 17 A, No. 4, 315-325.