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MODELLING OF PASSENGER CAR EQUIVALENCY UNDER HETEROGENEOUS TRAFFIC CONDITIONS

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ABSTRACT

In studying heterogeneous traffic, passenger car equivalents (PCE) play a significant role in converting the mixed traffic flow into equivalent hypothetical homogeneous traffic that consists of passenger cars only. As can be seen in the literature there are different measures of impedance (speed, density, vehicle-hours etc.) based on which PCE values are calculated for different types of vehicles. Since vehicle-hours and speed are functions of vehicle density, PCE values invariably depend on density. Measuring or estimating the density value is difficult under heterogeneous traffic conditions, and at the same time density is independent of vehicle length and vehicle width. Due to these reasons using the density value as a measure of impedance in calculating PCE values under mixed traffic conditions may lead to erroneous results. In this paper an alternative measure of density termed as area occupancy, is used as a measure of impedance to estimate the PCE values. A simulation technique is used to estimate PCE values under different traffic regimes. These values will be helpful in analyzing traffic flow patterns and in capacity analysis.

INTRODUCTION

Passenger car equivalents (PCE) are used in estimating the effect of different vehicles on a traffic stream compared to passenger cars. In developing countries traffic is composed of several types of vehicles and PCE values are being used to convert this traffic into equivalent homogeneous traffic. Several researchers have attempted to find PCE values for heavy vehicles under different roadway and traffic conditions. Very limited work has been done to estimate PCE values for small sized vehicles such as motorized two wheelers (TW) and three wheelers which are predominant in developing countries.

Since it is too complex to use analytical techniques, it is a common practice to use simulation models in estimating PCE values. In this context most of the works carried out in the past were based on micro simulation models based on conventional car following and lane changing models. Developing simulation models for the kind of traffic observed in developing countries like India is a tough task. Due to the presence of small sized vehicles such as TW and three wheelers, simple car following models may not be suitable to model this traffic. Few researchers have attempted to model this complex traffic with the help of simulation models developed based on explicit vehicle interaction rules.

One of the important aspects in estimating the PCE values is choosing a suitable performance measure. Headways, delay, platoon formation, speed, vehicle-hours, travel time are the commonly used performance measures in deriving PCE values. According to the HCM methodology (Highway Capacity Manual 2000) PCE values should be based on the same performance measure as the level-of-service designations for the respective facility types. HCM methodology has considered density as the performance measure in estimating these values. Under mixed traffic conditions density has no relevance (Khan and Maini 1999). Hence a suitable performance measure which incorporates important vehicle characteristics shall be used in deriving PCE values. One more important aspect of the performance measure is it should be easy to measure in field.

The main objective of this paper is to use a simulation model developed for mixed traffic in deriving PCE values for mid-block sections. PCE values are estimated for three types of vehicles namely buses, trucks, and TWs. It is also proposed that a modified measure of density called area occupancy be used as a performance measure. This new characteristic would be able to represent the mixed traffic nature in a better way when compared to density. Since very little work has been done in deriving PCE values for mixed traffic conditions this study would be helpful in traffic and capacity analysis.

Keeping in view the above objectives a detailed literature review is carried out which is discussed in the following section. In the third section, methodology adopted in choosing performance measure and in deriving PCE values is presented. Analysis of the results is presented in the fourth section. In the final section summary and conclusions are presented.

LITERATURE REVIEW

Methodology used to estimate PCE values consists of two major parts namely using a proper simulation model and a suitable performance measure. A detailed literature review regarding these two aspects is presented here.

For the first time PCE values were incorporated in HCM 1965. Since then several people have worked on estimating PCE values for different vehicles under different traffic and roadway conditions (Al Kaisy et al 2005; Kimber et al 1985; Sumner et al 1984; Webster and Elefteriadou 1999). Most of the works done in this area in past were aimed at developing PCE values for heavy vehicles such as trucks. In most of the cases PCE estimation is carried out for one type of vehicle. Some works were carried out to estimate different PCE values for different types of trucks classified based on weight to horse power ratio. Sumner et. al. (1984) proposed a model for the case in which traffic is composed of more than one class of heavy vehicle. But this method did not consider the interaction between different heavy vehicles (Demarchi and Setti 2003). Demarchi and Setti proposed a model in which aggregate equivalence factor is calculated for mixed flow.

Different people have used different performance measures in estimating the PCE values. The HCM 1965 method used relative speed reduction to derive PCE values for two lane highways and quantified this by the relative number of passings known as Walker method. Cunagin and Messer (1983) used relative delay as a performance measure in estimating the PCE values for trucks on multilane highways. Huber (1982) derived PCE values using three different performance measures namely speed, density and passenger car speed in both the traffic streams. Sumner et. al. (1984) used number of vehicle-hours as the measure of performance which is equivalent to the density. Vehicle-hours is a function of vehicle's velocity and its length. Elefteriadou et. al. (1997) used average speed as a performance measure. Webster and Elefteriadou (1999) used density as a performance measure to derive PCE values. Al-Kaisy (2002) used queue discharge factor as a measure of performance to estimate the PCE values during congestion.

Since the proportion of the trucks is very low when compared to passenger cars, the significance and usefulness of PCE values is limited under homogeneous traffic conditions when compared to their usefulness in mixed traffic conditions. Though PCE values are very useful under mixed traffic conditions, due to the limitations in modelling the complex traffic streams and collecting empirical data very limited work was carried out for these conditions.

Ramanayya (1980) used 'equivalent Design Vehicle' in place of passenger car unit to model the traffic observed on urban roads in India. This study is the first of its kind in measuring the flow using a metric other than PCU values. From this study it was shown that PCU value of the passenger car itself is not constant due to heterogeneous traffic conditions. In this model an attempt was made to convert all vehicles including car into 'equivalent design vehicle unit'. Subsequently this was not validated in any of the future studies. Chari and Badarinath (1983) made an attempt to quantify density under these conditions using areal density. This is the first study that considered vehicle areas in measuring the density. Areal density is defined as sum of the total vehicle area projected on the ground per unit area of road way. A time lapse camera with a 1-sec interval between successive exposures of the film was used for data collection. Madhava Kumar (1994) used traffic characteristics such as speed, flow and density to study the traffic observed on National Highways in India. In this work, four persons were deployed on each end of the road stretch to collect vehicle data such as time of entry, registration number, and type of vehicle simultaneously. Later from the collected field data, for every one minute interval, total number of vehicles located on the road stretch is calculated. Observed number of vehicles divided with the length of the road gives the density value. Bhuvanesh Singh (1999) used concentration as traffic characteristic, for validating the simulation model, which is defined as proportion of road space occupied by vehicles at an instant. In this study video graphic technique was used to collect concentration data at 15 second intervals. Bham and Benekohal (2004) used percent space occupancy in their work to represent congested traffic conditions in a better way when traffic is composed of vehicles with different lengths. According to them, space occupancy provides a better feel for the state of traffic since it incorporates length of each vehicle when compared to average length used in density. Khan and Maini (1999) have done an extensive review of heterogeneous traffic flow modelling studies and concluded that for mixed type of vehicles, linear density measurements are inadequate, and there should be a measure which includes the vehicle area. It was also concluded that the uniform definition of passenger car equivalent is not applicable and the values of equivalency depend on traffic composition, degree of saturation and location.

Rongviriyapanich and Suppattrakul (2005) derived PCE values for TWs near intersections and mid-blocks sections using time headways. They found that the PCE of motorcycle is continuously decreasing with the increase in the proportion. Chandra and Sikdar (2000) proposed a methodology to estimate PCE values for mixed traffic conditions. They have estimated the PCE values as a function of vehicle area and speed. According to their methodology PCE of any particular vehicle is formulated as follows

$$PCE_i = \frac{V_c / V_i}{A_c / A_i} \qquad (1)$$

where V_c and V_i = mean speeds of car and type i vehicle respectively, in the traffic stream; and A_c and A_i = their respective projected rectangular areas (length * width) on the road. According to them, since vehicles are not following lane discipline in mixed traffic the occupancy is better reflected by area.

From the review it can be found that many researchers have tried to incorporate different vehicle characteristics in estimating the PCE values under mixed traffic conditions. The main objective of their work was to incorporate vehicle area in estimating the PCE values. In the present work this is achieved with the help of a metric called area occupancy which is explained in detail in the following sections.

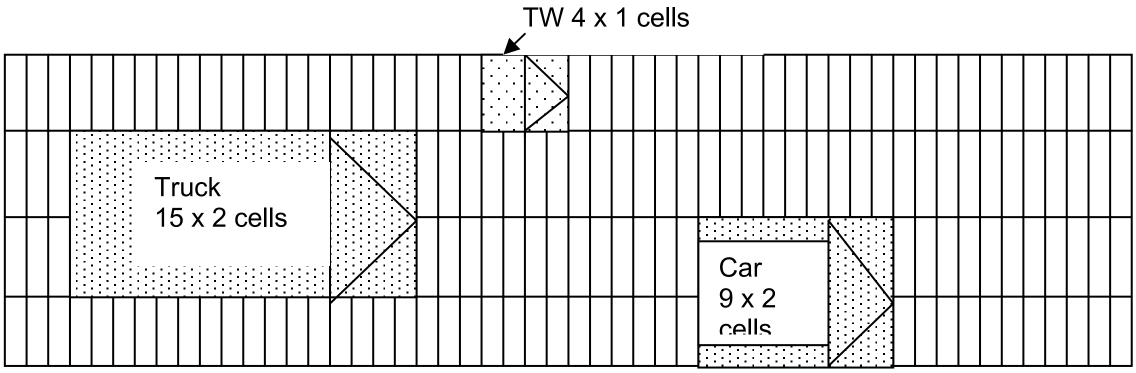

Figure 1: structure of the CA model used in the present study; a two lane one way road of 7m width

Simulation model

Simulation model is the basis on which PCE values are estimated as it is difficult to use analytical techniques under complex roadway and traffic conditions. Most of the recent works in this area have used established micro simulation models such as INTEGRATION, FRESIM etc.

The model used in the present study is developed based on the model developed by Nagel and Schreckenberg (1992). Nagel – Schreckenberg's model is based on the concept of cellular automata (CA) which has several computational advantages in modelling complex systems. In this model many interactions between the elements of model are incorporated implicitly and traffic is modeled using simple updating rules. Though this model could not reproduce all the observed traffic characteristics it was able to produce the trends observed in real traffic. Since then it has undergone so many changes and its applicability was extended to model network traffic flows (Barlovic et al 1998; Chowdhury et al 1997; Knospe et al 2002; Maerivoet and De Moor 2005; Nagel and Rickert 2001). Keeping the basic structure of the model intact an attempt is made to utilize its efficiency in modelling complex systems to model the heterogeneous traffic. It is modified to model different acceleration and deceleration characteristics of different vehicles which is crucial when traffic is composed of different types of vehicles. It is also possible to model no lane discipline of vehicles with this modified CA model. The three phase traffic flow model proposed by Kerner (1999) is used as the basis for the present simulation model.

Table 1: Different vehicle characteristics

Vehicle Type	Length (m)	Length (cells)	Free flow Speed (m/s)	Acceleration (m/sec^2)			Deceleration (m/s^2)
				V < 5.5m/s	5.5 m/sec≥ V > 11m/sec	V ≥ 11m/s	
Car	4.5	9	25	1.5	1.5	1	1.5
Bus	10.5	21	20	1	0.5	0.5	1.5
Truck	7.5	15	20	1	0.5	0.5	1.5
Two Wheeler	1.8	4	22.5	1.5	1	0.5	1.5

METHODOLOGY

CA based simulation model is chosen for this study due to its computational advantages over microscopic simulation models. For modelling mixed traffic, since conventional car following and lane changing models are not useful, some researchers (Arasan and Koshy 2005; Bhuvanesh Singh 1999) have developed simulation models based on explicit vehicle interactions. Though these models are able to reproduce the reality, they have computational disadvantages. To over come these problems the CA model is slightly modified to suit mixed traffic modelling. One more advantage with the CA model is that it is possible to take spatial, temporal and spatio-temporal measurements easily (Lan and Hsu 2006). The CA model with Kerner's updating rules (Kerner et al 2002) are used in this study. The basic vehicle features which are used in the present study are presented in Table 1**.** Four types of vehicles, cars, buses, trucks and two wheelers are considered in the present study. Values given in parenthesis are vehicle lengths in number of cells and each cell has a length of 0.5 m and a width of 1.75 m. The basic structure of a two lane CA model used in the present work is shown in **Figure 1**. Road is divided into cells of size 0.5 X 1.75 m so that it can adequately model velocity and acceleration behavior of different vehicles.

A brief description of the CA model that is used in the present work is given here. The major differences between the other CA models and the present one are car following and lane changing behavior of different vehicles. In car following behavior, for any particular vehicle there can be two leading vehicles and the effective gap available in the front will be the lesser of the two gaps related to the two leading vehicles. While in lane changing the vehicle can change lanes to its left or to right. One other difference between the CA model based on three phase traffic theory proposed by Kerner et. al. (2002) and the present model is synchronization distance. Here depending on the closest leading vehicle type the following vehicle's synchronization distance will vary. If the closest leading vehicle is a heavy vehicle the synchronization distance for the following vehicle will be greater.

In the following text, the vehicle updating procedure used in the present model is discussed in detail. Before updating vehicle's speed and position, the following parameters are to be calculated;

- Multiplication parameter used in calculating synchronization distance which will depend on the leading vehicle type. Synchronization distance is greater in case of heavy vehicle
- Synchronization distance
- Deciding the probability to be used in the velocity dependent randomization step. This value is a function of the present speed of the vehicle. Assign flag value as one in the case of stopped vehicle otherwise zero. If the vehicle speed is zero depending on the vehicle type the probability value is going to very.

Having completed the above steps, the updating procedure to be followed is described below;

1. If available gap is greater than the synchronization distance the vehicle will accelerate

   Speed = Minimum (Maximum speed (vehicle type), speed + acceleration (speed, vehicle type))

   Else

   If speed > Leading vehicle's speed

   Speed = Maximum (0, speed – deceleration(vehicle type))

   Else

   Speed = Minimum (Maximum speed (vehicle type), speed + acceleration (speed, vehicle type)

2. If Speed > Gap – safety gap (vehicle type)

   Speed = speed – safety gap (vehicle type)

3. Velocity dependent random acceleration and deceleration

   Stochastic deceleration:

   If flag value is one and probability < P_0

   Speed = Maximum (0, speed – deceleration (vehicle type))

   Else if probability < P_b

   Speed = Maximum (0, speed – 1)

   Stochastic acceleration:

   If probability < P_a

   Speed = Minimum (Maximum speed (vehicle type), speed + 1)

4. updating vehicle position based on the updated speed

Lane changing behavior proposed by Chowdhury et. al. (1997) is used in the present work except that the lane changing can be done on to the left side or to the right side.

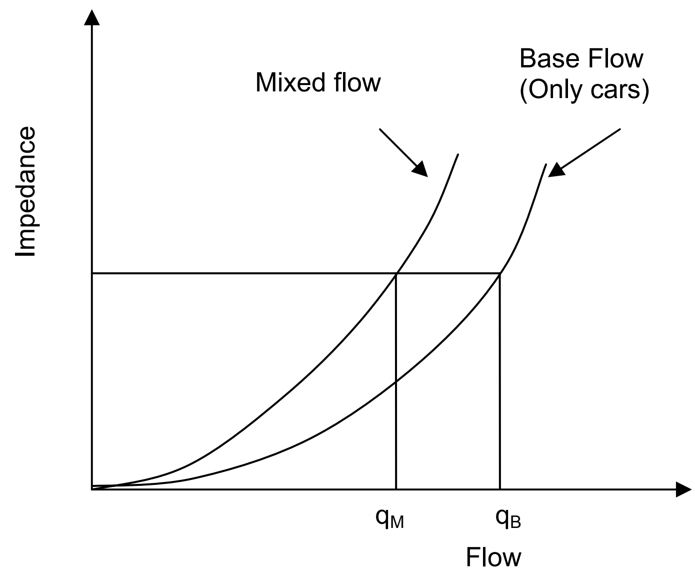

Figure 2: PCE derivation methodology proposed by Huber

PCE Estimation

The methodology proposed by Huber (1982) is used in this work to estimate PCE values. Huber assumed that a flow rate q_B of a base stream (containing only cars) and a flow rate q_M of a mixed stream, containing a proportion p of trucks and a proportion *(1-p)* of cars that shows the same performance measure, can be equated in the following way,

$$q_B = (1-p) * q_M + e * p * q_M \tag{2}$$

where e is the PCE of the trucks.

The procedure for the determination of q_M, q_B and e is described in the following four steps:

1. establish the relationship between the performance measure and flow rate for the base stream, containing passenger cars only
2. establish the relationship between the performance measure and flow rate for the mixed stream, containing *(1-p)* fraction of passenger cars and p fraction of trucks
3. find equivalent flow rates q_M and q_B for the same performance measure value as shown in **Figure 2** and
4. calculate the equivalence factor e

The above procedure is used to estimate the PCE values for buses, trucks and TWs. The effect of a combination of more than one vehicle in addition to cars is not considered in the present study.

Performance measure

Different performance measures are used in estimating PCE values under different traffic conditions. When estimating the PCE values for mid-block sections speed, vehicle-hours or density are commonly used performance measures. In the present work also PCE values are estimated for a mid-block section. Since PCE values are very important in analysing the mixed traffic flow, it is necessary that these values must represent reality. Density, from the definition will be representing the absolute number of vehicles over a unit road length. As discussed earlier, the absolute number of vehicles has no meaning under mixed traffic conditions. If the density is estimated from the occupancy, which is a normal practice now-a-days, it could incorporate vehicle length. Since mixed traffic consists of so many types of vehicles including small sized motorized two wheelers to large sized tractor trailers, even occupancy could not represent the actual traffic conditions. Due to the presence of small size vehicles lane discipline is not observed under mixed traffic conditions. To overcome this problem, a new metric called area occupancy is used in place of density. A detailed description of this new parameter is discussed in the following section.

Area occupancy

The conventional traffic characteristics may not exactly depict the collective traffic behavior moving in a 3-D region, including 2-D for the roadway (longitudinal and transverse) and 1-D for the time (Lan and Hsu 2006). To overcome these difficulties, in estimating this new metric, the absolute width of the road is considered irrespective of number of lanes. If this is the case, at any time instance there can be more than one vehicle depending on the vehicle size, across the road width. This term also considers the size of the vehicle, which has a significant bearing on the traffic behavior in mixed traffic conditions. For example, a truck moving with the same speed that of a two-wheeler will cause a bigger deterioration in the level of service due to its size, limited maneuverability and acceleration/deceleration characteristics compared to the two wheeler. When considering a small section (e.g. detector) of the road, *Area occupancy* expresses for how long a particular size of the vehicle is moving on that section of the road. Like occupancy, area occupancy can also be measured over time (*Temporal Area occupancy*). In the present work area occupancy measured over a general measurement region (over time T and over space L * W) is used and referred to through out this paper (Mallikarjuna and Ramachandra Rao 2006a).

$$\rho_A(A) = \frac{\sum_{i=1}^{N} \frac{L - x_i}{v_i} * w_i * l_i}{T * W * L} \tag{3}$$

where $\rho_A(A)$ is area occupancy measured over space and time across the entire road width; L is the length of the road section under consideration; x_i denotes the distance between the vehicle and any of the two reference lines, measured along the road length. This is significant at the beginning and at the end of the observation period when there will be some vehicles located on the road section. If there are no vehicles located on the observed road section at the beginning or at the end of the observation period, x_i becomes zero. $L - x_i$ denotes the actual distance traveled by the i^{th} vehicle over the observed road section; w_i is the width of the i^{th} vehicle; W is the width of the road and it is assumed to be constant for the entire road section.

While measuring this quantity it is assumed that the all vehicles are travelling in a straight line path over the observed road section. If it is possible to measure the total distance traveled by any vehicle (in case it is not equal to L), in the above formula L can be replaced with the measured distance.

In the present CA model taking this measurement is very easy as proposed by Lan and Hsu (2006) which is shown below

$$\rho_A(A) = \frac{\sum_{\Delta t} N_0(t) * \Delta t}{\sum_{\Delta t} N * \Delta t} \tag{4}$$

where the numerator denotes the total time spent by all the cells (vehicle is composed of several cells) in the general measurement region and the denominator denotes the total volume of the general measurement region; $N_0(t)$ denotes the number of cells occupied by vehicles in the measurement area $L * W$ at any time instance Δt; N is the total number of cells in the measurement region; Δt is the time increment used in CA model.

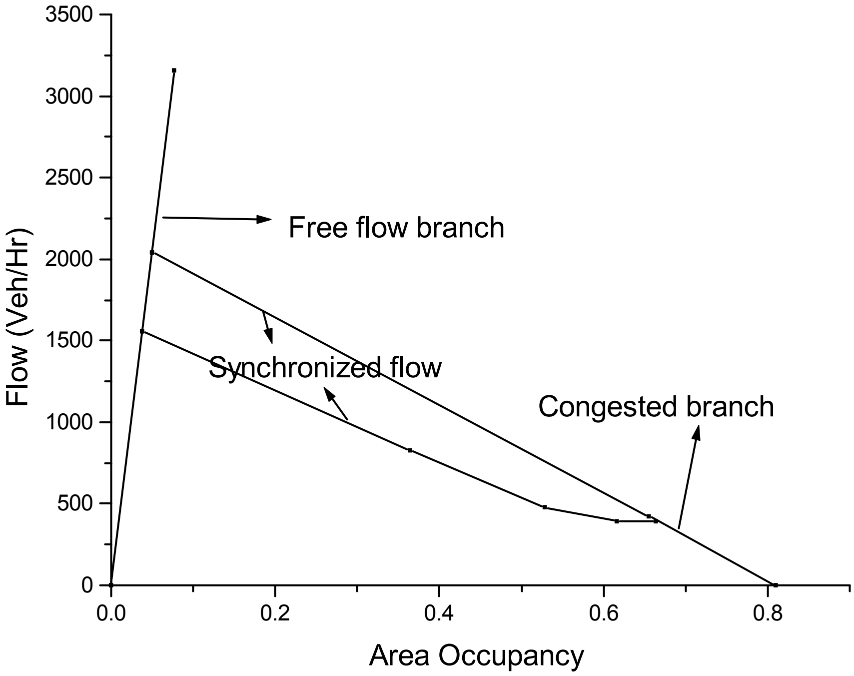

Figure 3: Relation between flow and area occupancy from the simulation model

RESULTS AND ANALYSIS

Results obtained from the CA based simulation model are presented in this section. First base flow, which consists of cars only, is simulated. The relationship between flow in vehicles/hr and area occupancy in fraction of the road space occupied by the vehicles is shown in **Figure 3.** In the congested regime, as shown in Fig. 3, the relationship between flow and area occupancy is two dimensional. It is similar for different types of vehicles when modeled individually and modeled together. Due to this reason after certain area occupancy value the PCE of a particular type of vehicle can take different values. This is true if the flow takes different values at the same density. According to the three phase traffic theory proposed by Kerner (1999), even under equilibrium conditions flow – density relationship is two dimensional and is known as synchronized flow.

As shown in Table 2, two wheelers are getting congested at lower area occupancy values when compared to the other three types of vehicles. This is the case even for mixed traffic stream with different proportions of TW ranging from 10% to 100% in addition to cars. Due to this reason as the area occupancy value increases the PCE value for TW is increasing. For an area occupancy value of 0.05, where the cars are still maintaining free flow or just transforming into synchronized flow, TW traffic is well into synchronized flow and on the verge of transformation into congested regime. Due to this reason the PCE value is as high as one when 10% TWs are present in the mixed traffic stream in addition to cars.

When compared to traffic stream consists of only cars, mixed traffic (cars plus either trucks or buses) is getting congested at higher area occupancy values. This is resulting due to the high proportion of the road space occupied (high area occupancy) by heavy vehicles even when less number of heavy vehicles are present on the road. Because of this, maximum PCE value for both bus and truck is increasing at low proportions and remains constant at high proportions with increasing area occupancy. This is reverse in case of minimum possible PCE value at different proportions of both trucks and buses. One more important phenomenon that can be seen from the observed results is that the PCE value for Bus is higher when compared to truck. This is due to the area occupied by bus which is more when compared to truck and mechanical characteristics (maximum speed, acceleration etc.) used for both vehicles are same. In **Figure 4**, variation in maximum possible PCE values for different proportions of buses, trucks, and TWs at an area occupancy of 0.0378 is shown. As the proportion of trucks is increasing the PCE value of bus and truck is coming down and for TW it is fluctuating at around 0.5.

Due to the lack of proper empirical data at microscopic and macroscopic levels, calibration and validation of this model was not carried out. In some of the previous studies on mixed traffic calibration and validation was done at microscopic level (Singh, 1999; Arasan and Koshy, 2005). However, the relevance of the parameters used in these studies is difficult to justify. A suitable data collection methodology for mixed traffic is currently under development (Mallikarjuna and Ramachandra Rao 2006b).

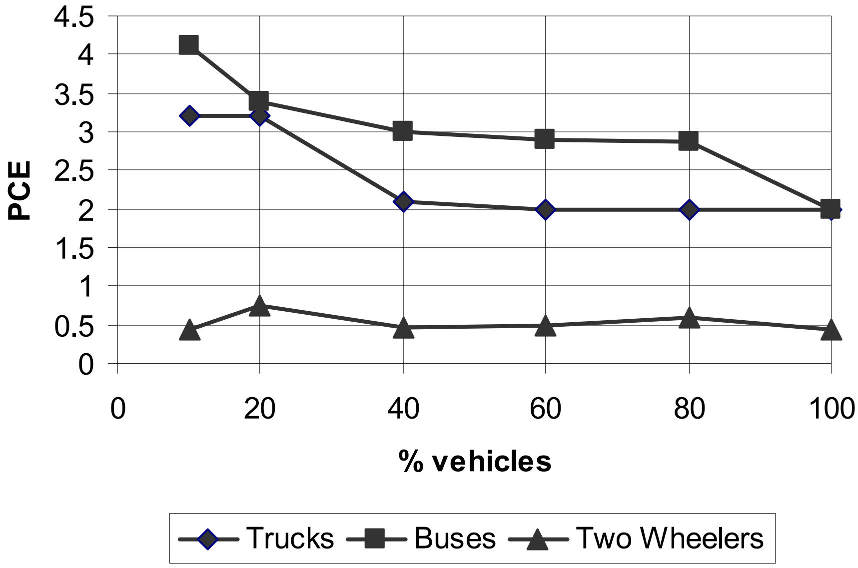

Figure 4: PCE variation at different proportions of buses, trucks and TWs at an area occupancy of 0.0378

Table 2: PCE values for different vehicles obtained from the simulation model

% Vehicles	Vehicle type	Area occupancy	PCE(max)	PCE(Min)
10%	Truck	0.038	3.20	3.20
		0.041	3.20	2.40
		0.050	6.00	1.00
	Bus	0.038	4.10	4.10
		0.039	4.10	3.60
		0.050	7.80	1.00
	TW	0.036	0.10	0.10
		0.038	0.44	0.10
		0.050	1.00	0.52
20%	Truck	0.038	3.20	3.20
		0.043	3.20	2.40
		0.050	4.63	1.36
	Bus	0.038	3.40	3.40
		0.043	3.40	2.66
		0.050	4.80	1.60
	TW	0.029	0.10	0.10
		0.038	0.76	0.10
		0.050	0.79	0.53
40%	Truck	0.038	2.10	2.10
		0.043	2.10	1.70
		0.050	2.73	1.20
	Bus	0.038	3.00	3.00
		0.050	3.00	1.88
		0.055	3.00	1.50
	TW	0.028	0.10	0.10
		0.038	0.46	0.10
		0.050	0.46	0.34
60%	Truck	0.038	2.00	2.00
		0.044	2.00	1.60
		0.050	2.33	1.28
	Bus	0.038	2.90	2.90
		0.050	2.90	1.95
		0.061	2.90	1.56
	TW	0.025	0.10	0.10
		0.038	0.48	0.12
		0.050	0.88	0.12
80%	Truck	0.038	2.00	2.00
		0.044	2.00	1.50
		0.050	2.00	1.32
	Bus	0.038	2.86	2.86
		0.050	2.86	1.00
		0.076	2.86	1.23
	TW	0.021	0.22	0.22
		0.038	0.60	0.25
		0.050	0.87	0.25
100%	Truck	0.038	2.00	2.00
		0.050	2.00	1.50
		0.062	2.00	1.23
	Bus	0.038	2.00	2.00
		0.050	2.00	1.50
		0.089	2.00	1.23
	TW	0.021	0.26	0.26
		0.038	0.45	0.36
		0.050	0.60	0.36

SUMMARY AND CONCLUSIONS:

PCE values are crucial in traffic flow analysis and in capacity estimates. Under mixed traffic conditions these values are more important since several types of vehicles are present in the traffic stream. A simulation model with appropriate performance measure is crucial in estimating the PCE values under these traffic conditions. A CA based simulation model, modified to model the mixed traffic is used in estimating the PCE values. Since density can not represent the mixed traffic characteristics a new metric called area occupancy is used as performance measure in estimating the PCE values under these conditions. This new metric is incorporated with speed and area of different vehicles which are crucial traffic characteristics under mixed traffic conditions. Since the CA model is based on three phase traffic theory, immediately after free flow, the flow vs. area occupancy relationship is two dimensional which is termed as synchronized flow. This phenomenon leads to a range of PCE values once the free flow conditions disappear. Estimated PCE values for buses, trucks and two wheelers are following the usual decrement with increase in their proportion. Since the PCE value for bus is higher than truck when both are having similar mechanical characteristics, it is proved that area occupancy is considering both area as well as mechanical characteristics of the vehicles. Further work would be carried out for different combinations, where the traffic stream consists of more than two vehicle classes.

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