Occupancy time-based passenger car equivalents at unsignalized intersections in India

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In developing countries, one of the vital steps involved in analysing the capacity of any transportation facility is the estimation of passenger car equivalents (PCEs) for different types of vehicles to convert the heterogeneous traffic stream into an equivalent stream of passenger cars. This study proposes occupancy time method for the estimation of PCEs for different types of vehicles generally observed at unsignalized intersections in India. PCEs for vehicles executing different movements at unsignalized intersections have been estimated in this study and the dynamic nature of PCEs has also been explored. However, PCEs were found to be statistically similar across different movements and across intersections of different geometry.

Keywords: Heterogeneous traffic conditions, occupancy time, passenger car equivalents, unsignalized intersections.

TRAFFIC in developing countries is characterized by the presence of a wide variety of motorized and non-motorized vehicles that share the same road space. Differences among vehicular traffic exist not only in their physical dimensions, but also in their operational characteristics and hence the performance of a vehicular category within a transportation facility will also depend on the proportions of other types of vehicles constituting the traffic stream. In order to evaluate the performance of a facility operating under heterogeneous traffic conditions, it is essential to convert the traffic stream in terms of a single vehicle type. This is achieved by the use of multiplicative factors termed as passenger car equivalents (PCEs) or passenger car units (PCUs).

The term PCE was first introduced in the 1965 edition of the *Highway Capacity Manual* (*HCM*)[1], to account for the effect of trucks and buses in the traffic stream on the basis of relative speed reduction. Prior to this, an equivalency factor of 2 was used for heavy vehicles on multilane highways in level terrain[2]. HCM[1] defined PCE as the number of passenger cars displaced from the traffic stream by a truck or a bus under the prevailing roadway and traffic conditions. An alternate definition was given by the UK Transport and Road Research Laboratory (TRRL)[3] as the number of cars of average size which when added to a traffic stream reduces the average speed of the remaining vehicles by the same amount as resulted from adding a single truck under prevailing traffic conditions. The latest edition of *HCM*[4] defined PCE as the number of passenger cars that will result in the same operational conditions as a single heavy vehicle of a particular type under specified roadway, traffic and control conditions.

Over the years, researchers used different measures to estimate PCE on various roadway facilities. They emphasized the need of utilizing the same parameters that are used in defining the level of service of the facility, as the basis of equivalence[5]. Some of these parameters include speed[6–8], density[5,9], headway[10,11], delay[12], queue discharge flow[13], area occupancy[14], platoon formation[7], etc. As an alternative to PCE, researchers have also developed equivalent factors in terms of motorcycles[15,16]. A previous study by the present authors compared three approaches for establishing PCE factors at unsignalized intersections in India[17]. It was found that the approach based on occupancy time is simpler for field application and suitable to all types of traffic conditions in comparison to other methods based on potential capacity and queue clearance rate.

Analysis of unsignalized intersections is often based on the assumption that major street traffic passes through the intersections unhindered. However, an earlier study found that the priority rules are not observed at intersections in India and even the major street traffic is forced to slow down by the minor street vehicles as they approach an intersection[18]. Hence it would be erroneous to use PCE values obtained at mid-block sections for removing the heterogeneity of the major street through traffic at unsignalized intersections. Therefore, in order to find the capacity of various movements at unsignalized intersections, it is essential to correctly estimate the PCE factors for different types of vehicles at these intersections. PCE values for unsignalized intersections currently used in India are given in IRC:SP 41-1994 (ref. 19), which is now more than 20 years old. A lot of improvement has occurred in the automobile industry over the years and hence using these values is not recommended. The present study estimates the values of PCE at unsignalized intersections for the present traffic scenario in India on the basis of the time that a particular vehicle type incurs in clearing the conflict area of the intersection.

Data were collected from unsignalized intersections located in different parts of India. These intersections were located in rural and semi-urban areas and were free from the effect of bus stops and pedestrians. Approaches to the intersections were free from speed-breakers, gradients and intersected one another at right angles. Table 1 provides geometric details of the intersections selected for this study. The first letter of the adopted nomenclature represents the intersection geometry (F, four-legged and T, three-legged); the first and second

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Table 1. Details of selected intersections

Location	Geometry	Major street	Minor street	Adopted nomenclature
Thiruvananthapuram, Kerala	Four-legged	Two-lane	Two-lane	F-22-1
Meerut, Uttar Pradesh	Four-legged	Four-lane	Two-lane	F-42-1
Faridabad, Haryana	Three-legged	Four-lane	Four-lane	T-44-1
Dwarka, Delhi	Three-legged	Four-lane	Four-lane	T-44-2
Bhubaneswar, Odisha	Three-legged	Two-lane	Two-lane	T-22-1
Maraimalai, Tamil Nadu	Three-legged	Four-lane	Two-lane	T-42-1
Peth Naka, Maharashtra	Four-legged	Four-lane	Two-lane	F-42-2
Khalapur Phata, Maharashtra	Three-legged	Four-lane	Two-lane	T-42-2

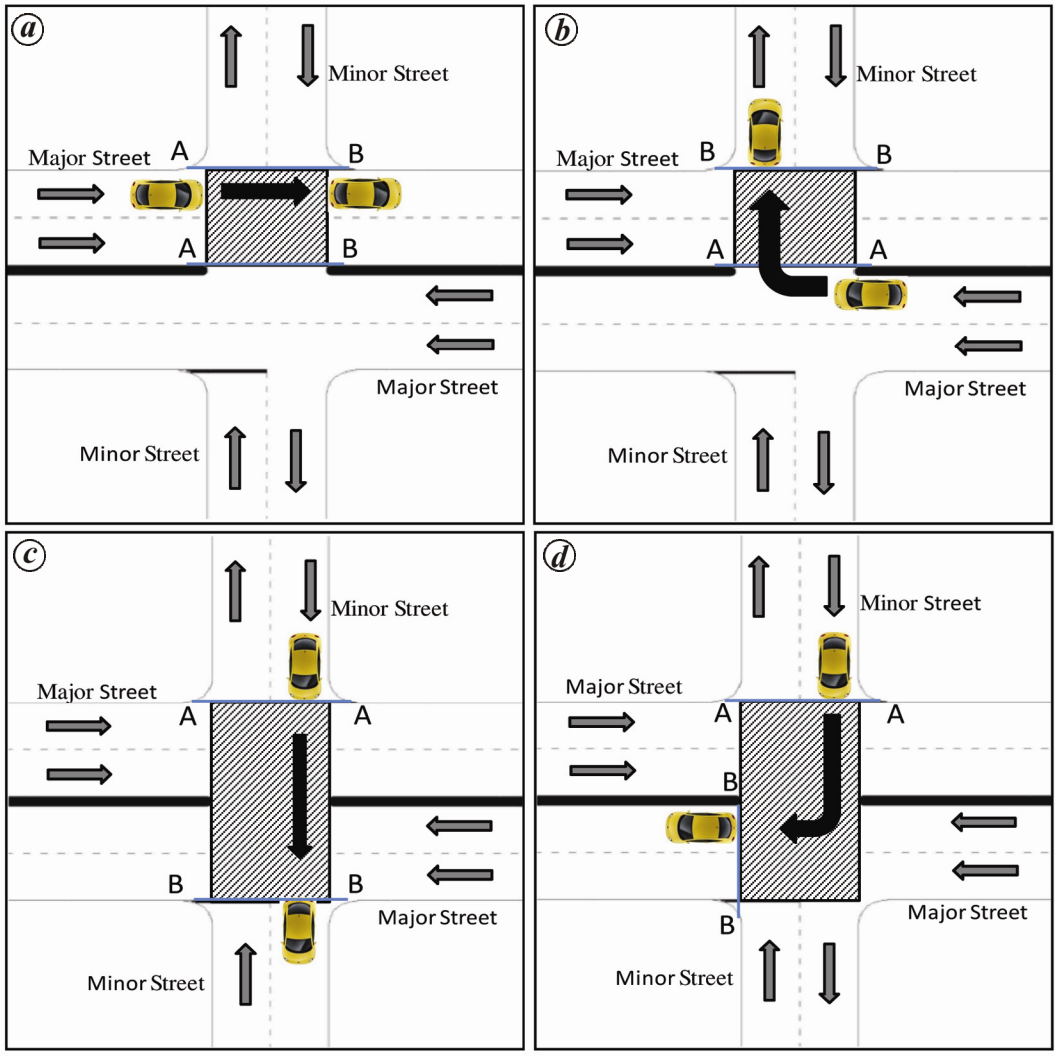

Figure 1. Conflict area at an unsignalized intersection. ***a***, Through on major; ***b***, right turn from major; ***c***, through on minor; ***d***, right turn from minor.

numerals respectively, represent the number of lanes on the major and minor streets (2, two-lane and 4, four-lane) and the last numeral represents the intersection number within a particular category (i.e. three-legged or four-legged). For example, F-42-2 is the second intersection having four legs constituted by a four-lane major street and a two-lane minor street.

Data were collected through video-recording with the camera placed at a vantage point so as to cover the entire conflict area of the intersection. Conflict area refers to the

region within the intersection where two or more traffic streams interact and compete for right of way. Figure 1 shows the conflict area for different movements at an intersection having four-lane divided major street. Occupancy time is measured as the time elapsed between the arrival of a vehicle at one end of its conflict area and its complete exit from the other end of the conflict area. Table 2 gives dimensions of different types of vehicles commonly found at intersections in India.

Occupancy time specifies the total time that a vehicle incurs in clearing the conflict area of the intersection. This will be the function of driver behaviour, intersection geometry, subject vehicle type, opposing traffic and the manner in which the conflict area is cleared. Thus, the occupancy time of a vehicle heavily relies upon the length and operational performance of the vehicle. A motorized two-wheeler is expected to have lesser occupancy time compared to a heavy vehicle. Therefore, occupancy time of a vehicle is a good measure of its impedance to traffic within the same stream as well as in the conflicting streams and hence it is used for estimating the PCE factors in this study.

Occupancy time data of two-wheelers and standard cars at intersections T-44-2 and F-42-2 were extracted from the videos. These datasets indicated a log-normal distribution with the parameters as given in Table 3. The distribution was validated through KS test. The variation in the occupancy times at an intersection could be mainly attributed to the difference in driver behaviour while clearing the intersection. While lower values of occupancy times to a large extent represent aggressive drivers, higher occupancy times are indicative of cautious drivers. Hence, the mean occupancy time was selected for estimating PCE at intersections as it would represent a balanced state between aggressive and cautious drivers.

The absence of lane discipline is quite common to traffic operations under heterogeneous traffic conditions. Vehicles move abreast within the same lane, even while clearing the intersection. Hence, the effect of vehicle width cannot be ignored as this parameter largely influences traffic operation within the conflicting stream. Presence of wider vehicles in the crossing or turning stream will discourage smaller-sized vehicles from fully utilizing their operational potential.

PCE factors of different vehicle types at uncontrolled intersections were estimated by considering the occupancy time and width of a vehicle type with respect to standard cars, as given by eq. (1). The ratio of occupancy times in eq. (1) signifies the relative effect of a vehicle on the subject and conflicting streams in comparison to standard cars. Further, owing to the loose lane discipline prevalent in India, vehicles clear the intersection area by travelling abreast also, and hence the width of the vehicles becomes a significant parameter in quantifying their impact[17]. Readers are encouraged to refer to the authors' publication[17] for further details regarding the occupancy time method.

$$\mathrm{PCE}_i = \frac{OT_i}{OT_{\mathrm{cs}}} \times \frac{W_i}{W_{\mathrm{cs}}}, \tag{1}$$

where OT_i is the average occupancy time of a vehicle type i(s), OT_{cs} the average occupancy of standard car (s), W_{cs} the width of standard car (m), W_i the width of vehicle type i (m) and PCE_i for vehicle type i.

Based on measured occupancy time, PCE values of vehicles executing various movements at the intersection were computed using eq. (1). Table 4 gives the estimated PCE values for major street vehicles travelling straight through different intersections. Similarly, PCE values for other movements at the intersections were established. Two-wheelers, owing to their smaller size and better operational performance, were able to clear the conflict area of the intersection quickly and hence had the least PCE value. While large-sized vehicles like trucks and buses had larger PCE value, which is the result of their larger size and inferior operational characteristics.

We examined the variation in PCE estimates of different types of vehicles among unsignalized intersections of similar and different geometry, and among different movements. PCE values were estimated for each 15 min duration of observation period and two-tailed t-test was used for comparing the mean PCE value of each type at 95% confidence level. According to the null hypothesis, there is no significant difference among means of PCE values for a vehicle category. According to the alternate hypothesis, the mean PCE values for a vehicle type executing different movements and at different intersections varied significantly. Intersection T-44-2 was used as the base for comparison as it had good sample size for individual vehicle categories executing different movements.

PCE values for different types of vehicles at one intersection were checked for their applicability to intersections of similar geometry. T-Test for difference among

Table 2. Dimensions of different vehicle categories

Vehicle type	Length (m)	Width (m)	Area (m^2)
Motorized two-wheelers (2W)	1.87	0.64	1.20
Motorized three-wheelers (3W)	3.20	1.40	4.48
Standard cars (CS)	3.72	1.44	5.36
Big cars (CB)	4.48	1.80	8.06
Light commercial vehicles (LCV)	6.10	2.10	12.81
Buses (BUS)	10.10	2.43	24.54
Two-axle/three-axle trucks (TRUCK)	7.50	2.35	17.63
Multi-axle vehicles (MAV)	15.24	2.44	37.19
Tractors	3.40	1.85	6.29
Tractors with trailer	7.40	2.20	16.28
Pedal cycles	1.90	0.45	0.86
Cycle rickshaws	2.70	0.95	2.57
Animal-drawn vehicles	5.50	1.75	9.63

Table 3. Distribution parameters of occupancy time for turning movements

Intersection	Movement	Vehicle type	Parameters(s)		KS test	
			Mean	Standard deviation	Observed	Critical*
T-44-2	RT major	2W	0.975	0.314	0.120	0.146
		CS	1.197	0.347	0.091	0.168
	RT minor	2W	1.390	0.315	0.098	0.116
		CS	1.612	0.296	0.045	0.094
F-42-2	RT major	2W	0.827	0.296	0.085	0.149
		CS	1.071	0.262	0.066	0.161
	TH minor	2W	1.711	0.270	0.042	0.097
		CS	1.926	0.269	0.064	0.184
	RT minor	2W	1.863	0.302	0.067	0.189
		CS	2.040	0.273	0.165	0.468

*At 99% level of significance.

Table 4. PCE values for through movement on major roads

Vehicle type	T-44-1	T-44-2	T-42-1	F-42-1	F-42-2	T-22-1	F-22-1
2W	0.454	0.476	0.461	0.563	0.587	0.399	0.383
3W	1.187	1.147	1.144	–	–	1.041	0.855
CB	1.302	1.228	1.219	1.185	1.440	1.228	1.245
LCV	1.845	1.854	1.570	1.896	1.976	1.695	1.844
BUS	2.251	2.301	2.199	2.316	2.325	–	1.963
TRUCK	2.233	2.533	2.003	2.496	2.884	–	1.927

–, Indicates absence of significant sample size.

Table 5. *t*-Test comparing mean PCE among intersections of similar geometry

Movement	Intersection	Statistics	Vehicle type					
			2W	3W	CB	LCV	BUS	TRUCK
RT major	T-44-2	Mean	0.346	0.938	1.067	1.909	2.413	–
	T-44-1	Mean	0.350	–	1.256	1.848	–	–
		t-Observed	0.120	–	1.255	–0.210	–	–
		t-Critical	2.110	–	2.160	2.201	–	–
		Significantly different	No	–	No	No	–	–
	T-42-1	Mean	0.282	0.781	1.215	1.468	2.703	–
		t-Observed	–1.476	–2.088	1.114	–1.859	0.657	–
		t-Critical	2.069	2.262	2.160	2.160	2.447	–
		Significantly different	No	No	No	No	No	–
RT minor	T-44-2	Mean	0.355	0.936	1.320	1.724	–	2.222
	T-44-1	Mean	0.408	–	1.210	1.730	–	2.591
		t-Observed	1.752	–	–1.241	0.032	–	1.190
		t-Critical	2.228	–	2.228	2.262	–	2.262
		Significantly different	No	–	No	No	–	No
	T-42-1	Mean	0.340	1.053	1.544	1.708	–	1.819
		t-Observed	–0.396	0.987	1.081	–0.080	–	–1.605
	T-42-1	*t*-Critical	2.228	2.306	2.306	2.228	–	2.228
		Significantly different	No	No	No	No	–	No

means was conducted between PCE values estimated at intersections T-44-2 and those at intersections T-44-1 and T-42-1. Table 5 provides the results of the above comparison. It can be concluded that there is no difference in the mean PCE values among intersections of similar geometry.

PCE values at a three-legged and four-legged intersection were then compared. Table 6 provides the results of the above comparison. This analysis found the PCE values to be statistically similar for intersections T-44-2 and F-42-2. However, all the previous analyses were carried out at intersections having the same major street

Table 6. *t*-Test comparing mean PCE among three-legged and four-legged intersections

Movement	Intersection	Statistics	Vehicle type				
			2W	3W	CB	LCV	BUS
RT major	T-44-2	Mean	0.346	0.938	1.067	1.909	2.413
	F-42-2	Mean	0.393	1.027	1.338	1.860	2.378
		t-Observed	1.361	0.760	2.118	–0.180	–0.077
		t-Critical	2.101	2.131	2.664	2.101	2.145
		Significantly different	No	No	No	No	No
RT minor	T-44-2	Mean	0.355	0.936	1.320	1.724	–
	F-42-2	Mean	0.386	–	1.426	1.460	–
		t-Observed	0.673	–	0.671	–1.770	–
		t-Critical	2.201	–	2.228	2.365	–
		Significantly different	No	–	No	No	–

Table 7. *t*-Test for mean PCE at intersections of different major street configurations

Movement	Intersection	Statistics	Vehicle type			
			2W	3W	CB	LCV
RT major	T-44-2	Mean	0.346	0.938	1.067	1.909
	T-22-1	Mean	0.318	0.855	1.167	1.707
		t-Observed	–0.608	–1.086	0.781	–0.730
		t-Critical	2.145	2.228	2.145	2.160
		Significantly different	No	No	No	No
	F-22-1	Mean	0.282	1.049	1.615	2.047
		t-Observed	–1.476	0.496	2.023	0.271
		t-Critical	2.069	2.145	2.160	2.131
		Significantly different	No	No	No	No

configuration (i.e. four-lane divided). In order to check the influence of major street configuration on PCE values, *t*-test was again carried out between PCE values at intersections T-44-2, T-22-1 and F-22-1. As given in Table 7, there is no statistical difference among the mean PCE values at intersections having different major street configurations.

The final step in ensuring that PCE values at uncontrolled intersections are static in nature is to compare the mean PCE values among different movements. Table 8 provides the results of *t*-test that compared the mean PCE values for different movements at intersection F-42-2. It is clear that except for two-wheelers on major street that travelled straight through the intersection, PCE values for all other vehicle types are statistically similar. This further provides evidence for the static nature of PCE.

The above analysis indicated that apart from two-wheelers travelling straight through the intersection, there were no statistical differences between the PCE values across intersections of different geometry and across different movements. Hence PCE values at unsignalized intersections in India are static in nature, and the final PCE values were obtained by taking the overall average of PCE values for different movements at selected intersections estimated through occupancy time method. PCE values of two-wheelers travelling straight through the intersection were considered separately. PCE values of vehicle types which were present in smaller numbers were also obtained in a similar manner; however, due to the smaller sample size, these were not used in the comparison. Table 9 shows the final PCE values for different types of vehicles applicable to unsignalized intersections in India.

This study has established the static nature of PCEs, which is different from majority of the studies which found PCEs to be dynamic in nature. However, it is worth noting that these studies were conducted on mid-block sections where there were large differences among the speeds of different vehicles. Since the vehicles are forced to slow down as they approach an intersection, their speeds becomes similar and thus their size prominently contribute towards PCEs which will result in fixed values of PCE at unsignalized intersections as derived in this study.

Although the determination of PCEs is a vital step in the analysis of unsignalized intersections in heterogeneous traffic conditions, not much research has been conducted in the past on this topic. Most of the studies on PCEs is limited to uninterrupted flow facilities and signalized intersection. The only available guideline for

Table 8. *t*-Test for mean PCE for different movements

Movement	Statistics	Vehicle type					
		2W	3W	CB	LCV	BUS	TRUCK
RT major	Mean	0.393	1.027	1.376	1.860	2.378	2.110
RT minor	Mean	0.419	–	1.426	1.307	–	–
	t-Observed	–0.299	–	–0.300	1.574	–	–
	t-Critical	2.145	–	2.074	2.160	–	–
	Significantly different	No	–	No	No	–	–
TH minor	Mean	0.341	1.116	1.365	1.709	2.063	2.466
	t-Observed	1.663	-0.906	0.085	0.638	1.053	1.684
	t-Critical	2.001	2.080	2.040	2.069	2.086	2.056
	Significantly different	No	No	No	No	No	No
TH major	Mean	0.631	–	1.443	2.027	2.331	2.902
	t-Observed	–4.232	–	–0.438	-0.588	0.129	–1.610
	t-Critical	2.201	–	2.074	2.131	2.131	2.110
	Significantly different	Yes	–	No	No	No	No

Table 9. Recommended PCE values at unsignalized intersections in India

Vehicle type	PCE
Motorized two-wheelers	0.48 – through movement on major 0.34 – all others movements
Motorized three-wheelers	0.98
Standard cars	1.00
Big cars	1.29
Light commercial vehicles	1.70
Buses	2.29
Two-axle/three-axle trucks	2.34
Multi-axle vehicles	3.06
Tractors	1.62
Tractors with trailer	3.13
Bicycles	0.42
Cycle rickshaws	1.29
Animal-drawn vehicles	3.85

PCEs at unsignalized intersections in India is the IRC SP-41 (ref. 19), which is outdated in the present traffic scenario.

This study uses occupancy time as the criterion for arriving at PCE values, as it explains the relative influence of a vehicle on the traffic stream while clearing the intersection. PCE values, thus obtained, were then checked for variations across movements and also across intersections of different geometry. The study established that PCE values for vehicles at intersections were static in nature and generalized PCE values applicable for Indian intersections have been developed in this study, which could be used by researchers and field engineers in ascertaining the capacity of the intersections. In short, the present study demonstrates the application of occupancy time method to arrive at generalized PCE values at unsignalized intersections in India.

Estimating PCEs is one of the most common steps in analysing any transportation facility in heterogeneous traffic conditions. Peculiar characteristics of traffic operations at unsignalized intersections emphasize the need for separate PCE factors at such facilities. Currently, PCEs at unsignalized intersections in India are taken from old manual, and it becomes essential to have PCE values that are relevant to the present traffic scenario in the country.

This study uses a method based on the time that a vehicle incurs in clearing the intersection area and its width in relation to standard passenger cars. The variation in PCE values at unsignalized intersections of different geometry and executing different movements was explored for statistically significant differences. However, apart from two-wheelers moving straight through the intersection, PCE values for different vehicles were statistically similar and hence the study found PCE values at unsignalized intersections to be static in nature.

The standard-type unsignalized intersections (right-angled and free from speed breakers and gradients) only are considered in the present study. Skewed intersections or those with approach having gradients or speed-breakers are not considered because of their low population. However, these conditions will definitely influence the occupancy time and hence will result in a different set of PCE values. This will be considered in future research.

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