Discharge Characteristics of Heterogeneous Traffic at Signalized Intersections

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ABSTRACT

The discharge characteristics of heterogeneous traffic, with a wide variation in vehicle characteristics, are significantly different from homogeneous traffic. In this paper, the speed at which heterogeneous vehicles move through the intersection area is analyzed in detail for four different motorized vehicle types — two-wheelers (motorcycles and scooters), three-wheelers (autorickshaws), cars, and buses. Traffic flow data captured on video are digitally analyzed to determine vehicle positions every second for three intersections in two Indian cities, Baroda and New Delhi. A coordinate conversion procedure is applied to obtain roadway coordinates from screen coordinates, and the speed of the vehicles is determined. The analysis shows that for a given intersection, the speed at which vehicles traverse the intersection space (clearing speed) does not vary significantly by vehicle type. It is expected that such detailed studies of discharge characteristics will help determine methods to estimate capacity at signalized intersections for heterogeneous traffic.

1. INTRODUCTION

Heterogeneous or mixed traffic systems operate very differently, compared to homogeneous traffic systems, due to the wide variation in the operating and performance characteristics of the vehicles. The traffic in mixed flow is comprised of fast moving and slow moving vehicles or motorized and non-motorized vehicles. The motorized vehicles include cars, buses, trucks, auto-rickshaws (three-wheelers), scooters, and motorcycles (both two-wheelers); and the non-motorized vehicles include bicycles, human-powered or cycle-rickshaws, and animal-driven carts. The vehicles also vary in size, maneuverability, control, and static and dynamic characteristics. Traffic is not segregated by vehicle type and therefore, all vehicles travel in the same right of way.

The movement of heterogeneous traffic is depicted in Figure 1. Lane markings are typically not provided for heterogeneous traffic conditions. Mixed flow traffic does not move in single files. On the contrary, there is a significant lateral movement, primarily by the smaller sized motor vehicles (bicycles, motorcycles, mopeds, and scooters). At intersections specifically, smaller vehicles use the lateral gaps between larger vehicles in an attempt to reach the head of the queue. Traffic in India follows the left hand drive rule, which is the opposite of the driving rule in the U.S.

FIGURE 1 Heterogeneous traffic at two intersection approaches.

The primary vehicle types are similar in most developing and developed countries. However, there are some vehicle types that are regional and found only in specific areas of the world or in specific countries. Data for this study has been collected in India, where the three-wheeled motorized auto-rickshaw is a significantly different type of vehicle. It is primarily used to transport people (as a taxi), although it is sometimes also used to transport freight. Vehicle characteristics and vehicle sales data for 7 types of vehicles are presented in Table 1.

TABLE 1 Vehicle Size and Sales Characteristics*

Vehicle Type	Length (m)	Width (m)	Vehicle Sales (1997)	Percentage of 1997 Motorized Vehicle Sales
Two-wheelers	1.85	0.70	2,288,460	71.3%
Auto-rickshaws	2.60	1.25	215,580	6.7%
Cars	3.65	1.50	410,810	12.8%
Buses	10.10	2.45	75,570	2.4%
Trucks	9.00	2.45	75,570	2.4%
Small Trucks	6.15	2.15	145,820	4.5%
Bicycles	1.50	0.50	—	—

* Association of Indian Automobile Manufacturers (1997). Vehicle sizes also measured.

As presented in Table 1, the two-wheeler vehicle is predominant and significantly smaller than other types of vehicles. It may be mentioned that the vehicle size of cars is significantly smaller compared to a typical car in industrialized countries [e.g., U.S. passenger car design vehicle: length = 5.8 m and width = 2.1 m (American Association of State Highway and Transportation Officials 1994)].

2. VIDEO DATA COLLECTION AND ANALYSIS

Vehicle flow and speed data can be collected in a number of different ways. Full motion video recording of traffic flow was used to collect data in India. This method offers several advantages. The video provides an accurate record of the data. In addition, the impact of special conditions can be considered. For example, if in a certain signal cycle, the discharge of vehicles is impacted by a vehicle not moving for a long period of time, that data can be isolated and analyzed separately.

The data collection and analysis procedure is described in detail separately (Maini and Khan 2000), and only a summary is provided here. Traffic flow data were recorded for three hours at thirteen intersection approaches at five different intersections in Baroda and New Delhi, India in October 1998. All the video recordings were digitally transferred at the rate of one frame per second. A recently developed tool, Vehicle Video Capture Data Collector (VEVID) (Wei et al. 1999), was used to determine the screen coordinates of vehicle positions by manually viewing individual frames of the transferred data. A specific video card (ATI Technologies 1998) used with VEVID was also used for this study.

A coordinate conversion procedure used in traffic studies 15 to 30 years ago (Huber and Tracy 1968, Chari and Badarinath 1983, Maini and Khan 2000) was used to convert the screen coordinates to roadway coordinates. The procedure is based on the one-to-one correspondence between the two spaces. Based on the x and y coordinates of four known points, with no three in a straight line, the correspondence can be established. Thus, the roadway coordinates for individual vehicles were determined at one-second intervals, and dynamic characteristics such as acceleration rate, deceleration rate, speed at which deceleration starts, and the speed achieved on accelerating from the intersection were determined. The estimated and actual roadway location measurements differed by –1.2 to +1.4% for ten pairs of reference points considered.

The primary characteristic analyzed in this paper is clearing speed at intersections. The clearing speed is the average speed at which vehicles traverse the intersection space (from the upstream crosswalk to the downstream crosswalk). Other important characteristics such as the traffic composition and the acceleration and deceleration rates that impact the clearing speed are presented first. It should be noted that although approximately 40 hours of data have been collected, due to the manually intensive procedure adopted only a small portion of these data have been reduced to date.

3. INTERSECTION AND TRAFFIC CHARACTERISTICS

The clearing speed was specifically studied for one intersection approach in Baroda (Khanderao Westbound) and two intersection approaches in New Delhi (Ashram Eastbound and Nehru Place Westbound). The clearing speeds were not affected by any downstream conditions or intersection effects. The intersections in New Delhi were controlled by signals, and in Baroda by a policeman. Certain basic characteristics of the intersection approaches are detailed in Table 2. Traffic flow and intersection operations were observed for 30 minutes of the AM peak period to determine these characteristics.

TABLE 2 Intersection Approach Characteristics

Characteristic	Ashram EB	Nehru Place WB	Khanderao WB
Approach width (m)	15.0	9.0	6.5
Movements accommodated	Right, Through*	Right, Through*	Right, Through, Left
Green time/cycle time	26.1%	22.2%	34.1%
Average green+amber phase (s)	41.3	30.8	30.6
Average red phase (s)	116.7	108.2	59.1
Right-turning traffic	28.0%	15.0%	22.9%
Through traffic	45.4%	57.7%	67.8%
Left-turning traffic	26.6%	27.3%	9.3%

* Left turns are free, and are not controlled by the signals.

The primary difference between the traffic in New Delhi and Baroda is the significantly greater proportion of cars, and larger vehicles (small trucks, trucks, and buses) in New Delhi. Traffic volume and composition data for the same 30-minute AM peak period are presented in Table 3. It should be noted that the Ashram and Nehru Place intersection approaches include the left-turning traffic not controlled by the signal.

TABLE 3 Traffic Volume and Composition (30-minute AM peak period)

	Ashram EB		Nehru Place WB		Khanderao WB	
Vehicle Type	Volume	%	Volume	%	Volume	%
Two-wheelers	339	27.0	220	34.2	562	51.3
Auto-rickshaws	269	21.4	134	20.8	255	23.3
Cars	458	36.5	232	36.0	45	4.1
Buses	94	7.5	23	3.6	22	2.0
Trucks	19	1.5	2	0.3	1	0.1
Small Trucks	21	1.7	8	1.2	8	0.7
Bicycles	49	3.9	22	3.4	194	17.7
Other NMVs	7	0.5	3	0.5	9	0.8
Total	**1,256**	**100.0**	**644**	**100.0**	**1,096**	**100.0**

As can be seen in Table 3, the three primary motorized vehicle types are two-wheelers, auto-rickshaws and cars. Although the proportion of auto-rickshaws is only 6.7% (shown in Table 1), since this vehicle is primarily used as a taxi, the vehicle miles traveled and the proportion of the traffic flow at intersections is significantly greater (over 20%).

Acceleration and deceleration rates for vehicles not interacting with other vehicles when departing from the stopped position (unconstrained vehicles) were determined from vehicle positions at one-second intervals for different vehicle types. Details are provided in another paper (Maini and Khan 2000), and only the summary results are presented here in Table 4. The acceleration rates were determined by observing 87 vehicles, and the deceleration rates by observing 73 vehicles. Approximately half of all the observations were made for two-wheelers. The acceleration rates were observed to be significantly higher during the initial two to four seconds of movement. This is in general agreement with other studies that have hypothesized that that acceleration rate decreases linearly with increasing speed (Buhr et al. 1969) or has a linear relationship with the movement time from a stop condition (Hossain 1996). However, in this study as acceleration rates have not been determined on a per-second basis the exact relationship has not been established.

TABLE 4 Unconstrained Vehicle Acceleration and Deceleration Rates

Vehicle Type	Acceleration Mean (m/s^2)	Acceleration Standard Deviation (m/s^2)	Acceleration Speed* (m/s)	Deceleration Mean (m/s^2)	Deceleration Standard Deviation (m/s^2)	Deceleration Speed* (m/s)
Two-wheelers	1.00	0.12	8.8	1.18	0.46	8.1
Auto-rickshaws	0.75	0.24	7.3	0.85	0.25	6.3
Cars	1.00	0.29	8.9	1.04	0.39	7.8
Buses	0.60	0.11	6.9	0.82	0.34	5.8
Bicycles	0.50	0.29	3.0	0.88	0.17	3.3

*Represents speed at which acceleration ends, or at which deceleration starts.

As shown in Table 4, the acceleration and deceleration rates of two-wheelers and cars are significantly greater than auto-rickshaws and buses. It may be mentioned that the acceleration and deceleration rates of the motorized vehicles are approximately half of the values reported in a study in Bangladesh (Hoque 1994). The speeds detailed in Table 4 are lower than the unconstrained free-flow speeds observed at mid-block locations. However, the speeds were observed in a limited segment recorded.

4. INTERSECTION CLEARING SPEED

The video recording of traffic at several intersections showed that the queue appeared to discharge at a uniform rate, irrespective of the operating characteristics of the individual vehicles in the traffic. It was also observed that bicycles had a negligible impact on the discharge at intersections. In Baroda, for an intersection with bicycles constituting approximately 18% of traffic volume, bicycles traveled on the extreme left side and did not interfere with the traffic flow.

A detailed analysis of intersection clearing speed for individual vehicles was performed. From the video recordings, frame numbers were recorded as vehicles passed the crosswalk located upstream and downstream of an intersection. The distance between the crosswalks was greater than 30 m for all three intersections analyzed. As the entire distance between the crosswalks was not visible for all three intersections, the last frame in which the individual vehicles were visible was observed. Based on the distance traveled and the travel time recorded, average clearing speed was estimated. It should be noted that the platoon does appear to disperse further downstream. Due to the limited field of view, the mid-block free- flow speeds could not be determined for the three intersection approaches considered in this study. However, significantly higher free-flow speeds (50 to 75% higher than the clearing speed) have been observed at other mid-block locations. This is in agreement with observations for homogeneous traffic, as presented in one study where the stop line speed appeared to plateau at about 15 m/s for facilities with speed limit ranging from 17.9 to 24.6 m/s (Bonneson 1992).

The intersection clearing speed was determined for a total of 128 motorized vehicles at the three intersection approaches. Where possible, the clearing speeds of 10 vehicles of the four primary vehicle types (two-wheelers, auto-rickshaws, cars, and buses) were randomly selected. The vehicles crossed the first crosswalk 5 to 31 seconds after the start of the green phase, with an average of 14 to 16 seconds, for each of the three intersection approaches. This crossing signified the entry of the vehicle into the intersection conflict area. The average distance over which the clearing speed was determined was 18.75 m for the Nehru Place intersection, 20.02 m for the Khanderao intersection, and 20.92 m for the Ashram intersection.

4.1 Variation by Vehicle Type

The average clearing speeds determined for the different vehicle types at the three intersection approaches are detailed in Table 5, and the individual observations are depicted in Figure 2.

TABLE 5 Intersection Clearing Speed (m/s) by Vehicle Type

Vehicle Type	Ashram EB		Nehru Place WB		Khanderao WB	
	Average Speed	Var*	Average Speed	Var*	Average Speed	Var*
Two-wheelers	7.66	1.30	5.71	1.09	5.62	0.42
Auto-rickshaws	6.71	0.71	4.99	0.44	5.22	0.61
Cars	7.41	0.54	5.43	0.39	5.48	0.48
Buses	6.39	0.74	5.05	0.49	5.14	0.39
Weighted Average	**7.09**	**1.00**	**5.37**	**0.69**	**5.38**	**0.48**

* Variance of the observations.

As detailed in Table 4, the acceleration rates of two-wheelers and cars are approximately 33% and 66% greater than that of auto-rickshaws and buses respectively. Thus, it was expected that the clearing speed of two-wheelers and cars would be significantly greater than auto-rickshaws and buses. However, as shown in Figure 2, for a given location, the average clearing speed of vehicles do not vary significantly by type of vehicle. This suggests that the two-wheelers and cars with higher acceleration are unable to fully accelerate, and therefore their discharge is limited by other types of vehicles in the traffic stream. As expected, the observed clearing speed (5 to 7.5 m/s) is significantly lower than the stop line speed observed for homogenous traffic (14.9 m/s).

Figure 2 also shows that the clearing speed observed for Ashram EB is significantly greater than that observed at the other two intersections. This intersection approach also has the greatest width and a higher proportion of buses and trucks. The variance of the different vehicle types demonstrates that for a given width and mix of vehicles, the vehicles at an intersection are discharged as a platoon at a platoon clearing speed or uniform intersection clearing speed.

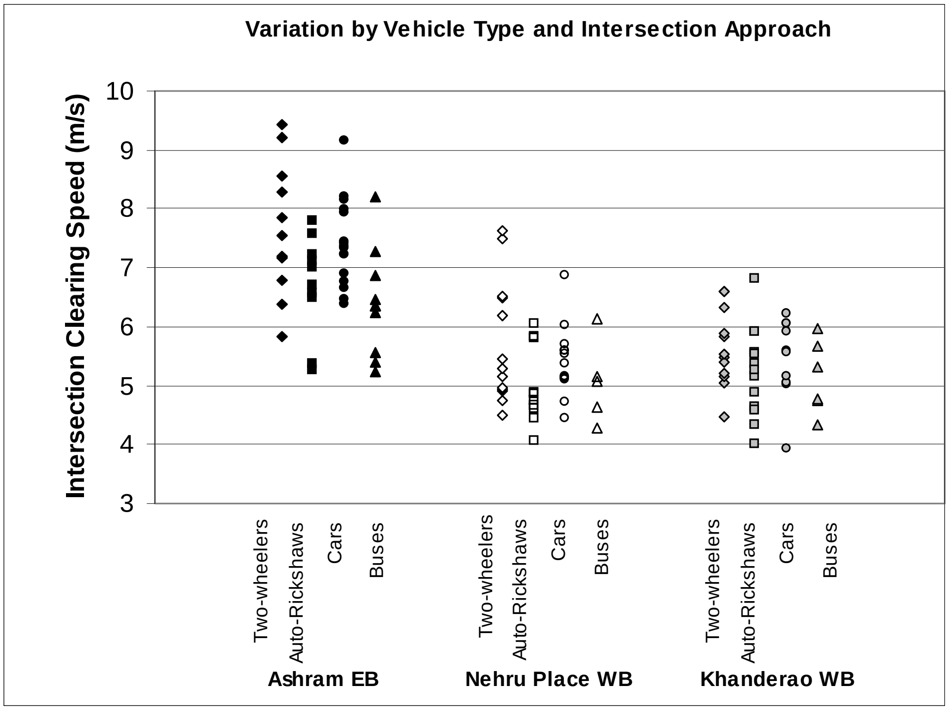

FIGURE 2 Intersection clearing speed observations.

There are two other studies that that specifically analyzed the clearing speed at intersections. In the first study (Bhattacharya and Mandal 1982), observations were made at 23 intersections, and the clearing speed of cars at the intermediate position was found to be significantly dependant on the clearing length [Clearing Speed (m/s) = 0.17 * Clearing Length (m), Coefficient of Regression = 0.966]. However, in the current study as measurements have been made at only three intersections, and as the entire clearing length was not visible in the view recorded, this relationship has not been examined. In the second study (Chandra et al. 1996), observations were made at 19 intersection approaches and time to clear the intersection for three to four vehicles of each category were used to determine the clearing speed. The clearing speed of each vehicle type was hypothesized to depend on the total traffic volume, the saturation flow rate and the clearing speed of the different vehicle types. The clearing speeds calculated based on the methodology presented in that second study are reasonably close to the field values presented in this paper and the same pattern (low to high for different vehicle types) is observed for the most part. As stated earlier, in the current study it has been determined that the clearing speed does not vary significantly by vehicle type, but possibly varies significantly based on approach characteristics.

4.2 Variation by Intersection Entry Time

When homogeneous traffic discharges from a signalized intersection, the clearing speed increases for the first few vehicles and then plateaus at a value less than the facility free-flow speed. In one detailed study in which the data for over 4,800 through vehicles was analyzed (Bonneson 1992), at four of the five sites the speed was observed to plateau after the 15th vehicle crossed the stop line (over 30 seconds after the start of the green phase). An attempt was made to see if this phenomenon was observed for heterogeneous traffic also. While determining the clearing speed for individual intersections, the time between the start of the green phase and the time a vehicle entered the intersection was also observed. The clearing speed and the intersection entry time is shown in Figure 3, 4, and 5 for the Ashram, Nehru Place, and Khanderao intersection approaches, respectively.

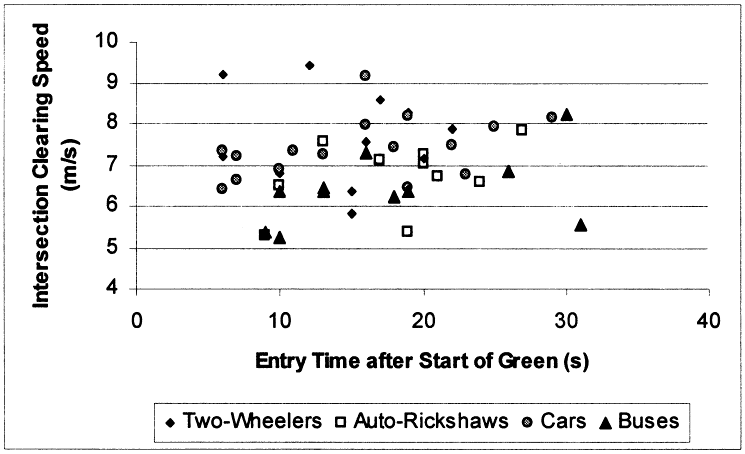

FIGURE 3 Ashram EB intersection clearing speed.

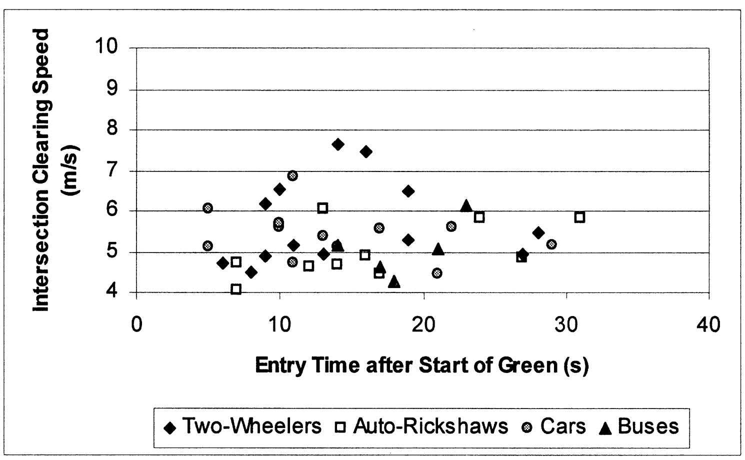

FIGURE 4 Nehru Place WB intersection clearing speed.

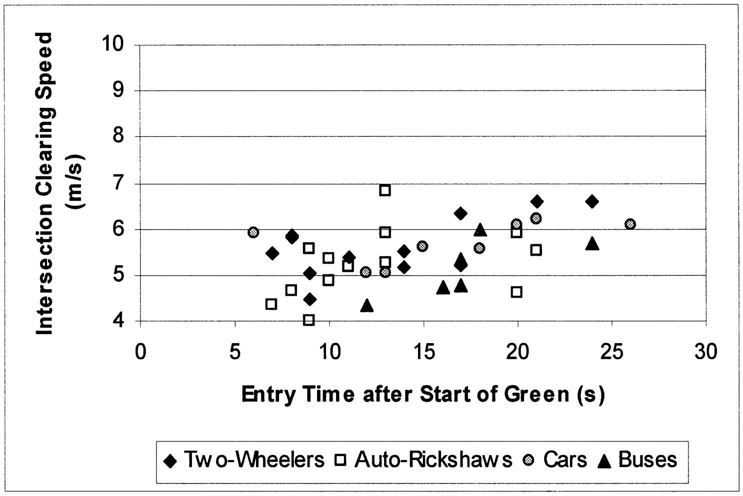

FIGURE 5 Khanderao WB intersection clearing speed.

A cursory examination of the data plotted in Figures 3 through 5 shows that the vehicles reach the plateau very quickly and there appears to be only a slight increase in the clearing speed as the intersection entry time increases. Given that significant variations were observed between the average clearing speeds at the different intersections (see Table 5), the average clearing speed for grouped intersection entry time are presented in Table 6.

TABLE 6 Intersection Clearing Speed Classified by Entry Time

Entry Time after Start of Green (s)	Ashram EB		Nehru Place WB		Khanderao WB	
	Average Speed (m/s)	Samples	Average Speed (m/s)	Samples	Average Speed (m/s)	Samples
5–10	6.65	13	5.26	11	5.11	12
11–15	7.07	8	5.48	11	5.26	13
16–20	7.25	16	5.38	7	5.44	10
> 20	7.26	11	5.33	10	6.11	6

The results presented in Table 6 also show that there appears to be a slight increase in the intersection clearing speed as the intersection entry time increases. The clearing speed measured in the period 5 to 10 seconds after the start of green is only 1 to 20 percent lower than the clearing speed at the end, thus showing that the clearing speed plateaus much earlier for heterogeneous traffic than for homogeneous traffic. These results also support the finding that the discharge of higher performance vehicles is limited by the presence of other vehicles. Possible reasons for this include the impact of lower performance vehicles, and the interaction between different vehicles as faster vehicles attempt to overtake the slower vehicles.

4.3 Variation by Movement in Queue Time Prior to Crossing Stop line

The intersection entry time after start of the green phase is a surrogate measure of the amount of time a vehicle travels before it enters the intersection. Typically, vehicles that are further back in the queue take longer to reach the intersection entry point. These vehicles have been moving for a longer time as compared to the vehicles that enter first.

Data for one intersection (Nehru Place WB) were analyzed in greater detail to study the relationship between the amount of time the vehicle had been moving when it entered the intersection, and the intersection clearing speed. These data are presented in Figure 6.

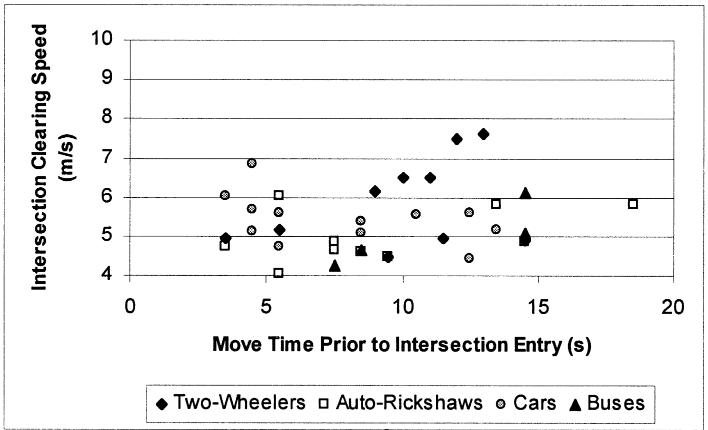

FIGURE 6 Nehru Place WB intersection clearing speed by movement time.

As shown in Figure 6, several vehicles, including higher performance two-wheelers and cars, attain a speed of 6.5 m/s or less after moving for 10 seconds or more. Assuming a uniform acceleration rate while the vehicles are increasing speed as they reach the intersection entry point, the acceleration rate is less than 0.65 m/s^2, which is 35 percent less than the average acceleration of those vehicle types. These data also demonstrate that all the vehicles in the queue appear to discharge at a similar speed, irrespective of their performance characteristics and position in the queue.

5. IMPACT ON INTERSECTION CAPACITY DETERMINATION

The intersection capacity is typically specified in terms of equivalent passenger cars (Passenger Car Units – PCUs). According to the Indian Roads Congress (1994), the approach capacity in terms of PCU per hour of green is 525*w*, where *w* is the width of the approach in meters. The passenger car unit values for different vehicle types for Indian roads are presented in Table 7.

TABLE 7 PCU Values for Different Vehicle Types

Study	Two-Wheeler	Auto-Rickshaw	Car	Bus/ Truck	Bicycle
Indian Roads Congress (1994)	0.5	1.0	1.0	3.0	0.5
Justo and Tuladhar (1984)	0.3	0.4	1.0	2.8	0.4
Chandra et al. (1996)*	0.18	0.54	1.0	2.78	—

*Values determined based on observed traffic composition at Nehru Place intersection.

Various studies have attempted to determine PCU values considering other characteristics including vehicle size, lateral clearance maintained, traffic composition, and vehicle speed. In two studies (Justo and Tuladhar 1984; Chandra et al. 1996), PCU values were determined specifically for intersections. In both these studies, the PCU value is based on the intersection clearing speed and the area for the individual vehicle types. This study has shown that the clearing speed does not vary significantly by vehicle type. As a result, the queue discharges in a platoon at a uniform clearing speed. The intersection clearing speed of a vehicle does not significantly vary based on the position in the queue. These findings suggest that the PCU values for a particular vehicle type may not depend on the intersection clearing speeds, but rather on a combined platoon clearing speed. The limited data analyzed in this study suggests that the platoon clearing speed may depend on factors such as traffic composition and intersection width. Additionally, in a related study (Maini and Khan 2000) it has been shown that different vehicle types maintain different lateral and longitudinal clearances both while moving and while stopped. These clearances also impact the queuing phenomenon and the length of the queue. A detailed analysis of the queue discharge phenomenon along with the findings of this study about the platoon clearing speed could help establish capacity analysis and delay estimation procedures. These procedures may be based on the speed of the shockwave propagation towards the rear and the rate at which the platoon clearing speed is attained. However, significant additional work is required before this can be accomplished.

6. CONCLUSIONS

This paper presents an analysis of clearing speeds of heterogeneous traffic at intersections. It was observed that the variation of clearing speed for different vehicle types is low, although two-wheelers and cars have acceleration rates that are 33% and 66% higher than those of auto-rickshaws and buses, respectively. This suggests that at the intersection, the entire queue is discharged as a single platoon and higher performance vehicles are limited by low performance vehicles.

It was also determined that the intersection clearing speed plateaus very quickly as compared to homogeneous traffic. The finding that the intersection clearing speed is relatively constant for different vehicle types at an intersection has the potential to impact the methodology for determining PCU values. Earlier studies have suggested that the clearing speed of individual vehicle types should be considered in determining the PCU values. Given the findings of this study, platoon clearing speed may be more relevant to estimating intersection capacity. Additional work is needed on queue formation and discharge to develop capacity and delay estimation procedures. It should be noted that the results of this study are applicable only for the range of traffic composition and intersection widths analyzed in this paper. Further research is needed to determine the impact of traffic composition, intersection width, and other factors on platoon clearing speed.

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