Modification of a Highway Capacity Manual Model for Evaluation of Capacity and Level of Service at a Signalized Intersection in India

Geetam TIWARI
Professor
Department of Civil Engineering, IIT Delhi
Transportation Research and Injury Prevention Program,
MS-808, Indian Institute of Technology Delhi,
Hauz Khas New Delhi 110016, INDIA
Telephone: 91-11-2659-1047
Fax: 91-11-2685-8703
E-mail: geetamt@gmail.com

Mariya KHATOON
Research Scholar
Department of Mathematics, IIT Delhi
Transportation Research and Injury Prevention Program,
MS-815, Indian Institute of Technology Delhi,
Hauz Khas, New Delhi 110 016, INDIA
Telephone: 91-11-2659-6575
Fax: 91-11-2685-8703
E-mail: mirza.mariya@gmail.com

Niharika SINGH
Graduate Student
Department of Civil Engineering, IIT Delhi
Room 815, 7th Floor Main Building,
Indian Institute of Technology Delhi,
Hauz Khas, New Delhi 110 016, INDIA
Telephone: 91-11-2659-6575
Fax: 91-11-2685-8703
E-mail: niharika2905@gmail.com

Prateek CHOUDHARY
Graduate Student
Department of Civil Engineering, IIT Delhi
Room 815, 7th Floor Main Building,
Indian Institute of Technology Delhi,
Hauz Khas, New Delhi 110 016, INDIA
Telephone: 91-11-2659-6575
Fax: 91-11-2685-8703
E-mail: prteek.choudhary@gmail.com

Joseph FAZIO
Associate Professor
South Dakota School of Mines and Technology
Civil and Environmental Engineering
Department, 118 CM, SDSMT, 501 E Saint Joseph Street
Rapid City, South Dakota 57701, USA
Telephone: 1-605-394-2442
Fax: 1-605-394-5171
E-mail: fazioj@gmail.com

Abstract: In India, signalized intersections experience heavy and non-homogeneous traffic flow. A proper traffic model must consider the varying characteristics of all the road users to effectively design and efficiently manage the signalized intersections. An evaluation reveals the applicability of Highway Capacity Manual's signalized intersection model for an Indian signalized intersection. The evaluation revealed that the model suffers from serious lacunae when applied to the Indian context. Measures are proposed for the modification of the model, and factors are developed based on proposed modifications in order to make it more suitable for Indian conditions. The factors evaluated are the lane width adjustment factor and passenger car equivalency factors. Mean right-turn width used is 3.6 m while the width provided was 3.3m. Equivalency factors for motorized two-wheelers ranged from 0.4 to 1.3 and for motorized three-wheelers from 5.6 to 9.1. In terms of pedestrian safety, LOS of the intersection is not acceptable.

Keywords: HCM2000 model, Indian signalised intersection, Level of service
1. INTRODUCTION

Signalized intersections use a common form of traffic control to address roadway operations. Signalized intersections allow road users to access new streets and change direction of travel. Intersections should be able to serve their varying traffic demands, provide minimum delay in passage, and maximum safety to all types of users especially pedestrians. One evaluates the functioning of a signalized intersection in terms of two parameters: (1) capacity, i.e., volume-to-capacity (v/c) ratio, and (2) the level of service (LOS), with its delay and queue ranges. These parameters are the function of traffic volume characteristics, signal characteristics, and geometry of the intersection. One evaluates capacity on the concept of saturation flow, whereas LOS is evaluated based on delay that a user experiences while crossing an intersection.

Researchers have developed various models to evaluate the effectiveness of signalized intersections in terms of their capacity and level of service. The basis of model selection for a particular purpose usually depends on the tradeoff between the difficulty of applying the model and the required degree of accuracy and confidence in the results. One evaluates the widely used Highway Capacity Manual's (HCM's) signalized intersection model for its applicability for Indian signalized intersections (HCM, 2000). Some practitioners allude that the HCM model suffers from serious lacunae when applied to mixed traffic flow of India with its significant proportions of motorized two wheelers, bicycles, and other entities. The traffic movement in India is complex due to the non-homogeneous characteristics of the traffic stream using the same right of way. The stream includes slow non-motorized vehicles at one extreme and fast moving passenger cars at the other with many intermediate vehicles such as motorized three wheelers. India's traffic depicts a wide variation in static and dynamic traffic entity characteristics.

In Indian heterogeneous traffic operations, no single vehicle group clearly dominates the traffic stream so that prediction of capacity is more sensitive to the vehicle mix than in Western countries where the passenger car group largely dominates traffic composition. The HCM defines LOS for signalized intersection in terms of control delay, which is a measure of driver discomfort, frustration, fuel consumption, and increased travel time. The determination of three types of level of services occurs separately: (1) motor vehicle LOS based on control delay, (2) bicycle LOS assuming no overflow delay, and (3) pedestrian LOS whose measure is average delay per pedestrian, i.e., wait time. The literature explored yielded some research on the applicability of HCM model to the Indian signalized intersections. This research contributes to proper evaluation and addressing of indigenous issues pertaining to Indian signalized intersections.

1.1 Background

Researchers have conducted a large number of studies on the HCM signalization intersection model, its applicability, and modifications. This section presents research studies addressing some of the important aspects of traffic models applicable to modeling heterogeneous traffic movement at signalized intersections.

Lane width and saturation flow:
Potts et al. (2007) investigated the relationship between lane width and saturation flow rate on urban and suburban signalized intersection approaches. The research indicates that saturation flow rate varies with lane width. These measured saturation flow rate values are generally lower than those currently used in the HCM. Furthermore, the percent difference in
saturation flow rate between sites with 2.9 m (9.5 ft) to 3.6 m (12.0 ft) lanes was found to be about half the value used in the HCM.

**Capacity and delay estimation:**
Cheng et al. (2008) demonstrated that the current procedure in the HCM for analyzing actuated signalized intersections and found that this procedure can lead to erroneous results in capacity and delay estimations. The authors developed a model that takes into account the stochastic nature of pedestrian crossings and their effects.

Kim (2006) demonstrated the shortcomings of the HCM delay model in the estimation of uniform delay of permitted left turns from an exclusive lane (PLTEL), and proposed a uniform delay model for PLTEL. The original HCM model tended to underestimate uniform delay, and the proposed model for uniform delay of PLTEL showed improved results.

**Effective green time estimation:**
Kim and Courage (2003) proposed a maximum green time design procedure consists of four components. One component is the estimation of the average green time of a traffic-actuated phase. The second component is the performance evaluation of the system through the HCM 2000 procedure. Formulation of an overall average control delay minimization problem is the third component, and the fourth component is a search process to find the most efficient set of maximum green time parameters that minimize the average control delay at an intersection. The authors demonstrated that the proposed average green time estimation models offer better results than the one in the HCM.

Janson et al. (2001) found that the HCM overestimates the effective green time of a shared left-turn lane. As a result, HCM may not indicate a de facto left-turn lane, even though its delay is much higher than the delay of adjacent lanes.

**Level of service (LOS):**
Vaziri and Dehghani Sanij (2008) evaluated freeways LOS and other quality measures describing LOS based on user perception. The authors developed fuzzy categories for traffic characteristics using fuzzy set theory and compared them with the HCM LOS categories. The authors found that fuzzy categories of LOS, maneuverability, and flow condition are not necessarily similar to HCM LOS categories in terms of category range.

Zhang and Revel andouros (2003) proposed a methodology to determine LOS at signalized intersection considering user perceptions. The methodology was an extension to the HCM model that combined delay and safety to yield a new comprehensive LOS indicator, namely, the delay and safety index (DS). The model efficiently captures the trade-off between safety and efficiency explicitly and considered both vehicle-to-vehicle and vehicle-to-pedestrian conflicts at signalized intersections.

Pan et al. (2008) presented the concept of safety level of service (SLOS). The authors develop a SLOS model for signalized intersections based upon vehicle conflicts, intersection geometrics, signal phasing, pavement markings, signage, pavement condition, and ambient lighting. SLOS model depends upon factors that influence intersection safety as well as the intersection operation.

Petritsch et al. (2006) developed an LOS model that accurately represents pedestrians’ perceptions of crossings at signalized intersections. This model incorporates perceived safety and comfort, i.e., perceived exposure and conflicts, and operations, i.e., delay and signalization. The resulting model provides a measure of the pedestrian’s perspective on how well an intersection’s geometric and operational characteristics meet pedestrian needs.
We conclude that HCM model needs modifications when applied in different traffic conditions. This study will help to understand the shortcoming of HCM signalized intersection model when it is applied in Indian context and propose modifications relevant for heterogeneous traffic.

2. OBJECTIVES

The study has three major objectives: (1) evaluation of the applicability of the HCM model to prevailing Indian conditions by determining the model's estimate of capacity and LOS at a signalized intersection in India, (2) propose modifications in the existing HCM 2000 Model for the analysis of signalized intersection to make it more suitable in Indian context, and (3) development of adjustment factors that account for the proposed modifications and deal with applicability issues of using the HCM signalized intersection model under Indian urban conditions.

3. SITE SELECTION AND SITE CHARACTERISTICS

The site selected (Figure 1) represented a typical Indian urban signalized intersection. The selected intersection experiences reasonably high and mix traffic volume flows so that the results of applying modifications in the HCM model can be reliably representing the Indian scenario.

The signalized intersection site is located underneath the Indian Institute of Technology Delhi (IITD) flyover intersection in New Delhi. The intersection has four legs as shown in Figure 1. This intersection experience heavy traffic flows almost uniformly throughout the day. The crossing of Gamel Abdel Nasser Marg and Aurobindo Marg forms the intersection. Both streets carry heavy traffic volume flows as it connects Delhi to adjoining industrial areas. The team collected data in the evening peak hour from 5:30 p.m. to 6:30 p.m. Some characteristics of the IITD intersection are mentioned: (1) five phases comprise the cycle, (2) drivers follow loose lane discipline on all traffic lanes and in between the lanes, (3) no special provisions for pedestrians and bicyclists, (4) 'free,' i.e., drivers make turns on RED without stopping, left turns on all the four approaches, (5) non CBD area type with absence of parking space and bus stops at the intersection, (6) actuated traffic signal, (7) intersection almost at right angles, and (8) cycle length averages 260 seconds during the peak hour.

Figure 1: Schematic diagram of the Indian Institute of Technology Delhi flyover intersection
4. DATA COLLECTION

Camcorders positioned atop the flyover recorded traffic at the signalized intersection underneath the IITD flyover. Camcorders recorded pedestrian and vehicle movements for two major crosswalks. Team members extracted the following data from video recordings and site visits: (1) through flows, right-turn flows, and speeds of traffic entities, (2) pedestrian movements and pedestrian characteristics as gender, age and type of pedestrian (pedestrian with heavy baggage, with children or in a group), (3) gap size and waiting time of pedestrians, and (4) geometrical characteristics of the intersection. For calculating speeds, one divides the travel length of the traffic entity by the time taken to travel the known length to cross a pre-marked line on the screen. Gap size (in sec) is defined as the difference between the time when each pedestrian arrives at crossing and when each conflicting vehicle enters at the crosswalk. The length of each gap is calculated from the differences between the arrival times of two consecutive vehicles, as indicated in Figure 2. This available gap is the gap presented to the pedestrian. If the pedestrian accepts the available gap (i.e., crosses the street within that gap), then it is an accepted gap; otherwise it is a rejected gap.

5. HCM SIGNALIZED INTERSECTION MODEL

HCM's signalized intersection model evaluates a signalized intersection in terms of capacity and LOS. The model considers a number of prevailing conditions including the amount and distribution of traffic movements, traffic composition, geometric characteristics, and details of intersection signalization. One evaluates capacity in terms of the ratio of flow rate to capacity. The model evaluates LOS terms of control delay per vehicle in seconds per vehicle. Control delay includes initial deceleration delay, queue move up time, stopped delay, and final acceleration delay. The HCM also evaluates a signalized intersection by computing average delay per pedestrian for a crosswalk (HCM, 2000).

6. INDIAN TRAFFIC CHARACTERISTICS AT SIGNALIZED INTERSECTIONS:

Indian, urban, signalized intersections are different in terms of their operations, users, infrastructure, and problems. An obvious difference is that Indian traffic drives on the left hand side of the road. One must adjust important factors in the HCM model to account for the opposite turning effects. Another difference is that vehicles do not follow lanes demarcations accurately. Vehicles intermingle a very much, not only between lanes belonging to the same lane group but also belonging to different lane groups. This
intermingling results in added congestion effects and reduces the serviceability of
intersections. Moreover, this effect has even graver consequences when through moving
traffic blocks the free left turn lane group.
Highly non-homogeneous traffic is composed almost equal proportion of passenger cars and
motorized two-wheelers with the remaining proportion evenly distributed between motorized
three-wheelers, heavy vehicles, and other slow moving vehicles (Jalihal et al., 2005). Another
difference is that, at Indian signalized intersections during peak hours, large queue
lengths are regular phenomena as waiting time is much longer because of heavy volumes. In
terms of geometry, Indian lanes are narrower at midblock than at the approach.

7. SHORTCOMINGS OF HCM SIGNALIZED INTERSECTION MODEL FOR
THE INDIAN CONTEXT

Many practitioners have globally accepted the HCM model for intersection evaluation. Its
applicability poses various difficulties for prevailing Indian signalized intersection
operations. To get reliable results in India, the HCM model needs modification. The
characteristics listed above strike against certain assumptions on which the HCM model
depends. Five major conflict areas exist. One can easily adjust for left-hand driving by
taking caution while calculating the parameters. Thus, this factor does not adversely affect
the basic applicability of the model. Vehicles do not follow lane demarcation challenge the
applicability of the HCM model as the model exclusively depends on the behavior of lane
groups. If Indian intersections have free left turns, ideally the green time for them should be
the full cycle length. However, long through movement queues choke most left turns during
the RED phase of the through traffic for the corresponding approach. When the through
vehicles block free left turns, the 100% effective green time assumption for these lanes is not
valid. This leads to the overestimation of the capacity for the free left turns and their
performance. Since India traffic is highly non-homogeneous, it does not suffice to have only
a factor for the percentage of heavy vehicles in the saturation flow calculation. To estimate
intersection capacity accurately, one should convert every vehicle group into a standardized
passenger car unit (PCU) to determine equivalent flow rates. Due to large queue lengths
observed along Indian intersection approaches, the formulae developed for LOS in HCM do
not calculate reliable results. Having Indian lanes that are narrower midblock than on
approaches implies that the formulae used in the HCM model based on uniform width of the
lanes cannot accurately represent Indian conditions.

The HCM model does not consider other important measures in the calculation of LOS such
as safety. The HCM model defines LOS in terms of the total control delay (HCM, 2000).
However, with increasing number of traffic crashes at intersections, it becomes inevitable to
include user safety as an important component while determining the LOS of the intersection.
Another consideration is having a combined measure for pedestrians and vehicles. The HCM
model does not give a combined measure for determining LOS of the intersection considering
all users. Requirements of pedestrian and vehicles differ from each other. Thus, a combined
measure must take into account pedestrians, vehicles, and their interaction.

By modifying the HCM model to reflect Indian intersections, the intersections gain improved
operations and safety performance. Whereas the model's structure need not change, it would
suffice to modify only certain adjustment factors since the basic functioning of intersections
remains the same everywhere in the world.
8. RESULTS

8.1 Development of Lane Width Adjustment Factor

Apparently some nations such as France and Italy do not delineate lanes at intersection approaches with pavement markings. Thus, their signalized intersection operational analysis models may not need a lane width adjustment factor. The USA MUTCD does specify it and the US HCM analyses (used in the study) are based on lane groups so a lane width adjustment factor becomes necessary to adjust lane discipline models to India's loose lane discipline. The Australian SIDRA also originally does signalized operational analysis by lane.

Firstly, to develop the lane width adjustment factor, linear regression analysis predicted the percentage of lane width used by right turning traffic using other known parameters. The identified variables to affect lane usage percentage were the number of right turning vehicles and modal shares of the different traffic entities comprising right turning traffic. In the future, linear regression modeling could easily predict an approximate value of the percentage of lane width used by right turning vehicles. Using mathematical software tools, linear regression analysis revealed no significant trend. The reason was the lack of sufficient number of observations. Future studies to obtain more observations are necessary so that the analysis can confirm the identified variables in the development of the lane width adjustment factor.

Subsequently, one obtains the lane width factor by retaining the HCM equation with a minor modification of its lane concept. The original formula uses lane widths as marked on the road and assumes that flowing traffic keeps to the demarcated lanes. However, this is not the case in India; most drivers ignore these pre-marked lanes so that the actual lane widths used by vehicles are determined by observing movements at the site. Team members observed traffic moving into the intersection from the All India Institute of Medical Science (AIIMS) approach against a grid of equally spaced seven columns on the video monitor. For each observation, team members noted total number of columns used by the right turning traffic and through moving traffic. From the observations, a derivation resulted in the percentage of the total lane width used by the right turning traffic and through moving traffic. Then, the average value of the percentage width used by the right turning traffic was calculated.

Total lane width of the road was 10.2 m (33 ft). Average values of lane width used by right turning and through moving traffic were 3.6 m (12 ft), i.e., 35.8% and 6.6 m (22 ft), respectively. The lane width allocated for right turning and through moving traffic was 3.3 m (11 ft) and 6.9 m (23 ft), respectively.

One can calculate the lane width adjustment factor as proposed for the HCM model modification for the obtained values of lane widths, i.e., estimated values. One can compare these lane width factor values with the values of lane width factors obtained using the lane widths marked on the road, i.e., theoretical values.

The lane width adjustment factor used in the HCM is

\[ f_w = 1 + \frac{(W - 3.6)}{9} \] (1)

Where \( W \) is the lane width used in meters (HCM, 2000).

The obtained theoretical and estimated values of lane width factor are as follows: (1) theoretical values \( f_w \) (right-turn lane) = 0.96, \( f_w \) (through lane) = 1.37 and (2) estimated values \( f_w \) (right-turn lane) = 1.00, \( f_w \) (through lane) = 1.33.
The lane width used by right turning traffic, i.e., 3.6 m (12 ft) is slightly more than the width allocated for the right turn movement, i.e., 3.3 m (11 ft). The values obtained by the experimental approach are only slightly different from the theoretical values. However, this slight difference will have a significant impact on final calculated values of flow and capacity because one multiplies these parameters by the base saturation flow rate of 1900 vehicles per hour per lane per green.

### 8.2 Obtainment of Passenger Car Equivalency Adjustment Factors

Capacity determination of the intersection is difficult with unrestricted mixing of different vehicle groups on the road. Vehicles of different sizes, speeds, and lateral gaps maintained by drivers share the carriageway. The conversion of prevailing traffic composition into an all passenger car flow takes into account the non-uniformity in the static and dynamic characteristics of vehicles. The most accepted conversion uses the PCU concept.

The HCM uses the density method to calculate PCU values for heavy vehicles and recreational vehicles. Density method assumes homogeneous traffic and does not include such traffic groups as motorized three-wheelers, motorized two-wheelers, and non-motorized traffic. HCM PCU values prove inadequate in determining values for Indian cities. Development of methodologies occurs to modify the HCM density method to calculate PCUs for non-homogeneous traffic that includes significant number of two-wheelers, three-wheelers, and non-motorized traffic entities. Under homogeneous traffic conditions, width that vehicles use is the same as lane width. Thus, linear density suffices. Dividing the flow rate in vehicles per hour by space mean speed in kilometers per hour easily obtains linear density. In the case of heterogeneous traffic, different vehicle types have widely varying widths. Further dividing the linear density by an appropriate width obtains the concentration per unit area of traffic entities. Dividing the concentration per unit area calculated for passenger cars by that calculated for each vehicle type obtains the PCU values. Concentration per unit area is calculated by the relation \( \frac{Q}{U} / W \) where \( Q \) is flow of the traffic entity in vehicles per hour, \( U \) is space mean speed of the traffic entity in km/h, and \( W \) is cross sectional width meters.

After calculating volume and space mean speed of different traffic entities, one calculates cross section width using three different approaches. Approach 1 uses the cross sectional width \( W \) that is used by 90 percent of the vehicles. For this purpose, team members studied the video against a monitor screen with grid lines. Team members observed the through moving traffic against a grid comprising six columns with each of equal 1.1 m (3.6 ft) width. Team members noted the number of vehicles in each vehicle group using each width. Then the cumulative frequency curve derived the 90th percentile width used by each vehicle group. In Approach 2, the average width of the vehicle is use as the cross-sectional width. Approach 3 is a purely empirical approach where the cross sectional width \( W \) used in calculations is the summation of the widths of those columns which witness a frequency of usage of more than 15 percent. The camcorder could effectively capture only one direction of movement so that evaluation of the through moving traffic coming to the intersection from the side of AIIMS occurred. The video was studied on a large monitor which divided the through moving traffic space into six columns of equal 1.1 m (3.6 ft) widths. The entire lane width used by the through moving traffic is 6.6 m (21.5 ft). After numbering the columns, team embers noted the number of each vehicle using each column.

Dividing flow by space mean speeds derived from field data obtains per unit area concentration in vehicles per kilometer-meter. One then divides the resulting linear density
value in vehicles per kilometer by width value \( W \). Using these values of the per unit area concentration, PCU values are obtained by dividing the concentration values for passenger cars by the concentration value for the particular traffic group. Table 1 presents the results of the calculations.

<table>
<thead>
<tr>
<th>Traffic Group</th>
<th>Flow (veh/h)</th>
<th>Mean Speed (km/h)</th>
<th>Approach 1</th>
<th>90th Percentile Width (m)</th>
<th>Concentration (veh/km*m)</th>
<th>PCU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger Car</td>
<td>1210</td>
<td>20.8</td>
<td>4.8</td>
<td>12.1</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Motorized Two Wheeler</td>
<td>910</td>
<td>16.0</td>
<td>6.3</td>
<td>9.0</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>Motorized Three Wheeler</td>
<td>170</td>
<td>20.0</td>
<td>6.0</td>
<td>1.4</td>
<td>8.6</td>
<td></td>
</tr>
<tr>
<td>Heavy Vehicle</td>
<td>130</td>
<td>11.8</td>
<td>6.0</td>
<td>1.8</td>
<td>6.6</td>
<td></td>
</tr>
</tbody>
</table>

|                     | Approach 2 |                 |            |                           |                          |     |
|                     | Average Vehicle Width (m) | Concentration (veh/km*m) | PCU |
|                     | 1.6        | 1.3              | 36.3       | 81.1                      | 1.6                      |
|                     | 0.7        | 0.4              | 6.5        | 4.6                       | 0.4                      |
|                     | 2.4        | 5.6              | 7.9        |                           |                          |

|                     | Approach 3 |                 |            |                           |                          |     |
|                     | Width (m)  | Concentration (veh/km*m) | PCU |
|                     | 3.3        | 2.0              | 17.8       | 26.0                      | 1.0                      |
|                     | 2.2        | 2.5              | 9.1        | 7.0                       |                          |

Table 1: Per unit area concentration and PCU value of traffic entities using different approaches

All three approaches in determining \( W \) based on the modified density method broadly produced similar PCU values. To be up-to-date, experimentally calculating PCU values at the selected site instead of adopting generalized values listed in codes in the Indian Roads Congress (IRC) Manual 86-1983(1983) leads to better accuracy. PCU values depend largely on traffic flow conditions and traffic mix at the intersection. The only difference in the three approaches in \( W \) determination is that of the value of cross sectional width \( W \) used in calculating per unit area concentration from linear density. Table 1 shows that the Approach 1 is the only approach that produced a motorized two-wheeler PCU value greater than 1.0. This could be due to the large value of the 90th percentile width calculated for motorized two-wheelers from the cumulative frequency percentage. The concept of using 90th percentile width was not considered very justifiable since it overlooked differences in concentration of vehicles across the lane. Thus, vehicles that are concentrated in the last few columns occupy larger 90th percentile widths even if they actually occupy lesser space on the road. The results of Approach 2 are most reasonable. The PCU value for motorized two-wheelers is similar to the IRC value. Further, this is the only approach that produces a PCU value for motorized three-wheelers less than that for heavy vehicles. Approach 3 produces a significantly high PCU value for motorized three-wheelers because a flat frequency distribution of motorized three wheelers across the complete lane width exists. Motorized three-wheelers are present across the entire lane width and thus adversely affect traffic flow across a large area. The low value of motorized three-wheeler flow also contributed to the high PCU value for three wheelers. Due to the low acceleration characteristics of three wheelers and heavy vehicles, fewer of them can cross the intersection in the same time as two wheelers and passenger cars cross the intersection. All approaches prove that speed of the traffic entity plays a major role in determining PCU values. High PCU values derived for heavy vehicles indicate the effect of speed on PCU values. Motorized two-wheelers generally have low PCU values since they have lower widths and higher speeds. Motorized
two-wheelers occupy less space while moving. The PCU values obtained using Approach 2 are the best indicator of PCU values at this particular intersection.

Overall, the values obtained in the three approaches are very different from the values outlined in the IRC manual especially for motorized three-wheelers and heavy vehicles. Yet, the values obtained are commensurate with each other. The PCU values will change with traffic mix and traffic flow characteristics. Since intersection traffic experiences high acceleration noise, PCU values are usually high. Low speeds and high acceleration noise produce a greater drag effect. Much future research work is required for further modifications in the calculation of the appropriate PCU values where non-homogeneous traffic prevails.

8.3 Observations for Time to Block Free Left Turns
The selected intersection has free left turn on all four sides. Ideally, the effective green time for free left turns would be the full cycle length. However, field observations show that left turning traffic is choked during the RED phase by the through traffic queue on the corresponding approach. The through vehicles queue length block the free left turns, and the left turns do not utilize the assumed 100% effective green time for these lanes. Team members calculated the value of the average time per signal cycle when free left turns are blocked for all directions of the selected intersection. At intersection underneath the IITD flyover, free left turns blockage time are measured. Toward Gurgaon, team members observed no blockage. Toward AIIMS, mean blockage time was 29 seconds. Free left-turning traffic on the approach toward Nehru Place had an average 175 seconds of blockage time. Towards IITD, mean blockage time was 151 seconds.

These blockage times determine the actual green time available for the movement of left turning traffic. Traffic moving towards Nehru Place had the maximum blockage time because at this location underneath the flyover diverting traffic reduces through traffic movement. The minimum blockage time is observed for the traffic moving towards AIIMS as the through traffic moving from Gurgaon to AIIMS direction is very high, and phase duration provided for through traffic is lengthy. Thus, through traffic clears and causes fewer blockages for left turning traffic. The traffic coming in from the direction of AIIMS does not experience any left turn blockage since a large channelization island separates the left turning traffic from other lane groups. This island eliminates the chances of left turning traffic to intermingle with through traffic.

After ascertaining blockage times, reducing the effective green time of free left turns to the value of blockage time leads to the obtainment of modified flow values. Effectively, this is the available time for left turning traffic to use ‘free’ left turns.

8.4 Level of service (LOS) measurements
Crossing a street in urban areas exposes pedestrians to the risk of road accidents (Lassarre et al., 2007; Duncan et al., 2002). In Delhi 40% of pedestrian crashes occur at signalized intersection (Tiwari et al., 2007). At the selected Intersection, pedestrians have safe signals (red phase for vehicle) to cross the road. Since free left turn is allowed at the intersection, pedestrians are forced to cross with moving traffic at this location. In the HCM 2000, LOS describes the operation of the intersection that depends upon the average control delay of vehicles and pedestrian and does not consider user safety at the signalized intersection. Level of service is a theoretical representation of the operation of an intersection. The lack of an intersection safety factor weakens the performance measure and the ability to utilize level of service as an operational predictor. Though, free left turn decreases the vehicles delay
however, it results in increasing risk to the pedestrians while crossing the road. Therefore, we consider gap size available to estimate risk to pedestrian at the free left turn. Pignataro gives the following standard formula to determine adequate gap size (Pignataro, 1973):

\[ G = \frac{W}{S} + (N - 1) \cdot H + R \]  

(2)

Where \( G \) is the minimum safe gap in traffic in seconds, \( W \) is the crossing distance or roadway width in meters, \( S \) is walking speed in meters per second, \( N \) is predominant number of rows, typically 1, \( H \) is time headway between rows in seconds, default value two seconds, and \( R \) is pedestrian start-up time in seconds, default value three seconds.

<table>
<thead>
<tr>
<th>Intersection Leg</th>
<th>IIT</th>
<th>AIIMS</th>
<th>Nehru Place</th>
<th>Mehrauli</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle Delay (s/veh)</td>
<td>1805.8</td>
<td>1264</td>
<td>2401.4</td>
<td>474.3</td>
</tr>
<tr>
<td>LOS(^i) criteria for vehicle</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
</tr>
<tr>
<td>Pedestrian Delay (s/p)</td>
<td>47.4</td>
<td>92.7</td>
<td>34</td>
<td>96.1</td>
</tr>
<tr>
<td>LOS(^i) criteria for pedestrians</td>
<td>E</td>
<td>F</td>
<td>D</td>
<td>F</td>
</tr>
<tr>
<td>Likelihood of Noncompliance for pedestrian (^i)</td>
<td>High</td>
<td>Very high</td>
<td>Moderate</td>
<td>Very high</td>
</tr>
<tr>
<td>Width of the free left turn crosswalk (m)</td>
<td>3.9</td>
<td>3.3</td>
<td>4.2</td>
<td>3.3</td>
</tr>
<tr>
<td>Adequate gap size for pedestrians while crossing free left turns (s)</td>
<td>6.25</td>
<td>5.75</td>
<td>6.5</td>
<td>5.75</td>
</tr>
<tr>
<td>Pedestrian safety at free left turn</td>
<td>Not acceptable</td>
<td>Not acceptable</td>
<td>Not acceptable</td>
<td>Not acceptable</td>
</tr>
</tbody>
</table>

\(^i\) as classified in HCM 2000

Table 2 shows that the different ranges for LOS classified for vehicular volume in HCM, do not have any significance for the selected intersection because the delay values far exceed HCM's delay threshold at the boundary between LOS E and LOS F. And, in terms of delay the LOS for pedestrian is acceptable at IIT and Nehru Place approaches at some extent, but at AIIMS and Gurgaon approach delay to pedestrian is high this leads to very high likelihood for noncompliance at these approaches. However, in terms of pedestrian safety LOS of the intersection is not acceptable at all.

Pignataro's equation produced an adequate gap size for free left turn at each approach. The adequate gap size to cross the free left turn at AIIMS approach is 5.75 seconds, IIT approach is 6.25 seconds, Gurgaon approach is 5.75 seconds and Nehru Place approach is 6.5 seconds. From the data observed on the free left turn of the crosswalks (AIIMS and Gurgaon approaches), the average accepted gap size is 4.2 seconds which is less than 5.75-second adequate gap size. The traffic pattern is almost same at all the approaches of intersection. Therefore, we assume that the average accepted gap size for IIT and Nehru Place approach is also less than the adequate gap size (6.25 and 6.5-seconds respectively). It shows that, these crosswalks are unsafe for pedestrians to cross. Hence, it is recommended that to enable safe crossing for pedestrian, free left turn should not be allowed at the intersection. Existing traffic facilities and infrastructure only favor a particular user type. We must insure pedestrian delay and safety as well, while improving LOS for vehicles at the intersection.
9. CONCLUSIONS

One objective was to evaluate the applicability of the HCM signalized intersection model at a selected intersection in New Delhi, India. Results show what model modifications can further improve the HCM model for the Indian context. However, shortcomings still exist that could be addressed using more sophisticated resources and techniques. In summary, the conclusions are:

1. Right turning traffic uses a 3.6 m (12 ft) road width. This width is slightly more than the 3.3 m (11 ft) allocated to the right turning lane group.

2. Motorized two-wheelers usually have PCU values less than one since their small size enables them to form a compact pack and occupy less space. The two wheelers cause lesser hindrance to surrounding vehicles. Motorized three-wheelers have a flat frequency distribution across the lane, and they produce a larger drag effect as compared to other traffic entities. Their high acceleration noise is also responsible for this effect. Thus, three wheelers have large PCU values. Large PCU values for heavy vehicles are attributable to their low speed and large size. Speed plays a major role in determining PCU values.

3. The traffic coming in from the direction of AIIMS does not experience any left turn blockage since a large channelization island separates this movement from other traffic movements. This eliminates the chances of left turning traffic to intermingle with other traffic movements. The blockage of free left turns are a big problem at Indian intersections, and it is recommended that left turning traffic should be segregated from through and right turning traffic when possible. The bay provided for left turns should be at a sufficient distance from the stop line.

4. The different delay ranges for LOS as classified in the HCM do not have any applicability at the selected intersection because delay values far exceed the HCM LOS E and LOS F delay boundary.

5. Adequate gap size for pedestrian to cross the road as determined by Pignataro’s equation is not available for the pedestrian to cross the carriageway at the free left turn. Inadequate gaps force pedestrians to accept dangerous lower gap durations. One can improve pedestrian safety at the intersection by calibrating the difference between adequate and actual gap sizes. Widening of the carriageway increases the requirement of adequate gap size for a crosswalk. This widening is beneficial for vehicles but causes problems in the movement of pedestrians. Traffic engineers and planners while calculating the LOS of intersection must ensure pedestrian safety in addition to improvement in delay to pedestrians and vehicles.

10. LIMITATIONS AND RECOMMENDATIONS

One can slightly modify the HCM signalized intersection model for better adaptation to Indian conditions. Laying this groundwork provides further development in this direction. Some problems have been outlined, modifications suggested, and adjustment factors developed given the time and resource constraints.

The major limitation of the study is the very limited no of observations. Due to practical difficulties in camcorder usage atop the flyover, team members accurately captured and analyzed traffic movement data in one direction. Videotaping traffic movement by individuals from atop a flyover without a pedestrian facility was extremely dangerous. Thus, the number of observations was very limited.
Due to insufficient sample size, no accurate trend analysis could occur on capacity, LOS, and safety comparisons with and without modifying factors for the entire intersection. In the future, large-scale data collection for studying the entire intersection would be able to serve the better understanding. The results obtained in that case will be beneficial for intersection planning. Much scope for future work exists in adapting homogeneous traffic models where non-homogeneous traffic prevails.

REFERENCES


Duncan, C., Khattak, A., & Hughes, R. "Effectiveness of pedestrian safety treatments for "hit along roadway crashes." In *81st Annual Transportation Research Board Meeting*, on TRB CD-ROM.


Transportation Research Board of the National Academies, Washington, D.C.


