Abstract

Walking is one of the main and sustainable traffic mode in urban transportation, particularly in India because of the flexibility and mobility involved in it. Pedestrians are facing problems during crossing at signalized intersection crosswalks under mixed traffic condition. Of all the problems faced by pedestrians in signalized intersection crosswalks, pedestrian delay is the most important parameter and it is difficult to estimate. Keeping this as the motivation, this research has been undertaken with the aim of developing a pedestrian delay model for signalized intersection crosswalks. The required model parameters were extracted based on the videographic survey conducted at a typical four arm signalized intersection in Mumbai, India. Analysis of the field data yielded some notable observations as follows: pedestrians adjust their crossing speed based on the traffic condition at that particular time, pedestrian non uniform arrival pattern was observed, and some of the pedestrians were crossing the crosswalk during flashing red signal phase and red phase. Considering the above mentioned pedestrian crossing behavioral factors, a new delay model suitable for Indian condition was developed based on three factors such as waiting time delay, crossing time delay and pedestrian – vehicular interaction delay. Waiting time delay is based on signal red timing for pedestrians in waiting area, crossing time delay is based on pedestrian walking speed, and vehicular interaction delay is based on acceptable gap and walking speed. The proposed new delay model was validated with the field data from the Holkar junction, Mumbai, India and compared with existing models. This new pedestrian delay model can also be used to evaluate of pedestrian level of services at signalized intersections.

Keywords: signalized intersection; crosswalks; mixed traffic; pedestrian delay

* Corresponding author. Tel.: +0-982-048-1495.
E-mail address: 124040001@iitb.ac.in
1. Introduction

Most of the Indian cities have high pedestrian deaths in road accidents. In Mumbai, poorly maintained and unplanned pedestrian infrastructure has become a major road safety issue and as per latest statistics which records as 57 of 100 people who die on Mumbai’s roads are pedestrians. Pedestrians are facing problems during crossing at signalized intersection crosswalks under mixed traffic condition. Of all the problems faced by pedestrians in signalized intersection crosswalks, pedestrian delay is the most important parameter and also difficult to estimate. Most of the research in transportation sector has been conducted only on vehicle delay at signalized intersections. Highway Capacity Manual (HCM), the most referred manual for development of roadways also focuses on the estimation and improvement of vehicle delay models at signalized intersections. Pedestrian delay at signalized intersection is more complex to estimate accurately because of pedestrian crossing behavior and mixed traffic conditions. Thus, pedestrian delay is the key performance indicator to evaluate a signalized intersection Level of Service (LOS) for pedestrians.

Generally used pedestrian delay estimation methods and models are mostly derived from HCM and that model is based on cycle length and red phase duration; also with few assumptions such as uniform pedestrian arrival rate, noncompliance pedestrian flow, fixed cycle length and pedestrians following the base rules without violating them. These assumptions are not suitable for Indian mixed traffic conditions and thus the model proposed by HCM is inefficient to estimate pedestrian delay for mixed traffic condition.

Commonly, pedestrians are prohibited to enter crosswalk during flashing red and red phases. But in India, traffic condition and pedestrian signal system differ and are complex with pedestrians attempting to enter crosswalk during non-green phases to avoid delay. Pedestrian violation depends on an acceptable gap level (Critical acceptable gaps are smaller with higher walking speeds) and who disobey the rules are considered as violators. Main reasons of pedestrian violation are low quality traffic management, no person specially assigned to manage pedestrians, very less traffic safety awareness and longer cycle time (more than 100 seconds). Major problem for failure of all existing models including Indian Road Congress (IRC) is the value of pedestrian walking speed estimated as 1.2 m/s. This constant value of pedestrian walking speed is not applicable for the Indian traffic conditions.

In recent times, research works on pedestrian delay due to vehicle-pedestrian interaction in crosswalks have been very less. Existing models are also based on pedestrian safety application only. If there is an acceptable gap with no person to manage the signalized intersection, pedestrians violate the traffic signal and try to cross from near side road and reach median or refuge islands. Violators are then waiting for next acceptable gap to cross to the far side road. In this situation, violators face delay in median or crosswalk because of vehicle movement and cause inconvenience to flowing traffic. During green phases, pedestrians get delayed due to irregular vehicle drivers who disobey traffic rules and cross the intersection and also from vehicles occupying the crosswalks partially or completely. Most of the existing delay models ignore pedestrian delay received during green phases by such vehicle interaction on crosswalk. Therefore, in this paper all of the above mentioned traffic conditions and pedestrian behavior prevailing in developing cities in India are considered and proposed to develop a new pedestrian delay model at signalized intersections. Finally conclusions and recommendations for future studies are provided.

2. Literature Review:

Review of existing literature suggests that a lot of attention has been paid to research on pedestrian delay models for developed countries in recent years, but very little has been done on the pedestrian delay models based on developing countries: traffic condition and pedestrian behavior. Lipovac et al. (2013) studied pedestrian crossing behavior at signalized intersection and Countdown display is used to reduce pedestrian crossing during red light traffic. Yordphol et al. (1986) examined the pedestrian characteristics in sidewalks and walkways in...

Kruszyna et al. (2006) proposed new delay estimation models and they differ in the degree of accuracy and complexity as well as practical utility and they are based on only arrival pattern of pedestrians. Heungun et al. (2000) developed pedestrian delay model based on maximum pedestrian crossing rate (MPCR). Chen et al. (2010) attempts to develop pedestrian delay estimation model for intersections considering automobile-pedestrian conflicts induced by driver’s bad behavior of not giving way to pedestrians. Qingfeng et al. (2005) proposed a Monte Carlo model to estimate pedestrian delays at with pre timed two-phase control in developing cities like Xi’an, China. The model includes four parts: vehicle generator, pedestrian generator, pedestrian model, and statistical model. Qingfeng et al. (2007) used Monte Carlo model to estimate the vehicle delays in the condition of green traffic-light controlled by pre-timed four-phase signal. Here the vehicle delay is mainly caused by pedestrians who disobey traffic signals at the road junction. From field study at China, some of the assumptions are made and new model has been developed based on average pedestrian delay and arrival sub-phases (Qingfeng et al. 2005). Xuan and Zong (2010) developed pedestrian delay model with a two-stage crossing design. The literature indicates that there is a need for a pedestrian delay model that incorporates pedestrian crossing behaviour and vehicular interaction. This study is an attempt in this direction.

3. Study Location:

India is a developing country in South Asia with a population of 121 crores (censusindia). Mumbai is the capital city of Indian state of Maharashtra. It is the most populous city in India and the fourth most populous city in the world, with a total metropolitan population of approximately 20.5 million (censusindia). Mumbai city is an excellent location for this pedestrian delay model development. Signalized intersection sites chosen for the study in Mumbai are of a typical four arm type and also fixed traffic signal cycle lengths. A detailed sketch of study locations selected in Mumbai is shown in Figure 1.

![Figure 1 Study Location: Developing city - India, Metropolitan city-Mumbai](image-url)
Collected data from video recording are tabulated in Table 1. Data were collected in 1 hour interval using a
video recording device. The video recording offered information about pedestrian crossing volumes, crosswalk
length, crossing locations (using the crosswalk or not using it), pedestrian phase time (in green phase, flashing
red phase and red phase), crossing behaviors (walking or running, alone or in groups and walking speed),
pedestrian appearance character (gender and age group) and pedestrian-vehicle interaction.

Table 1. Study Location and Field measurement data

<table>
<thead>
<tr>
<th>Site Identity</th>
<th>Intersection Name</th>
<th>Date of survey</th>
<th>Time of Survey</th>
<th>Length of Crosswalk (m)</th>
<th>Pedestrian Phase (Sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A 2</td>
<td>Holkar Junction</td>
<td>05.04.13</td>
<td>5pm – 6pm</td>
<td>25</td>
<td>22 3 55</td>
</tr>
<tr>
<td>A 1</td>
<td></td>
<td>22.05.13</td>
<td>5pm – 6pm</td>
<td>31.5</td>
<td>25 3 121</td>
</tr>
<tr>
<td>B 1</td>
<td>Mahim Junction</td>
<td>22.05.13</td>
<td>9am-10am</td>
<td>20</td>
<td>35 2 106</td>
</tr>
<tr>
<td>B 2</td>
<td>Juhu-Linking Road Junction</td>
<td>22.05.13</td>
<td>9am-10am</td>
<td>13.5</td>
<td>19 3 121</td>
</tr>
<tr>
<td>C</td>
<td></td>
<td>07.06.13</td>
<td>9am-10am</td>
<td>19</td>
<td>12 3 118</td>
</tr>
<tr>
<td>D 1</td>
<td>Malad-Marve Road Junction</td>
<td>07.06.13</td>
<td>5pm – 6pm</td>
<td>33.1</td>
<td>52 3 195</td>
</tr>
<tr>
<td>D 2</td>
<td></td>
<td>07.06.13</td>
<td>5pm – 6pm</td>
<td>23</td>
<td>46 3 201</td>
</tr>
</tbody>
</table>

4. Pedestrian Behavior Analysis

Most of previous studies are based on pedestrian flow characteristics and walking time in sidewalks and
walkways. Very few studies have focused on pedestrian crossing behaviors in signalized intersections and have
been developed only for pedestrian safety aspects and have also analyzed only for pedestrian crossing during red
phases with walking speed variations. At present, there is no pedestrian delay model that has been developed
solely based on all possible pedestrian crossing behaviors at signalized intersections in developing countries like
India. An attempt has been made in this paper to analyze pedestrian crossing behaviors like walking speed;
possible violation behaviors of pedestrians; and Pedestrian-vehicle interaction on crosswalk from collected field
data in Mumbai have also been studied as a means to develop a complete model.

4.1. Walking Speed

In India, the present design practice in signalized intersections is to assume the pedestrian walking speed to be
a constant value of 1.2m/sec. From field study conducted in Mumbai, the crossing behavior of pedestrians has
been found to be largely varying from the assumed constant value. The major reasons for walking speed variation
have been found to be of the following: (i) Very less pedestrian green phase, (ii) Violating behavior of
pedestrians, (iii) Platoon effect and (iv) Directional crossing effect

So during design of signalized intersections in developing countries like India, there arises a need to consider
all possible pedestrian crossing behavior and other influence factors. According to the analyzed field data from
five crosswalks at signalized intersections in Mumbai under mixed traffic conditions, the calculated pedestrian
walking speed are tabulated in Table 2 with necessary classifications such as pedestrian gender, age group,
platoon effect and traffic signal. From the field data, the crossing speed variations of pedestrian analyzed and
results are tabulated in Table 2.
Table 2. Pedestrian walking speed based on pedestrian and traffic characteristics at selected intersection crosswalk in Mumbai

<table>
<thead>
<tr>
<th>Site Identity</th>
<th>Crosswalk length (m)</th>
<th>Pedestrian walking speed (m/s) based on Characteristics</th>
<th>Traffic Signal</th>
<th>Platoon</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Gender Age Group</td>
<td>Red</td>
<td>Green</td>
</tr>
<tr>
<td>A 2</td>
<td>25</td>
<td>1.449 Male, 1.313 Female, 1.432 Adult, 1.40 Old, 1.417</td>
<td>1.487</td>
<td>1.307</td>
</tr>
<tr>
<td>A 1</td>
<td>31.5</td>
<td>1.464 Male, 1.317 Female, 1.457 Adult, 1.27 Old, 1.442</td>
<td>1.434</td>
<td>1.359</td>
</tr>
<tr>
<td>B 1</td>
<td>20</td>
<td>1.396 Male, 1.130 Female, 1.373 Adult, 1.24 Old, 1.242</td>
<td>1.300</td>
<td>1.130</td>
</tr>
<tr>
<td>B 2</td>
<td>13.5</td>
<td>1.239 Male, 1.174 Female, 1.248 Adult, 1.024 Old, 1.19</td>
<td>1.247</td>
<td>1.245</td>
</tr>
<tr>
<td>C</td>
<td>19</td>
<td>1.309 Male, 1.241 Female, 1.308 Adult, 1.242 Old, 1.29</td>
<td>1.42</td>
<td>1.326</td>
</tr>
</tbody>
</table>

From Figure 2, comparisons of pedestrian walking speed based on pedestrian characteristics were analyzed and the following inferences are made:

(i) The average walking speed of a male pedestrian (1.37 m/s) is more than a female pedestrian (1.26 m/s)
(ii) Adult pedestrian (of age 21 years to 60 years) walking speed (1.36 m/s) is more than that of an old pedestrian (1.23 m/s) (of age > 60 years)
(iii) Green phase walking speed (1.35 m/s) is more than red phase walking speed (1.32 m/s) because of very less pedestrian green time in India
(iv) Platoon or group of pedestrians walking speed (1.27 m/s) is less than that of a single pedestrian walking speed (1.34 m/s).
(v) Design value of 1.2 m/s was found to be of insignificance since the measured field value is 1.34 m/s.
(vi) The field value was found to be nearly equal to Qingfeng Li (2005) field value 1.33 m/s measured in China.
(vii) Table 3 shows the comparison of pedestrian walking speed with International studies.
It is suggested to use the above calculated walking speed from the field data as a constant value in development of delay estimate models for finding crossing time delay at signalized intersections in India under mixed traffic conditions.

4.2 Pedestrian Violation behavior

From the field observed data, it has been found that out of 1565 pedestrians, there were a total of 942 pedestrians who have violated the traffic rules and crossed in the red phase. According to the observations, the proportion of pedestrians who comply with the law is found to be 60.19% in Mumbai. Table 4 shows the percentage of violators in each collected crosswalk.

Table 4. Pedestrian walking speed and violator percentage at selected intersection crosswalk in Mumbai

<table>
<thead>
<tr>
<th>Site Identity</th>
<th>Crosswalk length (m)</th>
<th>N (Sample)</th>
<th>Mean Walking speed</th>
<th>Std Deviation</th>
<th>% of Violator</th>
</tr>
</thead>
<tbody>
<tr>
<td>A 2</td>
<td>25</td>
<td>54</td>
<td>1.4229</td>
<td>0.27101</td>
<td>65.06</td>
</tr>
<tr>
<td>A 1</td>
<td>31.5</td>
<td>337</td>
<td>1.4394</td>
<td>0.32091</td>
<td>65.28</td>
</tr>
<tr>
<td>B 1</td>
<td>20</td>
<td>402</td>
<td>1.2942</td>
<td>0.34111</td>
<td>43.89</td>
</tr>
<tr>
<td>B 2</td>
<td>13.5</td>
<td>272</td>
<td>1.2150</td>
<td>0.2295</td>
<td>56.62</td>
</tr>
<tr>
<td>C</td>
<td>19</td>
<td>143</td>
<td>1.2150</td>
<td>0.2295</td>
<td>89.87</td>
</tr>
<tr>
<td>D 1</td>
<td>33.1</td>
<td>13</td>
<td>1.5304</td>
<td>0.38084</td>
<td>65.41</td>
</tr>
<tr>
<td>D 2</td>
<td>23</td>
<td>20</td>
<td>1.2942</td>
<td>0.17953</td>
<td>64.85</td>
</tr>
</tbody>
</table>

Figure 3 Pedestrian violation at selected signalized intersection crosswalk based on gender and age group

From Figure 3, average male violators have been measured to be 65.27% and female violators were 60.14%. The major reason is male pedestrian accept small gap acceptance and increase the walking speed and cross the crosswalk during red phases. So the main aim of the pedestrians to violate the traffic signal is to reduce more waiting delay. Violators have also been found to receive delays because of vehicle interaction on crosswalk and far side vehicle movement. It is suggested that, during estimation of pedestrian delay at signalized intersections,
to consider 60% of red phase time utilizing by pedestrian. To further improve the delay model it is also suggested to consider pedestrian-vehicle interaction, platoon effect and directional effect also.

5. Model Development:

Holkar Junction in Mumbai were chosen for this study and shown in Figure 4. And the crosswalk on the western leg (A1) of the intersection was selected for pedestrian delay model development, as shown in Figure 5.

Figure 4 and 5. Study Location: Holkar Junction and selected crosswalk (A1) on the western leg of Holkar Junction

5.1. Pedestrian Behavior Analysis at Holkar Junction:

Holkar junction in Mumbai has been selected for pedestrian delay model development from the five crosswalks from which data has been extensively gathered. Data extracted from the one hour video survey has given information on the following parameters: Arrival pattern of pedestrians, Average walking speed, Violators, and Pedestrian-vehicle interaction.

The cycle time of 80sec is divided into sub-phases and each sub-phase is for a 10sec time interval. Figure 6 shows pedestrian non uniform arrival pattern at Holkar signalized intersection, Mumbai under mixed traffic conditions. Figure 7 shows walking speed distribution at Holkar junction and it follows normal distribution curve shape. The value of pedestrian walking speed is1.4m/s and violation rate is 65%.

Figure 6 and 7. Arrival pattern of pedestrian in each subphases and walking speed distribution at Holkar junction
5.2. Pedestrian delay model development

The developed new model has of three components. In first component, average waiting time delay is developed from HCM model. In second component, crossing time delay and pedestrian walking speed is set to 1.34 m/s (value from analyzed field data). In third component, pedestrian-vehicular interaction delay time is calculated from field.

And the proposed new model is as follows,

\[ D_{\text{avg}} = D_{\text{WT}} + D_{\text{CT}} + D_{\text{VIT}} \]  

where, \( D_{\text{WT}} \) = Average Waiting Time delay during non-green phases per pedestrian, \( D_{\text{CT}} \) = Average Crossing Time delay during all phases per pedestrian, \( D_{\text{VIT}} \) = Average Vehicular–Pedestrian Interaction Time delay during all phases per pedestrian.

5.2.1 Waiting Time Delay:

\[ D_{\text{WT}} = \alpha_1 (C - (G + \alpha_2 R))^2 / 2C \]  

where, \( \alpha_1 \) = Correction factor for non-uniform arrival rate, \( \alpha_2 \) = Percentage of pedestrian start crossing during non-green phases, \( C \) = Cycle time in sec, \( G \) = Pedestrian Green time in sec, \( R \) = Pedestrian Red time in sec, \( n_T \) = Total number of pedestrian arriving during all phases, \( n_R \) = Total number of pedestrian arriving pedestrian red phases only.

\[ \alpha_1 = (C/R)/(n_T/n_R) \]

According to data from field analysis, the violators were 60% of the total pedestrians and adjustment factor for uniform arrival pattern is 0.81 from equation 3. Using this new model, the waiting time delay is calculated to be 7.18 sec.

5.2.2 Crossing Time Delay

\[ D_{\text{CT}} = \text{Actual Crossing Time} – \text{Ideal Crossing Time} \]  

Actual crossing time was extracted from field data and ideal crossing time is the proportion of crosswalk length and pedestrian walking speed. The value of pedestrian walking speed taken from Table 3 and crossing delay time at Holkar junction is 0.8sec.

5.2.3 Vehicular Interaction Delay

Pedestrian-Vehicular interaction delay on crosswalk based on the following factors: Pedestrian gap acceptance, Pedestrian and vehicle volume, Pedestrian directional flow, and Time difference between pedestrians and vehicles arriving at crosswalk area.

At Holkar junction crosswalk (A1), the minimum pedestrian gap acceptance is 1.6 s and average pedestrian gap acceptance is 4.5 s. The entry vehicle volume is 2518pcu/hr and exit vehicle volume is 2670pcu/hr on crosswalk A1. U2D directional pedestrian flow is 164ped/hr and D2U directional pedestrian flow is 173ped/hr. And extracted value of pedestrian-vehicular interaction delay at Holkar junction is 11.78sec during pedestrian green and red phases.

And the overall average pedestrian delay at Holkar junction is 19.7sec by using equation (1).

6. Comparisons with existing pedestrian delay models:

The most widely used pedestrian delay model at signalized intersection is as follows,

\[ D = (C-G)^2 / 2C \]
where, $D$ is average pedestrian delay, $C$ is cycle length and $G$ is green time. The assumptions of developed model are uniform pedestrian arrival rate; fixed cycle length and pedestrian follow the traffic signal rules (HCM).

Braun and Roddin (1978) consider some pedestrian violate traffic signal and developed the following model,

$$D = F(C-G)^2/2C$$

where, $F$ is the fraction of pedestrians who arrive during non-green phases and comply with traffic signals. This equation assumes that pedestrians receive no delay if they violate traffic signals (Qingfeng et al., 2005).

Virkler (1998) developed a model based on pedestrian violation during clearance time and model is as follows,

$$D = (C-(G+0.69A))^2/2C$$

where, $A$ is clearance time.

Qingfeng et al (2005) developed pedestrian delay model in China and followed model based on non-uniform arrival rate and pedestrian delay during green phases

$$D = d_G + (K_N*U*K*R^2)/2C$$

where, $d_G$ is the average delay of pedestrians arriving during green phases, $K_N$ is the adjustment factor for non-uniform arrival rate, $k$ is the absolute value of the decreasing line and $R$ is effective red time.

Field delay is compared with existing models and shown in Figure 8. It is found that all the existing models were not able to estimate the field delay accurately with most of the models overestimating the delay time. And the proposed new pedestrian delay model in this paper estimated near value to field delay. And the percentage difference between field delay and new model delay is 8.12%. So the new model is applicable for developing cities like India under mixed traffic condition.

7. Conclusions

It has been proved in this paper that the existing models to calculate pedestrian delays at signalized intersection crosswalks fail to provide necessary accuracy of delay estimation. The major reason for this inaccuracy is attributed to assumptions which defer the models from considering all possible pedestrian crossing behaviors at signalized intersections under mixed traffic conditions in developing countries like India. Thus, the existing models are only applicable for selected types of signalized intersection crosswalks and are not general in
nature. The new methodology that has been introduced in this paper for delay estimation model development is found to be useful wherever the existing models have failed to predict accurately and this model include all of the possible pedestrian crossing behaviors in Mumbai. Further research is necessary in order to develop pedestrian-vehicular interaction delay model to fine tune the model results.

8. References


www.censusindia.gov.in/Tables_Published/A-Series/A-Series_links/1_00_003.aspx.


