Empirical Analysis of Pedestrian Delay Models
at Urban Intersections

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Abstract

Signalized crosswalks are useful pedestrian facilities but complexities in geometry and configuration arise, especially in congested urban areas, directly affecting safety, cycle length and delay. Universal design criteria are not dealt with by manuals. Scientific literature has proven that pedestrians look for the shortest path at crosswalks, sometimes even adopting unsafe behaviour. On the other hand, drivers’ habits are scarcely bothered by pedestrian signage. The analysis of pedestrians’ cognitive path and choices is fundamental as well as the prediction of irresponsible actions. Delay is a widely adopted parameter to assess pedestrian Level of Service. In this work, a comparison among renowned models to estimate pedestrian delay at signalized crosswalk is set and double-checked with a field study in the city of Bologna – Italy.

Keywords: Level of Service, pedestrian delay, traffic signal

1 Introduction

Pedestrian crossing time is basically a function of crosswalk length and walking speed [1-3]. However, when pedestrian demand increases at both sides of the crosswalk, interaction phenomena are present. The crossing time \(T_{c}\) can be estimated as a function (1) of initial start-up lost time \(I\), crosswalk length \(L\), walk-
ing speed \((v)\), crosswalk width \((w)\) and the flow rate of opposing platoons \((Q_1 - Q_2)\) [1]. Although, no assumptions are made on interaction and its effects on pedestrian speed.

\[
T_c = I + \frac{L}{v} + \left(2.09 \frac{Q_1}{w} + 0.52 \frac{Q_2}{w}\right) \quad \text{if } Q_1 \leq 5 \text{ ped/m} \\
T_c = I + \frac{L}{v} + \left(0.81 \frac{Q_1}{w} + 0.52 \frac{Q_2}{w} + 6.4\right) \quad \text{if } Q_1 > 5 \text{ ped/m} \tag{1}
\]

According to [4], bi-directional flow results in decrease of both walking speeds and capacity – irrespective of walkway’s dimensions. Other studies [5-7] claim that the total crossing time is divided into discharge time \(T_d\) and crossing time \(T_c\). The former is the time needed to engage the crosswalk and the latter the time needed to complete the crossing. Crosswalk width \((w)\), pedestrian encumbrance, cycle timing, split ratio, pedestrian speed, density are the principal determinants. With no pedestrian violation, \(T_c\) increases with increasing split ratio \((r)\) or decreasing \(w\).

Minimizing users delay by reducing signal cycle length is a critical issue: long cycles have negative effects on pedestrians, making them prone to signal violations [8-9]; indeed, relevant and equally split pedestrian demand results in a speed drop of almost 30\% compared to the unidirectional flow, with a further drop due to the presence high shares of elderly people [10].

The first attempts to derive pedestrian LOS were made in [11-13]. Intersection conditions as well as flow rate and geometry were first taken into account by HCM 2000. Widely used pedestrian delay estimation models follow the assumptions of uniform random pedestrian arrival rate, fixed cycle length and no pedestrian violation. Following Dunn and Pretty [11]:

\[
d = \frac{(C-g)^2}{2C} \tag{2}
\]

where:

\(d\) = average stopped delay per pedestrian  
\(C\) = cycle length of the intersection  
\(g\) = pedestrian green

Pedestrian LOS and signal violation are shown in Table 1 below.

<table>
<thead>
<tr>
<th>Level of service</th>
<th>Delay/pedestrian [s/ped]</th>
<th>Likelihood of crosswalk violation</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>&lt; 10</td>
<td>Low</td>
</tr>
<tr>
<td>B</td>
<td>10 – 20</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>20 – 30</td>
<td>Moderate</td>
</tr>
<tr>
<td>D</td>
<td>30 – 40</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>40 – 60</td>
<td>High</td>
</tr>
<tr>
<td>F</td>
<td>&gt; 60</td>
<td>Very high</td>
</tr>
</tbody>
</table>

Table 1 – Pedestrian level of service at signalized crosswalk (HCM)
In the original formulation by Webster [19], 2s on average for the 1st vehicle in the queue and further 2s for each ensuing vehicle were assumed to clear the intersection; pedestrians instead are assumed to engage the crosswalk as soon as the green starts, clearing the crosswalk faster than vehicles and minimizing the likelihood to run into delays per existing queue (Fig. 1 and 2).

\[ d = F \frac{(C-g)^2}{2C} \]  

(3)

A reduction in total delay (the shaded area in fig. 3 and 4) is observable if compared with Fig. 2. However, non-complying pedestrians are assumed to receive no delay, which is unrealistic.

\[ d = \frac{[C-(g+0.69A)]^2}{2C} \]  

(4)

For this reason, Virkler [13] assumed that a share of passengers crossing during the clearance interval \( A \) could reduce their delay (4).
Dunn & Pretty (1984) [11] derived a further formulation of pedestrian delay for intersections width of around 15m, which is still dependent on signal timing.

\[ d = \frac{(g+15)^2}{2(g+20)} \]  

(5)

Nevertheless, when high rates of violation are present, delay prediction models have to change: according to [14], violation rate is greatly influenced by pedestrian volume \((Q)\), crosswalk width \((w)\), non complying ratio \((NCR)\) and availability of pedestrian traffic signals. Delay \((d)\) is expressed as:

\[ d = 19,381 + 0,932 \frac{(C-g)^2}{2c} - 38,453(NCR) \]  

(6)

From those evidences, authors concluded that violations reduce the average delay; at the same time intersections with short cycles and long pedestrian green will experience low degrees of non-compliance. Finally, signal coordination is desirable.

Recently, literature has been focused on modelling mixed traffic conditions, violations by both vehicles and pedestrians as well as delay suffered by pedestrians arriving during green phases or due to the presence of conflicting vehicles [15]. Some works have been developed by many authors [16-18], often with reference to specific local conditions. In particular, Li et al. [18] derived that, if pedestrians arriving at the beginning or during clearance interval decide to engage the intersection rather than waiting for the next green, then pedestrian arrival rate cannot be casual or uniform. Authors derived the following expression for delay:

\[ d = d_g + \frac{(k_{nu} \delta R^2)}{2c} \]  

(7)

- \(d_g\) is the average delay of pedestrians arriving during green: if the amount of conflicting vehicular flow is negligible, it is assumed equal to 2,1 sec.
- \(k_{nu}\) is the adjustment factor for non-uniform arrival rate (8), where \(n_T\) is the overall number of pedestrians and \(n_g\) is the share arriving during green.
- \(R\) is the effective red.
- \(\delta\) is the absolute value of the decreasing line’s slope

\[ k_{nu} = \frac{c(n_T-n_g)}{n_T(C-g)} \]  

(8)

\[ R = C - (g + 0,67A) \]  

(9)

\[ \delta = 1 - (1 - (-0,08 + 0,9q)) \]  

(10)
2 Field analysis

A field survey has been conducted to verify the suitability of the models to real scenarios. A signalized intersection has been targeted in the city of Bologna – Italy (Fig. 5): situated in the core centre of the town, it has notable pedestrian flows with a relevant share of habitual users. Contrary to the basic assumptions of HCM formula and Li et al.’s methodology, cycle length is adjusted from a remote operation centre. The study’s aims were to verify Li et al.’s assumption on non-casual pedestrian arrival pattern during clearance and to collect data to verify some of the aforementioned models in order to assess which one fits best the target scenario. A total of 606 pedestrians have been observed. Cycle length has been split into green – clearance – red and pedestrian arrival rate has been measured for each phase (see fig. 7-8 below): 68% of pedestrians arrive at the crosswalk during red; in addition, %pedestrians arriving during clearance is relevant if compared to the short duration of that phase; hence the parameter $k_{nu}$ has been derived. Average pedestrian speed has been measured of 1.34 m/s. Fig. 9 below describes the distribution of pedestrian speed at the crosswalk.
Pedestrian delay is assumed as the difference between actual crossing time and ideal crossing time (11.57 s), which is the crosswalk length divided by the average speed. Following data have been collected for each phase of the cycle and for each cycle: arrival time at the crosswalk, initial and final time of crossing, phase length, cycle length, vehicular and pedestrian flows along the two directions, n° of pedestrian arriving during green, % pedestrian complying with traffic signal, average waiting time, average crossing time, average crossing speed, average delay for pedestrian and start-up lost time. Results are shown in Table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crosswalk width</td>
<td>w</td>
<td>15.5 m</td>
</tr>
<tr>
<td>Average cycle length</td>
<td>C</td>
<td>92 s</td>
</tr>
<tr>
<td>Average green time</td>
<td>v</td>
<td>24 s</td>
</tr>
<tr>
<td>Average clearance interval</td>
<td>A</td>
<td>5 s</td>
</tr>
<tr>
<td>Average green time for vehicles</td>
<td>g</td>
<td>54 s</td>
</tr>
<tr>
<td>Average pedestrian platoon</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average n° pedestrian</td>
<td>nT</td>
<td>15.95 ped</td>
</tr>
<tr>
<td>Average n° pedestrian arriving during green</td>
<td>ng</td>
<td>3.97 ped</td>
</tr>
<tr>
<td>Vehicular flow rate</td>
<td>q</td>
<td>744 veh/h</td>
</tr>
<tr>
<td>% pedestrian complying with traffic signal</td>
<td>F</td>
<td>77.73%</td>
</tr>
<tr>
<td>Average pedestrian delay</td>
<td>d</td>
<td>21.45 s</td>
</tr>
<tr>
<td>Average start-up delay</td>
<td>de</td>
<td>2.86 s</td>
</tr>
</tbody>
</table>

Table 2 – Parameters collected at crosswalk

3 Validation analysis

For each model, correlation has been explored between estimated delay and actual delay. Results are shown in Table 3.
Empirical analysis of pedestrian delay models at urban intersections

<table>
<thead>
<tr>
<th>Model</th>
<th>Average delay</th>
<th>% deviation</th>
<th>Correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average actual delay</td>
<td>21.45 s.</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Pretty</td>
<td>25.05 s.</td>
<td>+16.80%</td>
<td>+0.57</td>
</tr>
<tr>
<td>Braun e Roddin</td>
<td>19.57 s.</td>
<td>-8.73%</td>
<td>+0.66</td>
</tr>
<tr>
<td>Dunn e Pretty</td>
<td>32.41 s.</td>
<td>+51.11%</td>
<td>+0.45</td>
</tr>
<tr>
<td>Virkler</td>
<td>22.56 s.</td>
<td>+5.20%</td>
<td>+0.57</td>
</tr>
<tr>
<td>Li et al.</td>
<td>21.55 s.</td>
<td>+0.49%</td>
<td>+0.78</td>
</tr>
</tbody>
</table>

Table 3 – Comparison among models of pedestrian delay at signalized intersections

The formula proposed by Dunn e Pretty (5) does not fit the target scenario; reason for the deviation observed might be the dependence from the only parameter $g$. The formula proposed by Pretty (2) is affected by the assumptions of random pedestrian arrival and perfect compliance to traffic signal, hence a notable deviation from actual data is observed. This remarks upon the fact that a reduction in average pedestrian delay is possible by violating pedestrian signal. Finally, Li et al.’s formula (7) fits best the actual data as it includes more parameters, which are deemed significant in the assessment of delay. In Fig. 10-14, 38 pairs actual delay/estimated delay have been drawn, confirming results summarized in Tab. 3.

Figure 5 – Pretty.  
Figure 6 – Braun e Roddin.  
Figure 7 - Dunn e Pretty.  
Figure 8 - Virkler.
4 Conclusions

Pedestrian delay is a quantitative measure to evaluate the Level of Service (LOS) and then the efficiency and design of pedestrian infrastructures. Crosswalks with low LOS should be accurately investigated to grant higher efficiency. In scientific literature, a lot of models have been proposed, many of those relying on assumptions on pedestrian arrival rate, geometry and average speed. The capability of the models to interpret reality varies with the degree of maturity and concern of both drivers and pedestrian towards safety. Renowned models to assess delay have been tested on a case study in the city center of Bologna – Italy, following a methodology similar to the one adopted by Li et al., showing that simpler models – relying only on cycle timing and geometry parameters – are not adequate to understand and represent the actual delay. On the other hand, the knowledge of actual arrival rate at the intersection and speed distribution have proven to be determinant factor to successfully estimate delay.

References


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