Development of Pedestrian Crossing Warrants for Grade-Separated Pedestrian Crossing Facilities under Mixed Traffic Conditions

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Abstract

Pedestrian crossing warrants are used to determine when a crossing facility is required and which facility is appropriate for a particular road environment. Existing warrants commonly rely on pedestrian and vehicle volumes, road width, speed and PV^2 criteria, while the conditions at signalized midblock crosswalks (SMCs) are not always represented adequately. This study examined the conditions under which an SMC operating under heterogeneous traffic should be considered for upgrading to a grade-separated pedestrian crossing facility (GSPCF). Field observations were undertaken at eight SMCs and user-perception surveys were conducted at nine GSPCF locations. Video recordings were used to extract pedestrian and vehicle flow characteristics, queue lengths, crossing times and delays. Pedestrian delay modelling accounted for non-uniform arrivals, signal non-compliance and bidirectional pedestrian interactions; vehicle delay modelling considered mixed traffic and pedestrian influence. The proposed delay models were validated against field observations and the study reported estimation errors below 10%. Delay-based level-of-service (LOS) thresholds were developed using clustering and checked through support vector machine classification and user-perception ratings. The acceptable delays were 45 s for pedestrians and 25 s for drivers. Multi-objective optimization produced corresponding values of 48 s and 25 s, supporting LOS C as the pedestrian saturation threshold and LOS D as the vehicle saturation threshold. The GSPCF preference hierarchy identified by the survey was foot over bridge, hump subway and subway. The findings provide a delay-oriented basis for reviewing SMC performance and considering grade separation, subject to local validation and engineering feasibility.

Keywords: *Pedestrian crossing warrants; grade-separated crossing; signalized midblock crosswalk; pedestrian delay; vehicle delay; level of service; mixed traffic.*

1. Introduction

Walking forms part of almost every trip, including journeys made by public transport and private vehicles. At urban midblock locations, pedestrians may have to negotiate wide carriageways, high vehicle flows and heterogeneous traffic streams. Where crossing opportunities are inadequate, pedestrians may wait for long periods, accept small gaps or cross in violation of traffic signals. These behaviours increase exposure to pedestrian–vehicle conflicts and may also interrupt vehicle progression.

Pedestrian facilities can be broadly grouped into at-grade and grade-separated facilities. At-grade options include marked and zebra crossings, raised table-top crossings and signalized crosswalks. Grade-separated pedestrian crossing facilities (GSPCFs) provide a route above or below the carriageway and include foot over bridges (FOBs), subways and hump subways. Grade separation can remove direct pedestrian–vehicle conflict at the crossing point; however, its effectiveness depends on location, accessibility, convenience, personal security, maintenance and willingness to use the facility.

Pedestrian crossing warrants are intended to guide the selection and provision of crossing facilities. In India, IRC:103 provides guidance for pedestrian facilities and includes criteria such as pedestrian and vehicle volumes and PV^2-based assessment [1]. A limitation identified in the source study is that warrants for GSPCF provision have often been derived from conditions at uncontrolled midblock crossings. Pedestrian behaviour at an uncontrolled crossing differs from behaviour at a signalized midblock crosswalk: at the former, pedestrians search for acceptable gaps, whereas at the latter they are expected to wait for the pedestrian green phase. Consequently, delay and interaction conditions measured at an SMC should be considered when deciding whether it has reached a condition at which grade separation is warranted.

The present work addressed this gap by considering pedestrian and vehicle delays together, developing delay-based LOS criteria for SMCs, and examining user preferences among different GSPCF types. The central contribution is a framework that combines field delay, user-perceived acceptable delay, optimization and facility preference rather than treating all grade-separated facilities as a single option.

2. Background and Research Gap

Earlier warrant approaches have used pedestrian and vehicle volumes, operating speeds, number of lanes, accident records, road geometry, gap acceptance, delay, cost and qualitative assessments. Axler [2] considered pedestrian and vehicle volumes, speeds, alternative crossing availability, safety, feasibility and cost in developing overpass and underpass warrants. Braun and Roddin [3] examined the benefits of separating pedestrian and vehicle movements. International guidance has also considered road-user delay and economic assessment when comparing signalized and grade-separated alternatives [4].

Indian studies reviewed in the source document updated PV^2 thresholds and introduced adjustment factors for roadway width, pedestrian characteristics, crossing time, speed, lighting, signs, markings and other site conditions. Other studies considered lane-crossing time, delay-based LOS and combined pedestrian–vehicle delay. However, the review identified three continuing needs: (i) warrants should reflect the operational characteristics of SMCs; (ii) both pedestrian and vehicle delay should be considered; and (iii) the warrant process should distinguish between FOB, hump subway and subway rather than recommending grade separation as one undifferentiated facility [5–8].

Accordingly, the study objectives were to develop pedestrian and vehicle delay models for SMCs under mixed traffic, establish delay-based LOS criteria, identify acceptable and optimized delay thresholds, and derive a preference hierarchy for GSPCF types.

3. Study Locations and Methodology

3.1 Study design and locations

The investigation covered eight signalized midblock crosswalks (M-1 to M-8) and nine GSPCF sites (G-1 to G-9). The SMC sites were located in Hyderabad and represented mixed, commercial and residential land uses. They ranged from five to nine lanes, with road widths of 20.0–33.5 m and cycle times of 105–155 s. The GSPCF observations included six FOBs, two subways and one hump subway. The study used video-based observation for SMC traffic data and interviews/questionnaires for GSPCF user perceptions.

SMC site	Location	Lanes	Road width (m)	Cycle (s)	Pedestrian flow (ped/h)	Vehicle flow (veh/h)
M-1	Nizampet X Road	8	31.6	125	1,013	7,180
M-2	Moosapet	6	24.0	105	963	8,300
M-	Vivek	8	30.	120	822	8,44

3	Nagar		0			6
M-4	Dilsuknagar	6	23.5	155	750	5,699
M-5	Mettuguda	8	31.5	155	663	6,870
M-6	JNTUH Road	9	33.5	135	981	7,951
M-7	Madhapur	5	20.0	125	618	6,721
M-8	Vivekananda Nagar	7	26.5	125	363	7,862

Table 1. Summary of the eight signalized midblock crosswalks (site data reproduced from the study).

3.2 Video data collection and extraction

At SMC sites, video surveys were conducted during morning (08:00–12:00) and evening (16:00–21:00) peak periods. The camera view covered pedestrian waiting areas, the crosswalk and vehicle queue areas. Recordings were captured at 30 frames per second using a Sony HDR-PJ410 camcorder. Kinovea software was used to review the recordings frame by frame, while extracted observations were organized in spreadsheets. Pedestrian and vehicle arrivals and departures were recorded at short sub-phase intervals; queue lengths were obtained from cumulative arrivals minus cumulative departures. Pedestrian crossing times were measured from video frames and converted to seconds.

The extracted pedestrian variables included directional pedestrian flows, arrivals during the red phase, platoon size, actual and ideal crossing time, pedestrian speed, and the proportions of deviated, distracted and load-carrying pedestrians. Vehicle variables included arrivals, departures, vehicle type, speed, queue length and signal timing. The vehicle stream was heterogeneous, with two-wheelers forming the largest share at the selected locations.

3.3 Field delay measurement

Pedestrian waiting delay was estimated from the area under the pedestrian queue-length versus time curve. Queue length at sub-phase i was calculated as:

$$L_i = \text{Cumulative pedestrian arrivals}_i - \text{Cumulative pedestrian departures}_i$$

The area under the queue profile was evaluated using Simpson's 1/3 rule and divided by the pedestrian volume in the corresponding cycle to obtain average waiting delay. Pedestrian crossing delay was defined as the difference between actual crossing time under prevailing platoon conditions and ideal crossing time under minimal interference. Total pedestrian field delay was taken as waiting delay plus crossing delay. Vehicle field delay was estimated from the vehicle queue-length profile using the HCM-based area-under-the-curve approach.

3.4 User-perception surveys

A delay-perception survey used video clips representing six LOS conditions. Respondents rated pedestrian and vehicle delay on a six-point scale. The source study reports 532 responses and 6,384 ratings for the delay-perception exercise. A separate GSPCF preference survey was conducted at the selected facility locations; 742 responses were reported. Factors included frequency of facility use, additional time and effort, escalator/elevator availability, vendors, lighting, cleanliness, safety and security.

4. Delay Modelling

4.1 Pedestrian waiting delay

Conventional signalized-crossing delay models commonly assume uniform pedestrian arrivals and consistent compliance with the signal. The observed SMC conditions showed irregular pedestrian arrivals, platoon formation and variable signal violations. The study therefore introduced adjustment terms for non-uniform arrivals (Δ_1) and non-compliance behaviour (Δ_2), while also accounting for the effect of opposing pedestrian flow during crossing.

The coefficient for non-uniform arrivals was related to the ratio of pedestrian arrivals during the red phase (Q) to the red-phase duration (R). The fitted relationship reported in the source study was:

$$\Delta_1 = -0.612 \ln[-0.123 \ln(Q/R)] \; ; \; 0 < Q/R < 1 \; (R^2 = 0.713)$$

Here, Q is the number of pedestrians arriving during red time and R is the pedestrian red time in seconds. The model was selected after comparison of alternative curve fits. Its reported mean absolute percentage error was 5%, with RMSE of 0.112 for the Δ_1 estimation. The source study further incorporated non-compliance and bidirectional pedestrian effects into its modified waiting-delay formulation. The complete waiting-delay expression is not reproduced here because the source PDF's equation rendering is incomplete in the extracted text; it should be transcribed and checked against the original equation image before submission.

4.2 Bidirectional crossing delay

Pedestrians moving in opposite directions interact within the crosswalk. These interactions can cause path deviation, reduced walking speed and longer crossing time. Pearson correlation analysis identified pedestrian speed, directional split ratio and the fraction of deviated pedestrians as significant explanatory variables. The resulting multiple-regression model was:

$$dC = 6.773 - 0.297r - 5.011V_p + 3.786dV$$

where dC is pedestrian crossing delay (s), r is the directional split ratio, V_p is pedestrian speed (m/s), and dV is the fraction of deviated pedestrians. The model reported $R^2 = 0.772$ and adjusted $R^2 = 0.767$. The ANOVA F-statistic was 137.854 ($p < 0.001$), and the three predictors were statistically significant at the 95% confidence level.

4.3 Vehicle delay under mixed traffic

The vehicle delay model was developed by modifying the HCM approach to represent heterogeneous traffic and the influence of bidirectional pedestrian movement at an SMC. Vehicle arrivals and departures were extracted from the video recordings, and field delay was computed from the queue profile. The source study reports that the proposed pedestrian and vehicle delay models were validated against observed field delay and that both yielded errors below 10%. The full vehicle-delay equation is not reproduced in this manuscript because its mathematical expression is not legible in the extracted source text; the original equation must be inserted and verified before submission.

5. Results and Discussion

5.1 Observed field delays

The observed total pedestrian delay varied substantially across the eight SMCs. Waiting delay was the dominant component, while crossing delay was comparatively small but consistently reflected opposing pedestrian interactions. Vehicle delays were lower than pedestrian delays at most sites, consistent with the signal plans allocating a larger share of cycle time to vehicles.

Site	Waiting delay (s)	Crossing delay (s)	Total pedestrian delay (s)	Vehicle delay (s)
M-1	58.060	2.161	60.221	19.861
M-2	36.817	2.021	38.838	15.973
M-3	34.114	1.756	35.870	17.510
M-4	60.341	2.677	63.018	18.941
M-5	38.184	2.149	40.334	17.127
M-6	36.594	2.744	39.338	29.388
M-7	51.524	2.927	54.451	22.668
M-8	46.930	2.718	49.648	23.963

Table 2. Measured pedestrian and vehicle field delays at the SMC sites.

5.2 Development and validation of LOS criteria

The delay observations were grouped using k-means/k-median clustering. The Elbow

method and Silhouette index indicated five clusters, which were translated into six LOS bands (A–F). A linear support vector machine was then used to validate the classifications. The reported classification accuracy was 88.26% for pedestrian LOS and 79.6% for vehicle LOS. The study also reports that the classification performance measures for the LOS categories were generally above 0.7.

LOS	Pedestrian delay (s)	Vehicle delay (s)
A	≤35	≤15
B	>35–40	>15–19
C	>40–50	>19–23
D	>50–60	>23–27
E	>60–70	>27–32
F	>70	>32

Table 3. Delay-based LOS criteria proposed for signalized midblock crosswalks.

The resulting ranges differ from criteria developed for uncontrolled midblock crossings. At an SMC, the long pedestrian red phase creates a relatively high minimum pedestrian delay, while the longer vehicle green phase tends to reduce vehicle delay. This distinction supports the use of SMC-specific rather than directly transferred uncontrolled-crossing thresholds.

5.3 Acceptable and optimized delay thresholds

The perception survey indicated that an average pedestrian delay of 45 s was acceptable to a large proportion of respondents, while the acceptable vehicle delay was 25 s. The pedestrian value lies in LOS C and the vehicle value lies in LOS D. Multi-objective optimization of pedestrian and vehicle delays produced values of 48 s and 25 s, respectively. These values also fall within LOS C for pedestrians and LOS D for vehicles. The agreement between perception and optimization results was used to identify LOS C as the pedestrian saturation condition and LOS D as the vehicle saturation condition.

5.4 Preference hierarchy among GSPCFs

The GSPCF user-perception survey considered convenience, additional access time, vertical circulation facilities, vendors, lighting, cleanliness, safety and security. Based on the preferences reported in the study, the facility hierarchy was: (1) foot over bridge, (2) hump subway, and (3) subway. This hierarchy represents the respondents' stated preferences in the investigated context; it should not be interpreted as a universal engineering ranking. Site-specific factors such as drainage, groundwater, available right-of-way, accessibility, security and lifecycle cost remain important in selecting the final facility.

5.5 Implications for crossing warrants

The findings suggest that an SMC should be reviewed for possible upgrading when pedestrian delay reaches or exceeds the LOS C threshold and vehicle delay reaches or exceeds the LOS D threshold. The threshold values should be considered together with pedestrian and vehicle volumes, road width, number of lanes, operating speed, crash history, signal compliance, crossing demand and the feasibility of alternative at-grade improvements. The study's contribution is therefore a delay-based trigger to complement, not replace, established warrant and engineering assessment procedures. The source material indicates that the developed warrant chart combines quantitative delay thresholds with the hierarchy of GSPCF types; the chart itself should be inserted from the original thesis artwork if a graphical decision flow is required.

5.6 Practical interpretation of the warrant assessment

The findings can be translated into a staged screening process for agencies considering whether an existing SMC should be retained, modified or upgraded. First, the site should be confirmed as a midblock crossing with sustained pedestrian demand and a signal-controlled crossing arrangement comparable to those examined in the study. Second,

pedestrian and vehicle delay should be measured under representative peak-period conditions. The measurement should distinguish pedestrian waiting delay from crossing delay and should record the vehicle queue profile, signal cycle and green/red allocations.

Third, the measured delays should be compared with the proposed LOS bands. Pedestrian delay above 40 s enters LOS C, while vehicle delay above 23 s enters LOS D. The study identified these as the respective saturation levels, supported by the acceptable-delay survey and multi-objective optimization. Fourth, the delay results should be interpreted alongside pedestrian and vehicle volumes, road width, lane configuration, operating speed, observed non-compliance, pedestrian–pedestrian interaction and available alternative crossing opportunities. Delay thresholds are screening indicators and should not be treated as an automatic construction instruction.

Fifth, before grade separation is selected, the responsible authority should examine whether signal timing or other at-grade measures can address the operational problem. Where grade separation remains justified, the preference hierarchy found in the user survey—FOB, hump subway and subway—can inform option appraisal. The final choice should also consider access distance, stairs and vertical circulation, universal accessibility, lighting, drainage, cleanliness, surveillance, personal security, land availability, construction feasibility and recurring maintenance. Finally, post-installation monitoring should check actual use and whether pedestrians continue to cross at grade. This staged interpretation is consistent with the study's emphasis on both delay performance and facility-specific user preference.

6. Conclusions

This study investigated the operational conditions under which signalized midblock crosswalks under mixed traffic may require grade-separated pedestrian crossing facilities. Video observations at eight SMCs and perception data from GSPCF locations were used to develop and examine pedestrian and vehicle delay measures. The principal findings are:

1. Pedestrian waiting delay at SMCs is affected by non-uniform arrivals and signal non-compliance. Bidirectional pedestrian movement also contributes to crossing delay through speed reduction and path deviation.
2. The proposed crossing-delay regression model explained 77.2% of the observed variation ($R^2 = 0.772$). The source study reports that the proposed pedestrian and vehicle delay models produced validation errors below 10%.
3. Delay-based LOS criteria were developed for pedestrians and vehicles. The pedestrian LOS C band is greater than 40 s and up to 50 s; the vehicle LOS D band is greater than 23 s and up to 27 s.
4. User perception identified acceptable delays of 45 s for pedestrians and 25 s for drivers. Optimization yielded 48 s and 25 s, respectively, supporting LOS C as the pedestrian saturation threshold and LOS D as the vehicle saturation threshold.
5. The preference order reported for GSPCFs was FOB, hump subway and subway. Facility selection should nevertheless account for site conditions, universal accessibility, security, maintenance and lifecycle cost.

7. Limitations and Future Work

The delay models and warrant thresholds were developed using primary data from the selected study locations in Hyderabad. Their transferability to other Indian cities and different road environments requires validation. Future studies should test the models at additional locations, strengthen them with larger datasets where necessary, and develop adjustment factors where systematic differences are observed. The GSPCF hierarchy was based on user

perception; engineering, economic and lifecycle assessments should be incorporated to establish a broader facility-selection framework. The applicability of advanced pedestrian signal systems, including RRFB, HAWK, Pelican and Puffin systems, also requires investigation in the Indian context.

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