Opportunities to Leverage Existing Infrastructure to Integrate Real-Time Pedestrian Performance Measures into Traffic Signal System Infrastructure

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ABSTRACT

Managing the transportation system requires balancing the needs of many users and multiple transportation modes. Historically, traffic engineers have relied upon short term engineering studies and intuition to manage traffic signal systems. There is broad consensus in the traffic engineering community that real-time performance measures would enable better operations.

This paper presents motivation and means to provide real-time pedestrian performance measures using existing controller and vehicle detection technology. Applicable pedestrian service models are identified and procedures to collect data for pedestrian performance measures are recommended. The resulting pedestrian performance measures can be presented in an easy to interpret visual format that provides a valuable tool for assessing and comparing pedestrian service. Pedestrian service may be compared at different crosswalks in the jurisdiction for prioritization purposes, or at the same crosswalk under different conditions. The proposed pedestrian performance measures may be used in conjunction with existing vehicle performance measures, resulting in an integrated approach to assessing level of service for both vehicles and pedestrians under different conditions and for different signal timing plans.

INTRODUCTION

Managing roadways requires balancing needs of many users and modes. Technology and manpower limitations have resulted in reliance on short-term engineering studies, citizen input, and intuition to manage the operation of traffic signal systems. There is broad consensus that real-time performance measures would enable better operations.

There is emerging interest in combining analytical models and techniques developed for manual field studies with existing traffic signal infrastructure to obtain real-time performance measures such as vehicle volume to capacity ratios, vehicle delay, and vehicle progression (1,2,3). However, this work has not been extended to include real-time pedestrian performance measures. This paper identifies relevant models that can be used and recommends a procedure using existing infrastructure to collect performance measures for identifying and ranking pedestrian service at signalized intersections.

This paper reviews several relevant pedestrian level of service (LOS) models based upon space, delay, and vehicle-pedestrian interaction and describes how these can be implemented with existing infrastructure and used for making operational decisions. These techniques utilize existing technologies such as induction loops.

LITERATURE REVIEW

Literature for pedestrian LOS at signalized intersections consists of two models proposed by the Highway Capacity Manual (HCM, 4) and emerging models that extend the HCM methods to consider the negative impact of pedestrian-vehicle interaction with concurrent pedestrian service, as defined in the Manual on Uniform Traffic Control Devices (MUTCD) (5).

HCM Pedestrian LOS at Signalized Intersections

The HCM (4) provides two methods for calculating pedestrian LOS at signalized intersections based on 1) pedestrian delay and 2) pedestrian space.

Pedestrian delay LOS is based on cycle length, C, and effective pedestrian green, g, as shown in Equation 1. According to the HCM, g is the sum of the walk interval plus the first 4 seconds of the pedestrian clearance. The sample calculation is shown for a 6 second walk interval, a 26 second pedestrian clearance interval (resulting in a 10 second effective green time) and a 130 second cycle, which reflects the conditions for the crosswalk shown in Figure 1.

$$\begin{aligned} Pedestrian\ Delay &= 0.5\left(C-g\right)^2 / C \\ &= 55.4\ sec/ped,\ LOS\ E \end{aligned} \tag{1}$$

The delay methodology does not quantify the negative impact of turning vehicles on pedestrian service. In fact, the pedestrian LOS typically decreases when pedestrian signal timing strategies such as an exclusive pedestrian phase are implemented because they increase the cycle length (6).

Pedestrian space LOS (4) is based on crosswalk size, signal timing and pedestrian and turning vehicle volumes as shown in Equation 2. M is the space per pedestrian, L and W are the crosswalk length and width, W+FDW is the walk plus clearance interval, S_P is the pedestrian design speed, N_{tv} is the number of turning vehicles during the pedestrian interval (in vehicles), and N_{ped} is the number of pedestrians during the pedestrian interval (in persons). Sample calculations are shown for L = 127 ft, W_E = 15 ft, g = 32 sec (6 sec walk + 26 sec clearance), and S_P = 4 ft^2/s.

$$Space\ per\ Pedestrian, M = \frac{LW_E\left[\left(W+FDW\right)-L/\left(2S_P\right)\right]-40N_{tv}W_E}{N_{Ped}\left[3.2+\left(L/S_P\right)+\left(0.27N_{ped}\right)\right]}$$

$$\begin{aligned} &= 69\ ft^2/p, LOS\ A \\ &\quad for\ 11\ peds\ and\ 3\ vehicles\ in\ Figure\ 1a \\ &= 54\ ft^2/p, LOS\ B \\ &\quad for\ 11\ peds\ and\ 13\ vehicles\ in\ Figure\ 1b \end{aligned} \tag{2}$$

The first sample calculation corresponds to the conditions in Figure 1a with 11 pedestrians (N_{ped}) and 3 turning vehicles (N_{tv}), resulting in a LOS A. The second sample

a) **Pedestrians Compromised on Curb during Walk Interval Due to Right Turning Vehicles**

b) **Pedestrians Compromised in the Crosswalk during Pedestrian Clearance Interval Due to Right Turning Vehicles**

c) **Pedestrians Compromised on the Curb during Walk Interval Due to Left Turning Vehicles**

Figure 1. Pedestrians Compromised Due to Turning Vehicles

calculation corresponds to the conditions in Figure 1b with 11 pedestrians (N_{ped}) and 13 turning vehicles (N_{tv}), resulting in a LOS B.

Emerging Pedestrian LOS Models

Turning vehicles have been documented to negatively impact pedestrian service and safety, with negative impacts increasing as the volume of vehicles turning into the crosswalk increases (6,7,8,9,10,11). As can be seen in Figure 1, both right and left turning vehicles may compromise pedestrians crossing at signalized intersections, resulting in delay and reduced pedestrian comfort. As indicated by the example pedestrian space calculations shown in Equation 2, the pedestrians crossing in Figure 1a and 1b have an adequate LOS A and LOS B, even though they are delayed by vehicles turning into the crosswalk during the pedestrian interval.

A crosswalk with a low to moderate pedestrian volume but a high volume of turning vehicles may have an adequate HCM LOS, even though turning vehicles may cause delay and conflicts for pedestrians. For example, the LOS B conditions shown in Figure 1b (13 turning vehicles during the W+FDW interval of 32 seconds) correspond to an average vehicle headway of 2.5 sec/veh that the 11 pedestrians must co-exist with. Furthermore, although Equation 2 calculates space, it is based on the entire crosswalk and it does not reflect whether the space represents adequate gaps. These limitations reduce the usefulness of the HCM measures for evaluating the adequacy of pedestrian service, and make them ineffective for quantifying the benefits of pedestrian signal timing strategies that reduce interactions between turning vehicles and pedestrians. .

Conflict Based Models

A number of studies have evaluated vehicle and pedestrian conflicts at intersections (e.g., 8,10,12). Zhang developed a LOS model for signalized intersections that incorporates safety risk due to conflicts between permitted left turn vehicles and through vehicles and pedestrians (8), based on the volume of pedestrians and vehicles. This index is limited because it does not address conflicts between pedestrians and vehicles making right turns. Zhang also notes that the index does not capture reduced pedestrian safety at intersections where there are low pedestrian volumes (8).

This illustrates a deficiency of traditional conflict models. Traditional conflict analysis estimates interactions between pedestrians and turning vehicles based on the product of turning vehicles and the number of pedestrians. This does not capture the negative impact of turning vehicles at crosswalks with low pedestrian volumes. For example, a model proposed by Akin (10) does not differentiate a cycle with one turning vehicle and ten pedestrians from a cycle with ten turning vehicles and one pedestrian, although these two situations would obviously result in very different service levels for a pedestrian. Furthermore, models that rely on pedestrian volumes may not recognize that a dangerous crosswalk may exhibit a low pedestrian volume and subsequently a low accident rate because pedestrians are unwilling to cross where there is a high potential for conflict with turning vehicles.

Another potential limitation of safety based service assessments is that although they may quantify the negative impact of turning vehicles in terms of pedestrian safety, they may not quantify the negative impact of turning vehicles on pedestrians in terms of delay once the pedestrian interval begins. For example, conflict analysis may capture a vehicle swerving to avoid a pedestrian; however, it would not capture the delay and reduced service experienced by a pedestrian waiting on the curb while vehicles turn into the crosswalk during the walk interval (Figure 1a).

Percent Compromised Pedestrian Crossings

Following the spirit of the HCM freeway weaving and bicycle LOS models, a pedestrian LOS model that quantified the negative impact of turning vehicles on pedestrian service using the percent of compromised pedestrian crossings was proposed for signalized intersections (6). Pedestrian crossings were designated compromised if the pedestrian was delayed by turning vehicles or changed their travel path or speed in response to turning vehicles.

This research suggests that the percent of pedestrians compromised is related to the right turn flow rate during the pedestrian interval, as shown in Equations 3 and 4 for crosswalks outside the central business district (Non-CBD) and inside the central business district (CBD). Equation 5 illustrates the calculation of the right turn flow rate during the pedestrian interval.

$$Compromise\ \%_{Non-CBD} = 0.040\ (RT\ Flow\ Rate\ in\ Ped\ Interval\ in\ vph) \tag{3}$$

$$Compromise\ \%_{CBD} = 0.026\ (RT\ Flow\ Rate\ in\ Ped\ Interval\ in\ vph) \tag{4}$$

$$RT\ Flow\ Rate\ in\ Ped\ Interval\ in\ vph = \frac{RT\ veh\ count\ during\ ped\ interval}{Walk + Clearance\ Interval\ in\ sec} * \frac{3600\ sec}{1\ hr} \tag{5}$$

Limited Capabilities of Existing Pedestrian Detection Technologies

With pedestrian actuated phases, it is trivial to log the time of a pedestrian call. However, accurately quantifying the number of pedestrians per phase is very difficult using existing technology.

Pedestrian detection technologies include infrared, microwave, video, ultrasonic, and piezometric (pressure mat) technologies (13). These technologies have been used to extend the walk or clearance phase and to augment or replace the pedestrian button (13,14,15,16). However, their inability to detect pedestrians reliably (13,15) limits their effectiveness.

The following sections describe the application of real-time pedestrian performance measures and provide example applications. Although these performance measures use pedestrian phase calls, they are not dependent on detection of individual pedestrians.

REAL-TIME PEDESTRIAN PERFORMANCE MEASURES

Pedestrian service at signalized intersections is negatively impacted by delay (Equation 1), by a reduction in space due to additional pedestrians and turning vehicles in the crosswalk (Equation 2), and by the interaction of pedestrians and turning vehicles (Equations 3 and 4), Real-time performance measures that combine available controller information and standard signal systems sensors with accepted and emerging models (Equations 1 through 4), are needed to allow transportation agencies to evaluate pedestrian service and balance the needs of all users of signalized intersections.

Furthermore, once this kind of data is collected, there will be opportunities to log additional data, including:

- Vehicle speeds in the crosswalk during the pedestrian interval (17)
- Vehicle gaps in the crosswalk during the pedestrian interval
- Vehicle occupancy in the crosswalk during the pedestrian interval
- Volume to capacity ratio (v/c) for turning traffic that conflicts with pedestrians during the pedestrian interval

Pedestrian Performance Measures Utilize Existing Technologies

Existing controller capabilities and vehicle detection technologies may be used to quantify aspects of pedestrian service including delay and characteristics of vehicles turning into the crosswalk during the pedestrian phase.

Phase data from the signal controller and data from vehicle detection technologies may be used for real-time pedestrian performance measures. These real-time pedestrian performance measures allow evaluation of pedestrian service at numerous intersections and allow pedestrian service measures to be integrated and evaluated in conjunction with real-time vehicle performance measures. This integration is important for facilitating multi-modal LOS assessment (2,3). For example, the use of pedestrian performance measures in conjunction with vehicle performance measures will facilitate the evaluation of alternative signal timing strategies, such as protected rather than permitted left turn service, and a leading or exclusive pedestrian phase, on both pedestrian and vehicle service.

REAL-TIME DATA COLLECTION PROCEDURES

Real-time data collection procedures for pedestrian performance measures can use signal controllers with event based logging and vehicle detection technology to quantify the characteristics of vehicles turning into the crosswalk. Video detection and induction loop detection (3) are discussed in the following section, although microloops or other technologies could also be utilized.

Signal controllers with event based logging capabilities can log relevant data including phase indications, pedestrian phase actuations, and vehicle detector count and vehicle detector occupancy.

Vehicle detection technologies have traditionally been used to provide actuated service for vehicles at signalized intersections. More recently, these detection technologies have provided data for vehicle performance measures. Emerging techniques may utilize this data to provide real-time pedestrian performance measures from traffic signals (18).

The following sections describe the methodology to transform data into pedestrian performance measures.

Inductive Loop Detectors

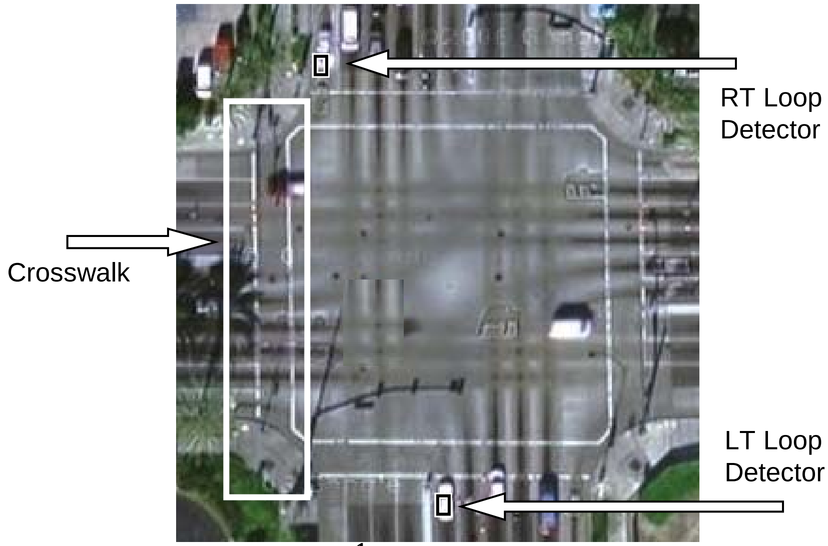
Many actuated intersections have induction loops in the right turn lane and the left turn lane. As shown in Figure 2a, these existing loop detectors in the right and left turn lane may be used to estimate pedestrian performance measures based on vehicle count data during the pedestrian interval (3). Count data from detectors in the right and left turn lane may be used to estimate the vehicle flow rate in the crosswalk during the pedestrian interval. Count data from detectors in the right turn lane may also be used to estimate the right turn v/c ratio during the pedestrian interval. However, detectors in turn lanes shared with through traffic could not be utilized for pedestrian performance measures.

Alternatively, detectors may be placed in the crosswalk to quantify additional characteristics of vehicles turning into the crosswalk during the pedestrian interval, as shown in Figure 2b. Loop detectors in the crosswalk may provide counts of vehicles turning into the crosswalk during the walk phase. This vehicle count data may be used to determine the average vehicle flow rate during the pedestrian interval. Detectors in the crosswalk may also provide presence detection of vehicles turning into the crosswalk. This vehicle presence data may be used to determine a number of pedestrian performance measures, including:

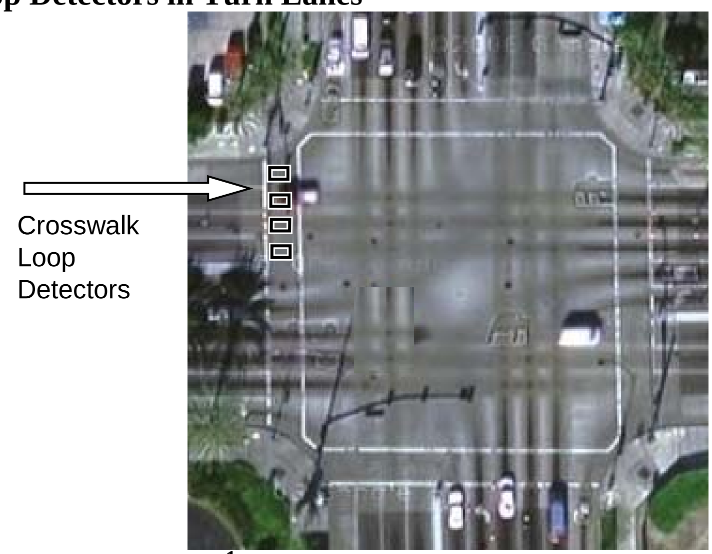
- Vehicle Occupancy in Crosswalk during Pedestrian Interval, based on the total time that the presence detector is on as a percent of the pedestrian interval
- Vehicle Gaps in Crosswalk during Pedestrian Interval, based on the duration that the presence detector is off during the pedestrian interval
- Vehicle Speeds in Crosswalk during Pedestrian Interval, based on an assumed vehicle length and the duration the presence detector is on

Video Detection of Vehicles in the Crosswalk

Video detection of vehicles in the crosswalk can provide similar data that induction loops in the crosswalk can provide, as shown in Figure 2c. Video detection of vehicles in the crosswalk may provide counts of vehicles turning into the crosswalk during the walk phase and clearance phase; this may be used to determine the average vehicle flow rate during the pedestrian interval. Video detection may also provide presence detection of vehicles turning into the crosswalk during the pedestrian interval, which may be used to determine vehicle occupancy, vehicle gaps and vehicle speed.



a. Existing Loop Detectors in Turn Lanes[1]



b. Loop Detectors in Crosswalk[1]

c. Possible Video Camera View for Video Detection

FIGURE 2. Vehicle Detection for Pedestrian Performance Measures

[1] Photo source: //maps.google.com/

Performance Measure Calculations

Sample equations for three applications are provided to illustrate how data from vehicle detectors can be used to support pedestrian performance measures evaluating the impact of turning vehicles on pedestrian service.

Right Turn Flow Rate during Pedestrian Interval

The right turn vehicle count during the pedestrian interval can be used to estimate the right turn flow rate during the pedestrian interval, and was shown in Equation 5. The right turn flow rate during the pedestrian interval may be used as a pedestrian performance measure, and will be described further in the following section. A higher right turn flow rate would be expected to impede pedestrians.

Left Turn Flow Rate during Pedestrian Interval

Similarly, the left turn vehicle count during the pedestrian interval can be used to estimate the left turn flow rate during the pedestrian interval, as shown in Equation 6. The left turn flow during the pedestrian interval for each cycle may be used as a pedestrian performance measure because a higher left turn flow rate would be expected to impede pedestrians.

$$LT\ Flow\ Rate\ in\ Ped\ Interval\ in\ vph = \frac{LT\ veh\ count\ during\ ped\ interval}{Walk + Clearance\ Interval\ in\ sec} * \frac{3600\ sec}{1\ hr} \qquad (6)$$

Vehicle Occupancy of Crosswalk during Pedestrian Interval

The total duration that the vehicle presence detector is on in the crosswalk during the pedestrian interval can be used to estimate vehicle occupancy in the crosswalk, as shown in Equations 7 and 8. Occupancy during the walk interval may be calculated as shown in Equation 7. Occupancy during both the walk and pedestrian clearance interval may also be calculated, as shown in Equation 8.

$$Vehicle\ Occupancy_{W} = \frac{Duration\ Presence\ Detector\ On\ in\ sec}{Walk\ Interval\ in\ sec} \qquad (7)$$

$$Vehicle\ Occupancy_{W+PC} = \frac{Duration\ Presence\ Detector\ On\ in\ sec}{Walk + Clearance\ Interval\ in\ sec} \qquad (8)$$

Occupancy in the crosswalk may be used as a pedestrian performance measure, because higher vehicle occupancy in the crosswalk would be expected to impede pedestrians. The MUTCD (5) assumes that pedestrians are able to step off the curb during the walk interval. If turning vehicles prevent pedestrians from entering the crosswalk during the walk interval, then they may not be able to finish crossing before the end of the clearance interval and they still be in the crosswalk when conflicting phases get a green light.

The vehicle occupancy during the walk interval (Equation 7) may be more relevant for near side pedestrians who step off of the curb into the conflict zone, and the vehicle occupancy the walk and pedestrian clearance interval (Equation 8) may be more relevant for far side pedestrians.

EXAMPLE APPLICATIONS OF PEDESTRIAN PERFORMANCE MEASURES

There are a number of potential pedestrian performance measures, as described in the previous section. This section describes the application of three potential performance measures: HCM LOS measures based on pedestrian delay and pedestrian space, and the right turn flow rate during the pedestrian interval. These three potential pedestrian performance measures are illustrated by examining their application at Northwestern Avenue and Stadium Drive in West Lafayette, Indiana.

A subsequent section compares the impact of right turn vehicles based on the right turn flow rate. Service at three crosswalks is compared:

- Northwestern Avenue and Stadium Drive in West Lafayette, Indiana
- River Road and State Street in West Lafayette, Indiana
- Powell and 82nd in Portland, Oregon

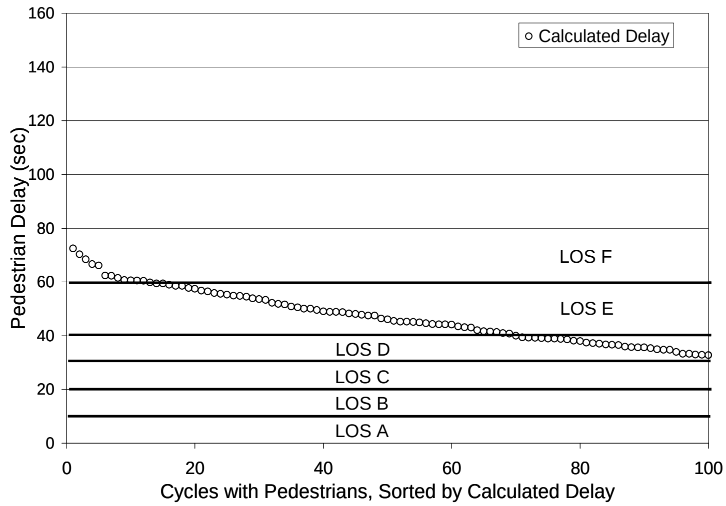
This example presents the benefits of using pedestrian performance measures to compare service, in this case at multiple crosswalks. A comparison of service at a single crosswalk under different vehicle volume conditions is also presented. It would also be useful valid to compare service at the same crosswalk under different signal timing strategies using real-time pedestrian performance measures..

HCM Delay

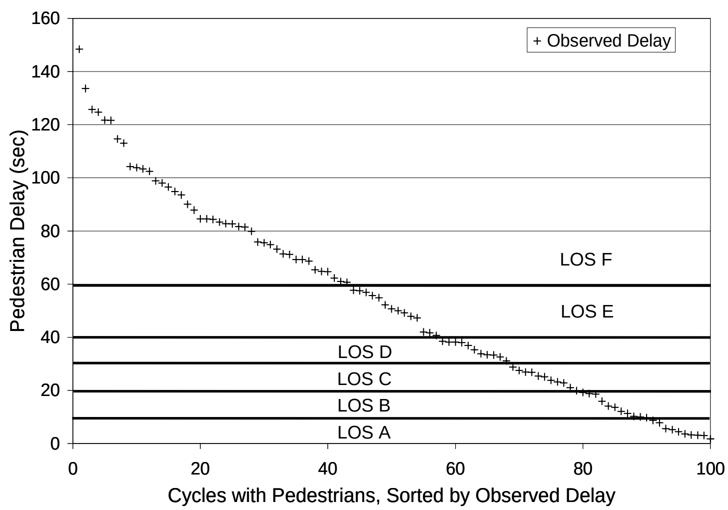
Figure 3 illustrates the pedestrian LOS based on delay for pedestrian phase 4 at Northwestern and Stadium, a crosswalk that pedestrians frequently complain is difficult to cross. The y-axis is delay and the x-axis is the cycle number. Cycles are sorted according to delay; cycle 1 has the lowest pedestrian service (highest delay). This presentation makes it easy to quickly identify the lowest service at a crosswalk. LOS thresholds for delay are 10 seconds (LOS A to B), 20 seconds (LOS B to C), 30 seconds (LOS C to D), 40 seconds (LOS D to E) and 60 seconds (LOS E to F).

Figure 3a shows the delay calculated using the HCM equation (Equation 1), with a 7 second walk and 19 second clearance interval (an effective green time of 11 seconds). The delay varies depending on the cycle length, which varies due to actuated control: 12 cycles have a LOS F, 57 cycles have a LOS E, and 31 cycles have a LOS D.

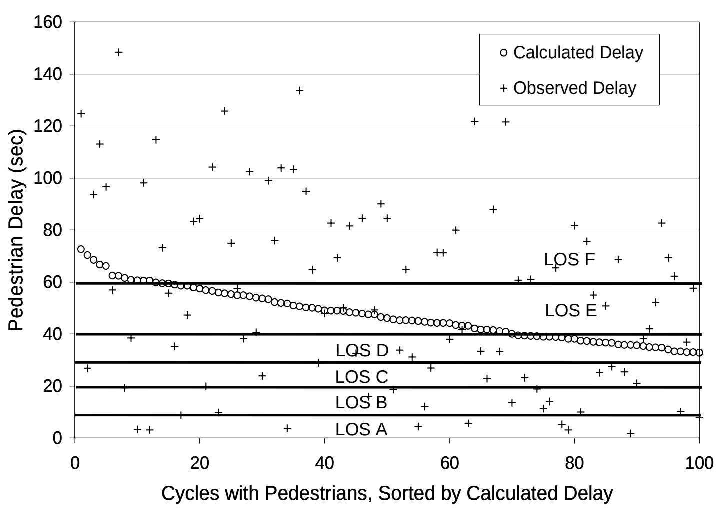
Figure 3b shows the actual pedestrian delay associated with the 100 cycles shown in Figure 3a, sorted according to actual delay. The actual delay is determined by subtracting the time that the pedestrian button was actuated from the time that the pedestrian phase begins. Forty-three cycles have a LOS F, 14 cycles have a LOS D, 11 cycles have a LOS D, 10 cycles have a LOS C, 10 cycles have a LOS B and 12 cycles have a LOS A.



a) Calculated Pedestrian Delay Based on HCM Methodology



b) Actual Observed Pedestrian Delay



c) Calculated and Actual Observed Pedestrian Delay

Figure 3. Pedestrian Delay at Northwestern and Stadium, West Lafayette, Indiana

The actual delay is generally higher than the calculated delay. Compliant pedestrians traveling the design speed can be served only if they arrive during the walk interval or first few seconds of the pedestrian clearance interval. This contrasts with vehicle service, in which compliant vehicles traveling the design speed can be served if they arrive within seconds before the end of the green indication.

Figure 3c presents the cycles sorted based on calculated delay, with the associated actual delay for each cycle shown as a separate series. This illustrates the limitations of the HCM delay calculation, since there is very little correlation between calculated pedestrian delay and actual pedestrian delay.

Although these plots of pedestrian delay are informative and provide an estimate of how long a pedestrian must wait for the walk signal, they provide no information regarding the traffic interruption, delay or potential conflicts to pedestrians due to vehicles turning into the crosswalk.

HCM Pedestrian Space

Figure 4 illustrates the HCM pedestrian space LOS for pedestrian phase 4 at Northwestern and Stadium. The y-axis is pedestrian space and the x-axis is the cycle number. Cycles are sorted according to pedestrian space; cycle 1 has the lowest pedestrian service (most space). This presentation makes it easy to quickly identify the lowest service at a crosswalk. Relevant LOS thresholds for space are 60 ft^2 per pedestrian (LOS A to B) and 40 ft^2 per pedestrian (LOS B to C), as shown in Figure 4.

This graph was calculated based on HCM pedestrian space (Equation 2), with crosswalk length of 73 ft and width of 6 ft; and a 7 second walk and 19 second clearance interval. The pedestrian space varies depending on the number of pedestrians and number of turning vehicles, which varied in each cycle. Comparing points a, b, and c, d, and e in Figure 4 illustrates that the HCM pedestrian LOS is more sensitive to the number of pedestrians during the cycle than the number of turning vehicles.

The maximum number of turning vehicles during the pedestrian interval was 10 vehicles, and the maximum number of pedestrians during the pedestrian interval was 5. There is a gap in the space per pedestrian plot between 160 ft^2 per pedestrian and 230 ft^2 per pedestrian; this marks the boundary between 1 pedestrian per cycle and 2 or more pedestrians per cycle. Only cycles with pedestrians are shown in Figure 4.

All but two cycles shown in Figure 4 had a LOS A. These two cycles had a LOS B. As shown in Figure 4, a single pedestrian would have LOS A even if 10 vehicles turned into the crosswalk during the 26 second pedestrian interval; the pedestrian might disagree with the LOS A assessment.

The plot in Figure 5 also illustrates that the HCM pedestrian space methodology is more sensitive to the number of pedestrians in the cycle than the number of turning vehicles. In Figure 5, the space per pedestrian at Stadium and Northwestern is shown for a range of pedestrian volumes (1 to 5) and right turn volumes (1 to 10 vehicles). The graph "steps up" each time the number of turning vehicles is reduced by one vehicle (points a, b and c). The number of pedestrians (1, 3, 5) is theoretical to illustrate the concept; the turning volumes shown illustrate the number of turning vehicles observed during the pedestrian interval at Stadium and Northwestern.

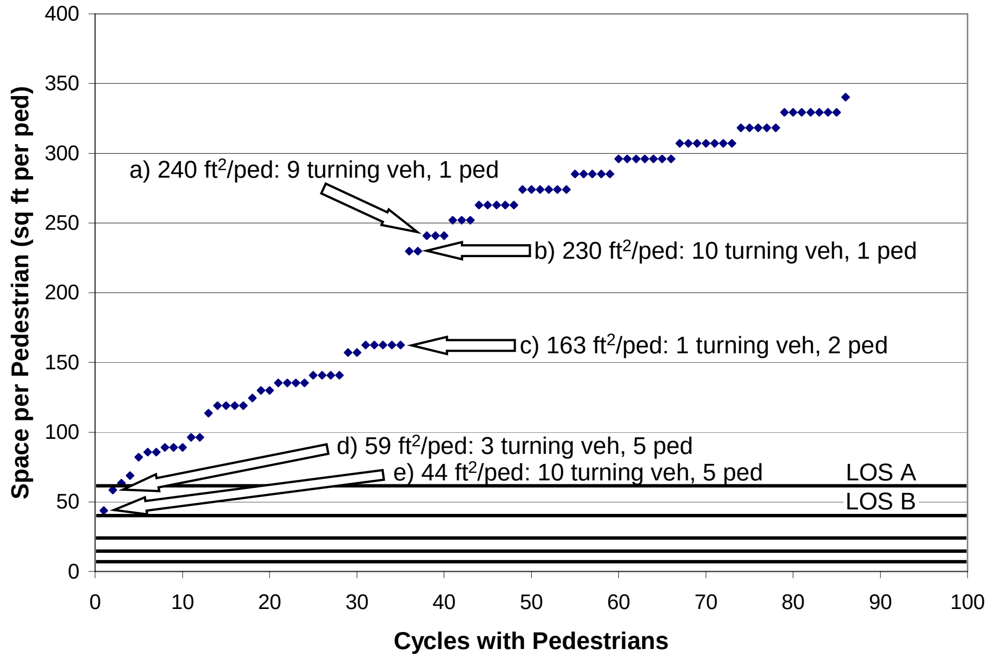


Figure 4. HCM Pedestrian Space LOS at Northwestern and Stadium, West Lafayette, Indiana

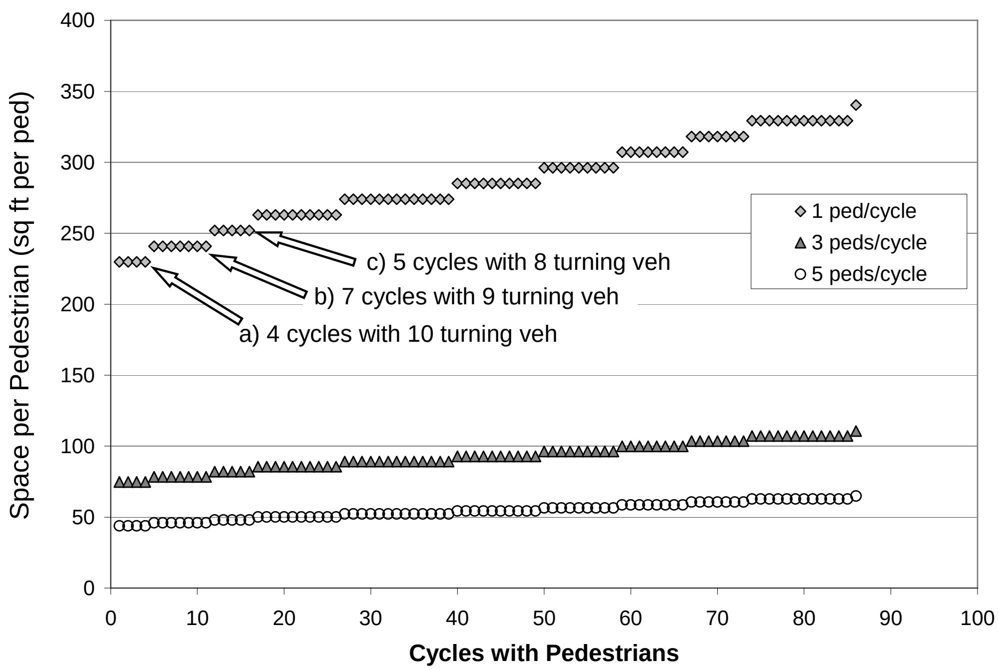


Figure 5. Theoretical Curves for HCM Pedestrian Space LOS by Number of Pedestrians at Northwestern and Stadium, West Lafayette, Indiana

Pedestrian space as a real-time performance measure requires an accurate count of the number of pedestrians in the crosswalk. This would not be practical using existing pedestrian detection technology. Alternately, an estimated pedestrian count could be used, and the real-time performance measure would vary according to the number of turning vehicles, as illustrated in Figure 5.

The range of LOS in Figures 4 and 5 illustrates the limitations of the pedestrian space LOS measure outside the CBD where low pedestrian volumes and high right turn volumes are common. The plots in Figures 4 and 5 do not provide useful information to evaluate the impact of turning vehicles on pedestrian service at crosswalks with low to moderate pedestrian volumes because the pedestrian space LOS is typically in the acceptable range.

Pedestrian Performance Measure: Right Turn Flow Rate during Pedestrian Interval

Figure 6 illustrates the right turn flow rate during the pedestrian interval, a proposed pedestrian performance measure. The y-axis is the right turn flow rate during the pedestrian interval and the x-axis is the cycle number. Cycles are sorted according to pedestrian space; cycle 1 has the highest vehicle flow rate. This presentation makes it easy to quickly identify the lowest service at a crosswalk.

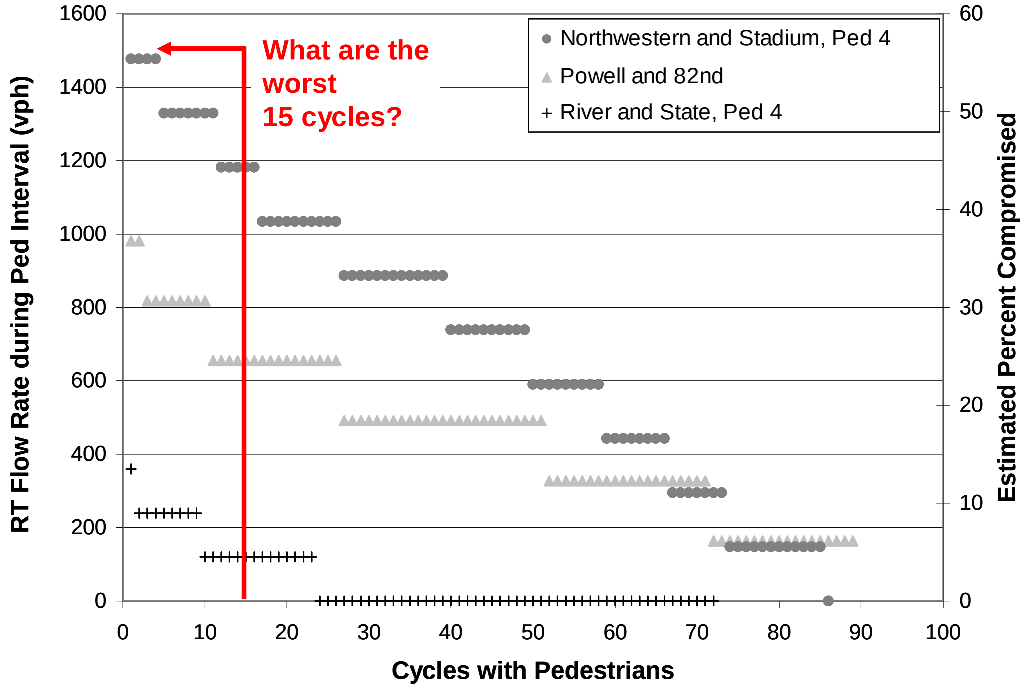
Figure 6a presents the right turn flow rate during the pedestrian interval at three crosswalks. This graph was developed based on visually inspecting each cycle for the right turn count, and converting this value to a right turn flow rate by dividing the right turn count by the duration of the pedestrian interval (6). The estimated percent compromised on the right axis is based on Equation 3, with a 7 second walk and 19 second clearance interval at Northwestern and Stadium; a 7 second walk and 15 second clearance interval at Powell and 82nd; and a 5 second walk and 25 second clearance interval at River and State.

The right turn flow rate is highest for Northwestern and Stadium, with a maximum value of 1,385 vph. The right turn flow rate is moderate for Powell and 82nd, with a maximum value of 982 vph. The right turn flow rate is lowest for River and State, with a maximum right turn flow rate of 360 vph. The right turn flow rate observed on the plot appears discrete rather than continuous because it is calculated based on the right turn vehicle count during the pedestrian interval. At each of these crosswalks, the duration of the pedestrian interval is a constant value, so the data “steps up” for each additional right turn during the pedestrian interval.

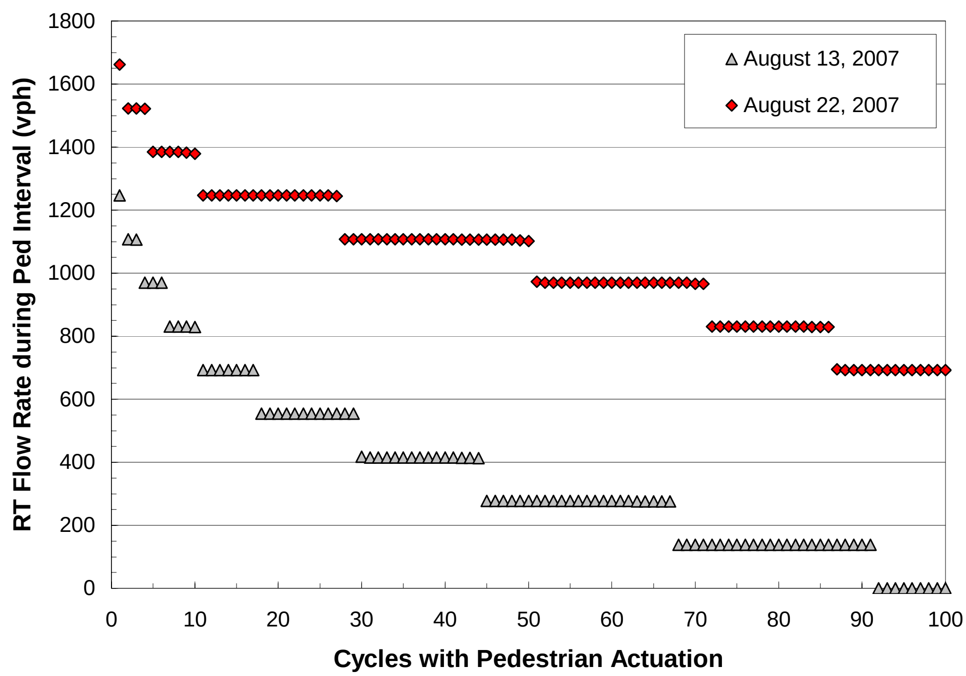
Additional data about these three pedestrian crosswalks is shown in Table 1. The percent of pedestrian crossings that were compromised at each crosswalk is shown in column c. A pedestrian crossing is compromised if the pedestrian is delayed by a turning vehicle or changes their travel path or speed in response to a turning vehicle. The percent compromised values shown in column c are based on field observation (6).

The percent compromised observed in the field for each crosswalk closely corresponds to the estimated percent compromised for the average right turn flow rate at each crosswalk, as shown in column e. This demonstrates the correlation between the right turn flow rate and the expectation of a compromised crossing.

Figure 6b shows the right turn flow rate for a single intersection (Northwestern and Stadium pedestrian phase 4) on two different days. This intersection is adjacent to



a) RT Flow Rate during Ped Interval at Three Crosswalks



b) RT Flow Rate during Ped Interval at Northwestern and Stadium (Ped 4) on Two Different Days

Figure 6. Right Turn Flow Rate as Pedestrian Performance Measure

TABLE 1. Percent Compromised Pedestrian Crossings at Three Crosswalks

a. Intersection	b. Number of Cycles	c. Observed Percent Compromised	d. Percentile	e. RT Flow Rate during Ped Interval	f. Estimated Percent Compromised[1]
Northwestern and Stadium, South Crosswalk (Ped 4)	86	30	Average	687	27
			15 percentile	1,108	44
Powell and 82nd	89	18	Average	458	18
			15 percentile	655	26
River Road and State Street, South Crosswalk (Ped 4)	72	4	Average	55	2
			15 percentile	120	5

[1]Estimated Percent Compromised = 0.04*(RT Flow Rate during Ped Interval)

Purdue University and varying traffic conditions are observed at different times of the year. On August 13, the university was not in session and the crosswalk exhibited the lowest right turn flow rate during the pedestrian interval. August 22 was the first week of school, and the right turn flow rate was much higher. This plot supports the anecdotal reports that pedestrian crossings at this intersection are much more difficult when school is in session. For example, when school is in session there are 30 cycles with pedestrian crossings that operate concurrently with conflicting right turn vehicles with an average headway of less than 3 seconds (vehicle flow rate of approximately 1200 vph during pedestrian Walk and Ped Clear Intervals).

The right turn flow rate during the pedestrian interval is a valuable tool for estimating the percent of pedestrian crossings that are compromised due to right turning vehicles. This underscores the utility of the right turn flow rate as a pedestrian performance measure. At intersections with permitted left turns, this concept may be expanded to include the left turn flow rate during the pedestrian interval.

INTERPRETATION OF PERFORMANCE MEASURES AND APPLICATIONS ALONG A CORRIDOR

The recommended pedestrian performance measures can easily be plotted and used as a quantitative tool for assessment of pedestrian service. Multiple crosswalks at the same intersection, multiple intersections along a corridor, or multiple crosswalks within the jurisdiction can easily be compared on a plot such as the one shown in Figure 6a. In Figures 3 through 6, the cycles are sorted by performance measure (e.g., pedestrian delay); this facilitates assessment based on the worst cycles of the day. Cycles may also be presented by time of day, facilitating assessment during the vehicle peak hour, the pedestrian peak hour, or other periods of interest.

In Figure 6a, flow rates of 1385 vph, 982 vph and 360 vph correspond to average headways of 2.6 sec/veh, 3.7 sec/veh and 10 sec/veh. It is not surprising that the intersection with the highest average headway during peak conditions has the lowest percent compromised (Table 1).

As shown in Figure 6, evaluation may be based on the threshold defined by the 15 cycles with the highest right turn flow rate throughout the day. If 20 percent compromised is used as a threshold for the worst 15 cycles, then both Powell and 82nd and Northwestern and Stadium would exceed the threshold and further study of these crosswalks would be recommended to identify strategies to improve pedestrian service. The crosswalk at River and State would not be a candidate for further evaluation due to the low right turn flow rate, and corresponding low likelihood that pedestrian crossings will be compromised.

A plot such as the one shown in Figure 6 may also be used to evaluate alternative signal timing strategies at a single crosswalk. For example, the right turn flow rate during the pedestrian interval may be used as a pedestrian performance measure to evaluate and compare concurrent pedestrian service with a leading pedestrian interval at the same crosswalk.

CONCLUSION

This paper has described how existing traffic signal equipment can be used to develop pedestrian performance measures that provide accurate and relevant information without significant investment.

- Pedestrian performance measures may be used to create graphic reports (Figures 3 through 6) using both legacy LOS models (Equations 1 and 2) and emerging models (Equations 3 and 4).
- Real-time pedestrian performance measures can easily be integrated with real-time vehicle performance measures. This allows multi-modal assessment of both pedestrian and vehicle operations under a variety of conditions and signal timing strategies.
- Utilizing controller and vehicle detection equipment facilitates data collection with large samples that could not be obtained using the manual data collection procedures traditionally used for pedestrian research. The ability to collect a large amount of relevant data will provide a better understanding of the factors affecting pedestrian service. Furthermore, the reliance on equipment rather than people for data collection makes it possible to undertake data collection on weekends and evenings, when agency personnel may not be available.
- The graphics to assess pedestrian performance measures are easily understood and simplify quantitative evaluation and prioritization of crosswalks. Pedestrian performance measures may be used to evaluate and compare pedestrian service at multiple intersections, which may be useful for prioritization purposes.

In summary, existing controller equipment and vehicle detection infrastructure currently may be utilized to collect data for real-time pedestrian performance measures with minimal marginal cost. This paper describes the analytical technique and graphical presentation that will transform that raw data into information helpful to transportation agencies. Turning vehicles have an impact not only on pedestrian service, but also on pedestrian safety. It may be appropriate to integrate some of the proposed real-time pedestrian performance measures into research related to pedestrian safety, as well.

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