Signalized Intersection LOS that Accounts for Safety Risk

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Approved for publication in the Transportation Research Record

Honolulu, Hawaii
July 31, 2002
Revised, November 15, 2002
Final Revision, March 21, 2003

Paper Length
5,400 words in text
1,750 words in seven (7) exhibits
7,150 words total (max = 7500)
ABSTRACT
A methodology that quantifies potential conflicts between left-turning vehicles and opposing through vehicles and pedestrians is presented. The methodology was based on and designed to be compatible with HCM 2000. A model was developed to combine delay and safety to get a comprehensive LOS indicator, the delay and safety index (DS). The case study of two intersections showed that if potential conflict is not considered, the signal timing plan with permitted left-turns delivers a better LOS than that with protected left-turns. However, if potential conflict is considered, the LOS under protected left-turn phasing is better than the LOS under permitted left-turn phasing according to DS, when the safety weight factors exceed a certain value. The proposed method models the tradeoff between safety and efficiency explicitly, and considers both vehicle-to-vehicle and vehicle-to-pedestrian conflicts associated with left turns.
INTRODUCTION

Level-of-Service (LOS) is an important measure of performance in analyses of signalized intersections. Average stopped delay and average control delay have been used as the measure of service in signalized intersection analysis since 1985. The reason for using delay as an indicator is that “delay is a measure of driver discomfort, frustration, fuel consumption, and lost travel time.” (J) However, in addition to delay, safety is a major concern for motorists, pedestrians and agencies responsible for the operation of signalized intersections. The LOS definition in HCM 1965, 1985, and the 1992 update included “safety”. Beginning with HCM 1994, “safety” was removed from the LOS definition. This was necessary since the measures used to define LOS do not correlate with safety. However, safety is an integral part of signalized intersection operations and it often dictates the choice of signal operation characteristics. Therefore efforts to incorporate safety into LOS are warranted.

In 2000, 44% of all reported crashes throughout the United States occurred at intersections. Nearly 23% of the total fatalities, 48% of all injury crashes, and 40% of all pedestrian incidents occurred at or within an intersection environment (2,3). Left turn collision constitutes 25% of collisions at urban four-leg signalized intersections. Furthermore, intersection safety is recognized as one of four priority areas in the Federal Highway Administration’s (FHWA) Performance Plan (3).

There is a tradeoff between delay and safety at a signalized intersection chiefly involved in the type of left turn operation (e.g., protected, permitted or prohibited.) If left-turning vehicles are permitted to make a turn, they are likely to experience a shorter delay, but collision risk is higher since they need to find an appropriate gap to drive through opposing traffic and pedestrians in the crosswalk. On the other hand, if an exclusive phase is provided for left-turning traffic, a larger delay is likely to be encountered on the average, but collision risk is lower because there are no conflicts between left-turning vehicles and opposing through vehicles and pedestrians. Therefore, in a comparative context, the use of delay as the sole measure of LOS usually penalizes intersections with protected left turn phases (except in cases of large intersections with heavy left turning traffic, e.g., left turn bays over 200 ft., twin left turn lanes, in which permitted operation was abandoned as both unsafe and inefficient.)

Although Chapter 18 in HCM2000 (1) addresses pedestrian delay and LOS at signalized intersections, the current assessment of LOS at signalized intersections does not account for the waiting time and safety risk experienced by pedestrians. It is desirable, therefore, to develop a comprehensive methodology that accounts for both efficiency and safety, and recognizes the co-existence of vehicular and pedestrian traffic at signalized intersections. Thus, the objective of this paper is to improve upon the HCM2000 methodology for the assessment of performance of signalized intersections by developing a set of models to quantify collision risk as a function of road geometry, traffic and signal variables. Our objective is to establish a method for representing the perceived safety risk and concomitant stress on drivers rather than on predicting crash rates. Collision risk is then combined with delay to achieve a comprehensive LOS measure (with or without pedestrians.)

The proposed methodology may provide a better representation of driver perceptions. Importantly, the proposed methodology may also aid agencies responsible for traffic signals to weigh the tradeoffs between intersection channelization, signalization cost and complexity on the one hand, and the quality of service and safety of vehicular and pedestrian operations on the other.

The remainder of this paper is organized as follows. The next section summarizes the development of the LOS concept and provides a brief review of traffic safety at signalized intersections. The methodology of analysis is detailed next, followed by two case studies. Elements of the methodology needing further study along with a summary complete this presentation.

LITERATURE REVIEW

The development of the concept of LOS dates back to the 1950s. LOS was formally introduced in HCM 1965 (4); it was recognized as “a qualitative measure of the effect of a number of factors, which include speed and travel time, traffic interruptions, freedom to maneuver, safety, driving comfort and convenience, and operating costs.” HCM 1965 defined load factor (LF) as a “ratio of the total number of green signal intervals that are fully utilized by traffic during the peak hour to the total number of green intervals for that approach during the same period.” LF was adopted as the measure for determining LOS at individual intersections. Difficulty in identifying loaded cycles by field observers, absence of a rational basis for breakpoints, and insensitivity to low traffic volumes were some of the problems with LF.

Among the various attempts to develop a more rational method for quantifying the different levels of service for signalized intersections, Tidwell and Humphreys (5) investigated the feasibility of using average
individual delay (AID) as a measure for LOS. They argued that “if speed is to be considered the criterion for uninterrupted flow conditions, then a delay index appears commensurate for intersection design.”

Subsequently, much research effort on field delay measurement techniques (6, 7) and analytical delay estimation (8, 9, 10, 11, 12) occurred before and after the publication of HCM 1965. HCM 1985 (13) first specified the average stopped delay per vehicle as a LOS measure for signalized intersections. Enhancements to delay estimation included adjustments and models for overflow conditions and signal progression (14, 15, 16). In 1997, control delay replaced stopped delay. The relationship between control delay and stopped delay was explored (17, 18), and a generalized delay model was built and validated (19, 20).

Although a lot of work has been done in fine-tuning the basic procedure since 1985, delay has been chosen as the only representation of motorist “losses” at signalized intersections without behavioral investigation and justification for making this choice. Furthermore, although the concept of LOS is meant to reflect traffic conditions perceived by road users, HCM’s LOS categories for signalized intersections have not been based on studies of user perceptions (21, 22). The work herein attempts to enrich the current methodology.

Left turn maneuvers are considered as the most difficult and complicated traffic maneuver at an intersection because a left-turning vehicle has to cross in front of oncoming traffic as well as avoid pedestrians in the crosswalk. According to accident statistics, 45% of all accidents occurring at intersections in the U.S. involve left-turning maneuvers while only 10% to 15% of all intersection traffic turns left (23). Exclusive left turn phasing reduces right-angle and pedestrian accidents significantly (24, 25, 26, 27, 28). Agent (24) showed that there was an 85% reduction in left turn accidents after a permitted left turn was replaced by protected left turn phasing. Based on the number of left turn accidents per million left-turning vehicles, Upchurch (25) identified that exclusive phasing has the lowest left turn accident rate, which was also corroborated by Shebeeb (28).

Historical crash data have been used widely as a direct measure of safety at intersections and other locations. However, attempts to estimate the relative safety of a highway facility are usually hindered by the unreliability of crash records and the long period to achieve adequate sample sizes. To overcome these problems, Perkins and Harris (29) first introduced the concept of traffic conflicts as a surrogate measure for predicting crash rates in 1967. A traffic conflict is defined as “an event involving two or more road users, in which the action of one user causes the other user to make an evasive maneuver to avoid a collision” (30). Traffic conflict analysis provides useful information for determining the predominant conflict types, identifying hazardous intersections, and assessing the effectiveness of safety actions. However, it was also criticized that less or poor correlations existed between conflicts and crashes (31, 32). Hauer (33) argued that it was the expected crash instead of the observed one that was correlated with the traffic conflict. Therefore, the traffic conflict technique should not be judged by its ability to predict crashes. Instead, the technique is deemed valid if it provides unbiased estimates and the variance of the estimate is small (34). If the technique is only used for a “before-and-after” or “with-or-without” comparison in which the same accident-to-conflict ratio applies, it is a valid and useful tool to provide good insights on relative safety of a traffic facility (34).

Ha and Berg (35) developed a computational procedure for a safety-based LOS using conflict opportunities, but the safety-based criteria they developed were not as sensitive to changes in prevailing traffic, roadway, and signal timing conditions as the traditional delay-based measure. At a conceptual level, Spring (36) proposed a method to integrate safety into the HCM using fuzzy set theory.

METHODOLOGY

The major difference between permitted and protected left turn phasing at a signalized intersection is the left turn discharge process and the related collision risk. Figure 1 illustrates a typical signalized intersection with shared left turn lanes and permitted left turn phases. The east-bound (EB) left-turning vehicles need to wait for appropriate gaps in opposing traffic that are also free of pedestrians in the crosswalk before executing the left turn maneuver. During this period, there are potential conflicts (PC) between left-turning vehicles and opposing traffic and pedestrians. A quantitative estimate of the number of potential conflicts is a reasonable starting point for incorporating safety into the concept of LOS.

Using potential conflicts instead of actual crash rates is a reasonable measure for assessing the quality of safety service because potential conflicts are routinely realized by drivers and add to driver stress whereas very few potential conflicts become actual crashes. Longer and more consistent delays with fewer conflicts are better than shorter but more volatile delays with more conflicts with opposing traffic and pedestrians. Drivers at some locations, or of specific demographics or at specific times of day may disagree with this statement, but agencies operating traffic signals would not.
The methodology is outlined in Figure 2 and is discussed below in three parts: potential vehicle-to-vehicle conflict, potential vehicle-with-pedestrian conflict, and the combination of delay and safety.

**Potential Vehicle-to-Vehicle Conflict**

The model is illustrated by focusing on the east-bound (EB) approach in Figure 1. When EB and WB traffic begin to release queues on green, there is no potential conflict between EB left turn and WB through traffic until the first left-turning vehicle on the EB approach arrives. This green time interval is defined as $g_f$ in HCM 2000 (1). It is noted that $g_f$ is equal to 0 for the case of exclusive permitted left turn lanes because left turn vehicles accumulate during the red phase before the beginning of the green phase. Furthermore, when the WB queue opposed by EB left turn begins to release, there is no potential conflict between EB left turn and WB through traffic because the EB left-turning vehicles are effectively blocked until the opposing queue clears. This portion of the green is referred to as $g_q$ (1). After the opposing queue clears, left-turning vehicles select gaps through the unsaturated opposing flow. This portion of green time is $g_u$ (1) and is estimated with equation 1.

$$g_u = \begin{cases} 
  g - g_q & \text{when } g_q \geq g_f \\
  g - g_f & \text{when } g_q < g_f 
\end{cases}$$

During the green period of $g_u$, left turn traffic needs to find appropriate gaps to drive through opposing traffic. Drivers will not make a left turn when small gaps such as 2 or 3 seconds (s) are available. Therefore, there is little or no probability of collisions involved with left-turning vehicles and opposing through traffic associated with small gaps. For large gaps (e.g., $\geq 10$ s), drivers have enough time to make a decision and clear the intersection safely without conflicts. Potential conflict, however, exists when the opposing gaps are medium sized, e.g., 5 to 9 s for a medium-sized intersection. (Potential conflict gaps are defined below.) Aggressive drivers accept potential conflict gaps and force opposing vehicles to decelerate to avoid a crash. When opposing traffic flow is heavy, appropriate gaps may be few and far apart. Frustration may increase by drivers waiting to turn left, so they may take a potential conflict gap which is not safe. Therefore, most potential conflicts are likely with potential conflict gaps during the green portion of $g_u$.

To estimate potential conflict gaps, the time for executing the left turn maneuver needs to be estimated. The typical path of a left-turning vehicle as well as key geometric characteristics of an intersection is illustrated in Figure 1. Left turn vehicles may make the maneuver from a stationary or non-stationary position, depending on the arrival pattern of left-turning traffic. However, for simplicity, all vehicles are assumed to turn from a stationary position. The left turn distance and left-turning maneuver time can be calculated with equation 2 and 3.

$$d_{LT(i)} + L_c = \frac{1}{2}at_{LT(i)}^2$$

where,

- $d_{LT(i)} =$ left turn distance from approach $i$ calculated with equation (3)
- $L_c =$ car length
- $a =$ acceleration rate
- $t_{LT(i)} =$ left-turning time from approach $i$

$$d_{LT(i)} = \frac{\pi}{2} \sqrt{\frac{W_{int(i)}^2 + W_{out(i)}^2}{2}}$$

where,

- $W_{int(i)} =$ left-turning vehicle intersection-entering radius, which consists of opposing approach width, median width, and one half of lane width of approach $i$
- $W_{out(i)} =$ left-turning vehicle intersection-exiting radius, which consists of opposite approach width, median width, and one half of an exiting lane width

By transforming equation 2, the turning time for a left-turning vehicle can be calculated as

$$t_{LT(i)} = \sqrt{\frac{2(d_{LT(i)} + L_c)}{a}}$$
Assuming an average car length of 15 ft. and average acceleration rate of 4.4 ft/s^2 yields

\[
t_{LT(i)} = \sqrt{2(d_{LT(i)} + 15)/4.4} \tag{5}
\]

Assuming a \( \delta \) s driver perception-reaction time, the total maneuver time for a left-turning vehicle to clear an intersection from approach \( i \) is \( t_{LT(i)} + \delta \) s. As previously stated, potential conflicts would happen when the gap is medium sized. Defining potential conflict gaps in opposing traffic as those between left turn maneuver time minus 2 s, denoted by \( t_{li} \), and left turn maneuver time plus 2 s, denoted by \( t_{ui} \), gives:

\[
\begin{align*}
t_{li} &= t_{LT(i)} + \delta - 2 \\
t_{ui} &= t_{LT(i)} + \delta + 2
\end{align*} \tag{6}
\]

where,
\( t_{li} \) = lower bound of potential conflict gaps which could result in potential LT conflicts on approach \( i \)
\( t_{ui} \) = upper bound of potential conflict gaps which could result in potential LT conflicts on approach \( i \)

In other words, all opposing vehicles arriving with headways within \( (t_{LT(i)} + \delta - 2) \) and \( (t_{LT(i)} + \delta + 2) \) are counted as potential conflict to left-turning traffic. Gaps smaller than \( t_{li} \) or greater than \( t_{ui} \) are not considered in the calculation of left turn potential conflicts.

It is also assumed that the headway of the opposing traffic follows a negative exponential distribution (a typical assumption in this context.) Then the probability of a headway falling between the lower \( (t_{li}) \) and upper \( (t_{ui}) \) bound of potential conflict gaps is:

\[
P_{PC(i)} = P(t_{li} \leq h \leq t_{ui}) = e^{-\lambda_{ol}t_{li}} - e^{-\lambda_{ol}t_{ui}} \tag{7}
\]

where,
\( P_{PC(i)} \) = probability of expected potential left turn conflict on approach \( i \)
\( \lambda_{ol} = V_{ol}/3600 \), arrival rate of opposing traffic of LT on approach \( i \), in veh/s
\( V_{ol} \) = hourly flow rate on opposing approach, in veh/hr

The following equation provides the number of vehicles that will be affected by potential conflict:

\[
PC_{veh} = \sum_{i} PC_{LT(i)} + PC_{OT(i)} \tag{8}
\]

where,
\( PC_{veh} \) = total expected number of vehicles with potential conflicts
\( PC_{LT(i)} \) = number of LT vehicles with potential conflicts on approach \( i \)
\( PC_{OT(i)} \) = number of opposing traffic with potential conflicts resulting from LT on approach \( i \)

\[
PC_{LT(i)} = PC_{OT(i)} = \begin{cases} V_{LT(i)} \cdot P_{PC(i)} & \text{if } V_{LT(i)} \leq V_{OT_{g_{u}}} \\ V_{OT_{g_{u}}} \cdot P_{PC(i)} & \text{if } V_{LT(i)} > V_{OT_{g_{u}}} \end{cases} \tag{9}
\]

where,
\( V_{LT(i)} \) = the number of left turn vehicles on approach \( i \)
\( V_{OT_{g_{u}}} \) = the number of opposing traffic of approach \( i \) during the green period of \( g_{u} \)
Potential Pedestrian Conflict

HCM 2000 (1) has adopted a new method on saturation flow adjustment for pedestrians at signalized intersections based on research by Milazzo et al. (37). Although Milazzo’s work discusses the effect of pedestrians on saturation flow for turning movements, the method can be employed to estimate the potential conflict between left-turning vehicles and pedestrians in the crosswalk.

An area termed “conflict zone” (Figure 1), where pedestrians and vehicles compete for space, was defined (37). Based on empirical data, Milazzo (37) developed a piecewise linear volume-occupancy model to get the pedestrian occupancy in the conflict zone during pedestrian green time.

\[
\begin{align*}
OCC_{pedg} &= V_{pedg}/2,000 \quad (V_{pedg} \leq 1,000) \\
OCC_{pedg} &= V_{pedg}/10,000 + 0.4 \quad (V_{pedg} > 1,000)
\end{align*}
\]

where,

\[
OCC_{pedg} = \text{average pedestrian occupancy in the conflict zone during pedestrian green time}
\]

\[
V_{pedg} = \text{pedestrian volume per hour of pedestrian green, p/h}
\]

\[
V_{pedg} = V_{ped} \times (C / g_p) \quad (V_{pedg} \leq 5,000)
\]

where,

\[
V_{ped} = \text{conflicting pedestrian flow rate, p/h}
\]

Drivers turning left must first check the opposing through traffic to find whether a safe gap is available. Therefore, opposing through traffic plays a role in protecting pedestrians. Milazzo (37) recognized that this protection has two phases: one is the duration until the opposing queue clears (equation 12); the other is the screen provided by opposing through traffic arriving with small headways which are not acceptable for turning left (equation 13).

\[
OCC_{pedu} = OCC_{pedg}[1 - 0.5(g_q / g_p)] \quad (g_q < g_p)
\]

where,

\[
OCC_{pedu} = \text{average pedestrian occupancy of the conflict zone after the opposing queue clears}
\]

\[
g_q = \text{the portion of the permitted green time blocked by a queue of opposing vehicles, s}
\]

\[
g_p = \text{pedestrian green time, s}
\]

\[
OCC_r = OCC_{pedu} \times P_{nsr}
\]

where,

\[
OCC_r = \text{average pedestrian occupancy of the conflict zone}
\]

\[
P_{nsr} = \text{expected proportion of no conflict zone screening}
\]

\[
P_{nsr} = e^{-t_g (v_o / 3600)}
\]

where,

\[
v_o = \text{opposing flow rate for permitted left turns, veh/h}
\]

\[
t_g = \text{critical gap, s}
\]

Drivers may choose to turn when the opposing gap is greater than \(t_{lt}\) and smaller than \(t_{ul}\), but potential conflicts of left-turning vehicles with opposing through vehicles and pedestrians could occur. When an opposing gap is less than \(t_{lt}\), opposing through vehicles screen pedestrians from left-turning traffic. Therefore, \(t_g\) in equation 14 can be set equal to \(t_{lt}\).

The relevant conflict-zone-occupancy \((OCC_r)\) could also be recognized as the likelihood that pedestrians would be involved in potential conflicts with left-turning vehicles. Therefore, the potential conflict for pedestrians could be expressed with equations 15 and 16.
\[ PC_{ped} = \sum_j PC_{ped(j)} \]  

where,

\[ PC_{ped} = \text{total expected potential pedestrian conflicts} \]
\[ PC_{ped(j)} = \text{expected potential conflict involving pedestrians on receiving approach } j \text{ resulting from left-turning vehicles from approach } i, \text{ p/h} \]
\[ PC_{ped(j)} = V_{ped(j)} \times OCC_{r(j)} \]  

where,

\[ V_{ped(j)} = \text{conflicting pedestrian flow rate on approach } j, \text{ p/h} \]
\[ OCC_{r(j)} = \text{average pedestrian occupancy of the conflict zone on approach } j, \text{ equation 13} \]

**Combination of Delay and Safety**

The potential conflict between vehicles (\( PC_{veh} \)) and the potential conflict between vehicles and pedestrians (\( PC_{ped} \)) can be estimated as explained above. The next step is to combine them together for evaluating the safety of signalized intersections, as follows:

\[ PC = PC_{veh} + PC_{ped} \]  

where,

\[ PC = \text{total expected potential conflicts} \]
\[ PC_{veh} = \text{total expected potential conflicts between left-turning and opposing through vehicles} \]
\[ PC_{ped} = \text{total expected potential pedestrian conflicts} \]

One way of combining safety with efficiency while retaining compatibility with HCM 2000 is to combine perception of inconvenience (delay) and risk (conflicts). This produces the *delay and safety index* (DS). Instead of delay alone, the delay and safety index can be used to determine the LOS for each lane group, approach and the intersection as a whole.

\[ DS = \frac{DS_{veh} \times V_{veh} + DS_{ped} \times V_{ped}}{V_{veh} + V_{ped}} \]  

where,

\[ DS = \text{delay and safety index} \]
\[ DS_{veh} = \text{delay and safety index for vehicles; equation 19} \]
\[ DS_{ped} = \text{delay and safety index for pedestrians; equation 20} \]
\[ V_{veh} = \text{total vehicle volume, veh/h} \]
\[ V_{ped} = \text{total pedestrian volume, p/h} \]

\[ DS_{veh} = d_{veh} + \left( \alpha \times \frac{PC_{veh}}{V_{veh}} \right) d_{veh} = \left( 1 + \alpha \times \frac{PC_{veh}}{V_{veh}} \right) d_{veh} \]  

\[ DS_{ped} = d_{ped} + \left( \beta \times \frac{PC_{ped}}{V_{ped}} \right) d_{ped} = \left( 1 + \beta \times \frac{PC_{ped}}{V_{ped}} \right) d_{ped} \]  

where,

\[ d_{veh} = \text{average vehicle control delay (s/veh)} \]
\[ d_{ped} = \text{average pedestrian delay (s/p)} \]
\[ \alpha = \text{safety weight factor for vehicle-to-vehicle conflicts} \]
\[ \beta = \text{safety weight factor for vehicle-to-pedestrian conflicts} \]
CASE STUDY

Two signalized intersections A and B with moderate traffic volume (Table 1(a)) are shown in Figure 3. Both intersections are in an urban area and pedestrian signals exist on all approaches. For intersection A, which has moderate left turn and through traffic, two different channelization and signal timing plans are shown, one with shared left turn lanes and permitted left turn phases, the other with exclusive left turn lanes and protected LT phases. For intersection B, which is characterized by high left turn traffic, there are also two signal timing plans (one protected LT and the other permitted LT); the geometry with exclusive left turn lanes is the same for both plans. Capacity analysis assumptions include level-terrain, non-CBD area, 12 ft. lane width, 100 p/h pedestrian volume for all approaches, no parking, no heavy vehicles and 4 s phase change interval. Optimized signal timings and the resultant delay and LOS for the two intersections under different signal plans were calculated based on HCM 2000 and are shown in Tables 1(a), 1(b) and 1(c).

The delay-based LOS results show that for both intersections the operation with permitted LT (2-phase operation) is better than that with protected LT (4-phase operation). However, the 4-phase operation of the intersection eliminates most conflicts associated with left turns. To assess the difference in safety between permitted and protected timing plans, potential conflicts involving left-turning vehicles with opposing through vehicles (Table 2) and pedestrians (Table 3) were calculated. Nearly 7.7% of the traffic at intersection A and 10.9% at intersection B is involved with left-turning related potential conflicts. In addition, 3.4% to 5.7% of pedestrians are vulnerable to potential conflicts with left-turning vehicles.

The proposed delay and safety indices (DS) for intersections A and B were calculated by applying equation 18 (Table 4). DS is 29.6 s (intersection A) and 44.2 s (intersection B) with protected left turn phases. DS for permitted left turn phasing with various values for the safety weight factors α and β were computed in Table 4(b). The numbers in boldface indicate that the calculated DS with permitted LT phase is greater than that with protected LT phases. For example, if α ≥ 2, and β ≥ 1, the LOS under protected left turns (DS=29.6) is better than that with permitted left-turns (DS>30) for intersection A. This is also true for intersection B but for α ≥ 7.

It is noted that pedestrian safety did not play a large role in the calculation of DS for these two intersections partly because of the low pedestrian volume used. For intersections in business areas where crossings process a large number of pedestrians, pedestrian safety will have a greater effect on DS and LOS. The relative insensitivity of pedestrian conflicts may also be attributed to small β values being used for calculation. According to research conducted by Kim (38), vehicle-pedestrian crashes are more severe than vehicle-vehicle crashes: 12 times more fatalities, 6 times more major injuries, and 1.7 more minor injuries. Therefore, it may be appropriate to apply larger safety factors for pedestrians (e.g., β could be an order of magnitude larger than α).

SUMMARY AND FUTURE STUDY

Delay has been used as the only index to evaluate the LOS at signalized intersections since 1985. Delay is widely used in the derivation and optimization of traffic signal timings plans. Delay, however, does not represent the safety concerns of motorists or collision risk. A tradeoff between delay and safety for signalized intersections does exist and it largely depends on the operation of the left turn movement.

Signalization phasing affects left turn-related conflicts the most. It also has smaller effects on other types of intersection collisions such as rear-end, sideswipe, and red-light running. Therefore, the major difference between permitted and protected left turn phasing at a signalized intersection is the left turn discharge process and the related collision risk. A methodology that quantifies potential conflicts between left-turning vehicles and opposing through vehicles and pedestrians was developed. The intent of the methodology is to reflect driver stress as a measure of quality of safety service. The methodology was based on and designed to be compatible with HCM 2000. A model was developed to combine delay and safety as the service measure used for assigning LOS: the delay and safety index (DS). The case study of two intersections showed that if potential conflict is not considered, the signal timing plan with permitted left-turns operates at a better LOS than that with protected left-turns. However, if potential conflict is considered, the LOS under protected left-turn phasing is better than under permitted left-turn phasing based on DS, when the safety weight factors exceed a certain value. This methodology represents the tradeoff between safety and efficiency explicitly, and considers both vehicle-vehicle and vehicle-pedestrian conflicts associated with left turns.

This research is being done as a continuation of past efforts to develop a comprehensive LOS for signalized intersections. Several elements require further study. They are listed below:

- The proposed methodology needs to be subjected to more testing with actual intersection data. The sensitivity of the delay and safety index under a variety of conditions needs to be assessed. This endeavor
coupled with intersection crash statistics may also provide an empirical base for establishing safety weights.

- The methodology presented in this paper is based on certain assumptions. Some parameters, such as the perception-reaction time and the value used to determine potential conflict gaps (lower and upper bound of potential conflict gaps) need to be calibrated using experimental data.
- Since pedestrians are more vulnerable, pedestrian safety could be more heavily weighted in DS.
- Other methods need to be tried and tested for combining delay and safety. An alternative method is to develop a set of independent safety-based LOS (this is a possible goal of the Highway Safety Manual being developed by TRB’s committees on safety), and then combine it with the delay-based LOS.
- The extant LOS concept needs enrichment with behavioral inputs from motorists and pedestrians with respect to quality of service (e.g., lost time, stoppages, speed fluctuations, safety risk.) As part of the proposed methodology, a motorist survey is being designed in order to establish safety weight factors for DS. Research with recruited motorists in real traffic is not possible due to liability and the limited control of experiment conditions. A video laboratory study is a feasible alternative because testers have more control over the experiment so that all subjects would experience the same traffic conditions in the safety of a laboratory setting. A video camera mounted on a vehicle will be used to videotape a pre-set number of scenarios of traffic situations from a driver’s vantage point. Several driving maneuvers in various conditions of traffic density will be determined and videotaped. The reaction of recruited motorists will be recorded in rating scales for operational and safety conditions. Statistical analysis will enable the estimation of perceived tradeoffs between efficiency and safety and from there weight factors for safety will be developed.
REFERENCES

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TABLE 1. HCM Inputs and Outputs for Intersections A and B.

(a) Traffic volume and signal timings.

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<th>Traffic Volume (vph)</th>
<th>Signal Timing (s)</th>
<th>Phase (see Fig. 3)</th>
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<td>8.7</td>
<td>29.0</td>
</tr>
<tr>
<td></td>
<td>RT</td>
<td>20</td>
<td>110</td>
<td>20</td>
</tr>
<tr>
<td>NB</td>
<td>LT</td>
<td>150</td>
<td>110</td>
<td>110</td>
</tr>
<tr>
<td></td>
<td>TH</td>
<td>600</td>
<td>110</td>
<td>110</td>
</tr>
<tr>
<td></td>
<td>RT</td>
<td>80</td>
<td>110</td>
<td>110</td>
</tr>
<tr>
<td>SB</td>
<td>LT</td>
<td>165</td>
<td>110</td>
<td>110</td>
</tr>
<tr>
<td></td>
<td>TH</td>
<td>650</td>
<td>110</td>
<td>110</td>
</tr>
<tr>
<td></td>
<td>RT</td>
<td>70</td>
<td>110</td>
<td>110</td>
</tr>
<tr>
<td>Total Traffic Volume</td>
<td></td>
<td>3,085</td>
<td>3,175</td>
<td>78</td>
</tr>
</tbody>
</table>

(b) Pedestrian signal timings.

<table>
<thead>
<tr>
<th>Movement</th>
<th>Ped. Signal (s)</th>
<th>Pedestrian Signal Timings</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-W</td>
<td>WALK</td>
<td>19.1</td>
</tr>
<tr>
<td></td>
<td>FDW*</td>
<td>11.0</td>
</tr>
<tr>
<td>N-S</td>
<td>WALK</td>
<td>28.9</td>
</tr>
<tr>
<td></td>
<td>FDW*</td>
<td>11.0</td>
</tr>
</tbody>
</table>

FDW = Flashing Don’t Walk

(c) Vehicle and pedestrian delay and LOS.

<table>
<thead>
<tr>
<th>Approach</th>
<th>Movement</th>
<th>Delay (sec.)</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Permitted LT</td>
<td>Protected LT</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(2-Phase)</td>
<td>(4-Phase)</td>
</tr>
<tr>
<td>EB</td>
<td>LT</td>
<td>34.50</td>
<td>14.7</td>
</tr>
<tr>
<td></td>
<td>TH+RT</td>
<td>27.84</td>
<td>14.7</td>
</tr>
<tr>
<td>WB</td>
<td>LT</td>
<td>23.43</td>
<td>9.3</td>
</tr>
<tr>
<td></td>
<td>TH+RT</td>
<td>26.85</td>
<td>9.3</td>
</tr>
<tr>
<td>Intersection Delay</td>
<td></td>
<td>28.0</td>
<td>12.0</td>
</tr>
</tbody>
</table>

LOS | C | B | C | B | C | B | D | C |

Zhang & Prevedouros
### TABLE 2. Potential Left-turn Conflicts among Vehicles at Intersections A and B.

#### (a) Calculation process.

<table>
<thead>
<tr>
<th>Input</th>
<th>Intersection A</th>
<th>Intersection B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EB</td>
<td>WB</td>
</tr>
<tr>
<td>$N_o$</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>$N_e$</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Lane Width</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Median Width</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>$d_{LT}$</td>
<td>56.5</td>
<td>56.5</td>
</tr>
<tr>
<td>$L_c$</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>$a$</td>
<td>4.4</td>
<td>4.4</td>
</tr>
<tr>
<td>$t_{LT}$</td>
<td>5.7</td>
<td>5.7</td>
</tr>
<tr>
<td>$t_l$</td>
<td>4.7</td>
<td>4.7</td>
</tr>
<tr>
<td>$t_a$</td>
<td>8.7</td>
<td>8.7</td>
</tr>
<tr>
<td>$V_o$</td>
<td>520</td>
<td>620</td>
</tr>
<tr>
<td>$l_o$</td>
<td>0.144</td>
<td>0.172</td>
</tr>
<tr>
<td>$P_{PC}$</td>
<td>0.223</td>
<td>0.222</td>
</tr>
<tr>
<td>C</td>
<td>78</td>
<td>78</td>
</tr>
<tr>
<td>g</td>
<td>30.1</td>
<td>30.1</td>
</tr>
<tr>
<td>$g_r$</td>
<td>0.6</td>
<td>1.1</td>
</tr>
<tr>
<td>$g_{u}$</td>
<td>7.6</td>
<td>10.2</td>
</tr>
<tr>
<td>$g_{u}$</td>
<td>22.5</td>
<td>19.9</td>
</tr>
<tr>
<td>$V_{OT_{gu}}$</td>
<td>150</td>
<td>158</td>
</tr>
<tr>
<td>$V_{LT}$</td>
<td>120</td>
<td>110</td>
</tr>
<tr>
<td>$PC_{LT}$ &amp; $PC_{OT}$</td>
<td>26.7</td>
<td>24.4</td>
</tr>
</tbody>
</table>

#### (b) Total and percentile potential conflicts.

<table>
<thead>
<tr>
<th>Intersection</th>
<th>Movement</th>
<th>Potential Conflict (PC)</th>
<th>$PC_{veh}$</th>
<th>Total Volume</th>
<th>% PC</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>LT</td>
<td>26.7 24.4 32.3 36.0</td>
<td>238.8</td>
<td>3,085</td>
<td>7.7%</td>
</tr>
<tr>
<td></td>
<td>TH</td>
<td>24.4 26.7 36.0 32.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>LT</td>
<td>41.6 41.7 48.2 42.1</td>
<td>347.2</td>
<td>3,175</td>
<td>10.9%</td>
</tr>
<tr>
<td></td>
<td>TH</td>
<td>41.7 41.6 42.1 48.2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
TABLE 3. Potential Conflicts between Left-turn Vehicles and Pedestrians at Intersections A and B.

(a) Pedestrian conflicts at intersection A.

<table>
<thead>
<tr>
<th>Approach</th>
<th>$V_{ped}$</th>
<th>C</th>
<th>$g_p$</th>
<th>OCC$_{pedu}$</th>
<th>$g_{up}$</th>
<th>OCC$_{pedu}$</th>
<th>$\nu_o$</th>
<th>OCC$_r$</th>
<th>$PC_{ped}$</th>
<th>% PC$_{ped}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>EB</td>
<td>100</td>
<td>78</td>
<td>39.9</td>
<td>195</td>
<td>0.098</td>
<td>0.258</td>
<td>0.085</td>
<td>680</td>
<td>0.035</td>
<td>3.5</td>
</tr>
<tr>
<td>WB</td>
<td>100</td>
<td>78</td>
<td>39.9</td>
<td>195</td>
<td>0.098</td>
<td>0.228</td>
<td>0.086</td>
<td>720</td>
<td>0.034</td>
<td>3.4</td>
</tr>
<tr>
<td>NB</td>
<td>100</td>
<td>78</td>
<td>30.1</td>
<td>259</td>
<td>0.130</td>
<td>0.339</td>
<td>0.108</td>
<td>620</td>
<td>0.048</td>
<td>4.8</td>
</tr>
<tr>
<td>SB</td>
<td>100</td>
<td>78</td>
<td>30.1</td>
<td>259</td>
<td>0.130</td>
<td>0.253</td>
<td>0.113</td>
<td>520</td>
<td>0.057</td>
<td>5.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\Sigma$=17.4</td>
<td>Avg.=4.4%</td>
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</table>

(b) Pedestrian conflicts at intersection B.

<table>
<thead>
<tr>
<th>Approach</th>
<th>$V_{ped}$</th>
<th>C</th>
<th>$g_p$</th>
<th>OCC$_{pedu}$</th>
<th>$g_{up}$</th>
<th>OCC$_{pedu}$</th>
<th>$\nu_o$</th>
<th>OCC$_r$</th>
<th>$PC_{ped}$</th>
<th>% PC$_{ped}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>EB</td>
<td>100</td>
<td>80</td>
<td>40</td>
<td>200</td>
<td>0.100</td>
<td>0.168</td>
<td>0.092</td>
<td>480</td>
<td>0.046</td>
<td>4.6</td>
</tr>
<tr>
<td>WB</td>
<td>100</td>
<td>80</td>
<td>40</td>
<td>200</td>
<td>0.100</td>
<td>0.108</td>
<td>0.095</td>
<td>590</td>
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<td>NB</td>
<td>100</td>
<td>80</td>
<td>32</td>
<td>250</td>
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<td>0.234</td>
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<td>822</td>
<td>0.035</td>
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<tr>
<td>SB</td>
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<td>80</td>
<td>32</td>
<td>250</td>
<td>0.125</td>
<td>0.181</td>
<td>0.114</td>
<td>700</td>
<td>0.042</td>
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<td></td>
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<td></td>
<td></td>
<td>$\Sigma$=16.4</td>
<td>Avg.=4.1%</td>
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</table>
TABLE 4. Delay and Safety Index (DS).

(a) DS for intersections A and B with protected LT Phases.

<table>
<thead>
<tr>
<th>Intersection</th>
<th>LT Signal</th>
<th>PC_{veh}</th>
<th>V_{veh}</th>
<th>PC_{ped}</th>
<th>V_{ped}</th>
<th>d_{veh}</th>
<th>d_{ped}</th>
<th>DS</th>
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</thead>
<tbody>
<tr>
<td>A</td>
<td>Protected</td>
<td>0</td>
<td>3,085</td>
<td>0</td>
<td>400</td>
<td>31.0</td>
<td>18.6</td>
<td>29.6</td>
</tr>
<tr>
<td>B</td>
<td>Protected</td>
<td>0</td>
<td>3,175</td>
<td>0</td>
<td>400</td>
<td>46.1</td>
<td>29.2</td>
<td>44.2</td>
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</tbody>
</table>

(b) DS for intersections A and B with permitted LT Phases.

<table>
<thead>
<tr>
<th>Intersection</th>
<th>LT Signal</th>
<th>Safety Weight Factor</th>
<th>DS</th>
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<tbody>
<tr>
<td></td>
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<td>α=2</td>
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<tr>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>β=4</td>
<td>28.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>β=5</td>
<td>28.4</td>
</tr>
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<td></td>
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<td>β=6</td>
<td>28.4</td>
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<td>β=7</td>
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<tr>
<td></td>
<td></td>
<td>β=2</td>
<td>28.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>β=3</td>
<td>28.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>β=4</td>
<td>28.9</td>
</tr>
<tr>
<td></td>
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<td>β=5</td>
<td>28.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>β=6</td>
<td>29.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>β=7</td>
<td>29.1</td>
</tr>
</tbody>
</table>
FIGURE 1. Potential conflict of left-turning vehicles with opposing through vehicles and pedestrians.
FIGURE 2. Proposed methodology.
Shared LT lanes and permitted LT phases. Exclusive LT lanes and protected LT phases.

Exclusive LT lanes and permitted LT phases. Exclusive LT lanes and protected LT phases.

FIGURE 3. Geometric configuration and signal phasing of case study intersections A and B.