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Leading Pedestrian Interval Implementation as a Marginal Costs and Benefits Problem

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Abstract

To improve the safety of people walking at particular signalized intersections, traffic signal engineers may implement leading pedestrian intervals (LPI) to provide pedestrians with a walk signal for a few seconds prior to the parallel vehicular green indication. Previous research using before-after studies and simple economic analyses shows that LIPs are low cost tools that can reduce vehicle-pedestrian conflicts and crashes at some signalized intersections. Despite this evidence, there is a little guidance for municipalities on when to implement LPIs. this paper develops a marginal costs and benefits framework using quantitative metrics, extending the concept of traffic conflicts and marginal safety-delay tradeoffs to analyze the appropriateness of implementing an LPI at specific signalized intersections. The guidance provided by this method helps quantify the probability of a conflict happening, and provides direction on whether or not to implement an LPI at a given location based upon macroscopic level inputs, including turning movement counts, crash data, and geometry. A case study with sample data indicates that an LIP is cost effective for the scenario presented.

Keywords

Benefit cost analysis, Case studies, Implementation, Macroscopic traffic flow, Metrics (Quantitative assessment), Pedestrian clearance interval (Traffic signals), Pedestrian safety, Signalized intersections, Traffic conflicts, Traffic delays

Disciplines

Civil and Environmental Engineering | Transportation Engineering

Comments

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ABSTRACT

To improve the safety of people walking at particular signalized intersections, traffic signal engineers may implement leading pedestrian intervals (LPI) to provide pedestrians with a walk signal for a few seconds prior to the parallel vehicular green indication. Previous research using before-after studies and simple economic analyses shows that LPIs are low cost tools that can reduce vehicle-pedestrian conflicts and crashes at some signalized intersections. Despite this evidence, there is little guidance for municipalities on when to implement LPIs. This paper develops a marginal costs and benefits framework using quantitative metrics, extending the concept of traffic conflicts and marginal safety-delay tradeoffs to analyze the appropriateness of implementing an LPI at specific signalized intersections. The guidance provided by this method helps quantify the probability of a conflict happening, and provides direction on whether or not to implement an LPI at a given location based upon macroscopic level inputs, including turning movement counts, crash data, and geometry. A case study with sample data indicates that an LPI is cost effective for the scenario presented.

INTRODUCTION

Walking as a healthy and sustainable transportation mode is gaining in popularity. According to the 2009 National Household Travel Survey (NHTS), an estimated 42 billion walking trips occur in the US each year, accounting for 10.5% of all trips taken (1). Pedestrian safety, however, remains a top concern. In 2014, 4,884 pedestrians were killed and 65,000 injured in traffic crashes in the US, with 78% of these fatalities occurring in urban areas and 19% at intersections (2).

Traffic signals in urban areas are locations where all modes converge – bicycles, pedestrians, trucks and transit competing for limited time and space. Traditional signal timing practices provide pedestrian service by concurrently serving the pedestrians along with vehicles, with right turning vehicles expected to yield to pedestrians in the crosswalk. However, not all drivers yield to pedestrians, leading to conflicts and crashes between pedestrians and motor vehicles. A leading pedestrian interval (LPI) is a treatment in which pedestrians are provided with a WALK signal for a few seconds prior to the parallel vehicular green indication thereby providing pedestrians with greater visibility by allowing them to enter the intersection before the turning vehicles can start. After the LPI, the vehicular green indication for the parallel movement is served and is timed concurrently. Many studies on LPIs have reported reduction in conflicts between pedestrians and turning vehicles (3,4,5,6,7). In addition to actual safety improvements, LPIs may also improve perceptions of safety. There is less research on the impact of LPIs on user delays, however parallel vehicular delay is expected to increase due to loss of green time.

While the safety benefits of LPIs have been well documented, cities still struggle with assessing the suitability of candidate locations for LPI implementation. Recent guidelines from the City of Toronto outline several criteria that should be considered prior to determining the suitability of a location (8). While a suitability assessment worksheet was developed as a part of this study, to determine if an LPI is an appropriate treatment for a particular location, the scoring rubric and thresholds were assumed and not based on research or underlying traffic theory.

The objective of this paper is to develop a marginal costs and benefits framework using quantitative metrics to assist in the decision making for implementation of an LPI at a particular location. The guidance provided by this method will quantify the probability of a conflict happening, and provide direction on whether or not to implement an LPI at a given location based upon macroscopic level inputs, including turning movement counts, crash data, and geometry.

LITERATURE REVIEW

LPI Impacts

Many studies have evaluated the safety impacts of LPIs by studying before and after crash data at treatment and control intersections. King studied the crash rates at 26 treatment locations in New York City with LPIs and also at control locations without LPIs. Analysis of the crash data showed significant reductions in motor vehicle and pedestrian crashes (7) at locations with LPIs. Hubbard et al. estimated the percent of compromised pedestrian crossings at 13 intersections in an effort to quantify pedestrian service (9). A crossing was defined as compromised if a pedestrian was forced to change his/her path or speed due to a turning vehicle (9). Hubbard et al. recommended that if the percentage of compromised crossings exceeded 15%, an LPI may be appropriate (9). In another study, Hubbard et al. compared the speed and headways of vehicles turning right on a red light vs. a green light at intersections and found that as expected mean speeds of vehicles turning right on red were lower and headways were higher than for vehicles turning right on green (10). They suggest that these factors must be taken into consideration when implementing an LPI (10). In another study, Hubbard et al. compared the percentage of pedestrians comprised with and without LPI, and found mixed results (11). The authors suggest that difference in choice of location (suburban vs. downtown) compared to other studies may explain the mixed results (11).

Van Houten et al. studied the implementation of 3-second LPIs at three intersections by examining conflicts (3). Their results revealed that conflicts between pedestrians and turning vehicles and occurrences of pedestrians yielding the right-of-way to turning vehicles were reduced (3). Using a before-after study design and data from 10 treatment intersections where the LPIs were implemented and 14 control intersections without LPIs, Fayish and Gross studied the safety effectiveness and found 58% reduction in pedestrian-vehicle crashes at treatment locations (6). Additionally, a simple economic analysis was conducted to assess the cost effectiveness of implementing an LPI (6). Using a cost benefit analysis, these researchers showed that LPI implementation was economically beneficial (6). However, only crash costs were included in the analysis and delay costs were excluded. Guidelines on assessing the suitability of candidate locations for LPI implementation have been scarce. Sainenejad and Lo proposed a suitability assessment worksheet for LPIs based on factors such as collision rates between pedestrians and turning vehicles, volume of pedestrians, school proximity, activity by elderly residents, impacts on vehicle delay, presence of visibility issues and intersections with special geometry (8).

A review of the literature reveals little to no research providing comprehensive evaluations of the cost effectiveness of an LPI.

Traffic Conflict as a Surrogate Safety Measure

The traffic conflict technique (TCT) was first proposed in 1967 by Perkins and Harris (12), defining a conflict as: “The occurrence of evasive actions, such as braking or weaving, which are forced on the driver by an impending accident situation or a traffic violation.” Conflicts were categorized as left-turn conflicts, weave conflicts, rear-end conflicts and cross-traffic conflicts. This methodology has been extended to quantify pedestrian safety by using the number of conflicts between vehicles and pedestrians (12-16).

The TCT gained wide publicity as a surrogate for measuring traffic safety for two main reasons. First, traffic conflicts are more frequently observed than crashes, so a large amount of information about intersection safety can be collected quickly. Cooper et al. (17) reported that, on average, the ratio of rate of crash to rate of serious conflicts lies in the range of 1:2000, so that 10 hours of observation of conflicts at a site provides information equivalent to 2-3 years of reported crash records. Second, traffic conflict observations provide an opportunity for traffic engineers to proactively improve the safety of a site instead of waiting for the crash history to evolve. Because of these advantages, the TCT was used by several agencies to investigate crash potential and operational deficiencies of intersections. There have been numerous research efforts to establish a direct relationship between crashes and conflicts (18, 19). A review in 1980 by Glauz and Migletz (20) identified 33 previous studies that (at least partly) dealt with the conflict-crash relationships (21-25).

Some concerns have been raised regarding TCT techniques (26) since the general approach initially used was to compare observed crashes with the observed surrogate measure. Since both the conflict and crash are randomly distributed events it is highly improbable to predict the exact number of crashes at a site. Glauz et al. (27) proposed a new approach that compared the expected crash rate as predicted by conflict ratios to the expected crash rate as predicted by crash histories. This study concluded that an estimate of the expected crash rates can be computed from the data obtained from traffic conflict counts with nearly the same accuracy as predicted by the crash history.

Some recent studies (28, 29) also advocate the use of traffic conflict events as a surrogate measure for traffic safety in micro-simulation packages. Gettman and Head (29) provided a detailed use-case analysis for using traffic conflicts as a surrogate measure for safety in a simulation package. Additionally, in recent years, traffic conflicts have been used as a safety surrogate to calculate the tradeoff between efficiency and safety for signal timing designs or simply to assess the safety impact of a new traffic signal improvement strategy (13,30-33). The marginal cost and benefits framework using TCT to quantify safety has also been used to design green extension logic for dilemma zone protection and evaluating exclusive pedestrian phasing (13,31,32). In summary, the literature review in this area indicates a long history of development for the traffic conflict technique which suggests that it can be used effectively as a surrogate measure of traffic safety at intersections. This paper extends the concept of traffic conflicts and marginal safety-delay tradeoffs to analyze the appropriateness of implementing an LPI at specific signalized intersections.

PROPOSED LPI MARGINAL COSTS-BENEFITS MODEL

An LPI can be implemented in an economically efficient manner when the following criteria is met: Estimated pedestrian safety benefits exceed vehicular movement delay costs. The question of LPI implementation suitability is cast as a marginal costs and benefits issue in **Equation 1**.

$$\begin{aligned} &Pedestrian\ Exposure\ Factor_{Inbound} \times Crash\ Risk\ Factor \times Cost\ of\ Crash \\ &\quad + Pedestrian\ Exposure\ Factor_{Outbound} \times Crash\ Risk\ Factor \\ &\quad \times Cost\ of\ Crash \geq Additional\ Vehicular\ Delay \times Cost\ of\ Delay \end{aligned} \quad \textbf{Equation 1}$$

Pedestrian exposure factor measures the probability of the simultaneous presence of a right turn vehicle and a pedestrian demanding the same right of way when indications are green for both users. The equation represents the case where an LPI simultaneously serves pedestrians in both directions (for example, both northbound and southbound crosswalks), the safety benefits from both directions need to be added to estimate the net benefit. Only one term in the left hand side of **Equation 1** will be used if the LPI is provided for only one direction of pedestrian movement (for example, northbound only). The exposure factor will increase as the number of right turning vehicles and pedestrians increase. The *crash risk factor* is the probability of having a crash occurring when the right turning vehicle and pedestrian demand the same right of way at the same time, and will depend on site specific characteristics. Sites with poor visibility or aggressive drivers may increase the crash risk at the same level of exposure, while the presence of more pedestrians may reduce the crash risk at the same level of exposure due to the increased expectation and visibility of pedestrians. The *cost of crash* can be estimated based upon severity distributions of pedestrian crashes involving right turning vehicles. The product of the three factors provides estimates of the safety dis-benefits of not providing an LPI at a signalized intersection for a given time period. It should be noted that an LPI only impacts conflicts where right turning vehicles and pedestrians are simultaneously present at the start of the green interval, not those that occur during the remaining green time. In subsequent sections only conflicts at the start of the green interval will be considered in the calculation of safety benefits.

The cost of additional delay incurred due to additional red experienced because of an LPI is calculated by multiplying *cost of delay* (in dollars) by the amount of *additional vehicular delay* (in time) incurred by the LPI. An LPI treatment is economically efficient when the safety benefits for pedestrians exceed the delay cost levied on the vehicular traffic. It should be noted that a decision maker can choose appropriate dollar values for safety or efficiency to appropriately weigh safety-efficiency tradeoffs as per agency preferences and user choices. Subsequent sections present approaches to estimate different factors expressed in **Equation 1**.

Pedestrian Exposure Factor

The pedestrian exposure factor is defined as the probability of the simultaneous presence of a right turning vehicle and a pedestrian demanding the same right of way at the onset of green. In simple scenarios when there is a separate right turn bay, no right turn on red and fixed red times are employed, the exposure factor can be calculated theoretically as shown below.

$$Probability\ of\ zero\ ped\ arrivals\ during\ (R+t) = P(ped_0) = e^{-q_{ped}(R+t)}$$ **Equation 2**

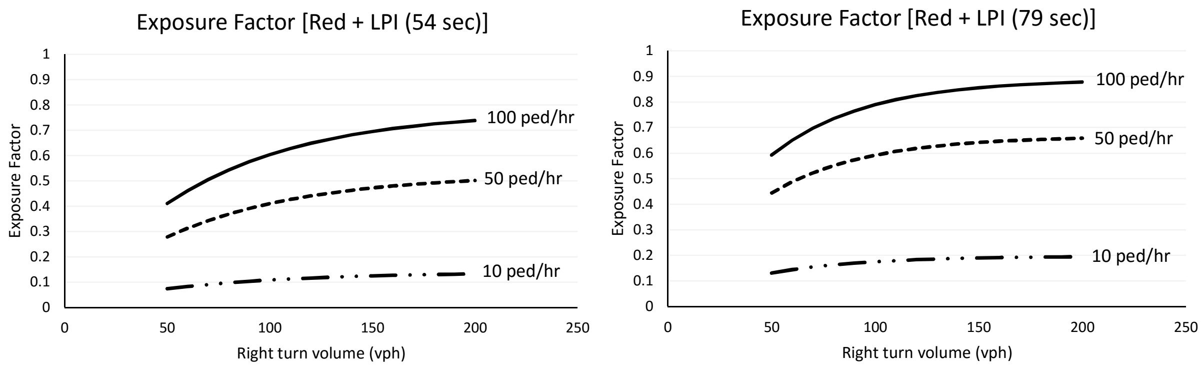
$$Probability\ of\ atleast\ one\ ped\ arrivals\ during\ (R+t) = P(Ped_{>0}) = 1 - P(ped_0) = 1 - e^{-q_{ped}(R+t)}$$ **Equation 3**

$$Probability\ of\ zero\ right\ turn\ arrivals\ during\ (R+t) = P(Rt_0) = e^{-q_{Rt}(R+t)}$$ **Equation 4**

$$Probability\ of\ atleast\ one\ ped\ arrivals\ during\ (R+t) = P(Rt_{>0}) = 1 - P(Rt_0) = 1 - e^{-q_{Rt}(R+t)}$$ **Equation 5**

$$Exposure\ Factor = Probability\ of\ both\ the\ events\ happening\ in\ the\ same\ cycle = P(RtPed_{conflict}) = (1 - e^{-q_{Rt}(R+t)}) \times (1 - e^{-q_{Ped}(R+t)})$$ **Equation 6**

Figure 1 displays the impact of three critical factors, namely red duration, pedestrian volume and right turn volumes on exposure factor. The exposure factor increases considerably as pedestrian and right turn volumes increase. Also, the increase in the duration of total red time (green time of the opposing phases) increases the exposure factor as it gives more time for pedestrians and right turning vehicles to come into the queue in cases where right turns on red are prohibited. It should be noted that the exposure factor is close to one under extremely high pedestrian and right turn volumes, implying that a right turn vehicle and a pedestrian will be present at every cycle at the start of the green time.



a) Shorter red times b) Longer red times

Figure 1: Impact of red duration, pedestrian volumes and right turn volumes on exposure factor

A simple two direction prototype agent based traffic signal simulator was used to calculate the exposure factor for a location with a shared right and through movement lane. Agent based simulation is a method that simulates actions and interactions of autonomous agents. Each agent may have its own rules of operation, interaction and communication with other agents. Three agents were used in the presented traffic signal simulator. The rules of operations are listed below.

1. A *Vehicle agent* represents a single vehicle that enters the system at a preset time. The vehicle agent's entrance time is randomly generated such that the vehicle arrivals follow a Poisson distribution. The average hourly volume is provided as a user input. At every simulation step (two seconds was chosen for this work) vehicles move one cell forward given that the cell in front of the vehicle is empty. At a traffic signal, vehicle agents will dissipate at a saturation headway of two seconds.
2. A *Pedestrian agent* follow similar rules as vehicle agents, which starts to move at the onset of green using a dissipation saturation headway of four seconds. To better illustrate the conflicts of pedestrians and right turning vehicles in this simulation, the vehicle is set to yield to the pedestrian at all times. Average hourly pedestrian volumes are provided as a user input and are Poisson distributed as well.
3. The *Traffic signal agent* has two states, 0 and 1, which represent the green indication on cross street (0) and main street accordingly (1). The signal agent follows the rules of signal change, which include gap-out and max-out principles. In this simulation, the gap-out time was set to be 4 seconds and the max-out time was 40 seconds. These are user defined parameters and can be changed to replicate field conditions.

Vehicle agents are populated at the end of approaches and move forward at every simulation time step given that the cell in front is not pre-occupied by another vehicle agent. Once the vehicle agent hits the stop bar detector, the presence of the vehicle is recorded to drive the traffic signal control. After running the whole program, each vehicle's exit time at the signal is recorded, along with the cycle length. The number of cycles where a right turn vehicle is present in conjunction with a standing pedestrian are counted. These cycles are divided by the number of cycles where there was no exposure. The ratio gives an estimate of exposure factor.

Table 1 presents simulation results for several combinations of thru, right turn and pedestrian volumes. Fixed parameters of this simulation are the following:

i) EB Thru volume: 1500 vph
ii) gap out: 4s
iii) max green: 40s
iv) simulation time: 1 hour
v) saturation headway: 2s.

These values are chosen for demonstration purposes; different values can be entered to replicate the field conditions. These results are consistent with Figure 1; the increase in right turn volume and pedestrian volumes increase the exposure factor. As an example, comparing Scenarios 1 and 2, the exposure factor increases from 0.04 to 0.09 as the pedestrian volumes increase from 50 peds/hour to 100 peds/hour. Similarly, comparing scenarios 1 and 5, as the right turn volume goes from 25 vph to 50 vph the exposure factor increases from 0.04 to 0.15. The bolded scenarios, 5 and 13 in Table 1, signify another point of importance; an increase in through volumes while keeping right turn and pedestrian volumes at the same levels reduces the exposure factor as there is less probability that a right-turning vehicle will be able to fill the front spot in the queue at the onset of green. By the same logic, a separate right turn lane would provide the highest exposure factor for the same right turn and pedestrian volumes.

The presented prototype can be easily extended to a multi-phase simulation by providing lanes and vehicular inputs in all directions and signal agents with multiple states corresponding to green indications serving multiple phases. More complex scenarios such as adaptive control and shared lanes (combined right and through movements) can be easily simulated using a simple agent based simulator developed in Microsoft Excel, such as the one developed for this study, or a more complex micro-simulator such as VISSIM. The advantage of using the simple Excel based simulator presented in this study is that it produces a quick estimate of safety costs/benefits compared to time intensive VISSIM estimates.

Table 1: Exposure Factor Sensitivity Analysis

Scenario	Total volume	Right turn volume	Right turn%	Thru volume	Ped volume	No. of Cycles	# of conflicts at green start	Expo-sure Factor	Avg. Cycle (s)
1	500	25	5%	475	50	47	2	0.04	75.66
2	500	25	5%	475	100	47	4	0.09	76.04
3	500	25	5%	475	150	47	5	0.11	76.45
4	500	25	5%	475	200	47	5	0.11	76.47
5	**500**	**50**	**10%**	**450**	**50**	**47**	**7**	**0.15**	**76.04**
6	500	50	10%	450	100	47	13	0.28	76.04
7	500	50	10%	450	150	47	14	0.30	76.04
8	500	50	10%	450	200	47	13	0.28	76.04
9	500	100	20%	400	50	47	9	0.19	75.66
10	500	100	20%	400	100	47	10	0.21	75.66
11	500	100	20%	400	150	46	25	0.54	77.87
12	500	100	20%	400	200	45	25	0.56	79.6
13	**1000**	**50**	**5%**	**950**	**50**	**38**	**3**	**0.08**	**92.95**
14	1000	50	5%	950	100	38	7	0.18	92.95
15	1000	50	5%	950	150	38	9	0.24	92.95
16	1000	50	5%	950	200	38	13	0.34	92.95
17	1000	100	10%	900	50	38	3	0.08	92.95
18	1000	100	10%	900	100	38	8	0.21	92.95
19	1000	100	10%	900	150	38	18	0.47	92.95
20	1000	100	10%	900	200	38	19	0.50	92.95
21	1000	200	20%	800	50	38	9	0.24	92.95
22	1000	200	20%	800	100	38	17	0.45	92.95
23	1000	200	20%	800	150	38	29	0.76	92.95
24	1000	200	20%	800	200	38	32	0.84	92.95
25	1500	75	5%	1425	50	38	1	0.03	92.89
26	1500	75	5%	1425	100	38	4	0.11	92.89
27	1500	75	5%	1425	150	38	6	0.16	92.89
28	1500	75	5%	1425	200	38	8	0.21	92.89
29	1500	150	10%	1350	50	38	10	0.26	92.89
30	1500	150	10%	1350	100	38	11	0.29	92.89
31	1500	150	10%	1350	150	38	15	0.39	92.89
32	1500	150	10%	1350	200	38	19	0.50	92.89
33	1500	300	20%	1200	50	38	12	0.32	92.89
34	1500	300	20%	1200	100	38	19	0.50	92.89
35	1500	300	20%	1200	150	38	27	0.71	93.05
36	1500	300	20%	1200	200	38	31	0.82	93.05

Crash Risk Factors

There have been attempts in the past to directly estimate the number of crashes using conflicting volumes a surrogate for exposure factor. As an example, Quaye et. al. (34) established a power function to estimate the number of crashes based on left turning vehicle movements and pedestrian volumes. Development of such functions requires a bigger crash data set as well as control for several contributing factors such as weather, intersection geometry, signal phasing details, etc. Even then, the generalizability of such models are often dependent on how closely the selected site matches the data set on which the model was trained, as well as the transferability of model.

In this paper, the probability of traffic conflicts given that there exists a right turning vehicle and pedestrian present (*Pr(TC|Exposure)*) is used as a surrogate of safety. This probability is defined as the total number of right turn and pedestrian conflicts at the start of green divided by the total number of cases where there was a simultaneous presence of a right turning vehicle and pedestrian at the start of green. As discussed previously, the number of conflicts can be easily observed by conducting a site survey. The probability will be site dependent as some sites with aggressive drivers and poor visibility can show significantly higher probabilities of traffic conflicts compared to sites with defensive drivers and good visibility.

After developing the crash risk factor, the next step is to compute the benefits of preventing the conflicts using one of two approaches. The first is to survey a representative set of pedestrians to obtain information on the cost they associate with each type of conflict. The second approach is to evaluate benefits by calculating the probability of having a crash given that a conflict has occurred (*Pr(Crash|TC)).* The comprehensive cost of each crash can then be used to calculate the benefits of preventing a traffic conflict. This paper uses the latter approach for calculating the safety benefits of preventing this pedestrian-vehicle conflict.

Table 2 illustrates an example calculation assessing the benefits of preventing a single traffic conflict. Columns 1 and 2 in Table 2 list the type of crashes and the comprehensive cost associated with them, respectively, as reported by the National Safety Council (35). The weighted average cost of the crash is calculated using the ratios of the pedestrian accidents reported in a recent NHTSA study (36). It is recommended to use city specific severity distributions for the right turn and pedestrian crashes for field implementation. The estimated benefits of preventing a traffic conflict are obtained as the product of the average crash cost and the probability of occurrence of a crash given a traffic conflict has occurred. The value used for the probability of a crash given a traffic conflict is obtained from research conducted by Baker et al. (18), which recommends that cities use existing crash databases and traffic conflict counts at particular sites to estimate this probability. The next step is to evaluate the probability of traffic conflicts. For this example, the probability of conflicts observed by Hubbard et.al. (11) at the test sites in her work were considered, which varied between 18% - 33%, and selected the lower number, 0.18. Using the estimated benefit of preventing a single traffic conflict of $27.30 and multiplying the probability of the occurrence of a traffic conflict with this value provides the benefits of preventing a single pedestrian from being exposed (simultaneous occurrence of right turn vehicle and pedestrian at onset of green). For this example, the value is $4.90. It should be noted that step of associating crashes with traffic conflicts can be avoided if a user survey is conducted to estimate the willingness to pay to avoid a traffic conflict given a particular cost of delay. Once the dollar value of a traffic conflict is obtained, that value can be multiplied directly by the probability of traffic conflicts to estimate safety benefits. The numbers presented in this example would be different for specific intersections and are used here only to illustrate the concept.

Table 2: Estimation of Cost Associated with a Traffic Conflict

Type of Crash	Comprehensive Cost, 2013 (35)	Ratio of Each Type of Crash (36)	Ratio * Cost
Death	$4,628,000	3.9	$18,049,200
Incapacitating Injury	$235,400	23.1	$5,437,740
Non-incapacitating evident injury	$60,000	35.4	$2,124,000
Possible Injury	$28,600	30.7	$878,020
No Injury	$2,600	3.8	$9,880
Weighted average comprehensive cost per crash [*Cost($/Crash)*]			$273,465.8
Probability of getting involved in a crash given a traffic conflict [*Pr(Crash|TC)*] *(Ref:18)*			0.0001
Estimated benefits of preventing a traffic conflict [Benefits($/TC)= Cost($/Crash) X Pr(Crash|TC)]			$27.30
Probability of having a traffic conflict [Pr(TC|Exposure)] (Ref:15)			0.18
Benefits of preventing one vehicle from its decision conflict zone *[Benefits($/Exposure)=Pr(TC\|Exposure) X Benefits($/TC)]*			$4.92

The cost of vehicular delay incurred due to an LPI can be calculated using the HCM methodology. Using this method, user delay is calculated using a larger value of lost time (increased by the number of seconds of an LPI phase) and subtracting the original delay for each phase from the newly calculated value. The increase in the total system delay is multiplied by the cost of delay ($/veh/seconds) to obtain the cost of providing LPI service. The following section presents a simple example using the above methodology.

Case-Study for Implementing Marginal Cost and Benefits Methodology

Table 3 lists the data set used to perform a case study on whether or not to implement an LPI based upon the methodology described in the preceding sections. Vehicular volumes were estimated using previously collected 24-hr tube counts and applying a ratio for each movement based on peak period turning movement counts at one real world intersection, SE 122nd and Division St in Portland, Oregon, USA. Pedestrian counts were estimated by combining available turning movement counts and pedestrian signal actuation data. It is assumed that each approach has two through lanes, one exclusive left turn movement lane and one exclusive right turn movement lane. It is also assumed that Right Turn on Red is not allowed in any direction (while this is not the norm, it may be the case where pedestrian safety is a concern). The following paragraphs outline steps taken for decision making.

Calculation of marginal increase in delay

<u>Step 1: Cycle length calculation for each hour</u>.

For this case study, Webster's equation (**Equation 7**) for finding optimal cycle length for a given hour is used. The total lost time is assumed to be 16 seconds (4 seconds per phase, E/W LT, E/W Through, N/S LT, N/S Through). A minimum cycle length of 60 seconds is assumed and the cycles are rounded up to closest multiple of 5. Cycle length for a simple LPI scenario where either the main street or cross street has an LPI phase is obtained by adding 4 seconds to the non-LPI cycle length. In the scenario where LPIs are provided for all directions, the cycle length is obtained by adding 8 seconds to the non-LPI cycle length.

$$Cycle\ Length = \frac{1.5 \times Total\ Lost\ Time + 5}{1 - Critical\ Flow\ Ratio}$$ **Equation 7**

<u>Step 2: Green time calculation</u>

The green time for each phase is calculated by distributing total usable green (Non-LPI cycle – total lost time) in proportion to the respective flow ratio. The green time for all three cases shown here remains the same because the LPI phase is equivalent to increasing lost time for vehicular phases, but does not change the original green required for vehicular phases.

<u>Step 3: Calculation of delay cost</u>

After obtaining the green times for each phase the vehicular delay is obtained using the uniform delay equation (**Equation 8**). The incremental delay could be used if the intersection degree of saturation, *X*, is approaching 0.8 or higher, but is not used in this example for sake of simplicity. The average delay is multiplied by the number of vehicles per hour to obtain the total vehicular delay for each of the three cases, namely non-LPI, LPI on one street, and LPI for both streets (LPI for a given street means that the LPI is offered for both crosswalks on that street). The marginal increase in delay for each hour is calculated by subtracting the hourly vehicular delay obtained for the LPI case from the vehicular delay obtained for the base non-LPI case.

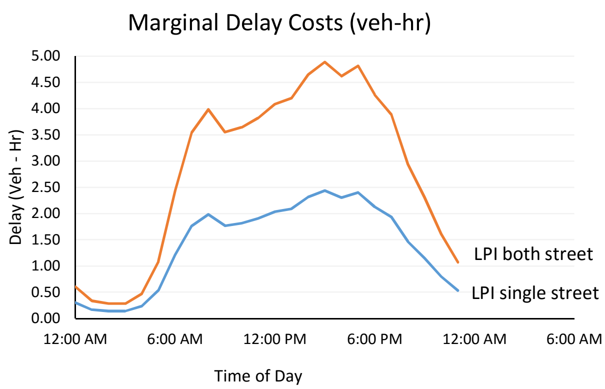
$$Unifo\quad Delay = d_1 = \frac{0.5C\left(1-\frac{g}{C}\right)^2}{1-\left[\min(1,X)\frac{g}{C}\right]}$$ **Equation 8**

Table 3: Case Study Data Set

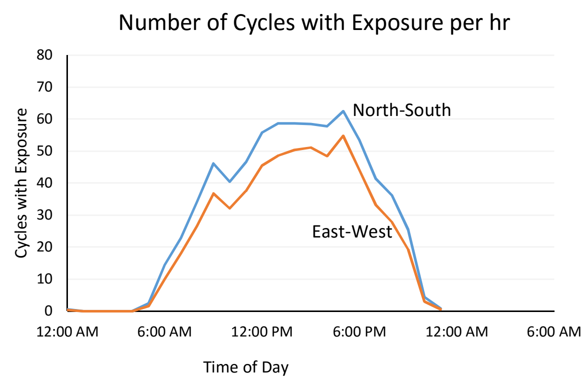
Time	NBL	NBT	NBR	NBPed	SBL	SBT	SBR	SBPed	EBL	EBT	EBR	EBPed	WBL	WBT	WBR	WBPed
12:00 AM	14	44	18	1	32	72	29	1	32	182	33	1	15	89	15	1
1:00 AM	6	20	8	0	18	39	16	0	17	98	18	0	10	60	10	0
2:00 AM	7	23	10	0	13	29	12	0	14	80	14	0	9	52	9	0
3:00 AM	7	23	9	0	11	24	10	0	12	66	12	0	12	72	12	0
4:00 AM	12	37	15	0	16	37	15	0	13	72	13	0	30	177	30	0
5:00 AM	27	86	36	2	34	76	31	4	25	141	25	3	70	412	71	3
6:00 AM	73	234	97	9	68	153	62	16	48	270	48	13	139	812	139	13
7:00 AM	159	513	212	12	115	259	105	22	84	472	84	18	119	700	120	18
8:00 AM	140	450	186	19	145	327	133	34	94	526	94	27	150	879	151	28
9:00 AM	115	370	153	29	123	276	112	53	100	565	101	42	133	781	134	43
10:00 AM	103	333	138	24	151	340	138	43	114	641	114	34	122	714	122	35
11:00 AM	103	331	137	28	171	386	157	51	122	688	123	40	120	701	120	41
12:00 PM	114	369	153	36	186	417	170	64	119	670	120	51	130	765	131	53
1:00 PM	111	358	148	40	178	401	163	72	127	717	128	58	140	823	141	59
2:00 PM	143	461	191	41	205	462	188	74	133	748	134	59	139	813	139	60
3:00 PM	149	480	199	42	246	554	226	75	125	703	126	60	143	838	144	61
4:00 PM	168	541	224	40	259	583	238	72	86	485	87	58	134	788	135	59
5:00 PM	163	525	217	48	258	581	237	85	107	603	108	68	137	805	138	70
6:00 PM	138	445	184	34	205	462	188	62	110	618	110	49	130	762	131	50
7:00 PM	99	319	132	24	172	386	157	43	132	742	133	35	118	693	119	35
8:00 PM	70	226	94	23	129	291	119	41	116	652	117	32	90	525	90	33
9:00 PM	56	181	75	17	96	215	88	30	93	521	93	24	77	454	78	25
10:00 PM	40	128	53	3	68	154	63	5	75	424	76	4	48	282	48	4
11:00 PM	26	85	35	1	45	102	41	1	48	273	49	1	37	215	37	1

Figure 2a, presents the marginal increase in delay over time of day for both single street LPI and LPI on both streets. Marginal increase in delay is multiplied by user delay cost, assumed to be $13/hour/vehicle, to obtain the total delay cost incurred by providing an LPI. The cumulative increase in delay per day for a single street LPI is found to be 33.55 veh-hr, equivalent to $436.15, and 67.38 veh-hr, equivalent of $875.94 for both streets. It should be noted for a simplistic assessment that if the assumed benefit of saving a single traffic conflict is valued at $27.30, as obtained in Table 1, then an LPI for a single street should be provided if the total traffic conflicts seen on that street are greater than 16 per day ($436.15/$27.30). LPIs for both streets should be provided if the number of conflicts seen is greater than 32 per day

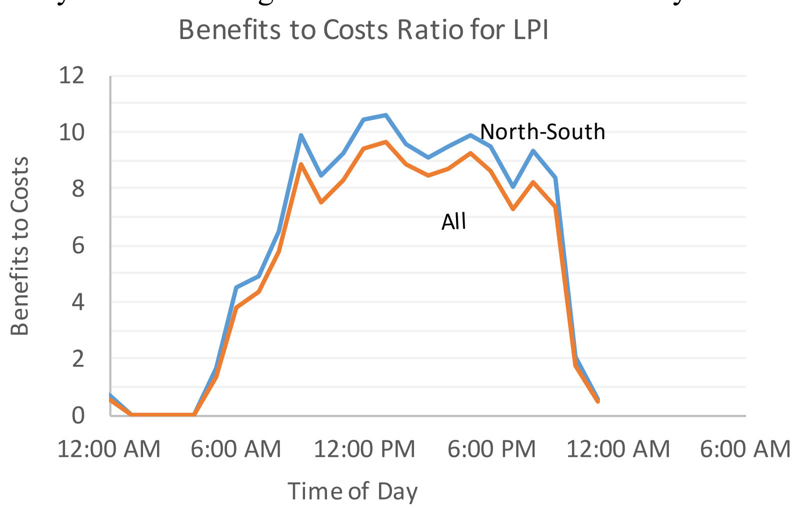
($875.94/$27.30). The next steps provide a more complex methodology for using hourly exposure rates calculated from pedestrian and right turn volumes.



a. Marginal delay costs of adding LPI



b. Number of cycles with exposure



c. Benefits to Costs Ratio of Providing LPI

Figure 2: Case study figures for benefits to costs ratio of providing LPI

Calculation of marginal improvement in safety

Step 4: Calculate exposure factor. **Equation 6** is used to calculate the exposure factor for each approach, providing the probability of exposure per cycle. This value is multiplied by the number of cycles per hour to obtain the number of cycles having the simultaneous presence of right turn vehicles and pedestrian at the onset of green. Figure 2b shows the distribution of the number of cycles with exposure over the time of day.

Step 5: Computation of Benefit Cost (BC) ratio

The total daily number of exposure cycles are obtained by summing up the hourly cycles for each direction, found to be 721 cycles in North-South direction and 590 cycles in the East-West direction. Assuming the cost of saving a cycle of exposure to be $4.92 as calculated in Table 2. the BC ratio can be obtained by dividing the dollar value of benefits of providing an LPI from the delay cost incurred by vehicular traffic by providing that LPI. In this case, the BC ratio for providing LPI on North-South street and both streets is estimated as 7 and 6.38 respectively. The BC ratio can be further increased if the LPI is provided only during specific hours of the day (the

LPI could also be provided by pushbutton only). Figure 2c presents the hourly BC ratio of providing North-South LPI and the hourly BC ratio of providing LPI both streets. For this location, the LPI is beneficial for all hours between 6 AM and 11 PM. With this methodology, the LPI could be applied only during hours where the BC ratio exceeded a desired threshold.

DISCUSSION AND CONCLUSIONS

This paper has developed a methodology to investigate the desirability of an LPI through the lens of a marginal safety BC ratio problem. Past literature was reviewed to highlight research germane to this solution in the area of LPIs, traffic conflict techniques, and the marginal cost/benefit framework. It was identified that although these techniques have been applied to various problems in the industry, they have not been applied to address the issue of an LPI in this form. The proposed methodology estimated pedestrian exposure using a Microsoft Excel operated agent based model. With exposure calculated, the cost savings of avoiding these conflicts can be calculated using survey data, or in this case, data from previous work. The costs can then be compared to the increased cost of delay incurred to vehicles due to use of an LPI on an hourly basis. A case study with sample data indicates that an LPI is cost effective for the scenario presented, but assumes the right turn is under capacity.

There are some signalized intersections that are pedestrian focused, and would be high priority to use an LPI regardless of the economic analysis. Others are vehicular focused, and may not need such an analysis to determine than an LPI would not be useful for a variety of reasons. It should be noted that given the high value attached to human life, an analysis such as this might come across as cold and calculating, however given the high priority historically given to vehicles at signalized intersections, this type of analysis may provide motivation for using this type of pedestrian focused safety measure at locations that fall far from the extremes described above.

It should be noted that while there are design treatments can be used to improve the safety of pedestrians (curb bulb outs, ped flags, etc.), there is little quantitative guidance for municipalities on when to implement an LPI. The methodology presented here can be used by cities to assess the suitability of a candidate location for LPI implementation in a such a manner, but there are still a number of questions and avenues for future research. The provision of LPIs by time-of-day may appeal to cities as a method to improve pedestrian safety while limiting user costs to certain time periods only, but may not be desirable because of user expectation issues. The framework for developing costs in this work was fairly robust, but in practice, the value of preventing a cost or conflict may be harder to judge given that many of these collisions are very low speed and result in only minor injuries. At intersections that are over capacity, a few additional seconds of lost time might cause the intersection to fail during certain time periods of the day, adding much more value to the additional delay incurred to vehicles. In the future, in addition to addressing these issues, this work could also be extended to other safety based options in the signal timing toolbox, such as the Barnes Dance, Split LPI, or the LBI (Leading Bike Interval).

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