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Vehicle and pedestrian safety impacts of signal timing optimization in a dense urban street network

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ABSTRACT

Intersection signal timing optimization is expected to affect both traffic mobility and safety. However, in safety impacts analysis, the existing studies mainly focus on estimating changes in vehicle crashes without addressing the influence of pedestrian related crashes. This study aims to simultaneously assess the overall impacts of vehicle and pedestrian crashes caused by signal timing optimization in dense urban street networks. An empirical Bayesian analysis method was introduced to estimate the safety impacts of intersection signal timing optimization in an urban street network in terms of vehicle-to-vehicle and vehicle-to-pedestrian crashes at intersections, as well as single and multiple vehicle crashes on street segments. A computational experiment was performed to apply the proposed method to the Chicago central business district that includes 875 signalized intersections and 2016 roadway segments. Results show that vehicle-to-vehicle and vehicle-to-pedestrian crashes at intersections are decreased in different crash severity levels and types, especially for angle and rear-end ones after signal timing optimization. Similar results are found for multi-vehicle rear-end crashes on street segments. These indicate that intersection signal timing optimization in dense urban street networks has a potential for improving traffic mobility, vehicle and pedestrian safety at intersections, and vehicle safety on street segments.

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1. Introduction

Every year, many crashes occur in the nation's highway network and a significant portion of them takes place in urban areas. Although the trend of fatal crashes in the United States has been decreasing due largely to safety programs in the context of engineering, enforcement, education, and emergency response, traffic safety still is a problem in the society. Owning to land scarcity, high project costs, and concerns of traffic disruption during the project construction, expanding the capacity of the urban street network is particularly challenging. Conversely, efficient utilization of urban areas' existing capacity has become the focus to potentially mitigate traffic congestion.

In the past several decades, significant progress has been made to develop new traffic stream models by accounting for the interdependency and connectivity of possible factors and their contribution to network modeling in different scales. Using more detailed approaches for characterizing the traffic flow, density, and speed relationships the accuracy of vehicle delay estimation could be improved to identify effective delay mitigation measures (Abbas et al., 2007; Mulandi et al., 2010; Sun et al., 2003). In addition, a number of research studies have developed pedestrian walking models to analyze the behaviors of pedestrians walking along sidewalks and crossing intersections (Antonini et al., 2006; Hoogendoorn and Bovy, 2004; Robin et al., 2009).

Recently, Roshandeh et al. (2014) developed a method for intersection signal timing optimization in an entire urban street network stemmed from the kinematic wave theory by simultaneously minimizing vehicle and pedestrian delays in each signal cycle over a 24 h period. A computational experiment revealed its strength for a wide range of practical applications, particularly due to its potential for addressing both vehicle and pedestrian delays in a holistic manner. Meanwhile, the impacts of this model on vehicle and pedestrian safety need to be evaluated. As such, the current study applies an empirical Bayesian (EB) before-after analysis method to investigate the effects consequences of traffic mobility improvements on vehicle-to-vehicle and vehicle-to-pedestrian crashes at intersections and vehicle crashes on street segments in dense urban street networks.

1.1. *Related work*

The impacts of traffic mobility and safety caused by altering the intersection traffic control in aspects of using signal coordination, green extension, and green time countdown devices, extending the cycle length of existing signals, increasing speed limits, and installing new signals have been studied since the 1970's (Moore and Lowrie, 1976; Short et al., 1982; Zeeger and Deen, 1978). Pant et al. (2005) found the advantages of using green extension at closely spaced high-speed intersections in terms of crash reduction. In particular, it was reported that a 3 s green extension could reduce vehicle conflicts by 37 percent during the a.m. peak period. Lum and Halim (2006) found that installing green signal countdown devices for driver's warning could reduce red-light running violations by 65 percent and thus could potentially reduce vehicle crashes. A Federal Highway Administration (FHWA) study conducted by Sabra et al. (2010) revealed that cycle length had the most significant impact on the total number of crashes at intersections and further noted that adopting a longer cycle length could reduce all types of movement conflicts. Pirdavani et al. (2010) evaluated safety conditions at 4-leg signalized intersections and found that increasing speed limits had detrimental impacts on safety. In another recent study, Stevanovic et al. (2013) analyzed the impacts of signal timing optimization on crash risks using a 12-intersection corridor and concluded that the number of movement conflicts could reduce by 7 percent after the treatment. However, pedestrian safety was not considered.

Some researchers have developed statistical models to explicitly analyze the correlation between crash occurrences and signal timing design features. Chin and Quddus (2003) introduced a random effect negative binomial model to analyze the relationship between crash occurrences and the geometric, traffic and control characteristics of signalized intersections in Singapore and concluded that traffic volumes on intersection approaches and the number of phases used for each signal cycle were among the most significant variables affecting the crash frequency. Guo et al. (2010) developed Poisson and negative binomial Bayesian statistical approaches to model the crash data from 170 signalized intersections in Florida and confirmed that the intersection size, and traffic volumes by turning movement, and coordination of signal plans for adjacent intersections had significant impacts on intersection safety. Agbelie and Roshandeh (2015) applied a random-parameter negative binomial model and found that the increase of the number of signal phases and approach lanes would yield the increase of the crash frequency at the majority of the intersections. Behnood et al. (2014) developed a latent class multinomial logit severity model and identified that traffic signal controls would decrease minor injury (i.e., crashes not ended up with fatality) and property damage only (PDO) for female drivers younger than 31 years old and alcohol-impaired.

1.2. *Aim*

Traffic mobility and safety are viewed to be correlated with each other. The improvement of mobility at an isolated intersection or on a roadway segment may or may not positively affect safety performance. The existing methods and models dealing with various aspects of signal timing designs such as signal coordination, green extension, and longer cycle length, are effective in terms of improving the mobility of isolated intersections, major corridors, and urban street networks. However, the interaction of mobility and safety performance, which can account for both vehicles and pedestrians in a large urban street network, has not been well studied. The current paper endeavors to fill this gap and apply an EB method to assess the overall safety impacts of signal timing optimization (i.e., treatment) in an urban street network.

The remainder of this paper is organized as follows: Section 1 elaborates on the proposed methodology, including a brief discussion on the method for urban street network signal timing optimization and the EB method for safety impacts analysis. Section 2 applies the proposed methodology in a computational study. Finally, Section 3 presents a study summary and draws conclusions.

2. Methodology

2.1. Method for urban street network signal timing optimization

2.1.1. The proposed method

As presented in Roshandeh et al. (2014), the method for urban street network signal timing optimization was developed using the kinematic wave theory. For an isolated intersection, the wave speeds (i.e., the traffic wave moving upstream through traffic as vehicles approaching at a queue slow down abruptly), maximum queue lengths, and vehicle delays for undersaturated (i.e., queue length would discharge in one cycle) and oversaturated (i.e., there would be residual queue length remaining from the previous cycle) traffic conditions can be estimated. Without changing the cycle length and signal coordination, the existing signal timing plans for the network are optimized to achieve the lowest level of weighed total of vehicle and pedestrian delays per cycle.

For the oversaturated traffic condition, vehicle delays per cycle are calculated by a function of the queue length before reaching traffic hump, minimum and maximum queue lengths, time of minimum and maximum queue lengths, and red interval. In order to estimate the pedestrian delays, two methods were used: the Highway Capacity Manual 2010 (HCM 2010) method (TRB, 2010) and the Levinson method (Li et al., 2012). The HCM 2010 method estimates pedestrian delays per cycle by a function of green, yellow, and red internals and effective green time for pedestrians to cross an intersection. Whereas the Levinson method calculates pedestrian delays per cycle by a function of the number of pedestrians crossing in the green interval in each phase, number of pedestrians waiting in the red interval in each phase, and red interval of each phase. The Levinson method is found to produce more realistic results (Roshandeh et al., 2014).

For calculating the weighed total of vehicle and pedestrian delays per cycle, the relative weights assigned to vehicle delays per cycle can be varied from 0 to 100 percent, representing the two extreme cases of emphasizing vehicle delays only and pedestrian delays only. Practically, a weighting factor between the two extreme values can be selected for single or multiple intersections along a major corridor or within a subarea of the network. Additionally, for each intersection, the relative weights between vehicle and pedestrian delays per cycle can be altered over different time periods of the day. The signal timing optimization model that seeks to minimize the weighed total of vehicle and pedestrian delays per cycle is formulated to satisfy a constraint concerning to minimize time loss due to the vehicle stoppage at the downstream intersection. By this way, a relationship can be made between the every two successive intersections to account for the interconnectivity between intersections within the study area.

2.1.2. The iterative computation process

The proposed method for the signal timing optimization is integrated into the metropolitan area travel demand forecasting model that conducts traffic assignments using the 24 h regional origin-destination (O/D) trip tables. The high fidelity simulation-based travel demand model is capable of updating the traffic volumes at each roadway segment on a second-by-second basis. With the traffic volumes at each intersection and the application of the proposed optimization model new signal timing plans can be developed for a.m. peak, p.m. peak, and the rest of the day time periods.

2.2. The EB method for safety impacts analysis

Fig. 1 illustrates the proposed EB method for assessing the safety impacts in the urban street network caused by the signal timing optimization. It begins with collecting multi-year observed field data in terms of vehicle-to-vehicle and vehicle-to-pedestrian crashes at individual urban intersections and vehicle-to-vehicle crashes on urban street segments, as well as traffic volumes at intersections and on street segments. All the periods are before the treatment (i.e., signal timing optimization). Then, it identifies appropriate safety performance functions (SPFs) to predict vehicle-to-vehicle and vehicle-to-pedestrian crashes at urban intersections and on street segments. In order to obtain the traffic volumes on each roadway segment for the after treatment, the regional travel demand forecasting model is executed using the updated signal timing plans. The field observed (before the treatment period) and simulated (after the treatment period) traffic volumes along with the appropriate SPFs are used to estimate the crash frequencies at each urban intersection and street segment over the multi-year period before and after treatment. In the next step, effectiveness of treatment in terms of safety improvement is assessed followed by conducting the statistical tests to ensure that the significance of the results is satisfied (TRB, 2010). The key analytical steps are explained in details in the later part of this section.

SPFs is used for predicting crashes at urban intersections and on street segments. As a key step of applying the proposed EB method to safety impacts analysis, SPFs need to be utilized to predict vehicle-to-vehicle and vehicle-to-pedestrian crashes at intersections and vehicle-to-vehicle crashes on street segments before and after treatment. Historically, Poisson and negative binomial modeling techniques have been used for SPFs calibration. The Poisson regression model assumes that the variance of crash frequencies in a given time period equals to the mean. Conversely, this assumption might not always be supported by the dataset. To overcome this limitation, the negative binomial modeling technique is typically used by adding a quadratic term to the variance in the negative binomial distribution to capture the extra Poisson variance due to variables that are not included in the model (Jovanis and Chang, 1986). Furthermore, the Poisson or negative binomial model may exhibit null crash occurrence. Zero-inflated Poisson, zero-inflated negative binomial

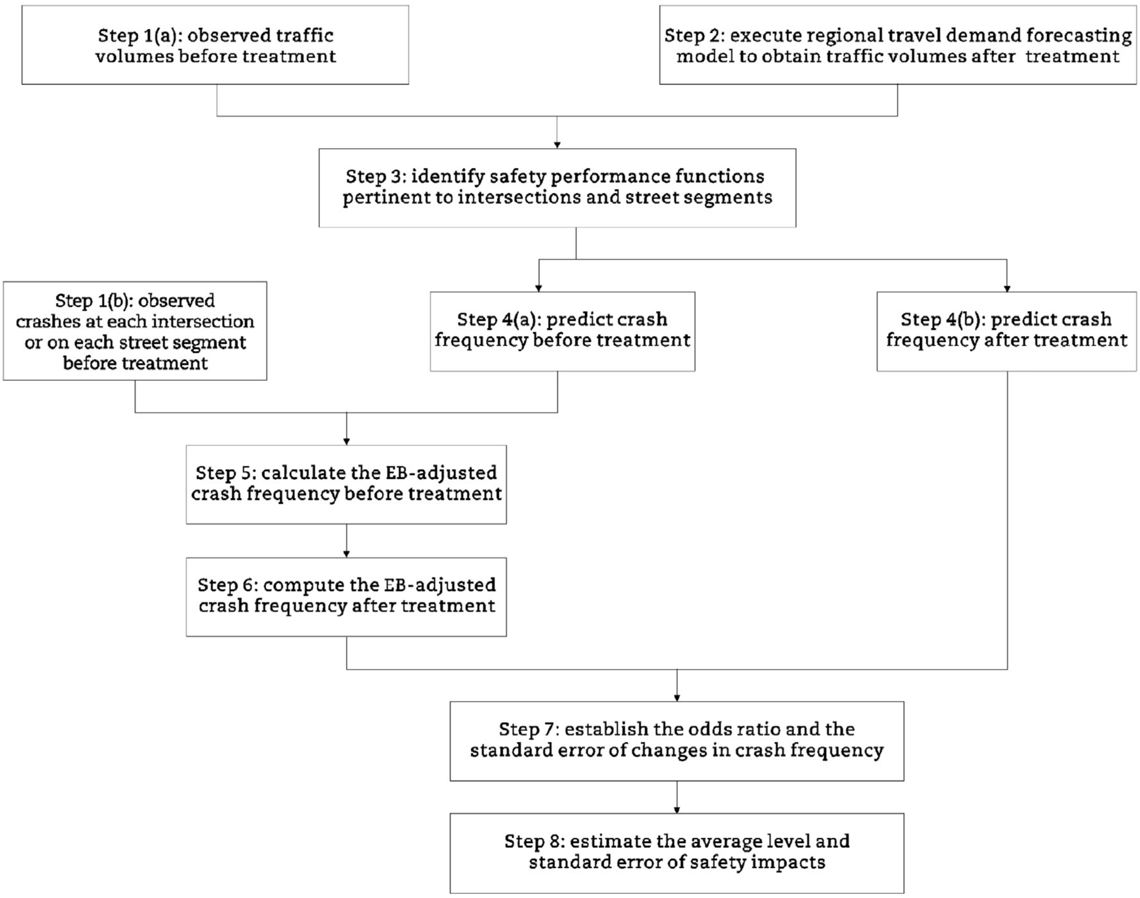

Fig. 1 – The proposed EB method for safety impacts analysis.

models, and zero-state Markov switching count-data models have been developed to account for the zero-crash cases (Long, 1997; Lord et al., 2005, 2007; Li et al., 2008; Malyshkina and Mannering, 2010). The following briefly describes SPFs for predicting fatal, injury, and PDO crashes in an urban street network documented in the 2010 Highway Safety Manual (HSM) (AASHTO, 2010).

$$CF_{v-to-v,int} = e^{\left[\alpha_0+\alpha_1\ln\left(AADT_{major}\right)+\alpha_2\ln\left(AADT_{minor}\right)\right]} \tag{1}$$

where $CF_{v-to-v,int}$ is the vehicle-to-vehicle crash frequency at an urban intersection, $AADT_{major}$ is the annual average daily traffic (AADT) on the urban intersection major street, $AADT_{minor}$ is AADT on the urban intersection minor street, α_0, α_1, and α_2 are model coefficients (Table 1), respectively.

For predicting urban intersection vehicle-to-pedestrian crashes, the SPFs is as follow

$$CF_{v-to-p,int} = e^{\left[\alpha_0+\alpha_1\ln(AADT_{total})+\alpha_2\ln\left(AADT_{minor}/AADT_{major}\right)+\alpha_3\ln\left(N_{ped}\right)+\alpha_4 C\right]} \tag{2}$$

where $CF_{v-to-p,int}$ is the vehicle-to-pedestrian crash frequency for an urban signalized intersection, $AADT_{total}$ is the daily total of vehicle traffic at the urban intersections, N_{ped} is the daily total number of pedestrians crossing all urban intersection approaches, C is a constant value taken as 700 for a signalized intersection experiencing a middle level of pedestrian traffic and 1500 for a medium to high level of pedestrian traffic, α_3, and α_4 are model coefficients (Table 1), respectively. The input data for pedestrian counts sources from a study of pedestrian traffic conducted in Chicago Loop area during 2007 (TranSystems and TransInfo LLC, 2008). The study includes over three million pedestrians counted at 510 locations, among which 335 are located in the Loop area. Pedestrians walking in either direction on sidewalks were counted for 10 h from 7:45 a.m. to 5:45 p.m.

For predicting urban street segment vehicle crashes, the SPFs is of the following general form

$$CF_{v-to-v,seg} = e^{\left[\alpha_0+\alpha_1\ln(AADT)+\alpha_2\ln(L)\right]} \tag{3}$$

where $CF_{v-to-v,seg}$ is the vehicle-to-vehicle crash frequency for an urban street segment, AADT is AADT on the urban street segment.

Table 1 summarizes coefficients of SPFs based on the HSM (AASHTO, 2010) that are employed for the current study. As can be seen in the summary table, negative binomial approach is calibrated for all models. For multi-vehicle crash predictions, the model coefficients of AADT on intersection major street approaches and street segments are greater than one. For single vehicle crash and vehicle-to-pedestrian crash predictions, the model coefficients of all other predictors are smaller than or equal to one. These indicate

Table 1 – Coefficients of SPFs for urban intersections and roadway segments (AASHTO, 2010).

Urban facility type	Crash type		Vehicle-to-vehicle crash								Vehicle-to-pedestrian crash					
			Single vehicle				Multiple vehicles									
	Crash severity	Model type	α_0	α_1	α_2	k	α_0	α_1	α_2	k	α_0	α_1	α_2	α_3	α_4	k
4-Leg signalized intersection	Fatal and injury	Negative binomial					−13.14	1.18	0.22	0.33						
	PDO	Negative binomial					−11.02	1.02	0.24	0.44						
	Total	Negative binomial					−10.99	1.07	0.23	0.39	−9.53	0.40	0.26	0.45	0.04	0.24
Street segment	Fatal and injury	Negative binomial	−7.37	0.61	1.00	0.54	−12.08	1.25	1.00	0.99						
	PDO	Negative binomial	−8.50	0.84	1.00	0.97	−12.53	1.38	1.00	1.08						

Table 2 – Crash modification factors for adjusting crash predictions.

Urban facility type		Design and traffic control feature	Crash modification factor	Source
4-Leg signalized intersection	Vehicle-to-vehicle crashes	Approaches with left-turn lanes	0.81	AASHTO (2010)
		Approaches with right-turn lanes	0.92	
		Approaches with right-turn prohibitions	0.96	
		Protected left-turn phasing	0.94	
		Lighting at intersection	0.91	
		Red-light running photo enforcement	0.86–0.98	Lee (2011)
	Vehicle-to-pedestrian crashes	1–2 bus stops within 1000 ft	2.78	AASHTO (2010)
		Any school within 1000 ft	1.35	
		1–8 alcohol sales within 1000 ft	1.12	
Street segment	Vehicle-to-vehicle crashes	Median width	1.01	Harkey et al. (2008)
		On street parking	$1 + p_{pk}(f_{pk}-1.0)$	Bonneson et al. (2005)
		Street-side fixed objects	$f_{offset}D_{fo}p_{fo} + (1.0-p_{fo})$	Zegeer and Cynecki (1984)

Note: p_{pk} is the proportion of curb length with on-street parking, $p_{pk} = 0.5\ L_{pk}/L$, L_{pk} is the sum of curb length with on-street parking for both sides of the streets combined, L is the length of street segment, f_{pk} is a factor depending upon type of parking (parallel, or angle) and land use (commercial or institutional), f_{offset} is fixed-object offset factor, $f_{offset} = 0.0044–0.2320$, D_{fo} is the fixed object density, p_{fo} is the proportion of fixed-object crashes out of total crashes.

that AADTs on the intersection major approaches and street segments are the most influential towards the potential vehicle crash. Except for the SPFs predicting multi-vehicle PDO crashes on urban street segments, the overdispersion factors for all other SPFs are lower than one, ranging from 0.24 to 0.99.

When applying the SPFs to predicate the crash frequency at a specific urban intersection or on a street segment, a crash modification factor (CMF) may need to be employed to modify the SPFs predicted crash frequency to account for the impacts of any geometric design characteristics or traffic control features of the study site that differs from the base condition assumed by the SPFs. The value of CMF might be greater than, or equal to, or lower than 1.0 if the aforementioned impacts are associated with a higher, or equivalent, or lower level of crash frequency compared with the base condition, respectively.

For a typical urban 4-leg signalized intersection, the frequency of vehicle-to-vehicle crashes predicted by SPFs needs to be adjusted using the CMFs accounting for the number of approaches with left-turn and right-turn lanes, protected phases for left-turn movements, right-turn prohibition, lighting installation, and red-light running photo enforcement. Furthermore, the frequency of vehicle-to-pedestrian crashes at an intersection may also need to be adjusted using CMFs pertinent to the existence of bus stops, schools, and liquor stores adjacent to the intersections that could potentially increase the crashes. Similarly, the factors that could affect single vehicle and multiple vehicle crashes on the urban street segment include on-street parking, median width, and roadside fixed objects for motorized and non-motorized guidance. Table 2 presents the CMFs used in this study.

2.2.1. *Safety impacts of intersection signal timing optimization in an urban street network*

In order to assess the effectiveness of treatment (i.e., intersection signal timing optimization) on safety performance in an urban street network, it is required to estimate crash frequencies at urban intersections and on street segments after signal timing optimization under two circumstances: i) using the redistributed traffic volumes obtained from simulation-based regional traffic assignments and applying the appropriate SPFs; ii) assuming that treatment had not been implemented and calculating the EB-adjusted crash frequencies after the treatment period. Dealing with the first circumstance is straightforward and it can be accomplished using the simulated traffic volumes and corresponding SPFs. However, the second circumstance needs to be handled by first calculating the EB-adjusted crash frequencies for the previous treatment period and further adjusting the EB values by accounting for changes in traffic volumes between later treatment period (simulated) and previous treatment period (observed).

For computing the EB-adjusted crash frequencies before treatment, it is denoted that $EB_{int,i,B}$ and $EB_{seg,i,B}$ are EB-adjusted multi-year crash frequencies before treatment at urban intersection or on street segment i, $w_{int,i}$, and $w_{seg,i}$ are weighting factors between SPFs predicted and field observed multi-year crash frequencies at urban intersection or on street segment i, $CF_{int,i,P,B}$, and $CF_{seg,i,P,B}$ are SPFs predicted multi-year crash frequencies before treatment with further adjustments according to the crash modification factors at urban intersection or on street segment i, $CF_{int,i,O,B}$, and $CF_{seg,i,O,B}$ are field observed multi-year crash frequencies before treatment at urban intersection or on street segment i. The EB-adjusted multi-year crash frequencies at urban intersection or on street segment i before treatment corrected for regression-to-mean biases is defined as below

$$EB_{int,i,B} = w_{int,i}CF_{int,i,P,B} + (1 - w_{int,i})CF_{int,i,O,B} \tag{4}$$

$$EB_{seg,i,B} = w_{seg,i}CF_{seg,i,P,B} + (1 - w_{seg,i})CF_{seg,i,O,B} \tag{5}$$

Further denoting that k_{int}, and k_{seg} are overdispersion parameters of the crash frequencies at urban intersections per year or on urban street segments per mile per year, $CF_{int,i,P,B,t}$, and $CF_{seg,i,P,B,t}$ are predicted crash frequencies before treatment at urban intersection or on street segment i in year (t), $L_{seg,i,B}$ is the length of the urban street segment i before treatment, $i = 1, 2, \cdots, n$, and $t = 1, 2, \cdots, T$. The overdispersion parameter determined in the process of SPFs' calibration is used to calculate the weighting factor ($w_{int,i}$ or $w_{seg,i}$) for a given urban intersection or a street segment as specified.

$$w_{int,i} = \frac{1}{1 + k_{int}T\sum_{t=1}^{T}CF_{int,i,P,B,t}} \tag{6}$$

$$w_{seg,i} = \frac{1}{1 + k_{seg}TL_{seg,i,B}\sum_{t=1}^{T}CF_{seg,i,P,B,t}} \tag{7}$$

For computing the EB-adjusted crash frequencies after the treatment, it is denoted that $EB_{int,i,B}$ and $EB_{seg,i,B}$ are EB-adjusted multi-year crash frequencies before treatment at urban intersections or on street segment i, $EB_{int,i,A}$, and $EB_{seg,i,A}$ are EB-adjusted multi-year crash frequencies after treatment at urban intersection or on street segment i, $AADT_{i,major,b}$, and $AADT_{i,minor,b}$, $AADT_{i,major,a}$, and $AADT_{i,minor,a}$ are AADTs on major and minor approaches of urban intersection i before and after treatment, respectively, $AADT_{i,b}$ and $AADT_{i,a}$ are AADTs on urban street segment i before and after treatment, respectively, $L_{seg,i,B}$ and $L_{seg,i,A}$ are lengths of urban street segment before and after treatment, respectively. The EB adjusted crash frequencies at urban intersection or on street segment i before treatment can be used to establish EB-adjusted crash frequencies after treatment as follows

$$EB_{int,i,A} = EB_{int,i,B}\frac{\sum_{a=1}^{A}(AADT_{i,major,a} + AADT_{i,minor,a})}{\sum_{b=1}^{B}(AADT_{i,major,b} + AADT_{i,minor,b})} \tag{8}$$

$$EB_{seg,i,A} = EB_{seg,i,B}\frac{\sum_{a=1}^{A}AADT_{i,a}}{\sum_{b=1}^{B}AADT_{i,b}}\frac{L_{seg,i,A}}{L_{seg,i,B}} \tag{9}$$

where a is a specific year for the after treatment period, b is a specific year for the before treatment period, A is the total number of years in the after treatment period, B is the total number of years in the before treatment period.

For estimating the treatment effectiveness, it is denoted that $CF_{int,i,P,A}$ and $CF_{seg,i,P,A}$ are predicted multi-year crash frequencies after treatment at urban intersection or on street segment i, $EB_{int,i,A}$, and $EB_{seg,i,A}$ are EB-adjusted multi-year crash frequencies after treatment at urban intersection or on street segment i, $Var(EB_{int,A})$, and $Var(EB_{seg,A})$ are variances of EB-adjusted multi-year crash frequencies after treatment at all urban intersections and on street segments, respectively. The odds ratios of safety impacts of signal timing optimization at all urban intersections, OR_{int}, or on all street segments, OR_{seg}, are computed as below

$$OR_{int} = \frac{\frac{\sum_{i=1}^{N} CF_{int,i,P,A}}{\sum_{i=1}^{N} EB_{int,i,A}}}{1 + \frac{Var(EB_{int,A})}{\left(\sum_{i=1}^{N} EB_{int,i,A}\right)^2}} \tag{10}$$

$$OR_{seg} = \frac{\frac{\sum_{i=1}^{N} CF_{seg,i,P,A}}{\sum_{i=1}^{N} EB_{seg,i,A}}}{1 + \frac{Var(EB_{seg,A})}{\left(\sum_{i=1}^{N} EB_{seg,i,A}\right)^2}} \tag{11}$$

Hence, the average levels of safety impacts of signal timing optimization as the percentage change in crash frequencies associated with all urban intersections, Eff_{int}, or all street segments, Eff_{seg}, are computed as below

$$Eff_{int} = 100 \times (1 - OR_{int}) \tag{12}$$

$$Eff_{seg} = 100 \times (1 - OR_{seg}) \tag{13}$$

The variances of safety impacts of signal timing optimization are determined as follow

$$Var(Eff_{int}) = \frac{\left(\frac{\sum_{i=1}^{N} CF_{int,i,P,A}}{\sum_{i=1}^{N} EB_{int,i,A}}\right)^2 \left[\frac{1}{\left(\sum_{i=1}^{N} CF_{int,i,A}\right)^2} + \frac{Var(EB_{int,A})}{\left(\sum_{i=1}^{N} EB_{int,i,A}\right)^2}\right]}{1 + \frac{Var(EB_{int,A})}{\left(\sum_{i=1}^{N} EB_{int,i,A}\right)^2}} \tag{14}$$

$$Var\left(Eff_{seg}\right) = \frac{\left(\frac{\sum_{i=1}^{N} CF_{seg,i,P,A}}{\sum_{i=1}^{N} EB_{seg,i,A}}\right)^2 \left[\frac{1}{\left(\sum_{i=1}^{N} CF_{seg,i,A}\right)^2} + \frac{Var(EB_{seg,A})}{\left(\sum_{i=1}^{N} EB_{seg,i,A}\right)^2}\right]}{1 + \frac{Var(EB_{seg,A})}{\left(\sum_{i=1}^{N} EB_{seg,i,A}\right)^2}} \tag{15}$$

The statistical significances of safety impacts of signal timing optimization can be tested as below

$$Test_{int} = \frac{Eff_{int}}{100 \times \sqrt{Var(Eff_{int})}} \tag{16}$$

$$Test_{seg} = \frac{Eff_{seg}}{100 \times \sqrt{Var\left(Eff_{seg}\right)}} \tag{17}$$

If the absolute value of $Test_{int}$ or $Test_{seg}$ is not lower than 1.7, it can be concluded that the safety impacts are statistically significant at a confidence level of approximately 90 percent. An absolute value of 2.0 or higher indicates a confidence level of at least 95 percent. The average level and variance of safety impacts, as well as the related statistical significance caused by intersection signal timing optimization can be separately assessed at all urban intersections and on street segments by crash severity level and crash type.

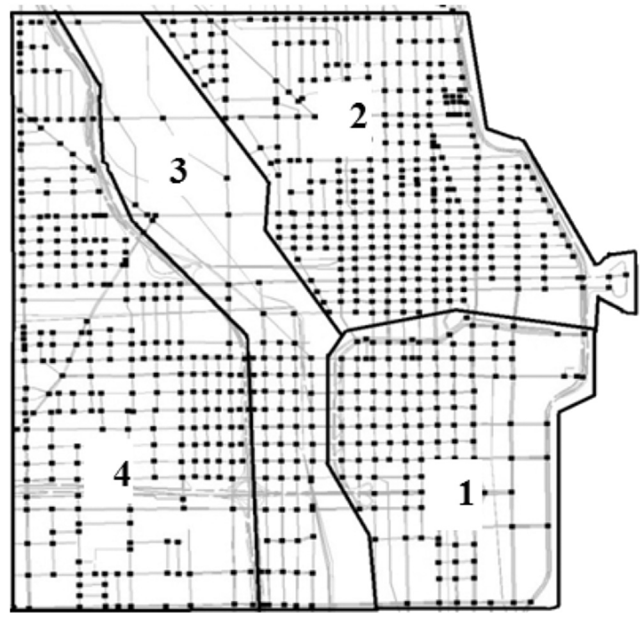

Fig. 2 – Illustration of the urban street network for methodology application.

2.2.2. *Target crash types affected by signal timing optimization*

Although signal timing optimization could potentially influence fatal, injury, and PDO crashes at urban intersections and on street segments, it may not necessarily affect all types of crashes. For urban intersections, listed in the following are four types of crashes that are more likely to be affected by signal timing optimization: i) angle; ii) rear-end; iii) sideswipe with one of more vehicles in the same or opposite directions; iv) head-on crashes. Since urban street segments interconnect intersection approaches, the aforementioned types crashes on street segments are also likely to be influenced by the treatment. In addition, the single-vehicle fixed-object crash type at urban street segments might be correlated with adjustments of intersection signal timing plans. As such, the above five types of crashes (angle, rear-end, sideswipe, head-on, and single vehicle fixed-object) are treated as target crash types for safety impacts analysis in the current study. The proportions of them might vary from urban intersections and street segments in general, change by intersections or street segments, and also fluctuate over different years at the same intersection or on the same street segment. Thus, the safety impacts of the treatment in an urban street network can be assessed in terms of changes in fatal, injury, and PDO crashes for the target crash types.

3. Methodology application

The urban street network in the Chicago central business district (CBD) was selected for signal timing optimization and further evaluating the safety changes at intersections and on

Table 3 – Distribution of vehicle crashes by severity level and type.

Facility type	Crash distribution		2004	2005	2006	2007	2008	2009	2010	Average	Percentage (%)
Intersection	Severity level	Fatal	9	9	4	8	2	2	0	5	0
		Injury A	345	289	263	210	197	245	220	253	2
		Injuries B, C	5082	4508	4315	3379	2902	2669	2390	3606	26
		PDO	11,739	10,431	9596	8406	8778	11,229	11,088	10,181	72
		Total	17,175	15,237	14,178	12,003	11,879	14,145	13,698	14,045	
	Type	Angle	5070	4436	4187	3290	3038	2883	3024	3704	26
		Head-on	192	176	150	105	141	185	186	162	1
		Rear-end	3990	3397	3127	2591	3236	4334	4486	3594	26
		Sideswipe	2141	1814	1817	1505	1547	1909	2127	1837	13
		Other	5782	5414	4897	4512	3917	4834	3875	4747	34
		Total	17,175	15,237	14,178	12,003	11,879	14,145	13,698	14,045	
Street segment	Severity level	Fatal	0	3	1	1	0	4	4	2	0
		Injury A	32	40	114	25	38	31	34	45	1
		Injuries B, C	253	251	230	295	306	263	327	275	6
		PDO	3947	3964	3853	4186	3802	3877	4165	3971	93
		Total	4232	4258	4198	4507	4146	4175	4530	4292	
	Type	Angle	212	179	167	51	135	123	71	134	3
		Head-on	27	18	12	12	25	23	11	18	0
		Rear-end	634	455	465	771	481	458	717	569	13
		Sideswipe	265	305	323	430	269	280	447	331	8
		Fixed object	120	149	133	301	212	219	336	210	5
		Other	2974	3152	3098	2942	3024	3072	2948	3030	71
		Total	4232	4258	4198	4507	4146	4175	4530	4292	

roadway segments. As shown in Fig. 2, the CBD consists of four areas. Area 1 is often called as Chicago Loop bounded by Wacker Drive along the Chicago River, Roosevelt Road, and Lakeshore Drive; area 2 is in the north of Loop bounded by the Chicago River, North Avenue, and Lakeshore Drive; area 3 is in the immediate west of Loop bounded by I-90/94, the Chicago River, North Avenue, and Roosevelt Road; and area 4 is located in the west of Loop bounded by Ashland Avenue, I-90/94, North Avenue, and Roosevelt Road. There are 140, 388, 77, and 270 major signalized intersections in the respective areas and 2016 urban street segments in the entire study area.

3.1. *Data collection and processing*

Detailed data was collected on vehicle crashes and traffic volumes associated with intersections and street segments of the study area over the period of 2004–2010. Table 3 presents the temporal distribution of vehicle crashes by crash severity level and type. For intersections, the total number of crashes fluctuated from 2004 to 2010 with the highest number of crashes recorded in 2004 and the lowest in 2008. Specifically, about 2 percent are fatal and injury type A, 26 percent are injury types B and C, and 72 percent are PDO crashes. More than 50 percent of crashes at intersections are angle and rear-end and these two types of crashes roughly take the equal share, approximately 13 percent are sideswipe, over one percent are head-on, and the remaining 34 percent are other types of crashes.

For street segments, the total number of crashes also varied over the period of 2004–2010 with the highest number of crashes recorded in 2010 and the lowest in 2008. For single and multiple vehicle crashes on street segments classified by crash severity level, about one percent are fatal and injury type A, 6 percent are injury types B and C, and 93 percent are PDO crashes. For vehicle crashes on street segments classified by type, more than 3 percent are angle, 13 percent are rear-end, approximately 8 percent are sideswipe, less than one percent are head-on, 5 percent are fixed-object, and approximately 71 percent are other types of crashes.

In this study, most of the intersections are 4-leg and each approach maintains two through movement lanes in each direction. The AADT ranges from 5149 to 73,938 vehicles daily with an average of 13,880 vehicles per day.

3.2. *Safety impacts at urban intersections after signal timing optimization*

Table 4 summarizes the average level, standard deviation, and statistical significance of safety impacts in terms of reductions in crashes at urban intersections. The positive value obtained for the average level of safety impacts indicates that a crash reduction is reached after treatment. The estimated results reveal that, for all weighting scenarios used for calculating vehicle and pedestrian delays in signal timing optimization, vehicle-to-vehicle and vehicle-to-pedestrian crashes at intersections have reduced for all crash severity levels and target crash types. The crash reductions remain fairly stable for different weighting scenarios. For vehicle-to-vehicle crashes, a higher extent of crash reductions is achieved for PDO crashes compared with those of fatal and injury crashes. For fatal and injury crashes combined, reductions are more significant for angle and rear-end crashes at over 12 percent for each target crash type, followed by sideswipe crashes at slightly over 10 percent and head-on crashes at nearly 10 percent. For PDO crashes, a similar reduction trend is discovered. Specifically, crash reductions are more significant for angle and rear-end crashes, at approximately 50–60 percent for each target crash type, followed by sideswipe crashes at over 35 percent, and head-on crashes

Table 4 – Safety impacts of signal timing optimization at intersections in a dense urban street network.

Relative weights of vehicle vs. pedestrian delays (w)	Vehicle-to-vehicle crashes								Vehicle-to-pedestrian crashes
	Fatal and injury				PDO				Fatal and injury
	Angle	Head-on	Rear-end	Sideswipe	Angle	Head-on	Rear-end	Sideswipe	
	Eff_{int} (%)								
100	8.38	3.86	7.89	4.80	57.14	19.32	45.61	30.81	11.99
90	12.84	9.77	12.68	10.07	59.41	25.07	48.84	35.16	17.80
80	12.65	9.89	12.48	9.81	59.38	25.37	48.84	35.11	17.98
70	12.66	9.74	12.54	10.07	59.36	25.15	48.82	35.23	17.90
60	12.66	9.74	12.54	10.08	59.36	25.14	48.82	35.24	17.89
50	12.58	9.65	12.44	9.97	59.32	25.07	48.76	35.16	17.80
40	12.68	9.77	12.55	10.08	59.37	25.18	48.83	35.24	17.93
30	12.54	9.63	12.42	9.95	59.31	25.05	48.75	35.15	17.78
20	12.49	9.58	12.36	9.89	59.29	25.02	48.72	35.11	17.74
10	12.16	9.24	12.00	9.46	59.14	24.76	48.52	34.81	17.51
w	$100 \times \sqrt{Var(Eff_{int})}$(%)								
100	4.17	5.01	3.16	3.04	1.94	4.29	1.85	2.21	2.60
90	3.96	4.72	2.99	2.87	1.84	4.01	1.75	2.07	2.44
80	3.97	4.71	3.00	2.88	1.84	4.00	1.75	2.08	2.43
70	3.97	4.71	3.00	2.87	1.84	4.00	1.75	2.07	2.44
60	3.97	4.71	2.99	2.86	1.84	4.00	1.75	2.07	2.44
50	3.97	4.71	3.00	2.87	1.84	4.01	1.75	2.07	2.44
40	3.96	4.72	3.00	2.87	1.84	4.00	1.75	2.07	2.43
30	3.97	4.72	3.00	2.87	1.84	4.01	1.75	2.07	2.44
20	3.98	4.72	3.00	2.88	1.84	4.01	1.75	2.08	2.44
10	3.99	4.74	3.02	2.88	1.85	4.03	1.76	2.08	2.45
w	Statistical significance of safety impacts [Abs ($Test_{int}$)]								
100	2.01	0.77	2.50	1.58	29.42	4.50	24.60	13.97	4.61
90	3.24	2.07	4.24	3.51	32.30	6.25	27.95	16.95	7.30
80	3.19	2.10	4.16	3.41	32.27	6.35	27.96	16.92	7.39
70	3.19	2.07	4.18	3.51	32.24	6.28	27.93	17.01	7.35
60	3.19	2.07	4.19	3.52	32.24	6.28	27.93	17.01	7.34
50	3.17	2.05	4.15	3.47	32.19	6.25	27.86	16.95	7.30
40	3.20	2.07	4.19	3.51	32.26	6.29	27.94	17.01	7.37
30	3.16	2.04	4.14	3.47	32.17	6.25	27.86	16.95	7.29
20	3.14	2.03	4.12	3.44	32.14	6.24	27.82	16.92	7.27
10	3.05	1.95	3.98	3.28	31.94	6.15	27.60	16.70	7.16

at about 25 percent. For vehicle-to-pedestrian crashes, reductions in fatal and injury crashes are around 18 percent.

The standard errors of safety impacts of all crash severity levels and target crash types are between 2 and 5 percent. Except for vehicle-to-vehicle crashes corresponding to fatal and injury severity levels and sideswipe type for the scenario of assigning 100 percent weight to vehicle delays as the basis of intersection signal timing optimization, the test statistics show that intersection safety improvements for all weighting scenarios are statistically significant at the 95 percent confidence level.

3.3. *Safety impacts on urban street segments after signal timing optimization*

Table 5 lists the results of safety impacts on street segments. Apart from single vehicle crashes and fixed object PDO crashes for the scenario of assigning 100 percent weight to vehicle delays, crash reductions are reached for all crash severity levels and target crash types. Similarly, reductions in crashes on street segments have not varied significantly corresponding to different weighting scenarios utilized for computing vehicle and pedestrian delays in intersection signal timing optimization. For single-vehicle fixed object crashes, reductions are about 12 percent for fatal and injury crashes and 4 percent for PDO crashes. For multi-vehicle crashes, reductions are generally higher for fatal and injury crashes than PDO ones. For fatal and injury crashes combined, crash reductions are at about 63 percent for rear-end crashes, followed by angle crashes at slightly over 7 percent, head-on crashes at about 5 percent, and sideswipe crashes at nearly 2 percent. For PDO, the reduction is most significant for rear-end crashes at about 43 percent. The crash reductions for the remaining target crash types including angle, sideswipe, and head-on are much lower, ranging from 0.4 percent to nearly 4 percent.

The standard errors of single-vehicle fixed object crash reductions are at 83 percent for fatal and injury crashes and at 55 percent for PDO crashes, respectively. The test statistics indicate that single-vehicle fixed object crashes for all crash severity levels are statistically insignificant for different weighting scenarios. For multi-vehicle crashes, reductions in fatal and injury for all target crash types are found to be statistically significant for all weighting scenarios. However,

Table 5 – Safety impacts of signal timing optimization on street segments in a dense urban street network.

Relative weights of vehicle vs. pedestrian delays (w)	Single vehicle crashes		Multiple vehicle crashes							
	Fatal and injury	PDO	Fatal and injury				PDO			
	Fixed objects	Fixed objects	Angle	Head-on	Rear-end	Side-swipe	Angle	Head-on	Rear-end	Side-swipe
	Eff_{seg} (%)									
100	11.60	−1.10	7.20	5.10	61.70	1.60	3.40	0.40	37.90	2.60
90	12.30	3.80	7.40	5.20	63.40	1.60	3.80	0.40	42.80	3.00
80	12.10	3.80	7.30	5.20	63.20	1.60	3.90	0.40	42.90	3.00
70	12.20	3.90	7.30	5.20	63.30	1.60	3.90	0.40	42.90	3.00
60	12.20	3.80	7.30	5.20	63.30	1.60	3.90	0.40	42.90	3.00
50	12.20	3.80	7.30	5.20	63.30	1.60	3.90	0.40	42.80	3.00
40	12.20	3.90	7.30	5.20	63.30	1.60	3.90	0.40	42.90	3.00
30	12.20	3.80	7.30	5.20	63.30	1.60	3.90	0.40	42.80	3.00
20	12.10	3.80	7.30	5.20	63.20	1.60	3.80	0.40	42.80	3.00
10	12.10	3.60	7.30	5.20	63.10	1.60	3.80	0.40	42.60	3.00
w	$100 \times \sqrt{\mathrm{Var}(Eff_{seg})}(\%)$									
100	82.86	55.00	3.85	2.73	32.99	0.86	2.41	0.28	26.88	1.84
90	82.00	54.29	3.52	2.48	30.19	0.76	2.12	0.22	23.91	1.68
80	80.67	54.29	3.48	2.48	30.10	0.76	2.17	0.22	23.83	1.67
70	81.33	55.71	3.48	2.48	30.14	0.76	2.17	0.22	23.83	1.67
60	81.33	54.29	3.48	2.48	30.14	0.76	2.17	0.22	23.83	1.67
50	81.33	54.29	3.49	2.49	30.29	0.77	2.17	0.22	23.78	1.67
40	81.33	55.71	3.48	2.48	30.14	0.76	2.17	0.22	23.83	1.67
30	81.33	54.29	3.49	2.49	30.29	0.77	2.17	0.22	23.78	1.67
20	80.67	54.29	3.49	2.49	30.24	0.77	2.12	0.22	23.91	1.68
10	86.43	51.43	3.53	2.51	30.48	0.77	2.13	0.22	23.93	1.69
w	Statistical significance of safety impacts [Abs ($Test_{seg}$)]									
100	0.14	0.02	1.87	1.87	1.87	1.87	1.41	1.41	1.41	1.41
90	0.15	0.07	2.10	2.10	2.10	2.10	1.79	1.79	1.79	1.79
80	0.15	0.07	2.10	2.10	2.10	2.10	1.80	1.80	1.80	1.80
70	0.15	0.07	2.10	2.10	2.10	2.10	1.80	1.80	1.80	1.80
60	0.15	0.07	2.10	2.10	2.10	2.10	1.80	1.80	1.80	1.80
50	0.15	0.07	2.09	2.09	2.09	2.09	1.80	1.80	1.80	1.80
40	0.15	0.07	2.10	2.10	2.10	2.10	1.80	1.80	1.80	1.80
30	0.15	0.07	2.09	2.09	2.09	2.09	1.80	1.80	1.80	1.80
20	0.15	0.07	2.09	2.09	2.09	2.09	1.79	1.79	1.79	1.79
10	0.14	0.07	2.07	2.07	2.07	2.07	1.78	1.78	1.78	1.78

reductions in PDO for all target crash types are statistically insignificant for the weighting scenario of assigning a weight of 100 percent to vehicle delays in intersection signal timing optimization.

3.4. *Discussion of results*

Vehicle crashes at intersections and on street segments in an urban street network are found to have changed after intersection signal timing optimization. This may be attributable to traffic redistribution across the network. For urban intersections, reductions in vehicle-to-vehicle and vehicle-to-pedestrian crashes are statistically significant for all crash severity levels and target crash types. It is generally most effective in reducing angle and rear-end crashes for all severity levels. Among fatal, injury, and PDO crash severity levels, the highest degree of reductions is achieved for PDO crashes. For street segments, intersection signal timing optimization is found to be statistically insignificant in reducing single-vehicle crashes. However, it is significant in reducing multi-vehicle crashes, particularly the rear-end ones. With no apparent changes in the daily total travel in the urban street network after intersection signal timing optimization, it provides evidence that crash reductions in the urban street network is not due to the decreases in the total travel. Rather, safety improvements could be explained by traffic redistribution in the urban street network in a more balanced way, coupled with less delays to vehicles and pedestrians traversing within the network after signal timing optimization.

4. Summary and conclusions

4.1. *Summary*

This study analyzed safety impacts of intersection signal timing optimization (referred to as treatment) in an urban street network aiming to simultaneously minimize vehicle and pedestrian delays at intersections. An EB before-after analysis method was introduced to assess reductions in vehicle-to-vehicle and vehicle-to-pedestrian crashes at intersections, and single- and multi-vehicle crashes on street segments after intersection signal timing optimization. The proposed method was applied to assess safety impacts of intersection signal timing optimization for the Chicago CBD street network. In particular, safety performance functions and seven-year data on field traffic counts and observed vehicle crashes were utilized to estimate EB-adjusted crash frequencies associated with individual intersections and street segments within the street network before signal timing optimization. A simulation-based regional travel demand model was executed iteratively to obtain the redistributed traffic counts after intersection signal optimization. The simulated traffic was then used in safety performance functions to obtain the expected crash frequencies at the corresponding intersections and street segments after signal timing optimization. The two sets of crash frequencies (i.e. before and after treatment) were used to evaluate the safety impacts as a result of intersection signal timing optimization in the urban street network.

For urban intersections, decreases in vehicle-to-vehicle and vehicle-to-pedestrian crashes were obtained for fatal, injury, and PDO crash severity levels and target crash types, including angle, rear-end, sideswipe, and head-on crashes. For different crash severity levels, the percent of crash reductions was found to be higher for PDO than fatal or injury crashes. Among the target crash types, the percent of crash reductions was higher for angle and rear-end ones. For safety impacts on street segments, it was revealed that intersection signal timing optimization was ineffective in reducing single vehicle crashes regardless of severity levels and target crash types. Conversely, reductions in multi-vehicle crashes were identified to be statistically significant for all severity levels and target crash types. Of which, reductions were highest for the rear-end type at fatal, injury, and PDO crash severity levels.

4.2. *Conclusions*

As part of the current study's findings, safety enhancements are found to be statistically significant only for some crash severity levels and target crash types, such as angle and rear-end crashes at the PDO severity level. This suggests that a net gain in safety performance as a result of signal timing optimization may be expected for an urban street network that historically would experience different vehicle and pedestrian crash types. Otherwise, a certain extent of mobility gain may be offset by the loss of safety performance. Under the related circumstances, safety impacts need to be explicitly considered along with mobility improvements in the decision-making process to ensure that a net gain in the overall performance is achieved. Hence, it is desirable to develop a practical guide for signal timing optimization to achieve significant reductions in vehicle and pedestrian delays while addressing safety concerns as well.

One of the major contributions of this study is to incorporate pedestrian mobility and safety effects into intersection signal timing optimization and assess the sensitivity of alternative weighting combinations for calculating the weighed total of intersection-related vehicle and pedestrian delays. The proposed method uses redistributed traffic in the entire urban street network as an input for safety impacts analysis. It requires executing a travel demand forecasting model responsive to intersection delays for regional traffic assignments. This process involves extensive data collection, processing, and computational efforts which might limit applications of the proposed method primarily to municipalities that do not maintain rich data on travel demand, traffic operations, data processing and preparation capacity, and high performance computing facilities to support the related calculations.

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