Optimal Design of Midblock Crosswalk to Achieve Trade-Off between Vehicles and Pedestrians

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Abstract: Midblock crosswalks are installed mainly at locations with heavy pedestrian traffic to increase the accessibility of points along the streets to pedestrians. However, midblock crosswalks may cause additional delays for vehicles. This paper presents an integrated design method for midblock crosswalks that balances the trade-off between the efficiency of vehicle operation and pedestrian crossing by making full use of the vehicular red time at the downstream intersection. The method combines location selection and signal timing in a unified optimization model that is formulated as a multiobjective linear programming problem. The Pareto frontier of the proposed model is obtained by iterating all possible combinations of the weights of the two objectives. For each combination of weights, the optimization problem becomes a single-objective mixed-integer linear programming problem that can be solved with the standard branch-and-bound technique. The results of extensive numerical analyses and case studies demonstrate the effectiveness of the proposed model and indicate its promising application in providing additional crosswalks for pedestrians while only slightly impacting vehicular operations. **DOI: 10.1061/JTEPBS.0000006.** *© 2016 American Society of Civil Engineers.*

Author keywords: Midblock crosswalk; Integrated design; Bandwidths; Crosswalk location; Signal timing.

Introduction

Midblock pedestrian crosswalks are installed mainly in some highly populated areas with heavy pedestrian traffic to increase the accessibility of points along the streets to pedestrians. The literature on pedestrian injury severity analysis found that collision speed was the most significant factor affecting the probability of pedestrian fatalities, where a higher speed was associated with a pedestrian fatality increase (Haleem et al. 2015; Hamdane et al. 2016; Olszewski et al. 2015). Although the law is that vehicles are supposed to yield to pedestrians, previous studies found that the percentage of drivers who yield to pedestrians at nonsignalized crosswalks is related to factors such as the driving speed, road width, marking, and turning (Gårder 2004; Sisiopiku and Akin 2003). Then, according to research on pedestrian crossing behavior (Li 2014; Pawar and Patil 2015; Pecchini and Giuliani 2015; Xie et al. 2013) and evaluations of pedestrian crossing safety (Guo et al. 2012; Tay et al. 2011), using signal control and providing protected signal phases are effective ways to ensure the right of way of pedestrians and enhance crossing safety (Baltes and Chu 2002; Koh et al. 2014; Mara and Antonio 2010). However, providing signalized midblock pedestrian crossings may cause additional delay for vehicles. How to balance the vehicle operation efficiency and pedestrian accessibility has long challenged transportation authorities engaged in traffic management.

Signal coordination is a widely used method to improve the operational efficiency of vehicles (Little et al. 1981; Liu and Chang 2011; Tian and Urbanik 2007). However, most studies have mainly focused on coordination of signal timings for arterial intersections without consideration of the impact of pedestrian crossings. To fill this gap, various techniques were investigated to minimize pedestrian impacts on coordinated signal systems (Tian et al. 2001), including the use of lead-lag phasing on the side street of an intersection. Other studies on signal timing have considered the benefits for both pedestrians and vehicles (Ma et al. 2014; Roshandeh et al. 2014). However, these studies focused on pedestrian crossings at intersections.

For midblock crosswalks, delay models have been established (Wang and Tian 2010) and midblock crosswalk signal timing optimization models have been proposed for different signal control patterns. A timing optimization model for a one-stage crosswalk has been established to minimize the weighted sum of the pedestrian and vehicle delays, with consideration of cycle length limitations (Feng 2008). Other studies (Ma et al. 2010, 2011) have focused on developing a signal timing optimization approach for two-stage midblock pedestrian crossings. Three types of signalization modes for a two-stage midblock crossing have been incorporated into a unified two-step optimization framework. The objectives of these studies were to enhance the efficiency of pedestrian crossings while considering the delay of vehicle flows. However, the location of the crosswalk was assumed to be given as an external input in these studies.

According to the literature, signal timing and coordination have been used for several decades, and much is known about their effectiveness and feasibility. However, signalized midblock crosswalks are commonly regarded as signalized intersections. This may pose some limitations:

- Only through movements are considered in most existing coordinated signal systems. If the midblock crosswalk is regarded as an intersection, turning vehicles at the downstream intersection may experience additional delay at the midblock crosswalk.

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Therefore, more movements should be considered for signal coordination to minimize negative effects on vehicle operations.

- The location of the crosswalk is predetermined. Because of the stochastic nature of the pedestrian crossing demand, the specific location of a crosswalk is not immovable, as an intersection is, and can be adjusted within a certain range. In addition, adjusting the crosswalk location may improve the signal coordination.

In this paper, a signal timing optimization model for a midblock crosswalk is proposed to address the conflict between the efficiency of pedestrian crossings and the efficiency of vehicle traffic on an urban arterial. The main idea is to provide an appropriate signal phase for the pedestrian using the red time of the vehicles at the downstream intersection. To produce a good coordination result, the location of the crosswalk may be adjusted within an appropriate range. Consequently, the optimization model combines location selection and signal timing in a unified framework.

The idea of integrated design of geometric layout and signal timing is not new. It has been successfully applied to the optimization for vehicles at intersections (Lam et al. 1997; Wong and Wong 2003; Wong and Heydecker 2011; Zhao et al. 2013), on arterials (Mahalel and David 2015; Zhao et al. 2014), and in networks (Chen et al. 2006; Wong and Wong 2002; Wong et al. 2007; Zhao et al. 2015). These studies have shown that integrated design of geometric layout and signal timing can achieve substantial increase in capacity and reductions in delay. However, the studies have mainly focused on vehicle traffic. This paper presents a model for optimizing the operation of a midblock crosswalk based on the perspectives of both crossing pedestrians and vehicles.

Concept of the Integrated Design

The basic concept of the proposed midblock crosswalk design is depicted in Fig. 1. The location and signal timing of the crosswalk should be carefully designed to ensure that each side of the midblock crosswalk is coordinated with the downstream intersection. The special considerations of the design includes

- Main idea: The signal phase for the pedestrian is provided by making full use of the vehicular red time at the downstream intersection. As a result, most of the vehicles trapped at the crosswalk are those that were supposed to meet the red signal at the downstream intersection in the absence of the crosswalk.
- Model framework: The design of the crosswalk location and the signal timing of the crosswalk are integrated in a unified framework.
- Optimization method: The Pareto frontier was adopted to analyze the trade-off between the operational efficiency of vehicles and that of pedestrians. The use of the Pareto frontier provides a means to investigate the relationships between different objectives.
- Coordinated movements: For vehicles, all movements, including left turns, through movements, and right turns, in both directions of the road between the crosswalk and the downstream intersection are considered. For pedestrians, the bandwidths of both pedestrian flow directions between the two sides of the road are considered.
- Input data requirements: To enhance the usability of the proposed model, no adjustment is made to the layout and signal timing of the adjacent intersections. Moreover, the two adjacent intersections are not required to be coordinated. The only requirement is that the two adjacent intersections have a common initial cycle length.

Integrated Optimization Model

Objective Function

The purpose of the model proposed in this paper is to coordinate the competitive relationship between the vehicle and pedestrian; therefore, two conflicting objectives are considered. One objective is maximizing the weighted average bandwidth between the crosswalk and the downstream intersection, which contains the left turn, through movement, and right turn vehicles in both directions of

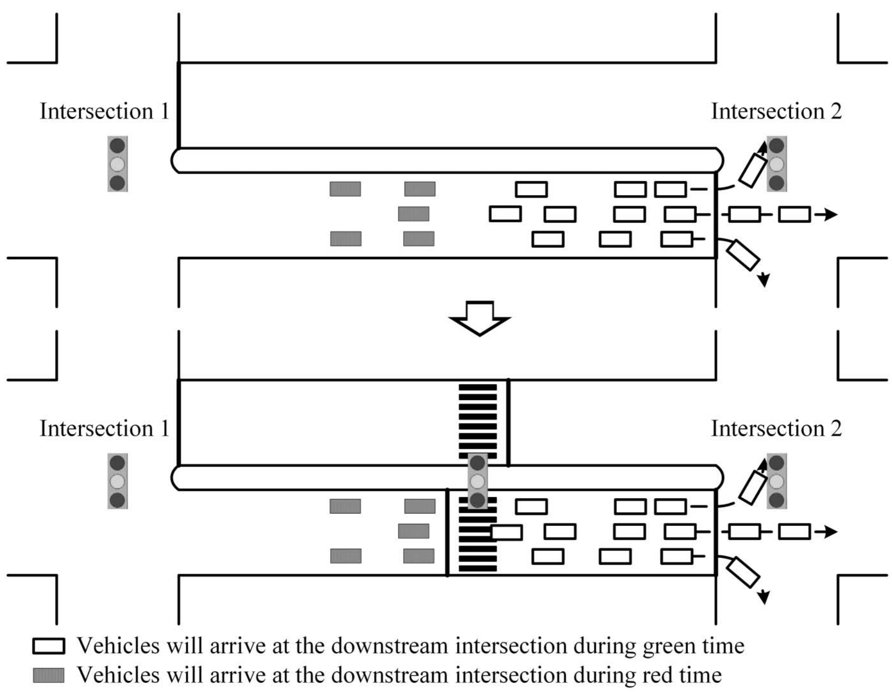

Fig. 1. Concept of the design

the road. The other objective is maximizing the weighted average bandwidth of pedestrians at the crosswalk in both directions. The objective functions are given by

$$\max B^v \tag{1}$$

$$\max B^p \tag{2}$$

where B^v = weighted average bandwidth of vehicles (s); and B^p = weighted average bandwidth of pedestrians (s).

Constraints

Weighted Average Bandwidth for Vehicles

The weighted average bandwidth for vehicles can be calculated from Eq. (3). All vehicular movements in both directions of the road are considered

$$B^v = \frac{\sum_{j\in\mathcal{J}} \sum_{m\in\mathcal{M}} q^v_{jm} b^v_{jm}}{\sum_{j\in\mathcal{J}} \sum_{m\in\mathcal{M}} q^v_{jm}} \tag{3}$$

where $\mathcal{J}$ = set of the side of the road; $\mathcal{M}$ = set of movements of vehicles; $j \in \mathcal{J}$ = index of the sides of the road, where $j = 1$ for the side of the road from Intersection 1 to Intersection 2, $j = 2$ for the side of the road from Intersection 2 to Intersection 1, as shown in Fig. 2; $m \in \mathcal{M}$ = index of turning movements of vehicles, where $m = 1$ for left turn, $m = 2$ for through movement, and $m = 3$ for right turn, as shown in Fig. 2; q^v_{jm} = vehicular flow of movement m in direction j (vehicles/h); and b^v_{jm} = bandwidth of vehicles for movement m at road side j (s) as shown in Fig. 2.

According to the basic idea of the MAXBAND model (Little et al. 1981; Pillai et al. 1998), the bandwidth from the crosswalk to the downstream intersection should satisfy Eqs. (4)–(8), as illustrated in Fig. 3

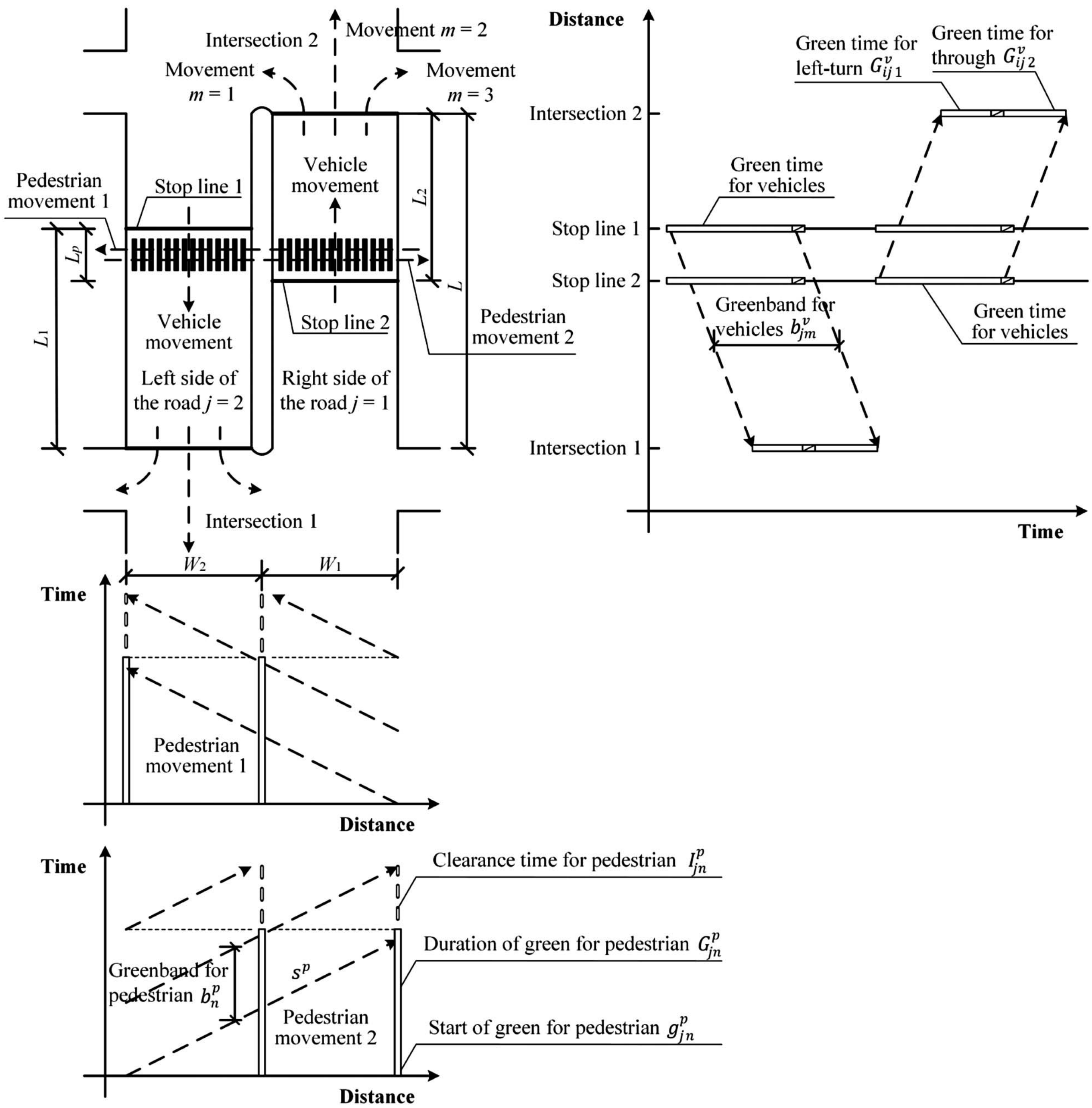

Fig. 2. Schematic for parameters

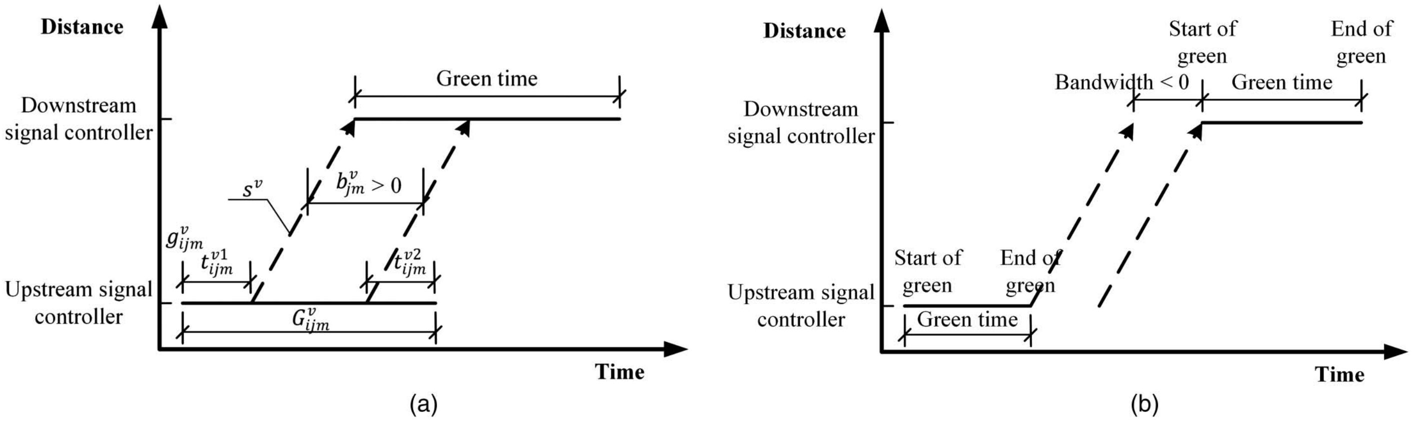

Fig. 3. Concept of bandwidth: (a) positive bandwidth; (b) negative bandwidth

$$G^v_{ijm} \geq t^{v1}_{ijm} + t^{v2}_{ijm} + b^v_{jm}, \quad \forall\ i \in \{1,2,3\}, j \in \mathcal{J}, m \in \mathcal{M} \quad (4)$$

where i = index of two adjacent intersections and the crosswalk, where $i = 1$ for the bottom intersection, $i = 2$ for the midblock crosswalk, and $i = 3$ for the top intersection, as shown in Fig. 2; G^v_{ijm} = duration of green of vehicles for movement m at signal control point i at road side j, as shown in Fig. 2; t^{v1}_{ijm} = time from start of green for vehicular movement m at signal control point i at road side j to the left edge of the green band from the midblock crosswalk to the downstream intersection, as shown in Fig. 3; and t^{v2}_{ijm} = time from end of green for vehicular movement m at signal control point i at road side j to right edge of the green band from the midblock crosswalk to the downstream intersection, as shown in Fig. 3

$$g^v_{ijm} + t^{v1}_{ijm} + \frac{L_j}{s^v} = g^v_{(i+1)jm} + t^{v1}_{(i+1)jm} + \alpha_{1(i+1)}, \quad \forall\ i \in \{2\}, j \in \{1\}, m \in \mathcal{M} \quad (5)$$

where g^v_{ijm} = start of green of vehicles for movement m at signal control point i at road side j, as shown in Fig. 2; L_j = distance from the stop line of the midblock crosswalk to the stop line of the intersection in direction j (m) as shown in Fig. 2; s^v = vehicular travel speed (m/s); and $\alpha_{1(i+1)}$, $\alpha_{1(i-1)}$, $\alpha_{2(i+1)}$, and $\alpha_{2(i-1)}$ = loop integer variables used to ensure that the left (or right) edge of the green band to be a fraction that lies between 0 and 1 of the cycle length

$$g^v_{ijm} + t^{v1}_{ijm} + \frac{L_j}{s^v} = g^v_{(i-1)jm} + t^{v1}_{(i-1)jm} + \alpha_{1(i-1)}, \quad \forall\ i \in \{2\}, j \in \{2\}, m \in \mathcal{M} \quad (6)$$

$$g^v_{ijm} + G^v_{ijm} - t^{v2}_{ijm} + \frac{L_j}{s^v} = g^v_{(i+1)jm} + G^v_{(i+1)jm} - t^{v2}_{(i+1)jm} + \alpha_{2(i+1)}, \quad \forall\ i \in \{2\}, j \in \{1\}, m \in \mathcal{M} \quad (7)$$

$$g^v_{ijm} + G^v_{ijm} - t^{v2}_{ijm} + \frac{L_j}{s^v} = g^v_{(i-1)jm} + G^v_{(i-1)jm} - t^{v2}_{(i-1)jm} + \alpha_{2(i-1)}, \quad \forall\ i \in \{2\}, j \in \{2\}, m \in \mathcal{M} \quad (8)$$

Eq. (9) confines the bandwidth of vehicles to be a fraction that lies between −1 and 1 of the cycle length. As illustrated in Fig. 3, the negative bandwidth equals the time difference between the start of green of the downstream signal controller and the time that the end of green of the upstream signal controller plus the travel time, as illustrated in Fig. 3(b). It indicates a gap between the end of green at the midblock crosswalk and the start of the green at the downstream intersection, which is a penalty for bad coordination

$$1 \geq b^v_{jm} \geq -1, \quad \forall\ j \in \mathcal{J}, m \in \mathcal{M} \quad (9)$$

Eq. (10) confines the time from the start (or end) of green for vehicular movement to the left (or right) edge of the green band to be a fraction that lies between 0 and 1 of the cycle length

$$1 \geq t^{v1}_{ijm}, t^{v2}_{ijm} \geq 0, \quad \forall\ i \in \{1,2,3\}, j \in \mathcal{J}, m \in \mathcal{M} \quad (10)$$

Weighted Average Bandwidth for Pedestrians

The bandwidth of a pedestrian is the time that person can cross the two sides of the street without stopping at the central refuge island. For the one-stage crosswalk, the bandwidth of pedestrian equals to the green time of pedestrians. For the two-stage crosswalk, it reflects the green time length and the signal coordination between the two sides of the crosswalk. The weighted average bandwidth for pedestrians can be calculated from Eq. (11)

$$B^p = \frac{\sum_{n \in \mathcal{N}} q^p_n b^p_n}{\sum_{n \in \mathcal{N}} q^p_n} \quad (11)$$

where $\mathcal{N}$ = set of movements of pedestrians; n = index of movements of pedestrians, where $n = 1$ for movement from the right side of the road to the left side of the road and $n = 2$ for movement from the left side of the road to the right side of the road, as shown in Fig. 2; q^p_n = pedestrian flow of movement n at the mid-block crosswalk (pedestrians/h); and b^p_n = bandwidth of pedestrian for movement n, as in shown Fig. 2.

For a two-stage crossing, the bandwidth between the two sides of road should satisfy Eqs. (12)–(14)

$$G^p_{jn} \geq t^{p1}_{jn} + t^{p2}_{jn} + b^p_n, \quad \forall\ j \in \mathcal{J}, n \in \mathcal{N} \quad (12)$$

where G^p_{jn} = duration for green of pedestrians for movement n at road side j, as shown in Fig. 2; t^{p1}_{jn} = time from start of green for pedestrian movement n at road side j to left edge of the green band; and t^{p2}_{jn} = time from end of green for pedestrian movement n at road side j to right edge of the green band

$$g^p_{jn} + t^{p1}_{jn} + \frac{W_j}{s^p} = g^p_{j'_n} + t^{p1}_{j'_n} + \alpha_{3n}, \quad \forall\ j, j' \in \mathcal{J}, j \neq j', n \in \mathcal{N} \quad (13)$$

where g^p_{jn} = start of green for pedestrians at the crosswalk for movement n at road side j, as shown in Fig. 2; W_j = length of the crosswalk square across the street at road side j (m), as shown in Fig. 2; s^p = pedestrian walking speed (m/s); and parameters α_{3n} and α_{4n} = loop integer variables used to ensure that the left (or right) edge of the green band is a fraction that lies between 0 and 1 of the cycle length

$$g_{jn}^{p} + G_{jn}^{p} - t_{jn}^{p2} + \frac{W_j}{s^p} = g_{j'_n}^{p} + G_{j'_n}^{p} - t_{j'_n}^{p2} + \alpha_{4n}, \quad \forall\ j, j' \in \mathcal{J}, j \neq j', n \in \mathcal{N} \tag{14}$$

The bandwidth of the pedestrians is a fraction that lies between −1 and 1 of the cycle length

$$1 \geq b_n^p \geq -1, \quad \forall\ n \in \mathcal{N} \tag{15}$$

Moreover, the time from the start (or end) of green for pedestrian movement to the left (or right) edge of the green band is a fraction that lies between 0 and 1 of the cycle length

$$1 \geq t_{jn}^{p1}, t_{jn}^{p2} \geq 0, \quad \forall\ j \in \mathcal{J}, n \in \mathcal{N} \tag{16}$$

Location of Crosswalk

The expected location of the crosswalk is limited within an appropriate range to reflect the externalities that constrain the position of the crosswalk in practice, e.g., geometry, sight distance, and approach speed. With the consideration of the distance between the intersections, crosswalks should be located no more than 60 to 90 m apart in high pedestrian volume locations (Broek 2011; Dougald 2004)

$$L = \sum_{j \in \mathcal{J}} L_j - L_p \tag{17}$$

where L = length of segment between two adjacent intersections (m), as shown in Fig. 2; and L_p = width of the midblock crosswalk along the street, m, as shown in Fig. 2

$$L_{j\max} \geq L_j \geq L_{j\min}, \quad \forall\ j \in \mathcal{J} \tag{18}$$

where $L_{j\max}$ and $L_{j\times\min}$ = expected location range of the midblock crosswalk (m).

Signal Timing of Crosswalk

To ensure good coordination between the crosswalk and the downstream intersection, they should have a common cycle length, given by

$$C_1 = C_2 = C_3 \tag{19}$$

where C_i = cycle length (s).

The signal control for the midblock crosswalk operates as a two-phase signal-controlled intersection because there are only two conflicting traffic movements: the vehicle through movement and the pedestrian crossing movement, as Eqs. (20) and (21) indicate

$$g_{2jm}^{v} = g_{jn}^{p} + G_{jn}^{p} + I_{jn}^{p} + \alpha_{5j} C_2, \quad \forall\ j \in \mathcal{J}; \quad m \in \mathcal{M}; \quad n \in \mathcal{N} \tag{20}$$

where g_{2jm}^{v} = start of green for vehicles at the crosswalk at road side j; I_{jn}^{p} = clearance time for pedestrians movement n at road side j, as shown in Fig. 2; and α_{5j} and α_{6j} = loop integer variables used to ensure that the starts of the green will be a fraction that lies between 0 and 1 of the cycle length

$$g_{jn}^{p} = g_{2jm}^{v} + G_{2jm}^{v} + I^{v} + \alpha_{6j} C_2, \forall j \in \mathcal{J}; m \in \mathcal{M}; n \in \mathcal{N} \tag{21}$$

where G_{2jm}^{v} = duration for green of vehicles at the crosswalk at road side j; and I^{v} = clearance time for vehicle movements (s).

Because the signal timing is cyclical, the start and duration of green should be confined within a signal cycle. Furthermore, the duration of green of a movement should be longer than the minimum value

$$C_2 \geq g_{ijm}^{v} \geq 0, \quad \forall\ i \in \{2\}, j \in \mathcal{J}, m \in \mathcal{M} \tag{22}$$

$$C_2 \geq g_{jn}^{p} \geq 0, \quad \forall\ j \in \mathcal{J}, n \in \mathcal{N} \tag{23}$$

$$C_2 \geq G_{ijm}^{v} \geq G_{\min}^{v}, \quad \forall\ i \in \{2\}, j \in \mathcal{J}, m \in \mathcal{M} \tag{24}$$

where $G_{\min}^{v}$ = minimum duration of green for vehicles (s)

$$C_2 \geq G_{jn}^{p} \geq G_{\min}^{p}, \quad \forall\ j \in \mathcal{J}, n \in \mathcal{N} \tag{25}$$

where $G_{\min}^{p}$ = minimum duration of green for pedestrians (s).

In addition to the common constraints presented previously, some special constraints for different signal control types should also be considered. Two signal control types for the midblock crosswalk are considered: a one-stage crosswalk and a two-stage crosswalk.

For the signalization of a one-stage crosswalk, the signal timing in both directions of pedestrian movement should be identical, as described by Eqs. (26) and (27). Furthermore, the clearance time for pedestrians (also called the pedestrian walk and flashing do not walk interval) should be long enough to ensure that a pedestrian can walk from one curbside to the opposite curbside, as shown in Eq. (28)

$$M(1-\delta_1) \geq g_{jn}^{p} - g_{j'n'}^{p} \geq -M(1-\delta_1), \quad \forall\ j, j' \in \mathcal{J}; \quad n, n' \in \mathcal{N} \tag{26}$$

where δ_1 and δ_2 = index of the signal control types of the one-stage and two-stage midblock crosswalk, respectively

$$M(1-\delta_1) \geq G_{jn}^{p} - G_{j'n'}^{p} \geq -M(1-\delta_1), \quad \forall\ j, j' \in \mathcal{J}; \quad n, n' \in \mathcal{N} \tag{27}$$

$$M(1-\delta_1) + I_{jn}^{p} \geq \frac{\sum_{j \in \mathcal{J}} W_j}{s^p}, \quad \forall\ j \in \mathcal{J}, n \in \mathcal{N} \tag{28}$$

For the signalization of a two-stage crosswalk, the signal timings for the two sides of the crosswalk can operate separately. Therefore, other than the clearance time for pedestrians, no special constraint concerning the start or duration of green needs to be set

$$M(1-\delta_2) + I_{jn}^{p} \geq \frac{W_j}{s^p}, \quad \forall\ j \in \mathcal{J}, n \in \mathcal{N} \tag{29}$$

Central Refuge Island Area

The total number of pedestrians waiting on the central island in both directions can be calculated using the following equation:

$$N_p = \sum_{n \in \mathcal{N}} \frac{b_n^p}{G_{jn}^p}, \quad \forall\ j = n \tag{30}$$

where N_p = total number of pedestrians waiting on the central island.

For the sake of safety, the maximum number of pedestrians waiting on the central refuge island should be less than the maximum acceptable number of pedestrians constrained by the level of service, given by

$$\frac{A}{A_{p\min}} \geq N_p \tag{31}$$

where A = central island space (m^2); and $A_{p\min}$ = minimum acceptable average pedestrian space (m^2/pedestrian).

Vehicular Queue Length

To prevent queue overflow, Eq. (32) restricts the queue storage ratio of the area between the midblock crosswalk and the upstream intersection to be less than 1. The back-of-queue size can be determined using the estimation model in the *Highway Capacity Manual 2010* (TRB 2010), shown as Eq. (33)

$$1 \geq \frac{L_h L_{qj}}{L - L_j}, \quad \forall\ j \in \mathcal{J} \tag{32}$$

where L_h = average space headway for queuing vehicles (m/vehicle); and L_{qj} = back-of-queue size (vehicles)

$$L_{qj} = \frac{C_2(C_2 - g^v_{2j2}) S_j \sum_{m\in\mathcal{M}} q^v_{jm}}{3{,}600(S_j - \sum_{m\in\mathcal{M}} q^v_{jm})}, \quad \forall\ j \in \mathcal{J} \tag{33}$$

where S_j = saturation flow rate of movement j (vehicles/h).

Solution Algorithm

With the objective functions given by Eqs. (1) and (2) and the constraints in Eqs. (3)–(33), the proposed optimization model is a two-objective (bicriteria) linear programming problem. This problem could be solved through a trade-off analysis, using the notion of a Pareto optimal solution (Nakayama et al. 2009). A solution is called a Pareto solution if it is not dominated by any other solutions (solution a dominates another solution b if a is equal or superior to b with regard to all of the objectives and a is superior to b for at least one objective). Each Pareto point is a solution of the multiobjective optimization problem. The set of Pareto solutions comprise a Pareto frontier (Bai et al. 2015). A designer selects the ultimate solution from the set of Pareto solutions on the basis of additional requirements, which may be subjective.

As noted previously, the proposed optimization model is a linear programming problem. Therefore, the multiobjective optimization problem can be reduced to maximization of an aggregate objective function with a linear (weighted) combination of the objective functions, as shown in Eq. (34) (Erfani and Utyuzhnikov 2011). The Pareto frontier of the proposed model can then be drawn by iterating all possible combinations of the weights that correspond to the decision maker's expectations (Messac and Messac 2000). For each combination of weights, the optimization becomes a single-objective mixed-integer linear programming problem that can be solved with the standard branch-and-bound technique

$$\max \beta^v B^v + \beta^p B^p \tag{34}$$

where β^v and β^p = weight factors for control objectives.

Numerical Examples

The performance of the proposed model was evaluated using both numerical examples and case studies. The results are presented in this section. The proposed model was first applied to a case study to assess its effectiveness. The impacts of various geometric configurations and traffic patterns on vehicular and pedestrian operations were investigated further through sensitivity analyses.

Case Study

A segment with three lanes on each side on Chang'an Road in Zhangjiagang, China, was used to evaluate the effectiveness of the integrated design model, as shown in Fig. 4. The vehicular traffic demand and signal timing of the two intersections are summarized in Table 1. The pedestrian crossing demand is 200 pedestrians/h in both directions. Placement of a midblock crosswalk in the segment is planned. The expected location is shown in Fig. 4. The width of the crosswalk is 6 m. The central island space is 15 m^2. In accordance with the German design manual (FGSV 2003), the minimum durations of green for vehicles and pedestrians are set to 10 and 5 s, respectively. The maximum duration of green for pedestrians is set to 60 s. The average vehicle speed and pedestrian walking speed are 12 and 1 m/s, respectively, according to the field survey.

The integrated design model was applied to this case study. The Pareto frontier is shown in Fig. 5. Because the Chang'an Road is a main road in the city, the decision maker only wants to add a safety access for pedestrians to cross the street, without regard for the signal coordination between the two sides of the crosswalk. Therefore, β^v was set to 1 and β^p was set to 0. The optimal signal timing is shown in Table 2 and the optimal location of the crosswalk is 150 m from the south intersection (the intersection of Chang'an Road and Jiyang Road). The green band analysis results are shown in Table 3. One can observe that most of the left turn and through vehicles are well coordinated.

The microscopic simulation package *VISSIM* was used to evaluate the performance of the model, using the average delay as the index. To overcome the stochastic nature of a microscopic simulation system, an average of 10 simulation runs was used.

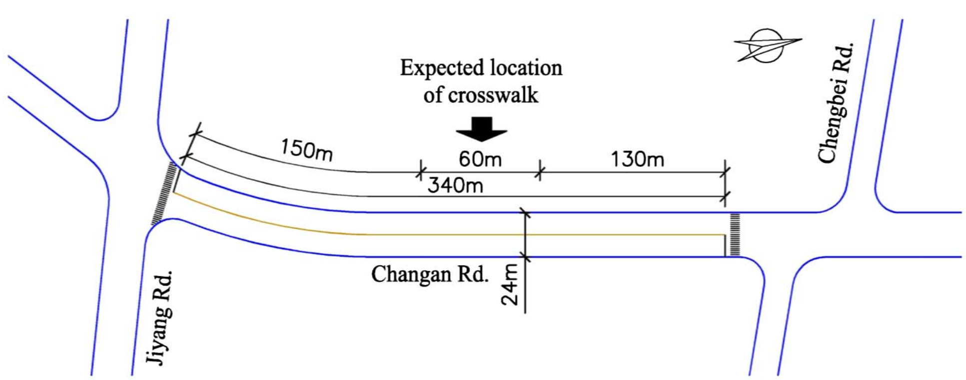

Fig. 4. Geometric layout of the case study segment

Table 1. Traffic Demand and Signal Timing for Case Study

Direction	Movement	Volume (vehicle/h)	Cycle length (s)	Start of green (s)	Duration of green (s)	End of green (s)
Southbound	Segment	980	—	—	—	—
	Left turn	300	120	38	25	63
	Through	515	120	0	41	41
	Right turn	165	120	0	41	41
Northbound	Segment	780	—	—	—	—
	Left turn	130	120	0	55	55
	Through	390	120	0	55	55
	Right turn	260	120	0	120	120

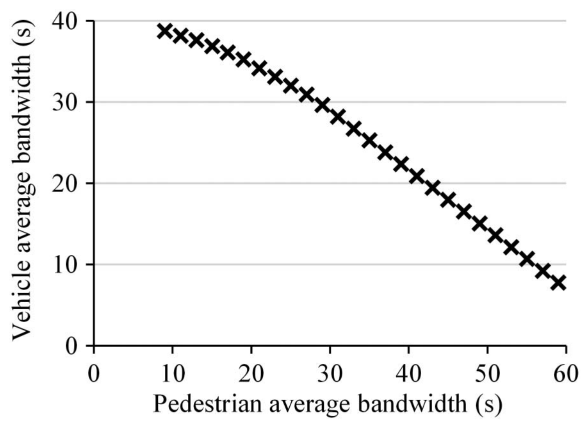

Fig. 5. Optimal frontier of the case study

Table 2. Optimized Signal Timing at the Crosswalk

Direction	Phase	Cycle length (s)	Start of green (s)	Duration of green (s)	End of green (s)
Southbound	Vehicle	120	104	60	44
	Pedestrian	120	47	33	80
Northbound	Vehicle	120	104	60	44
	Pedestrian	120	47	33	80

Table 3. Optimized Bandwidth

Direction	Movement	Bandwidth (s)	Ratio of the bandwidth to the green time at the intersection (%)
Southbound	Left turn	18.5	74.0
	Through	41	100.0
	Right turn	41	100.0
Northbound	Left turn	54.6	99.3
	Through	54.6	99.3
	Right turn	60	50.0

The results of the simulation for before and after setting of the midblock crosswalk are shown in Table 4. The results show that the design provides an additional crosswalk with only a slight increase in vehicular delay.

Sensitivity Analyses

Four impact factors were considered: the location of the midblock crosswalk, length of the crosswalk, duration of green of the vehicles at the two adjacent intersections, and through movement proportion of the traffic volume.

Impact of the Location of the Midblock Crosswalk

A 400-m-long segment with two adjacent intersections was considered. The input parameters such as the traffic demand, geometric layout, and signal timings of the two intersections are shown in Fig. 6. The minimum duration of green for the vehicles and pedestrians are set to 40 and 5 s, respectively.

According to the optimization results of the proposed model, the optimal location of the crosswalk is 263 m from Intersection 1 ($L_j = 263$ m). The possible locations of the crosswalk were further limited to be 50 and 100 m away from the optimal location. The comparison results are illustrated in Fig. 7. The following observations can be made:

- The performance of the crosswalk design decreases with increasing distance between the location of the crosswalk and the optimal location. Paired t-test results (Table 5) further show the significant difference between the bandwidth when the crosswalk is located at the optimal location and the bandwidth when the crosswalk is located at 50 and 100 m away from the optimal location, indicating that the proposed model could provide improved decisions for the location of crosswalks.
- A comparison of Figs. 7(a and b) shows that the two-stage design always outperforms the one-stage design and is less sensitive to the location selected.
- Moreover, as illustrated in Fig. 7(c), when the green time for pedestrians is given (20 s in this example) and the signal coordination for pedestrians is neglected ($\beta^p = 0$), the two-stage design always yields a suitable signal timing that provides the best operation performance for vehicles, regardless of where the crosswalk is located. The one-stage design fails to do so. An additional decrease of approximately 1.2% in the vehicular bandwidth occurs for every 10-m increase in the difference between the location of the crosswalk and the optimal one.

Impact of Crosswalk Length

Using the same segment described in Fig. 6, three crosswalk lengths were considered: 8, 12, and 16 m on each side of the crosswalk. The location of the crosswalk was fixed at the middle of the segment ($L_j = 203$ m). The comparison results are illustrated in Fig. 8. The following observations can be made:

Table 4. Vehicular Delay Comparison

	Without crosswalk			With crosswalk				
Movement	Mean (s)	Standard deviation	Test of normality	Mean (s)	Standard deviation	Test of normality	Significance (two-tailed)	Percentage of mean difference
SB-LT	43.3	1.97	0.549	48.5	1.28	0.793	0.000	12.01
SB-TH	37.8	1.50	0.859	39.2	0.90	0.809	0.020	3.70
SB-RT	39.8	1.34	0.833	39.7	1.02	0.863	0.941	−0.25
NB-LT	27.3	1.02	0.863	27.9	0.96	0.790	0.239	2.20
NB-TH	29.3	1.07	0.668	30.2	0.89	0.780	0.070	3.07
NB-RT	11.5	0.99	0.651	23.3	0.93	0.827	0.000	102.6

Note: LT, TH, and RT indicate left turn, through movement, and right turn, respectively; SB and NB indicate southbound and northbound, respectively.

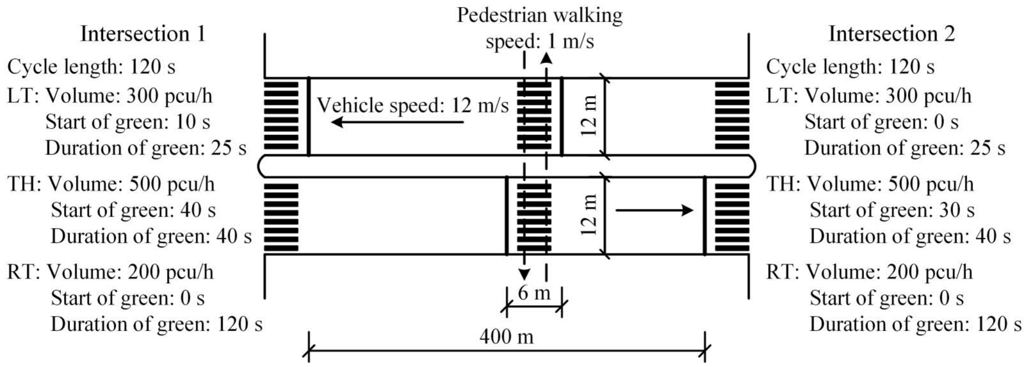

Fig. 6. Input parameters

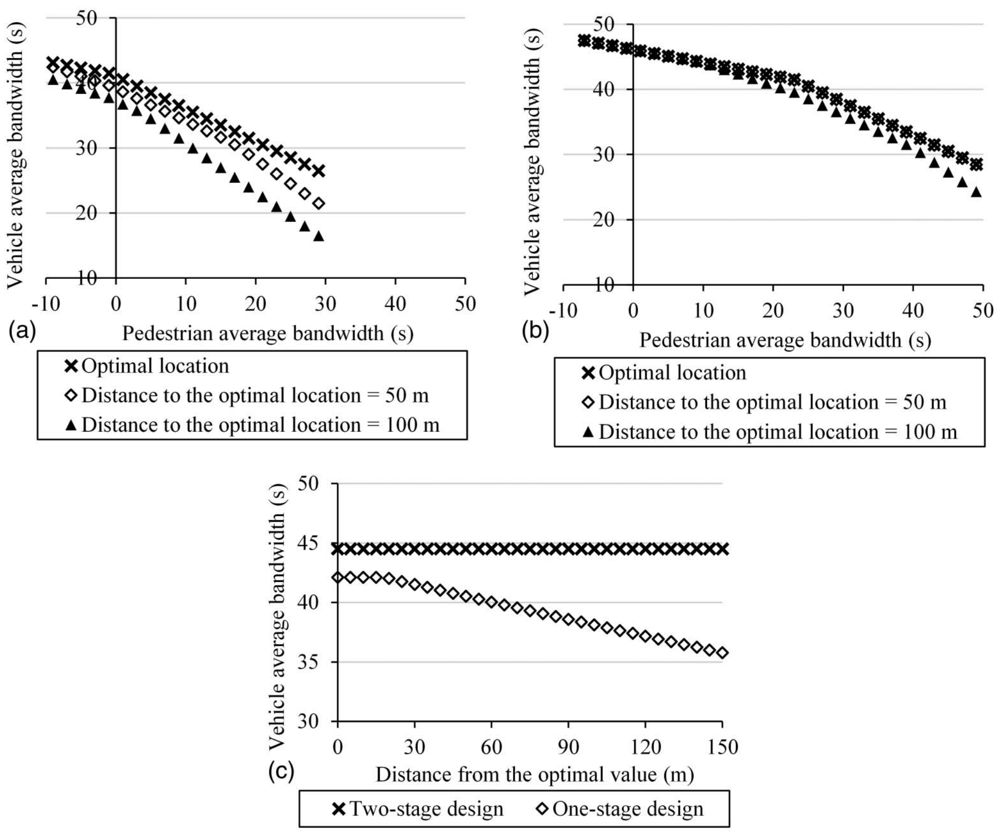

Fig. 7. Impact of the crosswalk location: (a) one-stage condition; (b) two-stage condition; (c) crosswalk location sensitivity to vehicle bandwidth

Table 5. Paired t-Test Results

Crosswalk type	Pair	Improvement (%)	Paired differences: Mean	Paired differences: Standard deviation	Paired differences: Standard error mean	t	df	Significance (two-tailed)
One-stage	Group 1–Group 2	7.86	2.294	1.140	0.255	9.001	19	0.000
One-stage	Group 1–Group 3	23.00	5.713	2.389	0.534	10.691	19	0.000
Two-stage	Group 1–Group 2	0.13	0.043	0.048	0.009	5.008	30	0.000
Two-stage	Group 1–Group 3	5.41	1.576	1.489	0.267	5.893	30	0.000

Note: Group 1 = bandwidth when the crosswalk is located at the optimal location; Group 2 = bandwidth when the crosswalk is located 50 m away from the optimal location; Group 3 = bandwidth when the crosswalk is located 100 m away from the optimal location.

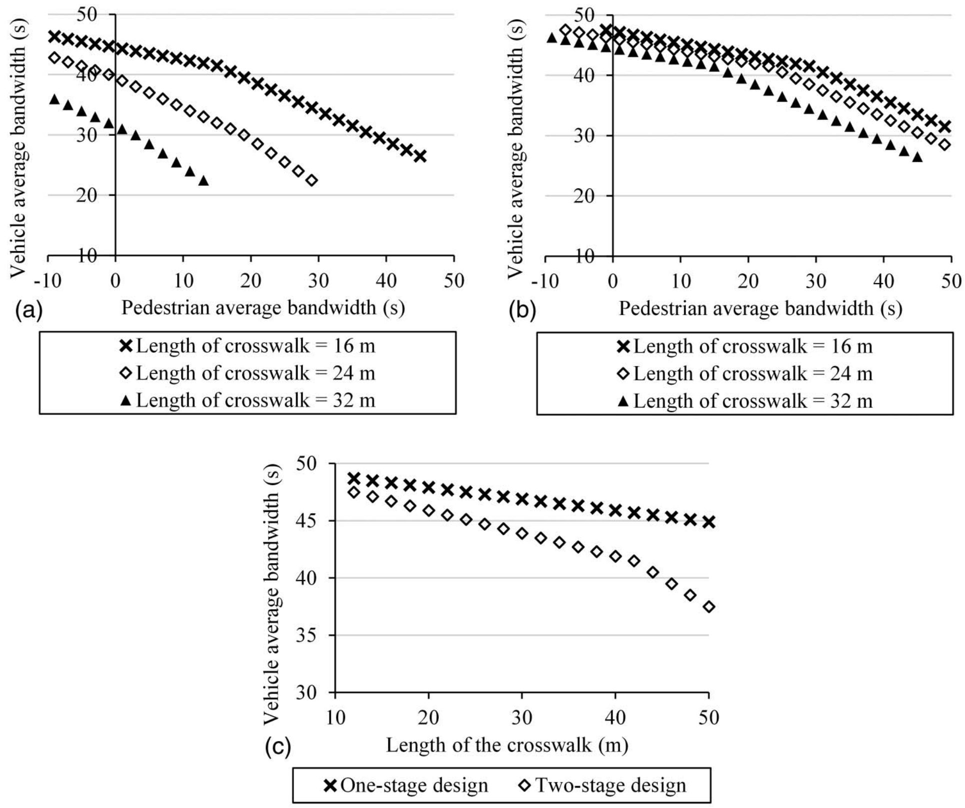

Fig. 8. Impact of the crosswalk length: (a) one-stage condition; (b) two-stage condition; (c) crosswalk length sensitivity to vehicle bandwidth

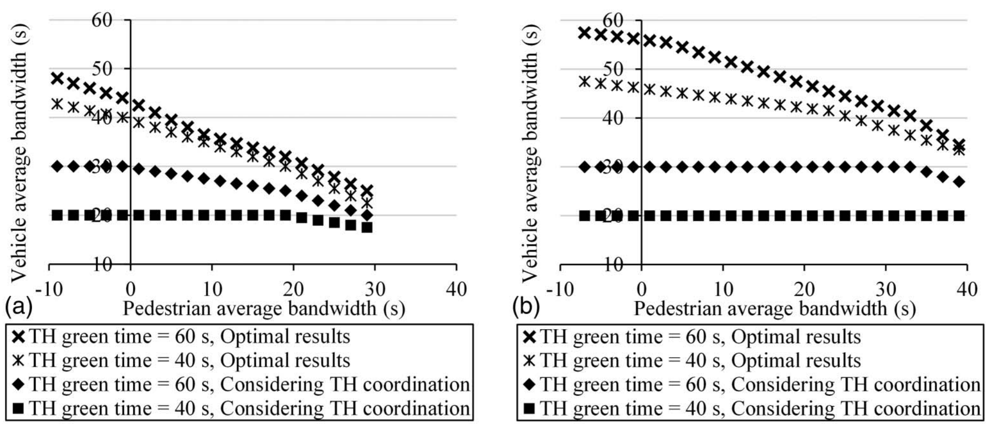

Fig. 9. Impact of the green time at the two adjacent intersections: (a) one-stage condition; (b) two-stage condition

- The performance of the crosswalk design decreases with increasing length of the crosswalk due to the fact that more clearance time is required for pedestrians.
- The length of the crosswalk is mainly determined by the width of the road section, which is an intrinsic characteristic of the road and cannot be optimized. However, the problem can be relieved using a two-stage crossing design because the length of the crossing could be shortened using a central refuge island. A comparison of Figs. 8(a and b) shows that the performance of a two-stage crosswalk design is much better and less sensitive than that of a one-stage design.
- Moreover, as illustrated in Fig. 8(c), when the signal coordination for pedestrians is neglected ($\beta^p = 0$) and only the minimum green time for pedestrians (5 s) is given, the benefits of the two-stage design are reflected in the increase in the crosswalk length. A 1-m increase in the crosswalk length is associated with a 0.5% increase in the vehicular bandwidth.

Impact of Duration of Green at Intersections

Using the same segment described in Fig. 6, two cases of the green time for through movement at the two adjacent intersections, 40 and 60 s, were considered. The location of the crosswalk was fixed at the middle of the segment ($L_j = 203$ m). The conventional designs that only consider the through movement coordination were used for comparison. The results are illustrated in Fig. 9. The following observations can be made:

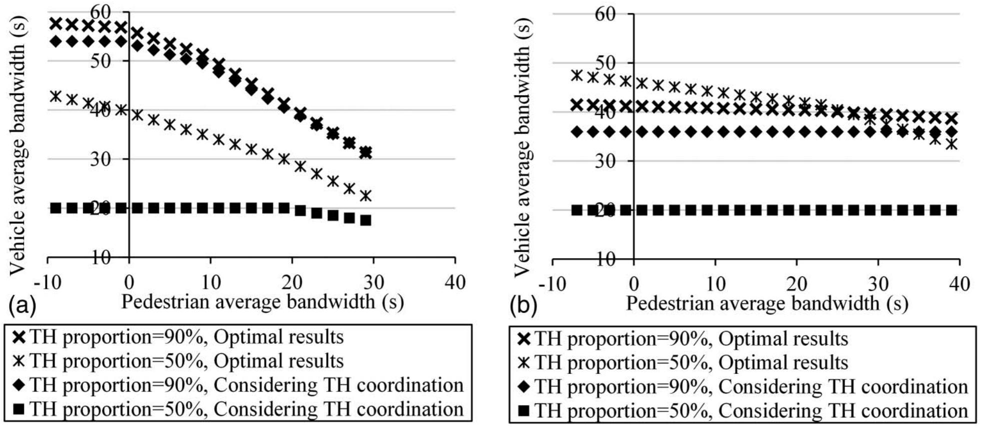

Fig. 10. Impact of the through movement proportion: (a) one-stage condition; (b) two-stage condition

- When the green time for through movement is high, better performance of the crosswalk design is obtained because the signal coordination can be implemented much more easily.
- As the results obtained from the proposed model show, there is a trade-off between the performance of the design for vehicles and pedestrians. Better coordination for vehicles may lead to worse coordination for pedestrians. However, if only through movements are considered, as in conventional designs, the vehicular bandwidth will reach a plateau with increasing vehicular green time, and decreasing green time for pedestrians at the midblock crosswalk seems to be meaningless. The benefits for vehicles are easy to underestimate, which may lead to inappropriate signal timing.

Impact of Through Movement Proportion

Using the same segment described in Fig. 6, two cases of the through movement of the volume at the two adjacent intersections were considered: 50 and 90%. The location of the crosswalk was fixed at the middle of the segment ($L_j = 203$ m). The results are shown in Fig. 10. The following observations can be made:
- The proposed model is less sensitive to changes in the through-movement proportion of the traffic volume because all movements are considered.
- When the through-movement proportion of the traffic volume is quite high (90% in the test, for example), the conventional design approach (in which only through movements are coordinated) may perform similarly to the proposed model.

Conclusions

An integrated design model for midblock crosswalks that increases the operation efficiency of both vehicles and pedestrians on urban arterials is presented in this paper. The model combines location selection and signal timing in a unified framework. To balance the trade-off between the operations of pedestrians and vehicles, the optimization model is formulated as a two-objective linear programming problem. The Pareto frontier of solutions obtained with the proposed model was drawn by iterating all possible combination of the weights. Extensive numerical analyses and case studies were conducted to evaluate the performance of the proposed design model. The following conclusions can be drawn from the results:
- The proposed model could provide improved decisions for the location of crosswalks. If the location of the crosswalk cannot be changed, there is an additional decrease of approximately 1.2% in bandwidth for every 10-m increase in the difference between the location of the crosswalk and the optimal location under one-stage design condition.
- The proposed model is less sensitive to changes in the through movement proportion of the traffic volume by considering all vehicular movements.
- The two-stage design performs better than the one-stage design and is less sensitive to the location selection, the length of the crosswalk, and the turning volume proportion.

There may exist access points between the signalized intersection and the crosswalk that may cause initial queue length at the intersection and decrease the travel speed. Therefore, the effective green time and the vehicular travel speed should be carefully adjusted before model application.

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