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Applicability of single and double phase mid-block crossings

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With the goal of improving pedestrians' convenience and safety, signalised mid-block crossings are commonly installed in highly-populated areas lacking convenient intersection crossings. However, few studies have sought to provide standards for the application of single- and double-phase crossings in highly-populated areas. Moreover, previous studies have not addressed the design capacities of single- or double-phase crossings with their associated vehicle lanes. This paper proposes an approach to determining the applicability of single- and double-phase crossings based on the relationships between control cycles, green time and clearance time at mid-block crossings. Single- and double-phase crossing efficiency along with several key crossing design parameters, such as crossing width, crossing length, traffic demand, are discussed in this paper. The research findings show that double-phase crossings provide superior flexibility for highly populated areas. Findings also show that the design crossing capacity is affected more by the crossing width than by length, while the design lane capacity is affected more by the crossing length than width. Finally, the paper provides a guideline for determining the applicability of single- and double-phase crossings in highly-populated areas.

Notation

A deceleration rate of vehicles
C cycle length
d_1 uniform control delay assuming uniform arrivals
d_2 incremental delay that accounts for effect of occasional cycle overflow
d_{gp} average delay of pedestrians arriving during the green time
d_p average pedestrian delay
d_p^{max} pedestrian maximum delay time in one cycle
d_{p1} phase-one average pedestrian delay for double-phase crossing
d_{p2} phase-two average pedestrian delay for double-phase crossing
d_{n2} delay for pedestrians walking from the near-end sidewalk in the second phase
d_{f2} delay for pedestrians walking from the far-end sidewalk in the second phase
d_v vehicle delay
E number of pedestrians arrived in a cycle
PF progression adjustment factor;
g'_p pedestrian flash green time ('flashing don't walk' time)
g_p pedestrian green time
g_v vehicle green time
g_v^{min} minimum green time for vehicle
G roadway grade
I upstream adjustment factor
K incremental delay factor
k_j adjustment factor for jaywalkers
k_{uv} adjustment factor for non-uniform vehicle arrival rate
L pedestrian crossing length
L_v length of a standard vehicle
N_p number of crossing pedestrians in one cycle
M pedestrian space required for a single pedestrian waiting for crossing
P distance from the departure STOP line to the far side of the pedestrian crossing
Q vehicle demand (veh/hour/lane)
q_p pedestrian arrival rate
Q_p pedestrian demand in one direction
r'_p pedestrian clearance red time
r_p pedestrian red time

r_v vehicle red time
r_v' vehicle clearance red time
s' saturation flow rate (veh/hour/lane)
S_{85} 85th percentile speed of approaching vehicles
S_{15} 15th percentile speed of approaching vehicles
t_c design minimum total clearance time in one cycle
t_m additional time needed to walk along the median
t_{off} offset time between phases in double-phase pedestrian signal
t_{px} pedestrian crossing time
t_{pxm} pedestrian crossing time from each sidewalk to the median
T duration of analysis period
u_v green ratio
v_p pedestrian speed
W pedestrian crossing width
X v/c ratio for a lane and typically referred to as degree of saturation;
y_v vehicle yellow time

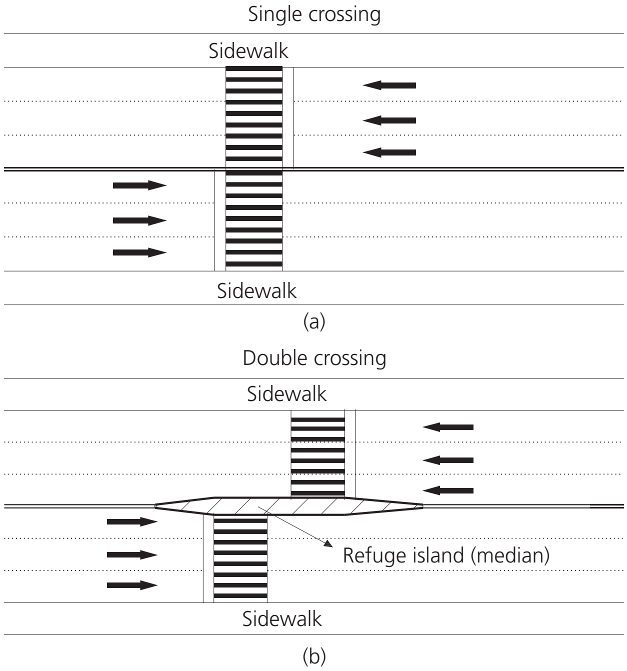

Figure 1. Types of signalised mid-block crossings: (a) single-phase crossing and (b) double-phase crossing

1. Introduction

A pedestrian crossing (or crosswalk) is a roadway segment designated for pedestrians to cross (NCUTLO, 2000). In terms of control types, pedestrian crossings can be categorised into two types: unsignalised crossings, which are usually designed for low traffic and pedestrian volumes, and signalised crossings which are designed for higher traffic and pedestrian volumes. Note that in the UK and certain other countries, some 'Zebra' crossings with flashing orange globes are considered as unsignalised crossings. In terms of installation locations, pedestrian crossings can also be categorised into two types: (1) mid-block crossings, and (2) intersection crossings (Axelson *et al.*, 1999). Intersection crossings are commonly seen in both urban and rural areas. Mid-block crossings are installed in some highly populated areas with heavy pedestrian traffic and placed far from the intersections. The distance from the mid-block crossing to the nearest intersection depends on pedestrian demand and behaviour. In China, a mid-block crossing is required if the nearest intersection is more than 250 m away in the city centre or 400 m away in industrial areas (SMEAB, 2007). Pedestrian activity is higher in more densely populated Asian cities (e.g. Beijing) and signalised mid-block crossings are fairly common. Two common types of signalised mid-block crossings adopted in Asia are: single-phase crossings and double-phase crossings. In this paper, a single-phase crossing is defined as a regular crosswalk where pedestrians cross the street without any stops, as shown in Figure 1(a). A double-phase crossing is defined as a crosswalk with a refuge island (or a median), as shown in Figure 1(b). Pedestrians have to cross the street in two phases: in the first phase, pedestrians waiting on the sidewalk walk to the refuge island; during the second phase, pedestrians waiting at the refuge island cross the other half of the street to complete the crossing. This type of crossing can improve crossing safety by allowing slower pedestrians, such as the elderly and disabled, to wait at the refuge island while crossing.

In highly populated areas, mid-block crossings are needed to connect major pedestrian origins and destinations on opposite sides of a street. In the Manual on Uniform Traffic Control Devices (MUTCD) (FHWA, 2009) and Manual of Traffic Signal Design (MTST) (Kell and Fullerton, 1991), a traffic control signal for mid-block crossings can be justified if the pedestrian volume is 100 per hour or more over four hours, or 190 or more during any given hour and there are fewer than 60 gaps per hour in the traffic stream for pedestrians to cross during the same period. The MUTCD and the MTST, however, do not specify the crossing types for different traffic and pedestrian situations. If the type of the signalised mid-block crossing is not properly determined and designed, vehicle and pedestrian delays may increase and the probability of signal evasions such as jaywalking and red light running would increase accordingly.

Pedestrian delays at different types of crossings have been investigated in previous research papers (Dunn and Pretty, 1984; Messer and Fambro, 1977; TRB, 2000; Chu and Baltes, 2003; Yang *et al.*, 2006, 2007; Ishaque and Noland, 2007; Zou *et al.*, 2009). Dunn and Pretty (1984) and Chu and Baltes (2003) further considered pedestrian delay at mid-block crossings. Alhajyaseen and Nakamura (2010) examined the required crosswalk widths for various pedestrian demands, and the effects of bi-directional flow on crossing speed are also discussed in their research. However, in most previous research, the applicability of different mid-block crossing types was not addressed, and few research papers have sought to provide a method for determining the appropriate type of signalised mid-block crossing. Even though Yang *et al.* (2006) provided an approach for determining the applicability of the signalised double-phase crossings based on average pedestrian delay, the vehicle delay and the maximum pedestrian delay were not considered in their models.

This paper aims to develop an approach to determine the applicability of single-phase and double-phase mid-block crossings. The rest of the paper is organised as follows. In the next section, the signal timing for mid-block crossings will be elaborated and calculated. Next, vehicle and pedestrian delays for each crossing type will be estimated. This will be followed by vehicle and pedestrian delay analyses for single- and double-phase crossings based on the key parameters of crosswalk width, crosswalk length and traffic demand. After obtaining delays and demands, guidelines for determining the applicability of single- and double-phase crossings will be proposed. Lastly, our conclusions and some recommendations for the design of pedestrian crossings will be given.

2. Methodology

2.1 Signal timing for mid-block crossings

In this section, the signal timing for single-phase crossings is introduced first. This signal timing can be further applied to double-phase crossings. Then, the cycle length for both crossing types will be estimated and used in the delay estimation in the Delay Calculation section.

2.1.1 Cycle length

Traffic control strategies for pedestrians have been theoretically developed in previous studies (TRB, 2000; Yang *et al.*, 2001). Even though cycle and delay calculations for double-phase crossings are not included their methods, the parameters and the concepts proposed in their research build the foundation for our research. For signalised mid-block crossings, two-phase control, one phase for vehicles and the other for pedestrians, is one of the most common strategies. A timing plan is shown in Figure 2. Stripe A is the signal timing for vehicles and stripe B is the signal timing for pedestrians.

Based on previous research (TRB, 2000; Yang *et al.*, 2001), the cycle length c is defined as

1. $$C = g_v + y_v + r'_v + r_v = r_p + g_p + g'_p + r'_p$$

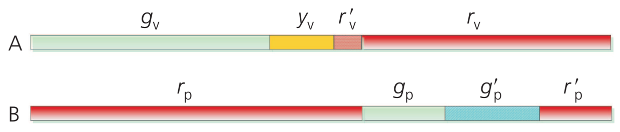

Figure 2. Signalised mid-block traffic signal timing

where g_v, y_v, r_v are the vehicle green, yellow, and red times respectively; r'_v and r'_p are the clearance red times (that is all-red times) for vehicles and pedestrians, respectively; g_p, g'_p, r_p, are the pedestrian green time, flashing green (that is 'Flashing Don't Walk (FDW)' time) and red times, respectively.

2.1.2 Clearance time calculation

In order to effectively estimate the cycle length, we redefine the cycle length as

2. $$C = g_v + g_p + t_c$$

where t_c is the total clearance time for pedestrians and vehicles. Thus, t_c is defined based on Equation 1 and shown as follows

3. $$t_c = y_v + r'_v + g'_p + r'_p$$

The calculation of yellow time and all red time for the vehicles is recommended by ITE as equations 4 and 5, respectively) (ITE, 1985; Roess *et al.*, 2004)

4. $$y_v = t + \frac{0{\cdot}28S_{85}}{2a + (64{\cdot}4 \times 0{\cdot}01G)}$$

5. $$r'_p = \frac{P + L_v}{0{\cdot}28S_{15}}$$

where t is the driver reaction time (s); S_{85} is 85th percentile speed of approaching vehicles (mile/h); a is the deceleration rate of vehicles (m/s^2); G is the roadway grade (%); P is the distance from the departure STOP line to the far side of the farthest conflicting pedestrian crosswalk (m); L_v is length of a standard vehicle (m); S_{15} is 15th percentile speed of approaching vehicles (mile/h).

In Equation 3, r'_p is the all red time for pedestrians. In practice, one second is used; g'_p is additional seconds that are required for pedestrians to cross safely. The minimum time for g'_p is

6a. $$g'_p = t_{px} = \frac{L}{v_p}$$

where t_{px} is the pedestrian crossing time; L is the crosswalk length, v_p is the pedestrian speed. Note that the pedestrian crossing time in Equation 6a is estimated for a single-phase crossing. In terms of double-phase crossings, the pedestrian clearance time for a double-phase crossing is only half of the single-phase crossing since pedestrians only need to cross half of the street. Thus, the pedestrian crossing time t_{pxm} is

6b. $$g'_p = t_{pxm} = \frac{L}{2v_p}$$

As defined in Equation 2, g_v and g_p are essential for calculating the cycle length. These two phase times are estimated below.

2.1.3 Green time calculation

2.1.3.1 GREEN TIME FOR VEHICLES

Vehicle green time is defined as follows (TRB, 2000)

7. $$g_v = \frac{qC}{sX}$$

8. $$g_v \geqslant g_v^{\min}$$

where s is the saturation flow rate (veh/hour per lane)); C is the cycle length; q is the vehicle demand (veh/hour per lane); $g_v^{\min}$ is a minimum green time for vehicles. X is design volume over capacity (v/c) ratio for a lane group and typically referred to as the degree of saturation. Note that the green time for vehicles should be long enough for all of the arriving vehicles to fully discharge in one cycle.

2.1.3.2 GREEN TIME FOR PEDESTRIANS

As indicated by HCM 2000 (TRB, 2000), the total crossing time required to clear an intersection crossing is recommended as

9. $$g_{pc} = 3{\cdot}2 + \frac{L}{v_p} + \begin{cases} \left(0{\cdot}81 \times \dfrac{N_p}{W}\right) & \text{for } W > 3{\cdot}0 \text{ m} \\ (0{\cdot}27 \times N_p) & \text{for } W > 3{\cdot}0 \text{ m} \end{cases}$$

where N_p is the number of crossing pedestrians in one cycle; W is the crosswalk width. N_p can be calculated as

10. $$N_p = q_p \times C$$

where q_p is the pedestrian demand (ped/h). If the flashing green is not considered as the pedestrian green time, then the minimum pedestrian green time can be calculated by removing the FDW interval (L/v_p) as shown in Equation 11.

11. $$g_p = g_{pc} - \frac{L}{v_p} = 3{\cdot}2 + \begin{cases} \left(0{\cdot}81^* \dfrac{N_p}{W}\right) & \text{for } W > 3{\cdot}0 \text{ m} \\ \left(0{\cdot}27^* N_p\right) & \text{for } W \leqslant 3{\cdot}0 \text{ m} \end{cases}$$

After substituting Equations 7, 10 and 11 into Equation 2, the signal cycle can be calculated as

12. $$C = \begin{cases} \dfrac{t_c + 3{\cdot}2}{1 - \dfrac{q}{sX} - 0{\cdot}81 \times \dfrac{q_p}{W}} & \text{for } W > 3{\cdot}0 \text{ m} \\ \dfrac{t_c + 3{\cdot}2}{1 - \dfrac{q}{sX} - 0{\cdot}27 \times q_p} & \text{for } W \leqslant 3{\cdot}0 \text{ m} \end{cases}$$

2.2 Delay calculation

Pedestrian delay has been used as a measure of pedestrian Quality of Service (QOS) for mid-block street crossings, and is also regarded as a Measure of Effectiveness (MOE) for evaluating pedestrian crossing convenience and safety (Chu and Baltes, 2003). Therefore, this paper adopts pedestrian delay as a MOE for determining the applicability of single- or double-phase crossings at mid-block. In addition to pedestrian delay, vehicle delay caused by pedestrian crossings is also considered and introduced.

2.2.1 Pedestrian delay

Pedestrian delay is the time pedestrians spend waiting to cross, either at the sidewalk or in the middle of the street (Chu and Baltes, 2001). Previous research indicates that the average pedestrian delay at signalised crossings is related to the cycle length and the green time in a cycle if all the pedestrians can cross the street during one cycle (TRB, 2000; Quan, 1989). Li *et al.* (2005) developed a pedestrian delay model based on field research data. Their model is of a more generalised form than previous models, and was adopted in this study as defined below

13. $$d_p = d_{gp} + \frac{k_{uv} k_j (C - g_p)^2}{2C}$$

where d_p is the average pedestrian delay (seconds per person in a cycle); d_{gp} is the average delay of pedestrians arriving during the green time; k_{uv} is the adjustment factor for non-uniform vehicle arrival rate; k_j is the adjustment factor for jaywalkers which refer to illegal or reckless pedestrians crossing of a roadway. Note that if the field survey is not conducted, the default values of d_{gp}, k_{uv} and k_j are 0, 1 and 1 respectively. In this case, the model will be identical to the average pedestrian delay model used in HCM 2000.

Equation 13 can be used to estimate pedestrian delay for single-phase crossings and the first phase of the double-phase crossings. However, the random arrival assumption cannot be supported for the second phase of the double-phase crossing. The second phase of a double phase crossing will begin with all of the crossing pedestrians queued on a wide and shallow median which will allow for very high pedestrian discharge rates with low variability. Therefore, the pedestrian delay for the second-phase of the double-phase crossing should be estimated separately, and the average pedestrian delay for the double-phase crossing is composed of the delays which occur in the first and second phases as shown in Equation 14

14. $$d'_p = d_{p1} + d_{p2} + t_m$$

where d_{p1} is the first phase delay which can be estimated by Equation 13; d_{p2} is the average pedestrian delay in the second phase; t_m is the additional time needed to walk along the median. It should be noted that pedestrians from either direction would suffer different delays because of the signal offset between two cycles. The average pedestrian delay should be calculated for two directions separately as is shown in Equation 15

15. $$d_{p2} = \frac{1}{2}(d_{n2} + d_{f2})$$

where d_{n2} is the delay for pedestrians walking from the near-end sidewalk (bottom of Figure 1(b)) in the second phase; d_{f2} is the delay for the pedestrians walking from the far-end sidewalk (top of Figure 1(b)) in the second phase.

Assuming the median is installed in the middle of the street, the pedestrian crossing time from each sidewalk to the median, t_{pxm} is equal to half of the crossing time of completely crossing the street (see Equation 6). To simplify the calculation process, assuming pedestrian volume from the near-end sidewalk is greater than or equal to the volume from the far-end sidewalk, the signal offset, t_{off}, should be designed equal to t_{pxm} plus t_m so as to minimise the pedestrian delay for the direction with higher volume. Thus, the pedestrian delay in the second phase of a double-phase crossing should be zero as shown in Equation 16

16. $$d_{n2} = t_{off} - t_{pxm} - t_m = 0$$

After substituting Equation 16 into Equation 15

17. $$d_{p2} = \frac{1}{2}(d_{n2} + d_{f2}) = \frac{1}{2}d_{f2}$$

Now the average pedestrian delay for the double-phase crossing in Equation 14 can be formulated as Equation 18

18. $$\begin{aligned} d'_p &= d_{p1} + d_{p2} + t_m \\ &= d_{gp} + \frac{k_{uv}k_j(C - g_p)^2}{2C} + \frac{1}{2}d_{f2} + t_m \end{aligned}$$

where d_{f2} should be determined based on the length of green time of the first phase of the near-end sidewalk. If the green time for the pedestrians from the near-end sidewalk is not long enough ($g_p \leqslant t_{pxm} + t_{off}$), all the pedestrians from the far-end will suffer delay in the second phase because they have to wait in the median for another cycle. When the green time for pedestrians from the near-end sidewalk is greater than total crossing time for both phases of a double phase crossing ($g_p > t_{pxm} + t_{off}$), then only a proportion of the pedestrians from the far-end can cross their second phase directly. This portion of the pedestrians can be calculated as

19. $$p = \frac{g_p - t_{off} - t_{pxm}}{g_p}$$

$$g_p > t_{pxm} + t_{off}$$

Then, the portion of the pedestrians who cannot complete the second phase can be calculated as

20. $$1 - p = \frac{t_{pxm} + t_{off}}{g_p}$$

$$g_p > t_{pxm} + t_{off}$$

In this case, the pedestrian delay for the far-end side in the second phase is defined as

21. $$d_{f2} = \begin{cases} C - t_{off} - t_{pxm} & \text{if } g_p \leqslant t_{pxm} + t_{off} \\ (C - g_p)\dfrac{t_{pxm} + t_{off}}{g_p} & \text{if } g_p > t_{pxm} + t_{off} \end{cases}$$

Note that the cycle length and the timing plan are determined by the direction with higher pedestrian volume, because the objective of the proposed design is to allow most of the pedestrians to cross the street successfully.

According to HCM 2000 (TRB, 2000), the likelihood of noncompliance rises to a 'high' level if pedestrians experience long waiting delay. Thus, the maximum pedestrian delay for each signal phase is also an important MOE for engineers' reference. The maximum pedestrian delay for each phase (both in single- and double-phase situation) of the crossing is defined as

$$d_p^{\max} = C - g_p \tag{22}$$

2.2.2 Vehicle delay

The vehicle delay was estimated by the first and the second terms of Webster's delay model shown in Equation 23 (TRB, 2000)

$$d_v = d_1(PF) + d_2 \tag{23}$$

where d_1 is the uniform control delay assuming uniform arrivals and PF is the progression adjustment factor. d_2 is the incremental delay that accounts for the effect of occasional cycle overflow. Based on the definition in the Highway Capacity Manual (TRB, 2000), Equation 23 can be rewritten as

$$d_v = \frac{0{\cdot}5C(1-u_v)^2}{1-\min(1,\,X)u_v}(PF) + 900T\left[(X-1)+\sqrt{(X-1)^2+\frac{8kIX}{sT}}\right] \tag{24}$$

where u_v is the green ratio; T is duration of analysis period; k is incremental delay factor; I is upstream adjustment factor. In this study, $k = 0{\cdot}5$ is used for pre-timed control. $I = 1$ is used for an isolated signal control.

3. Results and discussions

3.1 Delay analysis

In this section, the pedestrian and vehicle delays for single- and double-phase crossings will be analysed for different roadway conditions. The analyses serve as a foundation for determining crossing type applicability in the next section. In the following analysis, average pedestrian delay (Equations 13 and 18), maximum pedestrian delay (Equation 22) and average vehicle delay (Equation 24) will be calculated for both single-phase and double-phase crossing scenarios. The effects of crosswalk length, pedestrian volume, vehicle demand, and crosswalk width will also be analysed quantitatively.

3.1.1 Assumptions

Before applying the proposed delay model, the assumptions of the fundamental parameters in the model are summarised as follows

- saturation flow rate, $s = 1500$ veh/h per lane
- minimum green time for vehicles $g_v^{\min} = 10$ s
- yellow time plus all red time for vehicles $y_v + r_v = 3$ s
- additional time needed to walk along the median to the other crosswalk $t_m = 3$ s
- design volume over capacity (v/c) ratio $X = 0{\cdot}9$
- incremental delay factor $k = 0{\cdot}5$
- upstream adjustment factor $I = 1$
- duration of analysis period $T = 0{\cdot}25$
- pedestrian speed $v_p = 1{\cdot}2$ m/s (see TRB, 2000; Tarawneh, 2001; Bowman and Vecellio, 1994)
- required space for pedestrians in the queuing area: $M = 0{\cdot}3\text{m}^2$/ped (TRB, 2000)
- minimum width of the median = 2·0 m for pedestrians carrying bicycles or baby carriages.

The median length is determined by the average pedestrian volume at that crossing. If the pedestrian volume is high, then the crossing width and the median length should be increased accordingly. If the crossing width in Figure 1 is designed as 5 m wide, then the median should be a little longer than 10 m. Hence, the median can hold (10 × 2·0)/0·3 = 67 people. With a pedestrian red time of 40 s, a maximum arrival rate of 67/40 = 1·675 ped/s could be accommodated. This would equate to a maximum flow of 6030 ped/h. Thus, the storage of the median with 2·0 m width and 10 m length is sufficient even for high volumes of pedestrians. If the pedestrian volume is higher than 6030 ped/h, the median need to be expanded accordingly.

3.1.2 Effect of crosswalk length

Figure 3 shows the pedestrian and vehicle delay curves for different crosswalk lengths assuming the vehicle demand, q is 600 veh/h and the pedestrian demand, Q_p is 600 ped/h (300 ped/h in one direction). HCM (TRB, 2000) provides Level of Service (LOS) criteria based on pedestrian delay at signalised intersections. When pedestrians experience a delay longer than 40 seconds, the likelihood of noncompliance rises to a 'high' level. When pedestrian delay reaches 60 seconds, pedestrians are likely to cross the street during red time (TRB, 2000; Quan, 1989). This paper has adopted 40 seconds of delay as a critical case threshold value. This is conservative because pedestrians in highly populated areas tend to impatience. This threshold line is illustrated as a horizontal line in Figure 3(a). Thus, the critical crosswalk length can be determined by locating the crosswalk length which corresponds to the 40 second threshold on the maximum delay curve (for either single-phase or double-phase crossings).

From Figure 3(a), one can find that

- The average pedestrian delays are similar for single- and double-phase crossings.
- The single-phase crossing has much larger maximum delay. As the lane width increases, the maximum delay curve for single-phase crossings increases more rapidly than that for double-phase crossings. This is because

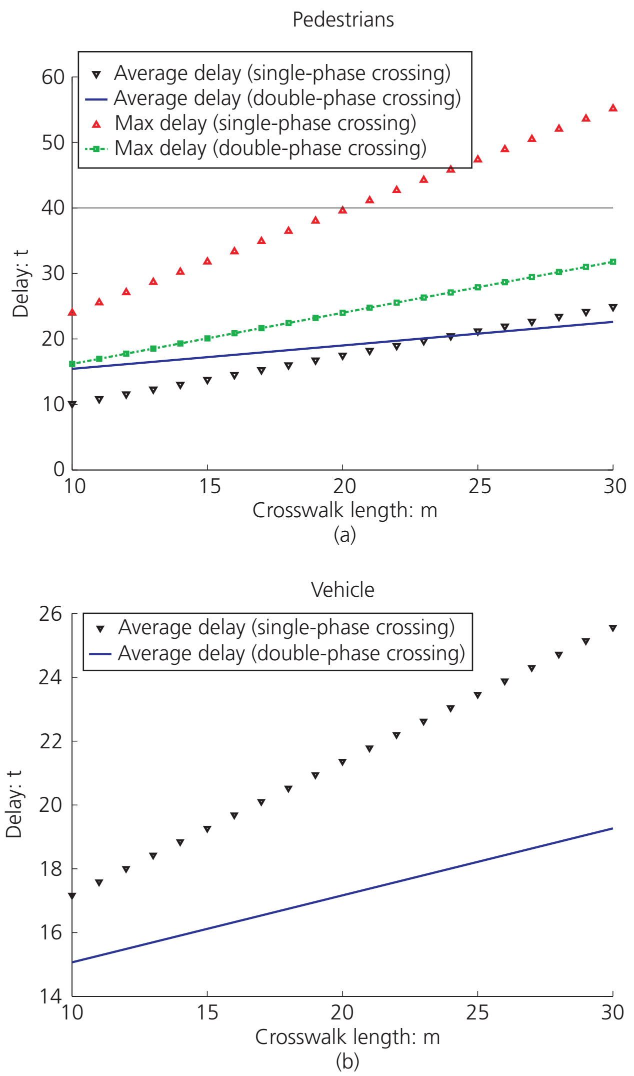

Figure 3. Effects of crosswalk length on (a) pedestrian delay, and (b) vehicle delay

single-phase crossings have a longer cycle time as calculated by Equation 12.

- The maximum pedestrian delay curve for single-phase crossings will exceed the 40 second threshold when the crosswalk length increases beyond 20 m, equivalent to the approximate width of four lanes. In other words, pedestrians are likely to violate the traffic light at a single-phase crossing if the crosswalk length is designed longer than four lane widths.

The average vehicle delay is shown in Figure 3(b), and one can find that

- As the crosswalk length increases, the average vehicle delay for single-phase crossings increases more rapidly than that of double-phase crossings. Overall, single-phase crossings have almost twice the delay of double-phase crossings.

3.1.3 Effect of demand

Figure 4 shows the effects of different pedestrian or vehicle demands on delays assuming a crosswalk width and length of $W = 3$ m and $L = 22$ m, the equivalent to a two-way four-lane street. Figures 4(a) and 4(b) show the delay variations with different pedestrian demands assuming the vehicle demand q is 600 veh/h. Figures 4(c) and 4(d) show the delay variations with different vehicle demands assuming the pedestrian demand Q_p is 600 ped/h.

Conclusions that may be drawn from Figure 4 are shown below:

- Figures 4(a) and 4(c) show that the double-phase crossing can allow higher pedestrian demand under the 40 second constraint and can provide more flexibility in the design of pedestrian crossings; the maximum pedestrian delay of a single-phase crossing is above the threshold even in a fairly low pedestrian volume (e.g. 100 ped/h at the beginning point of the curves in Figure 4(a)) because the single-phase crossing needs a longer cycle.
- Figures 4(b) and 4(d) show that the average vehicle delay at a single-phase crossing is larger than that of a double-phase crossing at different pedestrian and vehicle demand levels.

3.1.4 Effect of crosswalk width

Figure 5 shows the effects of different crosswalk widths on vehicle and pedestrian delays assuming the crosswalk length is $L = 15$ m (two-way four-lane road) and the vehicle demand q is 600 veh/h. Figure 5(a) shows the delay with different pedestrian demands assuming a crosswalk width of $W = 5$ m. Figure 5(b) shows the delay for different pedestrian demands assuming the crosswalk width $W = 10$ m.

The crosswalk width is one of the major factors that affect the maximum pedestrian volume at crosswalks. As shown in Figure 5(a), the delay will increase exponentially when the pedestrian demand exceeds a critical value. Figure 5(b) shows that all the delay curves have a similar trend but increases more slowly when the crosswalk is wider (10 m).

Hence, crosswalk width should be wider in highly populated areas, such as shopping districts and transportation terminals, in order to meet the demand of pedestrians crossing. Moreover, the maximum pedestrian delay of the single-phase crossing is much greater than that of a double-phase crossing. Since higher delays can lead pedestrians to have a higher likelihood of noncompliance (TRB, 2000), pedestrians are more likely to cross the roadway illegally in the single-phase crossing given high pedestrian volume.

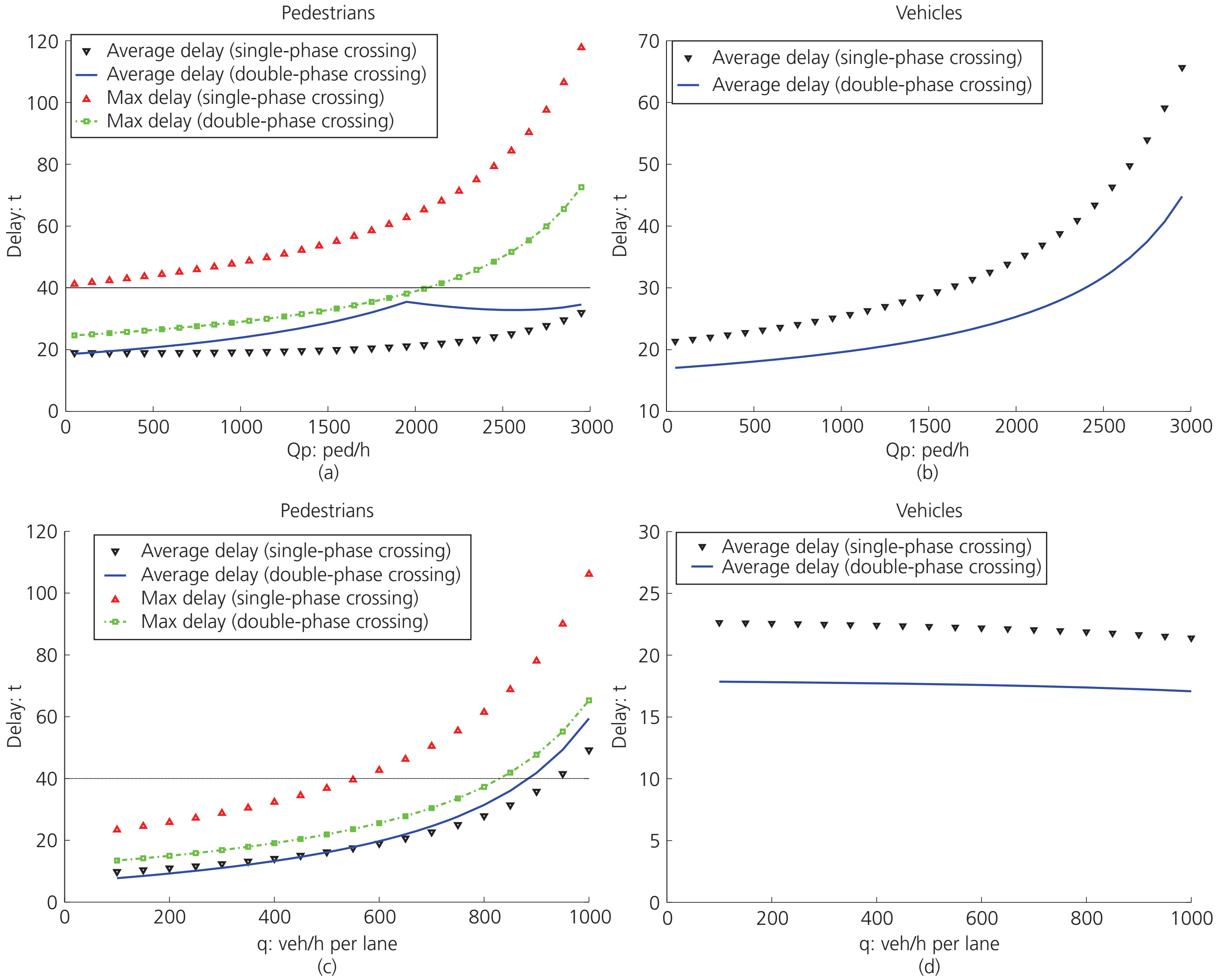

Figure 4. Effects of demand on pedestrian and vehicle delays: (a) pedestrian delay, assuming vehicle demand q is 600 veh/h, (b) vehicle delays, assuming vehicle demand q is 600 veh/h, (c) pedestrian delay, assuming the pedestrian demand Q_p is 600 ped/h, and (d) vehicle delay, assuming the pedestrian demand Q_p is 600 ped/h

3.2 Single-phase or double-phase crossing?

After analysing the effects of different parameters on pedestrian and vehicle delays, it is still difficult to decide whether a single- or double-phase crossing should be installed. It would be desirable to have a guideline to determine whether a single-phase or double-phase crossing would be optimal in a given location.

Figure 6 includes all the plots used for determining the applicability of crossing type based on different roadway conditions. In each graph, the *x*-axis is the vehicle demand and the *y*-axis is the pedestrian demand. Each plot has two curves that separate the plot into three regions (A, B and C respectively). Each point on the curve is generated by calculating the combination of allowable maximum vehicle and pedestrian demands under the critical pedestrian waiting time constraint of 40 seconds. Each combinatorial value can be calculated through the cycle length calculation (see Equation 12) and the maximum pedestrian delay model (see Equation 22).

Each graph represents the applicability of each crossing type and can easily be used for determining the optimum mid-block

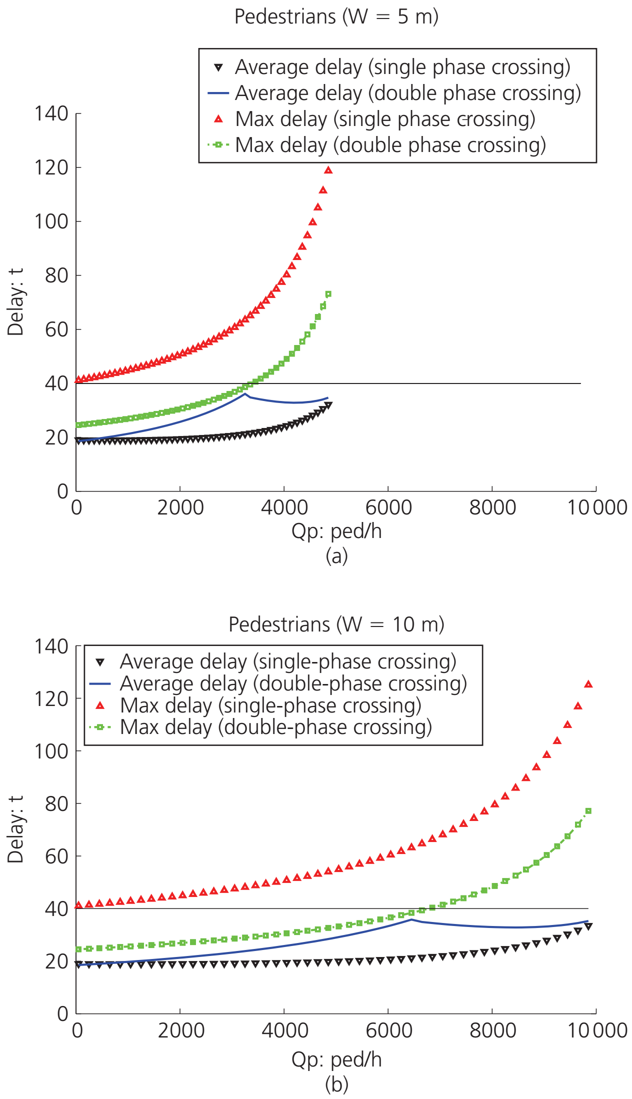

Figure 5. Effects of crosswalk width on pedestrian delay: (a) assuming crosswalk width W = 5 m; and (b) assuming crosswalk width W = 10 m.

crossing type. Region A represents the conditions that both single-phase crossing and double-phase crossing work satisfactorily. Region B represents the conditions that only double-phase crossings are recommended. Region C represents the conditions that neither single-phase nor double-phase crossings work well. Alternatives such as overpasses or tunnels should be considered.

The plots found in Figure 6 can also serve as tools to determine the maximum allowable vehicle demand (design lane capacity) and the maximum allowable pedestrian demand (design crossing capacity) for each crossing type. As shown in Figure 6, different roadway conditions are evaluated and findings can be summarised as follows

- By comparing the left and right columns of Figure 6, the design crossing capacity increases with crosswalk width. However, the crosswalk width has little effect on the design lane capacity for vehicles.
- By comparing each pair (each row) of Figure 6, crosswalk length has little effect on the crossing design capacity. This design capacity remains almost the same as the crosswalk length increases. However, the design lane capacity of vehicular traffic decreases as the crosswalk length increases. That is because the required pedestrian clearance time becomes larger as the crosswalk length grows. Keeping the pedestrian delay lower than 40 seconds imposes a maximum on the green time for vehicles.
- The design lane capacity at a double-phase crossing is larger than that at a single-phase crossing. In other words, the double-phase crossing can provide better efficiency when the vehicle demand is high. That is because the crosswalk length for a double-phase crossing is half of that for the corresponding single-phase crossing.

4. Conclusion

Signalised mid-block crossings are commonly installed in highly-populated areas, and are especially common in major Asian cities. This paper provides a novel approach for evaluating vehicle and pedestrian delays as well as determining the applicability of single- and double-phase crossings based on different traffic and facility parameters. Based on delay analyses, single- and double-phase crossings have similar average pedestrian delays. However, single-phase crossings have larger maximum pedestrian delays and larger average vehicle delays. These delays increase rapidly as pedestrian demand or vehicle demand increases. Thus, the double-phase crossing proved more suitable for high traffic/pedestrian conditions. Based on the delay analysis, the double-phase crossing should be recommended for highly populated areas given finite roadway space and budgets.

The proposed approach adopted the HCM-based models and can be applied to any highly-populated city, provided that some location-dependent parameters, such as pedestrian space and speed, are properly calibrated. Even though the proposed approach is designed for highly-populated areas, it can also be applied to determining the requirements regarding actuated pedestrian control systems based on the calculated delay during peak hours. For example, school areas may have inconsistently high traffic volume and pedestrian demand after school.

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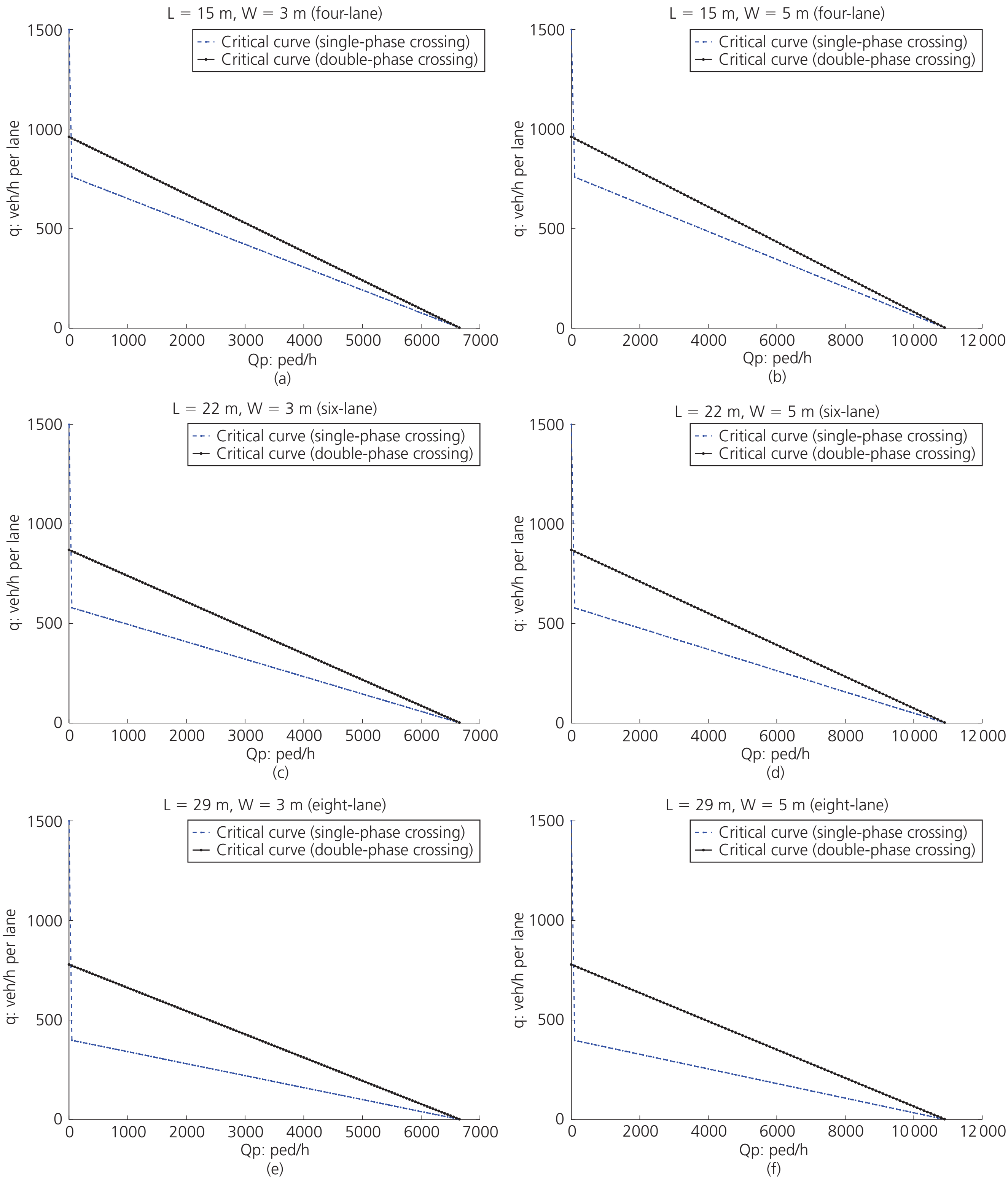

Figure 6. Plots for determining applicability of crossing types in different roadway conditions

REFERENCES

Alhajyaseen WKM and Nakamura H (2010) Quality of pedestrian flow and crosswalk width at signalised intersections. *IATSS Research* **34(1)**: 35–41.

Axelson PW, Chesney DY, Galvan DV *et al.* (1999) *Designing Sidewalks and Trails for Access*. Federal Highway Administration, Washington, DC, USA.

Bowman BL and Vecellio RL (1994) Pedestrian walking speeds and conflicts at urban median locations. *Transportation Research Record: Journal of the Transportation Research Board* **1438**: 67–73.

Chu X and Baltes MR (2001) *Pedestrian Mid-Block Crossing Difficulty, Final Report*. National Center for Transit Research, University of South Florida, Tampa, FL, USA, Report NCTR-392-09.

Chu X and Baltes MR (2003) Measuring pedestrian quality of service for mid-block street crossings: selection of potential determinants. *Transportation Research Record: Journal of the Transportation Research Board* **1828**: 89–97.

Dunn R and Pretty R (1984) Mid-block pedestrian crossings - An examination of delay. *Australian Road Research* **12(4)**: 118–127.

FHWA (Federal Highway Administration) (2009) *Manual on Uniform Traffic Control Devices* (MUTCD), 2009ed. FHWA, ATSSA, AASHTO and ITE, Washington, DC, USA. See http://mutcd.fhwa.dot.gov/kno_2009.htm (accessed 22/03/2012).

Ishaque MM and Noland RB (2007) Trade-offs between vehicular and pedestrian traffic using micro-simulation methods. *Transport Policy* **14(2)**: 124–138.

ITE (Institute of Traffic Engineers) (1985) *Recommended Practice: Determining Vehicle Change Interval*. ITE Technical Committee for A-16, ITE Washington, DC, USA.

Kell JH and Fullerton IJ (1991) *Manual of Traffic Signal Design*, 2nd edn. Institute of Transportation Engineers, Washington, DC, USA.

Li Q, Wang Z, Yang J and Wang J (2005) Pedestrian delay estimation at signalised intersections in developing cities. *Transportation Research Part A: Policy and Practice* **39(1)**: 61–73.

Messer CJ and Fambro DB (1977) Critical lane analysis for intersection design. *Transportation Research Record: Journal of the Transportation Research Board* **644**: 95–101.

NCUTLO (National Committee on Uniform Traffic Laws and Ordinances) (2000) *UVCMTO (Uniform Vehicle Code and Model Traffic Ordinance)*, Millennium Edition. NCUTLO, Evanston, IL, USA.

Quan RS (1989) *Urban Traffic Control*. China Communications Press, Beijing, China.

Roess RW, McShane WR and Prassas E (2004) *Traffic Engineering*, 3rd edn. Prentice Hall, Englewood Cliffs, NJ, USA.

SMEAB (Shanghai Municipal Engineering Administration Bureau) (2007) *Shanghai Urban Roads Planning And Design Of Pedestrian Crossing Facility Guide*. SMEAB, Shanghai, China.

Tarawneh MS (2001) Evaluation of pedestrian speed in Jordan with investigation of some contributing factors. *Journal of Safety Research* **32(2)**: 229–236.

TRB (Transportation Research Board) (2000) *Highway Capacity Manual 2000*. Transportation Research Board of the National Academies, Washington, DC, USA.

Yang X, Fu Q and Yang X (2006) Setting criterion of pedestrian double crossing at signalized control link. *China Journal of Highway and Transport* **19(4)**: 109–113.

Yang X, Chen B and Peng G (2001) Study of the way of setting pedestrian's traffic control system. *China Journal of Highway and Transport* **14(1)**: 73–80.

Yang X, Lao Y and Yun M (2007) Application of different pedestrian cross pattern to no-signal controlled segment. *Journal of Tongji University* **35(11)**: 17–21.

Zou Z, Zhou Z and Ge H (2009) Optimization of road section crosswalk signal design. *Journal of Transportation Systems Engineering and Information Technology* **9(6)**: 142–147.