

MODELLING THE EFFECTS OF PEDESTRIANS ON INTERSECTION CAPACITY AND DELAY WITH ACTUATED SIGNAL CONTROL

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ABSTRACT

The current procedure in the Highway Capacity Manual 2000 for analyzing actuated signalized intersections treats pedestrian crossing and timing in a fixed manner, which can lead to erroneous results in capacity and delay calculations. This paper introduces a new model that remedies such a shortcoming in the current procedure. The model takes into account the stochastic nature of pedestrian crossings and their effects. The model consists of calculations of the probability of having a pedestrian call in a cycle, and the corresponding capacities and delays for the traffic movements. The model was compared with the *SimTraffic* simulation model based on a generic intersection with semi-actuated signal control, and was found to produce consistent delay results between the two models. Using the proposed model, the effects of pedestrians on intersection capacity and delay were analyzed. Depending on the pedestrian volume conditions, the current Highway Capacity Manual procedure could produce results of significant errors, with the largest errors possibly occurring under low pedestrian volume conditions. For the vehicle movement that is concurrent with the pedestrian movement, it generally receives more green time with the increase of pedestrian volumes; therefore, higher capacity and lower delay would result. Consequently, the other movements would experience capacity reduction and delay increase. One interesting finding from the study was that the concurrent vehicle movement can achieve a higher capacity with a shorter cycle length with the same pedestrian volumes.

Key words: pedestrian crossing, timing, actuated signal, capacity, SimTraffic

1. INTRODUCTION

The current procedure in the Highway Capacity Manual 2000 (HCM) for analyzing actuated signalized intersections deals with pedestrian crossings and timings in a fixed manner (TRB, 2000). When a pedestrian phase is provided with an actuated push button, the HCM only provides limited guidance on how to set up the green split for the concurrent vehicle movement/phase. A concurrent vehicle phase is usually a through movement phase that runs parallel with the pedestrian phase. During a signal cycle when there is a pedestrian call, the pedestrian phase will be activated with an indication of the WALK interval followed by the pedestrian Flash-Don't-WALK (FDW) clearance interval. In this case, the phase green split must be at least the sum of the WALK interval and the FDW interval. While it has been recognized that the pedestrian phase is actuated only if there is a pedestrian call, the current HCM procedure recommends the phase split satisfying the pedestrian timing regardless of the pedestrian volumes. There are generally no problems if the required vehicle phase split is larger than the pedestrian phase time. Problem arises when the vehicle demand is low, but the pedestrian phase time is high, as in the case of an intersection with a wide major street but low traffic demand in the minor street. Similar to vehicular traffic, pedestrian crossings are

stochastic events. Pedestrian crossing does not occur every cycle, especially when the pedestrian volume is low. Therefore, the current HCM methodology in dealing with pedestrian crossings would produce results that are deviated from actual operations. The purpose of this paper is to address the effect of pedestrian crossing and timing on signalized intersection operations with the consideration of the stochastic nature of pedestrian crossings.

While the stochastic nature of pedestrian crossings has been realized by researchers and practitioners, no analytical models are available to address the pedestrian issues. In an earlier study by Tian et al. (2001), the effect of pedestrian on signalized intersection capacity was discussed based on a split-phase operation. The study found that pedestrian crossing has a profound impact when a street is controlled by a split phase. A model was developed to determine the conditions when the use of an exclusive pedestrian phase might actually increase the capacity compared to the typical split-phasing operation. In a separate study, Tian et al. also addressed the impact of pedestrian crossing on signal coordination (2000). They found out that accommodating pedestrian timing in the signal timing is generally a better strategy from the point of view of signal coordination, because the signal will remain in coordination even with pedestrian calls. However, no formal study was found to have addressed the capacity and delay issues while taking into account the stochastic effect of pedestrian crossings. The lack of international studies on this topic may be due to the unique practice on handling pedestrian crossings in traffic signal controllers in North America, where the pedestrian phases are generally handled with concurrent vehicular phases. Furthermore, the current analytical procedures in capacity and delay calculations are still primarily fixed-time based methodologies.

The remaining of the paper is organized as follows. First, a brief summary of how pedestrian crossings are handled in the current signal operations is provided. The discussions are primarily based on the current practice in North America, where the signal control is based on the ring and barrier concept. We will then provide a brief review of the current HCM procedure in capacity and delay analyses, particularly the way how pedestrian crossings are handled. Following that, we will present an analytical model that takes into account the stochastic nature of pedestrian crossings. A sample problem is then presented to illustrate the proposed model. A section of model validation is presented regarding comparisons between the proposed model and the *SimTraffic* simulation software. Finally, a summary and conclusions section is presented.

2. PEDESTRIAN HANDLING AT SIGNALIZED INTERSECTIONS

This section provides a brief summary of the current practice on how pedestrian crossings are handled in actual signal operations. For easy discussions, we use the data in Figure 1 to demonstrate the concept. The same intersection will be used later in the paper to illustrate the proposed model as well as the model validation results.

Figure 1 shows the layout of a generic signalized intersection. The pedestrian movement crossing the south leg is denoted as $m = 1$, and the pedestrian movement crossing the north leg is denoted as $m = 2$. The eastbound through movement/phase is therefore the concurrent movement/phase of $m = 1$, and the westbound through movement/phase is the concurrent movement/phase of $m = 2$. The numbers following the turning movement arrows are the traffic demands in veh/hr, which will be used in the later examples.

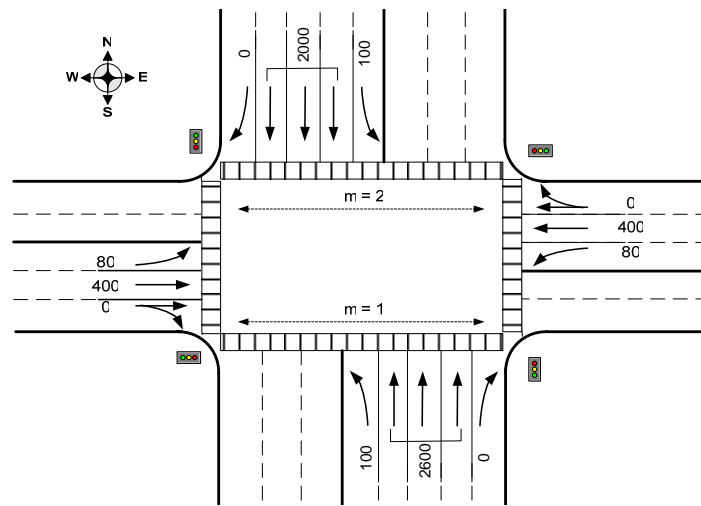


Figure 1: Sample Intersection Layout and Traffic Demand

Because the east/west through movement phases are the concurrent vehicle phases for the two pedestrian movements, the green splits for both through movement phases must satisfy the pedestrian WALK plus FDW intervals. The WALK interval is to initiate the pedestrians to get into the crosswalk, and the FDW is to clear the pedestrians, which must be long enough to allow pedestrians safely crossing the intersection. In practice, the WALK interval is typically set between 4 to 7 seconds (FHWA, 2003), and the FDW is determined based on the crossing distance and an assumed pedestrian walking speed, typically 4 ft/sec. The HCM also includes an equation to calculate the required pedestrian time, which also considers the width of the crosswalk in the equation:

A common situation seen in the field is at intersections where the minor street has low traffic demand, but the pedestrians have to cross a wide major street. In this case, the required green time to serve the traffic demand may be significantly shorter than what is needed for pedestrian crossings. If the signal is operating with fixed timing, the green split for the minor-street through movements must be set to a minimum of g_p , regardless of the vehicle demand. However, the majority of signalized intersections are now controlled by actuated signal controllers. In fully-actuated signal operations, the amount of green time needed for the minor street is totally governed by the pedestrian calls and controller parameter settings such as the minimum green, passage time, and the maximum green. When there is no pedestrian call, the phase will run the minimum green and then either gaps out or extends to its maximum depending on the traffic demands. When there is a pedestrian call, the phase will run a minimum of g_p , and then either gaps out or extends to its maximum.

3. THE HCM PROCEDURE

The current procedure in the HCM does not consider the stochastic effect of pedestrian crossings. The only guidance in dealing with pedestrian crossings is to set the green split to satisfy the pedestrian timing (split), if pedestrian phases and push buttons are provided. However, it is up the analyst to decide whether the pedestrian split or the vehicle split should be used to perform the analysis. A general practice is that the vehicle split is used when the pedestrian volume is low, and the pedestrian split is used when the pedestrian volume is high. However, traffic engineers only have a vague concept about the exact pedestrian volume threshold based on which each split option should be used. Most traffic analysis software that implements the HCM procedure does not provide more information beyond what is offered in the HCM. For example, both Synchro (Husch and Albeck, 2003) and the HCS software (McTrans, 2005) will display a warning message if the input green split is less than the pedestrian timing. The TRAFFIX software (DAI, 2005) does not provide any warning if the timing setting violates the pedestrian timing.

As a result, the current analytical procedure for analyzing signalized intersections could only produce two performance results: the result without pedestrian or the result with pedestrian. There are basically no differences among the results with different pedestrian volumes, except for some minor adjustments on the saturation flow rates. When pedestrian volume is low and pedestrian crossing does not occur every cycle, the current procedure would overestimate the capacity for the concurrent movement, and underestimate the capacity for the other movements, when the pedestrian split option is chosen.

4. MODEL DEVELOPMENT AND ANALYSES

4.1. Model Development

Equation 1 gives the final form of the proposed capacity model, which determines the final capacity, c_m , based on the weighted average of two capacities: the capacity without pedestrians, $c_{1,m}$, and the capacity with pedestrians, $c_{2,m}$.

$$c_m = p_{0,m}c_{1,m} + p_m c_{2,m} = p_{0,m}c_{1,m} + (1 - p_{0,m})c_{2,m} \quad (1)$$

where

c_m = final capacity for the pedestrian concurrent through movement m , vph

$c_{1,m}$ = capacity without pedestrians, vph

$c_{2,m}$ = capacity with pedestrians, vph

$p_{0,m}$ = probability of having no pedestrian calls, or equivalent to the proportion of cycles that has no pedestrian calls

p_m = probability of having pedestrian calls, or equivalent to the proportion of cycles that has pedestrian calls

Assume pedestrian arrivals are random and follow a negative exponential distribution, and x is a random variable denoting the number of pedestrian calls during a cycle on one approach. The average number of pedestrian calls per cycle, λ_m , can be calculated using Equation 2:

$$\lambda_m = \frac{V_{p,m}}{3600} C \quad (2)$$

where

$V_{p,m}$ = pedestrian volume of movement m , ped/hr

C = cycle length, sec

The probability of having x number of pedestrian calls, $p'_{x,m}$ is obtained by:

$$p'_{x,m} = \frac{\lambda_m^x e^{-\lambda_m}}{x!} \quad (3)$$

The probability of having no pedestrian calls, $p'_{0,m}$ is obtained by:

$$p'_{0,m} = \frac{\lambda_m^0 e^{-\lambda_m}}{0!} = e^{-\lambda_m} \quad (4)$$

The probability of having at least one pedestrian call, p'_m is obtained by:

$$p'_m = 1 - p'_{0,m} = 1 - e^{-\lambda_m} \quad (5)$$

If dual entry is set in the signal controller for the two concurrent vehicle phases on the minor street, any one approach that has a pedestrian call would trigger the pedestrian phase, thus the two through movement phases will extend to the WALK + FDW split. In this case, the probability of having at least one pedestrian call during a cycle is calculated by:

$$p_m = 1 - \prod_{m=1}^2 p'_{0,m} = 1 - (e^{-\lambda_1} e^{-\lambda_2}) = 1 - e^{-(\lambda_1 + \lambda_2)} \quad (6)$$

The probability of having no pedestrian calls, $p_{0,m}$ is then:

$$p_{0,m} = 1 - p_m = e^{-(\lambda_1 + \lambda_2)} \quad (7)$$

Equation 1 becomes:

$$c_m = e^{-(\lambda_1 + \lambda_2)} c_{1,m} + [1 - e^{-(\lambda_1 + \lambda_2)}] c_{2,m} \quad (8)$$

$$c_{1,m} = \frac{g_{1,m}}{C} s_m \quad (9)$$

$$c_{2,m} = \frac{\text{Max}(g_{1,m}, g_p)}{C} s_m \quad (10)$$

where

$g_{1,m}$ = green split without pedestrians, which can be determined based on the methodology developed by Webster (1969).

g_p = green split with pedestrians, $g_p = \text{WALK} + \text{FDW}$ or to be calculated by the HCM Equation.

s_m = saturation flow rate for movement , vph.

Delay can be calculated in a similar manner, as shown in Equations 11 and 12.

$$d_m = p_{0,m} d_{1,m} + (1 - p_{0,m}) d_{2,m} \quad (11)$$

$$d_m = p_{0,m} d_{1,m} + (1 - p_{0,m}) d_{2,m} = e^{-(\lambda_1 + \lambda_2)} d_{1,m} + [1 - e^{-(\lambda_1 + \lambda_2)}] d_{2,m} \quad (12)$$

$d_{1,m}$ and $d_{2,m}$ can be obtained from the delay equations in the HCM [see Equations (16-9) through (16-12) in the HCM] based on $c_{1,m}$ and $c_{2,m}$.

4.2. A Sample Problem

A sample problem is presented next to illustrate the applications of the proposed model. The sample problem is based on the same data shown earlier in Figure 1. All vehicles were assumed to be passenger cars, and the default saturation flow rate of 1900 vphpl was used. No other adjustments on the saturation flow rate are necessary. No right-turn traffic volume was assumed as it is usually not the critical movement. The subject movement is the eastbound through movement. The westbound through movement can be analyzed based on a similar approach.

In addition, the following variables and parameters were used in the example:

$m = 1$ (eastbound through), and $m = 2$ for westbound through

$C = 100$ sec; $L = 4.0$ sec; $WALK = 5.0$ sec; $FDW = 23.0$ sec; $V_{p,1} = V_{p,2} = 10$ ped/hr;

Results without pedestrians:

$Y = 0.68$; $X_{CI} = 0.81$; $y_l = 0.11$; $g_{l,1} = 12.9$ sec; $c_{l,1} = 492$ vph; $d_{l,1} = 52.1$ sec/veh

Results with pedestrians:

$p'_{0,1} = p'_{0,2} = 0.76$; $p_{0,1} = p_{0,2} = 0.574$; $g_p = 28.0$ sec; $c_{2,1} = 1064$ vph; $d_{2,1} = 29.2$ sec

Final capacity and delay:

$c_l = 0.574 * 492 + (1 - 0.574) * 1064 = 736$ vph

$d_l = 0.574 * 84.3 + (1 - 0.574) * 29.2 = 42.3$ sec/veh

If the current HCM procedure were applied, the capacity would be 1064 vph, and the delay would be 29.2 sec/veh. For this particular eastbound through movement, the capacity would be overestimated and the delay underestimated. It would be the opposite for the other movements, where capacity would be underestimated and the delay would be overestimated.

4.3. Model Comparison with Simulation

Validation of the proposed model was conducted using the *SimTraffic* software (Husch and Albeck, 2003) and based on the traffic data used in previous discussions. The reason of choosing *SimTraffic* software is its easy modeling of stochastic pedestrian crossings with actuated signal control. The simulation model was first calibrated against the HCM procedure based on two cases: without pedestrians and with pedestrians (recall). The purpose of the calibration is to ensure consistent results between the two models for the two base cases. In order to match the delay results with the HCM, adjustments were made in *SimTraffic* on the following parameters: detector length, passage time, and some driver and vehicle related parameters. After the model calibration, simulation runs were conducted using different pedestrian volumes and the results were compared with the proposed model. The simulation model was set up with a 3-min seeding period and a 15-min simulation period, which is consistent with the 15-min analysis period used in the HCM. Because *SimTraffic* does not directly provide capacity estimates, comparisons were mainly based on the vehicle delays from both models. A total of 20 runs were conducted for each pedestrian volume scenario, and the average intersection delays were selected for the comparison.

Figure 2 illustrates the delays from both the *SimTraffic* simulation model and the proposed model based on different pedestrian volumes. The results based on the current HCM are indicated by the solid lines, which has only two values: delay without pedestrians and delay with pedestrians

(recall). The results with pedestrians are the same regardless of the pedestrian volumes. The difference in delays between the current HCM procedure and the proposed model (also *SimTraffic*) is indicated by the triangular area, which can be regarded as the errors of the current HCM procedure.

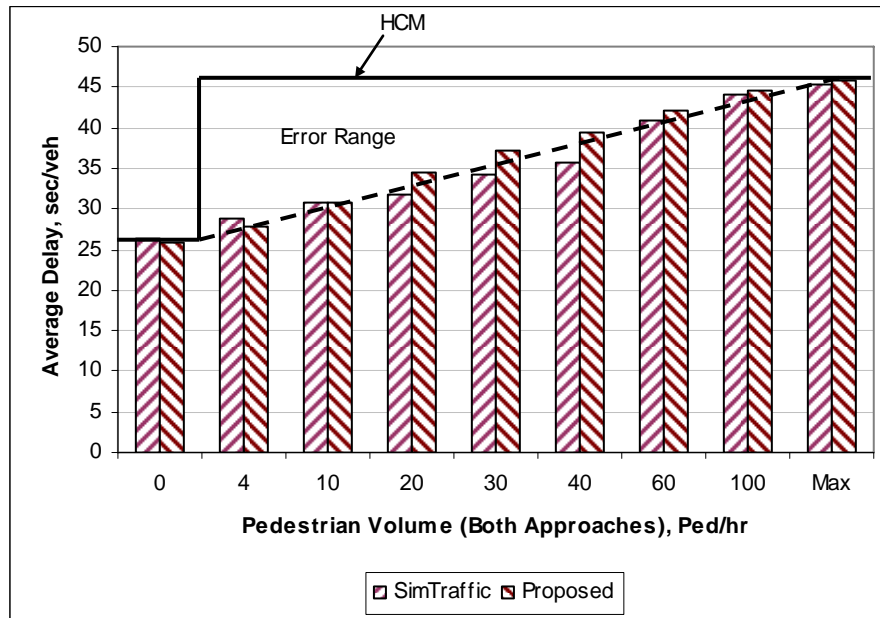


Figure 2: Comparison of Intersection Delays between SimTraffic and the Proposed Model

As Figure 2 indicates that the results matched well between simulation and the proposed model. Although the statistical tests indicate statistically different results (at the 0.05 significance level) for the pedestrian volumes of 20, 30, and 40, the differences are less than 3.0 sec/veh between the two models, which is considered minimal from the practical point of view. The two models (proposed and *SimTraffic*) yielded identical delay results for all other pedestrian volume scenarios. The current HCM procedure can result in delay errors as high as 18 sec/veh in the case of low pedestrian volume conditions.

4.4. Analyses of the Pedestrian Effects

Using the proposed model, analyses were conducted to examine the effects of pedestrian crossings on signal capacity and delay.

Figure 3 shows the effect of pedestrians on the minor-street through movement (e.g., eastbound through) and Figure 4 shows the effect on the major-street through movement (e.g., northbound through).

Figure 3 reveals some interesting findings. At the first glance, the results may seem counter-intuitive as higher capacities are achieved with lower cycle length. This can be well explained by the model. For the case of calculating $c_{2,m}$, the capacity with pedestrians, the eastbound phase always has the pedestrian time (i.e., 28.0 sec effective green in this example). With the increase of cycle length, the g/C ratio decreases, resulting in less capacity. Although the probability of having a pedestrian call increases with the increase of cycle length, the final weighted capacity still decreases. However, this is not the case for the major-street through movement as indicated in Figure 4.

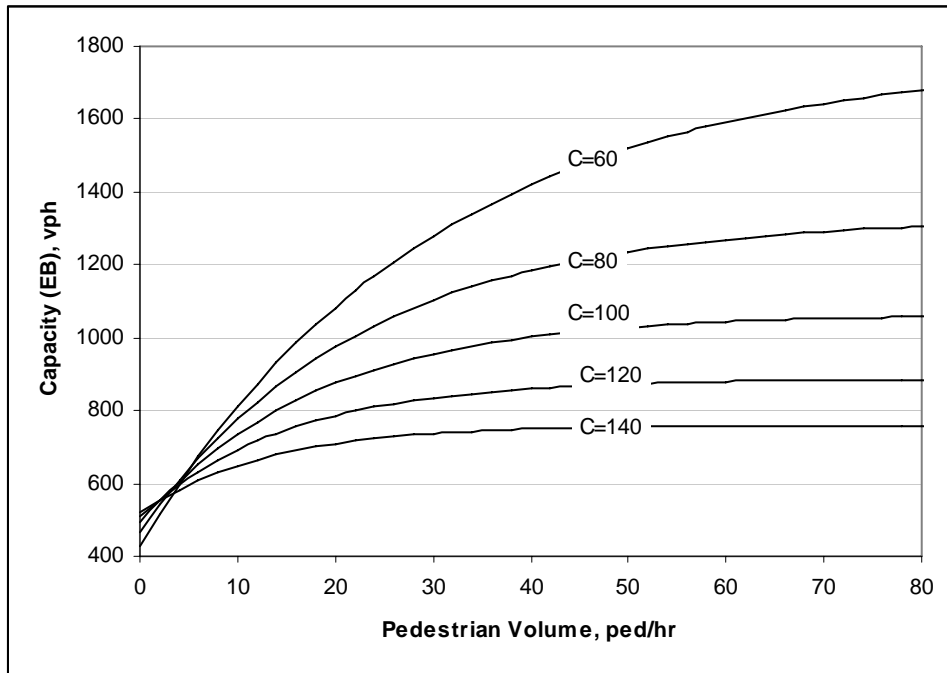


Figure 3: Effect of Pedestrians on Eastbound Capacity

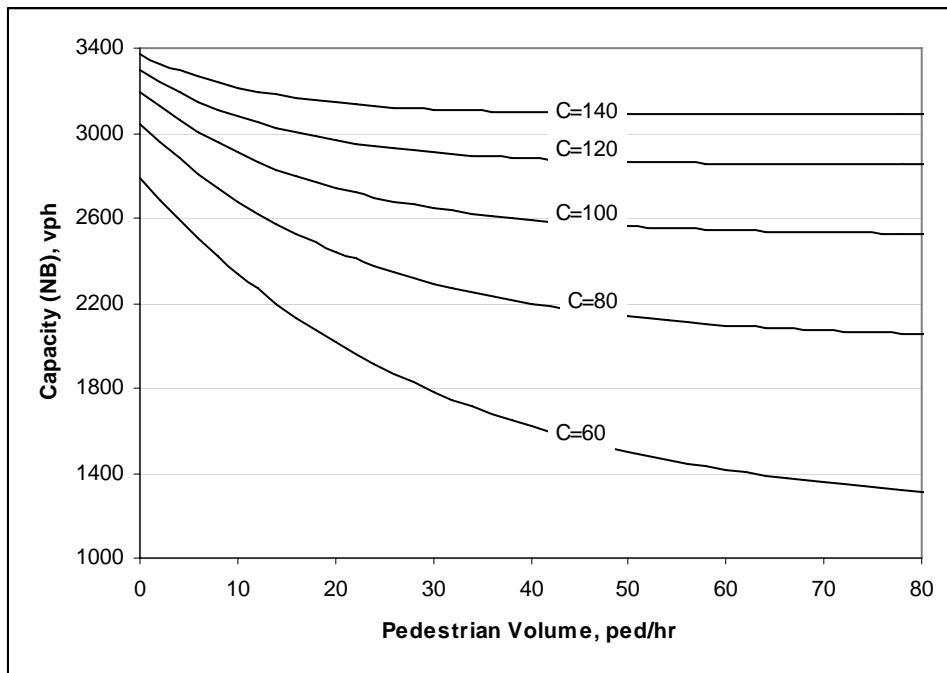


Figure 4: Effect of Pedestrians on Northbound Capacity

5. SUMMARY AND CONCLUSIONS

The paper documents a proposed capacity and delay model for analyzing signalized intersections with consideration of the stochastic effect of pedestrian crossings. The proposed model overcomes the shortcomings of the current analytical procedure in dealing with pedestrian effects. The model was validated based on *SimTraffic* simulation. Using the proposed model, further analyses were conducted on the effect of pedestrian crossings on intersection capacity. Major conclusions from the study are summarized below:

- Based on model validation using the *SimTraffic* software, the proposed model produced delay results that closely matched the results from *SimTraffic*. Therefore, the modeling approach seems promising in enhancing the current analytical procedure in dealing with pedestrian effects.
- Because the current analytical procedure treats the pedestrian crossings in a fixed manner, the analysis results could involve significantly high errors, especially under low pedestrian volume conditions. Based on the sample data set used in this study, the current analytical procedure in the HCM can result in delay estimate errors as high as 18 sec/veh.
- One finding from this study is that higher pedestrian volumes result in higher capacity and lower delay for the pedestrian-concurrent movement, because the movement phase will likely to get the pedestrian split, which is generally higher than the vehicle split. Another interesting finding is that a higher cycle length actually results in a lower capacity for the concurrent movement. This is especially the case when the vehicle demand is low but the pedestrian time is high.

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