

Implementing Actuated Signal-Controlled Intersection Capacity Analysis with Pedestrians

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For an actuated signalized intersection, pedestrian calls are likely to affect the effective greens serving the vehicle movements, which affect the capacity and delay of the intersection. However, the current procedure in the *Highway Capacity Manual 2000* (HCM) for analyzing actuated signalized intersections treats pedestrian crossing and timing statically, with either pedestrian calls at all signal cycles or no pedestrians at all. In reality, pedestrian arrivals are random events with some cycles having more pedestrians than others and other cycles having no pedestrian call at all. This paper demonstrates that the current procedure can lead to erroneous results in capacity and delay estimations. A model is introduced to overcome the shortcomings in the current procedure. The model takes into account the stochastic nature of pedestrian crossings and their effects. The model computes the probability of having pedestrian calls in a cycle and the corresponding capacities and delays for traffic movements. An implementation framework was developed to help practitioners conduct capacity analyses using the model. The model's results on a semiactuated signal-controlled intersection were comparable with the results from the Sim-Traffic microsimulation model. The effects of pedestrians on intersection capacity and delay were analyzed using the proposed model. Depending on the pedestrian volume and traffic conditions, the current HCM procedure could produce significant error, especially when the pedestrian volume is low, because it does not consider the stochastic nature of pedestrian arrivals.

For actuated signalized intersections, during a signal cycle in which there is a pedestrian call, the pedestrian phase will be activated with an indication of the solid Walk interval followed by a Flashing Don't Walk (FDW) clearance interval. Because pedestrian arrivals are random events, pedestrian calls may occur only in some cycles. When there is a pedestrian call, the corresponding green split needs to be at least the sum of the Walk and the FDW intervals. However, the current procedure in the *Highway Capacity Manual 2000* (HCM) for analyzing actuated signalized intersections does not consider the stochastic nature of pedestrian arrivals and timing (1). The current HCM procedure recommends that the phase split satisfy the pedestrian timing regardless of the pedestrian volumes even though there may be

no pedestrian call during some cycles. It is not a problem if the required vehicle phase split is greater than the pedestrian Walk plus FDW time. However, if the vehicle demand is low and the pedestrian time is high, the current HCM method may not provide accurate capacity and delay estimates. The objective of this paper is to incorporate the stochastic nature of pedestrian call events into the HCM capacity analysis procedure.

Although the stochastic nature of pedestrian crossings has been mentioned by researchers and practitioners, not many analytical models are available to address the pedestrian issues. In 2000, Tian et al. discussed the impact of pedestrian crossing on signal coordination (2). They found that accommodating pedestrian timing in the signal timing is generally a better strategy from the signal coordination point of view, because the signal will remain coordinated even when pedestrian calls occur. In 2001, Tian et al. addressed the effect of pedestrians on signalized intersection capacity on a split-phase operation (3). They developed a model to determine the conditions for which the use of an exclusive pedestrian phase might actually increase the capacity compared with the typical split-phasing operation. In 2006 Tian and Xu developed a mathematical model to capture the stochastic effect of pedestrians on the capacity and delay of a pedestrian movement phase (4). The present study further extends the model to evaluate the impact on the intersection capacity and delay. Furthermore, this paper provides a modeling framework for researchers and practitioners to implement the model when analyzing actuated signalized intersection operations.

To illustrate the model and its implementation, the paper includes the following sections. First, a brief review of current HCM procedure to handle pedestrian call events is given. Then, an analytical model is introduced that considers the stochastic nature of pedestrian calls. Next, a framework to incorporate the proposed model into the HCM capacity and delay analysis procedure is presented. Finally, the effect of pedestrians on capacity will be discussed and the conclusions reached from this study will be presented.

HCM PROCEDURE AND CURRENT PRACTICE

The current procedure in the HCM treats pedestrian calls as fixed events without considering their stochastic characteristics. When dealing with pedestrian crossings, the HCM recommends setting the green split to satisfy the pedestrian timing (split) of the Walk plus FDW intervals if pedestrian phases and push buttons are provided. However, it is up to the analyst to decide whether the pedestrian split should be used to perform the capacity analysis. A general practice is that the vehicle split is used only when the pedestrian volume is low and the pedestrian split is used when the pedestrian

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volume is high. However, traffic engineers do not have clear guidance on when to use pedestrian split and when not to. Most traffic analysis software that implements the HCM procedure does not provide more pedestrian application beyond what is offered in the HCM. For example, Synchro (5) and the Highway Capacity Software from McTrans (6) will display a warning message if the input green split is less than the pedestrian timing. The TRAFFIX software from Dowling and Associates, Inc. (7), does not provide any warning if the vehicle timing setting violates the pedestrian timing. Therefore, it is up to analysts to decide whether to consider pedestrian effects or not.

In summary, the current analytical procedure for analyzing signalized intersections can produce either the result without pedestrian calls or the result with pedestrian calls. There are normally no differences among the results with different pedestrian volumes, except some minor adjustments on the saturation flow rates based on the HCM procedure. When pedestrian volume is low and pedestrian crossings do not occur in every cycle, the current procedure overestimates the capacity for the pedestrian phase movement and underestimates the capacity for the other movements if the pedestrian phase split option is chosen. However, when the pedestrian split is not considered for a particular phase (i.e., a concurrent phase), the current procedure could underestimate the capacity for the phase and may overestimate the capacity of other phase movements.

PROPOSED ANALYTICAL MODEL

Model Development

This section presents the development of an analytical model for considering the stochastic nature of pedestrian crossing. For easy illustration, the data in Figure 1 are used to demonstrate the model. This diagram will be used later in the paper to discuss the effects of pedestrians on intersection capacity analysis based on the proposed model.

The geometric layout and traffic demands for each movement are presented in Figure 1, in which the north–south street is a major street and the east–west street is a minor street. To simplify the problem, only the east–west pedestrian crossings are considered, and it is

assumed that the north–south street has enough green time to cover pedestrian crossings on the north–south approaches. 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 is therefore the concurrent phase of $m = 1$, and the westbound through movement is the concurrent movement or phase of $m = 2$. The numbers following the turning movement arrows are the traffic demands in vehicles per hour (veh/h), which will be used in the examples that follow.

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 if both phases have pedestrian calls. The Walk interval is used to initiate pedestrians to enter the crosswalk, and the FDW is a clearance interval that must be long enough to allow pedestrians to safely cross the intersection. Typically, in practice the Walk interval is set between 4 and 7 s based on the FHWA *Manual on Uniform Traffic Control Devices* (8) and the FDW is determined based on the crossing distance and an assumed pedestrian walking speed, typically 4 ft/s. The HCM also includes an equation to calculate the required pedestrian time, which considers the width of the crosswalk in the equation as well.

In actuated signal operations, the amount of green time needed for the east–west minor street is governed totally by the pedestrian calls and controller parameter settings, such as the minimum green, passage time, and maximum green. When there is no pedestrian call, the vehicle phase will run the minimum green and then either gap out or extend to its maximum, depending on the vehicle demands. When there is a pedestrian call, the vehicle phase will run a minimum of Walk plus FDW and then either gap out or extend to the maximum. Pedestrian calls affect the length of the minimum green of a timing phase with pedestrian push button. Furthermore, pedestrian calls affect the capacity of movements corresponding to the previous timing phase.

Assume that pedestrian arrivals are random and follow a Poisson 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 from the pedestrian volume of the movement m using Equation 1.

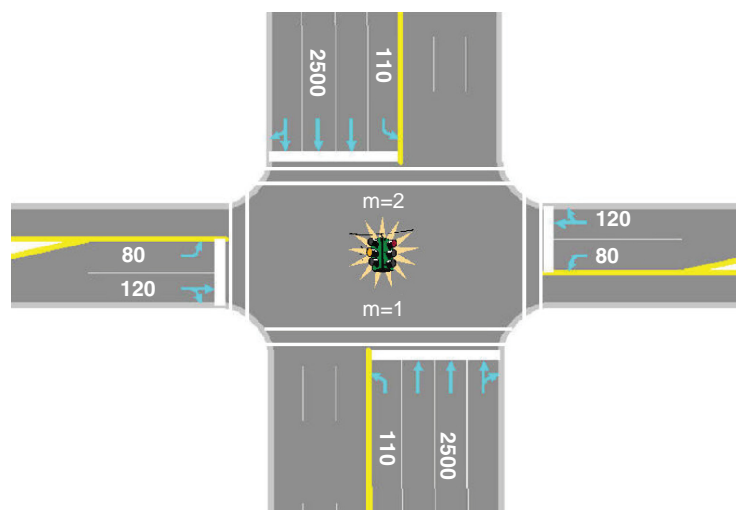


FIGURE 1 Sample intersection layout and traffic demand.

$$\lambda_m = \frac{V_{p,m}}{3,600} C \quad (1)$$

where $V_{p,m}$ equals pedestrian volume of movement m (ped/h) and C equals cycle length (s).

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

$$p'_{x,m} = \frac{\lambda_m^x e^{-\lambda_m}}{x!} \quad (2)$$

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

$$p'_{0,m} = \frac{\lambda_m^0 e^{-\lambda_m}}{0!} = e^{-\lambda_m} \quad (3)$$

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

$$p'_m = 1 - p'_{0,m} = 1 - e^{-\lambda_m} \quad (4)$$

For the case of a dual entry controller setup for the two concurrent vehicle phases on the minor street, any one approach that has a pedestrian call will trigger the pedestrian phase, thus the two through movement phases will extend to at least Walk plus FDW. In this case, the probability of having at least one pedestrian call during a cycle, p_m , is calculated by

$$p_m = 1 - \prod_{m=1}^2 p'_{0,m} = 1 - (e^{-\lambda_1} e^{-\lambda_2}) = 1 - e^{-(\lambda_1 + \lambda_2)} \quad (5)$$

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

$$p_{0,m} = 1 - p_m = e^{-(\lambda_1 + \lambda_2)} \quad (6)$$

The probabilities above would not be affected by the fact that pedestrians cross in groups. Equation 7 gives the proposed form of a capacity model, which determines the capacity of movement m based on the probabilities of two capacities: the capacity without pedestrians and the capacity with pedestrians.

$$c_m = p_{0,m} c_{1,m} + p_m c_{2,m} = p_{0,m} c_{1,m} + (1 - p_{0,m}) c_{2,m} \quad (7)$$

where

c_m = capacity for the pedestrian concurrent through movement m (veh/h);

$c_{1,m}$ = capacity without pedestrians (veh/h);

$c_{2,m}$ = capacity with pedestrians (veh/h);

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

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

Substituting Equations 5 and 6 into Equation 7, the following equations are obtained:

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

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

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

where

$g_{1,m}$ = green split without pedestrians, which can be determined on the basis of the methodology developed by Webster (9);

g_p = green split with pedestrians, g_p = walk + FDW or is calculated by the HCM equation; and

s_m = saturation flow rate for movement (veh/h).

Delay can be calculated similar to the way movement capacities are calculated, as shown in Equations 11 and 12.

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

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

where

d_m = delay for pedestrian concurrent through movement m (s),

$d_{1,m}$ = delay without pedestrians (s), and

$d_{2,m}$ = delay with pedestrians (s).

To obtain $d_{1,m}$ and $d_{2,m}$, the HCM procedure or any software implementing the HCM procedure can be used.

Model Validation with Microsimulation

To validate the analytical model result with the actuated signal operation with pedestrian push button, the proposed model was compared against the microsimulation results using SimTraffic by Husch and Albeck (10). The SimTraffic software was chosen because of the ease with which stochastic pedestrian crossings with actuated signal controls could be modeled. Certainly, other advanced microsimulation software can also work for this validation purpose.

At first, the simulation model was calibrated using the HCM procedure based on two cases that the HCM handles: (a) with pedestrian calls and (b) without pedestrian calls. The purpose of the calibration is to ensure that simulation results are consistent with the two base cases above. During the calibration with the two base scenarios using the HCM, adjustments were made in SimTraffic to the following settings: detector length, passage time, and some driver- and vehicle-related parameters. After the simulation model calibration, simulation runs were conducted using different pedestrian volumes. Each simulation was set up to have a 3-min seeding period and a 15-min simulation period, which is consistent with the 15-min analysis period used in the HCM. A total of 20 runs were conducted for each pedestrian volume scenario, and the average intersection delays were selected for comparison. The reason delay was selected for making comparisons is that SimTraffic does not explicitly produce capacity estimates.

To compare the different model results, Figure 2 illustrates the delays from the SimTraffic simulation model, the proposed model, and the HCM results based on different pedestrian volumes. Basically, the results based on the current HCM procedure are indicated by only two values: delay without pedestrians and delay with pedestrian calls. The HCM results with pedestrians are the same regardless of the pedestrian volumes.

Figure 2 indicates that the results matched well between the SimTraffic simulation and the proposed model. From a practical point of view, the proposed model and the simulation produced almost the same delay results for all pedestrian volumes. The HCM procedure has similar results for only very high pedestrian volumes and no pedestrian volumes. For all other pedestrian volumes, the HCM results are different from the other two models. The difference in delays

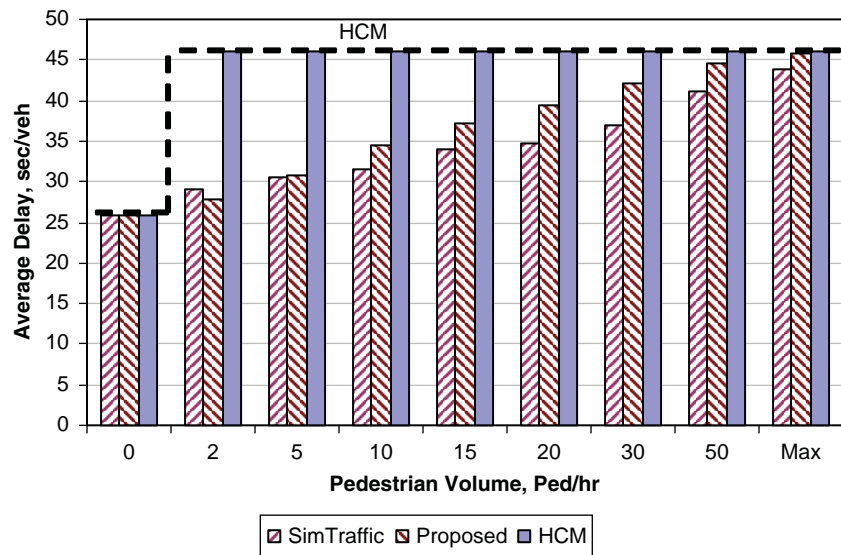


FIGURE 2 Comparison of intersection delays between SimTraffic and proposed model.

between the current HCM procedure and the SimTraffic and proposed models can be treated as the errors of the current HCM procedure. As the figure indicates, the highest error is at the lower end of pedestrian volumes.

IMPLEMENTING THE ANALYTICAL MODEL

To help practitioners use the proposed model to conduct capacity analysis, Figure 3 illustrates a procedure to estimate one vehicle movement with pedestrian phase when random arrivals of pedestrians are considered. When dealing with a semiactuated signal operation using the proposed model, normally only the dual entry through phase on the minor street needs to be considered because typically the green split on a major street through movement can accommodate the pedestrian crossing on a minor street. As indicated in the flowchart, an analyst needs to run the current HCM capacity procedure twice: with pedestrian call on crossing the major street and without pedestrian call on crossing the major street. Then the movements and intersection capacity and delay can be estimated using the proposed model in Equations 7 and 11. For a fully actuated signal-controlled intersection, the case becomes more complex because the cycle length of the intersection can change with the pedestrian calls, and pedestrian calls from both the major and minor streets need to be considered. However, the principle of using the stochastic approach is similar. It requires calculating the probabilities of no pedestrian calls, pedestrian calls on major street approaches only, pedestrian calls on minor street approaches only, and pedestrian calls on both major and minor streets. The sum of the probabilities above multiplied by the corresponding capacities will give the estimated intersection capacity. Similarly, one can obtain the delay for a fully actuated intersection with pedestrian push buttons.

SAMPLE CALCULATION

A sample problem is presented in this section to illustrate the applications of the proposed model. The sample problem is based on the data shown earlier in Figure 1. To simplify the procedure, all vehicles were

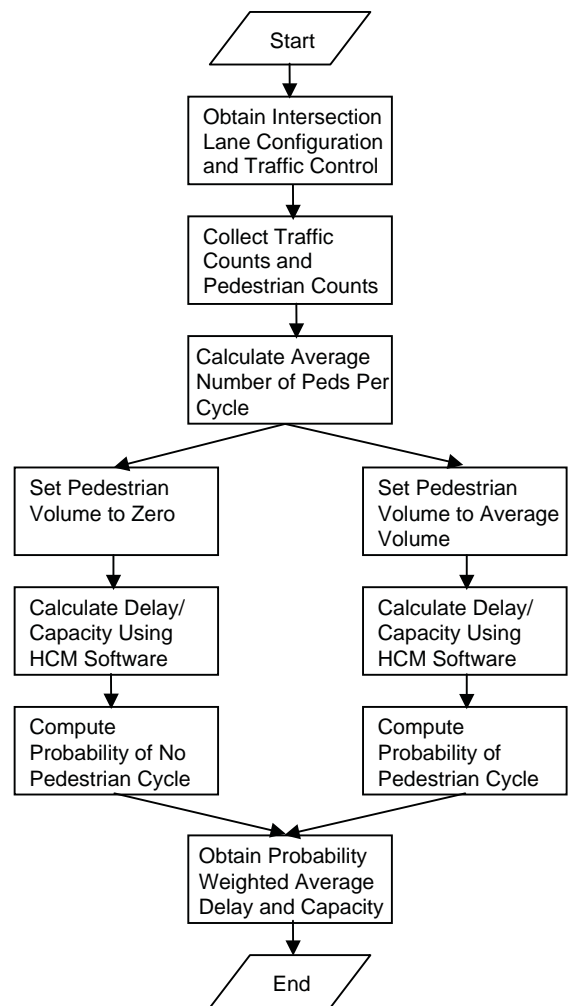


FIGURE 3 Capacity and delay procedure considering stochastic pedestrian calls.

assumed to be passenger cars and the default saturation flow rates of 1,900 vehicles per hour per lane (vphpl) for through movements and 1,805 vphpl for left-turn movements were used. No other adjustments on the saturation flow rate are made. This example addresses the eastbound through movement. The westbound through movement can be analyzed using a similar approach.

In the example, the following parameters are given: The intersection uses semiactuated coordinated signal control with cycle length, $C = 90$ s; lost time, $L = 4.0$ sec; Walk = 6.0 s; FDW = 24.0 s; $V_{p,1} = V_{p,2} = 20$ ped/h; where $V_{p,1}$ and $V_{p,2}$ are from $V_{p,m}$ defined previously; $m = 1$ for eastbound through movement; and $m = 2$ for westbound through movement.

Results without pedestrians:

$$Y = 0.61$$

$$X_{C1} = 0.74$$

$$y_1 = 0.11$$

$$g_{1,1} = 7.7 \text{ s}$$

$$c_{1,1} = 163 \text{ veh/h}$$

$$d_{1,1} = 55.1 \text{ s/veh}$$

where

Y = sum of intersection critical lane flow ratios,

X_{C1} = intersection critical volume capacity ratio,

y_1 = eastbound through movement critical lane flow ratio,

$g_{1,1}$ = eastbound through movement green split (s),

$c_{1,1}$ = eastbound through movement capacity (veh/h), and

$d_{1,1}$ = eastbound through movement delay (s/veh).

Results with pedestrians:

$$Y = 0.54$$

$$X_{C1} = 1.11$$

$$y_1 = 0.11$$

$$g_{1,1} = 30.0 \text{ s}$$

$$c_{1,1} = 633 \text{ veh/h}$$

$$d_{1,1} = 21.5 \text{ s/veh}$$

Based on Equations 5 and 6:

$$p_{0,1} = p_{0,2} = 0.368$$

$$p_1 = p_2 = 0.632$$

where $p_{0,1}$ and $p_{0,2}$ are defined by $p_{0,m}$ described previously with $m = 1$ and p_1 and p_2 are defined by p_m described previously with $m = 1$.

Final capacity, c_1 , and delay, d_1 , are calculated using Equations 7 and 11:

$$c_1 = 0.368 * 163 + (1 - 0.368) * 633 = 459 \text{ veh/h}$$

$$d_1 = 0.368 * 55.1 + (1 - 0.368) * 21.5 = 33.9 \text{ s/veh}$$

If calculated using the current HCM procedure, the capacity would be 633 veh/h and the delay would be 21.5 s/veh. For this eastbound through movement, the capacity would be overestimated by 38% and the delay underestimated by 37%. It would be the opposite for the other movements, in which capacity would be underestimated and the delay would be overestimated at this intersection. This exam-

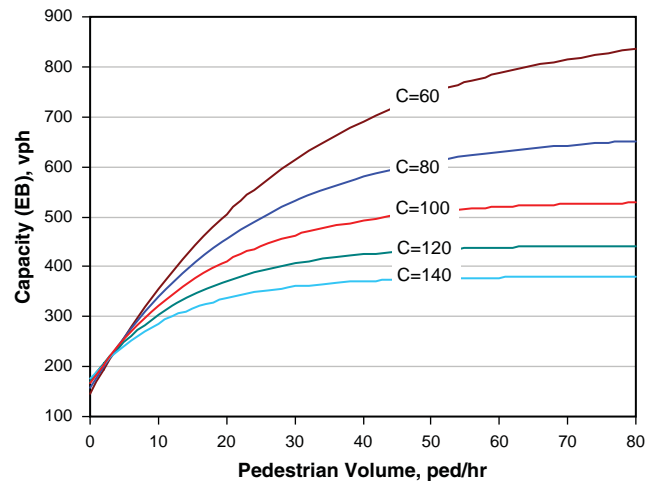


FIGURE 4 Effect of pedestrians on eastbound capacity.

ple demonstrates that the current HCM procedure could produce significant errors in capacity and delay estimations.

PEDESTRIAN EFFECT ON CAPACITY

On the basis of the proposed analytical model above, the effects of pedestrian crossings on intersection capacity and delay can be examined.

For the intersection illustrated in Figure 1, a wide range of pedestrian volumes and different cycle lengths are examined for each coordinated semiactuated signal operation. The effects of pedestrians on the minor street through movement (i.e., eastbound through) are illustrated in Figure 4. Figure 5 presents the pedestrian effects on the major street through movement (i.e., northbound through), and Figure 6 illustrates the pedestrian effects on the intersection capacity.

For the minor street, Figure 4 reveals some interesting findings. At first glance, the results may seem to be counterintuitive because higher capacities are achieved with lower cycle lengths for the eastbound

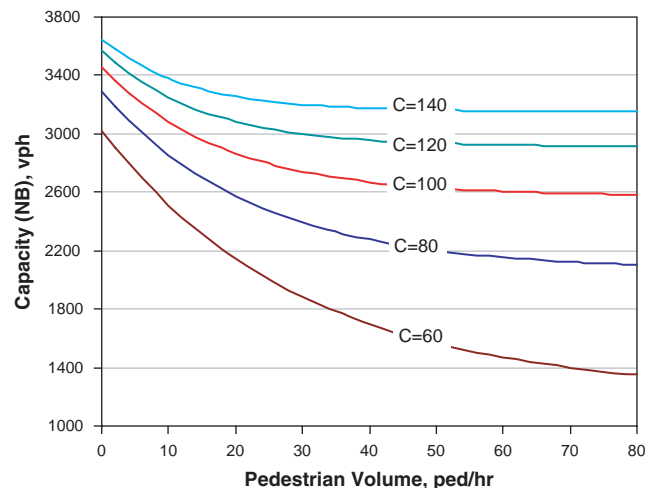


FIGURE 5 Effect of pedestrians on northbound capacity.

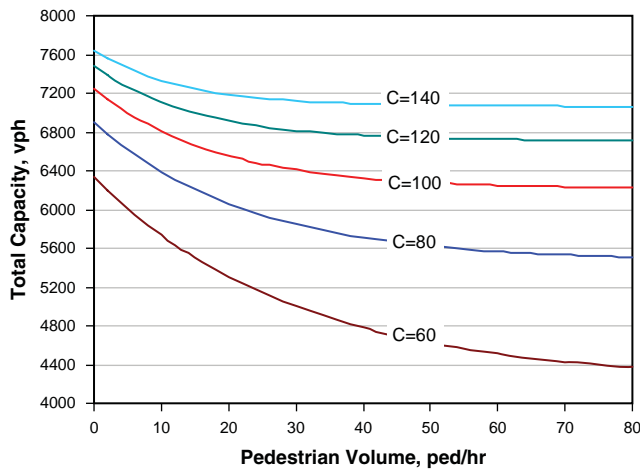


FIGURE 6 Effect of pedestrians on intersection capacity.

approach. This can be well explained by a closer examination. For the case of calculating the capacity with pedestrians, $c_{2,m}$, the eastbound phase always has the Walk plus FDW pedestrian time. 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.

For the major street through movement, the pedestrian effect on the capacity is just the opposite of the minor street, as indicated in Figure 5. The capacity decreases with the increase of pedestrian volume, and a shorter cycle length results in a larger decrease in capacity. This is caused by the decrease in the major street green time due to the increase of minor street green time needed to accommodate minor street pedestrian splits.

Figure 6 shows the overall intersection capacity decreases with the increase of the pedestrian volumes. This is logical because some effective green times are used to accommodate the needs of minor street pedestrian calls. The major street, which has higher traffic demand, has less capacity and more delay. Therefore, the overall intersection has less capacity when pedestrian volume increases. Also on the basis of the model results in Figure 6, pedestrians have less effect on longer cycle lengths than on shorter cycle lengths. This is reasonable because, for the same green time reduction on the major street, the resulting g/C ratio would cause a larger capacity reduction on a shorter cycle length than on a longer cycle length.

Overall, results from the proposed model seem to be reasonable. The pedestrian effects on capacity during a wide variety of pedestrian and cycle length scenarios are well represented by the proposed analytical model.

SUMMARY AND CONCLUSIONS

A proposed analytical model and its implementation method for analyzing actuated signalized intersections with consideration of the stochastic effect of pedestrian crossings were presented in this paper. Model results were compared against and validated by traffic microsimulation model. The proposed model overcomes the shortcomings of the current HCM procedure in which pedestrian arrivals are treated as static. The model can help researchers to better understand the pedestrian impact on various signal operation scenarios. The implementation flowchart can also assist practitioners in realistically computing the capacity and delay of intersections with actuated signal controls.

Based on the contents of this study, the following conclusions can be drawn:

- On the basis of the model validation results using microsimulation, the proposed model produced delay results that were consistent with results from SimTraffic. However, the current HCM procedure had apparent deviations from the simulation results.
- The proposed model improved the current analytical procedure in dealing with pedestrian effects on capacity and delay estimation. On the basis of the sample calculation in this study, the current HCM analytical procedure could produce significant errors, especially for a minor street with low pedestrian volumes. The error in the particular sample calculations was more than 30%.
- An implementation framework was proposed to incorporate the model into the current HCM procedures and to allow analysts to conduct capacity and delay analysis considering stochastic pedestrian call events.
- For coordinated semiactuated signal controls, one interesting finding from this study was that higher pedestrian volumes resulted in higher capacity and lower delay for the pedestrian-concurrent movement. The reason is that the minor street movement phase would be likely to get the pedestrian split, Walk plus FDW, which was generally greater than that based on the vehicle demand. Another interesting finding was that a longer cycle length actually resulted in a lower capacity for the concurrent movement. However, longer cycle lengths produce an overall higher capacity for the intersection.

This paper proposed an analytical model for dealing with pedestrian impacts on capacity and delay. It demonstrated the application of the model using a semiactuated signal control scenario. Further study would be to expand the model to handle fully actuated signalized intersections.

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