

Pedestrian Impedance of Turning-Movement Saturation Flow Rates

Comparison of Simulation, Analytical, and Field Observations

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TRAF-NETSIM and its successor CORSIM are comprehensive micro-simulation environments that have been widely used to model the urban traffic environment in the United States and abroad. CORSIM is employed in this study to simulate and evaluate the effects of pedestrian flows on right-turn saturation flow rates at signalized intersections. The saturation flow rates returned by CORSIM were compared with field data collected throughout the United States and with three existing analytical models in the United States, Australia, and Canada. These comparisons indicated that CORSIM models pedestrian interference with the turning vehicles more severely than the three analytical methods, but with a smaller effect than the empirical data indicate. Further, the empirical data exhibit a logarithmic relationship between saturation flow rate and opposing pedestrian volume, compared with the linear relationship used in the simulation and analytical models. Implications for the design and analysis of signalized intersections are presented.

At a signalized intersection, pedestrians crossing a street parallel to traffic flow interfere with turning vehicles and thus impede the saturation flow rate for the lane group that services turning traffic. This study evaluates the ability of Corridor Microscopic Simulation (CORSIM) (1) to simulate the interaction between pedestrians and right-turning traffic. The CORSIM version used in this analysis is in the beta testing stage, and thus is considered in transition to a more refined version. The pedestrian interaction module, however, has not been updated from the latest TRAF-NETSIM release 5.0 (2). To evaluate CORSIM's effectiveness in predicting effects of pedestrians on saturation flow rate, other analytical methods were included to provide a basis for comparison. Simulation results were compared with existing analytical procedures in the *Highway Capacity Manual* (HCM) (3); the Australian model, which is based on the values used in *Calibrating SIDRA* (4); and the *Canadian Capacity Guide for Signalized Intersections* (5). Field data were collected in conjunction with an FHWA-sponsored study on capacity analysis for pedestrian and bicycle facilities (6). The field data contain observations taken at several intersections in all regions of the United States.

ANALYTICAL METHODS

Current methods for modeling pedestrian impacts on right turns make use of adjustment factors to the saturation flow for the lane

group servicing turning traffic. The adjustment factors for right-turn lanes typically consider whether there are exclusive or shared lanes, the type of signal phasing (protected or permissive turns), pedestrian volume, proportion of right-turning vehicles, and proportion of vehicles using a protected phase. To accurately compare the different models, certain assumptions must be made to achieve a dependable comparison. In this analysis, a strictly permissive phase is considered, in conjunction with a single exclusive and shared right-turn lane.

The HCM provides a method for adjusting the saturation flow rate for lane groups servicing right-turning traffic through the factor f_{RT} :

$$f_{RT} = 1.0 - P_{RT} \left[0.15 + \left(\frac{PEDS}{2,100} \right) (1 - P_{RTA}) \right] \quad (1)$$

where

P_{RT} = proportion of right-turning traffic in lane group,

$PEDS$ = volume [pedestrians per hour (pph)] of pedestrians conflicting with right-turning traffic, and

P_{RTA} = proportion of right-turning traffic using protected phase.

The special case considered here assumes strictly permissive phases, thus $P_{RTA} = 0$ and Equation 1 simplifies to

$$f_{RT} = 1.0 - P_{RT} \left[0.15 + \left(\frac{PEDS}{2,100} \right) \right] \quad (2)$$

The 0.15 factor in Equation 2 is independent of the pedestrian flow, and is meant to simulate a reduction in saturation flow due to the lower turning speeds.

The Canadian Capacity Guide (5) evaluates the saturation flow adjustment factor (F_{ped}) for right turns crossing pedestrian flow in a three-step process. First, the average pedestrian flow rate during the walk interval and pedestrian clearance period is calculated from the two-way pedestrian flow on the crosswalk:

$$q'_{ped} = \frac{q_{ped} C}{g} \quad (3)$$

where

q'_{ped} = approximate average pedestrian flow rate during the walk interval and pedestrian clearance period (pph),

q_{ped} = two-way pedestrian flow on the crosswalk (pph),

C = cycle time (sec), and

g = effective green interval (sec).

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Second, if the average pedestrian flow rate on green is less than or equal to a threshold of 200 pph, then no adjustment is necessary ($F_{\text{ped}} = 1.0$). Finally, one of three functions is chosen based on specific local conditions. The Canadian Capacity Guide identifies three geographic locations. For this study, the Toronto site was chosen for comparison purposes. In this case,

$$F_{\text{ped}} = 0.60 - \frac{q'_{\text{ped}}}{8,516} \quad (4)$$

The Australian model is presented in *Calibrating SIDRA* (4) and is implemented in the SIDRA computer package. The adjustment factor used is identical to the HCM value, although it is implemented in the form of a through-vehicle equivalent as shown below:

$$e_{\text{LV}} = \frac{1.0}{0.85 - \frac{P}{2100}} \quad (5)$$

where

e_{LV} = through-car equivalent for turning light vehicles, and
 P = conflicting pedestrian volume (pph).

CORSIM SIMULATION OF PEDESTRIAN IMPEDANCE

CORSIM simulates the effects of conflicting pedestrians by randomly assigning a delay time to each turning vehicle separately. The first way in which pedestrian interaction can be varied in CORSIM is in the number of pedestrians on each link of a street system. There are four levels of pedestrian volume: none, light (100 to 250 pph), moderate (250 to 500 pph), and heavy (500+ pph). Based on these volumes, CORSIM generates an additional delay to each vehicle due to the presence of pedestrian interfering with a right-hand turn. Pedestrian interference is classified as either weak interaction or strong interaction. The strong interaction occurs for a user-input duration beginning at the start of the green phase and represents the queuing of pedestrians on the crosswalks. Weak interaction prevails for the balance of the green time. The default values set in CORSIM for the duration of a strong interaction are 0 sec for light pedestrian flow, 10 sec for moderate pedestrian flow, and 25 sec for heavy pedestrian flow. During the time that the strong interaction occurs, the delay for the next vehicle attempting to turn right is randomly selected from a decile delay distribution with mean = 3.8 sec and standard deviation = 4.7 sec. These times are doubled if the pedestrian flow level is heavy. During the weak-interaction period, a different distribution is used with delay mean = 0.9 sec and standard deviation = 1.9 sec. Thus, by effectively holding back the vehicles at the prescribed delay values, the saturation flow rates are reduced accordingly.

SIMULATION EXPERIMENTS

Network Set-Up

The first step in the simulation experiments is to set up the road network for both the shared through-right-turn lane and exclusive turn lane networks. The road networks are generated with the intent to generate multiple data points per simulation run, under heavy oversaturation, not to develop simulation case studies of real-world intersections.

Exclusive-Lane Network

The exclusive right-turn intersection in this simulation is four-way and has a through-only lane and a right-turn only lane in all directions, as shown in Figure 1. Each link length was set to the maximum 1220 m (4,000 ft) to allow for a continuous right-turn queue in the 15-min run-time. The volumes for the four entry links are 1,000 vehicles per hour (vph). This volume creates a saturated condition on each lane. The queue discharge headway was set at an ideal value of 1.9 sec, equivalent to a saturation flow rate of 1,900 vehicles per hour of green (vphg) for each lane. The turning percentage was set at 50 percent on all links. The four intermediate nodes (1,2,3,4) were controlled by stop signs on the minor roads and the main intersection (Node 5) is signalized using a four-phase split-signal plan. Each approach receives a green through and turn arrow for 25 sec and a yellow interval of 5 sec, resulting in a cycle length of 120 sec. No right turns on red were allowed in any runs.

Shared-Lane Network

The shared right-turn-through lane network is created as a separate file similar to the exclusive right-turn lane network. This intersection is a T-intersection, as shown in Figure 2. To begin construction of this intersection, the entry link (4,1) was set at maximum 1220 m (4,000 ft), ensuring that extensive queuing can occur. The two exit links (1,2; 1,3) were set only at 305 m (1,000 ft) because there is no need for queueing in this direction. To minimize computing time, the volumes for the entry links were set at 1,000 vph for link (8004, 4) and 500 vph for the remaining 2 entry links. All links have a single lane and are not channelized. The turning percentages were varied as described in the Simulation Runs section. The main intersection (Node 1) is signalized with two phases, each with 25 sec of green time and 5 sec of yellow time. The cycle length for this network is 60 sec.

Simulation Runs

Exclusive-Lane Network

A preliminary set of trials was run to determine if the input turning speeds in CORSIM affect the saturation flow rates for the exclusive right-turn lane. The values used included the default 14.2 km/hr (13 ft/sec), and two other values, 24.0 km/hr (22 ft/sec) and 28.3 km/hr (26 ft/sec). At each speed, 20 runs were made with the same 20 random number seeds. From each of these 20 runs, four turning-lane and through-lane volumes were collected from the output file for a total of 80 data points. The output file returns the number of vehicles discharged by each lane. This is converted in a spreadsheet to vph green by dividing it by the total effective green (8 cycles times 30 seconds green and yellow time minus 2.5 seconds of startup lost time). To determine the effects of pedestrians, 20 trials at 20 different random number seeds were run for each of CORSIM's four different pedestrian levels.

Shared-Lane Network

The next set of trials was run on the shared-lane network. Five groups of trials were run at five different right-turn volume percentages: 30 percent right–70 percent through, 40 percent right–60 percent through, 50 percent right–50 percent through, 60 percent

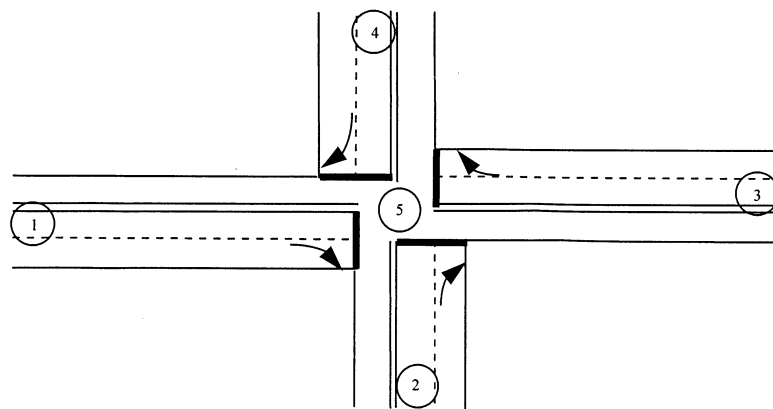
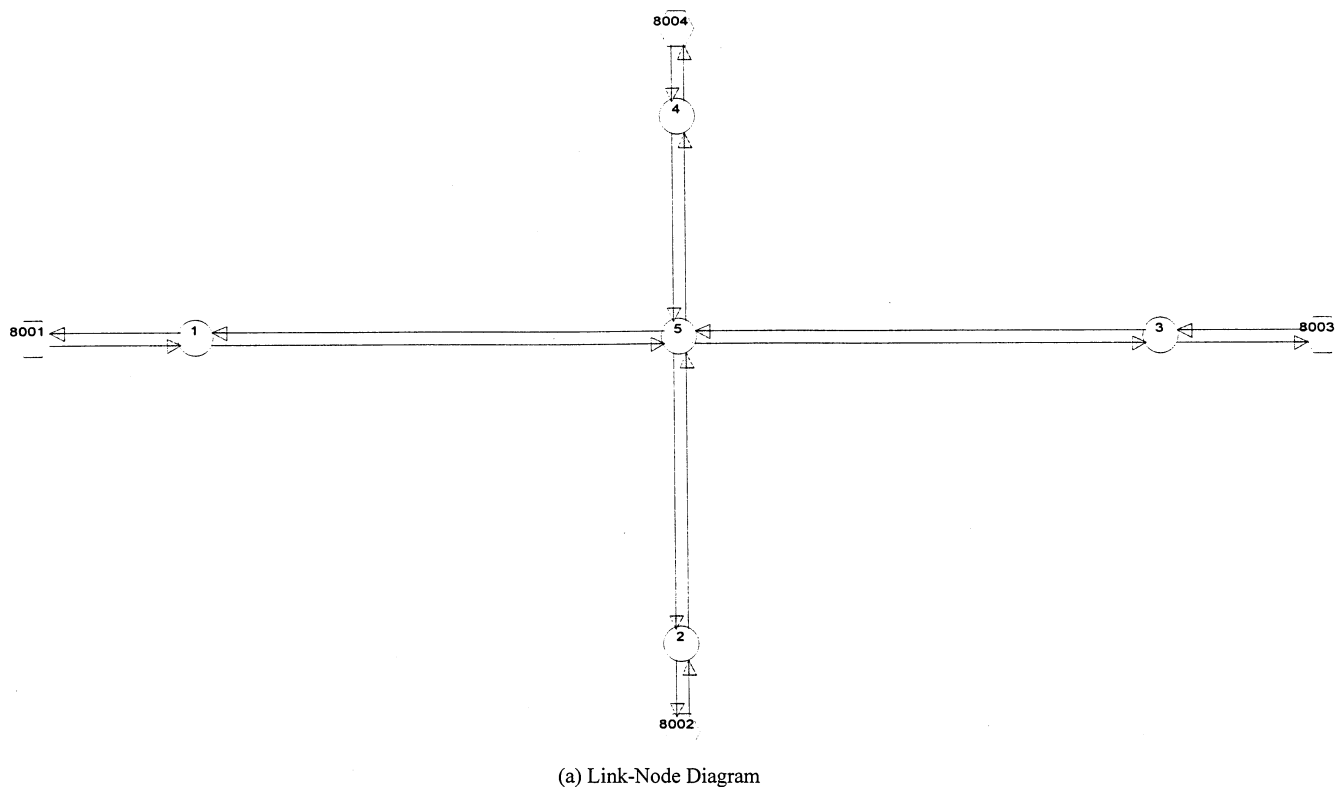


FIGURE 1 Exclusive right-turn lane network simulated in CORSIM.

right—40 percent through, and 70 percent right—30 percent through. For each of these turn volume percentages, 20 trials with 20 different random number seeds were run for each of the four pedestrian levels. There are only 20 data points for each pedestrian level on the shared network, as opposed to 80 on the exclusive, because there is only one direction in which volumes can be measured in this network.

SIMULATION RESULTS

Turning Speed

CORSIM predicted very little difference in the saturation flow rate with respect to turning speeds. The results for each trial are

summarized in Table 1. As the table shows, virtually no variation exists in the saturation flow rates for both the turning and through lanes. These first runs produced volumes for the through lane and right-turn lane that almost replicated the volumes predicted by the HCM. The HCM reports 1,900 vph for ideal saturation flow for through lanes; CORSIM reports through volumes ranging from 1,919 to 1,922. For turning movements with no pedestrian interference, HCM suggests an ideal saturation volume of 1,615 vph, whereas CORSIM produced volumes ranging from 1606 to 1610. The ratio of the two rates for each speed is 0.84. This ratio is consistent with the 0.85 adjustment factor established in the HCM and Australian manual for the effects of the turning radius and the decreased speeds it requires around a turn. One possible explanation for the discrepancies in the volumes is that the vehicles are at

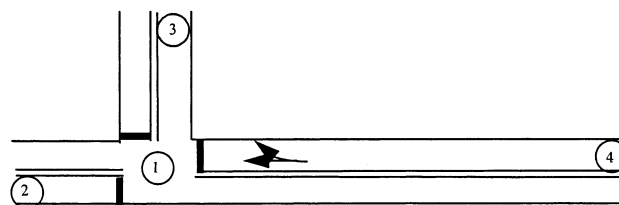
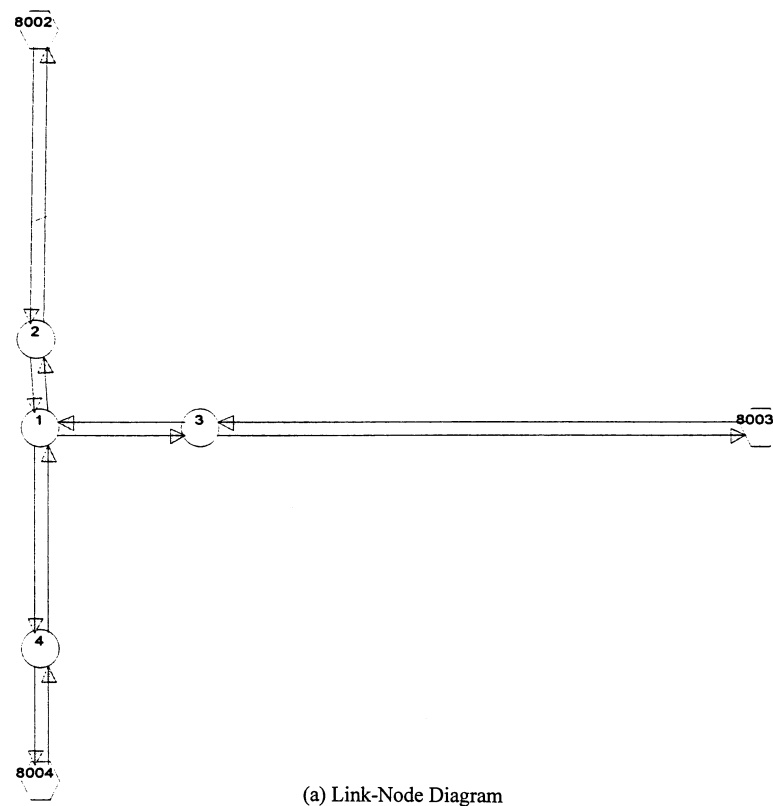


FIGURE 2 Shared right-turn lane network simulated in CORSIM.

saturation and are discharging from a standing queue. The effect of turning speeds was therefore ignored for the following runs and the default speed value of 14.2 km/hr was used throughout. The consistency of the 0.85 turning radius factor in the HCM, Australian manual, and CORSIM lends strong support to its validity for capacity analysis purposes.

Exclusive-Lane Network

The results for the 20 runs of the exclusive-turn lane network at each pedestrian volume are indicated in Table 2 along with the corresponding estimates of the HCM, Australian, and Canadian models. This data can be used to model pedestrian impact with good confidence. As shown in Figure 3, linear, exponential, and polynomial forms of the model were considered, all producing high R^2 values above 0.90. Although the polynomial model has a

slightly higher R^2 value, the linear model was used because of its simplicity and consistency with other analytical models.

CORSIM produced saturation flow rates that were in general much lower than those predicted by the analytical models with pedestrians present. As shown in Table 2, the saturation flow rate with no pedestrians predicted by CORSIM is very similar to the HCM model. When pedestrians are considered in the network, their

TABLE 1 Right-Turn Saturation Flow Rate Versus Turning Speeds in CORSIM: Exclusive Right-Turn Lane Network

Right Hand Turning Speed (km/hr)	Saturation Flow Rate (vphg)	
	Turn Lane	Through Lane
	AVG. (ST DEV)	AVG. (ST DEV)
14.2	1606 (49)	1919 (63)
24.0	1607 (50)	1922 (62)
28.3	1610 (52)	1919 (65)

TABLE 2 Saturation Flow Rates for Exclusive Right-Turn Lane

Pedestrian Volume (PEDS/hr)	Saturation Flow Rate (vphg)			
	CORSIM AVG (ST DEV)	1994 U.S. HCM	Australian	Canadian (Toronto)
NONE	1606 (49)	1615	1700	1140
LIGHT (175)	1197 (78)	1457	1533	970
MODERATE (375)	929 (101)	1276	1343	775
HEAVY (675)	413 (89)	1004	1057	483

impedance was much more significant in CORSIM than in most other analytical methods.

Shared-Lane Network

The results for the shared-lane model were equally convincing. CORSIM shows a strong linear relationship between pedestrian volumes and saturation flow rate. Results for all the shared-lane network trials for each turning vehicle proportion are graphed in Figure 4. Table 3 gives the average saturation flow rate for the four pedestrian volumes and the five turning proportions. The CORSIM model once again shows a greater impact on saturation flow rate at higher pedestrian volumes of the four models.

Delay Comparisons

CORSIM models pedestrian interaction by adding a randomly generated delay to the vehicle's discharge headway, as described

earlier. The total headway for a vehicle is inversely proportional to the saturation flow rate. For example, the average vehicle headway for a right-turning vehicle with no pedestrian interference is the inverse of the HCM's ideal of 1,615 vph or $3,600/1,615 = 2.25$ sec. This headway can be used to determine the delay caused by pedestrians by subtracting the average headway of a lane with no pedestrians from one with pedestrian interference. Table 4 converts the saturation flow rate for the HCM and CORSIM at the four average pedestrian volumes into the average headway. Using the average headway that is embedded within the defaults for the exclusive network created, CORSIM calculates the corresponding saturation flow rate, also shown in Table 4. The average headways derived from the HCM are much smaller than the values derived from the CORSIM results as well as the headway embedded in the arrays. These differences explain the recurring differences in the saturation flow rate adjustment factors from CORSIM compared with the other three models. Thus, to bring CORSIM saturation flow rates closer to the analytical models, a revision in its embedded decile delay distribution would be necessary.

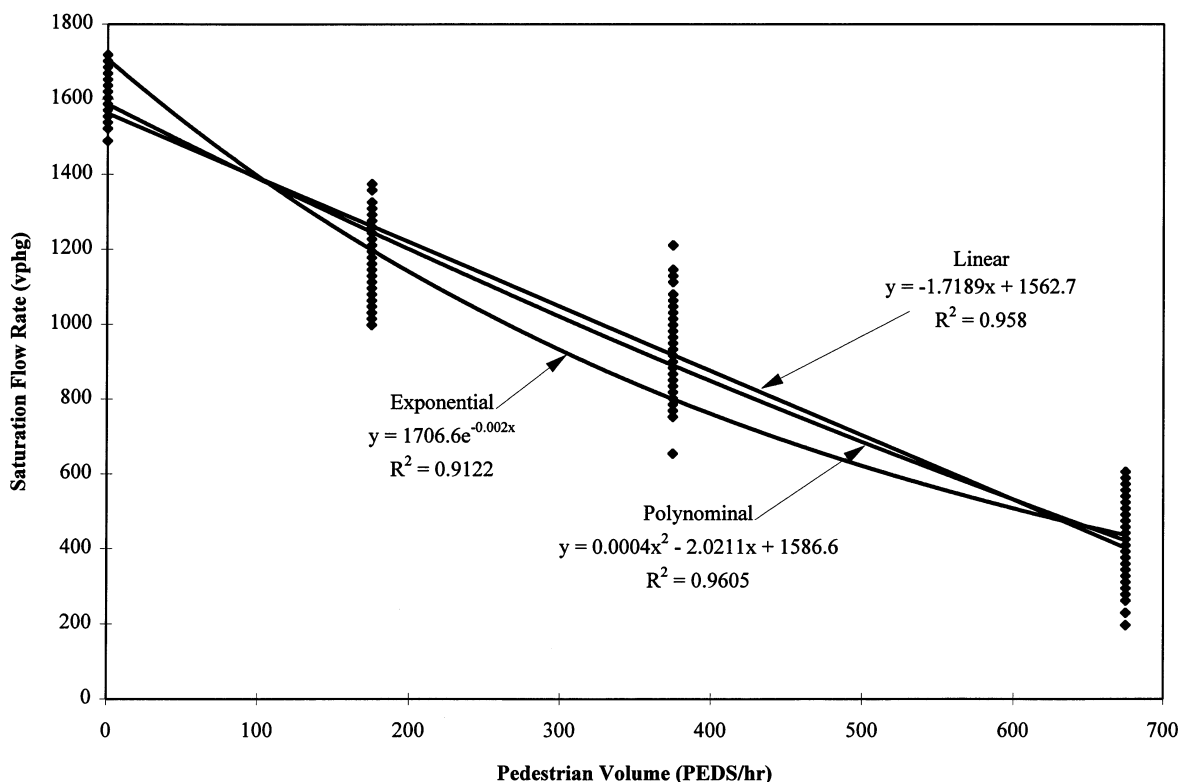


FIGURE 3 Results of CORSIM simulation of exclusive right-turn lane with varying pedestrian volumes (80 replications for each).

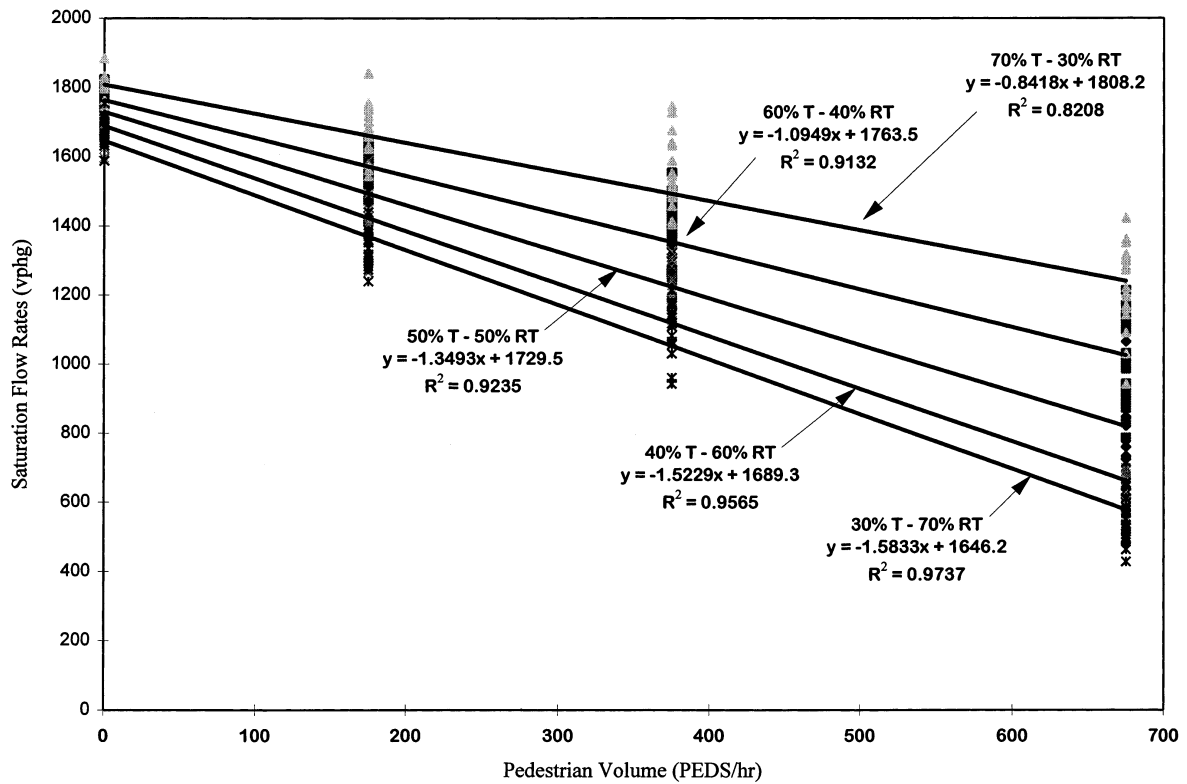


FIGURE 4 Results of CORSIM simulation of shared right-turn lane with varying pedestrian volumes and turning percentages (20 replications for each).

TABLE 3 Saturation Flow Rates for Shared Right-Turn Lane

Turn Split %T - %RT	Pedestrian Volumes (PEDS/hr)	Saturation Flow Rates (vphg)			
		CORSIM AVG. (ST DEV)	1994 U.S. HCM	Australian	Canadian (Toronto)
30-70	NONE	1658 (42)	1701	1790	1368
	LIGHT (175)	1329 (49)	1673	1673	1249
	MODERATE (375)	1093 (72)	1463	1540	1113
	HEAVY (675)	566 (69)	1273	1340	908
40-60	NONE	1677 (36)	1729	1820	1444
	LIGHT (175)	1389 (75)	1634	1720	1342
	MODERATE (375)	1202 (86)	1525	1606	1225
	HEAVY (675)	624 (58)	1363	1434	1050
50-50	NONE	1711 (42)	1758	1850	1520
	LIGHT (175)	1485 (64)	1678	1767	1435
	MODERATE (375)	1280 (75)	1588	1671	1338
	HEAVY (675)	789 (154)	1452	1529	1192
60-40	NONE	1740 (43)	1786	1880	1596
	LIGHT (175)	1567 (61)	1723	1813	1528
	MODERATE (375)	1413 (66)	1650	1737	1450
	HEAVY (675)	922 (122)	1542	1623	1333
70-30	NONE	1772 (50)	1815	1910	1672
	LIGHT (175)	1676 (69)	1767	1860	1621
	MODERATE (375)	1550 (101)	1713	1802	1563
	HEAVY (675)	1204 (131)	1631	1717	1475

TABLE 4 Relationship Between Saturation Flow Rate, Average Vehicle Headway, and Average Vehicle Delay Caused by Pedestrian Interference: Exclusive Lane Network

	Pedestrian Volume (PEDS/hr)			
	NONE	LIGHT (175)	MOD. (375)	HEAVY (675)
U.S. HCM				
Saturation Flow Rate (vp/hg)	1615	1457	1276	1004
Total Avg. Headway (sec)	2.23	2.47	2.82	3.59
Avg. Delay from peds (sec)	0.00	0.24	0.59	1.36
CORSIM Results				
Saturation Flow Rate (vp/hg)	1606	1197	929	413
Total Avg. Headway (sec)	2.24	3.01	3.88	8.72
Avg. Delay from peds (sec)	0.00	0.77	1.64	6.48
CORSIM Default Array				
Saturation Flow Rate (vp/hg)	1606	1146	738	366
Total Avg. Headway (sec)	2.24	3.14	4.88	9.84
Avg. Delay from peds (sec)	0.00	0.90	2.64	7.60

COMPARISON WITH FIELD DATA

In conjunction with an ongoing FHWA research project at North Carolina State University, field data were collected across all regions of the United States. These data consisted of discharge headways from vehicle queues (five or more vehicles) that were impeded solely by pedestrian traffic on the destination crosswalk. Although the analysis of these data is still in progress, a preliminary model was developed and evaluated that relates the saturation flow rate adjustment factor for left-turning vehicles to pedestrian flows, and occupancies of the pedestrian-vehicle conflict zone. The model has a strong explanatory value with $R^2 = 0.73$. The model is shown below:

$$f = 1.00 - 1.02[19 \ln(PEDS) - 85] \quad (6)$$

where f is the left-turn saturation flow rate adjustment factor and $PEDS$ is pedestrian volume per hour of green.

Figure 5 compares the regression model fitted to the empirical data with the four models already discussed. The comparison between the right-turn analytical-simulation models and the left-turn empirical model is justified because all field data were collected at sites in which left turns were made from a one-way to a one-way street, which are operationally similar to right turns for the purposes of this study. The empirical model exhibits a logarithmic relationship in which pedestrian interference has a stronger impact at lower pedestrian volumes. This impact levels out as the volume increases. This pattern is dissimilar from the other models, but is statistically significant. In fact, the shape of the relationship appears to be reasonable considering the strong impact the first few pedestrians have on right-turners. As pedestrian volumes increase, they will tend to platoon more at the beginning of the cycle. The impact additional pedestrians have on vehicles is lessened because their path is already interfered with by the other pedestrians in the platoon.

EXPERIENCE WITH CORSIM SOFTWARE

While simulating pedestrian impacts in CORSIM, many difficulties and inconsistencies were encountered. In an attempt to develop a more representative model over the entire range of pedestrian flows, the team attempted to generate pedestrian volumes in between the four default ranges. This was accomplished by changing the default

values for the duration of the strong interaction of pedestrians. The average pedestrian volumes were related to the duration of strong interaction in a linear model; each second of strong interaction corresponds to an increase in pedestrian volume of 20 pph, starting with a pedestrian volume of 175 pph at 0 sec of strong interaction. Unexpectedly, when these defaults were changed, there was no corresponding change in the saturation flow rate. The result was independent of all four default settings. Further, CORSIM only simulates the impact of the near-side pedestrian traffic whose platoon would interfere first. In reality, there may be strong interaction both at the start and the end of the green phase if the pedestrian platoons do not overlap.

CONCLUSIONS

A number of existing methods to estimate the impedance effect of pedestrians on turning traffic at signalized intersections have been examined. Three analytical models, a simulation model, and a model derived from field data were compared, leading to the following conclusions:

1. Currently used analytical models assume a linear relationship between pedestrian volume and saturation flow rate for turning traffic. This was found to be consistent with results from CORSIM simulations.
2. The effect of turning speed was found to be negligible based on simulation results. This may be attributable to the fact that in a queue-discharge mode, right-turning vehicles proceed from a standing queue that is stopped during the red phase.
3. In absence of pedestrians, the current HCM right-turn adjustment factor of 0.85 is identical to that obtained from CORSIM simulations.
4. Field data suggest a higher pedestrian impedance than that predicted by all analytical and simulation models.
5. Field data exhibit a nonlinear relationship between pedestrian volumes and saturation flow rates, with the largest impact occurring at the lower pedestrian volumes.
6. The CORSIM pedestrian simulation module does not operate properly outside the default values. Care should be taken in interpreting and extrapolating its results under such conditions.
7. There is a need to incorporate pedestrian impacts on left-turn saturation flow rates in the CORSIM model.

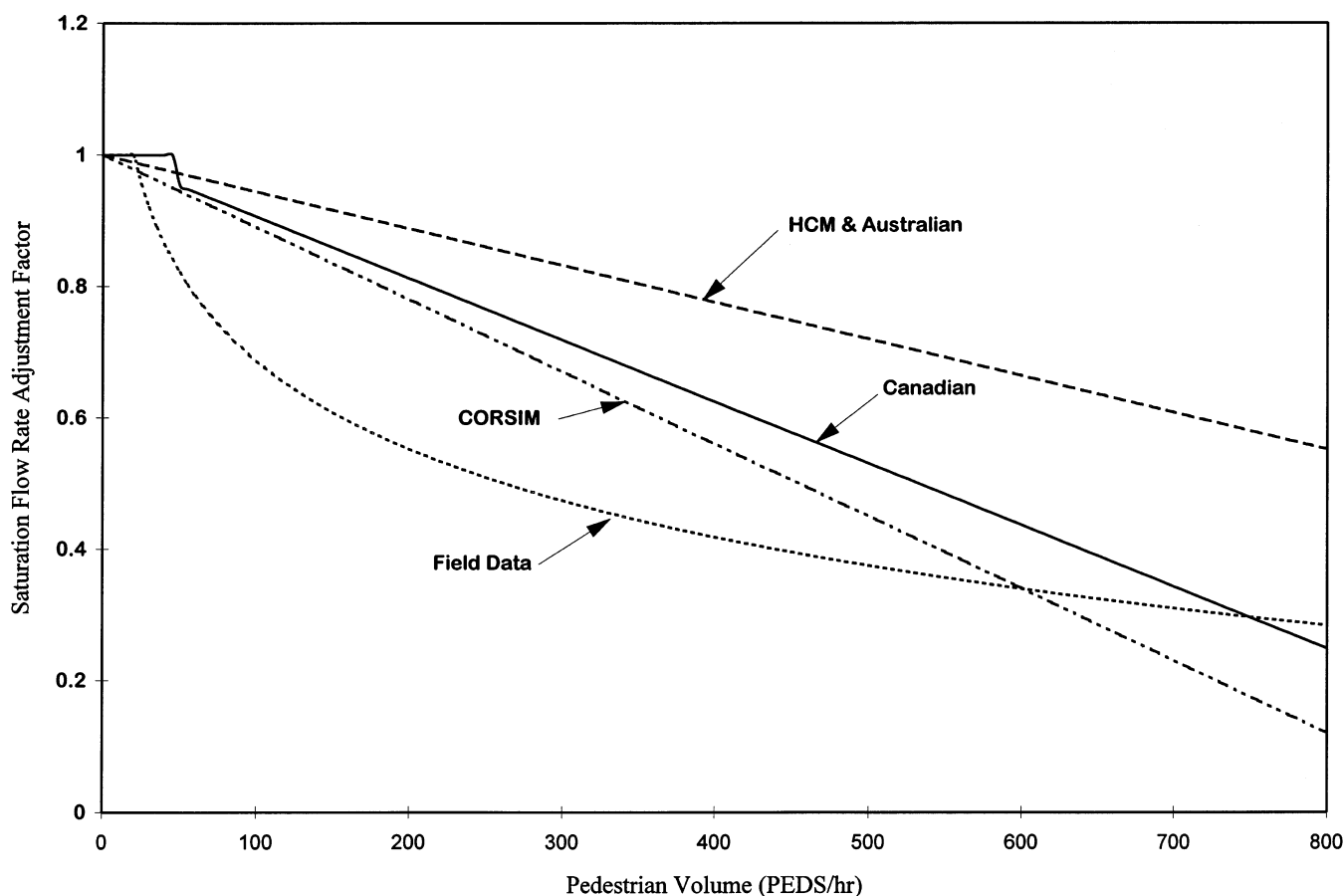


FIGURE 5 Summary comparison of saturation flow rate adjustment factors for exclusive right-turn lanes.

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