Combined Effect of Radius and Pedestrians on Right-Turn Saturation Flow at Signalized Intersections

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The interaction of pedestrians and vehicles on urban roadways is complex. Although concerns for safety usually prevail, capacity and convenience (i.e., quality of service) are also important considerations in the design and evaluation of transportation facilities. The effect of radius and pedestrian flows on saturation flow is of interest. These factors consequently affect the capacity of right-turn lanes at signalized intersections in which pedestrians share the crosswalk space during some portions of the green signal intervals. Canadian, Australian, and U.S. right-turn saturation flow adjustment procedures will be described, and some of the considerations being evaluated during the revision process of the *Canadian Capacity Guide for Signalized Intersections* (CCG) will be presented. A modification of the saturation flow adjustment techniques included in the CCG is recommended to express the combined effect of a small radius and the presence of pedestrians on right-turn lane capacity. The proposed procedure, process and rationale leading to the development of the suggestions, and implications for the 1985 *Highway Capacity Manual* are discussed.

The interaction of pedestrians and vehicles on urban roadways is very complex. Although concerns for safety usually prevail, capacity and convenience (i.e., quality of service) are also important considerations in the design and evaluation of transportation facilities. Radius and pedestrian flows affect saturation flow and consequently affect the capacity of right-turn lanes at signalized intersections in which pedestrians share the crosswalk space during some portions of the green signal intervals (Figure 1).

In North America, the issue is not significant at many intersections in suburban industrial and residential areas. As a rule, the radii are generous and pedestrian volumes are low. Nevertheless, the problem is critical in many central business districts, because the capacity of some intersections during peak hours may depend on the smooth flow of traffic in the right-turn lanes. As a consequence, these lanes may be the main constraints on the degree of congestion in downtown networks.

Major factors that influence the capacity of the right-turn lanes are radius and pedestrian volumes. Signal timing and several other conditions also contribute to the reduction of the basic saturation flow.

Some of these factors are being examined during the revision process of the *Canadian Capacity Guide for Signalized Intersections* (CCG) (*1*). A set of data was collected in Edmonton from 1983 to 1985. The surveys were relatively extensive; they included 1,098 signal cycles (of which 620 were used) at seven intersections used by over 25,000 pedestrians and almost 5,000 vehicles.

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Analysis indicates that a modification of the saturation flow adjustment techniques included in the CCG (*1*) would be advisable to express the combined effect of a small radius and the presence of pedestrians on right-turn lane capacity. The proposed procedure, the process and rationale leading to the development of the suggestions, and some implications for the 1985 *Highway Capacity Manual* (HCM) (*2*) are described in the following sections. The terminology generally follows the CCG (*1*), with additional terms from the HCM (*2*) and an Australian Road Research Board report (*3*) when necessary.

BACKGROUND

The CCG (*1*), which uses lane-by-lane analytical and design techniques based on saturation flow, identifies a set of calculation procedures to determine the saturation flow for specific local intersection conditions. The adjustment of the saturation flow for the effect of the radius is shown in Figure 2. The adjustment uses the curb radius or, for sharp curves, the inside tracking path. This definition may explain some differences between the CCG (*1*) and other documents.

For right turns with pedestrian interference, the CCG (*1*) identifies two empirical functions, one for Toronto and the other for Edmonton (Figure 3a). Users are advised to decide which driver behavior is more applicable to the case at hand. Lower values of right-turn saturation flow in Edmonton, compared to Toronto, are interpreted as reflecting a greater degree of respect for pedestrians and a lower traffic pressure in Western Canada, as well as the different signal practices of both cities. The two functions indicate the range of values of the strikingly different driver and pedestrian behavior in various regions of the country. For extreme situations, when pedestrian volumes are either very low or very high, only the Edmonton function is recommended. The CCG (*1*) expresses saturation flows in passenger car units (pcu). The procedure was formulated after extensive research (*4*) in Toronto, which was based on previous Australian work (*5*), as well as on preliminary results (*6*) of the previously mentioned Edmonton surveys.

The first step in determining the resulting adjusted saturation flow is the conversion of the pedestrian volume into the rate of flow for those periods when pedestrians can legally be in the crosswalk. For simplicity and practicality, the CCG

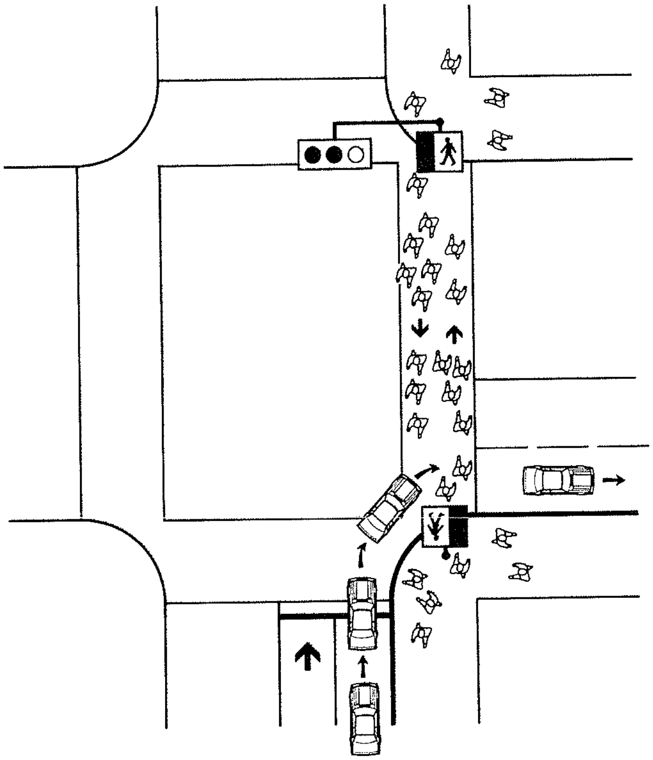

FIGURE 1 Capacity problem for right-turning vehicles penetrating a flow of pedestrians at the adjacent crosswalk.

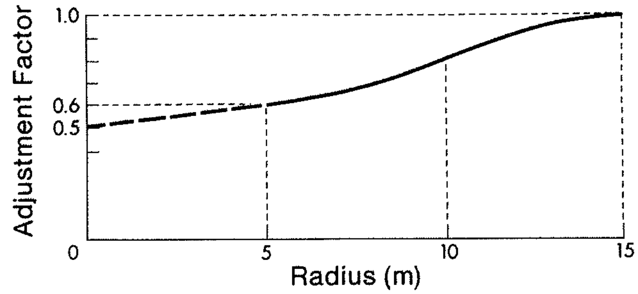

FIGURE 2 Turning radius adjustment factor in the CCG (*1*); curb radius is used where applicable, and the inside trailing edge of the vehicle is used otherwise, resulting in the portion of the function between 0 and 5.0 m in radius.

(*1*) assumes that pedestrians will be in the crosswalk during all portions of the green interval and that the pedestrian flow will be random or uniform, which, of course, may not be true in all cases. Nevertheless, those portions of the green signal interval during which no pedestrians are present (by design, rather than by default) are treated as right-turning flows without pedestrian interference. Right turns on red should also be considered separately. (If there is a portion of the green interval during which no pedestrians should legally be in the crosswalk, this period is subtracted from the green interval

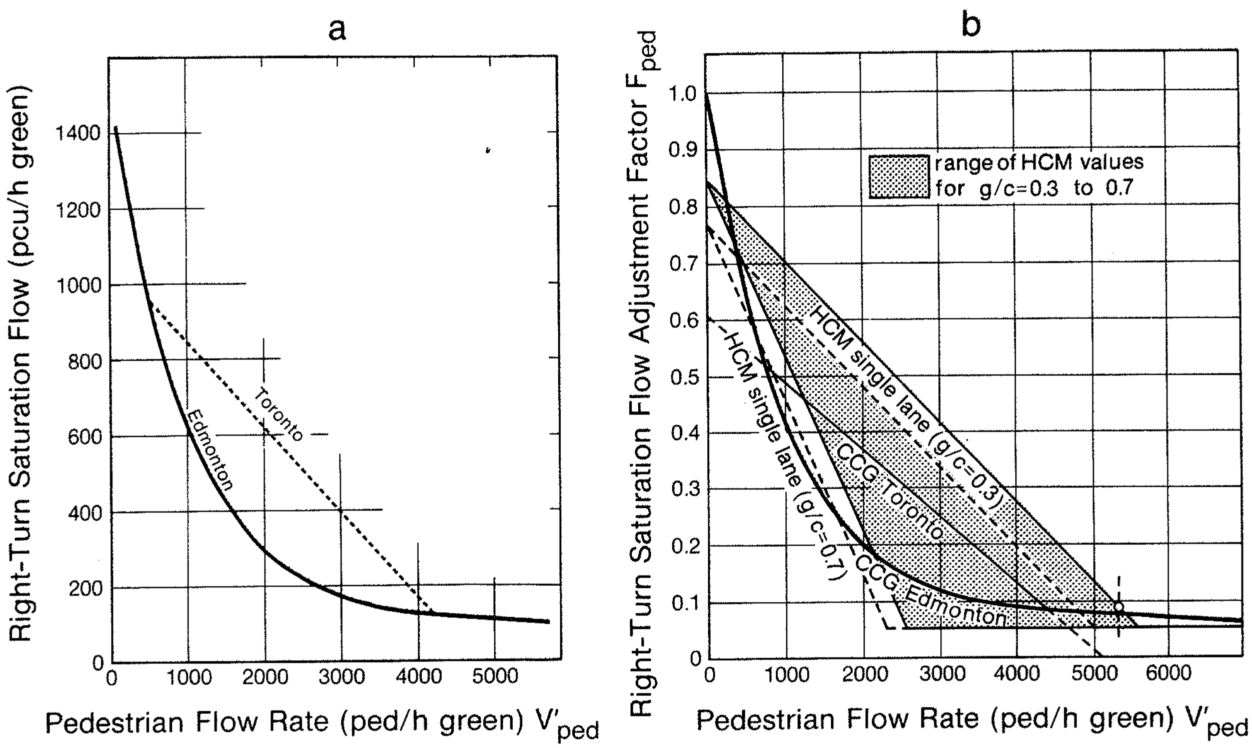

FIGURE 3 (a) Determination of right-turn saturation flow with pedestrian interference from the CCG (*1*). (b) Determination of the right-turn saturation flow adjustment factor for pedestrian interference based on the CCG (*1*) and HCM (*2*).

and analyzed separately, with the saturation flow adjustment for radius, if possible.)

The rate of pedestrian flow is determined as follows:

$$V'_{\text{ped}} = V_{\text{ped}}c/g \quad (1)$$

where

V'_{ped} = pedestrian flow rate (pedestrians per hour of green),
V_{ped} = pedestrian volume (pedestrians per hour),
c = duration of signal cycle (sec), and
g = effective green interval representing the period (sec) during which pedestrians can legally be in the crosswalk.

The functions for the resulting adjusted saturation flow for an exclusive right-turn lane are as follows:

Toronto equation:

$$S_R = 1{,}073 - 0.21V'_{\text{ped}} \quad (2)$$

Edmonton equation:

$$S_R = 1{,}450e^{-0.001V'_{\text{ped}}} + 100 \quad (3)$$

where S_R equals the right-turn saturation flow in passenger car units (pcu) per hour of green and e equals the base of natural logarithms. The results of these calculations may be further manipulated for shared-lane situations.

A somewhat simplistic technique was used in the *Saturation Flow Manual* (*6*), which was used in Edmonton between 1977 and 1984. The manual suggested that the adjustment factor for right turns with pedestrian interference (F_R) be determined as follows:

$$F_R = 1.0 - L_{\text{ped}}/g \quad (4)$$

where L_{ped} equals the average time lost (sec) by pedestrian interference per cycle and g equals the green interval (sec).

Although the definition of the time lost by pedestrian interference was left to the subjective judgment of the user (on the basis of brief local observations or measurements at existing intersections), the procedure seemed to produce realistic values in the hands of the city's traffic engineers.

The CCG (*1*) does not include a specific procedure for the effect of the radius in combination with the impact of pedestrian interference, but it makes several general recommendations. Section 4.413 of the CCG (*1*) indicates that the adjustment for the radius should be applied with caution if additional adjustments are made for heavy pedestrian volume, because the latter factor will govern. Section 4.521 states that right-turning flows with no or only minor pedestrian interference may be severely influenced by the corner radius, requiring that saturation flow be adjusted. Section 4.6, which discusses the accumulation of adjustment factors, warns the users as follows:

> Care must be exercised to ensure that "over-correction" does not occur. For example: where saturation flow for right-turning traffic is governed mostly by a high pedestrian flow rate, an additional correction for a tight radius is not appropriate. Some of the right-turning vehicles will have to stop more than once. Considerations regarding the effect of radius assume a continuous movement. On the other hand, where the number of pedestrians is very small, the adjustment for a tight radius is appropriate. Good knowledge of local driver behavior and conditions provides the best basis for these decisions.

The HCM (*2*) does not identify a separate procedure for the adjustment of the saturation flow for a tight radius but includes a right-turn factor, f_{RT}, that involves the effect of the lane and signal phasing type, the volume of pedestrians using the conflicting crosswalk, and the proportions of right-turning vehicles using the lane as well as individual portions of the phase. The HCM's (*2*) Table 9–11 identifies the factors for these conditions. The value of 0.85 for a lane that operates exclusively as a right-turn lane when no pedestrians are present seems to suggest the effect of radius alone.

The general HCM (*2*) formula that applies to dedicated right-turn lanes with pedestrian interference is as follows:

$$f_{\text{RT}} = 0.85 - \text{peds}/2{,}100 \quad (5)$$

where peds equals the volume of pedestrians (in pedestrians per hour) using the conflicting crosswalk. For a single-lane approach carrying only right-turning traffic interfering with pedestrians, the formula given in Table 9–11 is as follows:

$$f_{\text{RT}} = 0.765 - \text{peds}/2{,}100 \quad (6)$$

Figure 3b includes the two HCM (*2*) functions. However, the functions are shown only in approximate ranges because of the necessary conversion of pedestrian volumes per hour into the rate of pedestrian flow per hour of green. For the ratio of cycle time to green interval, a range of 1/0.3 to 1/0.7 has been used, because this range is considered to represent practical upper and lower limits. The HCM (*2*) recommends 0.05 as a minimum value for heavy pedestrian volumes. Akcelik (*8*) applied a range of 50 to 1,600 pedestrians per hour to the first HCM (*2*) function. The Canadian formulas for the adjusted saturation flow have been transformed to yield the adjustment factors using the local downtown saturation flows of 1,550 pcu per hour of green for Edmonton and 1,750 pcu per hour of green for Toronto (*1*).

Having determined all adjustment factors relevant to the lane group under consideration, the HCM (*2*) user determines the final saturation flow in vehicles per hour of green time by multiplying them as follows:

$$s = s_0 N f_w f_{\text{HV}} f_g f_p f_{\text{bb}} f_a f_{\text{RT}} f_{\text{LT}} \quad (7)$$

where s_0 is the ideal saturation flow rate per lane (usually 1,800 passenger cars per hour of green time per lane); N is the number of lanes in the lane group; and the factors represent the effect of width, heavy vehicles, approach grade, parking, buses, area type, right turns, and left turns, respectively.

The Australian procedure described by Akcelik (*3*) and used in the corresponding and significantly updated computer program Signalized Intersection Design and Research Aid (SIDRA–2) (*9,10*), includes the effects both of radius and pedestrian interference. The procedure treats both the left turns with opposing traffic (i.e., right turns in Australia) and

the right turns with pedestrian interference (i.e., left turns in Australia) in a similar fashion. Opposing flows are decomposed into portions that allow different degrees of traffic penetration by considering available gaps. The technique leads to the determination of a base saturation flow, which is then entered into the formula for the adjusted saturation flow as follows:

$$s = (f_w f_g / f_c) s_b \tag{8}$$

where

- s = saturation flow estimate (veh/hr),
- s_b = base saturation flow in through car units (tcu) per hour,
- f_w = lane width factor,
- f_g = gradient factor, and
- f_c = traffic composition factor (tcu per vehicle for a particular vehicle type and turning traffic mix).

The Australian definition of through car units in this application is not the same as the Canadian passenger car units. The CCG (*1*) applies factored passenger car units only as an intermediate calculation step for lanes that share more movements.

The SIDRA-2 program includes the effect of the radius in the calculation of the tcu equivalent for light and heavy vehicles:

$$e_{LV} = 1 + (150/r^3) \tag{9}$$

$$e_{HV} = 2e_{LV} \tag{10}$$

where e_{LV} equals light-vehicle equivalent and e_{HV} equals heavy-vehicle equivalent.

As in the results of the CCG (*1*), the resulting effect of radii greater than 15 m is negligible.

DATA

The 1983 to 1985 surveys (*6*) involved seven locations (lanes) at six intersections in Edmonton. Five of these intersections were in the newer part of the downtown business district, and one was in an area similar to many North American old historical downtowns (Figure 4).

All of the selected locations had dedicated right-turn lanes or lanes that functioned as such. Almost all vehicles belonged to the usual passenger car category. Although previous Canadian research (*11*) indicated that pickup trucks and vans have a slightly lower pcu equivalent (about 0.9), the difference was considered too small for the practical ends of this research. Some turning buses were observed at two locations, and at four locations the surveyed lanes were also used for straight-through buses. The cycles that included buses were excluded from the evaluation.

The turning radius was 8.5 m at five of these lanes, 13.0 m at one (Location 7), and 15.5 m at one (Location 6). According to the CCG (*1*), the last situation would need no adjustment for the effect of the radius.

Pedestrians had to cross four or six lanes of traffic. Because some roadways had a median, crosswalk lengths were between 17.1 and 22.0 m, with the exception of Location 3, which was only 13.7 m long. Hourly pedestrian volumes ranged from very low to several thousand people. Considering the cycle times of 80 and 90 sec, green intervals between 30 and 40 sec, and, with one exception, relatively long walk intervals between 18 and 25 sec, no excess pedestrian clearance period existed. That is, pedestrians could have been in the crosswalk during the whole duration of the phase (i.e., both during the green interval and signal change period). This situation was also true for Location 3, where walk intervals were correspondingly longer.

Figure 5 shows a typical layout and the conditions under which the saturation flow was measured. Vehicles were considered discharged when they passed an imaginary line about one-third of the way into the crosswalk (and continued their movement). Because most of the vehicles that had to stop did so just at the edge of the crosswalk, the situation was somewhat analogous to the usual Canadian measurement of saturation flow, although not at the stop line. The consequence of this definition difference can be considered negligible, because all vehicles that passed the stop line discharged during one signal cycle, even though they might stop again at the crosswalk.

All traffic data (i.e., vehicles crossing the reference line, pedestrians entering the interaction area, and signal changes) were recorded as a real-time event series on a tape recorder. The data were transcribed in the office and transferred to a computer for analysis. The evaluation included a relatively disaggregated approach by using 10-sec time slices of green intervals, whole fully saturated cycles, as well as an aggregate analysis in five-cycle averages. Both moving and consecutive averages were used. Because the consecutive five-cycle averages represent independent values in a practical period of 7.5 min (half of the standard HCM (*2*) analysis period), these averages were used. The CCG (*1*) allows users to use any analysis period, so further reduction of data to longer intervals was not considered appropriate.

The sneakers, vehicles that were delayed at the edge of the crosswalk into the amber interval and all-red period, were also recorded. Some of them (although not many) were discharging as late as the beginning of a conflicting vehicular green interval.

ANALYTICAL FOUNDATIONS

Figure 6 shows the basic interaction between the flows of pedestrians and right-turning vehicles in a situation in which the end of the walk interval plus the necessary pedestrian clearance period equals the beginning of the conflicting vehicular interval. In this case, even with a low pedestrian volume, some pedestrians may be in the crosswalk for the entire green interval and signal change period for the right-turning traffic.

The situation shown in Figure 7 is similar, except that the difference between the beginning of the conflicting green interval and the end of the pedestrian walk interval is much longer than the minimum necessary pedestrian clearance period. As a result, no pedestrians will be in the interaction zone during the last portion of the green interval for the right-turning traffic. The CCG (*1*) recommends that the period without pedestrians be considered a time of free flow of traffic,

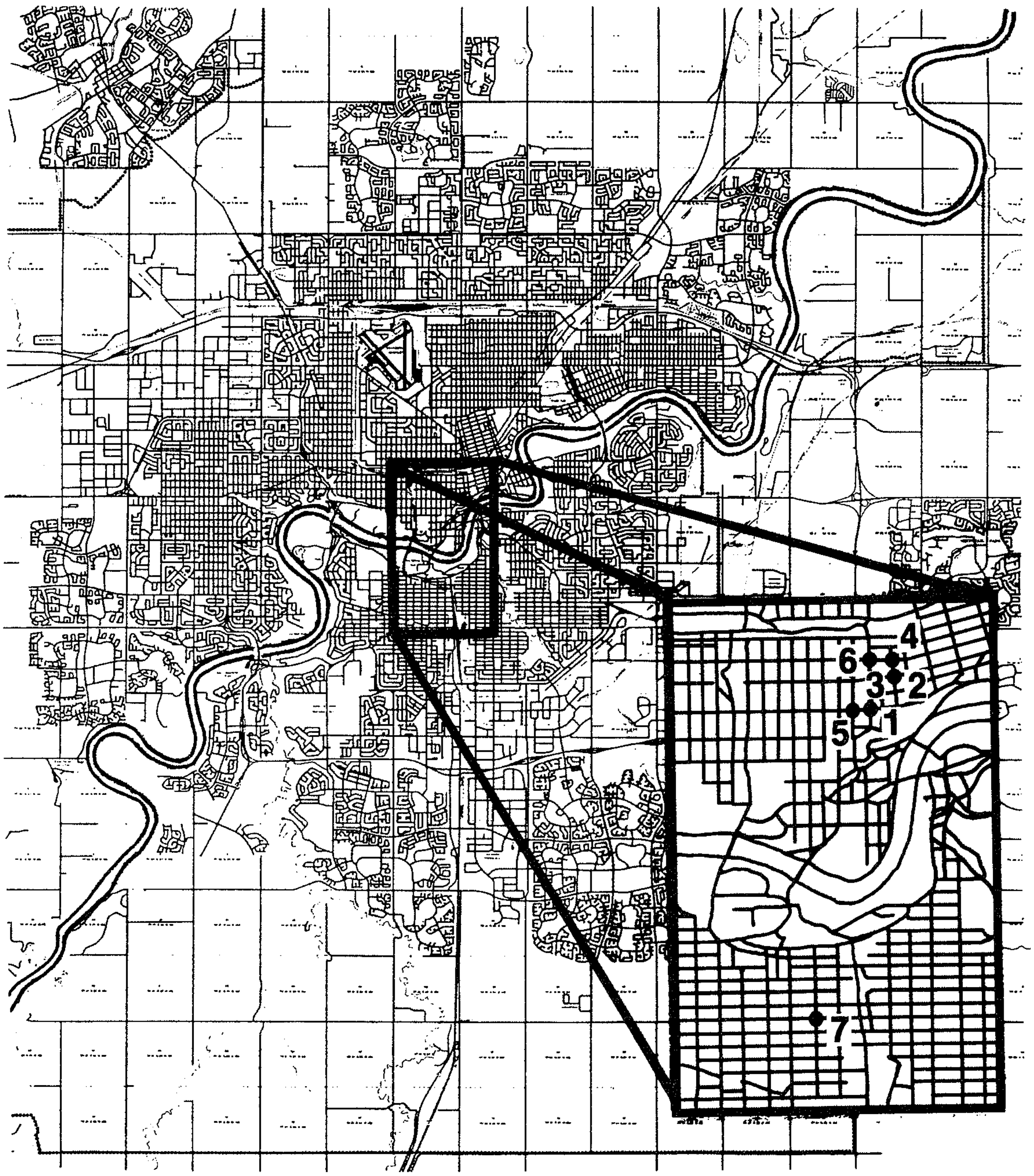

FIGURE 4 Edmonton survey locations for determining saturation flow adjustment for the combined effect of radius and pedestrian interference on right turns.

possibly influenced by a tight radius. However, this situation was not investigated.

As indicated in Figures 6 and 7, saturation flow during those portions of the green interval when pedestrians are present depends on several factors, such as the size of the first pedestrian group from the near-side sidewalk, the rate and pattern of the near-side pedestrian flow, the size and time of arrival of the far-side pedestrian group, and the rate and pattern of the following far-side pedestrian flow. These elements depend, in turn, on the volume both of near- and far-side pedestrians, cycle time, duration of walk interval, and width of the road. Behavior of regional drivers and pedestrians also plays a major role and is reflected in parameters such as driver acceptance of gaps in pedestrian streams, pedestrian expectations regarding drivers' respect for the crosswalk right-of-way, speed of pedestrians, location of vehicular stops, and a number of factors specific to a given location.

Many variations of the pedestrian flow and the resulting vehicular flow patterns shown in Figures 6 and 7 exist. Although sneakers represent a special category, and may or may not

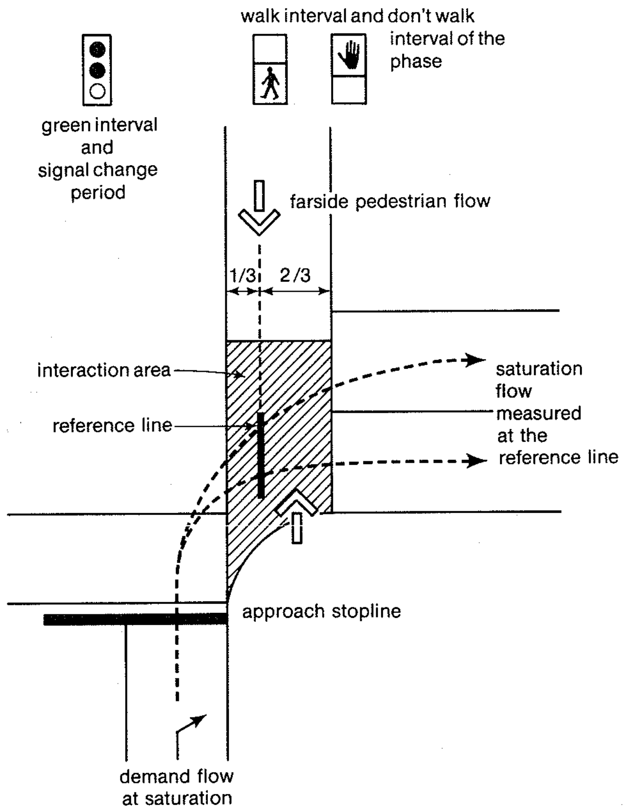

FIGURE 5 Basic conditions for the surveys of saturation flow for right turns with pedestrian interference.

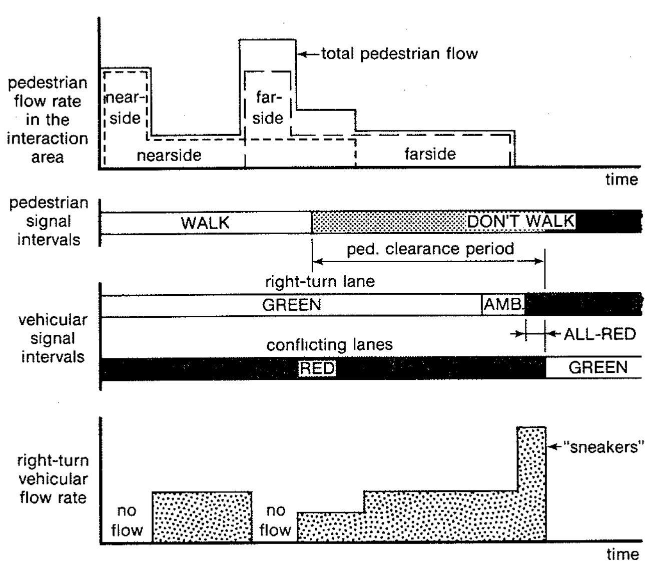

FIGURE 6 Schematic illustration of the relationships between pedestrian flows, signal timing, and vehicular flows for right-turning traffic in situations in which the necessary pedestrian clearance period takes up all the time between the end of the walk interval and the beginning of the conflicting vehicular green interval.

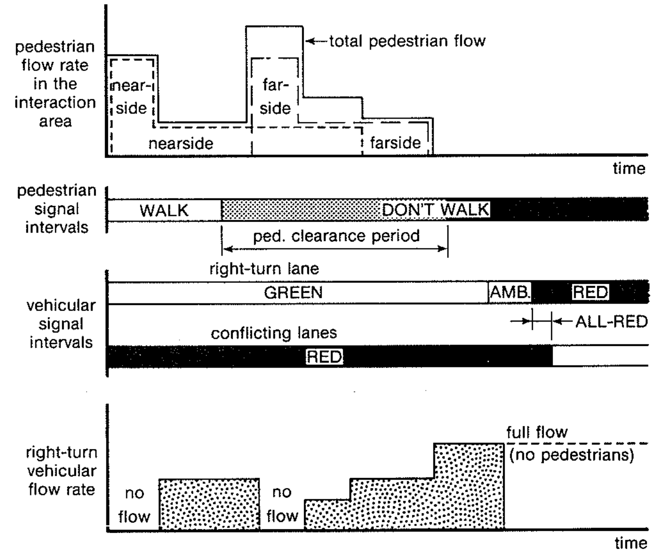

FIGURE 7 Schematic illustration of the relationships between pedestrian flows, signal timing, and vehicular flows for right-turning traffic in situations in which the necessary pedestrian clearance period is significantly shorter than the time between the end of the walk interval and the beginning of the conflicting vehicular green interval.

be present depending on the total pedestrian volume, signal timing, and degree of vehicular saturation, the 1984 CCG (*1*) includes them in the overall function.

Yagar (*12*) suggested a relatively complex analytical model that included some of the mentioned parameters. This model was tested on the previously described data set in 1984 and produced reasonable results at the higher end of the pedestrian flow scale. The more complicated interaction between pedestrians and vehicles when pedestrian flows were light, however, was not reflected well in that model (*6*).

The difficulty of capturing the complexity of the issue led to a concentration on the improvement of the empirical model, instead of a development of an analytical formula. This situation is not unusual in the engineering practice. A simple empirical model does not always represent a simple issue. Many times, the opposite is true.

ANALYSIS

The first part of the analysis involved calculation of saturation flow rates for 10-sec slices of green intervals in a manner similar to that described in the CCG (*1*) Appendix. The excess noise in these values prevented them from being useful in a practical analysis, but several observations were made.

The highest pedestrian flow rates, up to 8,000/hr, were experienced during the first 10 sec of green, which included the initial near-side group of pedestrians and usually a part of the initial far-side group. The remaining portion of the initial far-side group crossed the interaction zone in the first part of the second 10-sec time slice, resulting in pedestrian flow rates as high as 5,000/hr. The random flow of pedestrians fluctuated between 0 and 1,600/hr.

These pedestrian rates were reflected in identical average right-turn vehicular flow rates of 200 pcu/hr during the first and second 10-sec time slices. However, the rate fluctuated between 25 and 700 pcu/hr. The average vehicular penetration rate was about 600 pcu/hr, with 0 as the lower limit and 1,100 pcu/hr as the upper limit. Drivers who had stopped for the larger pedestrian flows were generally more pushy once the rate dropped than drivers giving the right-of-way to random pedestrians.

An analysis of the interaction between pedestrian and vehicular flows on a cycle-by-cycle basis, with flows averaged over the whole green interval, produced definite trends. As shown in Figure 8, the individual values exhibit a great deal of variation. The plots indicate the results at survey locations in similar groups. Locations 1 to 4, with an 8.5-m radius, covered a good range of pedestrian flow rates, whereas Locations 6 and 7 (with 13.5- and 15.0-m radii, respectively) featured only low to medium pedestrian rates.

In practice, however, traffic flows are rarely assessed on a cycle-by-cycle basis, so a longer time base was decided on. The HCM (*2*) uses 15 min, whereas the CCG (*1*) does not identify a specific time period but advises users to select one that reflects the peaking patterns. After some trials, a period of five cycles was selected for data aggregation. The use of 80- and 90-sec cycle times resulted in a time base of 6.66 or 7.5 min. A comparison of Figures 9 and 10 indicates that a longer time base would have reduced the scatter (and the data set) but would not have had a significant impact on the regression results.

Initially, five consecutive cycles in a moving average fashion were tried. As an example, the first data point would be determined as an average of Cycles 1 through 5. The next data point would be based on Cycles 2 through 6. This data set was used in Figure 11 to indicate the fit of the final recommended functions.

Because individual data points are not independent, this kind of data manipulation may not be considered permissible. For that reason, simple averages of five-cycle pedestrian and vehicular flows were adopted. As an example, if the first data point is defined from Cycles 1 through 5, the second point is based on Cycles 6 through 10.

The initial premise of the analysis assumed that the effect of the radius decreases with the increase of pedestrian flow rates. The first look at the data seemed to suggest that the saturation flow for pedestrian interference can be modified by the radius adjustment factor expressed as a function of the pedestrian flow rate. This process was originally proposed by Poss (*6*) and later modified for consideration in the CCG (*1*) revision. In principle, this modified procedure would proceed in the following steps:

1. Determine the combined radius and pedestrian adjustment factor:

$$F_{\text{rad ped}} = F_{\text{rad}} + (1 - F_{\text{rad}})V''_{\text{ped}}/2{,}000 \tag{11}$$

where F_{rad} equals the radius adjustment factor from Figure 2 and V''_{ped} equals the pedestrian flow rate in pedestrians per hour of green, up to a maximum of 2,000.

2. Determine the saturation flow for right turns with pedestrian interference and no effect of radius from a modified CCG (*1*) formula:

$$S'_{\text{ped}} = 1{,}000e^{-0.006V''_{\text{ped}}} + 140 \tag{12}$$

3. Determine the final saturation flow for the combined effect of the radius and pedestrian interference:

$$S_{\text{rad ped}} = F_{\text{rad ped}}S'_{\text{ped}} \tag{13}$$

The resulting family of functions is shown in Figure 9.

A closer investigation of the five-cycle averaged data points, including their cycle-by-cycle background, led to different conclusions:

1. The wide range of flow fluctuations at the low end of the pedestrian flow practically negated the fact that the average saturation flow for larger radii was slightly higher than the average saturation flow for smaller radii.
2. The apparent discontinuity of data in the range of 2,000 to 3,000 pedestrians per hour of green can be attributed to the fact that drivers could not find suitable gaps when a greater number of pedestrians were present. Because the first two cars were usually stopped in the intersection, they had to clear the conflict zone before the vehicles and pedestrians of the next phase arrived. As a result, they discharged during the intergreen (signal change) period, in some instances after the beginning of the following conflicting green interval. They became involuntary sneakers.
3. Virtually no sneakers were observed during periods of low and medium pedestrian flow rates, because the number of gaps was generally sufficient to discharge the vehicles waiting in the intersection space before or just after the beginning of the amber signal interval.
4. The number of sneakers during the cycles with high pedestrian flow rates was relatively constant, averaging about two per cycle.

Figures 12a and 12b show linear regressions through five-cycle data points for large and tight radius locations. Sneakers were excluded from the regression. Figure 12c compares the previous two linear regression lines with an overall average linear function for all data points regardless of the radius. Sneakers have been excluded. The individual linear functions are as follows:

1. For locations with radii equal to 13.5 or 15.0 m:

$$S_{\text{ped}} = 800 - 0.22V'_{\text{ped}} \tag{14}$$

2. For locations with an 8.5-m radius:

$$S_{\text{ped}} = 675 - 0.16V'_{\text{ped}} \tag{15}$$

3. For all locations, regardless of the radius:

$$S_{\text{ped}} = 775 - 0.19V'_{\text{ped}} \tag{16}$$

The data in the graphs of Figure 12 indicate that the trend may be nonlinear. A comparison of the average linear and an approximated average negative exponential function is shown in Figure 13. The 1984 CCG (*1*) functions are also included. Sneakers were excluded, and an approximate regression line is shown separately.

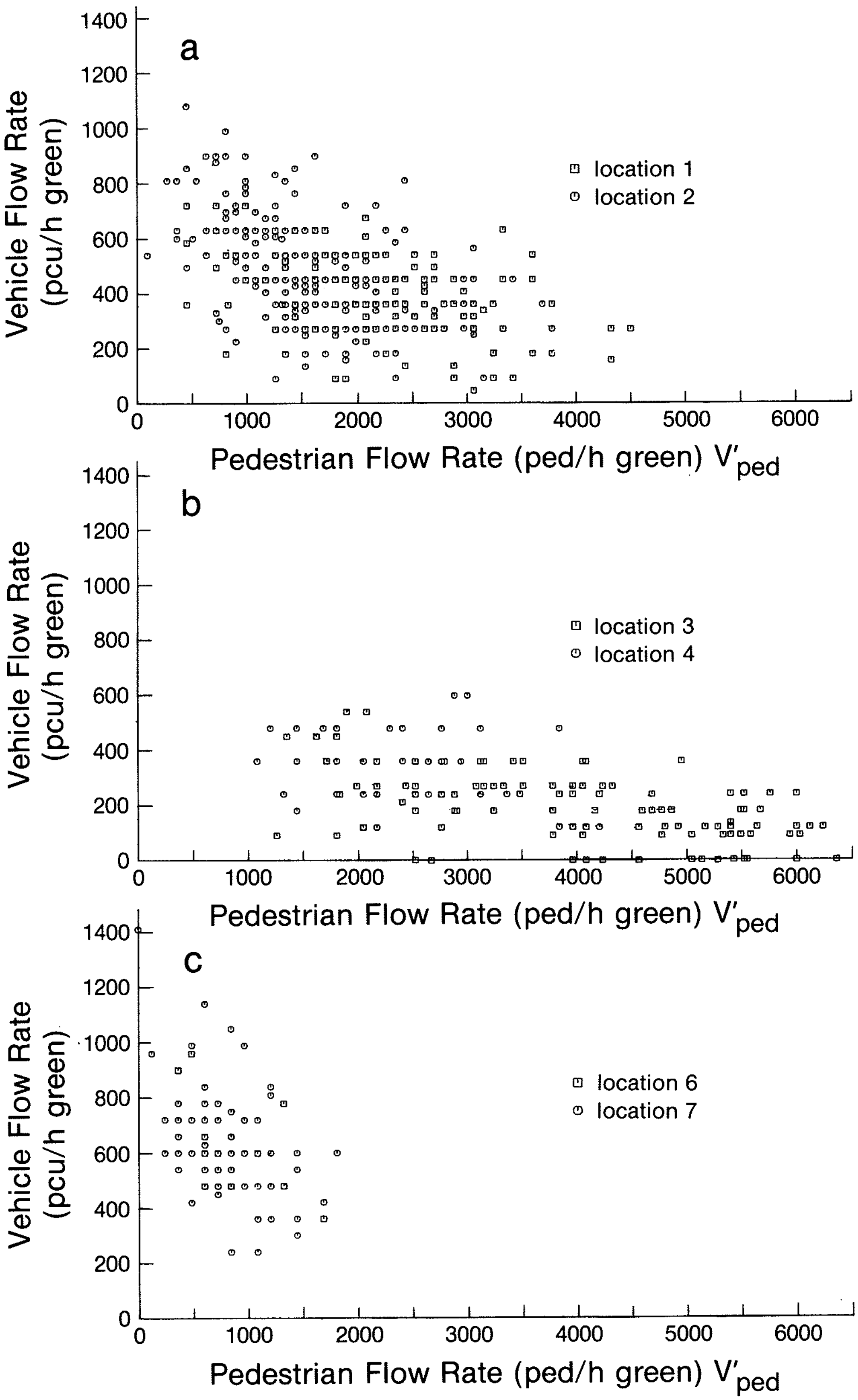

FIGURE 8 Measured cycle-by-cycle right-turn vehicular flow rates versus pedestrian flow rates on the conflicting crosswalk at several survey locations; pedestrian volumes were usually about 0.3 to 0.5 of the indicated pedestrian flow rates.

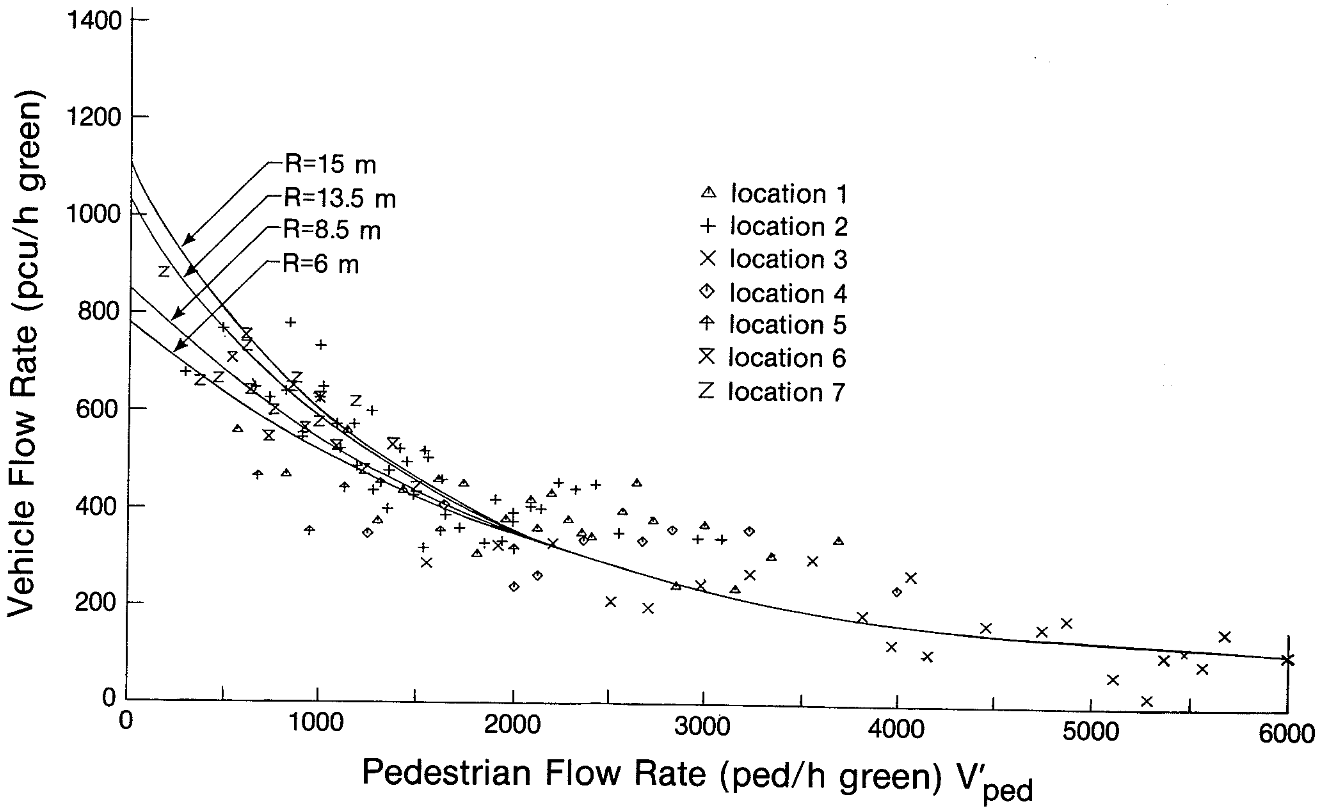

FIGURE 9 Measured right-turn vehicular flow rates averaged over five consecutive cycles versus average pedestrian flow rates in these cycles.

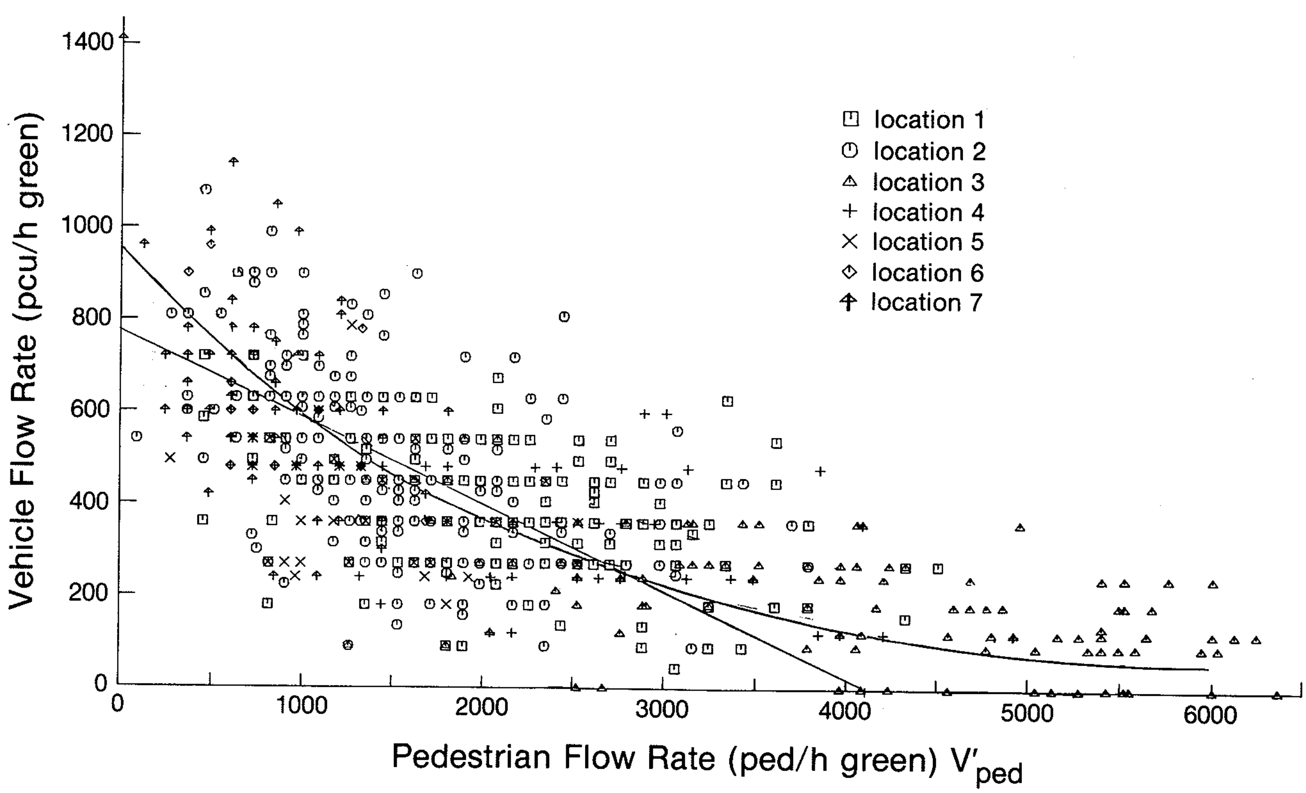

FIGURE 10 Linear and negative exponential regressions on the basis of five independent consecutive cycles plotted in the cycle-by-cycle data for right-turn saturation flows and pedestrian flow rates during green intervals for all survey locations.

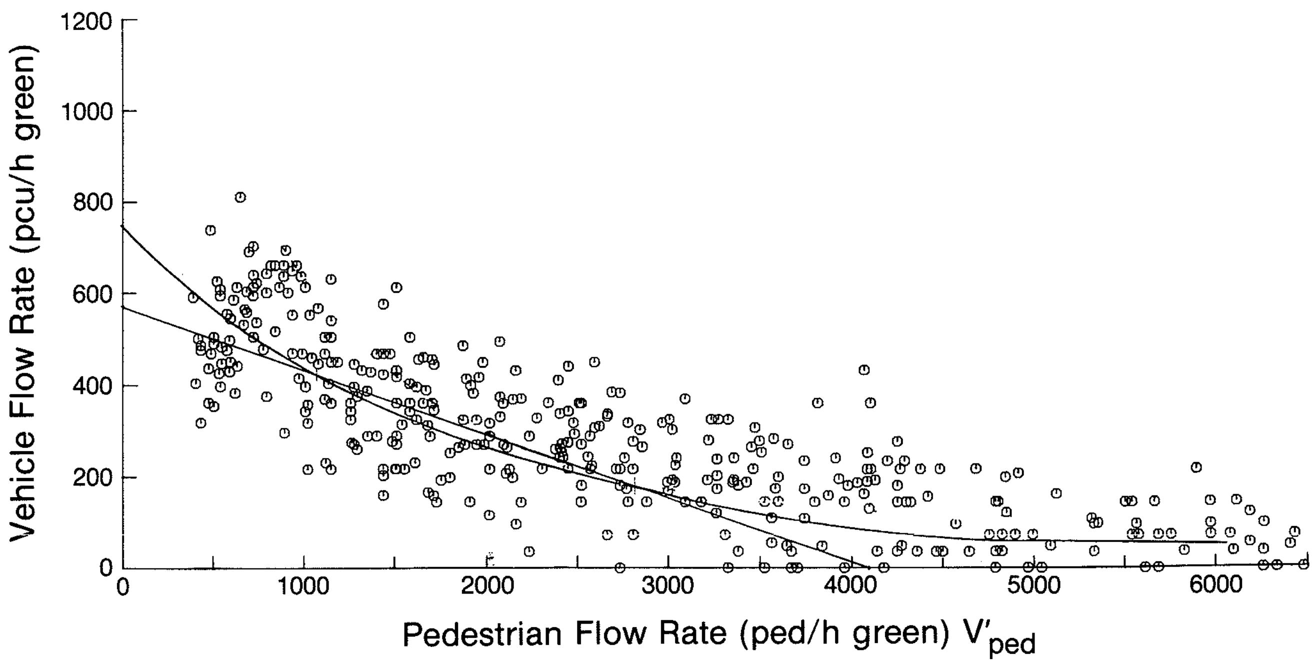

FIGURE 11 Linear and negative exponential regressions on the basis of five consecutive cycles plotted in a diagram of right-turn saturation flows and pedestrian flow rates during green intervals on the basis of data generated as moving averages over five consecutive cycles.

The nonlinear function in Figure 11 has the following form:

$$S_{\mathrm{ped}} = 950e^{-0.0005V'_{\mathrm{ped}}} \tag{17}$$

The fact that both the linear and the negative exponential functions in Figure 13 fall well within the two 95-percent confidence bands derived from the radius-related regressions indicates that either of them can be used without any loss of accuracy. A possible exception may be the very low pedestrian flow rates (0 to about 500 pedestrians per hour of green), which would probably justify a separate investigation on an appropriate data set. Figure 10, which includes all cycle-by-cycle data points, and Figure 11, which features five-cycle moving averages, also seem to confirm a relatively good representation of the relationship both by the linear and negative exponential functions.

The problem of sneakers is probably best shown in Figures 12b and 13. The discontinuity appears to begin at a pedestrian flow rate of about 2,500 pedestrians per hour of green and represents a flow rate of about 60 to 100 pcu/hr of green. The average number of cars using the signal change period was about two per cycle, which corresponds to a flow rate of about 80 or 90 pcu/hr of green. This number is shown at the right end of the diagram in Figure 10. Because of the high pedestrian flow rates in these cycles, only a few vehicles other than the sneakers were able to discharge. This occurrence explains the relatively high vehicular flows in some cycles with pedestrian flow rates over 4,000 pedestrians per hour of green in Figure 10. In Figures 11 and 13, these extreme values are hidden in the five-cycle averages.

OBSERVATIONS AND RECOMMENDATIONS

1. On downtown crosswalks where pedestrians are present or are expected by the drivers to be present, tight radii from about 8 m have no effect on right-turning vehicular saturation flows. That is, the combined effect of a tight radius and pedestrian flows does not follow a multiplicative or other combined function.

2. The previous observation is not valid in industrial or suburban residential areas, where no or few pedestrians are usually present. This statement is based on previous research (*7*) on the effect of radii, for which full basic saturation flow was measured at locations with low pedestrian flows and radii over 15 m.

3. The Edmonton saturation flows for right-turn lanes with pedestrians are still substantially lower than those in Toronto. Nevertheless, the trends identified (linear or flat negative exponential) are similar for both cities, which represent two extremes of Canadian driver and pedestrian behavior conditions.

4. The Edmonton function of the CCG (*1*) should be changed to either of the following equations:

$$S_{\mathrm{ped}} = 775 - 0.19V'_{\mathrm{ped}} \tag{16}$$

or

$$S_{\mathrm{ped}} = 950e^{-0.0005V'_{\mathrm{ped}}} \tag{17}$$

where S_{ped} equals the right-turn lane adjusted saturation flow and V'_{ped} equals the pedestrian flow rate during the green signal interval (in pedestrians per hour of green), calculated as follows:

$$V'_{\mathrm{ped}} = V_{\mathrm{ped}}c/g \tag{18}$$

5. The effect on capacity of right-turning vehicles discharging during the intergreen period (signal change period) should not be included in the saturation flow adjustment cal-

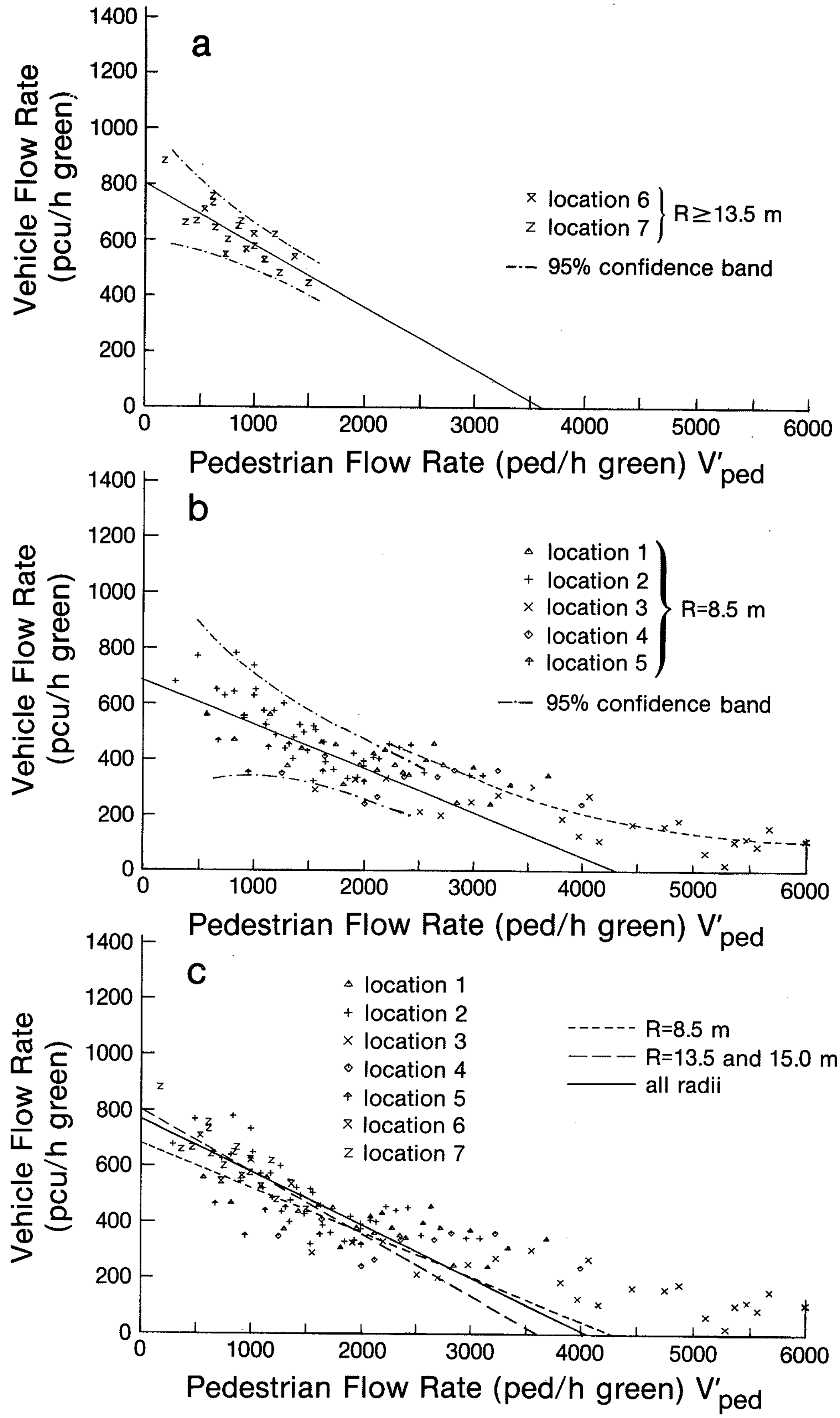

FIGURE 12 (a) Linear regression between pedestrian flow rate and right-turn saturation flow for locations with wide radii of 13.5 and 15.0 m. (b) Linear regression between pedestrian flow rate and right-turn saturation flow for locations with a tight radius of 8.5 m; sneakers are not included in the regression and are shown separately. (c) Comparison of the linear regressions for large and small radii with a linear regression for all data points regardless of the radius; sneakers are excluded.

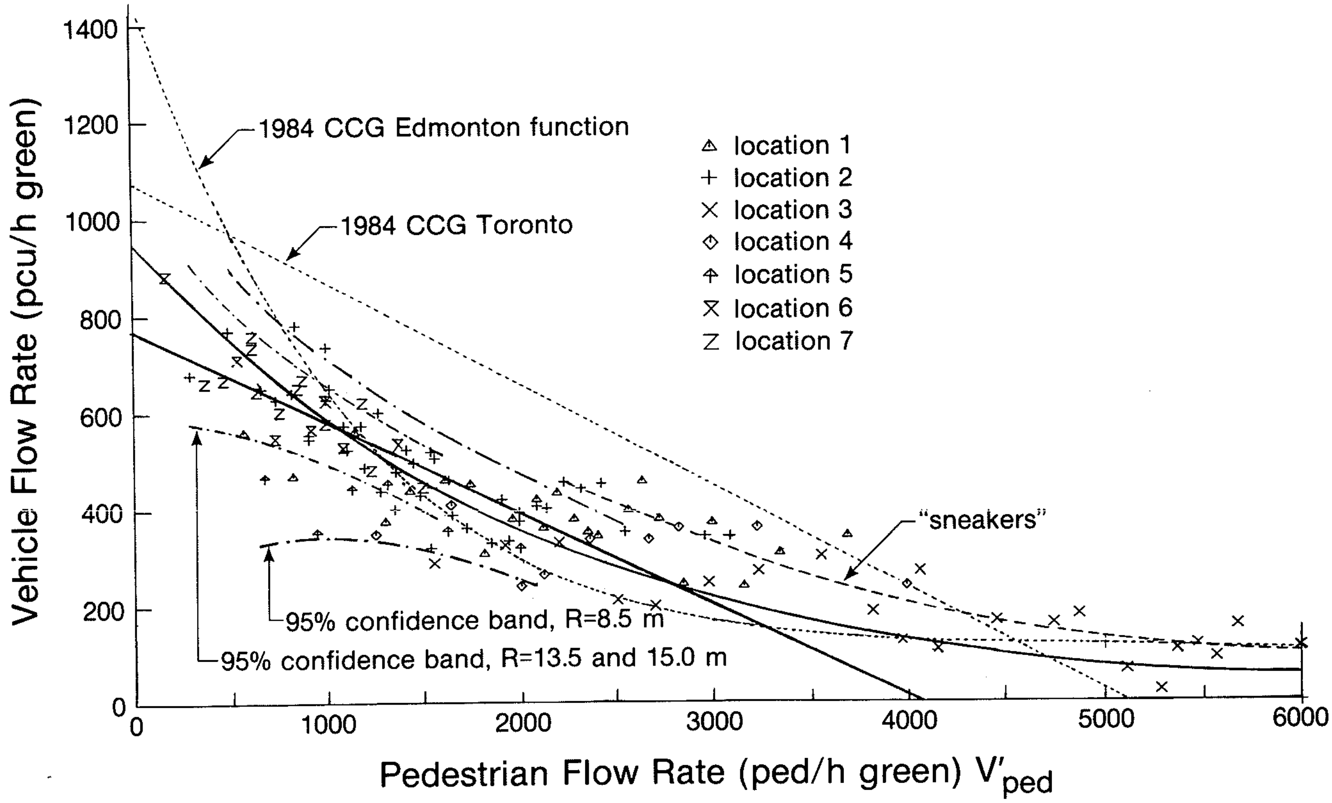

FIGURE 13 Comparison of a linear and an approximate negative exponential regression for all Edmonton locations regardless of the radius; approximate regression line for the sneakers is shown separately.

culation. A treatment of capacity similar to left turns on intergreen, in which these vehicles are added to the capacity of the green period (or discounted from the volume when designing green intervals), is suggested as follows:

$$C = S_a g/c + \text{flows during periods other than the effective green interval} \qquad (19)$$

where C equals the lane capacity (pcu/hr) and S_a equals the adjusted lane saturation flow in pcu per hour of green per lane.

Depending on the local situation, especially intersection geometry and local traffic behavior, one to two vehicles per cycle discharging during the later portions of the intergreen period (sneakers) may be considered.

Similarly, right turns on red should be analyzed separately, especially if the lane in question is a critical lane. If the lane is not critical, it is customary in Canada not to include right turns on red at all and consider them a capacity bonus.

6. The relative data trends for vehicles turning right during the effective green and vehicles using the later portions of the intergreen period (sneakers) seem to favor the negative exponential function that parallels the sneakers line. As a result, the addition to capacity from about 2,500 pedestrians per hour of green can be handled in a more continuous way.

7. Although sufficient data for the low pedestrian flow rates (below 200 to 300 pedestrians per hour of green, which is fewer than 100 pedestrians per hour) are not available, the cycle-by-cycle analysis indicated caution so that saturation flow would not be underestimated. The impact of pedestrians at these volumes, which generally represent fewer than two pedestrians per cycle, may be completely neglected, especially outside downtown areas. This recommendation was also made by Akcelik (*8*).

8. Saturation flow reductions for right-turning traffic with pedestrian interference may be better expressed as a reduction factor [as in the HCM (*2*), rather than as an absolute value as in the CCG (*1*)]. Figure 14 shows previous relationships converted to saturation flow adjustment factor functions using lane saturation flows of 1,550 pcu/hr of green for Edmonton and 1,750 pcu/hr of green for Toronto (Table 1, CCG). The conversions are as follows:

Linear, Toronto:

$$F_{ped} = 0.613 - V'_{ped}/8{,}335 \qquad (20)$$

Linear, Edmonton:

$$F_{ped} = 0.5 - V'_{ped}/8{,}200 \qquad (21)$$

Negative exponential, Edmonton:

$$F_{ped} = 0.612e^{-0.0005V'_{ped}} \qquad (22)$$

9. Although the adjustment factors that assume a certain local basic saturation flow value may appear to normalize the

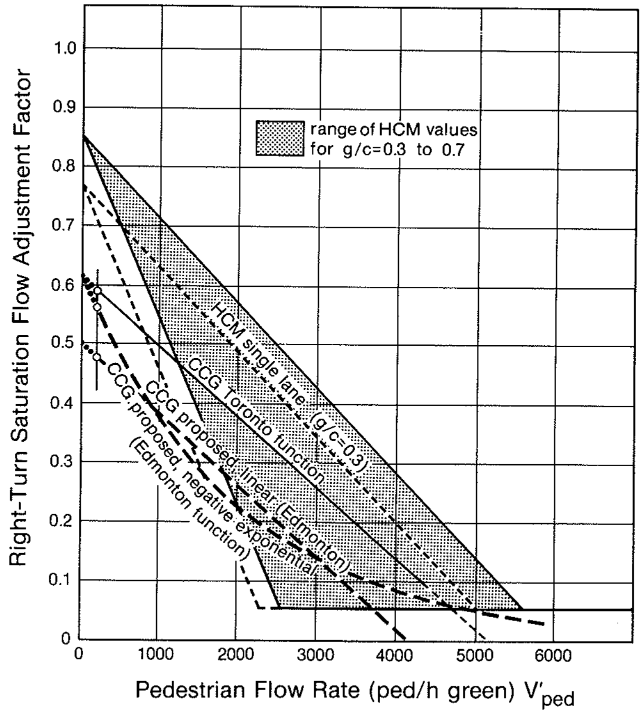

FIGURE 14 Comparison of the saturation flow adjustment factors for exclusively right-turn lanes with pedestrian interference from the CCG (*1*) with an approximate range of HCM (*2*) functions and with the functions considered for the next edition of the CCG (*1*).

functions (i.e., to bring them closer together), Figure 14 indicates that local differences are still substantial. As a result, users should be advised of the local conditions and basic saturation flows used in the derivation of the CCG (*1*) and HCM (*2*) adjustment factor functions.

10. Saturation flow for shared right and through lanes was not examined. However, the previous conclusions do not affect the CCG (*1*) factoring procedure for shared lanes.

11. As the shaded areas in Figures 3b and 14 indicate, pedestrian volume as used in the HCM (*2*) is not a good independent variable for determining the penetrating vehicular rate or saturation flow adjustment factor. The process is highly dependent on the actual flow of pedestrians in the periods during which they can legally be in the crosswalk and, consequently, on the timing of the signals. An average pedestrian flow rate during effective green intervals can be used as a good independent variable (in pedestrians per hour of green) to represent simply a complex set of events. The effective green interval should exclude periods with no pedestrian interference, if such periods exist at a given location.

CONCLUSIONS

Right-turning traffic competes with pedestrians for space and time at many signalized intersections in downtown areas. The determination of an appropriate value of saturation flow for these conditions represents a complex problem. Although this research was based on Edmonton data, which may be considered typical only for Western Canada and possibly some regions of the United States, several conclusions beyond the local application can be drawn, as follows:

- Respect for pedestrians and pedestrian expectations has a major impact on saturation flow, as evidenced by the differences in the Edmonton and Toronto values.
- Where pedestrians are in, or where drivers expect them to enter, the crosswalk, the effect of a tight radius can be neglected.
- The use of hourly pedestrian volumes for the determination of the right-turn saturation flow adjustment is not appropriate. The pedestrian rates of flow during the periods when pedestrians are legally in the crosswalk and during which the interaction with vehicles takes place should be substituted.
- Vehicles that have been waiting at the edge of the crosswalk for pedestrians to clear the conflict area beyond the end of the green interval, which clear the intersection during the signal change period (i.e., sneakers), should not be included in the saturation flow calculation. Because they do not discharge during the green interval, they can be treated as a capacity bonus, that is, added to capacity or discounted from the demand volume. The hourly volume of sneakers can be estimated from the average number of these vehicles that wait beyond the stop line in individual cycles and from signal timing (the number of cycles per hour).

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