Capacity of One-Way Yield-Controlled Intersections

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An empirical model for estimating capacity of yield-controlled streams at a one-way minor street crossing a one-way major street was developed. For Jordan conditions, results of the empirical and gap acceptance models were compared. Data were collected from different cities in Jordan. The data consisted of 854 min of at-capacity operation and included both geometric and traffic characteristics. Also, for comparison purposes, data on critical gap and move-up time were collected. The results of analysis indicated that major traffic flow, visibility-to-speed ratio, and widths of the major and minor street had a significant effect on the capacity of each minor stream. For each minor stream, the results indicated that the traffic speed and the width of the major street significantly influenced the size of the critical gap. On the basis of field observations and results presented in this paper, gap acceptance models would significantly overestimate the capacity at low major traffic levels and underestimate at high levels. In addition, the results indicated that gap-acceptance models would provide unrealistic capacity values even if critical gaps are estimated for conditions in Jordan. Finally, a set of equations and figures were presented for practical applications.

One of the most important tasks of a traffic engineer is to estimate the capacity of unsignalized intersections. In Jordan traffic engineers have been using the 1985 *Highway Capacity Manual* (HCM) (*1*) in estimating the capacity of such intersections. Unfortunately, even if the critical gap is estimated for the local condition, the estimated reserve capacity is very high under low major traffic demand. On other hand, the use of the empirical models developed by Kimber and Coombe (*2*) is restricted to T-intersections. Furthermore, driver behavior and operating rules may affect the capacity estimation. For these reasons, an effort was made to estimate the capacity of one-way minor-major street intersections.

In this study an effort was made to estimate the capacity of yield-controlled streams at a one-way street crossing a one-way major street. This type of intersection is used widely to improve capacity and safety in urban areas. Stop-controlled intersections were excluded because of the wide variability in stop sign compliance among Jordanian drivers.

The empirical approach using multiple regression analysis was adopted to estimate capacity of minor street movements and investigate the effects of different geometric design variables on the estimated capacity. For each minor street movement, the critical gap was estimated and used to calculate capacity on the basis of the 1985 HCM procedure. The results of these approaches were compared and presented in this paper.

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BACKGROUND

Chapter 10 of the 1985 HCM contains a procedure for estimating capacity and level of service at unsignalized intersections. The procedure is based on a German guideline developed in 1972, which was based mainly on Harders' formula (*3*). Different problems and limitations with the 1972 guideline and Chapter 10 of the 1985 HCM are cited in the literature (*4,5*) such as difference to simple Poisson model, concept and size of the critical gap, impedance factors, and reserve capacity. Furthermore, the German guideline was developed only for a single lane for each movement. According to German practice, multilane approaches are always signalized for safety purposes. Although a series of research was started to develop a new German guideline for practical application, the simple Poisson model will still be the basis of the future German guideline (*4*). Instead of using Harders' formula to estimate capacity, the new guideline will use Siegloch's formula.

On the other hand, the Transport and Road Research Laboratory has made extensive studies to estimate capacity of nonpriority streams in the United Kingdom (*2*). The developed empirical models indicated that the capacities of the nonpriority streams at T-intersections depend linearly on the flow in the relevant priority streams. The developed relationships depend on the lane width available to the nonpriority stream, visibility to waiting drivers, and width of the major street. Kimber (*6*) compared the performance of the simple gap acceptance and the empirical models. He concluded that the simple gap acceptance models are poor predictors of the capacity of nonpriority traffic streams in the United Kingdom, for they seriously overpredict at low values of priority flow and underpredict at high values.

METHODOLOGY

A number of one-way major-minor yield-controlled intersections were selected. The following criteria were adopted to determine the suitability of a given intersection for the purpose of this study:

1. The intersection operates at capacity during peak flow conditions. This criterion is achieved if a stable queue of vehicles is observed in the minor street. Furthermore, the intersection operates at capacity under low and heavy major traffic flow. This condition is necessary to develop a relationship that covers a wide range of major flow conditions.
2. The selected intersections should have different geometric design variables. This criterion was adopted to investigate the effects of the geometric design variables on the estimated capacity.
3. The selected intersections should be located in different cities to represent a wide range of driver populations and environmental conditions.

In this study, an empirical approach employing multiple regression analysis was used to estimate capacities of minor streams and identify variables that affect these capacities. The relationship between capacity of each minor stream and the major traffic flow was investigated from intersection-specific data. Once the basic form of this relationship was identified, the effects of geometric variables were included in the analysis.

For comparison, the same approach was used to develop critical gap and move-up time models for Jordanian drivers. The developed models were used to estimate the capacity of the minor stream using the gap acceptance approach (the 1985 HCM procedure).

DATA COLLECTION

In this study, two independent sets of data were collected. The first set was collected to develop an empirical relationship for estimating capacities of minor streams. The second set was collected to estimate the critical gap and move-up time for different minor streams. The data were collected from cities in Jordan including Amman, Irbid, Zarqa, and Mafraq. The data were collected during the summers of 1992 and 1993. Three forms of one-way yield-controlled intersections were investigated; they are shown in Figure 1. The selected intersections are located in urban or suburban areas.

For the first set, data were collected using manual techniques. Similar to previous studies (*1*), capacity data for each minor stream were observed separately. The observations were taken with stable queueing in the minor stream. Capacity of the minor stream and flow in the major street (total approach volume) were observed at 1-min intervals. Field observation revealed that no separate lane was available for turning movements in the major street. In most cases, lane markings were not provided on major and minor street approaches.

To account for heavy vehicles, the capacity and major traffic flow were expressed in passenger car units (PCU). For conversion into PCU, single-unit trucks were rated as 1.5 PCU, other trucks and trailers as 2.0 PCU, and motorbikes as 0.5 PCU. These values are considered satisfactory in different studies (*7,8*). The traffic speed on the approach of the major street was measured over a trap and the average value was computed for each interval. Tables 1, 2, and 3 present the data characteristics for Intersection Forms 1, 2, and 3, respectively.

For the second data set, a number of one-way, major-minor yield-controlled intersections were selected. A manual technique was used to collect gap and moving-up time data. Gaps, move-up time, and speed measurements were carried out by two observers equipped with stopwatches. In this study, no distinction was made between accepted gap and lag. A lag (first gap) is defined as the difference between the time at which a minor street vehicle arrives at the intersection and the time at which the next conflicting major street vehicle arrives. The move-up time represents the minimum headway between vehicles in a minor stream entering the same major stream gap. For each minor stream, the accepted gaps and move-up time were observed for 15-min intervals during peak and off-peak periods. Peak and off-peak periods were chosen to achieve variability in the major traffic flow. The collected data were used to determine the critical gap and the average value of the move-up time. The critical gap is defined as the median gap size accepted by minor street drivers. The measurements also included flow on the major traffic and the geometric variables of the major and minor streets.

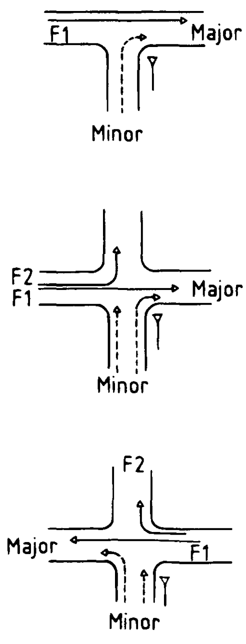

FIGURE 1 Forms of one-way major-minor street intersections: ***top,*** **Form 1;** ***middle,*** **Form 2;** ***bottom,*** **Form 3.**

DEVELOPMENT OF CAPACITY MODELS

The main purpose of capacity modeling is to develop useful relationships between capacity of the minor stream and a set of major traffic and intersection geometric variables. The developed models should be easy for practical applications and sensitive to alternative policies and design. In the analysis, the relationship between minor stream capacity and major traffic flow was investigated from intersection-specific data. For all forms of the investigated intersections, the relationship cannot be considered linear. For illustration, Figure 2 presents the scatter plot of right-turn capacity and major traffic flow for a T-intersection (Form 1). In the next step of the analysis, traffic and geometric variables were included to establish the statistical correlation matrices among variables. This step enables the selection of traffic and geometric variables that are correlated strongly with the minor stream capacity.

For all forms of intersections and minor streams, the analysis showed that minor stream capacity had high correlation with major traffic flow, major traffic speed, visibility to waiting drivers, and major and minor street widths. The analysis also showed that the angle of intersection, radius of minor street vehicle path, and gradients did not have strong effects on the minor stream capacity. Kimber and Coombe (*2*) indicated that angle of intersection, turning radius, and gradients had no detectable effect on the capacity; however, in this study the ranges of these variables were very limited.

Capacity of Right-Turn Stream

Multivariate regression analysis was conducted to determine the best form of the predictive equation for the right-turn capacity. A right-turn capacity model was developed for each intersection form.

TABLE 1 Ranges of Variables for Intersection Form 1

Variable	Range
Number of Intersections	32
Number of Observations	192
Minor Street Width, m.	3.0-7.8
Major Street Width, m.	6.0-9.0
Approach Speed, km/hr.	25-80
Major Traffic Flow, PCU/hr.	120-3000
Capacity of Right-Turn, PCU/hr.	60-960
Visibility, m.	20-150
Angle of Intersection, Degree	75-100

For Form 1, in Figure 1, the following regression equation was obtained:

$$C = 775\left(\frac{vis}{sp}\right)^{0.11}\left[1 + \frac{(Wm - 9)}{3.6}\right]^{0.94} \times \left[1 + \frac{(W - 3.6)}{3.6}\right]^{0.30}\left(\frac{1}{1 + F_1^2}\right)^{0.82} \qquad (1)$$

where

C = capacity of right-turn stream (PCU/hr),
vis = visibility to waiting drivers (m),
sp = major traffic speed (km/hr),
Wm = width of major street (m),
W = width of minor street (m), and
F_1 = flow of through traffic in major street (1,000 PCU/hr).

Similarly, for Intersection Form 2, in Figure 1, the best predictive equation for the right turn was as follows:

$$C = 710\left(\frac{vis}{sp}\right)^{0.12}\left(1 + \frac{W - 9}{3.6}\right)^{0.97}\left(1 + \frac{W - 3.6}{3.6}\right)^{0.37} \times \left(\frac{1}{1 + F_1^2}\right)^{0.80}\left(\frac{1}{1 + 0.4F_2^2}\right)^{0.78} \qquad (2)$$

where F_2 is the flow of the left-turn traffic in the major street (in 1,000 PCU/hr). All parameters in these equations were significant at the 95 percent confidence level. Investigation of Equations 1 and 2 indicates that 775 and 710 can be interpreted as capacity under ideal conditions. The ideal conditions include visibility to speed ratio equal to 1, major street width of 9.0 m, minor street width of 3.6 m, and zero traffic flow in the major street. Although each minor stream was observed so that no minor street was lane sharing, the capacity of right-turn for Intersection Form 2 is significantly lower than that of Intersection Form 1.

In Equations 1 and 2, the value 3.6 m represents the lane width. Therefore, the effect of number of lanes on the estimated capacity can be evaluated easily. The value 9.0 m represents the maximum width of the major street.

TABLE 2 Ranges of Variables for Intersection Form 2

Variable	Minor Street Stream	
	Right-Turn	Through
Number of Intersections	39	39
Number of Observations	168	168
Minor Street Width, m.	3.0-7.8	3.0-7.8
Major Street Width, m.	5.6-9.6	5.6-9.6
Approach Speed, km/hr.	30-80	30-80
Major Through Traffic Flow, PCU/hr.	30-3280	30-3280
Major Left-Turn Traffic Flow, PCU/hr.	0-720	0-720
Observed Capacity, PCU/hr.	60-720	60-660
Visibility, m.	20-160	20-160
Angle of Intersection, Degree	80-100	80-100

TABLE 3 Ranges of Variables for Intersection Form 3

Variable	Minor Street Stream	
	Left-Turn	Through
Number of Intersections	19	19
Number of Observations	171	155
Minor Street Width, m.	5.0-7.0	5.0-7.0
Major Street Width, m.	6.6-9.0	6.6-9.0
Approach Speed, km/hr.	25-45	25-45
Major Through Traffic Flow, PCU/hr.	30-2220	30-2220
Major Left-Turn Traffic Flow, PCU/hr.	0-600	0-600
Observed Capacity, PCU/hr.	60-660	120-720
Visibility, m.	25-60	25-60
Angle of Intersection, Degree	80-100	80-100

Capacity of Left-Turn Stream

A left-turn capacity predictive model was developed that is similar to the right-turn models. The best regression equation was as follows:

$$C = 675\left(\frac{vis}{sp}\right)^{0.11}\left(1 + \frac{Wm - 9}{3.6}\right)^{0.95}\left(1 + \frac{W - 3.6}{3.6}\right)^{0.30} \times \left(\frac{1}{1 + F_1^2}\right)^{0.8}\left(\frac{1}{1 + 0.4F_2^2}\right)^{0.78} \quad (3)$$

The coefficient of determination (R^2) for Equation 3 was 0.92. All parameters were significant at a 95 percent confidence level. Compared with the capacity of the right-turn stream, the left turn has lower capacity, which is expected because a left-turn movement is much more complicated. However, traffic and geometric parameters are almost equal to the parameters of Equations 1 and 2.

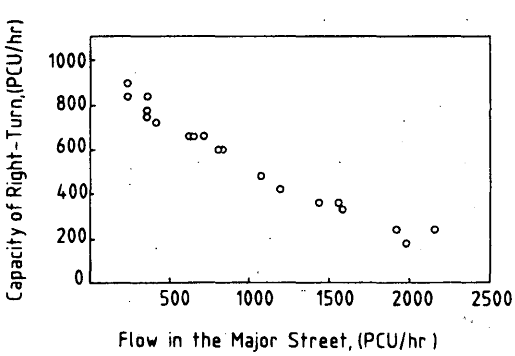

FIGURE 2 Scatter plot of right-turn capacity for intersection Form 1 with major street width 8.6 m, minor street width 7.8 m, and approach speed 40 km/hr.

Capacity of Through Stream

Two predictive equations for estimating capacity of the through stream were developed. For Intersection Form 2, the best regression equation was as follows:

$$C = 580\left(\frac{vis}{sp}\right)^{0.07}\left(\frac{Wm}{3.6}\right)^{-0.25}\left(\frac{W}{3.6}\right)^{0.53}\left(\frac{1}{1 + F_1^2}\right)^{0.93} \times \left(\frac{1}{1 + 0.8F_2^2}\right)^{1.19} \quad (4)$$

Similarly, for Intersection Form 3, the following equation was obtained:

$$C = 600\left(\frac{vis}{sp}\right)^{0.10}\left(\frac{Wm}{3.6}\right)^{-0.24}\left(\frac{W}{3.6}\right)^{0.57}\left(\frac{1}{1 + F_1^2}\right)^{0.93} \left(\frac{1}{1 + 0.8F_2^2}\right)^{1.11} \quad (5)$$

The coefficient of determination values (R^2) were 0.94 and 0.91 for Equations 4 and 5, respectively. All parameters in Equations 4 and 5 were significant at a 95 percent confidence level. With one standard error of parameter estimates, the geometric and traffic parameters in both equations were almost equal.

Modeling of Critical Gap and Move-Up Time

Regression analysis was used to identify the effect of major traffic and intersection geometric variables on the critical gap. The analysis indicated that the width of the major street and the speed of major traffic had a significant effect on the critical gap for right turn, left turn, and through stream. At the aggregate level, the analysis did not confirm the effect of major traffic flow on the estimated critical gap. But at the intersection level, the major traffic flow was correlated negatively with speed.

In this paper, the following regression equations for estimating the critical gap of right turn, left turn, and through stream were obtained:

$$Ln(CR) = 1.50 + 0.003\,(sp - 25) - 0.0423\,(Wm - 9) \quad (6)$$

$$Ln(CL) = 1.55 + 0.002\,(sp - 25) + 0.036\,Wm \quad (7)$$

$$Ln(CT) = 1.517 + 0.0017\,(sp - 25) + 0.035\,Wm \quad (8)$$

where

Ln = natural logarithm,
CR = right-turn critical gap (sec),
CL = left-turn critical gap (sec), and
CT = through traffic critical gap (sec).

All parameters in Equations 6, 7, and 8 were found to be highly significant. The coefficient of determination values (R^2) were 0.72, 0.66, and 0.81 for Equations 6, 7, and 8, respectively. It is worth mentioning that the minimum average speed of major traffic was 25 km/hr.

The developed equations indicate that critical gaps increase substantially with increasing speed on the major street. Critical gaps for left-turn or through traffic increase with increasing width of the major street. Compared with the critical gap for minor through traffic, slightly longer gaps are needed for left-turn traffic. Field observations indicated that left-turning vehicles from the minor street merge with major traffic and tend to use the far right lane in the major street specifically under high major traffic speeds. The 1985 HCM estimated the critical gap on the basis of major traffic speed and street width as well as turning radius and gradient. Brilon (*9*) reported that Harders (*10*) found that critical gap was influenced by the speed of opposing vehicles at give-way intersections. Although recent studies (*5,11*) indicated that critical gap cannot be considered constant, other studies (*12*) have indicated that major traffic flow and queue length do not appear to have a significant impact on the length of critical gap. Therefore, the results of this study are compatible with most cited literature.

In the analysis of move-up time, it was found that it is correlated strongly with the relevant critical gap for each minor stream. For each stream, the move-up time was approximately 60 percent of the critical gap. This result is compatible with the Swedish Capacity Manual, which assumed that the move-up time makes up about 60 percent of the critical gap (*13*).

DISCUSSION OF RESULTS

In this study an empirical approach using regression techniques was used to develop capacity models for yield-controlled streams at a one-way minor street crossing a one-way major street. For all minor streams, the results indicated that the relationship between capacity and both major traffic and intersection variables had a multiplicative form. Unlike the results of the study by Kimber and Coombe (*2*), here the relationship between minor stream capacity and major traffic flow would not be considered linear. If linearity exists, the capacity of minor stream will be zero at a high major traffic level. But field observations revealed that the actual capacity of the minor stream is at least 60 PCU/hr. Taking the sample size into consideration, Figure 2 may not confirm the linearity. However, further studies are recommended to highlight this issue.

Results of this study indicated that minor stream capacity increases with an increase in the visibility-to-speed ratio. For the same visibility level, doubling the major traffic speed would reduce the capacity by about 8 percent. This value is very small compared with values reported in the new German guideline (*4*). For right- or left-turning vehicles, increasing the width of the major street would increase capacity substantially. Increases in the width of a major street reduce the interactions between major and minor traffic and increase the turning capacity. For the same major traffic level, increasing the number of lanes from two to three in a major street would raise the right-turn capacity by about 45 percent (Figure 3). This gain may be explained by the fact that major street drivers tend to follow the far lane in the major street to avoid possible conflict with minor street vehicles. This behavior might provide better opportunities for minor vehicles to merge into the near-side lane of the major street.

The results also indicated that right- and left-turn capacity can be improved by increasing the number of minor street lanes. Unlike other highway facilities, increasing the number of lanes does not necessarily result in a corresponding increase in the capacity of the turning stream. For example, doubling the number of minor street lanes (from one to two lanes) would increase the right-turn capacity by 25 percent. This is expected, because right-turning vehicles rarely turn simultaneously from both lanes, as observed in the field. Despite the difference in traffic operation, the effects of doubling the number of minor street lanes on the right-turn and circular entry capacities can be compared. The circle can be considered as a series of T-shaped entries into a one-way cir-cular street. Brilon and Stuwe (*14*) found that the entry capacity increased by 30 to 40 percent when the number of entry lanes was doubled.

Furthermore, the results of the empirical and gap acceptance models were compared. Figure 4 shows the relationship between right-turn capacity and major traffic flow for an intersection of typical geometry. The intersection had a one-lane minor street (3.6 m), a three-lane major street (9.0 m), and a visibility-to-speed ratio of 2.0. Two curves are shown in Figure 4. The first curve (Curve A) was obtained using Equation 1 of the empirical approach, and the second curve (Curve B) was obtained using the gap acceptance model. For Jordanian drivers, the critical gap was estimated using Equation 6 with major traffic speed of 50 km/hr. Equation 6 indicates that the critical gap is 4.83 sec. Accordingly, the second curve was obtained using 4.83 and 2.9 sec for the critical gap and move-up (60 percent of the critical gap) parameters of Siegloch's formula. Siegloch's formula is as follows (*4*):

$$C = (3{,}600/t_f) * e^{-p[t_g - (t_f/2)]} \quad (9)$$

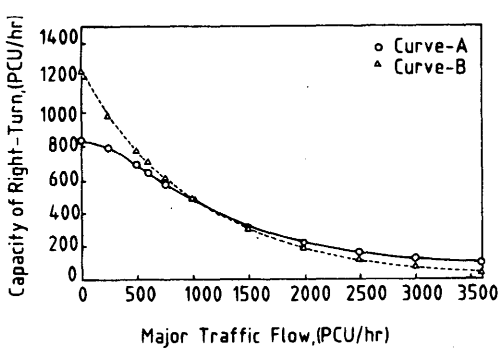

FIGURE 3 Estimation of right-turn capacity according to empirical and gap acceptance models.

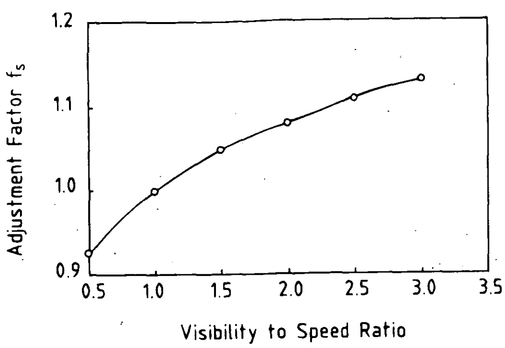

FIGURE 4 Effect of visibility-to-speed ratio on right- or left-turn capacity.

where

C = capacity of minor stream (PCU/hr),
$p = q/3{,}600$,
q = volume of major stream,
t_g = critical gap (sec), and
t_f = move-up time (sec).

Compared with empirical results, Figure 4 indicates that the gap acceptance model significantly overestimates the predicted capacity at low major traffic levels and underestimates it at high levels. As shown in Figure 4, the empirical approach indicates that the estimated capacity is 835 PCU/hr at low major traffic levels. In contrast, the gap acceptance model indicates that the estimated capacity is 1,240 PCU/hr. The difference, 405 PCU/hr, in the estimated capacity values is very large. This large difference would result in a poor estimate of the reserve capacity and level of service. For Jordanian conditions, agreement between the results of the empirical and gap acceptance approaches can be achieved if the move-up time is set at 4.31 sec. This value is very large compared with field observations and cited literature (*15*). Accordingly, gap acceptance models would provide unrealistic capacity values at low major traffic levels.

At high major traffic levels, the gap acceptance model underestimates the predicted capacity, suggesting that longer delay is associated with higher traffic flow and that right-turning drivers are willing to accept shorter gaps to enter the major street. In addition, field observations indicated that at high traffic flows, some major street drivers yield the right of way to the entering drivers, specifically under low speed levels. Therefore, to achieve correspondence between the results of the empirical and gap acceptance approaches, it is necessary to adjust gap acceptance parameters to reflect the effect of traffic flow level, which could be done by adjusting the speed in the critical gap models according to the major traffic flow level.

Also, Figure 4 shows that the minimum right-turn capacity is about 100 PCU/hr. This value is compatible with the suggested limit of practical capacity for minor traffic streams at unsignalized intersections in the future German guideline (*4*).

PRACTICAL APPLICATIONS

The results of the statistical analysis described in this paper provide a strong foundation for a method to estimate the capacity of one-way major-minor yield-controlled streams. The method is based on the models developed for each minor stream. It takes into account the effects of different geometric and traffic variables. Similar to other transportation facilities, the capacity of right- or left-turn stream in PCU/hr can be expressed as follows:

$$C = C_o * f_s * f_{Wm} * f_w * f_{F1} * f_{F2} \quad (10)$$

where C_o represents the capacity of the turning stream under ideal conditions [(vis/sp) = 1.0, Wm = 9.0, W = 3.6, $f_1 = \phi$, and $f_2 = \phi$). The value of C_o is 775 for an exclusive right-turn minor street. For a nonexclusive right-turn minor street, C_o values are 710 and 675 for right and left turns, respectively. The adjustment factor f_s represents the effect of the visibility-to-speed ratio on the estimated capacity. Values of f_s for different speeds and visibility-to-speed ratio are shown in Figure 5. The adjustment factors f_{Wm} and f_w represent the effects of major and minor street widths on the estimated capacity. Figure 3 provides values of f_{Wm} and f_w for different widths. Finally, f_{F1} and f_{F2} represent the effects of through and turning major traffic flows on the right-or left-turn capacity. Values of these adjustment factors are shown in Figure 6. For practical application, similar expression could be written to estimate the capacity of through stream from minor street.

In this study, capacity was estimated for each minor stream individually. However, if a lane (or lanes) is shared by more than one minor stream, the shared capacity is computed from the individual capacities according to the individual streams using Equation 10-1 in the HCM (*1*).

CONCLUSIONS

An empirical approach using regression techniques was used to develop capacity models for yield-controlled streams at a one-way minor street crossing a one-way major street. The results of this study led to the following conclusions:

1. Capacity models for yield-controlled streams were developed. In addition to the widths of the minor and major streets, the visibility-to-speed ratio and the major traffic flow level had a significant influence on the minor stream capacity. The relationship between the estimated capacity and both major traffic and intersection geometric variables had a multiplicative form.

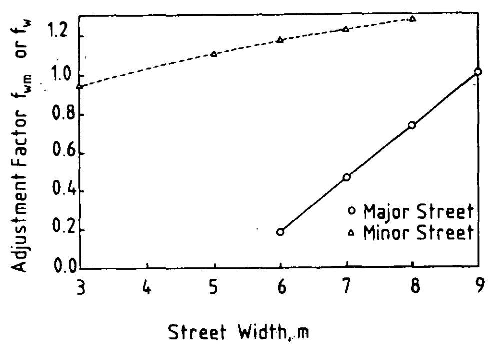

FIGURE 5 Effect of major and minor street widths on right- or left-turn capacity.

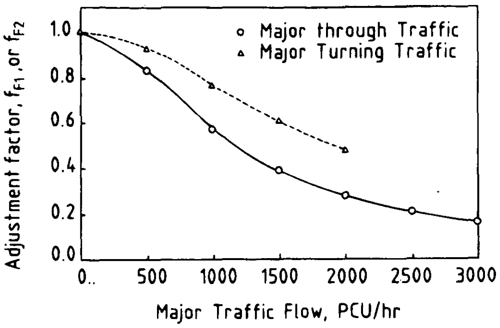

FIGURE 6 Effect of major traffic flows on right- or left-turn capacity.

2. For each minor stream, critical gap model was developed. Both the traffic speed and width of the major street were found to be significant for estimating the critical gap for each stream. The results indicated that the increase in the traffic speed tends to increase the critical gap for all minor streams. In contrast to the critical gap for right-turn stream, the critical gaps for the left-turn and through streams increase with the increase in the major street width.

3. Compared with results of the empirical approach, the gap acceptance models significantly overestimate the predicted capacity at low major traffic levels and underestimate them at high levels. The results indicated that even if critical gap is estimated for local conditions, the difference in estimating capacity is considerably large.

4. The 1985 HCM and the new Germany Guideline, which are based on gap acceptance models, would provide unrealistic minor stream capacity even if critical gaps were estimated for local conditions.

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Publication of this paper sponsored by Committee on Highway Capacity and Quality of Service.