Modeling the Left-Turn Adjustment Factor for Permitted Left Turns Made from Shared Lane Groups

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The findings of an FHWA project entitled "Levels of Service in Shared, Permissive Left-Turn Lane Groups at Signalized Intersections" are described. The project objective was to evaluate and improve the 1985 *Highway Capacity Manual* (HCM) model for estimating the impact of shared-permissive left-turn movements on lane group saturation flow. The study was based on a nationwide data collection effort that yielded 1,492 15-min data samples taken for 45 intersection approaches (at 25 intersections) in four regional areas. Field measurements included prevailing and ideal saturation flow rates for each period, critical portions of the green phase as defined in the 1985 HCM, subject and opposing flow rates, lost times, and other critical information. Because of the lack of off-peak–period queues sufficient to yield saturation flow rate measurements, only 22 percent of the data was used in model evaluations and calibrations. The resulting analysis documents flaws in the 1985 HCM model for the impact of shared, permissive left turns on saturation flow rates, and recommends simplified models that could be used in conjunction with the general analysis procedure of the 1985 HCM. Unique characteristics of single-lane approaches opposed by single-lane approaches are identified, and revised procedures for the analysis both of single-lane and multilane approaches involving shared-permissive left turns are recommended.

Chapter 9 of the 1985 *Highway Capacity Manual* (HCM) (*1*) describes a critical lane group technique for analysis of signalized intersections. The basic critical lane approach to signalized intersection analysis was originally developed by Greenshields (*2*) as a signal timing methodology in the 1930s. In the 1960s and 1970s, the English and Australians (*3*) systematically developed the approach as a capacity analysis methodology. The principal work on U.S. applications was conducted by Messer (*4*) and Berry (*5*) in the 1970s. The procedure appearing in the 1985 HCM (*1*) was assembled and calibrated by JHK & Associates (*6*) under NCHRP Project 3–28II, and was revised during the final preparation of the 1985 HCM (*1*) manuscript under NCHRP Project 3–28B by Messer and Roess (*7*).

Several FHWA efforts have been aimed at improving specific aspects of the 1985 HCM (*1*) procedure. Specifically, this effort is directed toward the improvement of models for estimating the left-turn adjustment factor applied to lane groups in which permitted left turns are made from shared lanes.

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BACKGROUND: THE 1985 HCM (*1*) METHODOLOGY

The 1985 HCM (*1*) methodology for signalized intersection analysis is organized into five distinct modules. The left-turn adjustment factor is used in the estimation of the prevailing saturation flow rate for each lane group, as follows:

$$s = s_0 N f_w f_{HV} f_g f_p f_{bb} f_a f_{RT} f_{LT}$$

where

- s = prevailing saturation flow rate in the lane group, vphg;
- s_0 = ideal saturation flow rate per lane, pcphgpl;
- N = number of lanes in the lane group; and
- f_i = adjustment factor for Characteristic i (w = lane width, HV = heavy vehicles, g = grade, p = parking, bb = local bus blockage, a = area type, RT = right turns, LT = left turns).

For permitted turns made from a shared-lane group, the HCM (*1*) specifies an analytically developed model for determining f_{LT}:

$$f_m = (g_f/g) + (g_u/g)\{1/[1 + P_L(E_L - 1)]\} + (2/g)(1 + P_L)$$

$$f_{LT} = [f_m + (N - 1)]/N$$

where

- f_m = left-turn adjustment factor applied to shared lane only;
- g = effective green time (sec);
- g_f = initial portion of green until arrival of first left-turning vehicle, sec;
- g_u = unsaturated portion of green after clearance of opposing queue, sec;
- P_L = proportion of left-turning vehicles in the shared lane; and
- E_L = number of through passenger cars displaced by one left-turning vehicle in the shared lane.

The model for the left-turn adjustment factor assumes that left turns have no impact on the operation of the shared lane during g_f, before the first left-turning vehicle arrives, that is, the effective factor during this period is 1.00. During the period $g_q - g_f$, that is, the green time between arrival of the first left turner and the clearance of the opposing queue, the shared lane is assumed to be blocked by the waiting left turner (the effective factor during this period is assumed to be 0.00). During the unsaturated portion of the green, left turns are made through an unsaturated opposing flow. Friction caused by these movements reduces the effectiveness of the use of green for the shared lane by a factor of $1/[1 + P_L(E_L - 1)]$. The last term of the equation accounts for sneakers, left-turners who complete their turns on the yellow or red portion of the phase.

In the relationship between f_{LT} and f_m, left-turning vehicles are assumed to affect only the shared lane, and the effective factor applying to other lanes in the group is assumed to be 1.00.

As no significant amount of data was available to calibrate or validate this model at the time of the 1985 HCM (*1*) publication, key variables such as g_f, g_q, and g_u were analytically estimated. Further, to determine the saturation flow rate on an approach, the opposing saturation flow rate was based on an estimated guess, and vice versa, leading to circular computations.

The objective of the research described herein was to obtain and analyze a substantial nationwide data base to evaluate the accuracy of the HCM (*1*) model in the estimation of key input variables and in the final estimation of left-turn adjustment factors for shared, permitted lane groups. Finally, the project called for the development of improved models for the prediction of the left-turn adjustment factor.

RESEARCH APPROACH

The basic research approach was to develop regression relationships for the prediction of critical portions of the green phase, and to attempt to recalibrate a revised model for the left-turn adjustment factor in the form of the 1985 HCM (*1*) model. Direct regression models for the left-turn adjustment factor were also investigated.

The form of the 1985 HCM (*1*) model can be simplified as follows:

$$f_m = (g_f/g) + (g_u/g)(\text{factor}) + (\text{sneakers})$$

No reductive factor is applied to the period g_f, as discussed previously. During g_u, the friction of left-turning vehicles passing through an opposing flow exercises a reductive impact on saturation flow in the shared lane, reflected by a systematic adjustment between 0 and 1. The last term of the equation accounts for the effective impact of sneakers who complete left turns during the yellow or red periods of the signal phase.

An examination of the data base led to the decision to eliminate the term for sneakers. As headways are recorded at the stop line, vehicles that wait in the intersection to complete their turns during the yellow or red have already been counted as part of the saturation flow. To count them again would constitute a double counting of these vehicles. Thus, the term for sneakers was dropped, and three basic model forms were investigated for prediction of the left-turn adjustment factor:

Form 1: $f_m = (g_f/g) + (g_u/g) - f_1$

Form 2: $f_m = (g_f/g) + (g_u/g)(1 - f_2)$

Form 3: $f_m = f(\text{independent variables})$

In Form 1, the reductive factor applied to g_u is subtractive. In Form 2, the reductive factor is multiplicative, with f_2 specifically representing that portion of the use of g_u that is lost to left-turning impedance. In Form 3, direct regression on independent variables was applied without requiring adherence to the basic format of the 1985 HCM (*1*) model.

FIELD MEASUREMENTS

Each intersection approach was videotaped for the period of study. In all cases, both the subject and opposing approach were taped, and the data from each were coordinated. Data reduction consisted of the recording of headways of all vehicles as they crossed the stop line (or appropriate building line where no stop line existed) using the front wheels as reference point. A separate indication of the last vehicle in each queue was also entered, as were changes in the signal indication. The type and movement of each vehicle were also noted and entered. From this basic data, a headway string for each lane of each approach during each signal cycle could be reconstructed and manipulated to directly observe the following parameters:

- s = prevailing saturation flow rate. For each lane, the average saturation headway during each 15-min period was taken by averaging every observed headway between the 4th vehicle in queue and the last vehicle in queue; lane saturation flow rates were computed as 3,600/hr, and the lane group saturation flow rate was computed as the sum of the saturation flow rates for each lane in the group, in vehicles per hour of green (vphg).
- s_0 = similar to the procedure for s, except that only ideal headways were included, that is, those between the 4th vehicle in queue and the last vehicle in queue that precede the first turning or heavy vehicle in queue. Adjustments for nonideal geometric conditions were applied as per the 1985 HCM (*1*); s_0 is stated as a per-lane value in passenger cars per hour of green per lane (pcphgpl).
- g_f = taken as the cumulative headway in the shared lane to the arrival of the first left-turning vehicle, in seconds, averaged for all cycles in the 15-min period.
- g_q = taken as the cumulative headway to the last vehicle in queue on the opposing approach, using the maximum value among all opposing lanes, in seconds, averaged over all cycles in the 15-min period.

Other values, such as percentages of turning and heavy vehicles, were also obtained for each cycle and each 15-min analysis period.

PREDICTION OF CRITICAL PORTIONS OF THE GREEN PHASE

Prediction of g_f

The value of g_f, the time until the arrival of the first left-turning vehicle, is expected to be strongly related to the number or proportion of left turns being made. A simple regression model expressing this relationship was calibrated as

$$g_f = g \exp(-0.876 \text{ LTC}^{0.70})$$

where LTC is the number of left turns per cycle.

$r = 0.87$

$n = 305$ 15-min samples

This model has a good correlation coefficient, and expresses a logical relationship. When there are no left turns, LTC = 0 and $g_f = g$. As LTC increases, g_f asymptotically approaches 0. Figure 1 shows the form of the model.

The relative accuracy of this regression model was tested against the 1985 HCM (*1*) computation of g_f using the calibration data base. The calibration data set was used because the FHWA contract did not permit collection of a separate data base for validation. In this analysis, the average error of prediction was computed as

$$\text{Average error} = \{[\sum(x_{\text{act}} - x_{\text{pred}})]/(n - 1)\}^{1/2}$$

where

x_{act} = field-measured value of the parameter,
x_{pred} = value estimated by the model being tested, and
n = number of samples.

The results of this analysis for g_f are presented in Table 1 and shown in Figure 2.

The proposed regression model is considerably more accurate than the analytic model of the 1985 HCM (*1*) in predicting g_f. Further, Figure 2 shows that the HCM (*1*) technique virtually always underestimates the value of g_f, sometimes significantly. This means that, in the context of the HCM (*1*) model logic, left-turn adjustment factors will be too low on the basis of these errors.

TABLE 1 AVERAGE ERROR IN PREDICTION OF g_f

MODEL	85HCM	RECOMMENDED
Single-Lane	6.22 Secs.	2.78 Secs.
Multilane	12.45 Secs.	2.74 Secs.

Prediction of g_q

Simple regression relationships for the prediction of g_q were also developed. In this calibration, however, two significant factors emerged:

1. For the first time, significant differences between single- and multilane approaches appeared in the modeling process. In single-lane cases, a left-turning vehicle within the queue delays the clearance of vehicles behind it. In multilane cases, vehicles behind a left-turner have the opportunity to change lanes to go around the vehicle.
2. Models for prediction of g_q all involve the variable opposing queue ratio (OQR), that is, the proportion of opposing flow originating in queues. This factor depends on progression and can be estimated from the platoon ratio, defined in the 1985 HCM (*1*) as OQR = $1 - R_p(g/C)$. The variable g_q is the time needed to clear the opposing queue, which depends on how much opposing flow there is (on a per-cycle basis) and

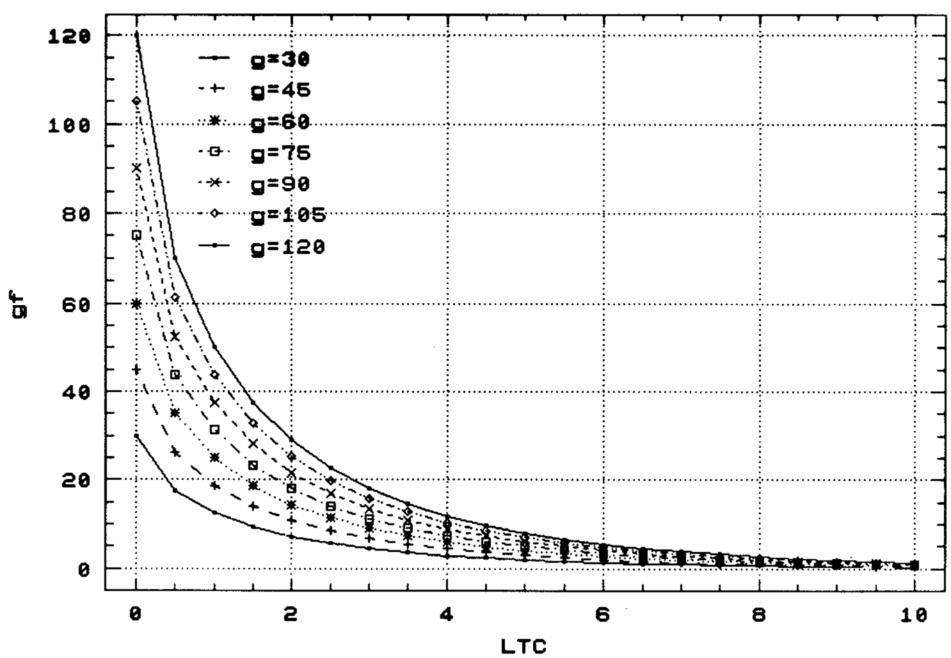
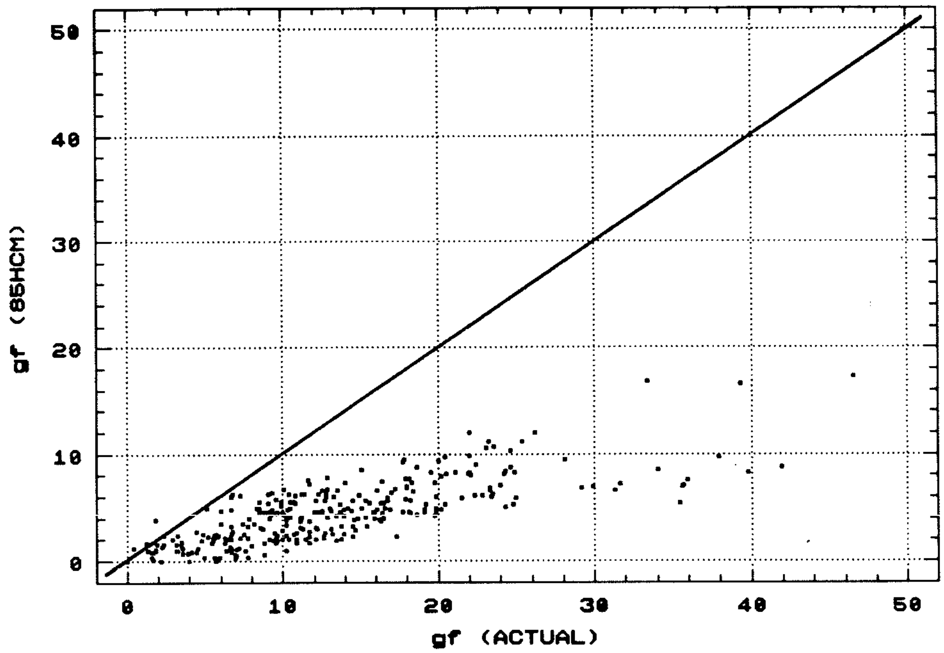
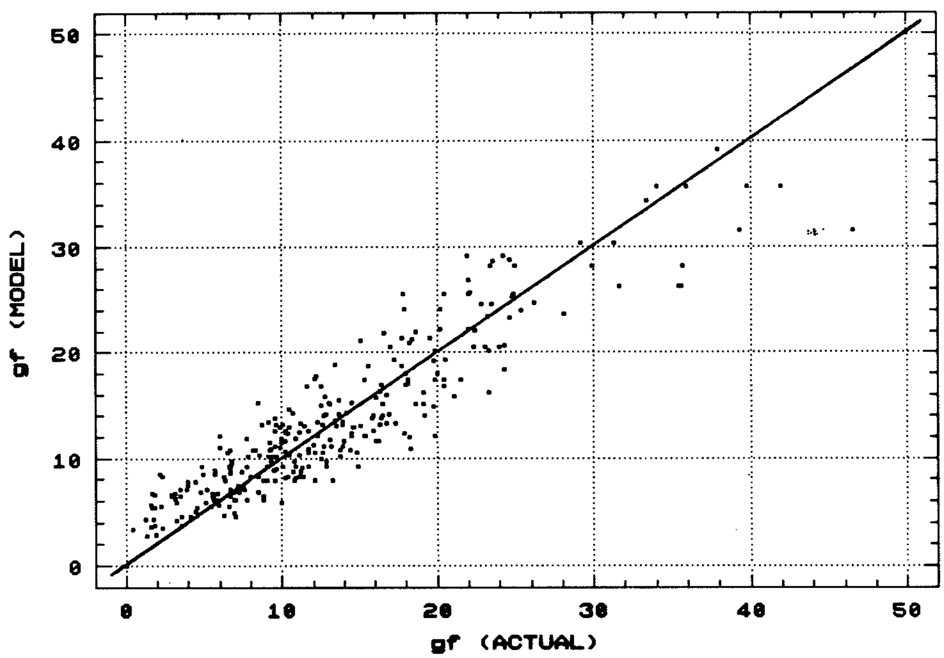


FIGURE 1 Illustration of the model for g_f.



a. 1985 HCM Predictions



b. Recommended Model Predictions

FIGURE 2 Comparative accuracy of predictions of g_f.

how much of this opposing flow originates in opposing queues. However, this relationship introduces a new element into the 1985 HCM (*1*) model: saturation flow rate depends on progression quality. In the 1985 HCM (*1*) model, only delay depends on progression.

The models calibrated for estimation of g_q are as follows:

Single-Lane Approaches:

g_q = 4.943 $\text{OFLNC}^{0.762}\text{OQR}^{1.061}$
r = 0.96
n = 102 15-min samples

Multilane Approaches:

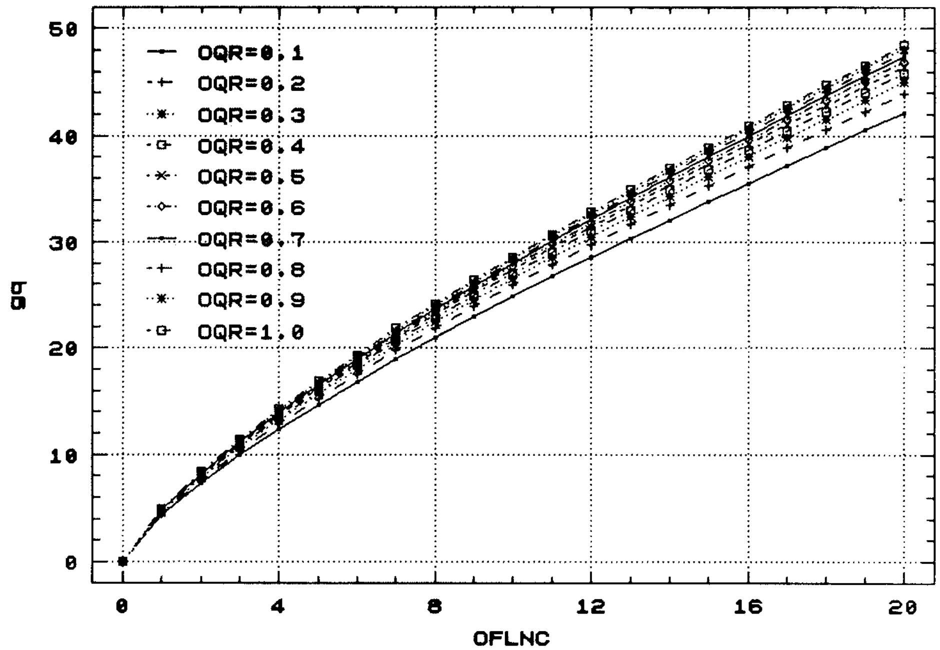
g_q = 9.532 $\text{OFLNC}^{0.569}\text{OQR}^{0.819}$
r = 0.87
n = 192 15-min samples

where OFLNC is the opposing flow per lane per cycle. The model is logical, and g_q is 0 when either OFLNC or OQR is

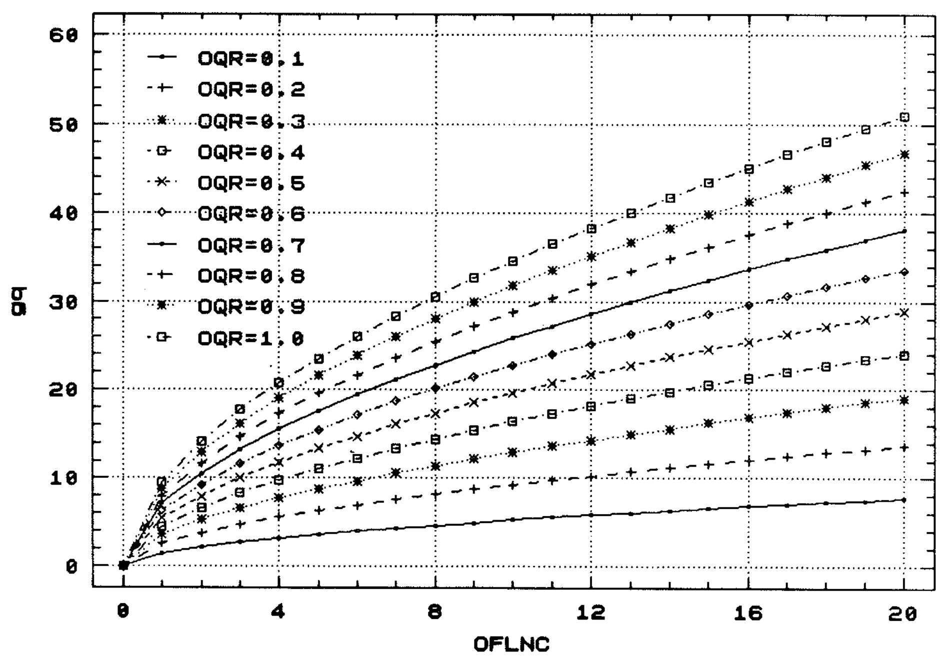
0. As either OFLNC or OQR increases, g_q also increases. However, there is no upper bound on g_q, so that a logical maximum value of g should be imposed in use.

The form of the relationship is shown in Figure 3. Table 2 presents the average error in prediction of g_q for the recommended regression model in comparison with the 1985 HCM (*1*), which is shown in Figure 4.

Again, the regression model is considerably more accurate than the 1985 HCM (*1*) in prediction of g_q. The HCM (*1*) prediction of g_q also tends to underestimate this value. The effect of this underestimation on f_m, however, offsets the underestimation of g_q. If g_q is underestimated, then g_u is overestimated, and the left-turn adjustment factor is made too large because of this.



a. Single-Lane Model



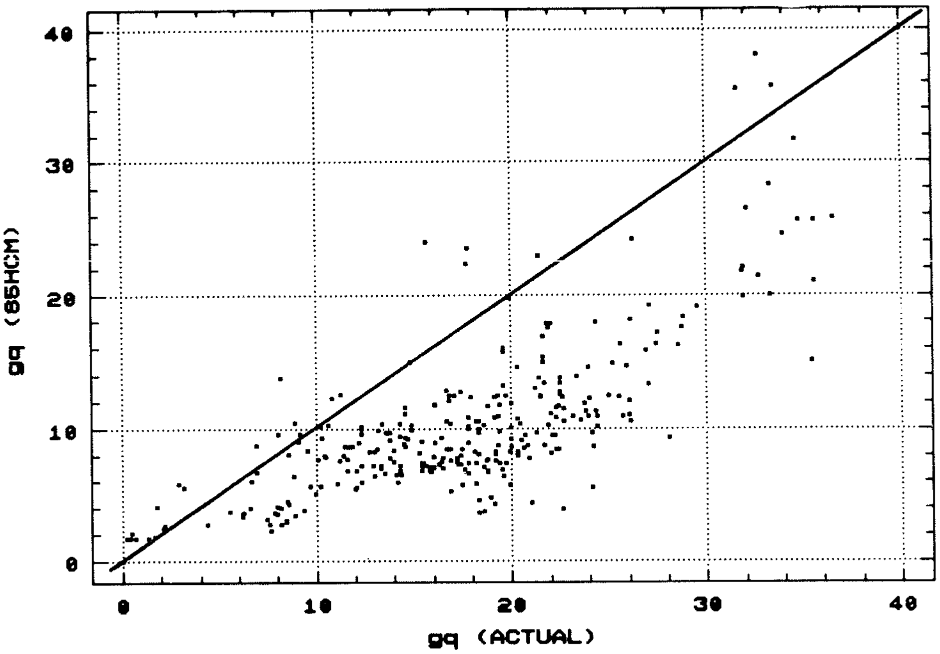
b. Multilane Model

FIGURE 3 Illustration of the model for g_q.

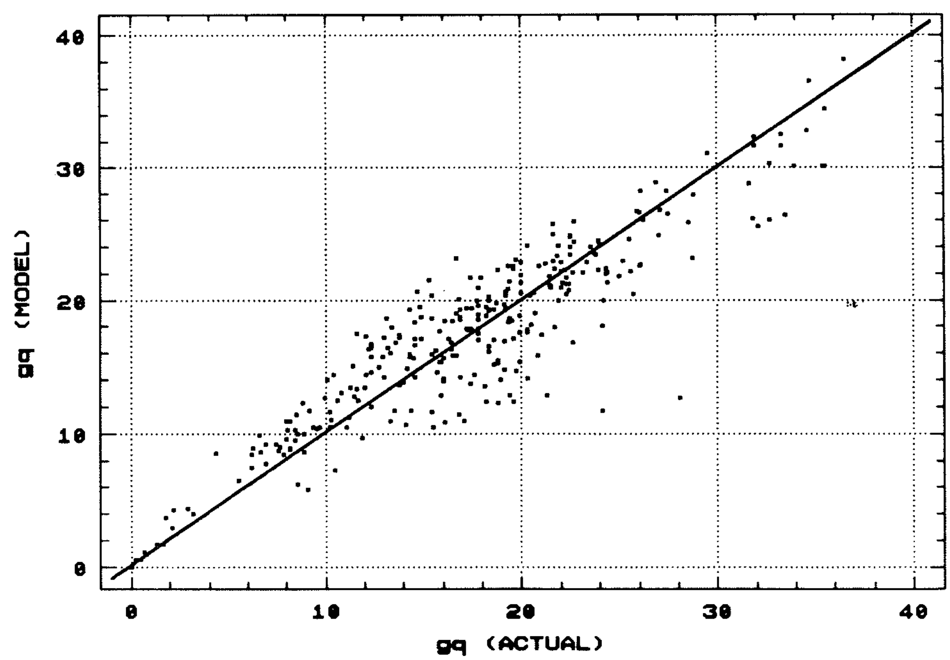
TABLE 2 AVERAGE ERROR IN PREDICTION OF g_q

MODEL	85HCM	RECOMMENDED
Single-Lane	8.83 Secs.	3.29 Secs.
Multilane	8.67 Secs.	3.48 Secs.

Note that the recommended models for prediction of g_q depend on opposing flow (on a per lane per cycle basis) and the quality of progression in the opposing direction (as quantified by OQR). The opposing saturation flow rate does not enter the model. Alternative forms using the opposing saturation flow rate were developed and considered, but resulted in significantly poorer correlations. Further, the circular logic



a. 1985 HCM Predictions



b. Recommended Model Predictions

FIGURE 4 Comparative accuracy of predictions of g_q.

of basing the estimation of prevailing saturation flow rate on an estimated guess of the saturation flow rate in the opposing direction [as in the 1985 HCM (1)] was specifically and deliberately avoided.

Prediction of g_u

In the 1985 HCM (1), g_u is independently estimated, and g_q is taken as $g - g_u$. In field studies, g_q can be independently determined, and g_u follows as $g - g_q$. A study of the relationship between g_q and g_u in this form reveals some inconsistencies in usage. Specifically, the logic has flaws when $g_f > g_q$, that is, when the first left-turning vehicle arrives after the clearance of the opposing queue.

Assume that such a case exists, and that g_u is computed as $g - g_q$. In such a case, the period g_f would overlap a portion of g_u (specifically, for a period of $g_f - g_q$). In the HCM (1) model for f_m, a factor of 1.00 is applied to g_f and a factor between 0 and 1 is applied to g_u. Thus, for the overlap period, a total factor of greater than 1.00 is applied, which is illogical. In essence, the overlap period is double-counted in the computation of the adjustment factor. This error may be corrected by adopting the following model:

$$g_u = g - g_q \qquad \text{if } g_f < g_q$$

$$g_u = g - g_f \qquad \text{if } g_f \geq g_q$$

Such an interpretation, which avoids the double-counting of the overlap period, should be used in conjunction with the regression models for g_f and g_q proposed herein.

PREDICTION OF f_m FOR SINGLE-LANE APPROACHES

Single-lane approaches opposed by single-lane approaches have a unique characteristic that is recognized in the 1985 HCM (1) planning methodology but ignored in the operational methodology. Left turns in one direction create gaps in the traffic stream that can be used by left-turners in the opposing direction. Left turns may even create gaps for opposing left-turners within the clearance of the standing queue, a period during which the 1985 HCM (1) model assumes that no left turns occur.

Thus, for single-lane approaches, saturation flow rates are not well correlated to the portions of the green phase as structured in the HCM (1). The left-turn adjustment factor for single-lane approaches opposed by single-lane approaches is best described by the following simple regression model:

$$f_m = 0.508 - 0.399P_{\mathrm{LT}}^2 + 0.201(v/100)^{0.5} + 0.01P_{\mathrm{LTO}}$$

where

P_{LT} = proportion of left turns in the subject approach flow,
v = flow rate in the subject approach, and
P_{LTO} = proportion of left turns in the opposing approach flow.

$r = 0.58$

n = 102 15-min samples

The trends displayed by the model are logical, but not immediately obvious. As the proportion of left-turners in the approach flow increases, the factor decreases as expected. As the proportion of opposing left turns increases, the factor increases, reflecting the effect of opposing left turns on creation of gaps in the opposing single-lane traffic stream. The correlation to flow rate is less obvious, and could reflect the impact of heavier approach flows on gap selection and movements around waiting left-turners. However, the data base was not reduced in a manner that would allow direct observation of this characteristic.

The average error in prediction of prevailing saturation flow rate is presented in Table 3 for three cases. In the first case, the 1985 HCM (1) model is used to find f_m and the saturation flow rate. In the second, the HCM (1) model is applied, but the values of g_f and g_u are found using the regression relationships presented herein. In the third, the direct regression model for f_m presented herein is applied. The results for the HCM (1) model and the recommended model are shown in Figure 5.

The regression model results in a 25 percent reduction in the average error in estimation of prevailing saturation flow rate, despite the low coefficient of determination achieved by the model. The insertion of regression-based estimates of g_f and g_u into the HCM (1) model does not improve its accuracy.

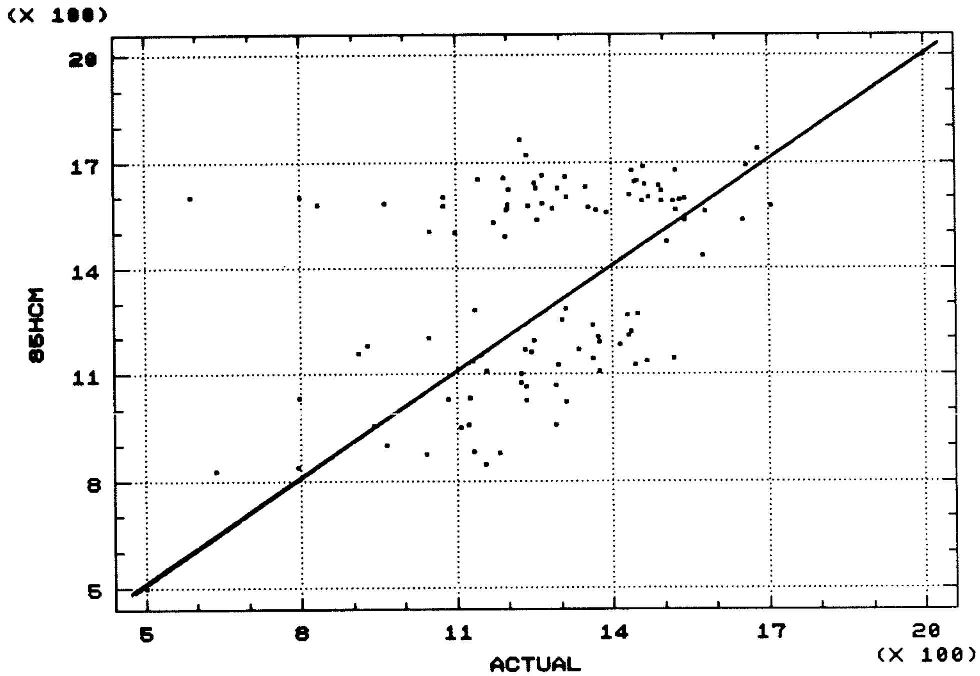
Rather, the use of more accurate estimates of g_f and g_u in the HCM (1) model causes greater inaccuracy in saturation flow rate predictions. This result suggests that the inaccuracy of the HCM (1) model is fundamental in nature, rather than the result of erroneous estimates of input parameters. In the case of the single-lane model, the ability of left-turning vehicles to use gaps within both the opposing queue and subsequent unsaturated flow created by opposing left turns substantially upsets the structure of the HCM (1) model, which assumes impermeability during the clearance of the opposing queue.

During the study, several models were developed for single-lane approaches that followed the general format of Forms 1 and 2 discussed earlier. However, none of these resulted in acceptable correlations, and all resulted in poorer estimates of prevailing saturation flow rate than the present HCM (1) model. The regression model presented herein, which is simple and straightforward, results in more accurate estimates of saturation flow rate. For single-lane approaches, $f_m = f_{\mathrm{LT}}$,

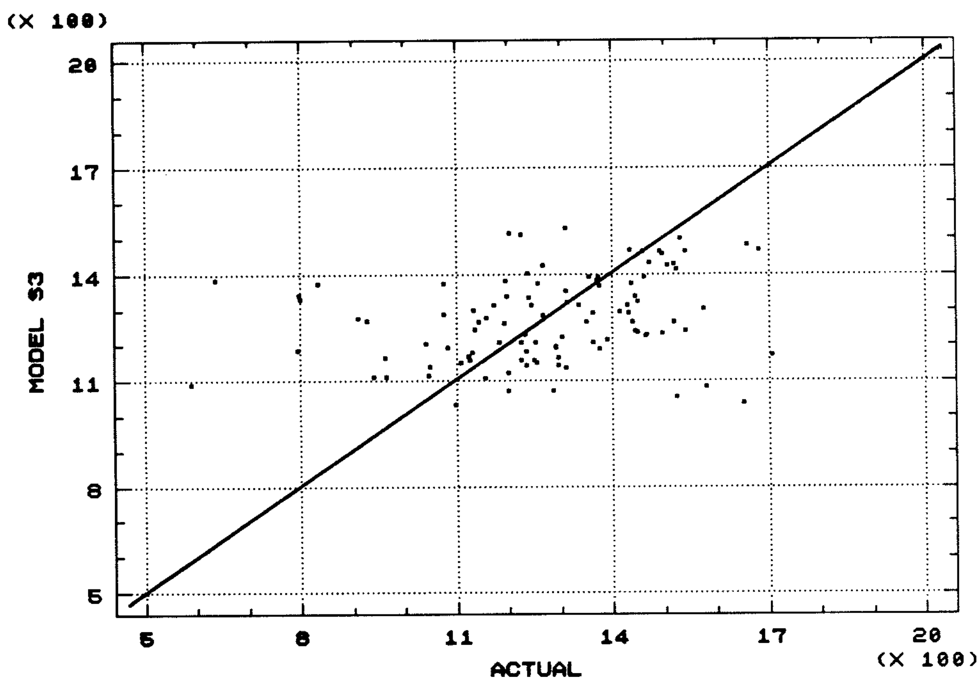
TABLE 3 AVERAGE ERROR IN PREDICTION OF SATURATION FLOW RATE FOR SINGLE-LANE APPROACHES

MODEL	AVERAGE ERROR
85HCM	295 VPH
85HCM (MOD)	428 VPH
RECOMMENDED	221 VPH

(Average Saturation Flow Rate = 1228 vphg)



a. 1985 HCM Model



b. Model S3

FIGURE 5 Comparative accuracy of saturation flow rate predictions for single-lane approaches.

and the regression model is all that is needed to make this estimation.

PREDICTION OF f_m AND f_{LT} FOR MULTILANE APPROACHES

Prediction of f_m

Two different relationships were calibrated for estimation of f_m for multilane approaches. The first follows the general format of the HCM (*1*), whereas the second is the result of direct regression:

Model 1: $f_m = (g_f/g) + 0.45(g_u/g)$

$r = 0.54$

$n = 192$ 15-min samples

Model 2: $f_m = 0.89 + 0.01g_f - 0.06g_q^{0.5} - 0.07\,(\text{LTC} \times \text{OFLNC})^{0.5}$

$r = 0.64$

$n = 192$ 15-min samples

In Model 1, the reductive factor applied to g_u is a constant. All analyses indicated virtually no correlation between this reductive factor and other relevant traffic variables. Although the range of variation in this factor from sample to sample was significant, it followed no consistent pattern that could be discerned as reflected by the low coefficient of determination.

Model 2, while a regression model, does not fully abandon the logic of the HCM (*1*), as it relies heavily on the critical portions of the green phase as defined in the HCM (*1*). The trends are reasonable. As g_f increases, the factor increases. As g_q increases, the factor decreases. As the conflict product LTC × OFLNC increases, the factor also decreases.

Finding f_{LT} from f_m

For multilane approaches, the relationship between f_m and f_{LT} must be carefully examined. The form of the HCM (*1*) model can be stated in general terms as

$$f_{LT} = [f_m + a(N - 1)]/N$$

In the 1985 HCM (*1*), the value of a is taken to be 1.00, that is, there is no impact of left-turning vehicles on lanes other than the shared lane from which the turns are made.

In examining this feature, the multilane data base was segregated into two- and three-lane approaches. The three-lane approaches, which accounted for only 28 of 192 15-min multilane samples, were all rather unusual in that they represented cases with low total volumes with left-turning vehicles dominating the shared lane on an almost-exclusive basis. Three models were developed, including one in which the value of parameter a was permitted to vary:

Two-Lane Approaches: $a = 0.912$

$r = 0.92$

$n = 164$ 15-min samples

Three-Lane Approaches: $a = 0.663$

$r = 0.29$

$n = 28$ 15-min samples

All Multilane Approaches: $a = 0.935 - 0.037\text{LTC}^2$

$r = 0.85$

$n = 192$ 15-min samples

The differences between two- and three-lane approaches are startling. The unique conditions found in the three-lane approach data base made this information highly suspect, as does the low coefficient of determination achieved when these samples are considered in isolation. The trend of the third form, in which a varies with LTC, is logical but blows up at high values of LTC, often yielding values of a that are less than f_m, which is not logical.

Given the deficiencies of the three-lane data base, the model calibrated for two-lane approaches in which $a = 0.912$ for all multilane approaches appeared best. This choice indicates that there is some impact of left-turning vehicles on lanes adjacent to the shared lane, which is reasonable in view of the lane changing that takes place near the intersection as drivers seek to avoid left-turn conflicts in the shared lane. Further, the overwhelming majority of multilane cases in which shared-lane groups exist have two lanes. On most larger arterials, left-turn bays and protected phasing are most often present.

Comparative Accuracy of Models

Table 4 presents the average errors in the estimation of prevailing saturation flow rate for four cases: (a) the HCM (*1*) model, (b) the HCM (*1*) model using regression estimates of g_f and g_u, (c) Model 1, and (d) Model 2 (as described herein). In order to illustrate the impact of two-lane versus three-lane

TABLE 4 AVERAGE ERROR IN PREDICTION OF SATURATION FLOW RATE FOR MULTILANE APPROACHES

MODEL	MULTILANE	TWO-LANE
85HCM	716 VPH	520 VPH
85HCM (MOD)	833 VPH	597 VPH
MODEL 1	579 VPH	393 VPH
RECOMMENDED	221 VPH	370 VPH

(Average Saturation Flow Rate = 3364 vphg)

approaches, results are shown for all multilane cases as well as for two-lane cases taken in isolation.

Both Models 1 and 2 improve considerably on the accuracy of the HCM (*1*) model. However, once again, the modification of the HCM (*1*) model to use the more accurate regression estimates of g_f and g_u makes the estimates of prevailing saturation flow rate worse. This result again points to flaws in the basic model structure, rather than inaccuracies in the input variables. As all models are considerably more accurate when applied to two-lane cases alone as compared to all multilane cases, the atypical nature of the three-lane data base is a considerable difficulty for the calibration.

Model 2 produces slightly more accurate estimates of saturation flow rate than Model 1. As there is no compelling evidence in the data to strictly retain the structure of the HCM model, a direct regression model for multilane cases could easily be adopted, as was the case for single-lane cases. As noted previously, Model 2 retains the importance of portions of the green as input variables, and therefore does not fully abandon the HCM (*1*) approach.

Figure 6 shows the accuracy of saturation flow rate predictions for the HCM (*1*) model and for Model 2 as described herein.

BOUNDARY CONDITIONS

As the regression models developed for left-turn adjustment factors do not have naturally occurring boundary conditions, such conditions should be externally applied. As in the 1985 HCM (*1*), the maximum value of either f_m or f_{LT} should be 1.00. A practical minimum value of f_{LT} should be set at 0.05, as is currently done in the HCM (*1*). This value reflects a minimum condition of from one to two sneakers per cycle using the shared lane when the opposing flow fully blocks the green phase. Further, f_m and f_{LT} should be set at 1.0 whenever there are no left-turning vehicles, and at the unopposed, shared-lane value stated in the HCM (*1*) whenever the opposing flow is zero.

CONSIDERATION OF THE IDEAL SATURATION FLOW RATE

As noted earlier, the data collection, reduction, and analysis procedures included the determination of the ideal saturation flow rate for each intersection. This determination was accomplished by averaging all observed ideal headways during all time intervals for the intersection approach. Adjustments for nonideal geometric conditions were applied as indicated in the HCM (*1*), and the ideal saturation flow rate determined as $3{,}600/h_i$, where h_i is the adjusted average ideal headway. Table 5 presents the values observed for the various sites used.

From the results of Table 5, for most of the sites observed, ideal saturation flow rates were higher than the default value recommended in the 1985 HCM (*1*) (1,800 pcphgpl). Even for single-lane sites, if the two lowest values are removed as atypical, the average value is close to 1,900 pcphgpl. These results are consistent with other observations across the United States in which values are consistently measured in the 1,900- to 2,000-pcphgpl range. An anomaly to this trend is recent studies in Texas, which show consistent average values in the range of 1,750 pcphgpl.

More disturbing than the values themselves is the variation in these values. These intersections were clustered in four distinct metropolitan areas, and many were adjacent to one another. The underlying assumption that ideal saturation flow rates are a basic driver characteristic that can be assumed to be relatively constant in a given area may not be supportable.

Figures 7 and 8 show an even more startling trend in ideal saturation headway at a single intersection approach over time. Each point represents an ideal saturation headway measured for a given 15-min sample. The variation displayed is alarming, particularly for the single-lane site, where the range is from 1.82 to 3.95 sec, a variation of 100 percent.

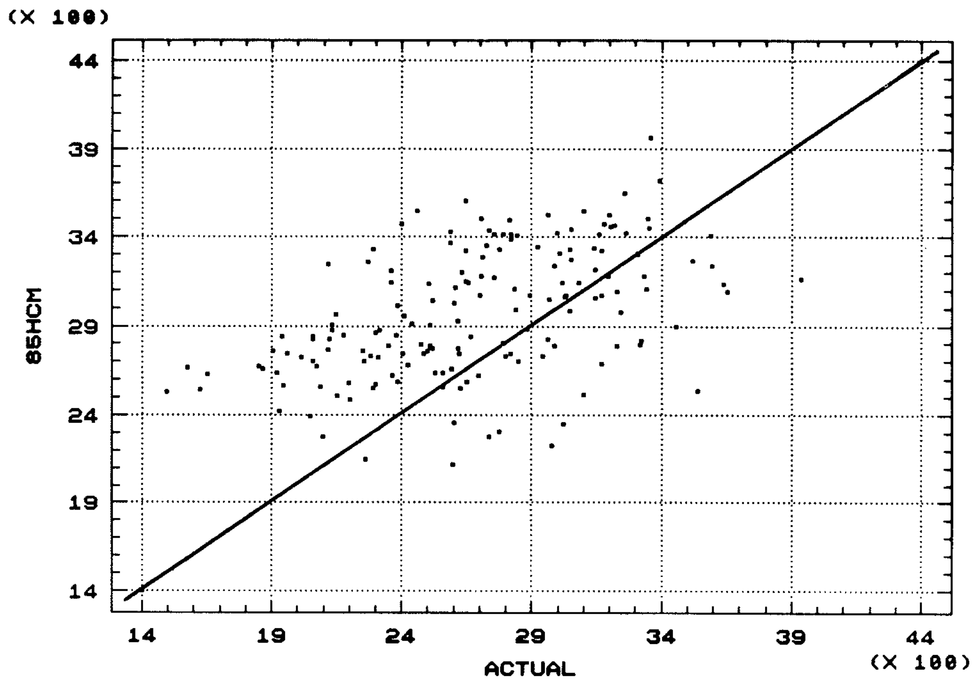
These results suggest that the base variable used in the 1985 HCM (*1*) is somewhat unstable, both in time and space. If the base ideal saturation flow rate varies significantly, the accuracy of prevailing saturation flow rate predictions based on this base will vary similarly. Thus, the accuracy achieved both by the existing HCM (*1*) model and those recommended herein must be considered good. The average error in the prediction of prevailing saturation flow rate (using the recommended models) is 18 percent for single-lane sites and 11 percent for multilane sites. Although these errors are larger than desirable, they are good considering the underlying variability of the base parameter.

This variability also strengthens the need to calibrate local values of the ideal saturation flow rate, as is recommended in the HCM (*1*). All calibrations reported herein were based on the calibrated ideal saturation flow rates presented in Table 5. Alternative calibrations using the standard 1,800-pcphgpl value were also performed, but in all cases resulted in poorer and less accurate predictions of the prevailing saturation flow rate.

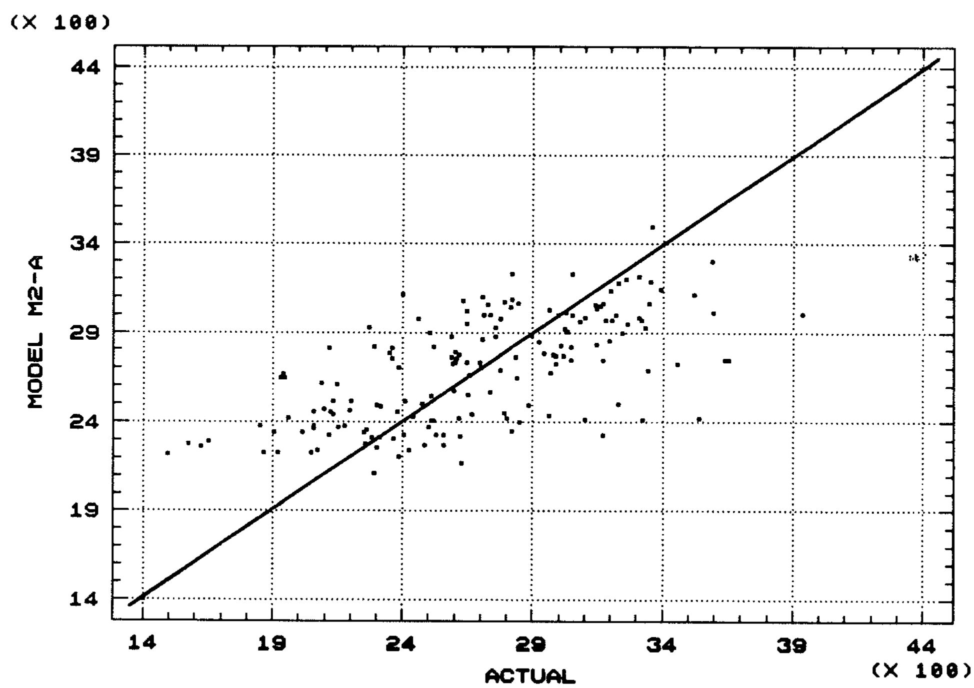
SUMMARY AND RECOMMENDATIONS

A number of interesting findings and recommendations are summarized as follows:

1. The HCM (*1*) model for g_f substantially underestimates this value, resulting in left-turn factor predictions that are too low. The HCM (*1*) model for g_q also underestimates this value, resulting in left-turn factor predictions that are too high. The two errors partially cancel each other in the HCM (*1*) model.
2. Single-lane approaches have unique characteristics that do not apply to multilane approaches. Left turns in one direction create gaps that can be used by left-turning vehicles in the other direction. These gaps may occur within the opposing queue or during the unsaturated portion of the phase. Because of this, the impact of left turns on saturation flow rate does not appear to strongly relate to the portions of the green phase as described in the 1985 HCM (*1*) model.
3. Incorporating more accurate estimates of g_f and g_u in the HCM (*1*) model does not improve its accuracy. Rather, the accuracy of saturation flow rate predictions becomes significantly worse, suggesting that there are flaws in the model logic as opposed to errors related to inaccurate input variable estimates.



a. 1985 HCM Model



b. Recommended Model

FIGURE 6 Comparative accuracy of saturation flow rate predictions for multilane approaches.

TABLE 5 FIELD VALUES OF IDEAL SATURATION FLOW RATE

FOR SINGLE-LANE APPROACHES:		FOR MULTILANE APPROACHES:	
Site No.	Ideal Sat. Flow	Site No.	Ideal Sat. Flow
EB51 NY	1240 pcphgpl	EB11 CH	1815 pcphgpl
WB51 NY	1496 pcphgpl	WB11 CH	1668 pcphgpl
NB11 TX	1590 pcphgpl	NB32 CH	1973 pcphgpl
SB11 TX	1933 pcphgpl	SB32 CH	1672 pcphgpl
NB33 LA	1902 pcphgpl	EB11 LA	2031 pcphgpl
SB33 LA	1961 pcphgpl	WB11 LA	2030 pcphgpl
EB31 NY	1799 pcphgpl	EB23 LA	2139 pcphgpl
WB31 NY	2092 pcphgpl	WB23 LA	2009 pcphgpl
EB21 NY	1950 pcphgpl	EB11 NY	2182 pcphgpl
WB21 NY	1950 pcphgpl	WB11 NY	2361 pcphgpl
		EB61 TX	1711 pcphgpl
		WB61 TX	1833 pcphgpl
		EB83 TX	1811 pcphgpl
		WB83 TX	1818 pcphgpl
		EB62 CH	2007 pcphgpl
		WB62 CH	2041 pcphgpl
		NB93 TX	1831 pcphgpl
AVERAGE	**1791 pcphgpl**	**AVERAGE**	**1937 pcphgpl**

4. For multilane approaches, the basic approach of the 1985 HCM (*1*) is supported in that portions of the green phase are critical to the determination of the left-turn adjustment factor. However, direct regression models do so more accurately than models specifically constrained to the HCM (*1*) format.
5. The default value of 1,800 pcphgpl suggested in the HCM (*1*) appears to be too low to represent average national characteristics. A value of 1,900 pcphgpl more closely represents the data base for the study. However, observed variation in this value strongly supports the use of local calibrations wherever possible.

Although Item 2 adequately explains why the HCM (*1*) model logic does not apply to single-lane sites, the failure of the HCM (*1*) structure to adequately describe multilane cases is less clear. The rigid adherence of the HCM (*1*) to the structure of opposing queue clearance followed by unsaturated opposing flow may in itself be unrealistic. With good progression, a tightly packed moving platoon arriving after the queue clears may in fact block opposing left turns as completely as the standing queue. Thus, the assumption of radically different operating modes during the defined portions of the green phase may not be universally applicable, and may depend on the quality of progression and the density, size, and frequency of opposing moving queues.

The project final report makes some additional recommendations concerning related cases such as (a) single-lane approaches opposed by multilane approaches, (b) exclusive LT lanes with permitted phasing, (c) shared lanes with protected plus permitted phasing, and (d) exclusive LT lanes with protected plus permitted phasing. Although some data were collected for shared lanes with protected plus permitted phasing, most of these are rational extensions of the work reported herein.

Shared-lane, permitted left turns are perhaps the single most complex operational situation in traffic. Considerations

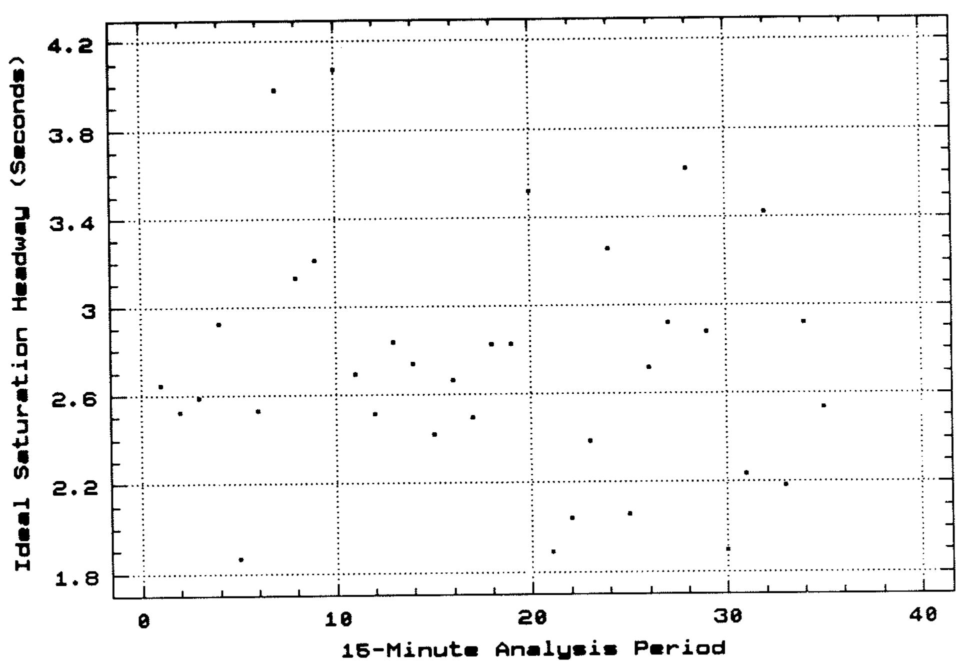


FIGURE 7 Variation in ideal saturation headway at a single-lane site.

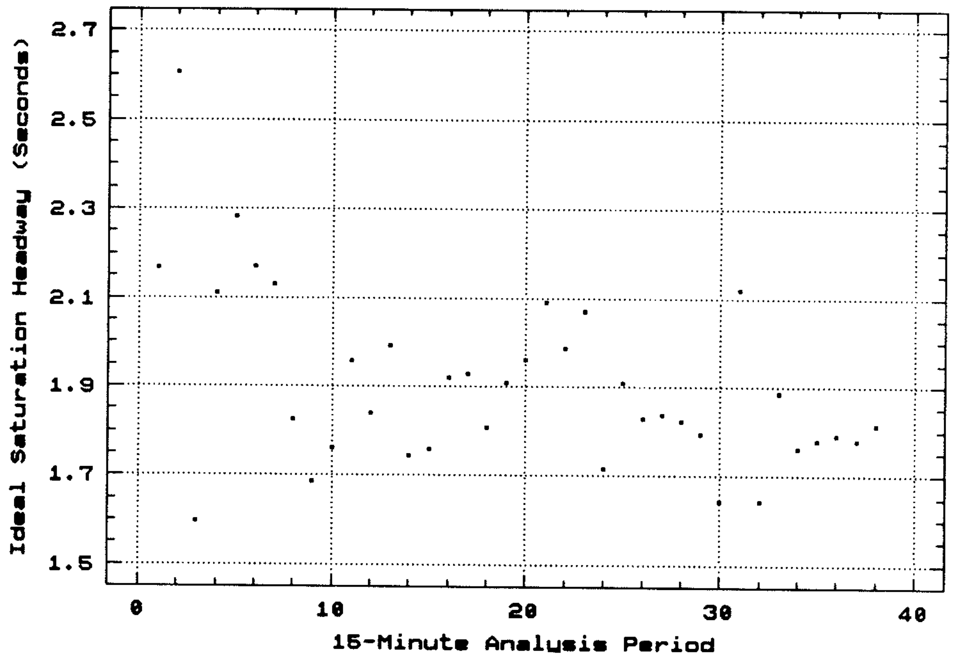


FIGURE 8 Variation in ideal saturation headway at a multilane site.

for revisions to the HCM (*1*) must balance consideration of accuracy against the simplicity and ease of use, with full recognition of the computational tools now available and in common use. The models developed improve the accuracy of prevailing saturation flow rate predictions, while also providing for simplification. They could be implemented within the overall structure of the 1985 HCM (*1*) methodology for signalized intersections without substantially changing the critical lane group approach taken therein.

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The conclusions and recommendations made represent the views of and judgments of the authors, and do not imply the endorsement or agreement of the FHWA.

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