Left-Turn Adjustment for Permitted Turns from Shared Lane Groups: Another Look

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Initial research on the left-turn adjustment factor for shared, permissive left-turn lane groups resulted in the recommendation that the theoretical model presented in the 1985 *Highway Capacity Manual* (HCM) be replaced by regression models. After several meetings and spirited debates, the Signalized Intersection Subcommittee of the Highway Capacity and Quality of Service Committee recommended that the regression-based models not be adopted for the HCM. The weaknesses in the 1985 HCM are discussed. Illustrations are provided to show how improved accuracy can be achieved with a hybrid model that uses parts of regression-based models inserted into the theoretic framework of the HCM model. The hybrid model is compared with the 1985 HCM and with other suggested methods. The hybrid model was found to be best for predicting saturation flow on the basis of field data for 267 data periods of 15 min each. At a workshop in summer 1992, the committee concluded that the hybrid model will be incorporated into the HCM.

In early 1990 the results of the FHWA-sponsored effort *Levels of Service in Shared, Permissive Left-Turn Lanes at Signalized Intersections* were reported in both a Final Report (*1*) and a TRB paper (*2*). The recommendations of the report included replacing the theoretic model for left-turn factors for shared, permissive lane groups in the 1985 *Highway Capacity Manual* (HCM) (*3*) with regression-based models. These models more accurately predicted field-measured values of saturation flow rate from 25 intersections in four urban areas across the United States.

The regression models were simpler than those of the 1985 HCM but lacked the clear logic of the theoretic approach. For single-lane approaches, the conclusion that the left-turn adjustment factor did not depend on the opposing flow rate was also counterintuitive, although rational explanations could be constructed.

Over the following 3 years, several meetings and discussions by the Signalized Intersection Subcommittee of the TRB Committee on Highway Capacity and Quality of Service led to the recommendation that the regression models not be adopted for inclusion in the HCM. The full committee directed the subcommittee to organize and conduct a workshop in summer 1992 to reexamine all aspects of the controversy and come to a positive conclusion on what to incorporate into the HCM.

This paper is the result of one of the analyses conducted for that workshop. It presents an argument for merging some key aspects of the regression models developed in the research effort into the general theoretic framework of the 1985 HCM. Some key modifications to that framework are also recommended to address important omissions.

At the workshop in summer 1992, the committee approved this hybrid method of merging the regression models into the 1985 HCM framework, and it is to be incorporated into the next printing of Chapter 9 of the HCM. At the same time, it was decided that the ideal saturation flow rate for an intersection should be increased from 1,800 to 1,900 per cars per hour of green time per lane (pcphgpl). This was one of the recommendations made in the initial FHWA-sponsored research and was developed on the basis of the measurements observed for ideal saturation flow rate at the 25 intersections used in the data base.

The recommended hybrid model given in this paper is compared with other methods that have been recommended for analyzing permitted left turns. All of the methods are compared using 1,900 pcphgpl as the ideal saturation flow, because this number has already been approved as the new ideal saturation flow rate for the HCM.

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1985 HCM MODEL: A THEORETIC FRAMEWORK

The 1985 HCM model for the left-turn adjustment factor applied to permitted left turns made from shared lane groups is

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

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

where

- f_m = left-turn adjustment factor applicable only to lane from which left turns are made,
- f_{lt} = left-turn adjustment factor applicable to the entire lane group from which left turns are made,
- g_f = green time until arrival of first left-turning vehicle in subject lane group,
- g_u = unsaturated portion of green phase; effective green remaining after clearance of opposing queue,
- P_L = proportion of left-turning vehicles in left lane, and
- E_L = through-car equivalent of a left-turning vehicle.

The model for f_m presumes a rigid structure of the green phase into three component portions. In addition to g_f and g_u, there is also g_q, defined as the green time consumed in clearing the opposing queue of waiting vehicles from the intersection.

When the light turns green, the opposing queue takes g_q sec to clear. During this time, it is assumed that no left turns can be made, as the clearing queue effectively presents an opposing flow without gaps. The remaining time, $g - g_q$, is by definition, g_u. During g_u, left turns are made through gaps in an unsaturated opposing flow. There is, however, the initial period, g_f, during which flow from the shared lane proceeds uninterrupted, because no left turns are present. The 1985 HCM presumes that g_f should never be more than g_q, an assumption that will be discussed later. The basis of HCM model is therefore the following:

- During g_f, there are no left turns present. Thus, the left-turn factor for this portion of the green should logically be 1.00. The term g_f/g is therefore multiplied by 1 in the model.
- Assuming that the first left-turning vehicles arrives before the clearance of the opposing queue, there is a period $g_q - g_f$, during which the first left-turning vehicle blocks the shared lane while waiting for the unsaturated portion of the green phase. Because there is no flow in the shared lane during this period, the left-turn factor during this period is logically 0.00. There is no term addressing this period in the model for this reason.
- During g_u, left turns are made through the unsaturated opposing flow. The friction of the left-turn conflict with opposing vehicles, however, restricts the rate at which these can be made. An adjustment factor of between 0.00 and 1.00 logically applies here. The HCM computes a factor based on E_L that is computed as 1,800 (1,400 $- v_o$), which is the ratio of the ideal saturation flow rate to the saturation flow rate of left turns made through an opposing flow.
- The last term of the HCM model accounts for "sneakers," who complete their left turns during the clearance interval. Each sneaker effectively adds 2 sec to the effective green—hence, $2/g$. The model posits that between 1 and 2 such vehicles will exist on the basis of the proportion of left turners in the shared lane, P_L.

In the HCM model, f_m is extended to f_{lt} by assuming that there is no impact of left turns in the shared lane on adjacent through lanes in multilane approaches. In effect, an average adjustment factor is computed for all lanes, assuming that f_m applies to the shared lane, and that 1.00 applies to all others in the lane group.

DIFFICULTIES WITH HCM MODEL

There are three principal difficulties with the HCM model as it is currently constituted. The first is the assumption that g_f should not be permitted to be more than g_q. In practice, of course, the first left-turning vehicle can arrive either before or after the clearance of the opposing queue. In the data base developed for the FHWA study, a significant portion of the periods studied had $g_q < g_f$. If the HCM rule is followed in this case, an adjustment factor of 1.00 is applied only through g_q. For the period $g_f - g_q$, the adjustment factor for g_u is applied. Thus, for some portion of the green, a factor of less than 1.00 is applied when there are no left turns present. Figure 1 illustrates this anomaly and the recommended correction. A factor of 1.00 should be applied until the arrival

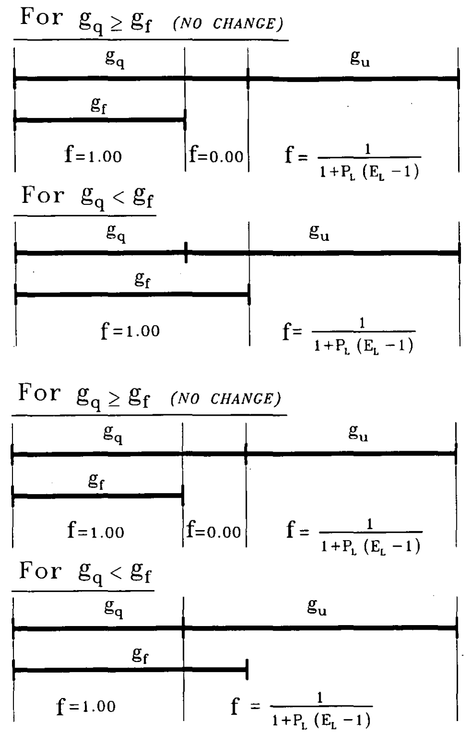


FIGURE 1 Interpretations of g_f, g_q, and g_u: *top*, recommended model; *bottom*, 1985 HCM model.

of the first left-turning vehicle, regardless of whether this is before or after clearance of the opposing queue. Thus, g_f should not be constrained. Then, g_u would be redefined as follows:

$$g_u = \begin{cases} g - g_q & g_q \geq g_f \\ g - g_f & g_q < g_f \end{cases}$$

With this revision, an adjustment factor less than 1.00 is only applied to the unsaturated portion of the green for which left-turn demand exists.

The second major difficulty with the HCM model occurs when it is applied to single-lane approaches. In these cases, the assumption that no left turns can be made during the period $g_q - g_f$ (for those cases in which $g_q > g_f$) is incorrect. When single-lane approaches are opposed by single-lane approaches, left turns in one direction open a gap for left turns in the other to be made, as illustrated in Figure 2. Thus, if the opposing queue of vehicles includes left-turning vehicles, some left turns will be made through gaps opened in the opposing queue. Thus, the adjustment factor applied during the period, $g_q - g_f$ should not be 0.00 for the case of opposing single-lane approaches. A recommendation for what it should be will be presented.

Opposing left turns that open gaps for each other is a unique characteristic and is one reason that regression models did not indicate any sensitivity of left-turn factors to opposing flow for such cases. Left turns will be made regardless of opposing flow on the basis of the balance of left-turning vehicles in the opposing and subject flows. Whereas the HCM model attempts to address this by eliminating left turns from

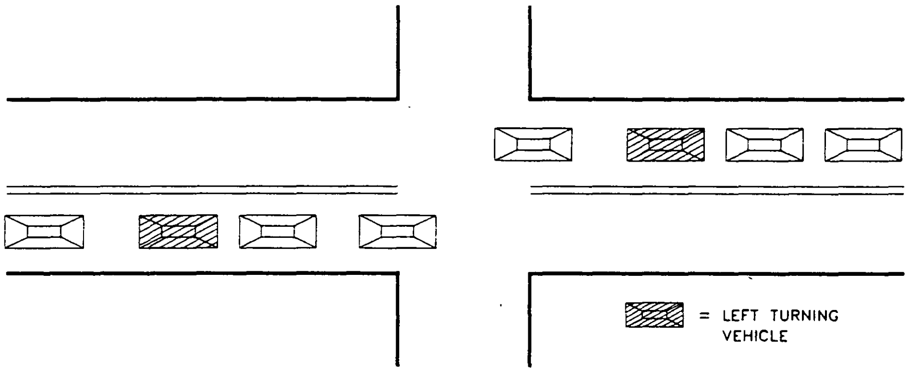


FIGURE 2 Opposing left turns on a single-lane approach.

a single-lane approach from the computed opposing flow rate, this is an arithmetic approach that does not explicitly account for left turns made through the opposing queue and the resulting reduction in the blockage of the shared lane.

The third difficulty is the assumption (for multilane approaches) that left-turning operations in a shared lane have no impact on adjacent lanes in the subject lane group. In multilane situations, left-turners create delay in the shared lane that other drivers seek to avoid by moving into adjacent lanes, causing additional turbulence in adjacent lanes. It would be logical to assume that there is some impact in these lanes as well, perhaps at some reduced level. Results of the research demonstrated that there was such an impact.

There are two additional problems with the HCM model, which are more practical than theoretical. The HCM model, in predicting g_u and g_q, does not consider the effect of signal progression and and the platooning of vehicles on the queue clearance time. Thus, for example, changing the offset at an intersection that is part of an arterial will have no effect on the queue or the queue clearance time in the current model. Second, the HCM model necessitates an initial "guesstimate" of saturation flow rate in the opposing direction before the saturation flow rate is computed for the subject direction. This creates a circular logic that should most properly be iterated, which is not done in the HCM.

An additional problem was uncovered during tests of the models using varying ideal saturation flow rates. It was found that reducing the ideal saturation flow rate yielded more accurate results. This was perplexing, particularly because the FHWA study included direct observations of this parameter and suggested that 1,900 pcphgpl is a more realistic value to use. This is explained by a simple fact—the studies of left-turn adjustment factors assume that all other factors given in the HCM are correct. That better results are achieved using lower ideal saturation flow rates indicates that the other factors do not account for all of the negative impact of other nonideal conditions.

RECOMMENDATIONS FOR IMPROVEMENTS

Adopt Regression Models for g_q, g_f, and g_u

The HCM model starts with a "guesstimate" of opposing saturation flow rate because one is needed to establish g_f, g_u, and g_q analytically. Use of regression models for these values avoids this need and removes the need to iterate a circular procedure in which opposing values of saturation flow rate are interdependent. The FHWA research produced models for predicting these values that were more accurate than the HCM. The models for g_f are summarized by the following:

$$g_f = \begin{cases} G\exp(-0.860\,\mathrm{LTC}^{0.629}) - t_L & \text{single-lane approaches} \\ G\exp(-0.882\,\mathrm{LTC}^{0.717}) - t_L & \text{multilane approaches} \end{cases}$$

where

G = actual green time for the phase;
LTC = average number of left turns per cycle, which may be fractional; and
t_L = total lost time per phase (sec).

Figure 3 illustrates the accuracy of these models in predicting g_f compared with the HCM model for 305 study periods, each 15 min long, at 25 intersections in four major urban regions: New York; Chicago; Austin, Texas; and Los Angeles.

The models for g_q are

$$g_q = \begin{cases} 4.943\, v_{olc}^{0.762}\, qr_o^{1.061} - t_L & \text{single-lane approaches} \\ 9.532\, v_{olc}^{0.560}\, qr_o^{0.819} - t_L & \text{multilane approaches} \end{cases}$$

where

v_{olc} = opposing flow expressed in units of per lane and per cycle,
t_L = total lost time per phase, and
qr_o = opposing queue ratio.

The models for g_f and g_q were calibrated from the beginning of the actual green time for the given movement. Because it is the effective green time that needs to be partitioned into periods of use for left turns, the model values are adjusted by the lost time, t_L, to account for the difference between effective green time and actual green time.

The opposing queue ratio, qr_o, is defined as the proportion of opposing flow originating in the opposing queue (i.e., during g_q). For most cases, this can be taken as the same as the proportion of vehicles arriving on red, or 1 − (proportion of vehicles arriving on green). Because the proportion of vehicles arriving on green is needed to implement new models for delay estimation, this recommendation does not introduce another variable into the overall intersection methodology.

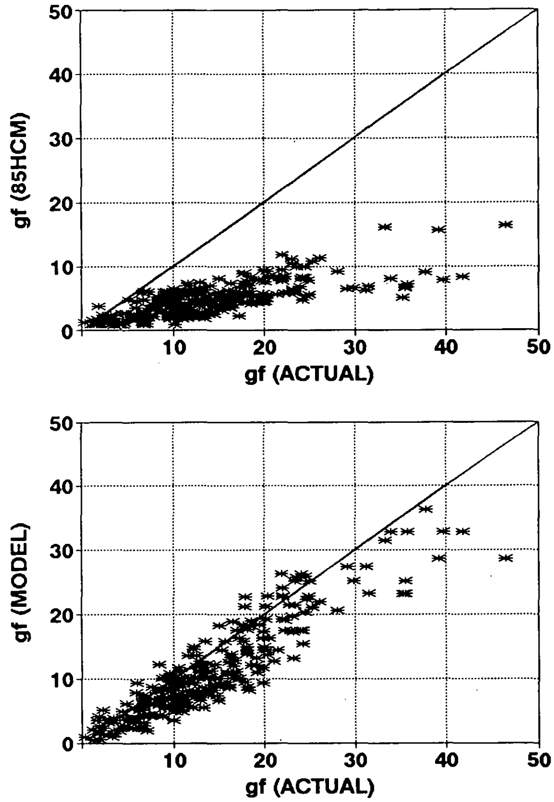


FIGURE 3 Comparative accuracy in prediction of g_f: *top*, 1985 HCM predictions; *bottom*, recommended model predictions (*1*).

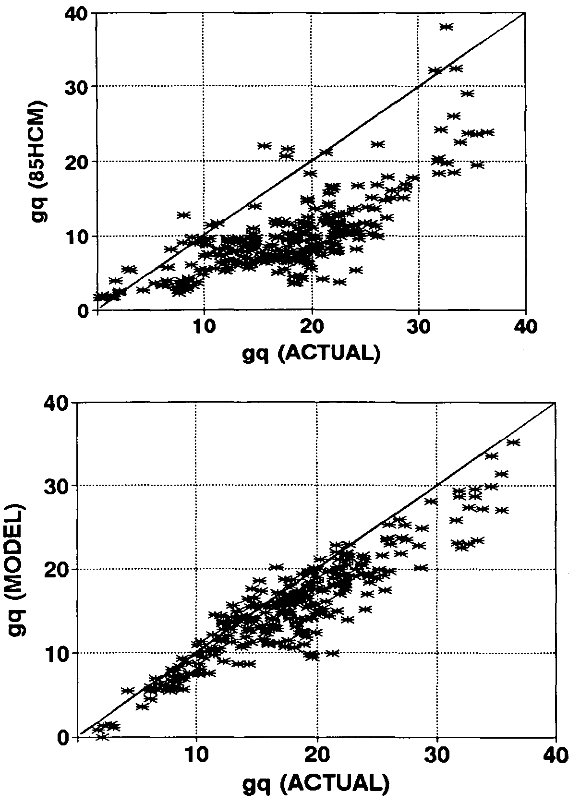


FIGURE 4 Comparative accuracy in prediction of g_q: *top*, 1985 HCM predictions; *bottom*, recommended model predictions (*1*).

It might be argued that a moving platoon without gaps has as much impact on left turns as the clearance of a standing queue. The blocking effect of a moving platoon of vehicles through a well-coordinated signal progression can be handled by including these vehicles in the opposing queue ratio.

Figure 4 illustrates the relative accuracy of these models in predicting g_q. When g_f and g_q are estimated, g_u is deduced as previously recommended.

$$g_u = \begin{cases} g - g_q & g_q \geq g_f \\ g - g_f & g_q < g_f \end{cases}$$

Develop Adjustment Factor for Left Turns Made Through Opposing Queue on Single-Lane Approaches

The theoretical structure of the HCM model does not allow for left turns made within g_q, the time during which the opposing queue clears the intersection. For single-lane cases, this is not correct, because left turns may be made through gaps created by opposing left turns. Thus, during the critical interval between the arrival of the first left turn and the clearance of the opposing queue (i.e., $g_q - g_f$), for which the HCM model assumes no flow in the shared lane, left turns may in fact occur, and flow in the shared lane is therefore not only possible, but probable.

It is therefore necessary to construct a model for an adjustment factor to be applied during this period. During g_u, the adjustment factor is

$$f_1 = 1/[1 + P_L(E_L - 1)]$$

where E_L is the through-car equivalent of a left-turning vehicle.

What is needed for single-lane cases is a model for E_{L2}, a through-car equivalent for a left-turning vehicle during the $g_q - g_f$ period. Such a model may be developed relatively simply. At g_f, there is, by definition, a left-turning vehicle waiting for service. This vehicle will wait until a gap in the opposing queue occurs as a result of an opposing left-turning vehicle. The expected value of the waiting time for this vehicle is found by considering the probability of the first, second, third, and so on opposing vehicle being a left turner. In the limit, no opposing left turner occurs during the $g_q - g_f$ period. The expected waiting time of the left-turning vehicle arriving at g_f is

$$\sum_{i=0}^{n} [2\, i\, P_{THO}^{i-1} P_{LTO}] + [(g_q - g_f)\, P_{THO}^{n}]$$

where

P_{LTO} = proportion of left-turning vehicles in opposing flow;
P_{THO} = proportion of through vehicles in opposing flow;
n = maximum number of opposing vehicles that arrive during period $g_q - g_f$, taken as $(g_q - g_f)/2$; and
2 = assumed saturation headway for opposing vehicles.

The first term of the equation accounts for the probabilities of an opposing vehicle arriving among the n opposing vehicles during $g_q - g_f$. The second term accounts for the probability that all opposing vehicles during this time are through vehicles.

A value of E_{L2} is estimated by dividing this expected waiting time by the saturation headway of 2 sec. Doing this and algebraically clearing the series results in

$$E_{L2} = (1 - P^n_{THO})/P_{LTO}$$

which can easily be converted to a multiplicative adjustment factor. This simple approach ignores the impact of left-turning vehicles arriving after g_f, that is, a second, third, or fourth left turner. These would have a smaller impact per vehicle because their maximum wait time is reduced. Thus, applying this single value of E_{L2} to all of the left turns occurring during the $g_q - g_f$ period is a conservative approach.

Implement Regression Model for f_{LT}

One of the key conclusions of the FHWA study was that there was a nonnegligible impact of left turns from a shared lane on adjacent lanes in a multilane group. Rather than arbitrarily assigning a value of 1.00 for the left-turn factor to adjacent through lanes, the study suggested the following:

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

where N is the number of lanes in the lane group, and a is the factor applied to through lanes in the lane group.

Whereas the study attempted to establish an algorithmic expression for a on the basis of the proportion or number of left turns in the shared lane, the best fit to data from 192 study periods, each of 15 min, on multilane sites occurred when $a = 0.91$, a constant.

Remove Sneakers from Model

During the research for FHWA by Polytechnic, it was observed that the number of sneakers completing the turn during the clearance interval was much smaller than that predicted by the 1985 HCM. In addition, these vehicles were being double counted because vehicles are counted as they cross the stopline. For the recommended model, therefore, the procedure does not represent sneakers, and the sneaker term is dropped from the equation.

Use Messer-Fambro Left-Turn Equivalent

E_L, in the current manual is calculated on the basis of the ratio of the ideal saturation flow rate and a simple model for the saturation flow rate of left turns through an unsaturated opposing flow, 1,800 (1,400 − v_o). This model assumes that the left turn equivalent is the same for a left turning vehicle crossing a given volume per hour, whether that volume is in one, two, or three or more lanes. In a paper by Messer and Fambro (*4*), more realistic values for E_L were developed that account for the effect of the number of opposing lanes. Table 1 gives these values and has been incorporated into the procedures.

Increase Heavy Vehicle Equivalency

An additional change recommended is to the heavy vehicle equivalency value used in determining F_{HV}. The manual now uses a heavy vehicle equivalency of 1.5. The authors have suggested changing this value to 2.0. Zegeer (*5*) conducted surveys to study the effects of heavy vehicles on headways that suggested a heavy vehicle passenger car equivalent of 1.92.

TABLE 1 Through-Car Equivalents, E_L, for Permitted Left Turns

No. of Signal Phases	Type of Left Turn Lane	No. of Opposing Lanes	E_L by Opposing Flow, V_o[1]				
			200	400	600	800	1000
2-PHASE	Shared	1	2.0	3.3	6.5	16.0*	16.0*
		2	1.9	2.6	3.6	6.0	16.0*
		≥ 3	1.8	2.5	3.4	4.5	6.0
	Exclusive	1	1.7	2.6	4.7	10.4*	10.4*
		2	1.6	2.2	2.9	4.1	6.2
		≥ 3	1.6	2.1	2.8	3.6	4.8
Multiphase	Shared	1	2.2	4.5	11.0*	11.0*	11.0*
		2	2.0	3.1	4.7	11.0*	11.0*
		≥ 3	2.0	2.9	4.2	6.0	11.0*
	Exclusive	1	1.8	3.3	8.2*	8.2*	8.2*
		2	1.7	2.4	3.6	5.9	8.2*
		≥ 3	1.7	2.4	3.3	4.6	6.8

* Generally indicates turning capacity only available at end of phase - sneakers only.

1 For the purpose of determining v_o and N_o, opposing right and left turns from exclusive lanes are not included in v_o, nor are the exclusive lanes in N_o.

Summary of Model for f_{LT}

Table 2 gives a summary of the recommendations and illustrates the model recommended for implementation.

TABLE 2 Recommended Model

ITEM	Single Lane Approaches	Multilane Approaches
g_f	$G\ e^{-0.860\ LTC^{0.629}} - t_L$	$G\ e^{-0.882\ LTC^{0.717}} - t_L$
g_q	$4.943\ V_{olc}^{0.762}\ qr_o^{1.061} - t_L$	$9.532\ V_{olc}^{0.560}\ qr_o^{0.819} - t_L$
g_u	$g - g_q$ for $g_q \geq g_f$ $g - g_f$ for $g_q < g_f$	$g - g_q$ for $g_q \geq g_f$ $g - g_f$ for $g_q < g_f$
Period	**Factor Applied - Single lane**	**Factor Applied - Multilane**
$\frac{g_f}{g}$	1.00	1.00
$\frac{g_q - g_f}{g}$	$\frac{1}{1 + P_L(E_{L2} - 1)}$ $E_{L2} = \frac{1 - P_{THO}^n}{P_{LTO}}$	0.00
$\frac{g_u}{g}$	$\frac{1}{1 + P_L(E_L - 1)}$ where E_L is found in Table 3	$\frac{1}{1 + P_L(E_L - 1)}$
f_{LT}	$f_{LT} = f_m$	$f_{LT} = \frac{f_m + 0.91(N - 1)}{N}$

COMPARING RESULTS OF SEVERAL METHODOLOGIES

Using 192 data periods (each 15 min) for two-lane sites and 102 data periods (each 15 min) for single-lane sites from the FHWA study, the relative accuracy of the recommended hybrid model was compared with that of the 1985 HCM model and several other suggested models.

The models tested include

- The recommended model, described in this paper,
- The 1985 HCM Model,
- Modifications to the 1985 HCM suggested by Messer,
- A model recommended by Lin in a paper presented at TRB in 1992 (*6*),
- A model recommended by Levinson in a paper presented at TRB in 1992 (*7*).

The Messer modifications have not been published, but they include revision of the starting assumption of opposing saturation flow rate to reflect nonideal conditions and carrying forward this modification to every use of either the opposing saturation flow rate or the opposing saturation headway in the model. A second modification involves the assumption that multilane opposing flow is not uniformly distributed across available lanes. A third modification adjusts the equation for g_f to account for no left turns arriving during g_q.

Table 3 gives the average error in predicting saturation flow rate and the percent error for each of the models. The data indicate that using an ideal saturation flow rate of 1,900 pcphgpl, the recommended model yields the best results for both single- and two-lane approaches.

Another finding of note is that the best of these models results in an average error of somewhat less than 20 percent of the observed saturation flow rate. The plots in Figure 5 help explain this. The variation in measured ideal saturation flow rates from the FHWA study are shown. Even when averages over 15-min intervals are considered, the variation in this value is extremely large. This phenomenon was evident in the study, with variations occurring from site to site, and even at the same site over time. For single-lane sites, average ideal saturation headways ranged from 1.8 sec/vehicle to more than 3.4 sec/vehicle. For multilane sites, values ranged from 1.6 sec/vehicle to more than 2.3 sec/vehicle.

Because all of the model structures considered in this paper operate on the basis of modifying a constant ideal saturation flow rate, the considerable actual variation in the base variable more than explains the approximately 20 percent average errors in predictions of prevailing saturation flow rate.

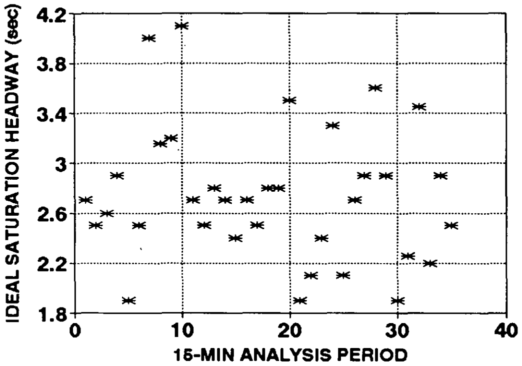
FINAL THOUGHTS AND RECOMMENDATIONS

Because of the base variation in ideal saturation flow rate, it is unlikely that any model developed by modification will result in much better accuracy than those examined in this paper. Given, then, the ballpark nature of the computation of prevailing saturation flow rate, the great complexity of

TABLE 3 Average Errors in Predicting Saturation Flow Rate for Various Left-Turn Models

Ideal Sat Flow (S_o)	Model	Single Lane Approaches (Avg Sat = 1300 vphg)		Two-Lane Approaches (Avg Sat = 2600 vphg)	
		Avg Error	% Error	Avg Error	% Error
1900	1985 HCM	355	27%	569	22%
	Messer	401	31%	509[1]	20%
	Lin	357	27%	966	37%
	Levinson	354	27%	760	29%
	RECOM	289	22%	496	19%

[1] Application of multilane factor "a" shown here; without "a" error = 590 vph



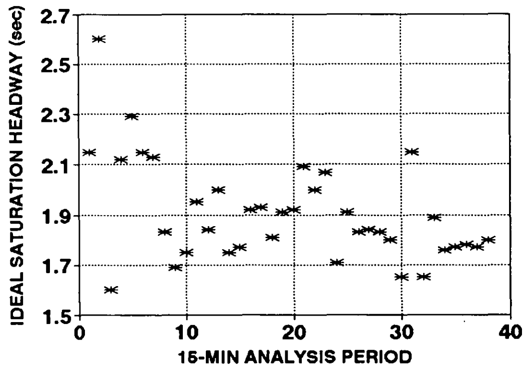


FIGURE 5 Observed variation in ideal saturation flow rate: *top*, single lane approaches; *bottom*, multilane approaches (*1*).

some models is not justified. Unless complexity yields significant benefits in accuracy, it becomes a liability in users' ability to comprehend and properly apply the procedure.

The procedure presented in this paper has the following advantages:

- The circular logic of the HCM, requiring a "guesstimate" of saturation flow rate in one direction to compute in the other is eliminated.
- The regression models for g_f and g_q yield significantly better estimates of these variables than the HCM model, and therefore introduce more appropriate sensitivities to these variables into the overall model.
- The recommended model results in saturation flow estimates that are better than that produced by other models.
- The use of the recommended model simplifies computations for f_{LT}.
- The recommended model explicitly corrects several difficulties in the HCM model, particularly for single-lane approaches.
- The recommended model retains the basic theoretic structure of the HCM model, and is a rational depiction of driver behavior in permitted left-turn situations.

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