Utilization of Auxiliary Through Lanes at Signalized Intersections

JAMIE W. HURLEY

The capacity of signalized intersections is sometimes increased by adding an auxiliary lane for use by through traffic. The effectiveness of an auxiliary lane depends on the amount of traffic using it. Equal distribution of traffic between a continuous and an auxiliary through lane would result in the greatest total capacity of this lane pair, but traffic, land use, and geometric factors are usually such that this does not occur. The 1985 *Highway Capacity Manual* does not address this situation. A concept of captive and choice lane users was used in modeling auxiliary lane use for intersection configurations with a single continuous through lane and an auxiliary lane beginning upstream of the intersection and extending downstream of it. Stepwise multiple regression was performed on data collected at sites in Tennessee to determine, from a candidate list of factors, those that significantly affect choice use of the auxiliary lane. These factors were found to be (*a*) through flow rate, (*b*) right turns off of the facility in the last 500 ft of the auxiliary lane, (*c*) downstream auxiliary lane length, and (*d*) urban area size. For the sites studied, it was found that traffic distribution between lanes for intersection configurations with a single continuous through and an auxiliary lane is much different from the value given in the *Highway Capacity Manual* for two continuous through lanes.

A common practice for increasing the capacity of signalized intersections is to use exclusive turning lanes. Although less common, signalized intersection capacity may also be increased by adding an auxiliary lane for use by through traffic. A lane configuration typically used in urban areas is illustrated in Figure 1. The effectiveness of the continuous and auxiliary through lanes depends on the amount of traffic using the auxiliary lane. Equal lane distribution between these lanes, if it could be achieved, would result in the greatest total capacity of this lane pair.

Intersection configurations such as that shown in Figure 1 are not addressed in the 1985 *Highway Capacity Manual* (HCM) (*1*). The HCM procedures do, however, treat configurations with two continuous through lanes, which could be thought of as the Figure 1 configuration with infinite upstream and downstream auxiliary lane lengths.

This paper defines, on the basis of sample site data, the factors that significantly affect lane distribution for the continuous and auxiliary through lanes as shown in the Figure 1 intersection configuration. It also presents, using these same data, a means of estimating the corresponding volume by lane.

BACKGROUND

The 1985 HCM uses lane utilization factors to account for the distribution of traffic across multiple lanes continuing through an intersection. These factors are based on the assumption that the most heavily traveled lane in a group of two serves 52.5 percent of the total flow. Although the basis for these factors is not mentioned in the 1985 HCM, the factors themselves are the same as those in *Transportation Research Circular 212* (*2*). It is stated (*2*) that the 52.5 percent value is a compromise between the 55/45 percent volume split assumed by Messer and Fambro (*3*) and an assumption of equal (50/50 percent) lane distribution during peak conditions.

The first known capacity-related effort for the study intersection configuration is that of Leisch (*4*). In this work, Leisch developed a nomographic procedure for solving intersection capacity problems that was based on the 1965 HCM, similar to that which he developed and based on the 1950 HCM. In addition to these basic intersection capacity nomographs, Leisch included procedures for certain "special conditions" not covered in the 1965 HCM, one of which is the Figure 1 configuration. Unfortunately, Leisch did not discuss the methods used to develop these procedures.

McCoy and Tobin (*5*) observed the use of auxiliary through lanes, evaluated the effect of the length of these lanes on their use by through vehicles, and incorporated their findings into the critical movement analysis technique of *Transportation Research Circular 212* (*2*). As part of their work, however, McCoy and Tobin also studied the work of Leisch (*4*). Using stepwise multiple regression analysis of the data, McCoy and Tobin developed a linear model for estimating the mean number of through vehicles discharging from the additional through lane as a function of green time for the through and right movements and the total length of the lane addition (upstream plus downstream). They noted that the number of right-turning vehicles did not significantly affect the usage of the auxiliary through lane by through vehicles. Finally, McCoy and

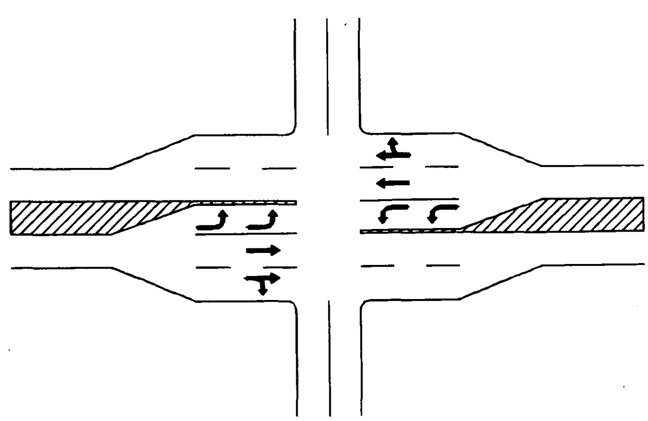

FIGURE 1 Adding auxiliary lane to increase capacity.

Department of Civil Engineering, University of Memphis, Memphis, Tenn. 38152.

Tobin also concluded that length requirements for the additional lane as determined using the Leisch guidelines are too short to achieve an average use by through vehicles of more than 1.5 passenger cars per cycle.

STUDY APPROACH

As stated previously, the effectiveness of a through auxiliary lane depends on the number of drivers using it. Lieberman (*6*), in developing a lateral deployment model for the TRAFLO macroscopic traffic simulation program, employed a variation of Wardrop's first principle: that every motorist will select a lane on an approach consistent with his or her intended turn maneuver and with any specified lane channelization so as to minimize his or her perceived travel time. In reviewing research efforts related to the factors that most influence intersection capacity, Stokes (*7*) concluded that although there is general agreement on the effects of certain physical factors on capacity, a class of factors characterized as "driver behavior" does not lend itself to quantification in any systematic fashion. Stokes believes that the effects of these factors are site-specific.

It is suggested here that the concepts of Lieberman and Stokes are substantially correct with regard to the study intersection configuration, and probably with regard to any other intersection situation involving lane choice. This is best explained in terms of "captive" and "choice" users of the auxiliary through lane. Captive users are those through movement drivers who *must* use the auxiliary lane because of their need to turn right downstream of the intersection (into driveways). Some auxiliary lane users are captive because they turn into the auxiliary lane from the right side of the roadway immediately upstream of the intersection. There are captive users of the continuous through lane as well. These are those turning left into driveways downstream of the intersection and those turning left onto the facility from driveways immediately upstream of the intersection. The primary characteristic of captive users of either the continuous or the auxiliary lane is that they use those lanes because of their association with adjacent land use. Traffic demand, signal timing, and (in a sense) auxiliary lane length, for example, have nothing to do with their use of continuous lanes. There is obviously some zone of influence upstream and downstream of the intersection beyond which drivers entering and exiting the facility, should the auxiliary lane be long enough, have enough space to change lanes. It is assumed here that captive drivers are those who, within the length of the auxiliary lane, exit driveway downstream of the intersection.

Choice users of an auxiliary lane are drivers who travel continuously through the intersection and who have decided to use the auxiliary lane. This choice may or may not be based on perceived travel time alone. Turning movements onto and off of the left side of the roadway will cause interference with traffic in the leftmost continuous lane, thereby making the auxiliary lane a more attractive choice. Conversely, turning movements onto and off of the right side of the roadway tend to inhibit use of the auxiliary lane by drivers having a choice of lanes. Proper analysis of these inhibiting effects required that a determination be made as to *which* turning movements most affect lane choice: those near the intersection, those near the downstream end of the auxiliary lane, or the total over the entire downstream length.

It was considered that other factors in addition to turning movements could affect auxiliary lane use by choice drivers. These include geometrics, urban area size, demand magnitude, and the number of heavy vehicles in the traffic stream. The total portion of through traffic in the auxiliary lane may be expressed as

$$P_{\text{total}} = \frac{P(Q - RTOFF - LTOFF) + RTOFF}{Q}$$

where

P_{total} = total portion of through traffic in auxiliary lane,
P = portion of choice users in auxiliary lane,
Q = total through flow rate (vph),
RTOFF = right turns off of facility downstream of intersection (per hour), and
LTOFF = left turns off of facility downstream of intersection (per hour).

For the study intersection configuration, the lane utilization factor, U, used in the HCM will be the larger value of $2P_{\text{total}}$ or $2(1 - P_{\text{total}})$.

MODEL DEVELOPMENT

Since no theory existed by which lane distribution could be predicted, a model was developed using stepwise multiple regression analysis. The basic model form for regression analysis is of the form

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_i X_i + \ldots + \beta_k X_k$$

where

Y = value of dependent variable (in this case, some measure of auxiliary lane use),
$X_1, \ldots, X_k$ = values of independent variables (i.e., for factors that affect lane distribution), and
$\beta_0, \ldots, \beta_k$ = numerical coefficients (determined in regression process).

A problem with this model structure is that it is linear—that is, if one of the X's is flow rate, the portion in the auxiliary lane can (theoretically, at least) increase to infinity. This, of course, is not realistic. It would be more realistic to expect voluntary lane use to increase as demand increases, but up to a maximum limit. For example, under very low demand, one would expect the portion of through traffic in the auxiliary lane to be very small, since nothing could be gained by using it. With increasing demand, however, one would expect the portion of choice users in the auxiliary lane to increase.

A curve shape that better represents lane choice behavior is the hyperbolic tangent function given here and illustrated in Figure 2.

$$\tanh X = \frac{e^X - e^{-X}}{e^X + e^{-X}}$$

The basic hyperbolic tangent function has a range from -1 to $+1$ and passes through the origin. However, the function can be shifted both horizontally and vertically by replacing X with a mathematical function. It was desired to model P, the choice portion of drivers using the auxiliary lane such that P ranged from 0 (at the origin) up to the "ideal" or maximum value of choice auxiliary lane use. (The

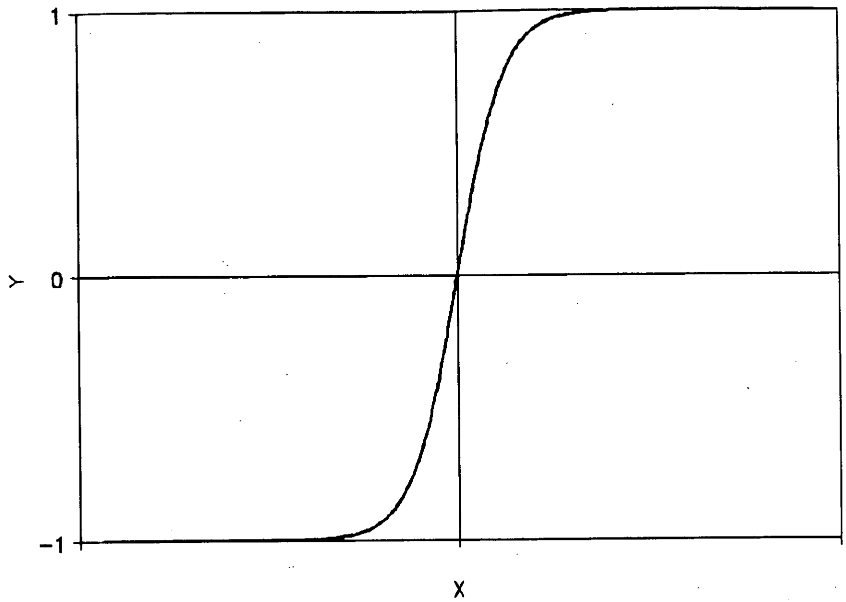

FIGURE 2 Hyperbolic tangent function.

ideal value is based on field data collected as part of the study.) This variation is illustrated in Figure 3 for an ideal choice auxiliary lane use of 50 percent. To force the curve to behave in this manner, the X in the hyperbolic tangent function is replaced by

$$\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_k X_k$$

Mathematically then, the model for the choice users of the auxiliary lane is

$$P = P_{\text{ideal}} \tanh(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_k X_k)$$

Another positive quality of the hyperbolic tangent function is that it is inverted easily. In general terms, the inverse is written in the following form:

$$\tanh^{-1} X = \frac{1}{2} \ln\left(\frac{1 + X}{1 - X}\right)$$

It is convenient here to define a dependent variable, Y, as

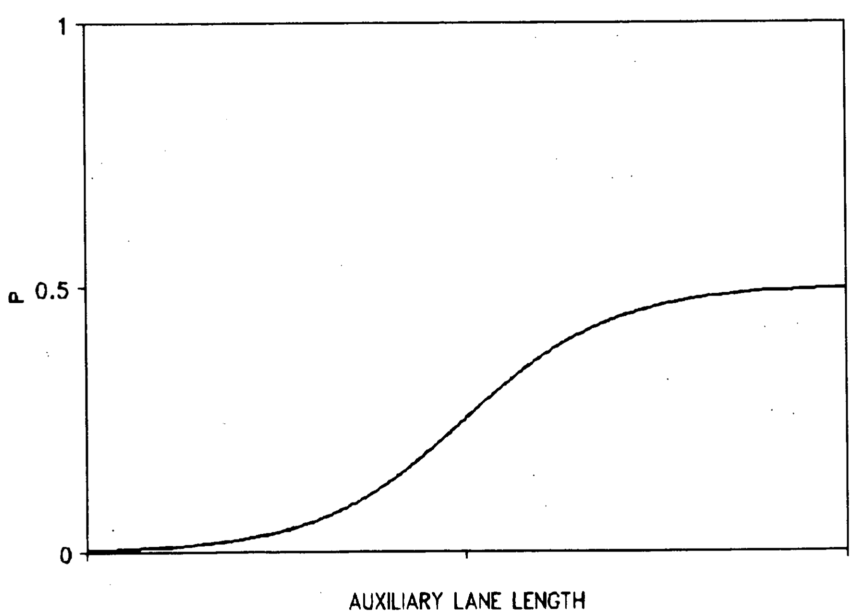

FIGURE 3 Expected auxiliary lane usage.

$$Y = \frac{1}{2} \ln\left(\frac{P_{ideal} + P}{P_{ideal} - P}\right)$$

Describing the dependent variable, Y, in this manner makes it possible to write the following:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_i X_i + \ldots + \beta_k X_k$$

This model form made it possible to perform stepwise multiple regression on data collected in the field beginning with a number of "candidate" independent variables that may or may not influence auxiliary lane choice and ending with a model containing only those variables that do (statistically) influence it. The candidate independent variables considered in the analysis are:

- Peak 15-min flow rate,
- Area size (0 = large cities, 1 = small towns),
- Product of peak 15-min flow rate and area size,
- Percentage trucks,
- Upstream auxiliary lane length,
- Downstream auxiliary lane length,
- Total auxiliary lane length,
- Right turns on at intersection,
- Right turns off at intersection,
- Left turns off at intersection,
- Total right turns on downstream of intersection,
- Total right turns off downstream of intersection,
- Total left turns on downstream of intersection,
- Total left turns off downstream of intersection,
- Right turns on in first 107 m (350 ft) downstream of intersection,
- Right turns off in first 107 m (350 ft) downstream of intersection,
- Left turns on in first 107 m (350 ft) downstream of intersection,
- Left turns off in first 107 m (350 ft) downstream of intersection,
- Right turns on in first 152 m (500 ft) downstream of intersection,
- Right turns off in first 152 m (500 ft) downstream of intersection,
- Left turns on in first 152 m (500 ft) downstream of intersection,
- Left turns off in first 152 m (500 ft) downstream of intersection,
- Right turns on in last 107 m (350 ft) downstream of intersection,
- Right turns off in last 107 m (350 ft) downstream of intersection,
- Left turns on in first 107 m (350 ft) downstream of intersection,
- Left turns off in last 107 m (350 ft) downstream of intersection,
- Right turns on in last 152 m (500 ft) downstream of intersection,
- Right turns off in first 152 m (500 ft) downstream of intersection,
- Left turns on in last 152 m (500 ft) downstream of intersection,
- Left turns off in last 152 m (500 ft) downstream of intersection,
- Right turns on in first 122 m (400 ft) upstream of intersection,
- Right turns off in first 122 m (400 ft) upstream of intersection,
- Left turns on in first 122 m (400 ft) upstream of intersection,
- Left turns off in first 122 m (400 ft) upstream of intersection,
- Right turns on in first 91 m (300 ft) upstream of intersection,
- Right turns off in first 91 m (300 ft) upstream of intersection,
- Left turns on in first 91 m (300 ft) upstream of intersection,
- Left turns off in first 91 m (300 ft) upstream of intersection,
- Total right turns on upstream of intersection,
- Total right turns off upstream of intersection,
- Total left turns on upstream of intersection, and
- Total left turns off upstream of intersection.

DATA COLLECTION

To determine and evaluate the model coefficients, lane use and upstream and downstream turning movement studies were conducted at a number of sites.

Study Sites

It was desired that study data be obtained from five sites. To assess the effect, if any, of urban area size, two sites were to be in small towns. Five sites in western and middle Tennessee were selected for analysis of the study intersection configuration:

1. Southbound US-45 at US-64 (Selmer),
2. Southbound US-43 at SR-50 (Columbia),
3. Westbound Quince at Kirby (Memphis),
4. Eastbound Quince at Kirby (Memphis), and
5. Northbound Kirby at Quince (Memphis).

The data collected at Site 5 were not used in the analysis, primarily because several equipment failures were encountered while attempting to collect data at that site. During this period, mud tracked by vehicles from a nearby upstream construction site obscured the upstream pavement markings to the extent that the beginning of the upstream auxiliary lane could not be seen. It was thought that, since drivers could not ascertain the beginning of the auxiliary lane, measurements of upstream section length (taken before markings were obscured) were meaningless.

Data Collection Techniques

The data required for intersection analysis are of two types: (*a*) an inventory of site geometric and land use data and (*b*) traffic data collected in the field. The inventory data, obtained from drawings or physical measurements (or both) at the sites included

- Length of auxiliary lane on approach to intersection (neglecting taper),
- Length of auxiliary lane downstream of intersection (measured from stop bar to beginning of taper),
- Existence of parking in vicinity of intersection,
- Location of driveways and identification of land use adjacent to the facility, and
- Presence of local bus stops in the intersection area.

Traffic data collection involved volumes, turning movements both at and in the vicinity of the intersection, vehicle mix, and, of course, lane distribution. Data were collected for at least 2 hr at each intersection. At locations with short peak periods, it was necessary to revisit the site to obtain more data under high-volume conditions.

The primary tool for data collection was the video camera with a character generator, an option that displays lapsed time to 1/10 sec. The videotape provides a permanent record of the basic data and contains heavy-vehicle data in addition to basic lane distribution data. With proper camera positioning, intersection turning movements may be recorded as well.

Where applicable, data collection personnel were stationed upstream and downstream of the intersection to record turning movements from and into the traffic stream. Where possible, these data were recorded by hand on data forms. Where there were a relatively large number of driveways or a high rate of driveway activity, the data were recorded verbally onto microcassette tapes. These tapes were also used to record any unusual activity such as cycle failures. Using stopwatches synchronized with the video camera character generator, the end of each 15-min period of the study was announced so that all data collected would be consistent by time.

DATA ANALYSIS

To be consistent with the 1985 HCM procedures, the data collected were analyzed in 15-min segments so as to represent peak 15-min flow rates. For a given site, then, each 2-hr period represented eight data points.

A preliminary screening analysis to assess the candidate independent variables was undertaken before the stepwise regression analyses were performed. This not only sheds light as to which variables might not be of statistical importance, but provides information as to candidate variable interaction. In Figure 4, for example, the variation in choice use of the auxiliary lane is plotted with flow rate. Examination of the data might lead to the conclusion that the data do not appear to follow any particular form. However, when the data are taken in conjunction with their origin, two patterns emerge. One is data on the left side of the figure that come from smaller towns and the other is the data on the right that come from large towns. There are actually two patterns, then, on the same graph, which leads to the suspicion that the product of urban area size (a value of 0 for large cities and 1 for small ones) and flow rate might, when treated as a single variable, significantly affect choice of the auxiliary lane.

Prediction Model

After preliminary screening and the stepwise regression process, the following model was obtained:

$$P = 0.22 + 0.22 \tanh (\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4)$$

where $\beta_0 = -2.36191$, $\beta_1 = 1.391615$, X_1 = (peak 15-min flow rate)/1,000, $\beta_2 = 3.587243$, X_2 = (peak 15-min flow rate × area size)/1,000, $\beta_3 = -0.94191$, X_3 = [right turns off in last 152 m (500 ft) downstream]/100, $\beta_4 = 2.975039$, and X_4 = (downstream length in meters)/1,000.

The 0.22 terms appearing in the model are based on a value of $P_{\text{ideal}} = 0.44$. This value for P_{ideal} was developed from the model for a value of zero right turns off in the last 500 ft downstream, a small town, and the maximum 15-min flow rate measured at any of the intersections studied. It is emphasized that P_{ideal} applies only to *choice* users of the auxiliary lane.

It is desirable that the t-values used in the stepwise regression process be at least 2.0 in magnitude. The interpretation of this is that one would be at least 95 percent confident that that particular coefficient (β) is not 0. The t-value for β_4 was only 1.62. However, since that was the only variable representing either upstream or downstream section length, and since one would still be almost 90 percent confident that β_4 is not 0, it was included in the final model. R^2, the coefficient of multiple determination for this model is 0.80.

Because the model has four independent variables, the degree to which the model follows the data is difficult to understand when plotted in two dimensions. However, by examining Figure 5, the manner in which the model tries to duplicate each data point may be observed to some extent. The means absolute error for choice users of the auxiliary lane was found to be approximately 2.8 percent. It is believed that the model performs reasonably well.

It should be pointed out that the upstream auxiliary lane length did not appear in the equation for choice use of the auxiliary lane.

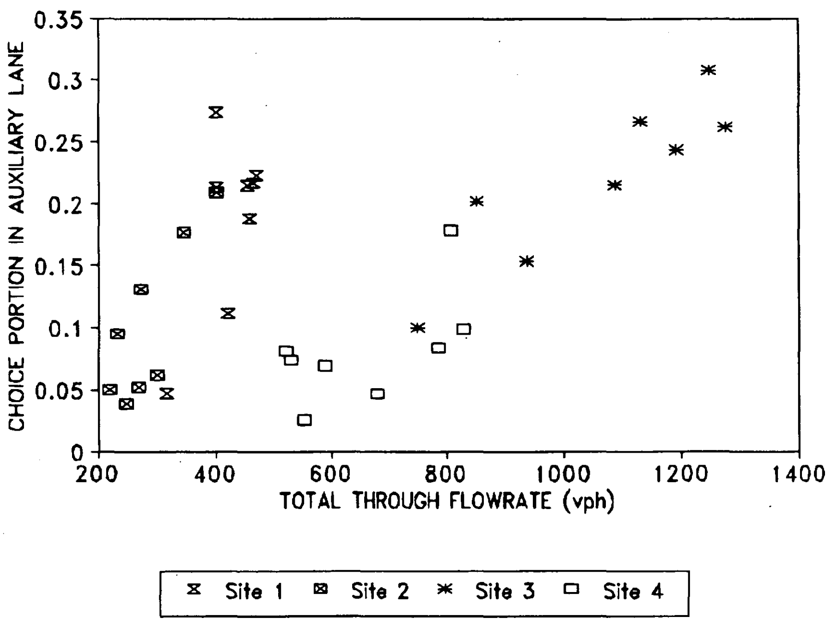

FIGURE 4 Variation of site data with flow rate.

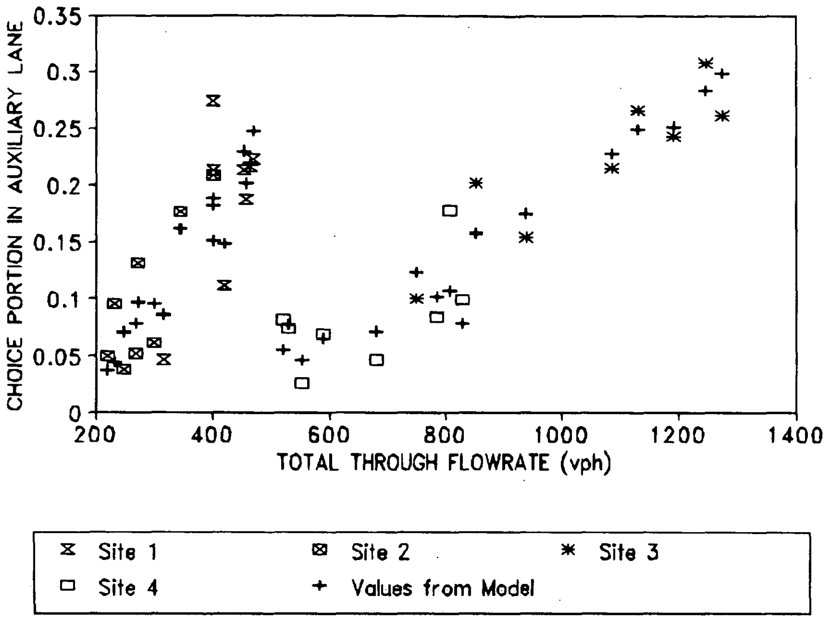

FIGURE 5 Model and site data.

This does not mean that upstream lane length plays no role in lane choice. It is probable that the upstream section lengths at the study sites were long enough that the effects of upstream length could not be ascertained.

Observation

During the data collection portion of this study, the total observed auxiliary lane use varied from 14 to 32 percent of the through traffic movement, which means that 68 to 86 percent of the through traffic (for the data collected) was in the more heavily traveled lane. This value differs markedly from the 52.5 percent used in the HCM for two continuous through lanes. It should not be assumed that the maximum auxiliary lane usage that can be obtained in practice is 32 percent, for it is not. There are a variety of reasons for the values measured, including auxiliary lane lengths too short to achieve greater use.

CONCLUSIONS

A new approach has been used for determining lane utilization—that of choice and captive auxiliary lane users. This concept could be used for intersections without auxiliary lanes as well. The potential increase in accuracy of intersection capacity analyses for these cases is not yet known, although this paper has shown that field measurements involving auxiliary lanes differ greatly from the HCM value for two continuous lanes. Although the lane distribution model developed is based on the behavior of Tennessee drivers only, the approach could be used for developing a similar model on a larger geographical scale—perhaps nationally. The model could also be used in the design process of these intersection configurations by including the effect of downstream auxiliary lane length on intersection operation.

The greatest difficulty in using the model presented is the estimation of driveway turning movements downstream of the intersection. Actual driveway count data at the site being evaluated are obviously superior to anything else, but it is possible that other data sources requiring less effort could be adequate. The ITE *Trip Generation* manual (*8*) is a possible source of data, although no attempt has been made to assess the adequacy of its data for this purpose. Another approach would be to make a reasonable assumption of driveway movements and then assess the sensitivity of the operation on the basis of these estimates with plus and minus deviations from these estimates. To provide some insight as to the magnitude of these turning movements, the turning movement data measured during this study are presented in Table 1. Should an attempt be made to use these data in some manner, it is particularly important to consider the time of day during which the data were collected and the location. For example, trips to and from shopping centers are much greater in the p.m. peak period than in the a.m. peak.

The need for some additional research has already been indicated: a model based on "national" driver behavior, and an assessment of the captive/choice approach for intersections without auxiliary lanes. A lane utilization model is also needed for intersection configurations involving two continuous through lanes and a through auxiliary lane. Finally, if the approach taken herein is of value, some attempt should be made to develop default driveway turning movement data so that excessive effort is not required to use this type of model.

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TABLE 1 Measured Downstream Turns

TOTAL THROUGH FLOWRATE (vph)	RIGHT TURNS OFF (vph)		LEFT TURNS OFF (vph)	
E.B. Quince at Kirby (Memphis) - P.M. Peak				
	Service Station/Convenience Store	Small Shopping Center	Small Office Center (Side Entrance)	Townhouse Driveway
528	8	28	0	4
520	24	48	4	0
552	16	64	0	4
588	16	48	0	4
680	20	56	0	0
784	16	48	0	4
808	16	48	0	4
828	12	72	0	16
W.B. Quince at Kirby (Memphis) - A.M. Peak				
	Service Station/Convenience Store	Small Shopping Center	Multi-Story Office Building	
1088	56	12	36	
1132	56	16	40	
1192	32	24	100	
748	56	44	88	
1764	40	20	56	
1700	28	28	128	
1652	56	40	88	
1360	48	24	48	
S.B. U.S. 43 at SR 50 (Columbia) - Mid Day				
	Fast Food Restaurant/ Small Shopping Center Driveway		Vision Center	Bank
476	32		0	4
436	48		8	8
356	28		12	0
512	52		8	0
372	36		4	0
516	20		8	0
492	20		4	4
524	36		0	0
S.B. U.S. 45 at U.S. 64 (Selmer) - P.M. Peak				
	Service Station/Convenience Store	Fast Food Restaurant	Service Station/Convenience Store	Hardware Store
464	36	16	12	12
400	36	16	32	16
452	24	16	12	8
420	48	16	20	12
468	32	8	36	16
400	28	8	20	8
456	40	16	12	4
316	28	20	4	8

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