Computer Simulation Study of the Operational Effects of Two-Way Left-Turn Lanes on Urban Four-Lane Roadways

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The two-way left-turn lane (TWLTL) is commonly used to solve safety and operational problems on four-lane undivided roadways that result from conflicts between through-traffic and drivers making mid-block left turns. Numerous studies of the safety effects of TWLTL medians have been conducted, but studies of their operational effects have been limited. Consequently, attempts to develop guidelines for the use of the TWLTL have focused on safety benefits and have not adequately accounted for the operational savings it provides. In this study, computer simulation was used to determine the operational effects of TWLTL medians on urban four-lane roadways. Multiple regression analyses of the results of the simulation runs were conducted to determine the relationships between the operational effects of TWLTL medians and prevailing roadway and traffic conditions. Regression equations were developed for predicting the reduction in stops and delay provided by TWLTL medians. This paper includes a description of the simulation model as well as the procedures, findings, and conclusions of the study.

The two-way left-turn lane (TWLTL) is commonly used to solve safety and operational problems on four-lane undivided roadways that result from conflicts between through-traffic and drivers making mid-block left turns. As illustrated in Figure 1, left turns from a four-lane undivided roadway are made from through-traffic lanes, causing through vehicles in these lanes to change lanes or be delayed. But on a roadway with a TWLTL the deceleration and storage of left-turn vehicles are removed from the through-lanes as illustrated in Figure 2. Thus, conflicts between through- and left-turn traffic are eliminated, and through-vehicles can pass by left-turn vehicles without changing lanes and without delay.

Although the potential safety and operational effects of the TWLTL are recognized by highway engineers, there are no generally accepted guidelines that define the circumstances under which the costs of providing TWLTL medians are justified. Numerous before-and-after studies, which provide measures of the safety effectiveness of the TWLTL, have been conducted. However, empirical data pertinent to the assessment of the operational effectiveness of the TWLTL are limited. Therefore, previous attempts to develop guidelines for the use of the TWLTL have focused on the safety benefits and have not adequately accounted for the operational effectiveness of the TWLTL. Consequently, there are no definitive guidelines for the cost-effective use of TWLTL medians.

The overall objective of the research was to develop guidelines for the use of TWLTL medians on urban four-lane roadways that account for the operational as well as the safety effects of these medians. Specific objectives of the research were (1) to evaluate the safety and operational effectiveness of TWLTL medians on urban four-lane roadways, (2) to develop a methodology for evaluating the cost-effectiveness of the TWLTL, and (3) to apply this methodology to develop guidelines for cost-effective use of TWLTL medians on urban four-lane roadways. The methodology and guidelines were developed to enable the identification of sections of urban four-lane undivided roadway on which the costs of installing TWLTL medians would be justified.

Computer simulation was used to determine the effects on the efficiency of traffic operations that result from the installation of TWLTL medians on urban four-lane undivided roadways. The computer simulation study was conducted using the Two-Way Left-Turn Lane Computer Simulation Model (TWLTL-SIM) developed by Ballard and McCoy at the University of Nebraska-Lincoln. This model has been used in several published assessments of TWLTL operations (*1–4*). The results of the computer simulation study were incorporated into the cost-effectiveness methodology developed in this research to compute the operational benefits of TWLTL medians. Presented in this paper are a description of the simulation model and the procedures, findings, and conclusions of the study.

SIMULATION MODEL

The TWLTL-SIM model used in this study is capable of simulating traffic operations on four types of roadways: (1) two-lane undivided roadways, (2) two-lane roadways with TWLTL medians, (3) four-lane undivided roadways, and (4) four-lane roadways with TWLTL medians. The model was written in the General Purpose Simulation System Version H (GPSS/H) Language, which is a special-purpose language particularly suited to modeling discrete systems (*5, 6*). The following discussion presents the input, logic, output, and validation of the model.

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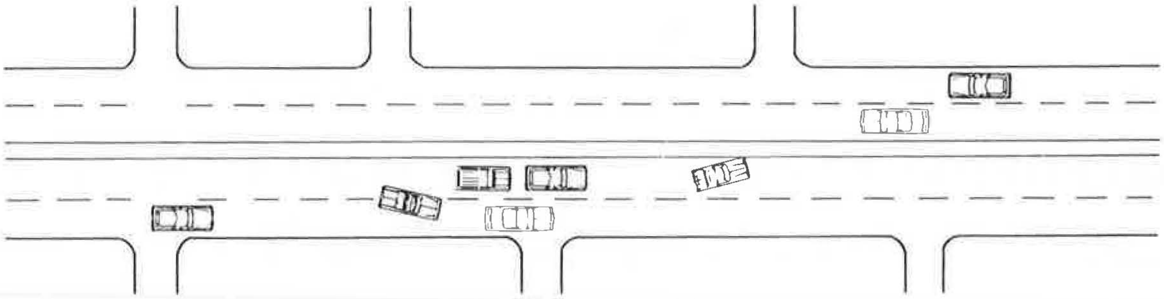

FIGURE 1 Four-lane undivided roadway.

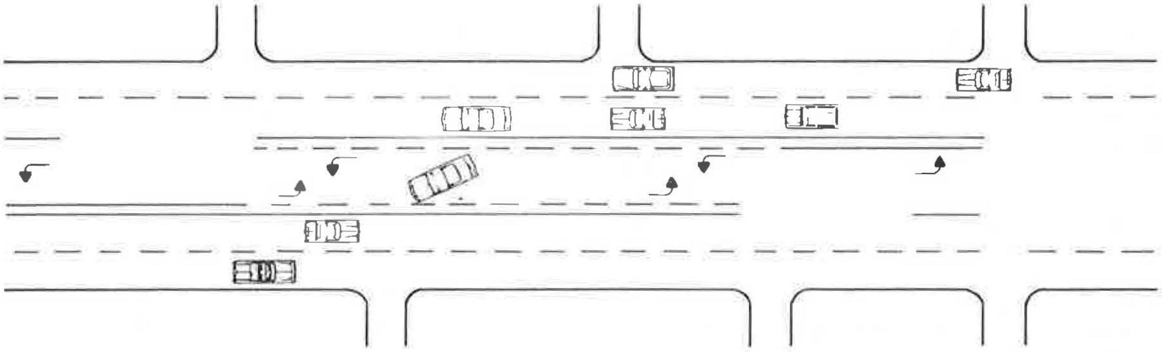

FIGURE 2 Four-lane roadway with TWLTL median.

Input

The input to the model consists of roadway geometrics and traffic characteristics data. These data include the following information:

- number of through-lanes
- presence or absence of a TWLTL
- length of roadway simulated
- locations of individual driveways
- entering traffic volume by lane in each direction, in vehicles per hour (vph)
- arrival distribution of entering traffic
- turning movement percentages at individual driveways
- travel speed in each direction, in miles per hour (mph)
- random number seeds that serve as the basis for the probabilistic generation of entering traffic headways, turning locations, and gap acceptance criteria

The model can generate nonrandom as well as random arrival patterns, so the effects of an upstream traffic signal can be simulated.

Because of the nature of the GPSS/H language, the roadway geometry is defined in terms of sections. Each lane on the roadway is divided into 20-ft. sections. Driveway locations are defined by the numbers of the sections in which they are located. Also, specified for each driveway on a roadway with a TWLTL is the section number of the farthest point upstream at which a vehicle turning left into the driveway can enter the TWLTL. Typically, left-turn vehicles enter the TWLTL at a distance of 200 feet upstream from the driveway into which they turn.

As an example, the geometry of a 1,000-ft. segment of two-lane roadway with a TWLTL is illustrated in Figure 3. Each lane is divided into fifty 2-ft. sections, which are numbered as follows:

- Lane 1: Sections 1–50
- Lane 2: Sections 51–100
- TWLTL: Sections 101–150.

The section numbers of the driveway locations and their corresponding TWLTL entry points that would be input to the model for the roadway in Figure 3 are shown in Table 1. In the case of a 1,000-ft. segment of two-lane undivided roadway, Section Nos. 101–150 would not exist. Therefore, only the section numbers of the driveway locations would be input to the model, because there would be no TWLTL and no TWLTL entry points.

Logic

In the TWLTL-SIM model, traffic enters the simulated roadway segment at either end in accordance with the traffic volumes and arrival patterns specified in the input. Three paths are possible for any vehicle entering at either end of the segment. The vehicle may (1) traverse the entire length of the segment without turning and exit at the far end, (2) traverse a portion of the segment and exit by turning left at one of the driveways, or (3) traverse a portion of the segment and exit by turning right at one of the driveways. On entering the segment, the path to be taken by each vehicle is determined probabilistically in accordance with the turning percentages specified in the input.

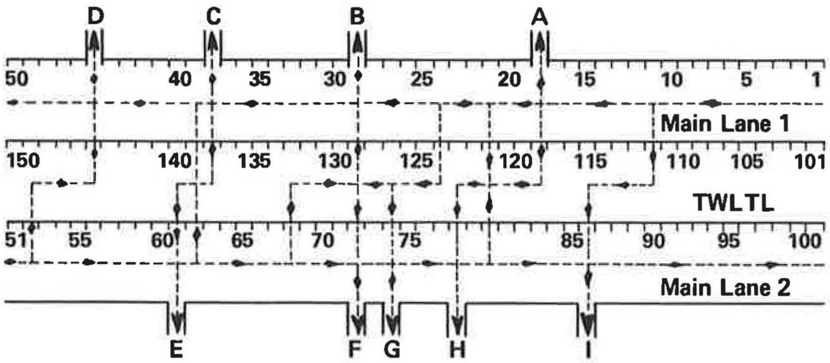

FIGURE 3 Geometry of 1,000-ft. segment of two-lane roadway with TWLTL median.

TABLE 1 SECTION NUMBERS INPUT FOR ROADWAY SEGMENT IN FIGURE 3

Driveway	Driveway Entered From	Location Section No.	TWLTL Entry Point Section No.
A	2	18	121
B	2	29	133
C	2	38	139
D	2	45	149
E	1	61	139
F	1	72	124
G	1	74	124
H	1	78	121
I	1	86	111

In addition to the vehicles entering the roadway segment at either end, some vehicles enter the segment by turning right onto the roadway from a driveway. All of these vehicles traverse the remainder of the segment and exit at the far end. The model does not include the capability to simulate left turns onto the roadway from driveways.

Left turns off the roadway may delay following vehicles or force them to stop if no TWLTL is present; such delay provides a measure of TWLTL effectiveness. The right turns onto and off the simulated roadway have no direct impact on TWLTL effectiveness. However, a right turn off the roadway could create a gap through which an opposing vehicle could turn left, while a right turn onto the roadway could fill such a gap so that it would not be available to opposing left-turn vehicles.

Vehicles move through each 20-ft. section in the main lanes at a constant speed specified in the model input and maintain at least 2-second headway. When a 2-second headway cannot be maintained behind a vehicle slowing or stopping to make a turn, following vehicles will use a uniform deceleration rate of 5 ft/sec^2. Then, when system conditions warrant, vehicles will accelerate at a uniform rate of 5 ft/sec^2 to regain their specified speed. The constant speed assumption means that the entering headway distribution is preserved until modified by the responses to turning vehicles. The assumptions of a constant speed and a constant minimum headway are an oversimplification of driver speed selection and car-following behavior on actual highways. However, these assumptions are justified in this case since the objective of the model is not to estimate the actual travel speed on arterial streets, but rather to simulate the left-turn gap acceptance process and estimate its impact on traffic operations.

In a model run with two through-lanes, one in each direction, vehicles entering in one of the through-lanes continue in that lane until they turn or exit at the other end of the roadway segment. If these vehicles encounter vehicles stopped in the through-lane ahead, they must also slow down and stop if necessary. They are not allowed to pass to the right of the stopped vehicles.

In a model run with four through-lanes, through-vehicles are assigned probabilistically to either the inside or outside lane at the entrance point of the simulated roadway. Through-vehicles that are delayed by turning vehicles on a four-lane roadway may change lanes to avoid delay. Vehicles that intend to turn right from the roadway are assigned to enter in the outside lane and continue in that lane until they reach their designated turning point. A vehicle that intends to turn left enters the segment in the inside lane and remains in the inside lane until it reaches its turning point. If there is no TWLTL, this turning point is the driveway into which it is to turn. If there is a TWLTL, this point is the TWLTL entry point of the driveway into which it is to turn. In the case of a TWLTL, the vehicle begins to decelerate at the TWLTL entry point. When it has slowed to a speed of 10 mph, it enters the TWLTL and moves ahead in the TWLTL until it reaches the driveway into which it is to turn or until it is stopped by vehicles already in the TWLTL waiting to turn left. The model continuously monitors the TWLTL and adjusts the entry point for left-turning vehicles as queues develop in the TWLTL.

If a turning vehicle reaches its entry point to the TWLTL and finds that the TWLTL section is already occupied by a left-turning vehicle from the other direction, it remains in the through lane and moves ahead until it (a) finds an unoccupied section in the TWLTL upstream from the driveway into which it is to turn, (b) reaches the driveway and stops in the through lanes, or (c) aborts the turn. In model runs at high flow rates both with and without a TWLTL, a vehicle will abort its turn and proceed ahead when stopping would cause locked or jammed flow. This capability to abort a turn was added to the model to prevent it from ceasing operation due to jamming under very high flow conditions.

In all situations, a left-turn vehicle must have a minimum acceptable gap in the opposing traffic stream before it can turn left. The required length of gap is determined probabilistically in accordance with the left-turn gap acceptance function derived by Gerlough and Wagner (*7*). The cumulative distribution function is shown in Table 2. The gap acceptance distribution based on Gerlough and Wagner was one of several candidates considered for the model. It produced the closest agreement with the field data collected for model validation.

If the left-turn vehicle is at the head of the queue and the required gap is available, the vehicle turns left. Otherwise it waits for an acceptable gap. However, if a left-turn vehicle is not at the head of the queue, it will follow the preceding left-turn vehicle across the opposing roadway as long as the available gap is longer than a minimum clearance time (1.5 seconds to cross one lane, 2.86 seconds to cross two lanes).

Output

The output from the model includes the following data:

- number of vehicles entering and exiting the segment
- number of left turns attempted and completed
- number of stops
- travel time in the segment
- stopped-time delay
- number of lane changes

The travel time, stops, and delay totals for through-vehicle, left-turning vehicles, and all vehicles are output separately.

TABLE 2 LEFT-TURN GAP ACCEPTANCE FUNCTION (7)

Gap(Seconds)	Probability of Accepting a Shorter Gap
3.0	0.00
3.5	0.15
4.0	0.32
4.5	0.52
5.0	0.69
5.5	0.82
6.0	0.90
6.5	0.95
7.0	0.97
7.5	0.986
8.0	0.993
8.5	0.997
9.0	0.998
9.5	0.999
10.0	1.000

[a] Source: Reference 7.

Validation

Time-lapse film of traffic flow on three roadway sections was taken in order to validate the model. Two sites were located in Omaha, Nebraska, and the third site was located in Lincoln, Nebraska. One of the sites in Omaha was a four-lane undivided section of roadway. The other site in Omaha and the one in Lincoln were four-lane sections with TWLTL medians. A total of 6 hours of film was obtained.

The films were analyzed to determine the volumes, left-turn percentages, travel times, delays, and percentage of vehicles stopping on the roadway sections. The model was then run using the actual traffic volumes, left-turn percentages, and roadway geometrics as input data. The results of the simulation runs were compared with those obtained from the films.

Paired *t*-tests were conducted to compare the mean stopped-time delay and mean percentage of vehicles stopping predicted by the model with those computed from the film analysis. As shown in Table 3, there was no statistically significant difference at the 0.05 level of significance between the predicted and observed means at the four-lane undivided site. Likewise, at the TWLTL sites, there was no statistically significant difference at the 0.05 level of significance between the predicted and observed values of mean stopped-time delay. However, there was a significant difference at the 0.05 level of significance between the predicted and observed values of mean percentage of vehicles stopping at the TWLTL sites, although this difference was not significant at the 0.01 level of significance. Based on a review of the film analysis, it was determined that this difference was attributable to the difficulty of the judgments required of the film analysts to distinguish vehicle stops. Therefore, it was concluded that the model was statistically valid.

In addition to statistical validation, the model has been subjected to considerable face validation. During the past 5 years, the model has been used to simulate traffic operations on several roadway segments with a wide variety of conditions (*1–4*). In each case, the model provided reasonable and consistent results.

PROCEDURE

In order to determine the operational effects of TWLTL medians on urban four-lane roadways, two sets of computer simulation runs were made with the model. One set of runs was made for four-lane undivided roadways without TWLTL medians. The second set of runs was made for four-lane roadways with TWLTL medians. Both sets of runs were made over the same ranges of traffic volumes and driveway densities. The effects of the TWLTL on stops and delay were then determined by pairwise comparisons of the model outputs for the two sets of runs for identical combinations of traffic volumes and driveway densities. Thus, for every combination of traffic volumes and driveway density, the effects

TABLE 3 COMPARISON OF MODEL AND OBSERVED RESULTS

Site	Measure of Effectiveness	Mean Difference (Model-Observed)	Std. Dev. of Difference	t	Significant[a]
Four-lane undivided	Percentage of vehicles stopping	30.33	24.58	2.14	No
	Average stopped delay (veh-min/hr)	1.13	2.17	0.65	No
Five-lane with TWLTL	Percentage of vehicles stopping	28.00	7.0	6.93	Yes[b]
	Average stopped delay (veh-min/hr)	0.17	4.05	0.07	No

[a] Statistical significance at 0.05 level of significance unless otherwise specified.

[b] Statistically significant at the 0.05 level, but not at the 0.01 level of significance.

of the TWLTL on stops and delay were computed as the differences between the respective outputs of the two runs. Multiple regression analyses of the results of the simulation runs were conducted to determine the relationship between the effects of TWLTL medians and prevailing roadway and traffic conditions. As a result of these analyses, regression equations were developed for predicting the reductions in stops and delay provided by TWLTL medians.

Simulation Runs

A series of paired runs were made to simulate traffic operations on a 1,000-ft. section of four-lane roadway while varying the traffic volume, left-turn percentage, and driveway density. Six levels of traffic volume, five levels of left-turn percentage, and three levels of driveway density were used. Simulation runs were made for a total of 54 combinations of those variable levels. The specific combinations that were simulated are shown in table 4. For each combination indicated, a pair of simulation runs were made, one run with a TWLTL and one run without a TWLTL. In each pair of runs, the same random number seeds were used, so that the identical traffic stream was used in each run. Three to five paired runs were made for each combination indicated in table 4. The combinations used in this study were selected based on the results of previous studies (*1, 2*) conducted with the TWLTL-SIM model. The combinations focus on the range of traffic operations that is of most practical interest. Lower volume levels would produce very few stops and little delay; whereas higher volume levels would produce jammed conditions because the capacity of the roadway would be exceeded.

For each driveway density simulated, the driveway locations input to the model were equally spaced driveways staggered on opposite sides of the roadway. Intuitively, the locations of the driveways within the 1,000-ft. section would have an effect on the efficiency of traffic operations. But it was beyond the scope of this study to investigate these differences within driveway density levels. Instead the primary concern of the study was to examine the differences between driveway

TABLE 4 CONDITIONS SIMULATED

Traffic Volume[a] (vph)	Driveway Density[b] (driveways/ mile)	Left-Turn Percentage[c] 2.5%	5%	7.5%	10%	12.5%
100	30			X	X	X
	60			X	X	X
	90			X	X	X
300	30			X	X	X
	60			X	X	X
	90			X	X	X
500	30			X	X	X
	60			X	X	X
	90			X	X	X
650	30			X	X	X
	60			X	X	X
	90			X	X	X
900	30		X	X	X	
	60		X	X	X	
	90		X	X	X	
1,100	30	X	X	X		
	60	X	X	X		
	90	X	X	X		

[a] Traffic volume in each direction.

[b] Total of driveways on both sides of roadway.

[c] Percentage of sum of traffic volumes in both directions.

density levels. Therefore, only the one configuration of driveway locations was used for all levels of driveway density.

The direction split used in making all simulation runs was 50/50. Preliminary runs made using 60/40 splits indicated that more stops and delay resulted using 50/50 splits. More gaps in the lower volume direction of a 60/40 split were available to accommodate the higher left-turn volume from the other direction. Therefore, it was assumed that maximum stops and delay occur with a 50/50 split.

In all simulation runs, a left-turn or right-turn vehicle was equally likely to turn into any of the driveways on the side of the roadway appropriate for the turn. Thus, all driveways had the same turning volumes. Also, all simulation runs were made using 10% right turns into driveways and 10% right turns out of driveways. As noted above, these right-turn maneuvers do not directly impact stops and delay, but they do create gaps for left turns and fill gaps that could otherwise be used for left turns.

The travel speeds used approximated the speed-volume relationships on urban arterial roadways (*8*). A travel speed of 40 mph was used for traffic volumes of 650 vph or less. A travel speed of 35 mph was used for traffic volumes greater than 650 vph.

Each simulation run was initialized by running the model for a few minutes to achieve system stability. Once stability was reached, the model was run for one hour of stimulated time. Traffic operations data were than output for this hour.

Data Analysis

The effects of TWLTL medians on stops and delay were computed for each set of conditions indicated in table 4 from the model output for each pair of simulation runs made for the particular set of conditions. The reductions in stops and delay provided by the TWLTL were computed by subtracting the stops and delay output for the run with the TWLTL from the stops and delay output for the run without the TWLTL. Once

TABLE 5 AVERAGE REDUCTIONS IN STOPS[a]

Traffic Volume[b] (vph)	Driveway Density[c] (driveways/ mile)	Left-Turn Percentage[d]				
		2.5%	5%	7.5%	10%	12.5%
100	30			1	1	0
	60			1	1	3
	90			1	1	2
300	30			14	13	13
	60			3	8	9
	90			3	10	9
500	30			34	51	66
	60			30	41	45
	90			26	42	61
650	30			129	154	182
	60			96	137	167
	90			106	143	139
900	30		588	896	844	
	60		338	449	466	
	90		224	305	482	
1,100	30	971	1,133	933		
	60	849	1,314	1,154		
	90	1,090	1,190	1,035		

[a] Stops per hour.

[b] Traffic volume in each direction.

[c] Total of driveways on both sides of roadway.

[d] Percentage of sum of traffic volumes in both directions.

the reductions in stops and delay had been computed for all the conditions simulated, multiple regression analyses were conducted to determine the relationships between these reductions and the various levels of traffic volume, left-turn percentage, and driveway density.

The Statistical Analysis System (SAS) (9) was used to conduct the multiple linear regression analyses. These analyses were performed using a step-wise procedure with both forward and backward selection at the 0.05 level of significance. The dependent variables used in these analyses were reduction in stops (number per hour) and reduction in delay (seconds per hour). The natural logarithms of these variables were also used as dependent variables. The independent variables considered were traffic volume (vehicles per hour), left-turn volume (vehicles per hour), driveway density (driveways per mile), left-turn volume per driveway (vehicles per hour), and product of traffic volume (vehicles per hour) times left-turn volume (vehicles per hour).

FINDINGS

The average reductions in stops computed for the combinations of traffic volume, left-turn percentage, and driveway density for which simulation runs were made are shown in table 5. In no case did the TWLTL increase stops. Within each level of driveway density, the average reduction in stops increased as traffic volume was increased. Likewise, within each level of driveway density, the average reduction in stops usually increased as left-turn percentage was increased, except at the highest level of traffic volume. The influence of driveway density within each level of traffic volume was not consistent; however, in most cases, the average reduction in stops was highest at 30 driveways per mile. This was because the left-turn volume was apportioned equally among the driveways. Therefore, the left-turn volume per driveway at 30 driveways per mile was two and three times greater than it was at 60 and 90 driveways per mile, respectively. Conse-

TABLE 6 AVERAGE REDUCTIONS IN DELAY[a]

Traffic Volume[b] (vph)	Driveway Density[c] (driveways/ mile)	Left-Turn Percentage[d] 2.5%	5%	7.5%	10%	15%
100	30			3	4	4
	60			3	3	3
	90			2	3	3
300	30			31	44	63
	60			26	37	53
	90			22	32	45
500	30			215	333	518
	60			180	279	434
	90			155	241	374
650	30			723	1,103	1,683
	60			605	924	1,409
	90			522	796	1,215
900	30		8,607	14,037	22,893	
	60		5,277	6,739	8,607	
	90		4,570	5,431	6,455	
1,100	30	34,559	64,454	117,190		
	60	26,290	35,449	47,800		
	90	24,077	29,733	36,718		

[a] Seconds per hour.

[b] Traffic volume in each direction.

[c] Total of driveways on both sides of roadway.

[d] Percentage of sum of traffic volumes in both directions.

TABLE 7 REGRESSION EQUATIONS FOR PREDICTING REDUCTIONS IN STOPS AND DELAY

Traffic Volume[a] (vph)	Reduction	Equation[b]	R^2
<800	stops	$\ell_n S = 0.00579 V_t + 0.0117 V_\ell - 0.00678D$	0.975
	delay	$\ell_n D = 0.00845 V_t + 0.0330 V_\ell - 0.00561D - 0.0000308P$	0.978
≥800	stops	$\ell_n S = 0.00610 V_t + 0.0282 V_d$	0.996
	delay	$\ell_n D = 0.00898 V_t + 0.0652 V_d$	0.996

[a] Traffic volume in each direction.

[b] S = reduction in stops (number per hour per 1,000 ft.)

D = reduction in delay (seconds per hour per 1,000 ft.)

V_t = average traffic volume per direction (vph)

V_ℓ = sum of left-turn volumes in both directions (vph)

V_d = average left-turn volume per driveway (vph per driveway)

D = driveway density (driveways per mile)

$P = V_t \cdot V_\ell$

quently, more queuing of left-turn vehicles would tend to occur at 30 driveways per mile. At 60 and 90 driveways per mile, vehicles waiting to turn left at several driveways would be more likely to turn left through the same gap in the oncoming traffic stream.

The average reductions in delay that were computed from the simulation runs are shown in table 6. In all cases, the TWLTL provided reductions in delay. The pattern of these reductions with respect to traffic volume, left-turn percentage, and driveway density was more consistent than that of the average reductions in stops. The average reductions in delay increased with increases in traffic volume and left-turn percentage, and they decreased with increases in driveway density.

As a result of the regression analyses, two sets of regression equations were developed for predicting the reductions in stops and delay that would result from the installation of a TWLTL on a four-lane undivided roadway. One set of equations was for traffic volumes below 800 vph, and the other set was for traffic volumes of 800 vph or higher. Each set contained two equations. One equation was for predicting the reductions in stops, and the other equation was for predicting the reductions in delay.

The regression equations are shown in table 7. For traffic volumes below 800 vph, the stops and delay reduction equations were exponential functions of traffic volume, left-turn volume, and driveway density and, in cases of delay reduction, the product of traffic volume and left-turn volume. These equations accounted for more than 97% of the variations in the natural logarithms of the reductions in stops and delays.

For traffic volumes of 800 vph or higher, both the stops and delay reduction equations were exponential functions of traffic volume and left-turn volume per driveway. These equations account for more than 99% of the variations in the natural logarithms of the reductions in stops and delay.

The independent variables in all four of these regression equations were statistically significant at the 0.05 level of significance.

CONCLUSIONS

Based on the results of the computer simulation study, it was concluded that (1) as expected, the installation of TWLTL medians on urban four-lane undivided roadways provided reductions in stops and delay over a wide range of traffic volume, left-turn percentage, and driveway density variables; and (2) the magnitudes of these reductions were exponential functions of traffic volume, left-turn volume, and driveway density. It was also concluded that the stops and delay reduction equations presented in table 7 should be used in the cost-effectiveness methodology developed in this research to compute the operational benefits of the TWLTL medians. The cost-effectiveness methodology is presented elsewhere (*10*).

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