curbs are the standard, an asphalt wedge approximately 1 ft long and 2 in. high should be added to the bottom of the ramp if the sidewalk is less than 11 ft wide. Another suggestion is to have sidewalks that slope down (maximum of 1:20) to a 6-in. curb height at the beginning of the ramp.

4. Repavement of streets: Special care should be taken to ensure that the bottom of the curb ramp is not affected when the street is repaved. The city of Charlottesville uses an 8-in. curb (and an asphalt wedge on ramps) so that a 6-in. curb is retained after the street is repaved.

5. Sidewalk slope: Where there is a sidewalk slope to permit drainage from the sidewalk to the curb, the ramp length should be increased to maintain the slope specified in the design. The following equation should be used to calculate the ramp length:

$$L = \{(ECH/RS)/[1 - (SS/RS)]\} + CW \quad (1)$$

where

L = ramp length (ft);
RS = ramp slope;
SS = sidewalk slope;
CW = curb width (ft); and
ECH = effective curb height (ft) = CH - (CW • RS), where CH is the curb height (ft).

CONCLUSION

The guidelines for the design and placement of curb ramps presented in this paper are comprehensive. Curb ramp design dimensions based on sidewalk width and placement relative to obstructions, crosswalks, and types of intersections are addressed.

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Abridgment

Operational Effects of Two-Way Left-Turn Lanes on Two-Way, Four-Lane Streets

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One method of relieving excessive congestion on a two-way street that has a substantial number of midblock left turns is the construction of a two-way left-turn lane (TWLTL). Although the safety effectiveness of the TWLTL has been the subject of many studies, few studies have been made of its operational effectiveness. The objective of this study was to quantify the effects of a TWLTL on the efficiency of traffic flow on a two-way, four-lane street. By using computer simulation models specifically developed and validated for the purpose of this study, traffic operations were simulated over a range of traffic volumes and driveway densities. The reductions in stops and delays that result from a TWLTL were computed from the outputs of these simulation runs. Isograms of stops and delay reductions were prepared to facilitate the use of the results of this study to evaluate the potential cost-effectiveness of TWLTL installations.

The two-way left-turn lane (TWLTL) is recognized as a possible solution to the safety and operational problems on two-way streets that are caused by the conflict between midblock left turns and through traffic. The extent to which a TWLTL can improve the efficiency of traffic operations depends on the traffic volumes and driveway densities involved. Although the principle of the complex relation between these factors and the operational effectiveness is intuitively apparent, it has yet to be quantitatively expressed for two-way, four-lane streets. McCoy, Ballard, and Wiyaya (1) have reported on the operational effectiveness of a TWLTL on two-way, two-lane streets.

An extensive review of the literature and a nationwide survey of experience with the TWLTL were conducted by Nemeth (2) in developing guidelines for the application of the TWLTL; in most cases it was considered to have noticeably improved the quality of traffic flow. Likewise, in developing guidelines for the control of access on arterial streets, Glennon and others (3) reported that empirical data pertinent to the determination of the operational effectiveness of the TWLTL were lacking.

In response to the need of traffic engineers to be able to more precisely predict the operational effectiveness of a TWLTL and more clearly define those circumstances that justify its installation, a series of studies of the operational effects of a TWLTL were conducted at the University of Nebraska-Lincoln. The objective of these studies was to quantify the effects of a TWLTL on the efficiency of traffic flow on a two-way street. The results of the first study, as reported by McCoy, Ballard, and Wiyaya (1), were limited to the study of a TWLTL on two-way, two-lane streets.

A continuation of the previous study led the Transportation Research Group at the University of Nebraska-Lincoln to study the operational effectiveness of a TWLTL on a two-way, four-lane street. The procedure and findings of this study are reported in this paper.

SIMULATION MODELS

The two computer simulation models developed in this study were written in the general purpose simulation system (GPSS/H) language (4,5). These models are basically the same, except that one is for a two-way, four-lane street with a TWLTL and the other is for a two-way, four-lane street without a TWLTL. A brief description of the input, logic, and output of these models follows.

Input

The input to the models consists of two types of information: traffic characteristics and street geometry. The traffic characteristics are the volume and average speed of traffic in each lane in each direction and the percentage of the traffic volume turning left into each driveway on the street. Because of the nature of the GPSS/H language, the street geometry is defined in terms of sections. Each lane on the street is divided lengthwise into 20-ft sections. Driveway locations and TWLTL entry points on the street are defined by the numbers of the sections in which they are located.

Logic

In both models traffic enters the street segment at either end in accordance with the traffic volumes and arrival patterns specified in the input. A vehicle entering the segment in the curb lane will traverse the length of the segment without turning. A vehicle entering the median lane will take one of three courses:

1. It will traverse the entire segment and exit in the median lane at the other end;
2. If the median lane is blocked, it may at some point move to the curb lane (change lanes) and exit at its ends; or
3. It may traverse a portion of the segment and exit by turning left at one of the driveways.

The course taken by each vehicle entering the segment is determined probabilistically in accordance with the lift-turn percentages specified in the input. In the model without the TWLTL, turning vehicles remain in the median lane until they reach the driveway into which they turn. However, in the model with a TWLTL, a turning vehicle enters the TWLTL, if possible, at the point designated in the model input for the driveway. At this point the speed is reduced and the vehicle proceeds until it reaches the driveway into which it turns, or until it is stopped by a vehicle already in the TWLTL. In both models a turning vehicle must have an acceptable gap (determined probabilistically) in the opposing traffic stream before it can turn left.

Output

The output from the models includes 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, and number of lane changes. The travel time, stops, and delay totals are output separately for through vehicles in each lane, turning vehicles, and all vehicles.

PROCEDURE

The operational effects of a TWLTL on a two-way, four-lane street were determined in this study by a pair-wise comparison of the outputs from the two models for identical traffic volumes and driveway densities. The two models were used to simulate traffic operations on a street segment (with and without a TWLTL) under four levels of balanced traffic volume in each direction (350, 700, 1,050, and 1,400 vehicles/hr), three levels of left-turn volume in each direction (35, 70, and 105 vehicles/hr), and three levels of driveway density on both sides of the street (30, 60, and 90 driveways/mile). These values were selected as being comparable to the range of levels of volumes and driveway density that were used by Glennon and others (3) in developing guidelines for control of access on two-way, four-lane arterial streets.

The average running speeds used for each traffic volume level were 35 mph for 350 and 700 vehicles/hr, 30 mph for 1,050 vehicles/hr, and 25 mph for 1,400 vehicles/hr. According to the Highway Capacity Manual (6), these speed-volume relations were reasonable for a two-way, four-lane urban arterial street. Only one configuration of driveway locations--one that had evenly spaced driveways throughout the segment and the same number of driveways on each side of the street--was evaluated for each density level because it was beyond the scope of this study to investigate the differences in traffic operations within driveway density levels.

In conducting the computer simulation experiments with each model, the variability was reduced by using common random numbers so that the same traffic flow and gap acceptance sequence was always used for each driveway configuration. Therefore, for a given combination of traffic and left-turn volume levels, the differences in traffic operations were due only to the effects of the driveway configurations and the TWLTL. Every simulation run was initialized by running the model for a few minutes to achieve system stability. Then the model was run for 1 hr of simulated time.

FINDINGS

The reductions in stops per hour and delay in minutes per hour that result from the installation of a TWLTL on a two-way, four-lane street were computed

Table 1. Reduction in stops by driveway density.

Driveway Density[a] (no./mile)	Traffic Volume[b] (vehicles/hr)	Reduction in Stops (no./hr) by Left-Turn Volume[c]		
		35 vehicles/ hr/1,000 ft	70 vehicles/ hr/1,000 ft	105 vehicles/ hr/1,000 ft
30	350	8	6	24
	700	13	59	87
	1,050	100	78	599
60	350	5	9	24
	700	17	45	105
	1,050	98	237	–[d]
90	350	5	7	26
	700	12	38	114
	1,050	88	271	589

[a] Total number of driveways on both sides of street.
[b] Volume in each direction, including left turns (divided equally in each lane).
[c] Volume in each direction.
[d] Jammed flow in no-TWLTL case.

Table 2. Reduction in delay by driveway density.

Driveway Density[a] (no./mile)	Traffic Volume[b] (vehicles/hr)	Reduction in Delay (min/hr) by Left-Turn Volume[c]		
		35 vehicles/ hr/1,000 ft	70 vehicles/ hr/1,000 ft	105 vehicles/ hr/1,000 ft
30	350	1.5	1.1	2.7
	700	0.8	6.2	8.7
	1,050	8.4	58.6	112.6
60	350	0.2	1.9	5.9
	700	0.8	4.6	23.9
	1,050	6.8	36.3	–[d]
90	350	0.4	0.9	4.1
	700	0.4	3.0	22.2
	1,050	5.8	44.6	142.3

[a] Total number of driveways on both sides of street.
[b] Volume in each direction, including left turns (divided equally in each lane).
[c] Volume in each direction
[d] Jammed flow in no-TWLTL case.

Figure 1. Reductions in stops for 60 driveways/mile.

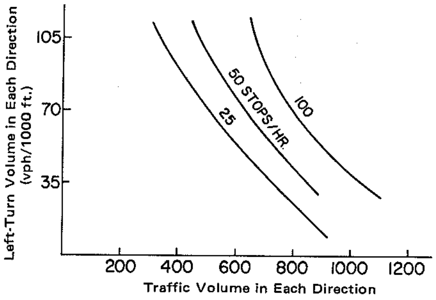
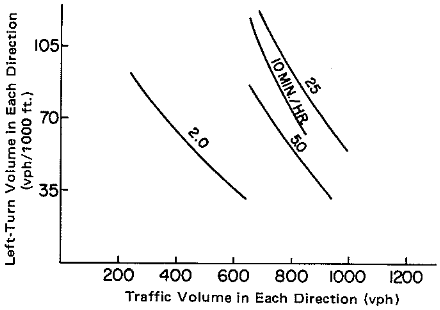


Figure 2. Reductions in delay for 60 driveways/mile.



by a pair-wise comparison of the outputs from the two simulation models. These reductions are given in Tables 1 and 2. The data in these tables reveal that in no case did the TWLTL increase stops and delay, and in every case there were reductions in stops and delay. As expected, the amounts of these reductions increased within each level of driveway density as the traffic volume was increased; in every case but two the amount of these reductions increased within each level of driveway density as the left-turn volumes were increased.

The data in Tables 1 and 2 indicate that the effect of driveway density within each level of traffic volume was not consistent over the range of traffic and left-turn volumes. The lack of a driveway density effect within each left-turning volume is best explained by the fact that the left-turning volume was spread evenly across each driveway; therefore, for the 90 driveways/mile case, approximately one-third less left-turning volume existed at each driveway than in the 30 driveways/mile case. This leads to more queuing at left turns in the 30-driveway case. Also, vehicles waiting to turn left at several driveways will make use of the same gap in the oncoming traffic stream. Hence the effect of driveway density in the amount of reduction in stops and delay is minimized. Similar findings are reported by McCoy, Ballard, and Wiyaya (1) for the two-way, two-lane streets.

The reductions in stops and delay determined in this study provide a basis for evaluating the effectiveness of a TWLTL on a two-way, four-lane street from the standpoint of user costs, energy consumption, and air quality. The reduction values for stops and delay are directly applicable to procedures for evaluating traffic engineering improvements, such as the procedure outlined by Dale (7). Therefore, to facilitate this application of the results of this study, isograms of the reductions in stops and delay were constructed from the data in Tables 1 and 2. The stops-reduction and delay-reduction isograms for 60 driveways/mile are shown in Figures 1 and 2.

CONCLUSIONS

Based on the findings of this study it is concluded that the installation of a TWLTL on a two-way, four-lane street improves the efficiency of traffic operations over a wide range of traffic volumes, left-turn volumes, and driveway densities. Under balanced traffic flow conditions a TWLTL is particularly effective at traffic volumes greater than 700 vehicles/hr in each direction with more than 70 midblock left turns per 1,000 ft from each direction.

The findings of this study are similar to those of a previous study (1) of the operational effects of two-way left-turn lanes on two-way streets. The pattern of reductions in stops and delay were similar; however, the magnitude of the reductions was greater for two-lane roads than for four-lane roads.

The stops- and delay-reduction isograms developed in this study facilitate the quantitative evaluation of the operational effectiveness of a TWLTL under balanced traffic flow conditions on a two-way, four-lane street. When used within the context of a cost-effectiveness analysis, these isograms contribute to the identification of the circumstances under which the installation of a TWLTL on a two-way, four-lane street would be justified.

This study is only a start; the need for further research is obvious. Additional studies need to be conducted for more levels of traffic volume, left-turn volume, and driveway density. Further studies should address unbalanced as well as balanced traffic flow conditions, and the effects of driveway configuration need to be evaluated.

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Functional Analysis of Stopping-Sight-Distance Requirements

TIMOTHY R. NEUMAN, JOHN C. GLENNON, AND JACK E. LEISCH

A basic highway design concept is that the driver should be provided a sufficient visible length of highway to enable collision avoidance. Translating this concept to appropriate standards and criteria is an important design consideration. The concept of safe stopping-sight distance (SSD) as developed by AASHTO is reviewed and discussed. A functional SSD model is offered as a means of demonstrating shortcomings and inconsistencies in AASHTO design policy. In addition, the geometry of SSD is evaluated through the use of sight-distance profiles. Significant conclusions are presented that relate to SSD design values on horizontal curves and special problems with trucks on horizontal curves. The functional SSD model is helpful in understanding accidents at locations that have inadequate SSD.

Stopping-sight distance (SSD) is an important highway design feature. The concept of providing a sufficient length of highway visible to the driver for collision avoidance is basic to the safe design of highways. However, translating this concept to design standards and criteria is not as simple as it may appear.

A critical review of current design practice for SSD is presented in this paper. The concepts and conclusions presented are drawn from a study of SSD conducted for FHWA as a part of a research project entitled, "Effectiveness of Design Criteria for Geometric Elements."

A concept of SSD that focuses on highway operational requirements has been developed. Shortcomings and inconsistencies in AASHTO design policy are revealed by applying this operational SSD concept. Also, by using sight-distance profiles, additional insights are gained on the relation between sight distance and highway safety.

OPERATIONAL AND SAFETY CONCEPT OF SSD

Analysis of the operational and safety aspects of SSD requires an understanding of the concept of SSD as it relates to highway operations. The geometric design policy published by AASHTO discusses the need for SSD (1-3):

> If safety is to be built into highways the designer must provide sight distance of sufficient length in which drivers can control the speed of their vehicles so as to avoid striking an unexpected obstacle on the traveled way....
>
> The minimum sight distance available on a highway should be sufficiently long to enable a vehicle traveling at or near the likely top speed to stop before reaching an object in its path. While greater length is desirable, sight distance at every point along the highway should be at least that required for a below average operator or vehicle to stop.

This short discussion alludes to many of the operational elements of SSD: vehicle performance, driver ability, and the roadway alignment. This AASHTO operational model of SSD provides a reasonable starting point for considering SSD and highway operations.

AASHTO SSD Operational Model

AASHTO defines minimum SSD requirements in terms of a passenger car encountering a stationary object in its path. This basic functional model has not changed since 1940. The following review of the evolution of AASHTO SSD policy illustrates the reasoning behind this model. It also demonstrates the need to go beyond this simple abstraction to gain insight on the safety relations of SSD.

In 1940 AASHO formally recognized the need for a sight-distance requirement to help drivers avoid collision circumstances other than passing encounters. Although AASHO recognized that a clear sight line to the pavement was desirable, analyses of how