15. J.S. Baras, W.S. Levine, A.J. Dorsey, and T.L. Lin. Advanced Filtering and Prediction Software for Urban Traffic Control Systems. U.S. Department of Transportation, Feb. 1981.
16. L. Breiman. Predicting Input Flows. Systems Development Corp., Santa Monica, CA, Tech. Memorandum TM-4638/016/01, Sept. 1971.
17. M.J. Ganslaw. A 5-Minute Volume and Speed Predictor for the UTCS/BPS Second Generation Software. TRW Systems, Houston, TX, Sept. 1975.
18. Sperry Systems Management. Development of Traffic Logic for Optimizing Traffic Flow in an Intercity Corridor. FHWA, April 1, 1976.
19. W.R. McShane, E.B. Lieberman, and R. Goldblatt. Developing a Predictor for Highly Responsive System-Based Traffic Signal Control. TRB, Transportation Research Record 596, 1976, pp. 1-2.
20. E. Lieberman, W.R. McShane, R. Goldblatt, and D. Wicks. Variable Cycle Signal Timing Program: Volume 4--Prediction Algorithms, Software and Hardware Requirements, and Logical Flow Diagrams. KLD Associates, Inc., Huntington, NY, June 1974.
21. J.B. Kreer. Factors Affecting the Relative Performance of Traffic Responsive and Time-of-Day Traffic Signal Control. Transportation Research, Vol. 10, 1976, pp. 75-81.
22. J.B. Kreer. A Comparison of Predictor Algorithms for Computerized Traffic Control Systems. Traffic Engineering, Vol. 45, No. 4, April 1975, pp. 51-56.
23. P.K. Houpt, M. Athans, D.G. Orlahac, and W.J. Mitchell. Traffic Surveillance Data Processing in Urban Freeway Corridors Using Kalman Filter Techniques. Research and Special Projects Administration, U.S. Department of Transportation, Nov. 1978.
24. L.J. Pignataro, W.R. McShane, K.W. Crowley, B. Lee, and T.W. Casey. Traffic Control in Oversaturated Street Networks. NCHRP, Rept. 194, 1978.
25. W.R. McShane and K.W. Crowley. Regularity of Some Detector-Observed Arterial Traffic Volume Characteristics. TRB, Transportation Research Record 596, 1976, pp. 33-37.
26. D. Ghosh and C.H. Knapp. Estimation of Traffic Variables Using a Linear Model of Traffic Flow. Transportation Research, Vol. 12, No. 6, Dec. 1978, pp. 395-402.

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

PATRICK T. McCOY, JOHN L. BALLARD, AND YAHYA H. WIJAYA

The two-way left-turn lane (TWLTL) has been installed on two-way streets under a wide variety of conditions as a solution to the safety and operational problems caused by the conflict between midblock left turns and through traffic. Although the safety effectiveness of the TWLTL has been the subject of many studies, very few studies have been made of its operational effectiveness. Consequently, its effects on the efficiency of traffic flow have not been precisely measured. The objective of this study was to quantify the effects of a TWLTL on the efficiency of traffic flow on a two-way two-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. From the outputs of these simulation runs, the reductions in stops and delays that result from a TWLTL were computed. Isograms of the stop 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 primary function of the TWLTL is to eliminate this conflict by removing the deceleration and storage of vehicles making these turns from the through lanes, thereby enabling through traffic to move past them without delay. However, the extent to which a TWLTL can improve the efficiency of traffic operations depends on the traffic volumes and density of driveways involved. Although the principle of the complex relationship between these factors and the operational effectiveness of the TWLTL is intuitively apparent, it has yet to be quantitatively expressed. Consequently, traffic engineers have not been able to precisely predict the amount of improvement in the efficiency of traffic operations that would result from the installation of a TWLTL.

An extensive review of the literature and nationwide survey of experience with the TWLTL were conducted by Nemeth (1) in developing guidelines for its application. This effort revealed that the TWLTL has been installed under a wide variety of conditions. In most cases, it was considered to have noticeably improved the quality of traffic flow. Numerous before-and-after accident evaluations were found that provided measures of the safety effectiveness of the TWLTL. But similar studies of its effect on the efficiency of the traffic were rare, and measures of the operational effectiveness of the TWLTL were not found.

Likewise, in developing guidelines for the control of access on arterial streets, Glennon and others (2) found that empirical data pertinent to the determination of the operational effectiveness of the TWLTL were lacking. This deficiency precluded the precise estimate of the delay-reduction potential of the TWLTL. And this in turn limited the specificity with which the conditions that warrant installation of a TWLTL could be defined.

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 study of the operational effects of a TWLTL was conducted at the University of Nebraska-Lincoln. The objective of this study was to quantify the effects of a TWLTL on the efficiency of traffic flow on a two-way two-lane street. Two computer simulation models were developed and validated for this study. One of the models was used to simulate traffic operations on a two-way two-lane street with a TWLTL, and the other model was used to simulate traffic operations on a two-way two-lane street without a TWLTL. Traffic operations were simulated with both models over a range of traffic volumes and driveway densities. The outputs of these simulation runs were then compared to determine the reductions in stops and delays that resulted from the TWLTL.

This paper presents the procedure and findings of this study. Also presented is a brief description of the simulation models and their validation, and to facilitate the implementation of the results of the study, isograms of the stop and delay reductions provided by a TWLTL over the range of traffic volumes and driveway densities are included.

SIMULATION MODELS

The two computer simulation models developed in this study were written in the General Purpose Simulation System (GPSS) language (3). These models are basically the same, except that one is for a two-way two-lane street with a TWLTL and the other is for a two-way two-lane street without a TWLTL. A brief description of the input, logic, output, and validation of these models follows.

Input

The input to the models consists of two types of information--traffic characteristics and street geometry. The traffic characteristics input to the models are the volume and average speed of traffic in each direction and the percentage of the traffic volume turning left into each driveway on the street. Also, the arrival pattern of the traffic entering at each end of the street is specified. The models can generate random and nonrandom arrival patterns, so that the effects of traffic signals can be simulated by the models.

Because of the nature of the GPSS language, the street geometry is defined in terms of sections. Each lane on the street is divided lengthwise into 20-ft sections, and driveway locations on the street are defined by the numbers of the sections in which they are located. Also, input for each driveway in the model with the TWLTL is the section number of the farthest point upstream at which a vehicle turning left into the driveway can enter the TWLTL.

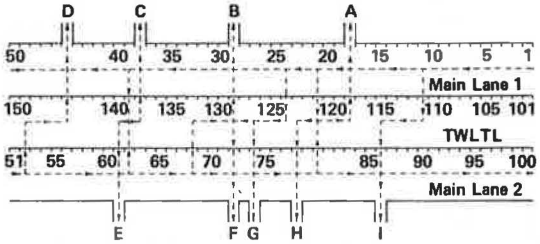
The geometry of a 1000-ft street segment with a TWLTL is illustrated in Figure 1. Each lane is divided into fifty 20-ft sections, which are numbered as follows:

Lane 1: sections 1-50,
Lane 2: sections 51-100, and
TWLTL: sections 101-150.

The section numbers of the driveway locations and their corresponding TWLTL entry points that would be input to the model with the TWLTL are shown below:

Driveway	Lane No. Entered From	Driveway Location Section	TWLTL Entry Point Section
A	2	18	121
B	2	29	133
C	2	38	139
D	2	45	149

Figure 1. Geometry of 1000-ft street segment with TWLTL.



Driveway	Lane No. Entered From	Driveway Location Section	TWLTL Entry Point Section
E	1	61	139
F	1	72	124
G	1	74	124
H	1	78	121
I	1	86	111

In the case of a 1000-ft street segment without a TWLTL, sections 101-150 would not exist. Therefore, only the driveway location section numbers would be input to the model without a TWLTL.

Logic

In both models, traffic enters the street segment at either end in accordance with the traffic volumes and arrival pattern specified in the input. The course of any vehicle entering the segment will be one of two types: (a) traverse the entire length of the segment without turning left and exit at the other end or (b) traverse a portion of the segment and exit by turning left at one of the driveways. On entering the segment, the course taken by each vehicle is determined probabilistically in accordance with the left-turn percentages specified in the input.

Vehicles move through each section in the main lanes at the average speeds specified in the input and maintain at least 2-s headways. Thus, if a vehicle is stopped, the time required for it to traverse the next section is at least 2 s plus the travel time at the average traffic speed. Vehicles traversing the entire street segment remain in the main lanes and do not pass other vehicles in their lanes.

In the model without the TWLTL, turning vehicles also remain in the main lanes until they reach the driveways into which they turn. However, in the model with the TWLTL, a turning vehicle remains in the main lane until it reaches the entry point to the TWLTL, which is designated in the model input for the driveway into which it turns. The vehicle then moves from the main lane to the TWLTL. Once in the TWLTL, a vehicle moves ahead at a speed of 10 mph until it reaches the driveway into which it turns or until it is stopped by vehicles already in the TWLTL waiting to turn left.

If a turning vehicle reaches its entry point to the TWLTL and finds that the section is occupied by a left-turning vehicle from the other direction, it remains in the main lane and moves ahead until it finds an unoccupied section in the TWLTL upstream from the driveway into which it turns or until it reaches the driveway. If it reaches the driveway before it finds an empty section in the TWLTL, it turns left into the driveway from the main lane.

In both models, a turning vehicle must have an acceptable gap in the opposing traffic stream before it can turn left. The required length of the gap is determined probabilistically in accordance with the left-turn gap-acceptance function derived by Gerlough and Wagner (4). If the required gap is available, the vehicle turns left. Otherwise, it waits until one is available. However, in the model without the TWLTL, if this wait exceeds 30 s, the attempt to turn is aborted and the vehicle traverses the entire length of the segment as if it were a through vehicle.

Output

The output from the models includes the following data:

1. Number of vehicles entering and exiting the segment,
2. Number of left turns attempted and completed,
3. Number of stops,
4. Travel time in the segment, and
5. Stopped-time delay.

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

Validation

In order to validate the models, traffic flow on two two-way two-lane street segments (one with and one without a TWLTL) in Lincoln, Nebraska, was filmed. Those films were analyzed to determine the volumes, left-turn percentages, travel times, delays, and stops of the traffic on the two street segments. The traffic volumes, left-turn percentages, and geometries of the segments were then input to the models to simulate the traffic operations on them.

A series of t-tests comparing the simulation and observed mean delay times and number of stops indicated that there were no significant differences ($\alpha = 0.05$) between the simulation and observed mean values. In addition, during the conduct of this study, the models were used to simulate operations on segments that have a wide range of traffic characteristics and driveway densities, and in all cases the models gave consistent and reasonable results.

PROCEDURE

The operational effects of a TWLTL on a two-way two-lane street were determined in this study by a pairwise 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 1000-ft street segment, with and without a TWLTL, under three levels of traffic volume, left-turn volume, and driveway density. Simulation runs were made for all of the 27 possible combinations of these variable levels. The specific values used for these levels are given in Table 1. These values were selected as being comparable with the low, medium, and high levels of volumes and driveway density, which were used by Glennon and others (2) in developing guidelines for control of access on two-way two-lane arterial streets.

The traffic volumes given in Table 1 include left turns. And both the traffic volumes and left-turn volumes given are the volumes in each direction. Thus, the evaluation of the TWLTL in this study was for balanced traffic-flow conditions (i.e., the same traffic flow in each direction).

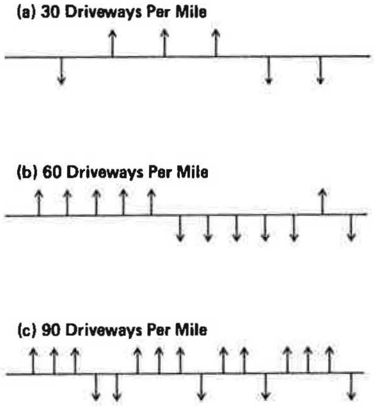
Also, the left-turn volumes are the total number of left turns made into all the driveways on one side of the 1000-ft street segment. In this study, all the driveways on one side of the segment had the same volume of entering left turns. Therefore, for a given left-turn volume, the number of left turns entering each driveway was inversely proportional to the number of driveways.

Table 1. Volume and driveway-density levels studied.

Level	Traffic Volume[a] (vph)	Left-Turn Volume[b] (vph/1000 ft)	Driveway Density[c] (no./mile)
Low	350	35	30
Medium	700	70	60
High	1000	105	90

[a] Volume in each direction, including left turns.
[b] Volume in each direction.
[c] Total number of driveways on both sides of street.

Figure 2. Driveway configurations.



The average running speeds used for each traffic-volume level were 35 mph for 350 vph, 30 mph for 700 vph, and 25 mph for 1000 vph. According to the Highway Capacity Manual (5), this speed-volume relationship was reasonable for a two-way two-lane urban arterial street.

Intuitively, the location of the driveways within the street segment has an effect on the efficiency of traffic operations. However, it was beyond the scope of this study to investigate the differences in traffic operations within driveway density levels. Instead, our primary concern was to examine the differences between driveway density levels. Therefore, only one configuration of driveway locations was evaluated for each density level. In each configuration, the driveways were evenly spaced throughout the segment. However, the side of the street on which each driveway was located was determined at random. The driveway configurations used are shown in Figure 2.

When the computer simulation runs were conducted with each model, the variability was controlled by selecting the random number variates 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. Once stability was achieved, the model was run for 1 h of simulated time. Traffic operations data were collected and output for this hour.

FINDINGS

The reduction in stops and delay that results from the installation of a TWLTL on a two-way two-lane street was computed by a pairwise comparison of the outputs from the two simulation models. The results of these computations were expressed in terms of the number of stops per hour and minutes of delay per hour that were eliminated by the installation of the TWLTL. These reductions are given in Tables 2 and 3. Although these two tables contain the same information, they are arranged differently. The reduction in stops and delay is given within driveway density in Table 2. In Table 3, it is given within traffic volume.

Examination of Table 2 reveals that in no case did the TWLTL increase stops and delay. In only one case, there was no reduction in stops and delay. Also, as expected, the size of this reduction increased within each level of driveway density as the traffic and left-turn volumes were increased. These increases in the reduction were greatest above the 700-vph traffic-volume level with more than 70 left turns per 1000 ft in each direction.

Table 2. Reduction in stops and delay within driveway density.

Driveway Density[a] (no./mile)	Traffic Volume[b] (vph)	Left-Turn Volume (vph/1000 ft)[c]		
		35	70	105
Reduction in Stops (no./h)				
30	350	23	36	45
	700	98	157	290
	1000	186	612	982
60	350	0	14	29
	700	69	189	206
	1000	140	804	1216
90	350	18	27	48
	700	74	206	244
	1000	326	814	1630
Reduction in Delay (min/h)				
30	350	4.1	8.8	11.4
	700	13.7	16.8	43.8
	1000	19.4	44.2	79.8
60	350	0	3.8	9.0
	700	5.3	24.1	30.3
	1000	16.1	75.6	123.6
90	350	1.8	6.5	14.4
	700	6.9	30.2	37.6
	1000	47.3	83.6	271.1

[a] Total number of driveways on both sides of street.
[b] Volume in each direction, including left turns.
[c] Volume in each direction.

Table 3. Reduction in stops and delay within traffic volume.

Traffic Volume[a] (vph)	Driveway Density[b] (no./mile)	Left-Turn Volume (vph/1000 ft)[c]		
		35	70	105
Reduction in Stops (no./h)				
350	30	23	36	45
	60	0	14	29
	90	18	27	48
700	30	98	157	290
	60	69	189	206
	90	74	206	244
1000	30	186	612	982
	60	140	804	1216
	90	326	814	1630
Reduction in Delay (min/h)				
350	30	4.1	8.8	11.4
	60	0	3.8	9.0
	90	1.8	6.5	14.4
700	30	13.7	16.8	43.8
	60	5.3	24.1	30.3
	90	6.9	30.2	37.6
1000	30	19.4	44.2	79.8
	60	16.1	75.6	123.6
	90	47.3	83.6	271.1

[a] Volume in each direction, including left turns.
[b] Total number of driveways on both sides of street.
[c] Volume in each direction.

A review of Table 3 indicates that the effect of driveway density within each level of traffic volume was not consistent over the range of left-turn volumes. The reduction in stops and delay increased with driveway density only at the highest levels of traffic and left-turn volume. At the lower volume levels, these reductions were generally larger at the level of 30 driveways/mile than at 60 driveways/mile. This is probably because the average number of left turns entering each driveway at the level of 30 driveways/mile is twice that at 60 driveways/mile. However, when the driveway density was increased from 60 to 90 driveways/mile, these reductions are increased rather than decreased. One explanation of this apparent contradiction is the fact that unlike the levels of 30 and 60 driveways/mile, 90 driveways/mile did not have the same number of driveways on each side of the street segment. As illustrated in Figure 2, there were 11 driveways on one side and 5 on the other.

Thus, it is apparent that driveway configuration has an effect on the amount of the reduction in stops and delays that can be realized by a TWLTL. Therefore, application of the results of this study should be limited to street segments with driveway configurations that are similar--at least with respect to the number of driveways on each side of the segment--to those shown in Figure 2.

Another factor that should be remembered in using the results of this study is that the simulation model without the TWLTL assumed that the maximum length of time that any driver will wait to turn left was 30 s. Thus, in the model, when this wait exceeds 30 s, the turn was aborted. Although this assumption worked in the validation of the model, it was based on simulation stability requirements rather than on observed driver behavior. Wait limits much greater than 30 s caused the simulation to break down at the highest volume levels. The numbers of aborted left turns experienced in this study are given in Table 4.

The reduction in stops and delay determined in this study provides a basis for evaluating the effectiveness of a TWLTL on a two-way two-lane street from the standpoint of user costs, energy consumption, and air quality. The stops and delay reduction values are directly applicable to procedures for evaluating traffic engineering improvement, such

Table 4. Number of left turns aborted per hour.

Driveway Density[a] (no./mile)	Traffic Volume[b] (vph)	Left-Turn Volume (vph/1000 ft)[c]		
		35	70	105
30	350	5	6	18
	700	6	15	18
	1000	12	26	49
60	350	0	1	3
	700	2	9	11
	1000	9	31	50
90	350	2	6	13
	700	2	11	20
	1000	8	36	96

[a] Total number of driveways on both sides of street.
[b] Volume in each direction, including left turns.
[c] Volume in each direction.

Figure 3. Reduction in stops: 30 driveways/mile.

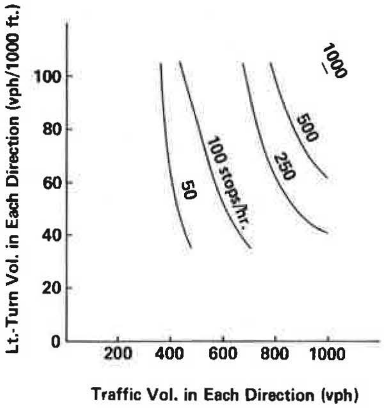


Figure 4. Reduction in stops: 60 driveways/mile.

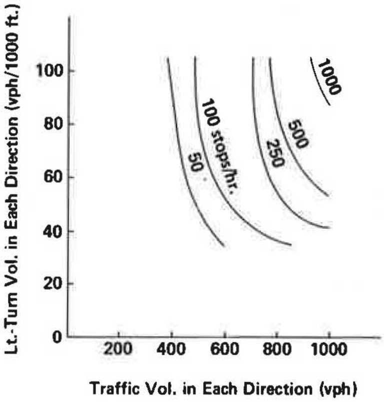


Figure 5. Reduction in stops: 90 driveways/mile.

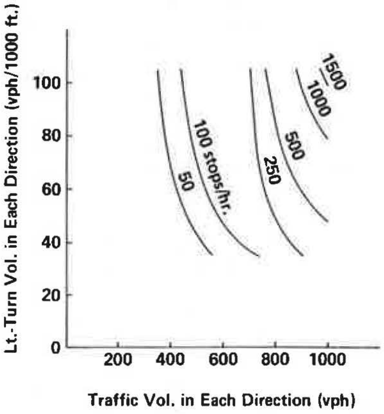


Figure 6. Reduction in delay: 30 driveways/mile.

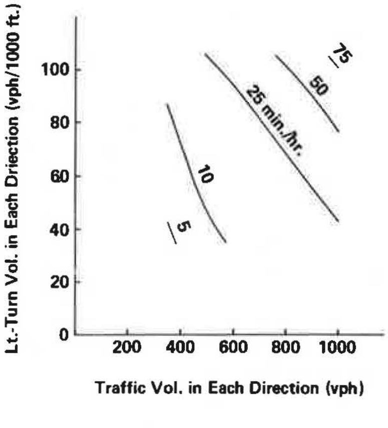


Figure 7. Reduction in delay: 60 driveways/mile.

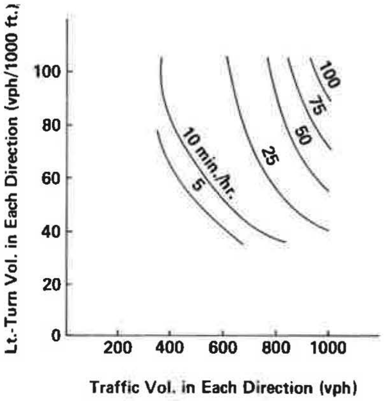
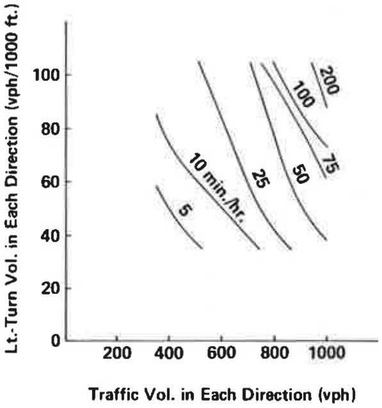


Figure 8. Reduction in delay: 90 driveways/mile.



as the procedure outlined by Dale (6). Therefore, to facilitate this application of the results of this study, isograms of the reduction in stops and delay were constructed from the data in Table 2. The stop-reduction isograms for the three levels of driveway density are shown in Figures 3, 4, and 5, and the delay-reduction isograms are shown in Figures 6, 7, and 8.

CONCLUSIONS

Based on the findings of this study, it was concluded that the installation of a TWLTL on a two-way two-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, it is particularly effective at traffic volumes above 700 vph in each direction with more than 70 midblock left turns per 1000 ft from each direction.

The stop and delay reduction isograms that were developed in this study facilitate the quantitative evaluation of the operational effectiveness of a TWLTL under balanced traffic-flow conditions on a two-way two-lane street. 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 two-lane street would be justified.

However, this study is just 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. Future studies should address unbalanced as well as balanced traffic-flow conditions, and the effects of driveway configuration need to be evaluated. Of course, similar research needs to be conducted to evaluate the operational effects of a TWLTL on two-way four-lane streets.

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REFERENCES

1. Z.A. Nemeth. Development of Guidelines for the Application of Continuous Two-Way Left-Turn Median Lanes. Engineering Experiment Station, Ohio State Univ., Columbus, Final Rept. EES 470, July 1976.
2. J.C. Glennon, J.J. Valenta, B.A. Thorson, and J.A. Azzeh. Technical Guidelines for the Control of Direct Access to Arterial Highways--Volumes 1 and 2. FHWA, Repts. FHWA-RD-76-86 and FHWA-RD-76-87, Aug. 1975.
3. T.J. Schriber. Simulation Using GPSS. Wiley, New York, 1974.
4. D.L. Gerlough and F.A. Wagner. Improved Criteria for Traffic Signals at Individual Intersections. NCHRP, Rept. 32, 1967.
5. Highway Capacity Manual. HRB, Special Rept. 87, 1965.
6. C.W. Dale. Procedure for Evaluating Traffic Engineering Improvements. ITE Journal, April 1981, pp. 39-46.

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Effects of Trucks on Freeway Vehicle Headways Under Off-Peak Flow Conditions

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The results of a study to determine the effects of the presence of heavy trucks on traffic flow in sections of freeway as an operational measure of total throughput capacity are presented. The variable used to evaluate truck impacts was time headway. Data were collected at two sites on the Houston, Texas, freeway system during off-peak flow conditions. After each observed headway had been classified as to types of vehicles involved in the interaction, various statistical tests were performed to analyze variations in headway due to headway type, lane width, and traffic volume. Headway type (i.e., the types of vehicles involved in the headway interaction) was shown to be the major determinant in length of the headway; those that involved trucks exhibited the greatest magnitude.

In recent years the construction of new highway facilities has not kept pace with the expansion of vehicular travel. In urban areas in particular, concern with measures to increase the efficiency of traffic operations has aroused increasing interest as the emphasis has shifted toward making the existing system work as well as it can. The diverse mixture of vehicle sizes, weights, and operating characteristics has become a potential limiting factor in trying to attain maximum efficiency and minimum accident experience from the highway system.

Of approximately 145 million motor vehicles in operation in this country today, nearly 7 million are trucks with empty gross vehicle weights of 10 000 lb or more. When these trucks are involved in accidents with the passenger cars in the traffic stream, the results can be startling. Although heavy trucks comprise less than 2 percent of the vehicle population, they were involved in accidents that accounted for almost 9 percent of all traffic fatalities in 1976. Of these, 91 percent were persons in other vehicles that conflicted with the trucks (1).

The problem is further complicated by an increasing polarization of the vehicle mix into very small cars and very large trucks. The trend toward smaller, more efficient passenger cars is undeniable. In 1963, automobiles made up 84.3 percent of the total vehicle fleet and included about 8 percent automobiles with registered vehicle weights of 3000 lb or less (2). By 1978, automobiles were down to 79 percent of the vehicle total but the small-car portion had risen to 22 percent. By 1990, the proportion of automobiles is expected to be 75 percent while more than 50 percent of those will have registered weights of less than 3000 lb (3). Unfortunately, the quest for more economical personal transportation vehicles has been pursued through methods that reduce the survivability of the passengers in an accident, since the smaller passenger cars generally are characterized by reduced track width, higher center of gravity, reduced horsepower, reduced weight, reduced structural integrity, and lower driver eye height.

Spurred by both demand for more fuel-efficient vehicles due to rapidly rising gasoline prices and mandatory standards set in the Energy Policy and Conservation Act of 1975, gains in mileage per gallon have been attained primarily by lowering horsepower and increasing ratios of weight to horsepower. These changes have tended to reduce acceleration rates and therefore the vehicle performance capabilities (3). A study by Woods and others (4) showed that although smaller vehicles accelerated adequately at low speeds, their acceleration capability at highway speed was substantially lower than that of full-size cars. Indeed, at 50 mph, more than 200 additional ft were required for the 85th-percentile small cars to pass another automobile. A recent study by the Institute for Highway Safety (5) showed relative injury rates on a normalized experience basis by make and model of automobile. The best vehicles from the standpoint of protecting occupants were full-size cars, and the worst were subcompacts or smaller. For example, drivers of a Honda Civic are three times as likely to be killed