provide a basis for more flexible and cost-effective design policies.

We are gratified that the comments by Mulinazzi echo this need for flexibility in roadside design. The results of this study indicate that improvements in roadside design can be cost effective, but unfortunately we are a long way from achieving the goal of maximum cost-effectiveness through flexible design.

REFERENCES

1. J.L. Graham and D.W. Harwood. Effectiveness of Clear Recovery Zones. NCHRP, Rept. 247, 1982, 68 pp.
2. F.M. Council and others. Accident Research Manual. FHWA, Rept. FHWA/RD-80/016, Feb. 1980, 144 pp.
3. SAS Users' Guide. SAS Institute, Cary, N.C., 1979, 494 pp.
4. B. Ostle. Statistics in Research, 2nd ed. Iowa State Univ. Press, Ames, 1963, 585 pp.
5. S.A. Smith and others. Identification, Quantification, and Structuring of Two-Lane Rural Highway Safety Problems and Solutions, Final Report. FHWA, Oct. 1981.
6. J.C. Glennon. Roadside Safety Improvement Programs on Freeways--A Cost-Effectiveness Priority Approach. NCHRP, Rept. 148, 1974, 64 pp.
7. O.K. Dart and L.S. McKenzie. Study of Ran-off-Roadway Fatal Accidents in Louisiana. TRB, Transportation Research Record 847, 1982, pp. 7-14.
8. P.H. Wright and P. Zador. Study of Fatal Rollover Crashes in Georgia. TRB, Transportation Research Record 819, 1981, pp. 8-17.
9. J.C. Glennon and C.J. Wilton. Effectiveness of Roadside Safety Improvements. FHWA, Rept. FHWA-RD-75-23, Nov. 1978, 67 pp.
10. A Manual on User Benefit Analysis of Highway and Bus-Transit Improvements. AASHTO, Washington, D.C., 1977.
11. A. Kimboko and L. Henion. Critical Evaluation of AASHTO's Manual on User Benefits of Highway and Bus-Transit Improvements. TRB, Transportation Research Record 826, 1981, pp. 22-28.
12. R.R. Blackburn and others. Effectiveness of Alternative Skid Reduction Measures--Volume 1: Evaluation of Accident Rate-Skid Number Relationships. FHWA, Rept. FHWA-RD-79-22, Nov. 1978, 241 pp.

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Abridgment

Comparing Operational Effects of Continuous Two-Way Left-Turn Lanes

DAVID P. McCORMICK AND EUGENE M. WILSON

In this paper the operational effects of continuous two-way left-turn lanes (TWLTLs) were compared with four-lane sections and five-lane Z-turn-pattern sections. Both three-lane and five-lane TWLTL sections were examined. These comparisons were made in order to determine under which circumstances a particular alternative will produce the best results from the standpoint of movement efficiency and safety. The following variables were monitored and evaluated in this study: traffic counts, speed surveys, lateral placement, conflicts, accident histories, site accesses, turning movements, day or night operations, and dry or wet pavement conditions. The TWLTL treatments were effective under a variety of turning and main line volumes. Statistically, lower mean conflict rates were observed for the five-lane TWLTL when compared with either the four-lane or Z-pattern treatments. Three-lane TWLTLs were superior to four-lane segments under more selective circumstances.

One of the consequences of locating retail establishments outside the confines of a central business district (CBD) has been the advent of strip commercial areas. These areas rely on the linear high densities provided by traffic on arterial systems as a substitute to the CBD, while catering to the public's desire for drive-up convenience. Although such areas have been successful for some retail establishments, the transportation implications of strip commercial zones create one of the toughest design problems for the transportation engineer.

In developed strip commercial areas, continuous two-way left-turn lanes (TWLTLs) have been used as a possible arterial improvement. In this paper the operational effects of TWLTLs were compared with four-lane sections and five-lane Z-turn-pattern sections. This comparison was made in order to determine under what circumstances a particular alternative will produce the best results from the standpoint of movement efficiency and safety.

LITERATURE REVIEW

A literature search revealed several aspects about TWLTL operations. Glennon and others (1) suggested that the use of a TWLTL is warranted when the average daily traffic (ADT) volumes are between 10,000 and 20,000. This range is typical of the operating conditions found in the literature. In many cases the volume data were not broken down further than ADT. The appeal of using peak-hour data was alluded to by Cribbins and others (2): "Findings of this investigation indicate that median openings, per se, are not necessarily accident prone under conditions of low volumes, wide medians, and light roadside development; however, as volumes increase and development increases commensurately, the frequency of median openings does have a significant effect on accident potential." Following this logic, the proper condition for monitoring problems in median control is under high-volume, peak-hour use.

Left turns from median openings account for the largest proportion of driveway accidents. Of the left-turn accidents, rear-end occurrences are the

most numerous. Studies indicate that about 42 percent of all median opening accidents were accountable to left turns, 19 percent to right turns from the street, and 39 percent while exiting the driveway (2). Utkotter (3) indicated that left-turn movements were involved in 71 percent of personal injury driveway accidents. Left-turn accidents in a strip commercial setting are significantly more severe than other types of driveway accidents.

The majority of all studies on TWLTLs have focused on accident rates. Many reports indicated that TWLTLs reduce accidents where no previous turn lane existed (1,4-6). Accident reductions up to 62 percent were reported.

Relatively few researchers chose to apply conflict analysis to their study sites. Of those that did, the following conclusions were reached. Nemeth (4) participated in three before-and-after studies--two studies on two lanes that were restriped in order to accommodate three lanes, and one study on a four-lane section that was expanded to five lanes. His studies indicated that, at one site, the conflicts were reduced significantly by the use of the TWLTL. Walton and others (5) observed conflicts and indicated no significant variation in conflicts by type of design.

It has been suggested that TWLTLs be used only where conventional raised or flush medians are not practical. The warrant developed by Glennon and others (1) stated that "the level of development should exceed 60 driveways per mile, with less than 10 high volume driveways." Staggered accesses have been indicated as being particularly well suited for TWLTLs.

When a four-lane roadway section has been changed to a five-lane TWLTL, main line delay on high-volume, high-access-density facilities has decreased. Nemeth (4) indicated that when a four-lane section was retrofitted with a three-lane roadway section with a TWLTL, an increase in delay occurred because of the reduction in the number of lanes. He concluded that, "It appears that the access function of this roadway was improved at the price of measurable deterioration of the movement function." Volume appeared to be the key variable when retrofitting a four-lane roadway with a three-lane TWLTL because Jomini (7) reported that, on a facility with a lesser traffic volume, no significant increase in delay and no substantial reduction in accidents occurred.

It is apparent from the literature that, although much has been learned about TWLTLs, there are a number of gaps in the knowledge of the operational characteristics of these facilities. Some of the most obvious are (a) lack of understanding of the effects of nighttime conditions on operations, (b) absence of a study on adverse weather effects on TWLTL operations, and (c) comprehensive comparison of TWLTLs with other types of median treatments.

COMPARISON OF ALTERNATIVE GEOMETRIC DESIGNS

A conflict analysis was used in order to evaluate the operational differences of various geometric designs. Although the traffic conflicts technique did not correlate well with many types of accidents (r^2 between 0.21 and 0.70), it appears to have a strong relation to left-turn accidents. Glave and Migletz (8) stated that, "In particular, accidents involving cross traffic and opposing left turns may be correlated to traffic conflicts of an analogous nature." One definition of a traffic conflict is, "An event involving two or more road users, in which one user performs some atypical or unusual action, such as a change in direction or speed that places another user in jeopardy of a collision unless an evasive maneuver is undertaken" (8).

An important aspect to note is that unless two road users are present a conflict cannot occur. Also, an unusual action must occur. For example, stopping at a stop sign does not qualify as a conflict. When an unusual action takes place that does not place another vehicle in jeopardy, it is categorized as a potential conflict. Potential conflicts were included for improper driving maneuvers only. Twelve different traffic conflicts were observed in this study.

Seven study sites were selected--three with five-lane TWLTLs, two with Z-pattern left-turn lanes, one with a three-lane TWLTL, and a four-lane road that does not have a turn lane (see Figure 1). Volumes ranged from 750 to 2,200 vehicles/hr, and speed limits were from 30 to 40 mph. Section widths on the four- and five-lane sections were from 50 to 68 ft, and the three-lane section was 46 ft wide. Turn lanes varied from 10 to 14 ft, and access density ranged from 27 to 165/mile.

Analysis of data from 58 hr of observations was performed in order to isolate specific aspects of driver behavior by type of facility. Visual studies of the data served as the original step in the analysis of these observations. The first step in this visual analysis was to plot conflicts by site under a number of different groupings: percentage of left turns, vehicles per hour, day or night operations, wet or dry conditions, and accesses per mile.

Figure 2 shows that a tight linear grouping exists in the data points when broken down by type of median treatment. These data suggest a linear relation between conflicts and percentage of left turns, as well as a difference in conflicts by treatment type.

Conflicts were then broken down by type. The most prevalent conflict was the rear-end conflict for all treatments, except the three-lane TWLTL section. This conflict reflects the ability of each

Figure 1. Lane geometry.

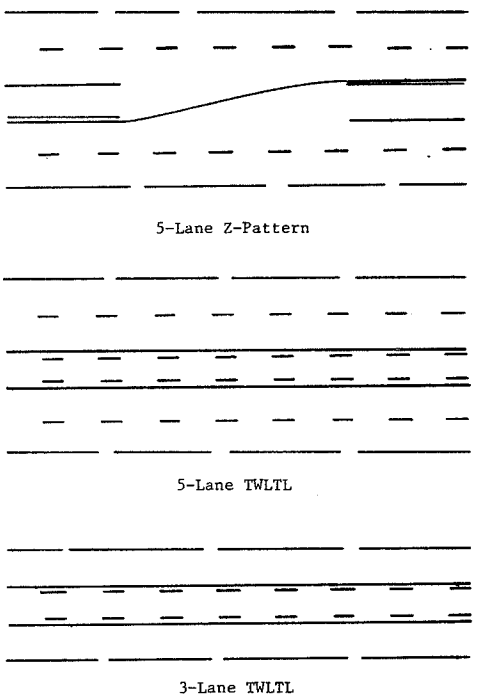

Figure 2. Conflicts versus lane geometry and percentage of left turns.

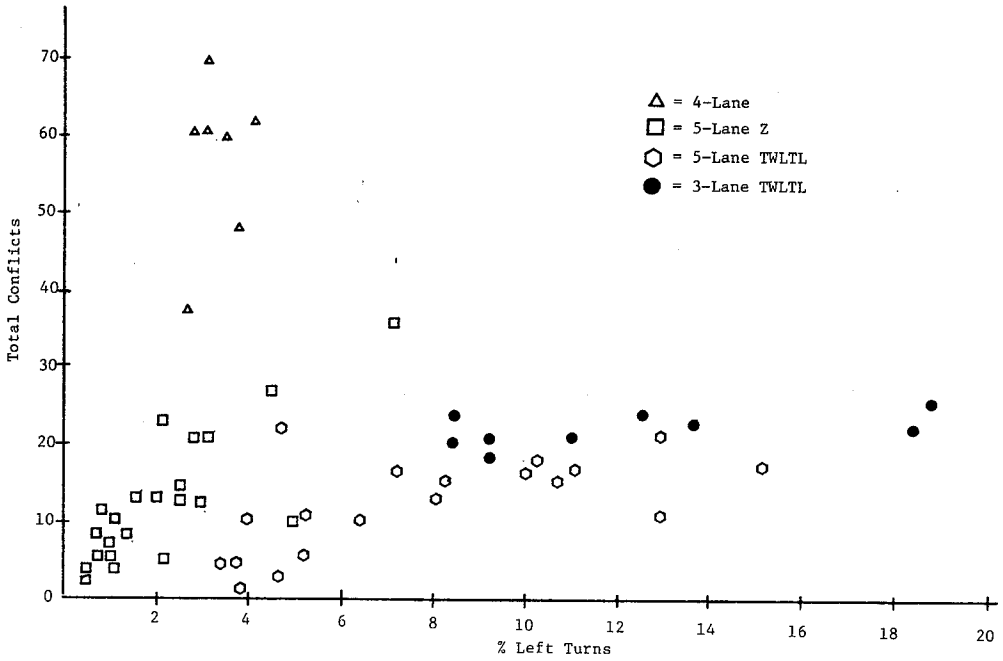

Figure 3. Conflict occurrence by type of median treatment.

	CONFLICT OCCURRENCE BY TYPE (% OBSERVED)												
	1	2	3	4	5	6	7	8	9	10	11	12	
5-Lane TWLTL	0.8	0.4	3.9	0.8	0.0	18.4	41.0	3.3	2.5	0.0	29.9	0.0	100
3-Lane TWLTL	0.0	1.6	2.2	0.0	0.0	6.9	16.5	8.0	4.3	12.8	0.0	47.9	100
Z-Pattern	1.9	0.0	0.8	1.9	3.8	3.4	61.8	0.0	7.2	0.0	19.1	0.0	100
4-Lane	0.2	0.0	3.7	7.2	0.0	0.0	83.6	0.0	0.0	0.0	5.2	0.0	100
Total Observations	7	4	30	40	10	66	678	23	33	24	151	90	1156

treatment to remove vehicles from the travel lane when needed. The data in Figure 3 indicate that the three-lane section had the lowest percentage of rear-end conflicts, followed by the five-lane TWLTL, the Z-patterns, and finally the four-lane section. The Z-pattern has only limited value in separating turning traffic from the through lane in strip commercial areas because of midblock turns. The high percentage of rear-end conflicts on the five-lane TWLTL section suggests that, even with the turn lane, a large number of vehicles do not make use of it when performing a turn. Also note the high percentage of conflicts from passing in the turn lane (48 percent) in the three-lane section. This is the result of right-turning vehicles blocking the through lane and, consequently, traffic moving around it. This misuse of the TWLTL does not occur in the five-lane section because of the additional lane.

Statistical procedures were used to augment, analyze, and prove this visual inspection, as well as to probe other hypotheses intuitive to engineering experience. Analysis of variance and covariance were the statistical tools used. Conflict data were normalized to reflect 300-ft study sites (except for conflict data) compared to the percentage of left turns, which were already normalized.

It was discussed previously that the seven sites were investigated jointly by median type. The assumption was that the locations that use the same treatment behaved similarly under the same conditions and could be treated as a homogenous group for analysis. By using analysis of variance at the 0.05 level, this hypothesis could not be rejected, which

Table 1. Statistical summary.

Null Hypothesis	Statistical Test	Test Results
Mean conflict rates equal for similar TWLTL	F	$F = 2.112 < F_{1,20,0.05} = 4.35$ Cannot reject Ho
Mean conflict rates equal for Z-patterns	F	$F = 0.00 < F_{1,12,0.05} = 4.75$ Cannot reject Ho
Mean conflict rate equal between median treatments	F	$F = 90.72 > F_{3,54,0.05} = 2.80$ Reject Ho
Mean conflict rate equal between median treatments (adjusted for vehicles per hour and percentage of turns)	F	$F = 51.35 < F_{3,52,0.05} = 2.80$ Reject Ho
Mean conflict rates equal over all observed volumes (adjusted for percentage of turns)	F	$F = 16.119 > F_{4,52,0.05} = 2.57$ Reject Ho
Mean conflict rates equal over all percentages of turns observed (adjusted for vehicles per hour)	F	$F = 7.30 > F_{2,54,0.05} = 3.19$ Reject Ho
Mean conflict rates equal for day and night operation (adjusted for vehicles per hour and percentage of turns)	F	$F = 0.649 < F_{1,54,0.05} = 4.04$ Cannot reject Ho
Mean conflict rates equal for snowpack and clear conditions (adjusted for vehicles per hour and percentage of turns)	F	$F = 0.204 < F_{1,54,0.05} = 4.04$ Cannot reject Ho

indicated that the data may be analyzed by median treatment and not strictly by study site.

Scheffe pairwise comparisons were performed at the 0.05 level on all four treatment means, and it was revealed that each mean was contained in a different subset. A summary of these statistical test results is given in Table 1. The analysis was refined further by using analysis of covariance to factor out the effects of volume and percentage of left turns. The results also indicated a significant difference in conflict rates between sites. The adjusted mean conflict rates were highest for the four-lane section (22.1) and the three-lane TWLTL (17.6), and the Z-pattern and five-lane conflict rates were 9.1 and 4.8, respectively. Although the three-lane TWLTL conflict rate is high, it is a treatment often used to improve Z-lane streets to reduce the left-turn problem. The three-lane section conflict rate is less than the four-lane section, which suggests that the three-lane section may be superior when a high-volume, high-turn rate situation arises and width is not available to restripe to five lanes.

Other hypotheses were applied to test for differences in conflict rate due to volume, access density, percentage of left turns, day or night operation, and adverse weather conditions. It was found that as the volume increased the mean conflict rate increased. The data suggest a relation between conflicts and volume that is similar to the relation between volume and accident rates. As the percentage of turns increased, the conflict rate also increased. The type of treatment was not isolated in this analysis.

Because of large numbers of vehicles that do not use the turn lane and because of the generally adverse conditions while snowpack conditions were present, it was expected that an increase in conflicts would occur; this was not the case. The hypothesis that mean conflict rates are equal for snowpack and clear conditions was not rejected. It can only be reasoned that the poor driving conditions were offset by increased driver awareness.

The comparison of day and night operation with the hypothesis that mean conflict rates are equal for day and night operation also could not be rejected. This may be partly explained by the generally excellent lighting found along the study sites and along strip commercial areas in general.

SUMMARY AND CONCLUSIONS

The provision of a safe, efficient means of accessing strip commercial areas (or other locations that have a high density of unsignalized intersections and accesses) is a challenge to the transportation engineer. Left turns have the potential to significantly increase delay, reduce capacity, and increase accident rates. With this in mind, the continuous TWLTL was observed and compared to two other common treatments: the five-lane Z-turn pattern and the four-lane section that does not have turn lanes. Seven study locations were evaluated by conflict analysis, speed surveys, lateral placement, turning movements, and other techniques. Statistical techniques were used to evaluate conflicts with respect to median treatment, day or night operation, and snowpack or clear condition.

The results of this research indicate that a properly installed TWLTL functioned efficiently on urban arterial streets with high roadside development. The following specific conclusions have been reached during the course of this investigation.

1. The TWLTL had a substantially lower mean conflict rate than either the four-lane or Z-pattern treatment. Conflicts were one-fifth those obtained on the four-lane treatment and nearly one-half those on the Z-pattern treatment.
2. The five-lane TWLTL lowered conflict rates over a wide range of volumes, speeds, and turning frequencies. The results of this study suggest that TWLTLs are warranted under much lower turning frequencies and volumes than previously had been suggested. However, under low opposing volumes (<400 vehicles/hr), TWLTLs will probably be ignored by a large number of drivers. The advantage of spatial separation should not be overlooked.
3. The TWLTLs virtually eliminate U-turn conflicts. The suggested use of barrier medians to control conflict locations and prevent left turns often results in increased U-turns. Only seven U-turns were observed during this study (out of 75,000 total vehicles).
4. The five-lane TWLTL alternative is recommended over the four-lane section without any median treatment when left turns are permitted on arterials that have strip commercial development.
5. The three-lane TWLTL may be superior to the four-lane section that does not have median treatment, especially when the width of the four-lane section is limited and left turns are permitted on arterials that have established strip commercial development.

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REFERENCES

1. J.C. Glennon and others. Evaluation of Techniques for the Control of Direct Access to Arterial Highways. FHWA, Rept. FHWA-RD-76-85, 1976.
2. P.D. Cribbins and others. Median Openings on

Divided Highways: Their Effect on Accident Rates and Level of Service. HRB, Highway Research Record 188, 1967, pp. 140-158.
3. D.A. Utkotter. Analysis of Motor Vehicles at Commercial Driveway Locations. Purdue Univ., West Lafayette, Ind., Rept. 74-9, June 1974.
4. Z.A. Nemeth. Development of Guidelines for the Application of Continuous Two-Way Left Turn Median Lanes. Ohio Department of Transportation, Columbus, Rept. DOT-09-76, 1976.
5. M.C. Walton and others. Design Criteria for Median Turn Lanes. FHWA, Rept. FHWA/TX-781 06-212-1F, 1978.
6. R.B. Sawhill and D.R. Neuzil. Accident and Operational Characteristics on Arterials Utilizing Two-Way Median Left-Turn Lanes. Univ. of Washington, Seattle, Res. Rept. 7, Oct. 1962.
7. P. Jomini. Report to the City of Billings. Traffic Division, Billings, Mont., 1981.
8. W.D. Glave and D.J. Migletz. Application of Traffic Conflict Analysis at Intersections. NCHRP, Rept. 219, 1980, 109 pp.

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Accident Implications of Shoulder Width on Two-Lane Roadways

JAMES C. BARBARESSO AND BRENT O. BAIR

Previous studies regarding the accident implications of shoulder width have been inconclusive and their results contradictory. Engineering guidelines concerning shoulder width have been established, but emphasis is placed on the minimum shoulder width necessary for emergency parking and not on the effects of shoulder width on accident experience. The accident implications of shoulder width on two-lane roadways in an urban county in Michigan are investigated. Some liability claims against the county road agency have alleged that shoulders, which are at variance with shoulder-width guidelines, are hazardous because they do not adhere to the suggested guidelines. One intent of this paper is to determine whether these allegations are substantiated. Analyses were performed to determine whether there is a significant difference in accident frequency between two-lane roadways that meet shoulder-width guidelines and those that do not meet the guidelines. The results of this research do not support the premise that roadways with wider shoulders have significantly fewer accidents than roadways with narrow shoulders. No significant difference in accident frequency was found between roadways that meet shoulder-width guidelines and those that do not meet the guidelines. Accident data reviewed in this study reveal that shoulder width is not related to the frequency of overturn accidents, head-on type accidents, or to accident frequency in general, even after traffic volume and other variables are considered. A relation was discovered between the frequency of fixed-object accidents and shoulder width, but the findings indicate that fixed-object accident frequency is significantly lower on roadways with shoulders <7 ft wide than it is for roadways with wider shoulders. It was concluded from this research that (a) projects to reduce accident frequency should focus on factors that exhibit greater influence on accident frequency than does shoulder width; and (b) although it is desirable to adhere to current guidelines wherever possible, when undertaking certain types of construction projects it may be acceptable to retain existing shoulders of <8 ft in width unless a review of accident data for the project location indicates otherwise.

Previous studies regarding the accident implications of shoulder width have been inconclusive and their results contradictory (1-7). Engineering guidelines concerning shoulder widths have been established (8,9), but these guidelines emphasize the minimum shoulder width necessary for emergency parking and not the impact of shoulder width on accident experience. It would be advantageous to provide adequate facilities for emergency parking, but to adhere to these guidelines on all roadways would not be financially feasible.

It is more practical to investigate the effect of shoulder width on accident occurrences and pinpoint locations where accident experience can be related to shoulder width or a combination of shoulder width and other roadway factors. If such locations can be determined, then countermeasures to alleviate the accident situation could be implemented.

The accident implications of shoulder width on two-lane paved roadways are investigated in this paper. Analyses were performed to determine

1. Whether there is a significant difference in accident frequency between two-lane roadways with shoulder widths that meet the guidelines and those that do not meet the guidelines, and
2. Whether there is a relation between certain accident types and shoulder width.

The primary purpose of this research was to determine the relation between accident characteristics and shoulder width on two-lane roadways in Oakland County, Michigan. The research did not address the liability exposure of the residents of Oakland County or the Oakland County Road Commission (OCRC) due to shoulder widths less than those recommended by current engineering guidelines. Nevertheless, some liability claims against the Road Commission have cited narrow shoulders as contributing factors in certain accidents because the shoulders do not conform to the guidelines. If shoulder width is a contributing factor in certain accident types or the frequency of accidents, corrective action by OCRC may be justified.

PREVIOUS STUDIES

The multiplicity of studies concerning the effects of shoulder width on accident occurrences has resulted in an array of contradictory and often inconclusive findings. Transportation professionals have been forced to choose among these varied results for years.

In a critique of these past research attempts, Zeeger and Perkins (10) concluded that studies that found wider shoulders associated with safer conditions were the most reliable. They based their con-