Traffic Operations Study of the Turning Lanes on Uncontrolled Approaches of Rural Intersections

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A time-lapse film study of the traffic operations on 14 intersection approaches on rural two-lane highways in Nebraska was conducted. The purpose of the study was to evaluate the safety effects of turning lanes on the uncontrolled approaches of intersections on rural two-lane highways. The turning lanes evaluated were left-turn, right-turn, and fly-by lanes. Traffic operations on the approaches with turning lanes were compared with those on similar approaches without turning lanes to determine the safety effects of the turning lanes. The measures of safety effectiveness used in the study were *(a)* standard deviation of mean approach speed, *(b)* traffic conflict rate, *(c)* frequency of abnormal turning maneuvers, and *(d)* improper lane utilization. Lower values of these measures were assumed to be indicative of safer traffic operations. The results of the study indicated that the provision of turning lanes on uncontrolled approaches of intersections on rural two-lane highways improved the safety of traffic operations on these approaches, especially those without paved shoulders. It was also apparent from the results of the study that consideration must be given to the adequate design of these lanes, particularly left-turn and fly-by lanes, in order to eliminate their improper use and encroachments by turning vehicles on adjacent through lanes, which negate the safety benefits provided by such lanes.

Turning lanes are provided on uncontrolled approaches of intersections on rural two-lane highways to remove the deceleration and storage of turning vehicles from the through traffic lanes and thereby enable through vehicles to pass by without conflict and delay. Thus, turning lanes are intended to improve the safety and efficiency of traffic operations at these locations. Although the functions of turning lanes are well understood by highway engineers, there are no generally accepted warrants that define the circumstances under which the costs of constructing and maintaining turning lanes are justified. Therefore the University of Nebraska–Lincoln in cooperation with the Nebraska Department of Roads conducted research to develop warrants for turning lanes on uncontrolled approaches of rural intersections.

The specific objectives of the research were to *(a)* evaluate the safety and operational effects of turning lanes on uncontrolled approaches of intersections on rural two-lane highways, *(b)* develop a methodology for evaluating the cost-effectiveness of these lanes, and *(c)* use this methodology to develop guidelines for the cost-effective use of these lanes. The formulation of the cost-effectiveness methodology was based on a benefit-cost analysis approach. The benefits considered were the accident and operational cost savings provided to the road user by the turning lanes. The costs were those of constructing and maintaining the turning lane.

An analysis of intersection accidents on rural two-lane highways in Nebraska was conducted to determine the safety effects of turning lanes. In addition, a study of traffic operations on selected intersection approaches was conducted to further assess these safety effects. The procedure, findings, and conclusions of the traffic operations study are presented in this paper. The accident analysis, the formulation of the cost-effectiveness methodology, and the guidelines derived from its application have been reported elsewhere *(1)*.

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TYPES OF TURNING LANES

Three types of turning lanes are commonly used on two-lane highways in Nebraska: left-turn, right-turn, and fly-by lanes. A left-turn lane is usually constructed by widening the highway on both sides of the intersection to provide a protected lane for left-turning vehicles on one or both of the intersection approaches (Figure 1). A right-turn lane is normally con-

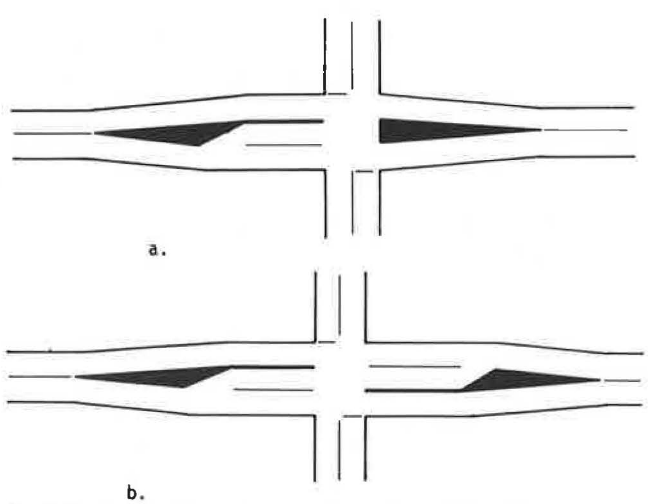

FIGURE 1 Left-turn lane configurations at four-leg intersection: *(a)* left-turn lane on only one approach; *(b)* left turn lanes on both approaches.

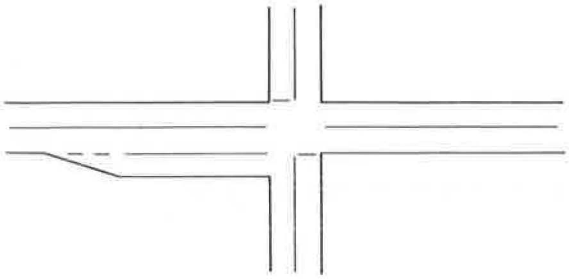

FIGURE 2 Right-turn lane configuration.

structed by widening the highway on the approach side of the intersection to provide a protected lane for right-turning vehicles on the intersection approach (Figure 2). A fly-by lane is usually provided at a T-intersection as a low-cost alternative to a left-turn lane. It is constructed by widening the highway on both sides of the intersection to provide a third lane through the intersection (Figure 3). This third lane is to be used by through vehicles to pass to the right of any left-turning vehicles that have slowed or stopped in the middle lane. When there are no left-turning vehicles, the through vehicles are to remain in the middle lane as they pass through the intersection. Thus, with a fly-by lane, the deceleration and storage of left-turning vehicles are not protected from the following through traffic as they are when there is a left-turn lane.

PROCEDURE

The traffic operations study was conducted on uncontrolled intersection approaches with and without turning lanes on rural two-lane highways in Nebraska. The study involved the time-lapse filming of traffic operations on the approaches. The films were analyzed to determine the effects of turning lanes on the safety of traffic operations.

Study Sites

The study sites were selected as representative of uncontrolled intersection approaches with and without turning lanes on rural two-lane highways in Nebraska. In the accident analysis phase of the research *(1)*, an inventory of all intersections on rural two-lane highways on the state highway system in Nebraska was compiled from the state highway map. The uncontrolled approaches of these intersections were classified according to type of turning lane present (none, left-turn, right-turn, or fly-by) and shoulder condition (paved or unpaved). Six approach categories were found:

Category	*Turning Lane*	*Shoulder*
I	None	Unpaved
II	None	Paved
III	Left-turn	Unpaved
IV	Left-turn	Paved
V	Right-turn	Unpaved
VI	Fly-by	Unpaved

The approaches without turning lanes and the approaches with left-turn lanes were found to have either paved or unpaved shoulders. However, the approaches with right-turn lanes and those with fly-by lanes were all found to have unpaved shoulders. In the case of an approach with a right-turn or fly-by lane on a highway that had paved shoulders, the turning lane was constructed on the paved shoulder and another paved shoulder was not added to the right of the turning lane.

From the inventory that was compiled in the accident analysis phase of this research, 36 approaches (6 from each of the 6 turning-lane categories used in the accident analysis) were selected as candidate sites for the conduct of the traffic operations study. However, field inspections of these sites revealed that only 14 of them had sufficient turning volumes and suitable vantage points from which to film. These 14 sites included at least one approach from each of the six turning-lane categories. Therefore, these 14 approaches were selected to be the study sites for the traffic operations study.

Eight of the study sites were approaches without turning lanes, five of which had no paved shoulders and three of which had paved shoulders. Three of the study sites had left-turn lanes, only one of which had a paved shoulder. Two of the study sites had right-turn lanes, and only one had a fly-by lane. The dimensions of the turning lanes at the study sites were in compliance with AASHTO *(2)* and Nebraska *(3)* geometric design standards. The route markings on all the study approaches were in accordance with standards for rural intersections of marked routes given in the *Manual on Uniform Traffic Control Devices for Streets and Highways* (MUTCD) *(4)*.

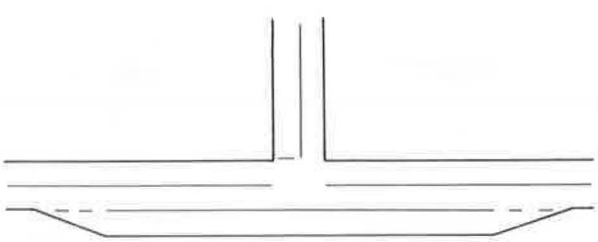

FIGURE 3 Fly-by lane configuration.

Data Collection

The traffic operations data were collected at the study sites by means of time-lapse photography. A 16-mm Automax Model 16-010 Cine-Pulse camera was used. The camera was operated at the film speed of 2 frames per second (fps). Depending on the particular location of the elevated vantage point from which the filming was conducted, a 25-, 50-, or 75-mm lens was used to provide a satisfactory field of view that extended from the far side of the intersection back upstream along the approach to a point 1,000 ft in advance of the intersection.

A total of 50 hr of traffic operations were filmed at the 14 study sites. Depending on the traffic volume, the length of the filming session at each site ranged from 2 hr to over 5 hr in order to obtain at least 100 turning movements of the appropriate type in each of the six turning-lane categories. The film used was 200-ft reels of 16-mm Kodak Ektachrome 7256 MS.

For filming at 2 fps, each reel of film provided about 1 hr 6 min of filming. Therefore, to minimize the amount of film used, the camera was only turned on when vehicles were on the approach.

Before a new reel of film was started, traffic cones were placed at 100-ft intervals on either side of the approach lane or lanes for a distance of 1,000 ft in advance of the intersection. From the vantage point, the focus of the camera was fixed to provide the necessary field of view. The approach was then filmed for a few seconds in the cine mode to provide a frame of reference for the subsequent analysis of the film. The traffic cones were then removed from the approach and time-lapse filming began.

Data Analysis

The time-lapse film was analyzed with a Lafayette 16-mm analyzer Model 300 projector, which was equipped with a frame counter and a range of viewing speeds both in forward and reverse. Each reel of film was projected onto a white paper screen. Once proper focus had been obtained, the film was stopped at the beginning of the reel, which showed the traffic cones placed on both sides of the approach lane in advance of the intersection. The locations of the traffic cones were marked on the screen and connected with straight lines to form a reference grid for the analysis of the film. Thus, a new reference grid was established for each reel of film analyzed.

Each reel of film was viewed several times at various speeds, both forward and in reverse, to record the position of each vehicle within the reference grid in each film frame (every ½ sec) as it traversed the approach. As a result, a time-space trajectory in three dimensions (time, distance, and lane placement) of each approach vehicle was obtained. In addition, the type and turning movement of each approach vehicle and the presence of an opposing vehicle at the intersection during its approach were recorded. Moreover, each film was viewed an additional time to record any traffic conflicts that occurred on the approach. These data were coded and input to the computer for further analysis.

Programs were written to compute the following measures of traffic operations safety on the approaches:

- Standard deviation of mean approach speed,
- Traffic conflict rate,
- Frequency of abnormal turning maneuvers, and
- Lane utilization factor.

Comparisons of these measures among the study approaches were used as indications of the relative safety of traffic operations on the approaches and measures of the safety effectiveness of the turning lanes.

Preliminary analysis of the speed data indicated that the mean speed of an approach vehicle over the 1,000 ft in advance of the intersection was affected by the turning movement and type of vehicle, the presence and turning movement of the vehicle ahead of the approach vehicle, and the presence of a vehicle on the opposing approach. Therefore, to eliminate the confounding effects of these factors on the comparisons of speed variance between approaches with and without turning lanes, stratified random samples were drawn from the original speed data so that the speed data used to make these comparisons were representative of similar traffic conditions. The standard deviations of mean approach speed were computed from these stratified random samples.

FINDINGS

Data were analyzed for more than 4,600 approach vehicles. The overall distributions of these data by turning movement and by vehicle type are shown in Table 1. The findings relative to each measure of effectiveness computed in the data analysis are presented in the following paragraphs.

Standard Deviation of Mean Approach Speed

In previous research *(5)* it has been found that, in general, the lower the speed differences between vehicles traveling on a

TABLE 1 OVERALL DISTRIBUTION OF TRAFFIC OPERATIONS DATA

Turning-Lane Category[a]	Turning Movement (%)			Trucks (%)	Sample Size
	Left-Turn	Through	Right-Turn		
I: None w/o shldr	13	82	5	30	1,222
II: None w/shldr	8	90	2	18	1,526
III: LT w/o shldr	26	73	1	35	370
IV: LT w/shldr	34	66	0	20	410
V: RT w/o shldr	0	53	47	16	560
VI: FB w/o shldr	13	87	0	17	780

[a]None - no turning lane; LT - left-turn lane; RT - right-turn lane; FB - fly-by lane;

w/o shldr - approaches without paved shoulders;

w/shldr - approaches with paved shoulders.

rural highway section, the lower the accident rates on the section. Therefore, the standard deviation of mean approach speed was used in this research to assess the safety of traffic operations on the intersection approaches. It was assumed for the purpose of this analysis that smaller standard deviations of mean approach speed were indicative of safer traffic operations on the intersection approaches.

Stratified Random Samples

As mentioned previously, in order to provide for meaningful comparisons between approaches with turning lanes and those without turning lanes, it was necessary to eliminate the confounding effects of those traffic conditions that affected mean approach speed by drawing from the original data random samples that were stratified according to the frequency with which these factors were present in the original data. Because, as shown in Table 1, the original sample sizes for the two approach categories without turning lanes were much larger than those of the four approach categories with turning lanes, the stratified random samples were drawn from these two larger samples in accordance with the distributions of data collected on the approaches with turning lanes and the corresponding percentage of trucks shown in Table 1.

Thus, in order to compare the standard deviation of mean approach speed on approaches with left-turn lanes and without paved shoulders with that on approaches without turning lanes and without paved shoulders, a stratified random sample was drawn from the original data for approaches without turning lanes and without paved shoulders so that the data used to compute the standard deviation of mean approach speed on left-turn lanes without paved shoulders were representative of the distribution of the data collected on the approaches with left-turn lanes and unpaved shoulders. Two additional stratified random samples were drawn from the original data for approaches without turning lanes and without paved shoulders, one to compare the standard deviation of mean approach speed of approaches with right-turn lanes and without paved shoulders and those without turning lanes and without paved shoulders and the other to compare approaches with fly-by lanes and without paved shoulders and approaches without turning lanes and without paved shoulders.

Only one stratified random sample was drawn from the original data for approaches without turning lanes and with paved shoulders. This sample was drawn in accordance with the distribution of the data collected on the approach with a left-turn lane and paved shoulder to compare approaches with left-turn lanes and paved shoulders and approaches without turning lanes and with paved shoulders.

Comparisons

The comparisons of the standard deviations of mean approach speed between approaches with turning lanes and those without turning lanes are shown in Table 2. These comparisons indicate that among the approaches without paved shoulders, the standard deviations of mean approach speed of through vehicles on approaches with turning lanes were statistically significantly lower than those of through vehicles on approaches without turning lanes, whereas those of left-turn and right-turn movements were not significantly different, according to the results of F-tests conducted at the 5 percent level of significance. The comparisons among approaches with paved shoulders, on the other hand, indicate that the standard deviation of mean approach speed of through vehicles on approaches with left-turn lanes was not significantly different from that of through vehicles on approaches without turning lanes. These findings suggest that the provision of turning lanes on approaches with-

TABLE 2 COMPARISONS OF STANDARD DEVIATIONS OF MEAN APPROACH SPEED

Comparison[b]	Turning Movement					
	Left-Turn		Through		Right-Turn	
	s	n	s	n	s	n
None w/o shldr vs.	5.1	97	6.8	269	6.8	4
LT w/o shldr	5.1	97	5.7[c]	269	5.0	4
None w/shldr vs.	5.8	139	5.9	269	-	0
LT w/shldr	5.6	139	6.0	269	-	0
None w/o shldr vs.	-[d]	0	6.6	297	5.7	113
RT w/o shldr	-	0	5.0[c]	297	5.6	113
None w/o shldr vs.	5.5	102	7.0	678	-	0
FB w/o shldr	5.7	102	5.2[c]	678	-	0

[a] s - standard deviation (mph); n - sample size.

[b] None - no turning lane; LT - left-turn lane; RT - right-turn lane; FB - fly-by lane; w/o shldr - approaches without paved shoulders; w/shldr - approaches with paved shoulders.

[c] Significantly lower than the standard deviation on similar approaches without turning lanes ($\alpha = 0.05$)

[d] (-) - no data for this case.

TABLE 3 LEFT-TURN-LANE ACCIDENT REDUCTION FACTORS

Accident Type	Approaches Without Paved Shoulders	Approaches With Paved Shoulders
rearend + sideswipe	60%	10%
left-turn	-770%[a]	_[b]
right-turn	50%	0%

[a] "-" indicates an increase instead of a reduction.

[b] Infinite percentage increase in mean accident rate, because similar approaches without turning lanes had a zero mean accident rate for this type of accident.

out paved shoulders would improve the safety of traffic operations for the through vehicles on these approaches and not adversely affect the safety for the turning vehicles. However, the provision of left-turn lanes on approaches with paved shoulders would not improve the safety of these traffic operations. This observation was consistent with the findings of the accident analysis phase of the research *(1)*, shown in Table 3, in that the accident reduction factors for left-turn lanes on approaches with paved shoulders were lower than those for left-turn lanes on approaches without paved shoulders.

Traffic Conflict Rate

Any evasive actions by drivers to avoid collisions with other vehicles, other than normal braking and lane changing, were recorded as traffic conflicts. It was assumed that the lower the rate at which traffic conflicts occurred on an approach, the safer the traffic operations were on the approach. However, the rates of occurrence of traffic conflicts observed on the study approaches were so low that meaningful comparisons among the approaches were not possible.

The most frequently occurring traffic conflicts were on the approaches with left-turn or fly-by lanes. The most common one observed on approaches with left-turn lanes was between a left-turning vehicle and a through vehicle on the opposing approach. This conflict occurred when the sight distance between these two vehicles was obstructed by left-turning vehicles on the opposing approach. The most common conflict observed on the approach with a fly-by lane was between a through vehicle in a through lane and a through vehicle in the fly-by lane. This usually occurred when a second through vehicle arrived behind a left-turning vehicle and entered the fly-by lane before the through vehicle in front of it did. This conflict also occurred when a through vehicle attempted to use the fly-by lane to pass to the right of slower-moving through traffic.

Abnormal Turning Maneuvers

Another measure of effectiveness used to evaluate the safety of traffic operations on the study approaches was the percentage of turning vehicles that did not negotiate their turn in the normally expected manner along a curvilinear path without encroaching on shoulders, adjacent lanes, or both. Four types of turning maneuvers were defined as abnormal for the purpose of this analysis. The first was the wide turn, in which the turning vehicle did not complete its turn without swinging out and encroaching on shoulders, adjacent lanes, or both at the beginning or the end, or both, of its turn. The second was the straddle turn, in which the turning vehicle straddled the centerline of the highway from which it was turning for some distance before beginning its turn. This was usually done by left-turning vehicles to allow following through vehicles to pass; however, it was also observed to have been done by left-turning vehicles that were not being followed. By definition, the straddle turn did not apply to approaches with left-turn lanes.

The remaining two types of abnormal turns were only applicable to approaches with turning lanes: in the first, the angle turn, the turning vehicle cut diagonally across the turning lane without actually traveling in it, and in the second the turning vehicle never completely entered the turning lane to negotiate its turn.

Of course, the frequency of occurrence of abnormal turning maneuvers on the study approaches was not only influenced by the presence of turning lanes and paved shoulders but also by the turning radii provided on the approaches and the presence of other vehicles. However, for the purpose of this analysis, it was assumed that the lower the percentage of turning vehicles making abnormal turning maneuvers, the safer were the traffic operations on the approach.

Passenger Cars

The percentages of abnormal turning maneuvers by passenger cars for each approach category are shown in Table 4. On the basis of results of chi-square tests conducted at the 5 percent level of significance, the only statistically significant difference found in the abnormal-turning-maneuver percentages was between approaches with left-turn lanes and paved shoulders and those with left-turn lanes and unpaved shoulders. For some reason, on the approach with a left-turn lane and paved shoulders a significantly higher percentage of left-turning vehicles did not completely enter the left-turn lane to make their turns. Other than the possibility that the additional space provided on

TABLE 4 ABNORMAL TURNING MANEUVERS BY PASSENGER CARS[a]

Turning-Lane Category[b]	Turning Movement (%)									
	Left-Turn					Right-Turn				
	Abnormal				Normal	Abnormal				Normal
	Wide	Strad.	Angle	Inc.		Wide	Strad.	Angle	Inc.	
I: None w/o shldr	4.1	2.1	NA	NA	93.8	6.3	0	NA	NA	93.7
II: None w/shldr	0	2.1	NA	NA	96.1	3.2	0	NA	NA	96.8
III: LT w/o shldr	0	NA[d]	3.9	1.3[e]	94.8	33.3[f]	0	NA	NA	66.7
IV: LT w/shldr	3.0	NA	5.0	22.5[e]	69.5	-	-	NA	NA	-
V: RT w/o shldr	-[c]	-	-	-	-	4.1	0	1.7	7.5	86.7
VI: FB w/o shldr	1.1	0	NA	NA	98.9	-	-	NA	NA	-

[a] Wide - wide turn; Strad. - straddled center line; Angle - crossed turning lane diagonally; Inc. - never completely entered turning lane.

[b] None - no turning lane; LT - left-turn lane; RT - right-turn lane; FB - fly-by lane; w/o shldr - approaches without paved shoulder; w/shldr - approaches with paved shoulders.

[c] (-) - no turning movements of this type were made from approaches of this turning-lane category.

[d] NA - This type of abnormal turning maneuver is not applicable to this turning-lane category.

[e] Statistically significant difference between "LT w/o shldr" and "LT w/shldr" categories ($\alpha = 0.05$).

[f] Significantly higher than other turning lane categories ($\alpha = 0.05$).

the approach by the paved shoulder may have caused fewer drivers of these vehicles to perceive the need to completely enter the left-turn lane before making their turn, it was also possible that the path or turning radius provided by the left-turn channelization was not sufficient to encourage drivers to do so. However, the dimensions of the left-turn channelization were more than adequate for passenger cars according to AASHTO *(2)* and Nebraska *(3)* geometric design standards.

In the case of right-turning passenger cars, the only statistically significant difference found was in the percentage of right-turning vehicles making wide turns, which was significantly higher on approaches with left-turn lanes and unpaved shoulders than it was on those with right-turn lanes or without turning lanes. Nearly all of the wide turns made on the former approaches involved a right-turning vehicle that swung out to the left and encroached on the adjacent left-turn lane to begin its turn but did not encroach on the opposing lane of the intersecting highway to complete its turn. This higher percentage of wide turns did not appear to be due to shorter turning radii on these approaches, but instead to a greater inclination of right-turning drivers to encroach on adjacent left-turn lanes than on adjacent opposing lanes.

Trucks

The percentages of abnormal turning maneuvers by trucks for each approach category are shown in Table 5. Approaches with left-turn lanes had the lowest percentages of normal left-turn maneuvers because of the high percentages of left-turning trucks that did not completely enter the left-turn lanes to negotiate their turns. Instead, these trucks remained partly in the through lanes, apparently in order to maximize the radii of their turns. As was expected because of the longer turning radii of these turns, the results of chi-square tests conducted at the 5 percent level of significance indicated that the percentage of these abnormal turning maneuvers by trucks was significantly higher than that by passenger cars. In addition, it was noted that the percentage of wide-turns by left-turning trucks on approaches without turning lanes was not significantly different from that on approaches with left-turn lanes. However, because the dimensions of the left-turn channelization on these approaches were more than adequate for the trucks involved according to AASHTO *(2)* and Nebraska *(3)* geometric design standards, this finding suggested that the truck drivers merely took advantage of the additional space provided by the left-turn lanes to make a wide turn.

The abnormal-turning-maneuver percentages for right-turning trucks indicated that the provision of right-turn lanes on approaches without paved shoulders would significantly reduce the percentage of right-turning trucks that make wide turns. However, there was no significant difference in the percentage of normal right-turn maneuvers between approaches with right-turn lanes and those without right-turn lanes because of the percentage of right-turning trucks on approaches with right-turn lanes that made angle turns or failed to completely enter the right-turn lane in order to maximize the radii of their turns. In general it was also found, as expected, that because of the longer turning radii of trucks, the percentage of abnormal turning maneuvers by right-turning trucks was significantly higher than the corresponding percentage of abnormal turning maneuvers by right-turning passenger cars shown in Table 4.

Proper Lane Utilization

The final measure of effectiveness used to evaluate the safety of traffic operations on the study approaches was the percent-

TABLE 5 ABNORMAL TURNING MANEUVERS BY TRUCKS[a]

Turning-Lane Category[b]	Turning Movement (%)									
	Left-Turn					Right-Turn				
	Abnormal				Normal	Abnormal				Normal
	Wide	Strad.	Angle	Inc.		Wide	Strad.	Angle	Inc.	
I: None w/o shldr	3.4	0	NA	NA	96.6	28.5[e,f]	0	NA	NA	71.5
II: None w/shldr	6.7	0	NA	NA	93.3	-	-	NA	NA	-
III: LT w/o shldr	10.0	NA[d]	0	61.9[f]	28.1	-	-	NA	NA	-
IV: LT w/shldr	6.3	NA	15.4[f]	56.6[f]	21.7	-	-	-	-	-
V: RT w/o shldr	-[c]	-	-	-	-	6.9[e]	0	6.9[f]	14.8[f]	71.4
VI: FB w/o shldr	0	0	NA	NA	100.0	-	-	-	-	-

[a] Wide - wide turn; Strad. - straddled center line; Angle - crossed turning lane diagonally; Inc. - never completely entered turning lane.

[b] None - no turning lane; LT - left-turn lane; RT - right-turn lane; FB - fly-by lane; w/o shldr - approaches without paved shoulders; w/shldr - approaches with paved shoulders.

[c] (-) - no turning movements of this type were made from approaches of this turning lane category.

[d] NA - This type of abnormal turning maneuver is not applicable to this turning-lane category.

[e] Statistically significant difference between "None w/o shldr" and "RT w/o shldr" categories (α = 0.05).

[f] Significantly higher than the corresponding percentage for passenger cars shown in Table 5 (α = 0.05).

age of turns that were made from the proper approach lane. On the approaches without turning lanes, all turns should have been made from the through lane. On the approaches with left-turn lanes, the left turns should have been made from the left-turn lane and the through and right turns should have been made from the through lane. On approaches with right-turn lanes, the left turns and through movements should have been made from the through lane and the right turns should have been made from the right-turn lane. On the approach with a fly-by lane, the left turns should have been made from the through lane and the through vehicles should have also used the through lane unless they arrived behind a left-turning vehicle, in which case they should have used the fly-by lane. Because the fly-by lane observed was at a T-intersection, there were no right turns made from the study approach. Turns made from shoulders, opposing traffic lanes, or the wrong approach lane were considered to be potential safety hazards. Therefore, it was assumed for the purpose of this analysis that higher percentages of proper lane utilization were indicative of safer traffic operations on the study approaches. The lane utilization by turning movements for each approach category is shown in Table 6.

Left Turns

In the case of left turns, only a few were not made from the through lanes on approaches without left-turn lanes. All the left turns not made from these through lanes were made from the opposing traffic lane in order to allow a following through vehicle to pass by on the right without delay. Such improper turns were not observed on the approaches with left-turn lanes. However, the results of a chi-square test conducted at the 5 percent level of significance indicated that a significantly lower percentage of left-turning vehicles used the left-turn lane on the approach with the paved shoulders than on the approach without paved shoulders. Instead, these vehicles turned left from the through lanes, in some cases even when being followed by a through vehicle. Therefore, perhaps the additional space provided by the paved shoulder caused the drivers of these left-turning vehicles not to perceive the need to use the left-turn lane. Although some of these drivers may not have been sure which way they needed to turn in order to reach their destination and therefore did not pull off into the turn lane, this was not apparent from the film analysis, because all of these turns were made without hesitation.

Through Movements

All of the through movements on approaches with left-turn or right-turn lanes were made from the through lanes. On the approaches without turning lanes, a few of the through movements were not made from the through lane. On the approaches with no turning lanes and unpaved shoulders, these improper through movements were made in the opposing traffic lane in order to pass on the left of a right-turning vehicle. On the approaches with no turning lanes and paved shoulders, these improper through movements were made on the shoulder in order to pass to the right of a left-turning vehicle.

On the study approach with a fly-by lane, about 5 percent of the through movements made in the fly-by lane were not necessary because there was no left-turning vehicle ahead of the through vehicle. Another 5 percent of these through movements were improper in that the through vehicle used the fly-by lane to pass to the right of a slower-moving through vehicle ahead. Only about 1 percent of the through movements made in the through lane should have been made in the fly-by lane in order to avoid slowing for a left-turning vehicle ahead and thus,

TABLE 6 LANES USED BY TURNING MOVEMENTS[a]

Turning-Lane Category[b]	Turning Movement (%)											
	Left-Turn				Through				Right-Turn			
	TL	Thru	Shldr	Opp	TL	Thru	Shldr	Opp	TL	Thru	Shldr	Opp
I: None w/o shldr	NA[d]	98.1	NA	1.9	NA	99.9	NA	0.1	NA	100.0[f]	NA	0
II: None w/shldr	NA	96.6	0	3.4	NA	99.7	0.3	0	NA	77.4[f]	22.6	0
III: LT w/o shldr	100.0[e]	0[e]	NA	0	0	100.0	NA	0	0	100.0	NA	0
IV: LT w/shldr	95.7[e]	4.3[e]	0	0	0	100.0	0	0	-	-	-	-
V: RT w/o shldr	-[c]	-	NA	-	0	100.0	NA	0	99.0	1.0	NA	0
VI: FB w/o shldr	0	100.0	NA	0	25.0[g]	75.0[h]	NA	0	-	-	NA	-

[a] TL - turning lane; Thru - through lane; Shldr - shoulder; Opp - opposing traffic lane.

[b] None - no turning lane; LT - left-turn lane; RT - right-turn lane; FB - fly-by lane; w/o shldr - approaches without paved shoulders; w/shldr - approaches with paved shoulders.

[c] (-) - no turning movements of this type were made from approaches of this turning-lane category.

[d] NA - Use of this lane is not possible on approaches in this turning-lane category.

[e] Statistically significant difference between "LT w/o shldr" and "LT w/shldr" categories ($\alpha = 0.05$).

[f] Statistically significant difference between "None w/o shldr" and "None w/shldr" categories ($\alpha = 0.05$).

[g] About 5% of these through vehicles unnecessarily usedthe fly-by lane, and another 5% of them used the fly-by lane to pass another through vehicle.

[h] Approximately 1% of these through vehicles should have used the fly-by lane.

in these instances, negating the safety and operational benefits to be derived from use of the fly-by lane.

Right Turns

All right turns were made from the through lanes on the approaches with no turning lanes and unpaved shoulders. However, on the approaches with no turning lanes and paved shoulders, more than 20 percent of the right turns were made from the shoulders, usually to allow following through vehicles to pass by on the left. On the approaches with left-turn lanes, all right turns were made from the through lanes. But on the approaches with right-turn lanes, only 99 percent of the right turns were made from the right-turn lanes. The remaining 1 percent was made by trucks from the through lanes in order to maximize the radius of their turns, even though, according to AASHTO *(2)* and Nebraska *(3)* geometric design standards, the turning radii provided were adequate for the trucks involved. In some cases, through vehicles were following these trucks and the safety and operational benefits of the right-turn lanes were thus negated.

CONCLUSION

In general, the results of the traffic operations study were found to support the findings of the accident analysis phase of the research, which has been reported elsewhere *(1)*. The measures of effectiveness computed indicated that the provision of turning lanes on the uncontrolled approaches of intersections on rural two-lane highways improved the safety of traffic operations on these approaches, especially those without paved shoulders. Comparisons of the standard deviations of the speed on the study approaches indicated that the provision of a turning lane (left-turn, right-turn, or fly-by lane) on an approach that does not have paved shoulders would improve the safety of traffic operations on that approach but that the provision of a left-turn lane on an approach that already has a paved shoulder would not.

The turning-maneuver and lane-utilization analyses that were conducted indicated that this failure of left-turn lanes to improve the safety of traffic operations on approaches that already had paved shoulders was due, at least in part, to the following driver behavior:

1. On approaches with left-turn lanes and paved shoulders, a high percentage of drivers (27.5 percent of passenger-car drivers and 78.3 percent of truck drivers) did not completely enter or properly utilize the turning lane to make a left turn;
2. On approaches with left-turn lanes and paved shoulders, a statistically significant percentage of drivers (4.3 percent) did not use the left-turn lane to make a left turn but instead turned left from the through lane; and
3. On approaches without a left-turn lane but with a paved shoulder, the shoulder was found to function as a fly-by lane for some through vehicles that were following left-turning vehicles and as a right-turn lane for right-turning vehicles.

These observations of driver behavior suggest that special attention should be given to the design, signing, and marking of left-turn lanes on approaches with paved shoulders in order to eliminate their improper use by drivers and encroachments by left-turning vehicles into adjacent through lanes, both of which negate the safety and operational benefits to be realized by the provision of left-turn lanes. Also, highway engineers should recognize that paved shoulders on approaches to intersections of marked rural highway routes are used by drivers as turning lanes so that these shoulders will be properly designed, both structurally and operationally, for this purpose.

The traffic operations study also revealed two potential operational problems with left-turn lanes and fly-by lanes that have been observed by others *(6, 7)*. The most common traffic conflict found on approaches with left-turn lanes was between a left-turning vehicle and a through vehicle on the opposing approach. This conflict occurred when the sight distance between these two vehicles was obstructed by left-turning vehicles on the opposing approach. Therefore, in providing left-turn lanes, the highway designer should avoid creating this problem by offsetting opposing left-turn lanes if necessary to provide adequate sight distance for left-turning and opposing through vehicles *(6)*.

The analyses of the traffic conflict and lane utilization data indicated the potential for improper use of the fly-by lane by through vehicles attempting to pass other through vehicles. To reduce this potential, the highway designer should give special attention to the proper design and application of fly-by lanes as recommended by Buehler *(7)*, using short approach lengths and long departure lengths of the fly-by lanes and not using fly-by lanes as substitutes for left-turn lanes at locations with higher traffic volumes.

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