Delay Alleviated by Left-Turn Bypass Lanes

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The effectiveness of a left-turn bypass lane on a two-lane rural T-intersection shown by delay data was examined in this research. The bypass lane was a 12-ft-wide marked lane that through traffic may use to move around a vehicle that has stopped to make a left turn onto the minor road of the T. Delay data were generated by the TRAF-NETSIM traffic simulation program sponsored by the FHWA. Delay can be converted into driver cost, which can be compared with the cost of constructing the lane, to provide a good indication of the point at which the extra lane would be warranted. Seven factors that may affect the need for the extra lane were tested: the opposing through volume, the opposing right-turn volume, the through volume, the left-turn volume, vehicle speed, and the distance to the nearest upstream and downstream signal. The presence of a bypass lane was also tested to allow comparison between situations with and without left-turn bypass lanes. Sixty-four simulations were run to test the factors and the interaction among factors. The results indicated that the presence of a bypass lane was a significant factor in delay, especially when higher levels of opposing and left-turn volumes were present. Significant delay and percent stops savings can be realized by including a left-turn bypass lane in certain situations.

Delay is the measure used to establish the effectiveness of a left-turn bypass lane on a two-lane rural road at a T-intersection in the research reported in this paper. Although left-turn bypass lanes have been thoroughly studied during the past twenty-five years on accident reduction and safety aspects, there has not yet been a thorough study of their effectiveness from a vehicle delay standpoint.

A left-turn bypass lane is defined here as a paved area to the right of the lane on the major road, opposite the minor road at a T-shaped intersection, on a two-lane rural road (see Figure 1). This area is designed to allow through-traveling vehicles to move around a vehicle that is stopped (or decelerating to stop) to make a left turn from the through road. Locally, interest in this subject was sparked because traffic volumes near Charlotte, North Carolina are growing at an alarming rate. As once-rural areas undergo development, transportation systems often cannot keep pace, leaving many two-lane roads that have inadequate turn capacity. Highway departments cannot afford to upgrade all of the two-lane roads that need capacity enhancements. The left-turn bypass lane may provide a temporary, inexpensive solution to handle left-turn problems until a road can be widened or left-turn bays constructed. However, this solution should not be overused, because costs will quickly mount. A left-turn bypass lane is clearly not warranted at every commercial or industrial driveway or residential street. The need for delay-oriented benefits from bypass lanes is apparent.

The literature was reviewed to gather information for subsequent activities. An experiment using a traffic simulation program was then designed and run and the important experimental factors were identified by an analysis of variance (ANOVA). On the basis of these important factors, delay and percent stops savings for the lane were developed and a methodology for practicing engineers to apply the savings is illustrated.

LITERATURE REVIEW

Before beginning the data collection phase of the project, an extensive literature review was performed. Any research that dealt with left-turn bypass lanes was examined. The studies that were pertinent to the project dealt with the design of, warrants for, or measures of effectiveness (MOEs) for these lanes. Several studies concerning left-turn bays were also included in this review.

In one of the earliest studies of bypass lanes, Failmezger (*1*) developed an index of hazard for the relative danger in making a left turn on the basis of opposing volumes and physical features of the site. Variables used in the index included the 8-hr maximum left-turn volume and the 8-hr opposing volume. Failmezger also developed a relative warrant equation that took into account the accident records and construction and maintenance costs of a particular site. These measures were intended for use as warrants for the inclusion of a left-turn lane at a particular intersection. This formula falls short of estimating the need for some accommodation of left-turn traffic because it overlooks other important factors such as the left-turn volume.

A significant step in this area was taken with the publication of *Volume Warrants for Left-Turn Lanes at Unsignalized Grade Intersections* (*2*). This research is important for bypass lanes because of the operational similarity between a bypass lane and a left-turn lane. This report produced a series of charts, which were to be used to determine whether a left-turn lane was warranted on the basis on volume information. These warrants were based on the probability of a through vehicle arriving behind a left-turn vehicle and being delayed. The formula used considered through volume, left-turn volume, opposing volume, and the speed of all vehicles. These equations considered gap acceptance by the left-turn vehicle, and added it to the overall delay factor. However, these warrants did not take into consideration individual driver characteristics, free-flow speed distributions, or platoon characteristics.

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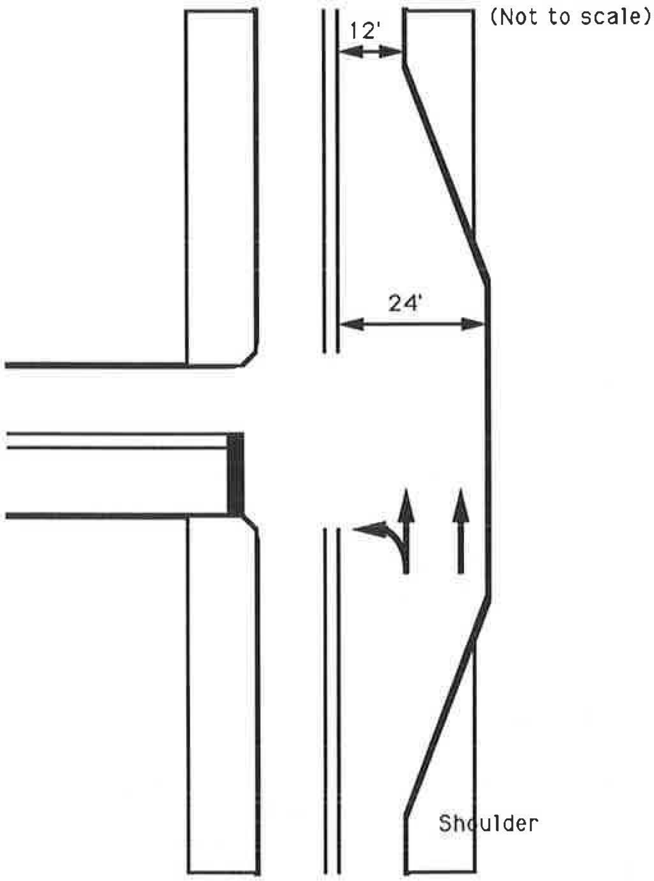

FIGURE 1 Left-turn bypass lane concept.

Each of these would appear to have a direct effect on the total delay through the intersection in question.

In 1979 Buehler published a report on bypass lanes at T-shaped intersections *(3)*. Buehler examined the question of the legality of bypass lanes and found that in Illinois the bypass lane was legal to use if it was not considered a shoulder and had been signed accordingly. He also theorized that the concept of the lane itself was a fairly simple one, which would be well understood by the public. In this report it was also mentioned that bypass lanes may be used to pass slower vehicles. This is an undesirable situation, mainly because of the increased chance of a side-swipe accident. Buehler suggested that the geometric design of the bypass lane is by far the most important factor in the use of these lanes. Buehler also noted that the bypass lane is much less expensive than the left-turn bay or lane. This would tend to make the bypass lane more attractive to developers who must finance the roadway improvements themselves. The report provided good arguments for the use of bypass lanes, but fell short of offering any practical guidelines for their use.

In 1982 another report appeared on the use of the left-turn bypass lane *(4)*, in which the legal aspects of these lanes was also addressed. It was concluded that the laws of the state of Delaware allowed for use of the lane to pass a car stopped to make a left turn. This report dealt with the cost savings associated with the use of the lane. Several existing bypass lanes, both marked and unmarked as such, were examined in the study. Data were collected for these sites by counting intersection and turning movements during 2-hr morning, noon, and evening peak periods. The observations were made especially to determine how many vehicles did or did not use the bypass lane. The benefits derived from the lane were identified as decreased delay, decreased fuel consumption, and decreased emissions. The annual cost savings for eight marked bypass locations totaled $53,726, with a mean value by location of $6,716. The unmarked locations had a total annual savings of $17,778, with a mean value of $2,224 per location. The report unfortunately did not compare this cost savings with the construction and maintenance cost of the bypass lane to assess the cost-effectiveness of the added lane.

Research conducted in Nebraska used the benefit-cost approach to analyze the bypass lane *(5)*. The benefits considered were the accident and operational savings, while the costs were for construction and maintenance. The researchers found that a paved shoulder area was being used as a bypass lane by certain motorists, as in the 1982 Delaware report *(4)*. It was suggested that special attention be paid to the design of the paved shoulders. In addition, it was recommended that bypass lanes be avoided in higher-volume situations because of the problem of its use as a passing lane as discussed earlier.

The *Road Design Manual* for the State of Nebraska addressed the bypass lanes *(6)*. The Manual specified the following for the lane:

1. A 300-ft-long taper out to two 12-ft lanes.
2. A 700-ft-long bypass lane that measures 600 ft from the end of the runout taper to the centerline of the minor street then continues for an additional 100 ft.
3. A 600-ft-long taper back to a single 12-ft lane.

This design makes clear how the bypass lane may be misused as a passing lane. The sign for the lane also includes the legend Passing Lane below the lane diagram, adding to the passing-lane confusion. The state of Nebraska has recently discontinued use of the bypass lane, citing the misuse of the lane for passing other through vehicles as one of the reasons.

The *Highway Capacity Manual (7)* offers no assistance on the question of whether left-turn bypass lanes are warranted. The chapter, Unsignalized Intersection, does not contain procedures for computing delay, and does not allow for computation of a level of service for through movements on the major streets.

The literature just discussed offered several justifications and warrants to include a left-turn bypass lane at a two-lane rural T-intersection. Factors that have been said to affect the need for this lane included accident costs, through volume, opposing volume, left-turn volume, speed, and delay. Although each of the reports presented some information on bypass lanes, some questions remain. These warrants and guidelines offered in previous research reports often do not agree and do not consider relevant factors. Furthermore, they often contain other flaws. Therefore, research is needed to answer these questions and present adequate warrants and guidelines for the use of these lanes.

EXPERIMENT DESCRIPTION

Delay data were generated for this research during an experiment run on the TRAF-NETSIM traffic simulation pro-

gram. TRAF-NETSIM is a detailed, stochastic, microscopic model developed by the Federal Highway Administration. The model was chosen for this research because of the high degree of experimental control it offered and the wide range of detailed MOEs computed. Although this simulation model was designed for signalized intersections, it was useful for this project because it treated unsignalized left turns as permissive turns at a signal with an infinite green time.

Eight factors were identified that may affect vehicle delay through a T-intersection and may be related to the presence or absence of a left-turn bypass lane in previous research and were studied in this experiment. The first of these factors was the volume of traffic opposing the left turn onto the minor street of the T. The second factor was the volume of right-turning traffic from the major street (i.e., opposing the left turn of interest). It can easily be seen why these two factors might affect delay experienced by vehicles turning left or, if left-turning vehicles must stop in the through lane, might affect vehicles traveling through the intersection. The third factor included was the left-turn volume at the intersection. Again, left-turning vehicles may affect the delay of the through vehicles by blocking the through lane while awaiting an acceptable gap. The fourth factor included was the through volume. The fifth factor was the speed of vehicles traveling through the intersection. This factor was included because speed might affect the variety of gaps appearing to left-turn vehicles at the intersection. The distance from the T-intersection to the nearest signal upstream and downstream were also included as variables in the experiment. These two factors were included because they also affect the variety of gaps created at the intersection. Signals upstream and downstream closer to the T-intersection would tend to create denser platoons of vehicles at the T, while signals farther from the T would tend to create more widely-distributed vehicle headway at the T. The presence of a left-turn bypass lane was the final factor included in the experiment. Note that the side-street volume was not considered as a factor in this experiment. This is because of the limited scope of the experiment and the fact that the bypass lane was expected to have a small effect, if any, on this volume.

Each factor was analyzed at two levels during the experiment:

- Through volume: 300 vehicles per hour (vph) and 700 vph;
- Opposing volume: 300 vph and 700 vph;
- Left-turn volume: 20 vph and 50 vph;
- Right-turn volume: 20 vph and 50 vph;
- Mean vehicle speed: 35 mph and 50 mph;
- Upstream signal distance: 0.5 mile and 1.5 miles;
- Downstream signal distance: 0.5 mile and 1.5 miles; and
- Bypass lane presence: no and yes.

The levels of each volume variable were selected to approximate level of service B (low level) and D (high level) for the two-lane roadway. For an unsignalized intersection, this meant that relatively low levels of left-turn volume were tested. The speed levels were chosen to represent the range of possible speed distributions for a two-lane rural road.

The bypass lane simulated during the experiment and the terms used to refer to various traffic movements at the T-intersection are given in Figure 2. Several features of the simulated lane are worthy of discussion. The bypass lane simulated was 12-ft-wide, began 350 ft before the T-intersection, and terminated at the T-intersection. The 350-ft length was based on AASHTO specifications *(8)* and practices in the Charlotte area, which call for a 300-ft-long taper. A full-width lane length of 50 ft was then assumed because a bypass lane 350-ft-long, on either side of the intersection, would be unlikely to encourage much same-direction passing by through vehicles. Also, for the relatively low left-turn volumes tested, the simulated bypass lane storage-capability was much more than adequate. Noted that the simulation reflects bypass lanes that are long enough for through vehicles to maintain their speeds as they use the bypass lane. Shorter bypass lanes may cause through vehicles greater amounts of delay when a left-turn vehicle is present than observed in this experiment. Figure 2 illustrates that all through traffic moved to the right (bypass) lane during the simulation. This was done so that all through vehicles gained the benefit of the bypass lane when a left-turn vehicle was present, and caused no bias since lane changes in TRAF-NETSIM are completed without delay (i.e., instantaneously), and the vehicle speeds are maintained. Again, the simulation results may not apply as well to low-speed bypass lanes, where lane changes take time and cause delay. Finally, terminating the bypass lane at the T-intersection introduced no bias to delay results because of the instantaneous lane change made by TRAF-NETSIM and made data easier to collect and summarize.

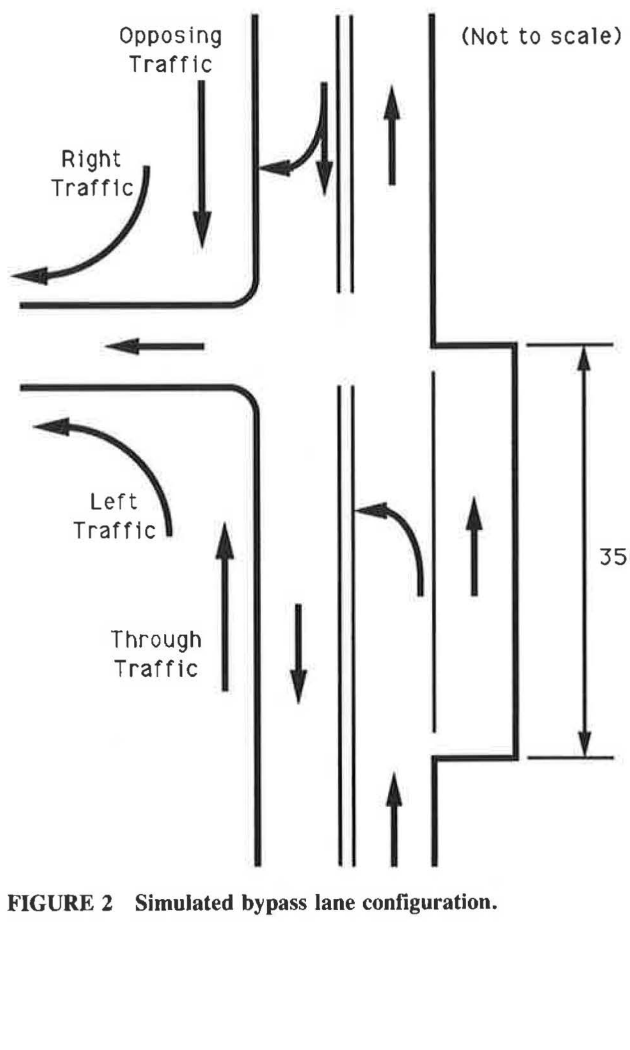

FIGURE 2 Simulated bypass lane configuration.

The network for this experiment was designed as a two-lane rural T-intersection. It was composed of several nodes (intersections) and links (roads) between the nodes. See Figure 3. Node 3 was the T-intersection—the primary point of interest in this experiment. One of the main drawbacks of the TRAF-NETSIM program—traffic enters the network at unrealistic uniform rates—was mitigated by the presence of signals at Nodes 1 and 5 upstream and downstream of the T-intersection. In addition, high turning percentages were designed in the network at Nodes 1 and 5. Since the selection of particular simulated vehicles to turn at a node in TRAF-NETSIM is governed by a random process, high turning percentages at Nodes 1 and 5 helped create more realistic non-uniform arrival patterns at Node 3.

In addition to the eight variables, several factors were kept constant throughout the experiment. Five percent trucks was assumed for all traffic flows. Also, no grades or curves were included in the model. The default distributions for variables such as gap acceptance and vehicle turning speeds provided in TRAF-NETSIM were used during the experiment because these were appropriate for the context of the experiment: a rapidly developing suburban-exurban area with relatively aggressive drivers.

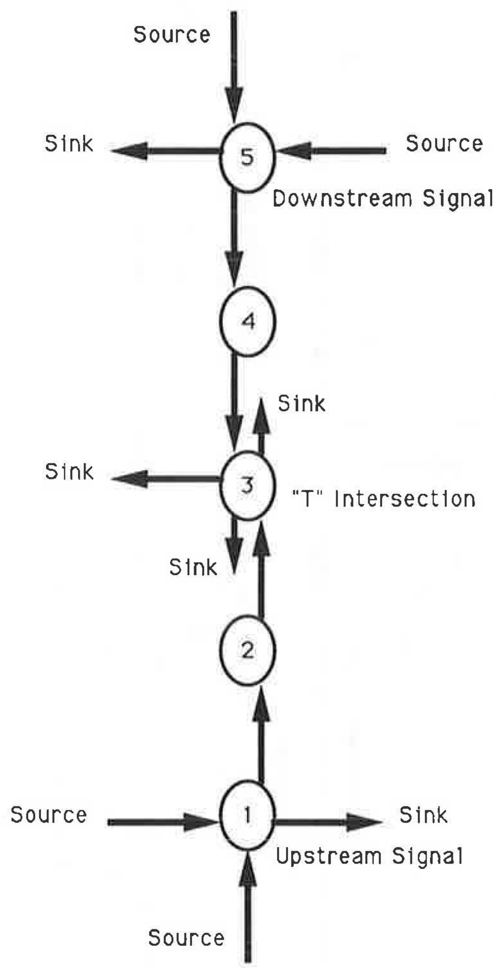

FIGURE 3 TRAF-NETSIM network used during experiment.

DATA COLLECTION

The experiment was designed for 8 variables, each at 2 levels, which provides 256 different combinations if completely crossed. To conduct the experiment efficiently, a one-quarter replication was used, which reduced the number of combinations to be tested to 64. The primary assumption made to achieve this one-quarter replication was the reasonable assumption that all interactions between three or more factors were negligible and were included in the model error term. Complete information was available with this experimental design on all individual factors and interactions of two factors.

Mod 2 arithmetic was used to construct a list of the 64 combinations that needed to be run on NETSIM. The expressions

$$A + B + C + D + E = 0 \quad (1)$$

$$A + B + F + G + H = 0 \quad (2)$$

were used in this process. Each letter in Equations 1 and 2 represented one of the experiment variables. A 0 was used to represent a variable at a low level, and a 1 was used to represent a variable at a high level. The 64 runs tested were those represented by letter combinations which solved the above equations in Mod 2 arithmetic. A list of these runs appears in Table 1.

Each run was made using TRAF-NETSIM Version 2.00 on a 286-based microcomputer *(9)*. The runs were all created from a master file that contained all eight variables at their low levels. The NETSIM random number seed was kept constant for all 64 runs. Each run was 30 simulated minutes long, after an equilibrium had been established between the number of vehicles entering and leaving the network.

Data were analyzed using ANOVA on the SAS statistical package *(10)*. Two MOEs were taken from the TRAF-NETSIM printout of each run: delay and percent stops for the vehicles going through the intersection on the major road approach from which left-turn vehicles were turning (termed "through" delay and percent stops). All of the MOE data were collected between Nodes 2 and 3 for the through traffic. None of the MOEs were gathered on opposing traffic or right turning traffic because of the presence of a bypass lane should not affect the delay experienced by these vehicles.

A 95 percent confidence level was used to determine factors and two-level interactions that had significant effects on the MOEs. Two-level interactions involving the bypass lane variable were of special interest because it was these interactions that would allow delay and percent stop savings to be calculated for the bypass lane.

RESULTS

The results of the experiment provided for the formulation of delay and percent stops savings for the bypass lane. According to the ANOVA results for main effects, shown in Table 2, many variables turned out to be significantly related to the through delay and percent stops.

Variables that were significant in helping to explain through traffic delay included through volume, opposing volume, left-turn volume, speed, upstream signal distance, and the pres-

TABLE 1 VARIABLE COMBINATIONS TESTED DURING EXPERIMENT

Run Number	Variable Combination	Run Number	Variable Combination
1	I	33	BCDEF
2	AB	34	ACDEF
3	CD	35	BEF
4	ABCD	36	AEF
5	GH	37	BCDEFGH
6	ABGH	38	ACDEFGH
7	CDGH	39	BEFGH
8	ABCDGH	40	AEFGH
9	DE	41	BCF
10	ABDE	42	ACF
11	CE	43	BDF
12	ABCE	44	ADF
13	DEGH	45	BCFGH
14	ABDEGH	46	ACFGH
15	CEGH	47	BDFGH
16	ABCEGH	48	ADFGH
17	FH	49	BCDEH
18	ABFH	50	ACDEH
19	CDFH	51	BEH
20	ABCDFH	52	AEH
21	FG	53	BCDEG
22	ABFG	54	ACDEG
23	CDFG	55	BEG
24	ABCDFG	56	AEG
25	DEFH	57	BCH
26	ABDEFH	58	ACH
27	CEFH	59	BDH
28	ABCEFH	60	ADH
29	DEFG	61	BCG
30	ABDEFG	62	ACG
31	CEFG	63	BDG
32	ABCEFG	64	ADG

Letter Key

Letter	Variable	Units	Level With No Letter	Level With A Letter
A	Through volume	VPH	300	700
B	Opposing volume	VPH	300	700
C	Left turn volume	VPH	20	50
D	Right turn volume	VPH	20	50
E	Mean vehicle speed	MPH	35	50
F	Upstream signal distance	Miles	0.5	1.5
G	Downstream signal distance	Miles	0.5	1.5
H	Bypass lane present	---	No	Yes
I	Variables A through H all at "no letter" level			

ence of the bypass lane. It is interesting that the left-turn volume and the opposing volume were significantly related to through traffic delay. This is because as the left turn or opposing volumes increase, left-turn queues build up, and through vehicles must stop behind this queue. The presence of the bypass lane saved through vehicles, on average, about 0.50 sec per vehicle in delay.

The through vehicle percent stops MOE was significantly affected by the opposing volume, left-turn volume, and the presence of the bypass lane. Again, the relationship of the left-turn volume and opposing volume to through traffic MOEs is interesting. The presence of the bypass lane reduced the percentage of through vehicles required to stop from 1.45 to 0.00.

Table 3 lists the results from the analysis of the two-level interactions involving the bypass lane. The through delay and percent stops were both affected only by the interaction of the bypass lane with opposing volume and the left-turn volume. Higher opposing and left-turn volumes meant more delay savings and fewer stops for through traffic as a result of the bypass lane being present.

DRIVER COST ANALYSIS

The final step in the project was to use the two-level interaction means to estimate a driver benefit that corresponds to the delay savings. The driver benefit can be estimated by using

TABLE 2 EXPERIMENT RESULTS FOR MAIN EFFECTS

Variable	Level	Through Traffic Delay, sec/veh		Through Traffic Percent Stops	
		Mean	Significant at 0.05 Level?	Mean	Significant at 0.05 Level?
Through Volume	300 vph	0.73	Yes	0.78	No
	700 vph	1.32		0.67	
Opposing Volume	300 vph	0.96	Yes	0.25	Yes
	700 vph	1.10		1.20	
Left Volume	20 vph	0.95	Yes	0.43	Yes
	50 vph	1.10		1.03	
Right Volume	20 vph	1.05	No	0.78	No
	50 vph	1.01		0.67	
Speed	35 mph	1.18	Yes	0.89	No
	50 mph	0.87		0.57	
Upstream Signal Distance	0.5 mi	0.88	Yes	0.77	No
	1.5 mi	1.18		0.68	
Downstr. Signal Distance	0.5 mi	1.05	No	0.77	No
	1.5 mi	1.00		0.69	
Bypass Lane Present	No	1.25	Yes	1.45	Yes
	Yes	0.80		0.00	

TABLE 3 EXPERIMENT RESULTS FOR INTERACTIONS

Interaction *	Level **	Through Traffic Delay, sec/veh		Through Traffic Percent Stops	
		Mean	Significant at 0.05 Level?	Mean	Significant at 0.05 Level?
Opposing Volume & Bypass Lane	300 & No	1.11	Yes	0.50	Yes
	300 & Yes	0.80		0.00	
	700 & No	1.39		2.41	
	700 & Yes	0.80		0.00	
Left Volume & Bypass Lane	20 & No	1.09	Yes	0.86	Yes
	20 & Yes	0.81		0.00	
	50 & No	1.41		2.05	
	50 & Yes	0.79		0.00	

* All other two-factor interactions involving the bypass lane were not significant at the 0.05 level for both MOEs.

** Volumes are given in vehicles per hour.

the average hourly salary for the drivers passing through the intersection or any other measure of travel cost in use at an agency. The following example will allow the practicing engineer to use these results in their own situations.

For this example, a site that is similar to the one simulated by the experiment is used (i.e., T-intersection, no grades, etc.), which has the following traffic characteristics:

- Through and opposing volumes of 600 vph in peak hours and 250 vph in non-peak hours,
- Left-turn volume of 40 vph in peak hours, and 15 vph in non-peak hours,
- Four peak hours, and 7 non-peak hours per 11-hour traffic "day," and
- Average driver wage of $4.25/hr.

The first step is to calculate the peak hour savings for through traffic. This is done by multiplying the delay savings by the number of vehicles, and by the number of peak hours in the day as follows:

$$600 \text{ vph} \times 0.5 \text{ sec/veh} \times 4 \text{ peak hrs/day} = 1{,}200 \text{ sec/day}$$

The 0.5 sec/veh savings in delay estimated in this calculation is derived from the data in Table 3. The opposing volume is near 700 vph, which had a savings of 0.59 sec/veh for the bypass lane condition, and the left-turn volume is near 50 vph, which had a savings of 0.62 sec/vehicle for the bypass lane condition. On this basis, the 0.50 sec/veh is a reasonable conservative estimate of the delay savings.

The next step is to use the same method to calculate the non-peak hour savings as follows:

$$600 \text{ vph} \times 0.5 \text{ sec/veh} \times 7 \text{ non-peak hrs/day} = 2{,}100 \text{ sec/day}$$

The total delay saving is found by adding each of these numbers

$$1{,}200 + 2{,}100 = 3{,}300 \text{ sec/day} = .917 \text{ hrs/day}$$

Based on 250 working days a year, and the $4.25 hour salary rate, the annual delay savings can be calculated as

$$.917 \text{ hr/day} \times 250 \text{ days/year} \times \$4.25/\text{year} = \$974/\text{year}$$

Savings for non-working days and other hours of the working day could be computed and added to the estimated savings given here. However, the annual maintenance cost of the lane has not been included in this cost estimate, and this amount would have to be subtracted from the annual delay savings. This savings can be compared with the cost of constructing the bypass lane to analyze the cost-effectiveness. Typically in the Charlotte area, a bypass lane would cost approximately $5,000. Given this cost and the delay and stop savings, this lane would pay for itself in approximately 5 years at 0 percent interest, 7 years at 6 percent interest, and 8 years at 10 percent interest.

CONCLUSION

An experiment was conducted to examine the effectiveness of a left-turn bypass lane on a two-lane road in terms of delay and stops experienced by through vehicles at a T-intersection. The experiment allowed examination of eight independent variables that may affect delay and stops at unsignalized intersections, and was conducted using the TRAF-NETSIM traffic simulation model. In general, the presence of a left-turn bypass lane was found to significantly reduce delay experienced by vehicles traveling through on the major road in the direction of the left-turn traffic by about 0.50 sec/veh. In addition, it was found that the number of stops experienced by these through vehicles was reduced in the presence of a left-turn bypass lane. Findings from the experiment should not be generalized outside the conditions of the experiment, which included low left-turn volumes, low-to-moderate speeds, five percent trucks, and no grades or curves.

Adding a left-turn bypass lane was particularly beneficial in the following situations:

1. At intersections where the through volume approached 700 vph, the delay savings for through traffic was found to be approximately 0.6 sec/veh and the percent stops was reduced from about 2.4 to 0.0.
2. At intersections where the through volume approached 300 vph, the delay savings for through traffic was found to be approximately 0.3 sec/veh and the percent stops was reduced from about 0.5 to 0.0.
3. At intersections where the left-turn volume approaches 50 vph, the delay savings for through traffic was found to be approximately 0.6 sec/veh and the percent stops was reduced from about 2.0 to 0.0.
4. At intersections where the left-turn volume approached 20 vph, the delay savings for through traffic was found to be approximately 0.3 sec/veh and the percent stops was reduced from about 0.9 to 0.0.

These findings lead to the conclusion that for sites with the higher through, left-turn, and opposing volume conditions tested for long periods, the left-turn bypass lane is warranted on the basis of delay. When the savings allowed by the bypass lane are compared with the low cost of construction and maintenance, the bypass lane quickly becomes a cost-effective alternative. For lower through, left-turn, and opposing volume conditions, the bypass lane is certainly worth consideration and may be warranted on local conditions.

Additional interesting findings were that the delay and percent stops experienced by through traffic on the major road (in the same direction as the left-turning traffic from the major road) were significantly related to the left turn and opposing traffic volumes. Perhaps future revisions of the chapter, Unsignalized Intersections, in the *Highway Capacity Manual* should include comments on this effect, because no information on this relationship is now available to practitioners. The results of this experiment provide a start in that direction.

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