Effect of Left-Turn Bays on Fuel Consumption on Uncontrolled Approaches to Stop-Sign-Controlled Intersections

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Associated with the reductions in delay and stops that result from the provision of left-turn bays is a reduction in fuel consumption. Less delay and fewer stops mean less fuel consumed by vehicle idling and speed-change cycles. The objective of this research was to estimate the effect of the provision of left-turn bays on fuel consumption on uncontrolled approaches to stop-sign-controlled intersections over a range of volumes, approach speeds, and truck percentages on two-way, two-lane roadways. A series of paired computer simulation runs was conducted by using the NETSIM traffic simulation model to evaluate the fuel consumption of the traffic on the uncontrolled approaches with and without left-turn bays. A pairwise comparison of the NETSIM fuel-consumption output from these runs provided the measure of fuel savings due to left-turn bays. Over the range of conditions studied, the fuel savings varied from zero to more than 20 gal/h for traffic on the approach. The amount of the fuel savings was a complex function of approach volume, opposing volume, left-turn percentage, free-flow approach speed, and truck percentage. Graphs and adjustment factors were developed to describe this relation and provide a means of estimating the fuel savings associated with left-turn bays.

Left-turn bays are provided on uncontrolled approaches to stop-sign-controlled intersections to improve the safety and efficiency of traffic operations on these approaches. The primary function of these left-turn bays is to remove the deceleration and storage of left-turning vehicles from the through lanes and thereby enable through and right-turning traffic to move by them without conflict and delay. Thus, the benefits derived from the provision of these left-turn bays are reductions in accidents, delay, and stops. Previous research (1-3) has found the amounts of these reductions to be functions of the approach, opposing, and left-turn volumes.

Associated with the reductions in delay and stops that result from the provision of left-turn bays is a reduction in fuel consumption. Less delay and fewer stops mean less fuel consumed by vehicle idling and speed-change cycles. The objective of this study was to estimate the effect of the provision of left-turn bays on fuel consumption on the uncontrolled intersections. This effect was evaluated over a range of volumes, approach speeds, and truck percentages. However, the scope of the study was limited to approaches on two-way, two-lane roadways. This paper presents the procedure and findings of this study.

PROCEDURE

A series of computer simulation runs was conducted by using the NETSIM traffic simulation model (4) to simulate traffic operations at a four-legged intersection of two, two-way, two-lane roadways. The intersection was controlled by stop signs on the approaches of the minor roadway. One set of simulation runs was made with left-turn bays on the uncontrolled approaches of the major roadway, and a second set of runs was made without left-turn bays on these approaches. Both sets of runs were made over the same range of volumes, approach speeds, and truck percentages. The effect of the left-turn bays on fuel consumption was then determined by a pairwise comparison of the NETSIM fuel-consumption output from the two sets of runs for identical combinations of volumes, approach speeds, and truck percentages. Thus, for a given combination of these conditions, the effect of a left-turn bay on an approach was computed as the difference between the two runs in the amount of fuel consumed by traffic in the direction of the approach. The results of these computations were then analyzed to examine the relation between the effect of left-turn bays on fuel consumption and traffic conditions.

Intersection Description

The basic intersection used in this study was a four-legged intersection of two, two-way, two-lane roadways with stop sign control on the minor roadway. One configuration of this simulated intersection had left-turn bays on the approaches of the major roadway, and the other simulated configuration had no left-turn bays on these approaches. These two configurations are shown in Figure 1.

Also shown in Figure 1 is the link-node representation of the intersection that was input to the NETSIM model. Links 1-5 and 3-5, which represented the approaches on the major roadway, were coded with and without the left-turn bays. The approach volumes on these links were generated according to the shifted exponential headway distribution contained in the NETSIM model.

Simulation Runs

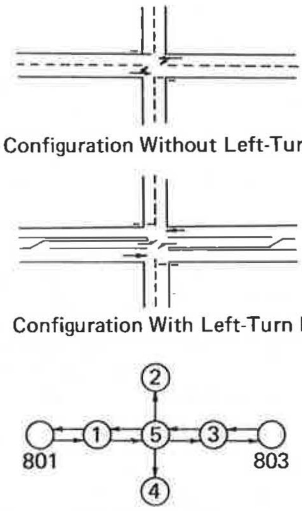
Simulation runs with and without left-turn bays on the major roadway approaches were made over a range of volumes for three approach speeds and three truck percentages. The free-flow speeds on the major roadway approaches were 30, 45, and 50 mph. The truck percentages used were 0, 10, and 20 percent.

For each of the nine combinations of approach speed and truck percentage, volumes were varied over ranges similar to those used by Lee (5) to develop design guidelines for left-turn lanes at priority intersections. The volumes on the study approach were varied over a range of 100-1500 vehicles/h. The volumes used on the opposing approach were equal to, one-half of, and twice the volume on the study approach. The percentage of left turns was varied from 1 to 50 percent of the vehicles entering on the approach. The percentage of left turns on the opposing approach was always equal to that on the study approach. The right-turn percentage was zero in every case. It was assumed that the provision of left-turn bays on the major roadway would have a negligible effect on the fuel consumed by traffic on the stop-sign-controlled approaches of the minor roadway. Therefore, the volumes on the minor roadway were always set equal to zero in order to minimize the computer time required to conduct the simulation runs.

A 30-min period of time was simulated during each run. Prior to the 30-min period, about 10 min of simulation time was required to achieve steady-state conditions.

The runs were initially chosen by using a modi-

Figure 1. Intersection studied.



a. Configuration Without Left-Turn Bays

b. Configuration With Left-Turn Bays

c. Link-Node Diagram

fied response surface design (6,7). This type of experimental design chooses five points for each variable. The points selected are close to the end points, the midpoint, and the 20th and 80th percentiles. This was done for the variables of approach volume and left-turn percentage.

Then the points chosen by the response surface design were run for all combinations of approach speed, truck percentage, and the approach-opposing volume relation. These points were simulated both with and without a left-turn bay on the major approaches. After analysis of these runs, it was determined that there were some major gaps in the data. Therefore, some more combinations were run to fill these gaps. A total of 723 combinations were run. A summary of the runs made is given in the table below [note: for each approach volume, the left-turn percentage combination shown was run for each of the following 27 combinations of opposing volume, free-flow approach speed, and truck percentage: (a) opposing volume equal to approach volume, 0.5 x approach volume, and 2 x approach volume; (b) free-flow approach speed at 30, 45, and 50 mph; and (c) truck percentage at 0, 10, and 20 percent]:

Approach Volume (vehicles/h)	Left-Turn Percentage
100	1,10,20,30,40,50
300	1,10,20,30,40,50
500	1,10,20,30,40,50
700	1,10,20,30,40,50
850	1,5,10,15,20,30,40,50
1000	1,3,5,8,10,15,20,30
1200	1,3,5,8,10,15,20
1500	1,2,5,8,10,15

Data Analysis

The output of all the NETSIM runs was first examined to determine if congestion had occurred on the approach. When congestion had occurred, infinite queues began to form on the approach, which made it impractical to compute the effect on fuel consumption of the left-turn bay. Therefore, the output of runs during which congestion had occurred was eliminated from the analysis.

By using the NETSIM outputs of gallons of fuel consumed and number of entering vehicles for each combination of volumes, approach speed, and truck percentage, the number of gallons of fuel consumed per vehicle by traffic in the direction of the approach (i.e., the fuel consumed on links 1-5 and 5-3 in Figure 1) was computed for both with and without a left-turn bay. The difference between these two values was then multiplied by the hourly approach volume to obtain the gallons of fuel saved per hour on the approach by the provision of a left-turn bay. The fuel savings computed for all combinations of volumes, approach speed, and truck percentage were then analyzed to determine relations between fuel savings and these conditions.

FINDINGS

Initial review of the output of the NETSIM runs determined that congestion occurred on runs with approach and opposing volumes equal to or greater than 1000 vehicles/h. Congestion was also found on runs with approach volumes greater than 500 vehicles/h and opposing volumes greater than 1000 vehicles/h. After these runs were eliminated from the analysis, 473 combinations of volumes, approach speed, and truck percentage remained.

A regression analysis of the fuel savings due to left-turn bays for the remaining 473 combinations was conducted by using linear and polynomial terms. But the results of the regression analysis were not able to provide a relation between fuel savings and traffic conditions that accounted for a satisfactory amount of the variation in fuel savings. However, a comparison of mean fuel savings, conducted at a five percent level of significance, determined that the means for approach speed and truck percentage were significant.

Therefore, since the regression analysis did not provide an acceptable description of the relation between fuel savings and traffic conditions, it was decided to show this relation graphically. Three graphs, one for each approach-opposing volume relation, that show the relation among fuel savings, approach volume, and left-turn percentage were prepared for the combinations of a 45-mph approach speed and 20 percent trucks, which was the approach speed, truck percentage combination that provided the greatest fuel savings. These graphs are shown in Figures 2, 3, and 4.

Based on the mean fuel savings of each of the nine combinations of approach speed and truck percentage, the set of adjustment factors shown in the table below was derived:

Truck Percentage	Adjustment Factors by Approach Speed 30 mph	45 mph	50 mph
0	0.1	0.5	0.6
10	0.2	0.7	0.7
20	0.7	1.0	0.9

The adjustment factor for each combination represents the average portion of the fuel savings of the 45-mph, 20 percent truck combination that is realized with the combination to which the particular factor applies. Thus, to estimate the fuel savings that would result from the provision of a left-turn bay on an approach with an approach speed, truck percentage combination other than 45 mph and 20 percent, the fuel savings found from the appropriate graph (Figure 2, 3, or 4) are multiplied by the appropriate adjustment factor from the above table. For example, if the fuel savings found from the appropriate graph were 10 gal/h and the approach had a 50-mph speed and 10 percent trucks, the fuel savings that would result from providing a left-turn bay on the approach would be 6.0 (10 x 0.6) gal/h for traffic in the direction of the approach.

The adjustment factors in the above table show that the fuel savings at all approach speeds in-

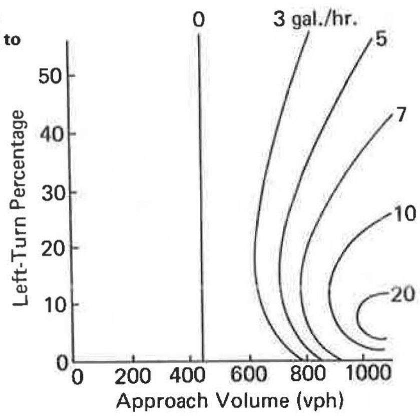


Figure 2. Fuel savings: opposing volume equal to approach volume.

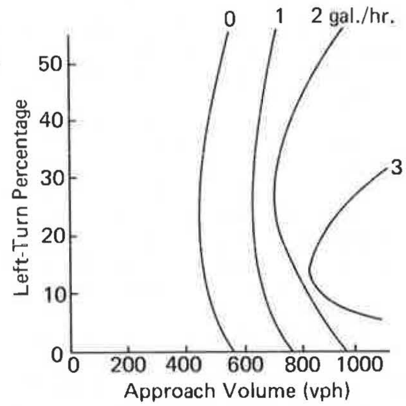


Figure 3. Fuel savings: opposing volume equal to one-half approach volume.

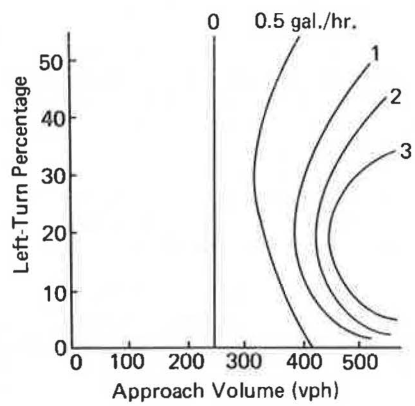


Figure 4. Fuel savings: opposing volume equal to two times approach volume.

crease with an increase in truck percentage, especially as the truck percentage increases from 10 to 20 percent. This increase resulted primarily from the more frequent occurrence of queues created by trucks during simulation runs without left-turn bays. These factors also indicate that the greatest fuel savings are realized for approaches with speeds of 45 mph and 20 percent trucks. The fuel savings for approaches with speeds of 50 mph are about the same as those for approaches with speeds of 45 mph. The fuel savings for approaches with 30-mph speeds average about one-half those on 45-mph approaches as a result of considerably lower fuel-consumption rates associated with speed changes at 30 mph.

Comparison of the graphs shown in Figures 2, 3, and 4 indicates that the pattern of fuel savings is similar on all three graphs, with the greatest fuel savings realized on the graph for opposing volumes equal to approach volumes (Figure 2). On all three graphs, fuel savings increase as approach volumes increase. However, in the case of equal opposing and approach volumes (Figure 2), no fuel savings are realized for approach volumes of less than 450 vehicles/h. In the other two cases, zero fuel saving is realized at approach volumes less than 450 vehicles/h when the opposing volume is one-half of the approach volume (Figure 3) and less than 250 vehicles/h when the opposing volume is twice the approach volume (Figure 4).

Also, on all three graphs, fuel savings increase with left-turn percentage up to a point and then decrease with further increases in the left-turn percentage. And, on all three graphs, the left-turn percentages for maximum fuel savings decrease as approach volumes increase. But, for a given approach volume, the left-turn percentage for maximum fuel savings in the case of equal opposing and approach volumes (Figure 2) is always lower than those of the other two cases (Figures 3 and 4). This was due to the fact that, in this study, the opposing left-turn percentage was equal to the approach left-turn percentage in all cases. Therefore, as the left-turn percentage increased, the opposing through volume actually decreased. Also, the right-turn percentage was zero in every case.

As an example to illustrate the application of the results of this study, consider the addition of a left-turn bay on an uncontrolled approach to a stop-sign-controlled intersection. The volume on the approach is 800 vehicles/h with 10 percent left turns and 10 percent trucks. The approach speed is 30 mph, and the opposing volume is equal to the approach volume. A fuel savings of 7 gal/h is found in Figure 2 for equal approach and opposing volumes of 800 vehicles/h with 10 percent left turns. However, this savings is for a 45-mph approach speed and 20 percent trucks. Therefore, an adjustment factor of 0.2 is found in the adjustment factor table presented earlier for a 30-mph approach speed and 10 percent trucks. The fuel saving of 7 gal/h found in Figure 2 is multiplied by this adjustment factor of 0.2 to obtain the fuel savings of 1.4 gal/h. Thus, the fuel savings that would result from the addition of the left-turn bay would be estimated to be about 1 gal/h.

CONCLUSIONS

In this study, the fuel savings that result from the provision of left-turn bays on the uncontrolled approaches to two-way stop-sign-controlled intersections on two-way, two-lane roadways ranged from zero to more than 20 gal/h per approach. The amount of the fuel savings was dependent on a complex relation among the following approach conditions: (a) approach volume, (b) opposing volume, (c) left-turn percentage, (d) free-flow approach speed, and (e) truck percentage. The greatest fuel savings were found on approaches with equal approach and opposing volumes with more than 950 vehicles/h, 5-10 percent left turns, 45-mph free-flow approach speeds, and 20 percent trucks. However, zero fuel savings were found on these approaches when the approach volume was less than 450 vehicles/h.

The lowest fuel savings were found on approaches with 30-mph free-flow approach speeds and no trucks. The fuel savings on these approaches was one-tenth of that found on approaches with 45-mph free-flow approach speeds and 20 percent trucks. Overall, the fuel savings on approaches with 30-mph free-flow approach speeds averaged about one-half those on approaches with 45-mph free-flow approach speeds. Also, the fuel savings on approaches with 10 percent trucks or less were about 50 percent of those found on approaches with 20 percent trucks.

Considerably lower fuel savings (usually less than 3 gal/h) were found on approaches where the opposing volumes were not equal to the approach volumes. However, under all conditions, the fuel savings on an approach increased with an increase in left-turn percentage up to a point beyond which further increases in left-turn percentage resulted in lower fuel savings. The left-turn percentage at which this point occurred decreased as approach volume increased.

The findings of this study can be used to estimate the fuel savings that would result from the provision of left-turn bays on approaches similar to those considered in the study. However, in using these findings, it should be noted that they apply to uncongested flow conditions with equal opposing and approach left-turn percentages and zero right-turn percentages. In addition, the fuel-consumption rates used in this study were those embedded in the NETSIM model (4), which represent weighted composite 1971 vehicles.

REFERENCES

1. R.B. Shaw and H.L. Michael. Evaluation of Delays and Accidents at Intersections to Warrant Construction of a Median Lane. HRB, Highway Research Record 257, 1968, pp. 17-33.
2. S.L. Ring and R.L. Carstens. Guidelines for the Inclusion of Left-Turn Lanes at Rural Highway Intersections. HRB, Highway Research Record 371, 1971, pp. 64-79.
3. J. Lee and T. Mulinazzi. Design of Left-Turn Lanes for Priority Intersections. TRB, Transportation Research Record 575, 1980, pp. 33-40.
4. E. Lieberman and others. NETSIM Model: Volume 4--User's Guide. FHWA, Rept. FHWA-RD-77-44, Oct. 1977.
5. J. Lee. Left-Turn Lane Design Guidelines for Priority Intersections in the State of Kansas. Center for Research, Inc., Univ. of Kansas, Lawrence, Rept. FHWA-KS-78-1, Feb. 1978.
6. W.G. Cochran and G.M. Cox. Experimental Designs. Wiley, New York, 1957.
7. R.H. Myers. Response Surface Methodology. Allyn and Bacon, Inc., Boston, 1971.