Effect of Left-Turn Bays at Signalized Intersections on Fuel Consumption

JOHN R. TOBIN AND PATRICK T. McCOY

A consequence of 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 cause less fuel to be consumed by vehicle-idling and speed-change cycles. The objective of this research was to estimate the effect of the addition of left-turn bays on fuel consumption on the approaches to two-phase, signalized intersections. These effects were evaluated over a range of approach, opposing, and left-turn volumes for both left-turn bays with and without a protected left-turn phase. However, the scope of the study was limited to isolated intersections of two-way, two-lane streets. A procedure based on the critical-movement-analysis method presented in Transportation Research Board Circular 212 was used to evaluate the effect of left-turn bays. With this technique, the fuel savings that result from the addition of left-turn bays with and without protected phases for 3360 combinations of traffic conditions were computed. These fuel savings ranged from 0.3 to 10 gal/h for traffic on the street on which the left-turn bays were added. A multiple regression analysis of these data determined that the fuel savings that result from the addition of left-turn bays with and without protected phases were curvilinear functions of the initial critical lane volume, opposing volume, and left-turn percentages. Nomographs of these relations were constructed to facilitate the calculation of potential fuel savings that result from the addition of left-turn bays at signalized intersections.

Left-turn bays are provided on approaches to signalized intersections to increase the capacity of the intersections and improve the efficiency of traffic flow through them. The primary function of the left-turn bay is to remove the deceleration and storage of left-turning vehicles from the through lanes and thus enable through and right-turning vehicles to move past them without conflict and delay. Among the benefits derived from the provision of these left-turn bays are reductions in delay and stops. Previous research (1) has indicated that the amounts of the reductions are functions of the approach, opposing, and left-turn volumes.

A consequence of 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 cause less fuel to be 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 the approaches to signalized intersections on fuel consumption. These effects were evaluated over a range of approach, opposing, and left-turn volumes for both left-turn bays with and without an exclusive signal phase. However, the scope of the study was limited to isolated intersections of two-way, two-lane streets with approach speeds of 30 mph. This paper presents the procedure, findings, and conclusions of this study.

PROCEDURE

Previous studies (2) of traffic operations at isolated signalized intersections have shown delay and stops to be functions of signal timing as well as lane configuration. Therefore, in an effort to isolate the effect of left-turn bays, the critical-movement-analysis method presented in Transportation Research Board (TRB) Circular 212 (3) served as the basis of the procedure used in this study.

For each combination of approach, opposing, cross-street, and left-turn volumes considered in this study, the critical-movement-analysis method was used to compute the intersection volume-to-capacity ratios with and without left-turn bays on both approaches of one of the two intersecting streets. Each of these volume-to-capacity ratios was then expressed in terms of stopped-time delay per vehicle by applying the relation between stopped-time delay and volume-to-capacity ratio presented in TRB Circular 212. The results are given in the table below (3):

Volume-to-Capacity Ratio	Stopped-Time Delay (s/vehicle)
0.00-0.60	0.0-16.0
0.61-0.70	16.1-22.0
0.71-0.80	22.1-28.0
0.81-0.90	28.1-35.0
0.91-1.00	35.1-40.0

Next, the following empirical relation determined by Reilly and others (4) was used to compute the percentage of vehicles stopped from the stopped-time delay values:

$$PVS = \log_{10} (1.3 \times STD) \times 55 - 14 \qquad (1)$$

where PVS is the percentage of vehicle stopped, and STD is the stopped-time delay (s/vehicle).

The difference in the stopped-time delay and percentages of vehicles stopped with and without left-turn bays were then computed. These differences were multiplied by the approach volumes on the street on which the left-turn bays had been added to determine the reductions in vehicle hours of delay and number of vehicles stopped that were caused by the provision of left-turn bays. The resultant savings in fuel consumption were then computed by using the following equation, which was based on fuel-consumption data for light-duty vehicles presented by Dale (5):

$$f = 0.65D + (9.3\ S_t/1000) + (1.3\ S_\ell/1000) \qquad (2)$$

where

- f = fuel savings for traffic on street on which left-turn bays were added (gal/h),
- D = reduction in stopped-time delay on street on which left-turn bays were added (vehicle-h/h),
- S_t = reduction in through vehicle stops on street on which left-turn bays were added (stops/h),
- S_ℓ = reduction in left-turn vehicle stops on street on which left-turn bays were added (stops/h),
- 0.65 = fuel-consumption rate of idling vehicle (gal/vehicle-h),
- 9.3 = stop-go fuel-consumption rate for stop from 30 mph (gal/1000 stop-go cycles), and
- 1.3 = stop-go fuel-consumption rate for stop from 10 mph (gal/1000 stop-go cycles).

As indicated in Equation 2, through vehicles were assumed to stop from and return to a speed of 30 mph and left-turning vehicles were assumed to stop from and return to a speed of 10 mph.

In this study, two basic cases were examined: (a) the addition of left-turn bays without a protected left-turn phase and (b) the addition of left-turn bays with a protected left-turn phase. In both cases, the street on which the left-turn bays were added initially had no protected left-turn phase. For each of the two basic cases, 1680 combinations of initial-condition (i.e., without left-turn bays) values of the following five variables were analyzed:

1. Initial level of service (C, D, and E),
2. Initial critical lane volume on the street on which left-turn bays were added (level-of-service E = 900-1500 passenger cars/h at 100 passenger cars/h intervals, level-of-service D = 800-1400 passenger cars/h at 100 passenger cars/h intervals, and level-of-service C = 700-1300 passenger cars/h at 100 passenger cars/h intervals),
3. Equivalent lane volume opposing initial critical lane volume on the street on which left-turn bays were added expressed as a percentage of the initial critical lane volume (30-100 percent at 10 percent intervals),
4. Percentage of left turns on the approach with the initial critical lane volume (10-50 percent at 10 percent intervals), and
5. Number of signal phases on the cross street (one and two).

Given the above initial conditions without left-turn bays, the critical-movement-analysis procedure was used to compute the peak-period passenger car volumes that would have yielded the initial level of service. Then, starting with these passenger car volumes, left-turn bays were added and a new level of service was computed. As explained previously, the volume-to-capacity ratios associated with this new level of service and the initial level of service were then used to compute the fuel savings that result from the addition of the left-turn bays. In the analysis of each case, it was assumed that (a) the percentage of left turns on the opposing approach was equal to that on the critical approach, (b) all lanes were 12 ft wide, (c) the peak-hour factor was 1.00, (d) the percentage of trucks and buses was zero, and (f) there were no right turns.

FINDINGS

The fuel savings that result from the provision of left-turn bays for the 3360 cases described above range from 0.3 to 10 gal/h on the street on which the left-turn bays were added. These data were analyzed to determine the relation between the fuel savings and the initial conditions. A stepwise multiple linear regression analysis was conducted with fuel savings as the dependent variable and the initial conditions as the independent variables. The regression analysis was applied to the data for each of the basic cases and to their combined data sets.

As a result of the regression analysis, the following relations were found to be statistically significant (α = 0.10). For left-turn bays without a protected phase,

$$f = -7.41 + (5.71V/10^3) + (2.48V_0/10^3) + 3.17 \log_{10} PLT - (1.24PLT^3/10^5) \quad (3)$$

For left-turn bays with a protected phase,

$$f = -8.60 + (6.12V/10^3) + (1.70V_0/10^3) + 3.591 \log_{10} PLT - (1.01PLT^3/10^5) \quad (4)$$

where

f = fuel savings for traffic on street on which left-turn bays were added (gal/h),
V = initial critical lane volume on street on which left-turn bays were added (passenger cars/h),
V_0 = equivalent lane volume opposing initial critical lane volume on street on which left-turn bays were added (passenger cars/h), and
PLT = percentage of left turns on initial critical-lane-volume approach.

These equations accounted for 90 percent of the variance of the fuel savings. Although these two equations contain the same independent variables with similar coefficients, it was determined that they are statistically different at the 10 percent level of significance.

The relations expressed in Equations 3 and 4 are consistent with the expectations that fuel savings should increase with increasing approach volumes and that fuel savings should increase with increasing opposing volumes. Also, as expected, the influence of the opposing volume is less in the case of left-turn bays with a protected phase than it is in the case of left-turn bays without a protected phase because, in the critical-movement-analysis method, the left-turn volume adjustment for protected left-turn movements is independent of the opposing volume (3).

Fuel savings would also be expected to be positively correlated with the percentage of left turns. But, in Equations 3 and 4, the percentage of left turns has both a positive and a negative influence on fuel savings. The negative influence is due to the fact that, in the critical-movement-analysis method, the actual approach volumes that correspond to a given equivalent volume adjusted for left turns on a one-lane approach decrease with an increase in the percentage of left turns. Therefore, since the actual approach volumes were used to compute the fuel consumption, the fuel savings will tend to also decrease with increased left-turn percentages. Thus, the fuel savings reflect the combined effects of a higher left-turn percentage increasing the volume-to-capacity ratio and decreasing the actual volume used in the calculation of fuel consumption.

To confirm this explanation of the dual effects of the left-turn percentage, a regression analysis of percent fuel savings versus the initial conditions was conducted. Because percent fuel savings is primarily sensitive to changes in the volume-to-capacity ratio, it was expected that the results of this regression analysis would only show a positive influence of left-turn percentage. The following statistically significant (α = 0.10) relations were the result of this regression analysis. For left-turn bays without a protected phase,

$$\%f = -37.8 + (15.3V/10^3) + (14.2V_0/10^3) + 31.7 \log_{10} PLT \quad (5)$$

For left-turn bays with a protected phase,

$$\%f = -49.9 + (22.9V/10^3) + (9.02V_0/10^3) + 34.0 \log_{10} PLT \quad (6)$$

where %f is the percent fuel savings for traffic on a street on which left-turn bays were added. As expected, no negative influence of left-turn percentage is found in Equations 5 and 6.

Over the entire range of conditions examined in this study, the fuel savings that result from the addition of left-turn bays without a protected left-turn phase were always greater than those that result from the addition of left-turn bays with a protected left-turn phase under the same set of conditions. There were two primary reasons for this occurrence. First, the addition of a left-turn phase does reduce the capacity of the intersection,

Figure 1. Fuel savings for left-turn bays without protected left-turn phase.

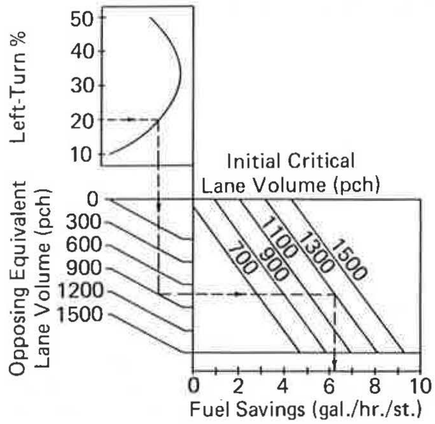
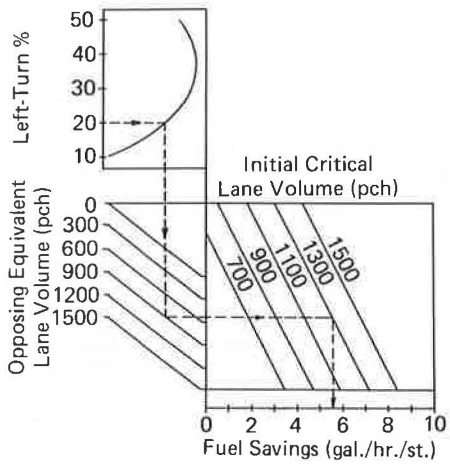


Figure 2. Fuel savings for left-turn bays with protected left-turn phase.



which tends to reduce the fuel savings to be realized. Second, in this study, the left-turn percentages on the opposing and critical-lane-volume approaches were equal for all conditions. Thus, the potential advantage of a left-turn phase tended to be negated as the left-turn percentage was increased because with an increased left-turn percentage, the actual approach volumes, which yielded the assumed equivalent lane volumes, tended to be decreased. As these volumes were decreased, so were the passenger car equivalents used to calculate the equivalent lane volumes of the unprotected left-turn movements. This effect tended to make the unprotected phasing more favorable. If instead an approach with a high left-turn percentage would have been opposed by an approach with a high volume and a low left-turn percentage, this effect would not have been present and the protected phasing would probably have been more favorable. Therefore, the limitation of this study to cases of equal left-turn percentage should be recognized when using its results.

To facilitate the calculation of potential fuel savings that result from the addition of left-turn bays at signalized intersections, Equations 3 and 4 are presented as nomographs in Figures 1 and 2, respectively. These nomographs represent the fuel savings on the approaches to which the left-turn bays were added over the range of conditions investigated in this study. Fuel savings realized on the cross street due to the improved level of service are not included in these figures. Also, the fuel savings in these figures are subject to the assumptions of this analysis.

CONCLUSIONS

The findings of this study indicate that the addition of left-turn bays at isolated, two-phase, signalized intersections of two-way, two-lane streets provide fuel savings for traffic on the street on which the left-turn bays are added. The fuel savings were found to range from 0.3 to 10 gal/h as a curvilinear function of the initial critical lane volume, the volume opposing the initial critical lane volume, and the percentage of left turns. In addition, on streets with equal left-turn percentages on its approaches, the addition of a left-turn bay without a protected left-turn phase always provided greater fuel savings than did the addition of a left-turn bay with a protected left-turn phase because of the combined effects of the lower intersection capacity caused by the addition of a phase and the reduction in the opposing through volume that accompanied an increase in the equal left-turn percentages. Unfortunately, only cases with equal left-turn percentages were considered in this study. Therefore, the fuel-savings breakeven point between protected and unprotected left-turn bays was not determined.

Although the procedures of this study are generally applicable, the application of the regression equations and nomographs developed in this study should be limited to the range of conditions examined in this study. Likewise, their application should recognize the following assumptions on which their development was based: (a) equal left-turn percentages, (b) 12-ft lanes, (c) peak-hour factor of 1.00, (d) no trucks or buses, (e) no right turns, and (f) 30-mph approach speeds. According to the critical-movement-analysis method (3) and the procedure of this study, fuel savings higher than those found in this study would be expected in cases with higher approach speeds and/or trucks and buses because of the higher fuel-consumption rates associated with these conditions. However, lower fuel savings would be expected on approaches with lower peak-hour factors, narrower lanes, and right turns because, for a given level of service, the higher passenger car equivalents associated with these conditions result in lower actual traffic volumes that consume fuel.

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