Additional Lost Time Caused by Permitted Left Turns

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Permitted left-turn phasing is commonly used to increase capacities and reduce delays at signalized intersections. But, under heavy traffic volumes, when they can only be made after the green, permitted left turns interfere with the start of subsequent phases, increasing the lost times and reducing the capacities of these phases. The primary objective of this research was to determine the additional lost time caused by permitted left turns. Additional lost times of protected left-turn phases, which were caused by cross-street permitted left turns, were measured at three signalized intersections. Multiple regression analysis of these data determined that the additional lost time depended on the number of permitted left turns made at the end of the cross-street green and the grade of the exclusive lane from which the protected left turns were made. The effects of the additional lost time on intersection capacity were evaluated. The results of this research provide a means of accounting for these effects in the analysis and design of signalized intersections.

Permitted left-turn phasing allows left turns to be made through gaps in the opposing traffic flow. The capacity of this phasing depends on the availability of adequate gaps in the opposing flow. As the opposing flow increases, the number of adequate gaps and the capacity of the permitted left-turn phase decrease. When there are no adequate gaps in the opposing flow, the only left turns that can be made are those made after the green by vehicles already waiting in the intersection for an adequate gap. Thus, for high opposing volumes, this becomes the major source of permitted left-turn capacity.

The 1985 *Highway Capacity Manual* (HCM) *(1)* recognizes this situation. It is assumed that an average of two vehicles can turn left after the green, therefore, two vehicles per signal cycle is considered to be the minimum capacity of a permitted left-turn phase. According to the HCM, if a permitted left-turn phase is used following a protected left-turn phase, the left-turn capacity provided by the protected or permitted left-turn phasing is at least two vehicles per cycle more than that provided by the protected left-turn phase alone.

However, under conditions of high opposing volumes, when the permitted left-turn capacity is at its minimum, left turns made after the green interfere with the start of the traffic flow on the subsequent phase. This interference increases start-up lost time at the beginning of the subsequent phase. Increased lost time reduces the effective green time of the subsequent phase, which in turn, reduces the capacity of the subsequent phase. Therefore, under these conditions, the increase in left-turn capacity provided by a permitted left-turn phase is offset to some extent by a decrease in the capacity of the subsequent phase. Of course, the effect of this capacity trade-off on the overall efficiency of traffic operations at a particular intersection depends on the prevailing conditions involved. But, in order to account for this effect in the analysis of intersection capacity and the design of signal timing plans, the amount of this increase in lost time must be determined.

BACKGROUND

Previous Research

The relatively inefficient transfer of right-of-way associated with permitted left-turn phasing is well-recognized by traffic engineers *(2)*; however, few studies of signalized intersection capacity have considered its effects. In an analysis of starting delays observed at 13 intersection approaches, Bartle et al. *(3)* noted that an important factor in explaining the variation in the mean starting delays among the approaches might be the volume of traffic on the cross streets, that is, the likelihood of left turns from the cross street being made after the cross-street green.

Webster and Cobbe *(4)* estimated the extra delay to the start of the subsequent cross-street phase, which is caused by left turns made at the end of the green, as follows:

$$d = 2.5\,(n_\alpha - n_l) - I \tag{1}$$

where

d = extra delay to cross-street traffic, in seconds;
n_α = average number of left turns per cycle;
n_l = maximum number of left turns per cycle that can use gaps in the opposing traffic; and
I = intergreen time, in seconds.

If the solution to Equation 1 is negative, no additional lost time would be experienced by cross-street traffic. The difference between n_α and n_l in Equation 1 represents the average number of left turns made at the end of the green. According to the 1985 HCM *(1)*, under conditions of high opposing volumes and minimum permitted left-turn capacity, this number would be two vehicles per cycle. For these conditions and an intergreen time or change interval of 3.0 sec, the additional lost time to the subsequent cross-street phase would be 2.0 sec, according to Equation 1. Webster and Cobbe *(4)* pointed out that in order to determine whether or not a particular sequence of signal timings will provide adequate capacity, it is necessary to make these calculations.

One of the objectives of a study conducted by Johnsen and Matthias *(5)* was to investigate the effect of cross-street, left-turning vehicles on the capacity of protected left-turn movements. The mean number of vehicles per loaded, protected left-

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turn phase with interference from cross-street, left-turning vehicles was compared with the mean number of vehicles per loaded, protected left-turn phase without interference. It was expected that the mean number of vehicles moving on the phases with interference would be less than that on the phases without interference. However, this was found to be true in only 10 of the 30 cases tested. In the other 20 cases, the presence of permitted cross-street, left-turning vehicles did not significantly reduce the capacity of the protected left-turn movements. It was concluded that these unexpected results indicated that further research was needed to determine if the intensity of interference varies under different conditions.

Objectives

The objectives of the research reported in this paper were: (a) to determine the additional lost time caused by permitted left turns, and (b) to evaluate the effects of the additional lost time on the analysis of signalized intersection capacity and the design of signal timing plans. The procedure, finding, and conclusions of this research are presented.

PROCEDURE

Field studies were conducted at three signalized intersections in Omaha, Nebraska. The studies involved the measurement of the lost time at the beginning of green times that followed permitted left-turn phases. A regression analysis was conducted to determine the relationship between the lost time and the number of cross-street left turns made at the end of the preceding phase green. The additional lost time caused by permitted left-turn phases was determined from this relationship.

Study Sites

The study sites selected were three right-angle, signalized intersections of major arterial streets in Omaha, Nebraska. The sites were selected because they were locations where left turns were frequently made after green times of permitted left-turn phases on the cross streets. Descriptions of the study sites pertinent to the objectives of this research are given in Table 1.

At all three study sites, lost times were measured for left turns from exclusive lanes controlled by protected left-turn phases that followed cross-street phases with permitted left turns. The cycle lengths at all three sites were 90 sec with 5.0-sec change intervals for the preceding cross-street phases. All lanes studied were 12 ft wide and located on 90-ft streets. The lanes at Sites 1 and 2 were on level grades, whereas the lane at Site 3 was on a 6 percent upgrade. The cross-street widths at Sites 1 and 2 were 80 ft; the cross-street width at Site 3 was 70 ft. Thus, from the point of view of this study, Sites 1 and 2 were identical. The major differences between Site 3 and the other two sites were that the lane studied at Site 3 was on a 6 percent upgrade, and those of Sites 1 and 2 were on level grades.

Data Collection

Lost time at the beginning of a green is the sum of the start-up delays experienced by the first few vehicles in a stopped queue. At the beginning of the green, these vehicles enter the intersection at headways greater than the average headway under saturation flow. Once these vehicles have entered the intersection, the remaining vehicles enter the intersection at the saturation flow rate. According to the procedure for the direct measurement of prevailing saturation flow rates, which is presented in the HCM *(1)*, the prevailing saturation flow rate from an approach lane occurs after the fourth vehicle in a stopped queue enters the intersection. Therefore, the lost time at the beginning of the green is the sum of the start-up delays experienced by the first four vehicles in a stopped queue.

The sum of the start-up delays experienced by the first four vehicles in the queue can be computed as follows:

$$D = T - 3H \qquad (2)$$

where

D = sum of the start-up delays experienced by the first four vehicles in the queue, in seconds;
T = total time required for the first four vehicles in the queue to enter the intersection, in seconds; and
H = average headway under saturation flow, in seconds.

If the first four vehicles in the queue experienced no start-up delays, the total time required for them to enter the intersection would be the number of headways between them, three, times the average headway under saturation flow, *H*. Therefore, the sum of their start-up delays, *D*, or in other words, the lost time

TABLE 1 STUDY SITES

Site No.	Intersection	Lane Studied[a] Width (ft)	Grade (%)	Approach Street Width (ft)	Cross Street Width (ft)	Change Internal (sec)	Cycle Length (sec)
1	72nd and Dodge	12	0	90	80	5.0	90
2	72nd and Pacific	12	0	90	80	5.0	90
3	90th and Dodge	12	+6	90	70	5.0	90

NOTE: All study sites were at right-angle intersections of major arterial streets.

[a] All lanes studied were exclusive left-turn lanes controlled by protected left-turn phases that followed cross-street phases with permitted left turns.

at the beginning of green, is the total time required for the vehicles to enter the intersection, T, minus the time that would be required for them to enter if there were no start-up delays, $3H$.

The additional lost time caused by the interference of permitted left turns from the cross street can be computed as follows:

$$\Delta D = D_i - D_0 \tag{3}$$

where

ΔD = additional lost time caused by interference of permitted left turns from the cross street, in seconds;
D_i = lost time at the beginning of green when there is interference, in seconds; and
D_0 = lost time at the beginning of green when there is no interference, in seconds.

Expressing the lost times in terms of Equation 2, Equation 3 becomes

$$\Delta D = (T_i - 3H) - (T_0 - 3H) \tag{4}$$

or

$$\Delta D = T_i - T_0 \tag{5}$$

where

T_i = total time required for the first four vehicles in the queue to enter the intersection when there is interference, in seconds; and
T_0 = total time required for the first four vehicles in the queue to enter the intersection when there is no interference, in seconds.

Thus, the data collected in this research were the times, T_i and T_0, required for the first four vehicles in stopped queues to enter the intersections with and without the interference of permitted left turns from the cross streets.

At each study site, the time required for the first four vehicles in a stopped queue to enter the intersection was measured for several signal cycles. This time was measured by starting a stop watch at the beginning of the green and stopping it at the instant the rear axle of the fourth vehicle in the queue crossed the stop line. For each measurement, it was noted as to whether or not there was interference by permitted left turns from the cross street (left turns being made from the cross street after the cross-street green). If there was interference, the number of permitted left turns causing the interference was recorded.

Data were collected only for passenger-car queues and were not collected for queues in which one or more of the first four vehicles was not a passenger car. At each study site, data were collected during the peak periods until at least 100 observations with interference and 100 observations without interference were obtained. To obtain this amount of data, 2 to 3 days of data collection at each site were required.

Data Analysis

A multiple linear regression analysis of the data collected was performed using the Statistical Analysis System (SAS) *(6)*. The regression model used was as follows:

$$Y_i = \beta_0 + \beta_1\chi_{1i} + \beta_2\chi_{2i} + \beta_3\chi_{3i} + \beta_4\chi_{1i}\chi_{2i} + \beta_5\chi_{1i}\chi_{3i} + \varepsilon_i \tag{6}$$

where

Y_i = time required for the first four vehicles in a stopped queue to enter the intersection in the ith cycle, in seconds;
$\beta_0, \beta_1, \beta_2, \beta_3, \beta_4$, and β_5 = regression parameters;
χ_{1i} = number of cross-street permitted left turns made after a cross-street phase green on the ith cycle;
χ_{2i} = 1 if location on the ith cycle is Site 2, zero otherwise;
χ_{3i} = 1 if location on the ith cycle is Site 3, zero otherwise; and
ε_i = random error on ith cycle.

The indicator variables χ_{2i} and χ_{3i} were used to account for the effects of study sites. The regression analysis was conducted using a stepwise procedure with both forward and backward selection at the 0.05 level of significance.

The regression function for the model in Equation 6 is

$$E(Y) = \beta_0 + \beta_1\chi_1 + \beta_2\chi_2 + \beta_3\chi_3 + \beta_4\chi_1\chi_2 + \beta_5\chi_1\chi_3 \tag{7}$$

where $E(Y)$ is the expected value of Y.

The regression functions for the individual study sites are as follows:

Site 1: $E(Y) = \beta_0 + \beta_1\chi_1$ (8)
Site 2: $E(Y) = (\beta_0 + \beta_2) + (\beta_1 + \beta_4)\chi_1$ (9)
Site 3: $E(Y) = (\beta_0 + \beta_3) + (\beta_1 + \beta_5)\chi_1$ (10)

Thus, the regression parameters of particular interest in this research were β_1, β_4, and β_5 because they were indicative of the additional lost times caused by permitted left turns. These additional lost times are: β_1 at Site 1; $(\beta_1 + \beta_4)$ at Site 2; and $(\beta_1 + \beta_5)$ at Site 3. If β_4 and β_5 were equal to zero, then the additional lost times would have been the same at all three study sites. If β_1 was also equal to zero, then there would have been no additional lost time due to the permitted left-turn phasing on the cross streets.

FINDINGS

Over 200 observations of the total time required for the first four vehicles in stopped queues to enter the intersections were made at each study site. About one-half of these observations

TABLE 2 SAMPLE SITES

Study Site	Level of Interference[a] 0	1	2	3	Total Sample Size
1	117	50	47	18	232
2	102	58	43	4	207
3	109	60	36	6	211

[a] Number of cross-street, permitted left turns made at the end of the cross-street phase green.

were made when there was no interference from permitted left turns from the cross street. The other one-half of the observations were made when there was one, two, or three cross-street, permitted left turns interfering with the start up of the stopped queue. The number of observations made at each study site under each level of interference is given in Table 2.

As a result of the regression analysis, the following prediction equation was found:

$$\hat{Y} = 8.74 + 1.28X_1 + 0.714X_3 - 0.256X_1X_3 \tag{11}$$

where $\hat{Y}$ is the predicted value of Y.

All of the regression coefficients in Equation 11 were statistically significant at the 0.05 level. The coefficient of determination (R^2) for Equation 11 was 0.67.

As indicated by Equation 11, the results of the regression analysis showed that there was no significant difference between Sites 1 and 2, but Site 3 was significantly different. This was not unexpected because the exclusive left-turn lanes studied were on level grades at both Sites 1 and 2, whereas the exclusive left-turn lane studied at Site 3 was on a 6 percent upgrade.

The prediction equation for Sites 1 and 2 (that is, Equation 11 with $X_3 = 0$) was

$$\hat{Y} = 8.74 + 1.28X_1 \tag{12}$$

This prediction equation for Site 3 (that is, Equation 11 with $X_3 = 1$) was

$$\hat{Y} = 9.45 + 1.02X_1 \tag{13}$$

Therefore, at Sites 1 and 2, the average time required for the first four vehicles in a stopped queue to enter the intersection without interference from cross-street, permitted left turns was 8.74 sec, and the average additional lost time per interfering permitted left-turn vehicle from the cross street was 1.28 sec. At Site 3, these values were 9.45 and 1.02 sec, respectively.

Because approach grade was the major difference between Site 3 and the other two sites, these findings suggest that the additional lost time was dependent on approach grade. The additional lost time per interfering vehicle was lower on the 6 percent upgrade at Site 3 than it was on the level approaches of Sites 1 and 2 (1.02 versus 1.28 sec). This lower additional lost time probably occurred because the slower start up of the queues on the upgrade afforded the permitted left turns from the cross street more time to clear without affecting the discharge of the queues. The slower start up of the queues on the upgrade was indicated by the fact that the time required for the first four vehicles in a stopped queue to enter the intersection, without interference, at Site 3 was 9.45 sec, and was only 8.74 sec at Sites 1 and 2.

CALCULATION OF ADDITIONAL LOST TIME

The findings of this research indicated that the amount of additional lost time experienced by traffic in an exclusive left-turn lane, which was controlled by a protected left-turn phase that followed a cross-street phase with permitted left turns, was dependent on the number of cross-street left turns made at the end of the cross-street phase green. On level approaches, this additional lost time was 1.28 sec per cross-street left turn made at the end of the cross-street phase green. Furthermore, on the 6 percent upgrade, lost time was 1.02 sec. Therefore, the average additional lost time per cycle for such lanes, which would be used in the analysis of intersection capacity and the design of signal timing plans, would be dependent on the average number of cross-street, permitted left turns per cycle made at the end of the cross-street phase green.

As indicated in Equation 1, Webster and Cobbe *(4)* estimated the average number of cross-street, permitted left turns per cycle made after the cross-street phase green to be equal to the average permitted-phase left-turn demand per cycle on the cross street minus the maximum number of permitted left turns that can be made per cycle during the cross-street phase green. According to the HCM *(1)*, the permitted left-turn capacity during the phase green of a permitted left-turn phase is

$$C_{PLT} = (1{,}400 - V_o)\,(g/C)_{PLT} \geq 0 \tag{14}$$

where

C_{PLT} = capacity of permitted left-turn phase at green, in vehicles per hour;
V_o = opposing traffic through flow plus right-turn flow rate, in vehicles per hour; and
$(g/C)_{PLT}$ = effective green ratio for the permitted left-turn phase, in seconds.

If the opposing flow rate V_o is greater than 1,400 vehicles per hour, the capacity C_{PLT} is equal to zero. Therefore, the average number of cross-street, permitted left turns per cycle made after the cross-street phase green is

$$N_{PLT} + (V_{PLT} - C_{PLT})/C \geq 0 \tag{15}$$

where

N_{PLT} = average number of cross-street, permitted left turns per cycle after the cross-street phase green;

V_{PLT} = left-turn demand on cross-street, permitted left-turn phase, in vehicles per hour; and
C = cycle length, in seconds.

If the capacity, C_{PLT}, is greater than the demand, V_{PLT}, the average number, N_{PLT}, is equal to zero. Of course, there is also a maximum value of N_{PLT}, that would depend on the intersection geometrics and signal timing, as well as the aggressiveness of local drivers. The HCM *(1)* assumes a maximum value of two vehicles per cycle for N_{PLT}. The maximum value of N_{PLT} observed in this study was three vehicles per cycle.

Also, it should be noted that V_{PLT} in Equation 15 is not necessarily the total left-turn demand on the cross street but is only that portion of the cross-street left-turn demand assigned to the permitted left-turn phase on the cross street.

Thus, the average additional lost time per cycle experienced by traffic in an exclusive left-turn lane, which is controlled by a protected left-turn phase that follows a cross-street phase with permitted left turns, is computed based on the approach grade of the exclusive left-turn lane as follows:

On level approaches: $\Delta l = 1.28\ N_{PLT}$ (16)

On 6 percent upgrades: $\Delta l = 1.02\ N_{PLT}$ (17)

where Δl = average additional lost time per cycle, in seconds.

The additional lost time, Δl, would be added to the lost time that would normally be used for the protected left-turn phase. Therefore, if a protected left-turn phase from exclusive left-turn lanes was normally assumed to have a lost time of 4.0 sec, the additional lost time, Δl, would be added to the 4.0 sec if the protected left-turn phase followed a cross-street phase with permitted left turns.

EFFECTS OF ADDITIONAL LOST TIME

Additional lost time at a signalized intersection reduces the capacity of the intersection, which, in turn, increases the cycle lengths required to accommodate given levels of demand. Both of these effects increase the intersection delay, which, according to the HCM *(1)*, reduces the level of service provided at the intersection.

For example, in the capacity analysis procedure described in the HCM *(1)*, the critical volume-to-capacity (V/C) ratio of a signalized intersection is computed as follows:

$$X_c = \frac{\sum_i (v/s)_{ci}\, C}{C - L} \tag{18}$$

where

X_c = critical V/C ratio for the intersection;
$\sum_i (v/s)_{ci}$ = summation of flow ratios for all critical lane groups, i;
C = cycle length, in seconds; and
L = total lost time per cycle, in seconds.

The total lost time per cycle, L, is the sum of the lost times for all critical lane groups.

The total additional lost time per cycle length caused by cross-street phases with permitted left turns is

$$\Delta L = \sum_j \Delta l_j \tag{19}$$

where

ΔL = total additional lost time per cycle, in seconds; and
$\sum_j \Delta l_j$ = summation of average additional lost times per cycle for all critical lane groups, j, that are protected left turns from exclusive left-turn lanes and that follow cross-street phases with permitted left turns, in seconds.

The average additional lost times, Δl_j, are computed with Equation 16 or 17, depending on the grade of the exclusive left-turn lane.

Thus, it follows from Equations 18 and 19, that the increase in the critical V/C ratio, X_c, that results from the consideration of the additional lost time caused by cross-street permitted left turns is

$$\Delta X_c = \left[\frac{\Delta L}{C - (L + \Delta L)}\right] 100 \text{ percent} \tag{20}$$

where ΔX_c = percentage increase in the critical V/C ratio. The total time per cycle, L, in Equation 20 is the sum of the lost times that would normally be assumed for all critical lane groups (that is, 3.0 to 5.0 sec per critical lane group).

For example, if 4.0 sec was the lost time normally assumed for each critical lane group, and there were four critical lane groups, the total lost time per cycle, L, would be 16.0 sec. If two of the critical lane groups were protected left turns, from exclusive lanes on level approaches, which followed cross-street phases with averages of two permitted left turns per cycle made at the end of the cross-street phase green, the additional lost time per cycle, ΔL, from Equations 16 and 19 would be 5.12 sec. If the cycle length, C, was 90 sec, the percentage increase in the critical V/C, ΔX_c, from Equation 20, would be 7.4 percent.

It also follows from Equations 18 and 19 that the increase in cycle length that results from the consideration of the additional lost time caused by cross-street, permitted left turns is

$$\Delta C = \left(\frac{\Delta L}{L}\right) 100 \text{ percent} \tag{21}$$

where ΔC is the percentage increase in cycle length. This percentage increase in cycle length, ΔC, is the increase in cycle length that would be necessary in order to maintain the same critical volume-to-capacity ratio, X_c.

Therefore, in the example cited above, if the cycle length was increased in order to avoid any increase in the critical V/C ratio, X_c (that is, ΔX_c = 0 percent), the percentage increase in the cycle length, ΔC from Equation 21 would be 32 percent. In other words, the cycle length would have to be increased from 90 to 118.8 sec in order to maintain the same critical V/C ratio, X_c.

Another aspect of the effects of the additional lost time caused by permitted left turns is their impact on the capacity of subsequent phases. The average additional lost time per cycle experienced by a subsequent, protected left-turn phase from an exclusive lane is computed by Equations 16 and 17. This lost time is the per-cycle reduction in the effective green time of the protected left-turn phase. Therefore, the reduction in the capacity of the protected left-turn phase is

$$\Delta C_{LT} = \Delta l/2.10 \tag{22}$$

where ΔC_{LT} is the reduction in capacity, in vehicles per cycle; and Δl is the average additional lost time per cycle from Equation 16 or 17, in seconds. The 2.10 sec in Equation 22 is the saturation-flow-rate headway for protected left turns from an exclusive lane *(1)*.

Under conditions of high opposing volumes, the HCM *(1)* assumes that the minimum capacity of a permitted left-turn phase is two vehicles per cycle, which are left turns made at the end of the green. For a subsequent protected left-turn phase from an exclusive lane on a level, cross-street approach, the average additional lost time, Δl, caused by these two vehicles would be 2.56 sec per cycle, according to Equation 16. Consequently, the reduction in the capacity of the protected left-turn phase, ΔC_{LT}, from Equation 22, would be 1.2 vehicles per cycle. Therefore, in effect, whereas the permitted left-turn phase increases the left-turn capacity of the street on which it applies by two vehicles per cycle, it also reduces the left-turn capacity of the cross-street by 1.2 vehicles per cycle. Of course, the consequences of the trade-off relative to the overall operational efficiency of the intersection would depend on the prevailing conditions involved.

CONCLUSIONS

Based on the results of this research, the following conclusions were reached in regard to the additional lost time caused by permitted left turns:

1. Permitted left-turn phases significantly increase the lost time of subsequent, protected left-turn phases from exclusive lanes on the cross streets; and thereby, reduce the capacities of the protected left-turn phases.
2. The amount of the additional lost time experienced by a protected left-turn phase depends on the number of permitted left turns made at the end of the preceding cross-street green, and the grade of the exclusive lane from which the protected left turns are made.
3. For protected left-turn phases from exclusive lanes on level approaches, the additional lost time is 1.28 sec per cross-street, permitted left turn made at the end of the cross-street phase green.
4. For protected left-turn phases from exclusive lanes on 6 percent upgrades, the additional lost time is 1.02 sec per cross-street, permitted left turn made at the end of the cross-street phase green.

The additional lost time caused by permitted left turns can reduce intersection capacity and substantially increase cycle length requirements. However, the significance of these effects relative to the operational efficiency of an intersection depends on the prevailing conditions involved. The results of this research provide a means of accounting for these effects in the analysis of intersection capacity and the design of signal timing plans.

Obviously, the application of the results of this study is limited to the analysis and design of signalized intersections that are similar to those studied in this research. Additional research would be required to determine the applicability of these results to (a) intersections with considerably different geometrics, timings, and driver populations; and (b) through phases that follow cross-street phases with permitted left turns.

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