

**Research Report
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**ANALYSIS OF LOST TIMES AT
SIGNALIZED INTERSECTIONS**

by

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16. Abstract <p>When determining the capacity of a signalized intersection, knowledge of certain traffic parameters is necessary. The previous investigation conducted under this study dealt with an analysis of saturation flow values. The objective of this investigation was to determine appropriate values to use for lost times at signalized intersections. The lost times at the beginning and ending of the phases were analyzed, as well as lost times during the phase due to the interference of pedestrians, local buses, and opposing traffic for left turns. Factors affecting those lost time values were identified. The lost time values, along with the previously identified saturation flow values, permit the calculation of capacity at signalized intersections and may be used as input when using computer models to simulate and optimize signal systems.</p> <p>Base values of 1.40 and 1.67 were found for beginning and ending lost time, respectively. Formulas were given that considered the effect of several factors on beginning and ending lost times. Case studies illustrating the use of those formulas are given.</p>					
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INTRODUCTION

When determining the capacity of a signalized intersection, knowledge of certain traffic parameters is necessary. The following equation may be used to define the capacity (C) of a specific lane at a signalized intersection:

$$C = (3600/H)(Ge/Cm) \quad (1)$$

in which C = capacity (vehicles per hour per lane),
 H = constant headway after initial lost time (seconds),
 Ge = effective green time (seconds), and
 Cm = maximum cycle length (seconds).

Previous investigations conducted under this study dealt with an analysis of saturation flow values (1). Saturation flow (S) is the maximum constant departure rate from the queue during the green period and is given by the following formula:

$$S = 3600/H \quad (2)$$

Substituting this equation into Equation 1 gives the following for capacity of a traffic lane:

$$C = (S)(Ge/Cm) \quad (3)$$

The maximum cycle length may be determined directly from signal timing. ~~The maximum cycle length is the sum of initial green times plus maximum possible extension times plus change interval times for all phases.~~ Saturation flow values can be determined using the procedure given in the previous report (1). Therefore, capacity of a specific traffic lane can be calculated given the effective green time. The formula for effective green time follows:

$$Ge = G + Y - Lb - Le - Lo \quad (4)$$

in which Ge = effective green time,
 G = green time (maximum),
 Y = change interval (includes

yellow plus all-red time),
 Lb = lost time at the beginning of the phase,
 Le = lost time at the end of the phase, and
 Lo = lost time during the phase due to various factors.

Green, yellow, and all-red times can be directly determined. If appropriate lost time values can be identified, the capacity can be calculated. Equations for beginning and ending lost times follow:

$$Lb = Tn - H(n) \quad (5)$$

in which Tn = time to clear n vehicles and
 n = queue position after which headway becomes constant.
 and

$$Le = G + Y - U \quad (6)$$

in which U = total time used in a loaded phase (from start of green to when last vehicle enters intersection).

The objective of this study was to determine appropriate values to use for lost times at signalized intersections. The lost times at the beginning and ending of the phases were analysed, as well as lost times during the phase due to the interference of pedestrians, local buses, and opposing traffic for left turns. Factors affecting those lost time values were identified. Those lost time values, along with the previously identified saturation flow values, allow for the calculation of capacity at signalized intersections and may be used as input when using computer models to simulate and optimize signal systems.

REVIEW OF LITERATURE

In the previous analysis of saturation flow, several factors, such as city population, vehicle type, and turning maneuver, were found to affect saturation flow (1). The literature was reviewed to identify factors affecting lost times. No

analyses were found with specific objectives of relating lost times to various factors. However, a few factors were listed as having effects on lost times. Lost time at the end of the cycle decreased with increasing traffic speeds (2). Lost time at the beginning of the cycle was related to the length of the preceding yellow period, with lost time decreasing as the length of the yellow period increased (3). Lost times have also been related to the total intergreen (yellow plus all-red) time, with lost times increasing as intergreen time increased (4).

Typical values to use for beginning and ending lost times have been given. A total lost time of four seconds was assumed in one study (5). Another study reported the lost time per change of phase to be one-half second less than the intergreen (yellow plus all-red) time or two and one-half seconds plus the travel time through the intersection of the last vehicle, whichever is greater (6). A third study recommended a lost time value equal to the intergreen time less one second (7). In a British study, lost time caused by starting delays and reduced flow during the yellow period amounted to a typical value of two seconds per phase, although values from zero to seven seconds were observed (8).

Other factors have been observed to increase headways or create additional lost time. Left-turns were converted to passenger-car equivalents (PCE's) (9). The PCE was 1.05 for unopposed left turns made from left-turn-only lanes while, for opposed left-turns, the PCE increased to 6.0 for an opposing volume of over 1,000 vehicles per hour. In another report, the average equivalents recommended for opposed left turns were 2.9 for cars and 3.9 for trucks (6). The effect of local buses (buses that make scheduled stops at the intersection) has also been considered. One study recommended a PCE value of 5.0 for each local bus (9). The effect of pedestrians has been taken into account, with recommended PCE values for right turns varying from 1.0 for light pedestrian activity to 2.0 for extremely heavy pedestrian activity (9).

PROCEDURE

The objective of this study was to determine magnitudes of lost times during signal phases and to analyze factors affecting those lost times. The following three types of lost times were considered:

1. Lb -- lost time at the beginning of the phase,
2. Le -- lost time at the end of the phase, and
3. Lo -- lost time during the phase due to various factors. Factors that were analyzed as contributing to Lo were pedestrian interference, local buses, and opposing traffic for left turns.

BEGINNING LOST TIME

Determination of beginning lost time (Lb) or start-up delay involved the same data base used to analyze saturation flow, with additional data collected when needed. The data sheet used and a detailed description of the data collection procedure are given in the previous report (1).

Equation 5 is the formula used to calculate Lb. The queue position (n) after which headway becomes constant was found to be three (1). For a given set of data, the average constant headway (H) after the third vehicle in the queue was calculated. The excess time required to clear the first three vehicles (compared to three vehicles proceeding at the average constant headway (H)) was then determined. This excess start-up time was the beginning lost time.

The average Lb was calculated by controlling factors that could affect this lost time. An analysis of several factors having the potential to affect Lb was conducted. This involved utilizing a program that allowed one factor to vary while holding others within specified ranges.

Factors related to Lb included the following:

1. city size,
2. location in city,
3. cycle length and length of green,

4. speed limit,
5. gradient,
6. preceding yellow,
7. vehicle type and turning maneuver,
8. turning radius,
9. peak versus non-peak conditions, and
10. distance from stop bar to intersection.

ENDING LOST TIME

As with Lb, the determination of lost time at the end of a phase (Le) utilized the data base used in the saturation flow analysis, supplemented with needed additional data. Equation 6 is the formula used to calculate Le. Data for determining Le could only be obtained during loaded phases, defined as those in which the green signal interval is fully utilized by traffic. The time from start of green to when the last vehicle crossed the screenline (stop bar) was subtracted from the total green plus yellow time to determine Le, as shown in Equation 6.

As with Lb, an analysis of several factors that had the potential to affect Le was conducted. The same methodology was used. The following factors were analyzed:

1. length of yellow,
2. cycle length,
3. length of green,
4. city size,
5. location in city,
6. gradient,
7. speed limit, and
8. type of lane.

OTHER LOST TIME

Other lost times (Lo) during the signal phase, due to various factors that may interfere with normal vehicle movement, were investigated. Three specific factors were analyzed:

1. pedestrians,
2. local buses, and
3. opposed left turns.

Data were collected at locations with various pedestrian volumes to show the increase in headways for turning vehicles due to pedestrian interference. To determine the lost time resulting from

pedestrian interference, data were collected in Lexington at locations having heavy pedestrian volumes. Whenever an interruption due to a pedestrian occurred, the appropriate code was noted on the data collection sheet.

A computer summary of the average headways associated with vehicles interrupted by pedestrians was compiled and compared with a similar summary for vehicles having no such interference. For each case of pedestrian interference, up to three headways could be affected. The logic used was, when a vehicle had to stop or slow for a pedestrian, a situation similar to the start of the green was created. This meant three headways could be affected before saturation flow conditions were again reached.

For local buses, average stopping times were obtained. The objective was to collect data that would allow an estimation of the delay due to local buses stopping at an intersection for passengers to enter or exit. The stopped time required for a bus to allow a certain number of passengers to enter or exit was obtained. Data collectors rode local buses in Lexington and obtained stopped time per bus stop and the numbers of passengers entering and exiting.

A situation in which substantial lost time occurs during the green phase is when there are opposed left turns. Data were collected at locations having a separate left-turn lane but no separate left-turn phase. During each green phase, the time to clear the left-turn vehicles was obtained, along with the numbers of opposing and left-turning vehicles. The lost time for each cycle was then calculated as the time required for the given number of left-turning vehicles to turn minus the time required for an equal number of vehicles to turn under exclusive phasing conditions. Saturation flow headways for left-turning vehicles were given in a previous report (1). An additional analysis was conducted considering the special situation when a lane is used as a combination through and left-turn lane.

RESULTS

Independent analyses were conducted to determine lost times at the beginning and ending of the phase as well as other lost times during the phase. Following are summaries of findings from those analyses.

BEGINNING LOST TIME

The approach used to analyze the lost time at the beginning of the green phase involved determining a base value and correction factors. Correction factors were developed for those variables significantly affecting the lost time. The base value for lost time at the beginning of the phase was 1.40 seconds. This was calculated using data for non-turning passenger cars and controlling for those factors significantly affecting the lost time. Results of that analysis are shown in Table 1.

A total of 11 factors were examined to determine their effects on beginning lost time. Following is a discussion of each of those factors.

City Size

Results of this analysis are shown in Table 2. The analysis was limited to through passenger cars at locations outside the central business district, with grades from minus 3.0 to plus 3.0 percent and speed limits of 35 to 45 mph. Results clearly show that, as city size increases, lost time at the beginning of the phase decreases, although the lost time was fairly constant for all cities with populations under 50,000. Lost time for the largest city was only slightly more than one-half that for the smallest cities.

Location in City

Each intersection investigated was classified as being in a central business district (CBD), fringe area, outlying business district (OBD), or residential area. This classification used definitions given in the Highway Capacity Manual (10).

An initial computer run was submitted to determine effects of location in city by controlling city size, grade, speed

limit, and yellow time. That analysis, limited to through passenger cars, showed lost time at the beginning of the cycle to be highest for the CBD and lowest for residential areas, with a relative difference of about 29 percent. However, later analysis indicated those results were affected substantially by cycle length, which is closely related to location in city. Cycle lengths are typically shorter in CBD and fringe areas and longer in OBD and residential areas. Therefore, another computer run was submitted, controlling cycle length. Results of that analysis are shown in Table 3. The additional restriction virtually eliminated the difference between CBD and fringe areas. The difference between the CBD and OBD locations was reduced from 17 percent to 10 percent. It was apparent that effects first observed for location in city were at least partially due to the effect of cycle length.

Cycle Length and Length of Green

A summary was prepared of lost time as a function of cycle length. This summary included through passenger cars and was controlled for city size, location in city, grade, speed limit, and yellow time. Results are shown in Table 4. A very strong relationship was observed between lost time at the beginning of the phase and cycle length. For longer cycle lengths, lost time tended to be much lower. Lost times for the longer cycle lengths was 40 percent smaller than for the shorter cycle lengths.

Closely related to cycle length was green time (length of green). A separate analysis of the effect of green time on lost time at the beginning of the phase, not controlling cycle length, was conducted, and results are shown in Table 5. Increased green time resulted in decreased lost time, with about a 50 percent difference between the longer and shorter green times. Obviously, green time and cycle length are related, and it could not be determined which was more responsible for the variation in lost time.

Speed Limit

An analysis was conducted to determine the effect of speed limit on beginning lost time. In this analysis, it was necessary to control city size, grade, and cycle length. The analysis was limited to through passenger cars, and the results are shown in Table 6. Lost time at the beginning of the phase increased substantially with increasing speed limit.

Gradient

The effect of gradient on lost time at the beginning of the phase was examined by controlling city size, speed limit, green time, yellow time, and cycle length, while allowing grade to vary. The analysis was limited to through passenger cars. Results of the analysis are presented in Table 7. Lost time tended to be greater for uphill grades and less for downhill grades.

Preceding Yellow

It was desired to determine how lost time at the beginning of the phase was affected by the length of yellow (plus all-red, if any) of the preceding phase. This analysis was limited to through passenger cars and controls were included for city size, grade, speed limit, and cycle length. No relationship was apparent between the length of yellow on the preceding phase and the lost time at the beginning of the phase.

Vehicle Type and Turning Maneuver

An analysis was conducted to determine the effects of vehicle type and turning maneuver on lost time at the beginning of the phase. This analysis controlled city size, location in city, grade, and speed limit. The results are presented in Table 8. Lost time was 21 percent higher for trucks and buses than for passenger cars. Left-turning vehicles (at locations with exclusive left-turn phasing) had an eight percent higher lost time than through vehicles, and right-turning vehicles had a five percent lower lost time.

The higher lost time for buses and trucks was expected, due to their higher start-up times. The higher lost time for left-turning vehicles was primarily due to

slightly lower saturation flow headways for left-turning vehicles. Initial headways for right-turning vehicles can be expected to be about the same as for through vehicles (since vehicles starting up do not have to slow down to negotiate a turn). Since the ultimate headway for right-turning vehicles is higher than for through vehicles, the lost time should be lower.

Turning Radius

The effect of turning radius on the beginning lost time of right-turning vehicles was investigated, and results are shown in Table 9. This analysis controlled city size, urban location, grade, and speed limit, and only right-turning passenger cars were included. Lost time was smaller at locations with a short turning radius. This was due to the fact that short turning radii do not affect the first three vehicles in the queue nearly as much as they affect later vehicles (which have to slow to negotiate the turn).

Peak versus Non-Peak Conditions

In an attempt to determine the effect of peak versus off-peak conditions, lost times at the beginning of the phase for loaded and non-loaded cycles were compared. No significant difference was observed.

Distance from Stop Bar to Intersection

The effect of the distance from the stop bar to the intersection on the lost time at the beginning of the phase was investigated. The analysis controlled city size, grade, speed limit, and cycle length, and was limited to through passenger cars. Results showed no apparent relationship between lost time and distance from stop bar to intersection.

ENDING LOST TIME

As with beginning lost time, a base value was determined for ending lost time, and adjustment factors were applied as required. Ending lost times for loaded cycles were determined as described in the procedure. A base value was determined

using data collected in Lexington and controlling factors having a significant effect on ending lost time. The base value for ending lost time was 1.67 seconds. A total of 334 loaded cycles was included in calculating this value.

The only instance in which data collected outside of Lexington were used in the analyses was in the "city size" summary. Unless otherwise indicated, all data used in calculating ending lost times included only non-turning passenger cars. For example, if a right-turning car was the last vehicle through the signal on a loaded cycle, the cycle was not included in the analysis.

As shown in the procedure, eight factors were related to ending lost time. Care had to be taken to account for interrelationships between some of the variables. Following is a discussion of the analyses used to find relationships between the variables and ending lost time.

Length of Yellow

A definite relationship was found between length of yellow and ending lost time, with higher lost times associated with longer yellow times. This relationship is shown in Table 10. This type of relationship was anticipated, since drivers should react to the start of the yellow and use a certain amount of the first part of the yellow period. As the length of yellow increases, the unused portion at the end of the yellow period would increase. The data also indicate that the amount of yellow time used increases as the length of yellow increases. There were no all-red times at these intersections so the times refer to yellow time only. This shows that there would be slightly less ending lost time if, for any given length of change interval, the change interval was devoted entirely to yellow rather than split between yellow and all-red. However, this does not consider the safety considerations of using periods of all-red.

Included in this summary are approaches with speed limits from 35 to 45 mph and grades from minus three to plus

three percent. All data were collected in Lexington, and data taken in the CBD were excluded. The summary indicated that an adjustment is needed if the length of yellow is less than 3.5 seconds or more than 4.5 seconds.

Cycle Length and Green Time

As shown in Table 11, ending lost time was directly related to cycle length, with lost time decreasing as cycle length increased. Included were approaches with speed limits from 35 to 45 mph, grades from minus three to plus three percent, and yellow times from 3.5 to 4.5 seconds. All data were collected in Lexington, and data taken in the CBD were excluded.

Since cycle length and green time are so directly related, both must be considered before any adjustment factor could be developed. The relationship between ending lost time and green time is shown in Table 12. The same controls were used. As with cycle length, ending lost time decreased for longer green times (greater than 60 seconds).

Both cycle length and green time summaries show that lost time decreases as the length of time a driver must wait if he stops for the yellow increases. An adjustment factor considering one of those two variables is appropriate.

City Size

Ending lost time data summarized by city size category are given in Table 13. Compared to Lexington data, ending lost time increased for the smaller cities and decreased for the largest city (Louisville). The summary excluded locations in the CBD, with a speed limit over 45 mph, with yellow times less than 3.5 or over 4.5 seconds, or with grades above plus three or below minus three percent.

The data show that adjustment factors are needed to decrease ending lost time from the base value in large cities (over 250,000 population) and to increase ending lost times in the smaller cities (under 20,000 population). This was expected and agrees with findings from the previous report in which saturation flow levels increased with increasing population (1).

Location in City

As previously described, each intersection was classified as being in the CBD, fringe, outlying business district, or residential area. Location of the intersection was related to ending lost time as shown in Table 14. Two sets of controls were used. The first set (data set "A" in Table 14) was similar to that used in previous analyses, with approaches included where grades were from minus three to plus three percent, the speed limit was from 35 to 45 mph, and the length of yellow was between 3.5 and 4.5 seconds. This analysis showed the highest values for ending lost time occurring in the CBD with values decreasing as the location got further from the CBD.

Additional controls for cycle length and green time were then placed on the data. These additional controls were added because of the effects cycle length and green time had on ending lost time, along with the fact that signals in the CBD generally had lower cycle lengths and green times compared to other locations. To be included in data set "B" in Table 14, the particular lane had to have a green time of 25 to 40 seconds and a cycle length of 70 to 100 seconds. This analysis again showed ending lost times to be highest in the CBD, indicating an adjustment factor was needed to account for location in the city.

Gradient

The gradient of the approach was related to end lost time, as shown in Table 15. Two sets of controls were used. In both sets, approaches were included where the speed limit was from 35 to 45 mph and the length of yellow was between 3.5 and 4.5 seconds. The difference was that set "A" excluded locations in the CBD while set "B" included CBD locations only.

Both data sets gave the same general result. Lost time at the end of the phase increased slightly for downhill approaches compared to "flat" approaches, while ending lost time for uphill approaches decreased. The lower ending lost times for uphill approaches could be related to the fact that drivers were accelerating up the hill and did not want to stop. This

would be particularly true for drivers of cars with manual transmissions. On a downgrade, drivers would not necessarily be accelerating and might be decelerating, making it easier to stop at the onset of yellow.

Speed Limit

Speed limit had an effect on ending lost time, as shown in Table 16. The controls used limited the analysis to approaches in non-CBD locations in Lexington with grades from minus three to plus three percent and yellow times from 3.5 to 4.5 seconds. Ending lost time dropped substantially when the speed limit reached 55 mph. This finding was expected, since drivers faced with the onset of the yellow interval will be more likely to proceed through the intersection when travelling at higher speeds.

Type of Lane

Ending lost time for exclusive left-turn lanes was compared to that for through lanes. The base value for through lanes was 1.67 seconds. Using identical controls to obtain a set of data for exclusive left-turn lanes yielded an average ending lost time of 1.27 seconds for the 59 headways averaged. This indicated that a lower ending lost time should be used for left-turn lanes.

OTHER LOST TIME

Additional lost times during the signal phase due to pedestrians, local buses, and opposing traffic for left turns were investigated. Following is a discussion of the results of the data analysis dealing with each of those three variables.

Pedestrians

The data included 230 cases of pedestrian interference, affecting a total of 552 headways (2.4 headways per case). Each case has the potential to affect three headways (as described previously) but may affect only one or two. For example, if two consecutive vehicles experienced interference, the first case would affect only one vehicle. Also, if the interference occurred near the end of

the queue, there may not be two following vehicles to be affected.

One example of the increase in average headway created by pedestrian interference follows. The average headway for a left-turning vehicle (in queue position four or above) not affected by pedestrians was 2.27 seconds, compared to 3.82 seconds for a similar vehicle that experienced pedestrian interference.

The total time (headway) required for the "pedestrian interfered" vehicles was compared to the time required for the same number of "non-interfered" vehicles. The "pedestrian interfered" vehicles required a total of 1,150.49 additional seconds. This represents the total lost time for the 230 cases of pedestrian interference. This resulted in an average of 5.00 seconds of lost time per case of pedestrian interference.

Local Buses

A summary of the stopped time required for passengers to enter or exit a local bus is given in Table 17. There was only a small amount of data for ten or more passengers so the summary was ended at nine passengers. Using linear regression, an equation for a best-fit line was determined:

$$y = 2.50x + 4.18 \quad (7)$$

in which y = stopped time (seconds) and
 x = number of entering and exiting passengers.

The coefficient of determination (r -squared) value for this equation was 0.90, which indicated a good relationship.

Opposed Left Turns

Plots of lost time per cycle versus opposing volume per cycle were drawn for both two-lane and four-lane streets as shown in Figure 1. The two-lane plot describes locations where the left-turners must turn across only one lane of opposing traffic, while the four-lane plot is for locations requiring a turn across two opposing lanes. Linear regression was used to determine best-fit lines. The r -squared values indicate lost time per cycle was very closely related to opposing

volume per cycle.

A special situation occurs when a lane is used as a combination through and left-turn lane. The plots in Figure 1 do not apply since they assume all vehicles are turning left. An estimation of lost time due to left turns in such a lane was conducted assuming that left-turning vehicles were randomly distributed in the queue as a function of the percentage of left-turning vehicles. Given the number of opposing vehicles per lane per cycle and the percent left turns in the combination through and left-turn lane, the average additional lost time due to left-turn interference was calculated statistically. Base beginning and ending lost times were used as given in Figure 1. As with Figure 1, the assumption was made that all opposing vehicles in the queue would clear and then left turns would be made. An average headway for opposing vehicles of 2.2 seconds was assumed. The following formula was derived to estimate the average additional lost time due to left-turning vehicles in a lane shared with through vehicles:

$$L_a = (x)((1-x)^{(i-1)})(2.2)(N_o+1-i) \quad (8)$$

(summing i from $i=1$ to $i=N_o$)

in which L_a = additional lost time due to left-turning vehicles,
 N_o = opposing volume per lane per cycle,
 x = percent left turns, and
 i = queue position in combination through and left-turn lane.

Values for L_a were calculated for percent left turns ranging from 5 to 50 percent and opposing volumes per lane per cycle from one to 30 vehicles. The value obtained for L_a was then added to the base lost time value to obtain total lost time. Total lost time for various left-turn percentages was then plotted as a function of number of vehicles per cycle in the highest volume opposing lane (Figure 2). For a two-lane street, this would equal the opposing vehicles per cycle. For a four-lane street, the distribution of vehicles must be considered. The number of opposing vehicles per cycle would be

multiplied either by 0.5 when equal distribution was assumed or by a factor higher than 0.5 when the assumption is made that one lane will be more utilized than the other.

RECOMMENDATIONS

BEGINNING LOST TIME

An estimate of lost time at the beginning of the green phase may be determined for a particular intersection, approach, and lane using the following formula:

$$L_b = B_b(C_p)(C_l)(C_c)(C_s)(C_g)(C_r) \quad (8)$$

in which L_b = lost time at beginning of of phase,

- B_b = base value to which correction factors are applied (1.40 seconds),
- C_p = correction factor for city population category,
- C_l = correction factor for location in city,
- C_c = correction factor for cycle length,
- C_s = correction factor for speed limit,
- C_g = correction factor for gradient, and
- C_r = correction factor for turning radius.

The base value, as described previously, was determined to be 1.40 seconds. Correction factors were initially determined from results described previously, although those initial values were modified on the basis of further tests. Those modifications were necessary because the initial analyses, while providing good indications of the directions of relationships between variables, did not always provide good indications of the quantity. The interaction of variables, combined with limitations in available data, made it extremely difficult to establish effects of individual variables. However, the correction factors presented here were tested on many combinations of variables and appeared to yield reasonably accurate

results. Case studies, demonstrating the proper use of those correction factors and the above formula, are presented in the Appendix. Presented below are recommended values for the various correction factors that were developed.

- C_p (correction factor for city population)
 - $C_p = 1.20$ for population under 50,000
 - $C_p = 1.10$ for population of 50,000 to 99,999
 - $C_p = 1.00$ for population of 100,000 to 250,000
 - $C_p = 0.90$ for population over 250,000

- C_l (correction factor for location in city)
 - $C_l = 1.20$ for central business district locations
 - $C_l = 1.10$ for fringe locations
 - $C_l = 1.00$ for outlying business district locations
 - $C_l = 0.90$ for residential locations

- C_c (correction factor for cycle length)
 - $C_c = 1.20$ for cycle length less than 80.0 seconds
 - $C_c = 1.10$ for cycle length of 80.0 to 99.9 seconds
 - $C_c = 1.00$ for cycle length of 100.0 to 119.9 seconds
 - $C_c = 0.90$ for cycle length of 120.0 to 150.0 seconds
 - $C_c = 0.80$ for cycle length greater than 150.0 seconds

- C_s (correction factor for speed limit)
 - $C_s = 0.90$ for 35 mph speed limit
 - $C_s = 0.95$ for 40 mph speed limit
 - $C_s = 1.00$ for 45 mph speed limit
 - $C_s = 1.05$ for 50 mph speed limit
 - $C_s = 1.10$ for 55 mph speed limit

- C_g (correction factor for approach gradient: uphill grade is positive, downhill is negative)
 - $C_g = 0.80$ for grades less than minus 3.0 percent
 - $C_g = 0.90$ for grades from minus 3.0 to minus 1.6 percent
 - $C_g = 1.00$ for grades from minus

1.5 to plus 1.5 percent
 $C_g = 1.10$ for grades from plus
 1.6 to plus 3.0 percent
 $C_g = 1.25$ for grades greater than
 plus 3.0 percent

Cr (correction factor for turning radius)

$$C_r = 1.00 + Fr(P/100) \quad (9)$$

in which P = percentage of traffic
 affected by radius
 (affected vehicles are
 those that turn right or
 that turn left from one
 one-way street to
 another), and

Fr = a factor for the radius
 affecting those vehicles,
 where Fr = -0.60 for turning radius of
 0 to 10 feet,
 Fr = -0.40 for turning radius of
 11 to 20 feet,
 Fr = -0.20 for turning radius of
 21 to 30 feet,
 Fr = 0.00 for turning radius of
 31 to 40 feet,
 Fr = 0.20 for turning radius of
 41 to 50 feet, and
 Fr = 0.40 for turning radius
 greater than 50 feet.

ENDING LOST TIME

To determine the most accurate ending
 lost time value for a specific
 intersection, approach, and lane,
 appropriate adjustment factors must be
 applied to a "base" value. The "base"
 value applies to passenger cars proceeding
 through an intersection under generally
 typical conditions. This value was found
 to be 1.67 seconds.

The following formula is recommended
 for use in estimating an appropriate value
 to use for ending lost time for a specific
 lane on an approach to an intersection:

$$L_e = B_e(F_y)(F_c)(F_p)(F_l) \quad (10)$$

$$(F_g)(F_s)(F_t)$$

in which L_e = ending lost time for
 specific intersection
 approach lane (seconds),
 B_e = base value (1.67 seconds)

for end lost time,
 F_y = adjustment factor for
 length of yellow,
 F_c = adjustment factor for
 cycle length,
 F_p = adjustment factor for city
 size (population),
 F_l = adjustment factor for
 location in city,
 F_g = adjustment factor for
 gradient,
 F_s = adjustment factor for
 speed limit, and
 F_t = adjustment factor for
 type of lane.

Since several of the variables were
 interrelated in varying degrees, care had
 to be taken to avoid counting the effects
 of certain variables in more than one
 factor. The maximum variation from the
 base value was considered. The lowest and
 highest ending lost times were determined
 at locations having substantial data. The
 factors were set so that no typical
 combination would result in an estimated
 ending lost time outside the limits found
 by the data. In almost all instances, no
 more than two factors would combine to
 increase or decrease ending lost time.
 The usual range of data, as well as the
 typical combinations of factors usually
 found, were both considered when
 developing the factors. The data showed
 that ending lost time typically did not
 vary more than plus or minus one second
 from the base value, so the range would be
 from approximately 0.75 to 2.75 seconds.
 Following is a listing of recommended
 values to use for the various adjustment
 factors:

F_y (adjustment factor for length of
 change interval (includes
 yellow plus all-red time))
 $F_y = 0.70$ for change interval
 time less than 3.5 seconds
 $F_y = 1.00$ for change interval time
 of 3.5 to 4.5 seconds
 $F_y = 1.20$ for change interval time
 greater than 4.5 seconds

F_c (adjustment factor for cycle length)
 $F_c = 1.15$ for cycle length less
 than 90 seconds

$F_c = 1.00$ for cycle length of 90 to 180 seconds
 $F_c = 0.85$ for cycle length greater than 180 seconds

F_p (adjustment factor for city size (population))
 $F_p = 0.85$ for population over 250,000
 $F_p = 1.00$ for population of 20,000 to 250,000
 $F_p = 1.10$ for population under 20,000

F_l (adjustment factor for location in city)
 $F_l = 1.20$ for central business district (CBD) locations
 $F_l = 1.05$ for fringe locations
 $F_l = 0.95$ for outlying business district and residential locations

F_g (adjustment factor for gradient)
 $F_g = 1.00$ for gradient of plus three percent or less
 $F_g = 0.95$ for gradient greater than plus three percent

F_s (adjustment factor for speed limit)
 $F_s = 1.00$ for speed limit of 45 mph or less
 $F_s = 0.70$ for speed limit above 45 mph

F_t (adjustment factor for type of lane)
 $F_t = 0.90$ for exclusive left-turn lane
 $F_t = 1.00$ for all other lanes

Case studies using this procedure to calculate ending lost time are presented in the Appendix. Comparisons between predicted and measured values are also presented.

OTHER LOST TIME

Following is a discussion of recommended procedures for predicting lost times due to pedestrians, local buses, and opposed left turns.

Pedestrians

An average of 5.00 seconds of lost

time per case of pedestrian interference was found. To utilize this finding, the amount of pedestrian interference or number of cases of pedestrian interference per cycle must be estimated. This value would vary from zero at locations with a very small pedestrian volume or with no turning traffic to one or more at locations with heavy pedestrian volumes and high turning volumes. As an example, data taken at a CBD location in Lexington having a heavy pedestrian volume as well as a high percentage of turning traffic yielded an average of 0.9 cases of pedestrian interference per cycle. This was the highest incidence of pedestrian interference found at any intersection in this study. Of course, higher values are possible, especially at CBD locations in very large cities. Once a value has been determined for the number of cases of pedestrian interference per cycle, this value can be multiplied by 5.00 seconds to obtain the lost time per cycle due to pedestrian interference.

Local Buses

This factor must be considered if a local bus route may require a stop in an approach lane for which the capacity is being determined. The lost time due to local buses is a function of the number of stops and the number of passengers entering or exiting the bus during each stop. Given an estimate of the number of entering and exiting passengers, an estimate of the stopped (lost) time per stop can be obtained from Equation 7. This time must then be multiplied by the number of bus stops per cycle to obtain the lost time per cycle due to local buses. An alternate procedure would be to multiply the number of stops per hour by lost time per stop and then divide by the number of cycles per hour to yield lost time per cycle.

Opposed Left Turns

Plots of total lost time per cycle as a function of opposing volume per cycle are shown in Figure 1. Those plots apply to separate left-turn lanes that do not have exclusive left-turn phasing. Separate plots were made for two-lane and

four-lane streets. As described previously, the two-lane plot is for left turns made across one lane of opposing traffic, while the four-lane plot is for turns across two opposing lanes.

Given the opposing volume per hour and cycle length, the opposing volume per cycle may be determined. The opposing volume would normally be opposing through vehicles but opposing right-turning vehicles would also be included when there was only one cross-street lane into which to turn. After opposing volume per cycle is determined, lost time per cycle is read directly from the plot. This lost time represents the total lost time per cycle for the left-turn lane; that is, no beginning or ending lost time should be added. The maximum possible lost time per cycle for any left-turn lane is assumed to be equal to the green time. The maximum lost time would actually be the green time plus the yellow and all-red time minus the yellow and red time used to turn. However, given other accuracy constraints, the maximum possible lost time can be assumed equal to the green time.

For combination left-turn and through lanes, the plots given in Figure 2 should be used. Given the percent left turns in the subject lane and number of vehicles per cycle in the highest volume opposing lane, total lost time per cycle may be estimated. As before, the maximum possible lost time may be assumed to be equal to the green time.

CAPACITY CALCULATION

As described previously, the capacity of a particular lane on a given approach to an intersection may be calculated when the saturation flow, effective green time, and cycle length are known. Saturation flow may be predicted as described in the previous report (1), and cycle length may be obtained from signal timing. Effective green time equals the actual green time plus yellow time minus total lost time per cycle for the lane in question. Therefore, capacity may be predicted for any lane when the total lost time per cycle is known for that lane.

In general, the total lost time per cycle for a given lane will equal the sum

of the lost time at the beginning of the phase, the lost time at the end of the phase, the lost time due to pedestrians, and the lost time due to local buses. For separate left-turn lanes with opposed left turns, the total lost time is obtained directly (Figure 1) and no additional adjustment is necessary. For lanes with both through traffic and opposed left turns, the total lost time may be obtained from Figure 2.

Once the appropriate lost times have been determined as described in the previous sections, an effective green time may be determined as described above. Capacity may then be predicted using Equation (3). A case study illustrating capacity prediction is given in the Appendix.

Comparisons were made between the capacity values obtained using the procedure recommended in this report and the procedure given in the Highway Capacity Manual (10). The procedure outlined in this report typically yielded substantially higher capacity estimates. An exception would be a location where the recommended procedure would identify factors contributing to significant lost times which would reduce the estimated capacity.

IMPLEMENTATION

The methodology developed in this report allows for the estimation of lost time values representative of conditions at a given intersection. Those values, along with saturation flow values, which may be determined using a procedure given in a previous report (1), provide the basic input needed in the calculation of intersection capacity. Accurate lost time values are also necessary as input to programs such as TRANSYT and SIGOP, which simulate and optimize signal systems.

REFERENCES

1. Agent, K. R.; and Crabtree, J. D.; "Analysis of Saturation Flow at Signalized Intersections," University

- of Kentucky, Transportation Research Program, Report UKTRP-82-8, July 1982.
2. Carstens, R. C.; "Some Traffic Parameters at Signalized Intersections," Traffic Engineering, August 1971.
 3. Branston, D.; "Some Factors Affecting the Capacity of Signalized Intersections," Traffic Engineering and Control, August/September 1979.
 4. Miller, A. J.; "The Capacity of Signalized Intersections in Australia," Australian Road Research Board, Bulletin No. 3, March 1968.
 5. Meser, C. J.; and Fambro, D. B.; "Critical Lane Analysis for Intersection Design," Transportation Research Board, Record 644, 1977.
 6. Miller, A. J.; "On the Australian Road Capacity Guide," Highway Research Board, Record 289, 1969.
 7. Saturation Flow Manual, City of Edmonton and University of Alberta, Canada, April 1980.
 8. Webster, F. V.; and Cobbe, B. M.; "Traffic Signals," Road Research Technical Paper No. 56, Road Research Laboratory, London, England, 1966.
 9. Interim Materials on Highway Capacity, Transportation Research Board Circular 212, January 1980.
 10. Highway Capacity Manual, Highway Research Board, Special Report 87, 1965.

TABLE 1. BASE VALUE FOR BEGINNING LOST TIME

QUEUE POSITION	TOTAL HEADWAYS	AVERAGE HEADWAY (SECONDS)
1	478	3.03
2	476	2.65
3	474	2.47
Above 3	3,306	2.25

Average Beginning Lost Time = 1.40 Seconds

Note: This analysis included all through vehicles at locations in Lexington with grades of -3.0 to +3.0 percent, speed limits of 45 mph, and cycle lengths of 90.0 to 120.0 seconds.

TABLE 2. EFFECT OF CITY SIZE ON BEGINNING LOST TIME

CATEGORY	CITIES	POPULATION	AVERAGE HEADWAY (SECONDS)				BEGINNING LOST TIME (SECONDS)
			1	2	3	OVER 3	
1	Louisville	490,100*	2.97	2.68	2.50	2.38	1.01
2	Lexington	204,200	2.88	2.58	2.45	2.21	1.28
3	Bowling Green	40,400	3.38	2.74	2.48	2.21	1.97
	Paducah	29,800					
	Frankfort	26,000					
	Richmond	21,700					
4	Winchester	15,200	3.60	3.09	2.76	2.50	1.95
	Somerset	10,600					
	Hazard	5,400					

Note: This analysis was limited to through passenger cars at non-CBD locations with grades of -3.0 to +3.0 percent and speed limits of 35 to 45 mph.

* Population of the urbanized area is 760,800.

TABLE 3. EFFECT OF LOCATION IN CITY ON BEGINNING LOST TIME
LOST TIME

LOCATION IN CITY	AVERAGE HEADWAY (SECONDS)				BEGINNING LOST TIME (SECONDS)
	ONE	TWO	THREE	OVER THREE	
CBD	3.52	3.07	2.79	2.61	1.55
Fringe	3.27	2.80	2.57	2.37	1.53
OBD	2.91	2.53	2.44	2.16	1.40
Residential	(No Data Available)				

Note: This analysis was limited to through passenger cars at locations in Lexington with grades of +3.0 percent or less, speed limits of 35 to 45 mph, green times of 25.0 to 40.0 seconds, amber times of 3.5 to 4.5 seconds, and cycle lengths of 70.0 to 100.0 seconds.

TABLE 4. EFFECT OF CYCLE LENGTH ON BEGINNING LOST TIME

CYCLE LENGTH (SECONDS)	AVERAGE HEADWAY (SECONDS)				BEGINNING LOST TIME (SECONDS)
	ONE	TWO	THREE	OVER THREE	
60.0 to 90.0	3.09	2.74	2.52	2.31	1.42
90.1 to 120.0	2.86	2.50	2.40	2.16	1.28
120.1 or more	2.58	2.37	2.32	2.14	0.85

Note: This analysis was limited to through passenger cars in Lexington at non-CBD locations with grades of +3.0 percent or less, speed limits of 35 to 45 mph, and amber times of 3.5 to 4.5 seconds.

TABLE 5. EFFECT OF GREEN TIME ON BEGINNING LOST TIME

LENGTH OF GREEN (SECONDS)	AVERAGE HEADWAY (SECONDS)				BEGINNING LOST TIME (SECONDS)
	ONE	TWO	THREE	OVER THREE	
30.0 or less	3.21	2.89	2.64	2.34	1.72
30.1 to 60.0	2.82	2.52	2.40	2.18	1.20
60.1 or more	2.70	2.52	2.40	2.19	1.05

Note: This analysis was limited to through passenger cars at non-CBD locations in Lexington with grades of +3.0 percent or less and speed limits of 35 to 45 mph.

TABLE 6. EFFECT OF SPEED LIMIT ON BEGINNING LOST TIME

SPEED LIMIT (MPH)	AVERAGE HEADWAY (SECONDS)				BEGINNING LOST TIME (SECONDS)
	ONE	TWO	THREE	OVER THREE	
35	2.40	2.31	2.28	2.13	0.60
45	2.80	2.53	2.37	2.18	1.16
55	2.99	2.50	2.18	2.04	1.55

Note: This analysis was limited to through passenger cars at locations in Lexington with grades of -3.0 to +3.0 percent and cycle lengths of 130.0 to 160.0 seconds.

TABLE 7. EFFECT OF APPROACH GRADIENT ON BEGINNING LOST TIME

GRADE (PERCENT)*	AVERAGE HEADWAY (SECONDS)				BEGINNING LOST TIME (SECONDS)
	ONE	TWO	THREE	OVER THREE	
Less Than -3.0	3.26	3.00	2.69	2.57	1.24
-3.0 to +3.0	3.35	2.84	2.64	2.36	1.75
Greater Than +3.0	3.59	3.05	2.60	2.44	1.92

Note: This analysis was limited to through passenger cars at locations in Lexington with speed limits of 35 to 45 mph, green times of 25.0 to 40.0 seconds, amber times of 3.5 to 4.5 seconds, and cycle lengths of 70.0 to 100.0 seconds.

* Uphill grades are positive and downhill grades are negative.

TABLE 8. EFFECT OF VEHICLE TYPE AND TURNING MANEUVER ON BEGINNING LOST TIME

CATEGORY	AVERAGE HEADWAY (SECONDS)				BEGINNING LOST TIME (SECONDS)
	ONE	TWO	THREE	OVER THREE	
Passenger Cars	2.88	2.59	2.44	2.07	1.80
Trucks and Buses	4.63	4.20	3.90	3.56	2.05
Through Vehicles	2.94	2.64	2.49	2.24	1.35
Left-Turning Vehicles	3.01	2.65	2.43	2.21	1.46
Right-Turning Vehicles	3.40	2.90	2.68	2.57	1.27

Note: This analysis was limited to non-CBD locations in Lexington with grades of +3.0 percent or less and speed limits of 35 to 45 mph.

TABLE 9. EFFECT OF TURNING RADIUS ON BEGINNING LOST TIME

TURNING RADIUS (FT)	AVERAGE HEADWAY (SECONDS)				BEGINNING LOST TIME (SECONDS)
	ONE	TWO	THREE	OVER THREE	
Less than 25	3.21	3.01	2.74	2.74	0.74
25 to 44	3.34	2.86	2.56	2.40	1.56
45 or More	(Insufficient data available)				

Note: This analysis was limited to right-turning passenger cars at non-CBD locations in Lexington with grades of +3.0 percent or less and speed limits of 35 to 45 mph.

TABLE 10. EFFECT OF LENGTH OF YELLOW ON ENDING LOST TIME

LENGTH OF YELLOW (SECONDS)	NUMBER OF LOADED CYCLES	AVERAGE ENDING LOST TIME (SECONDS)	AVERAGE YELLOW TIME USED (SECONDS)
Less than 3.5	44	1.03	2.0
3.5 to 4.5	334	1.67	2.3
Greater than 4.5	49	2.21	2.8

Note: This analysis was limited to non-CBD locations in Lexington on approaches with speed limits of 35 to 45 mph and grades of -3.0 to +3.0 percent. There were no all-red intervals at these intersections so the length of yellow refers to yellow time only.

TABLE 11. EFFECT OF CYCLE LENGTH ON ENDING LOST TIME

CYCLE LENGTH (SECONDS)	NUMBER OF LOADED CYCLES	AVERAGE ENDING LOST TIME (SECONDS)
Less than 90.0	100	2.09
90.0 to 120.0	122	1.62
120.1 to 180.0	76	1.62
Greater than 180.0	64	1.29

Note: This analysis was limited to non-CBD locations in Lexington on approaches with speed limits of 35 to 45 mph, grades of -3.0 to +3.0 percent, and yellow times of 3.5 to 4.5 seconds.

TABLE 12. EFFECT OF GREEN TIME ON ENDING LOST TIME

GREEN TIME (SECONDS)	NUMBER OF LOADED CYCLES	AVERAGE ENDING LOST TIME (SECONDS)
Less than 30	75	1.94
30 to 60	215	1.65
Greater than 60	44	1.35

Note: This analysis was limited to non-CBD locations in Lexington on approaches with speed limits of 35 to 45 mph, grades of -3.0 to +3.0 percent, and yellow times of 3.5 to 4.5 seconds.

TABLE 13. EFFECT OF CITY SIZE ON ENDING LOST TIME

CATEGORY	CITIES	POPULATION	NUMBER OF LOADED CYCLES		AVERAGE ENDING LOST TIME (SECONDS)
1	Louisville	490,100	53		1.25
2	Lexington	204,200	334		1.67
3	Bowling Green	40,400	94		1.79
	Paducah	29,000			
	Richmond	21,700			
4	Winchester	15,200	75		2.04
	Somerset	10,600			
	Hazard	5,400			

Note: This analysis was limited to non-CBD locations with speed limits of 35 to 45 mph, yellow times of 3.5 to 4.5 seconds, and grades of -3.0 to +3.0 percent.

TABLE 14. EFFECT OF LOCATION IN CITY ON ENDING LOST TIME

LOCATION IN CITY	NUMBER OF LOADED CYCLES		AVERAGE ENDING LOST TIME (SECONDS)	
	A	B*	A	B*
CBD	47	41	2.48	2.70
Fringe	155	45	1.77	2.18
CBD	154	52	1.59	1.78
Residential	25	**	1.57	**

*Additional controls were added relating to cycle length and green time.

**No data were available under this set of controls.

TABLE 15. EFFECT OF GRADE ON ENDING LOST TIME

GRADIENT (PERCENT)	NUMBER OF LOADED CYCLES		AVERAGE ENDING LOST TIME (SECONDS)	
	A	B*	A	B*
Less than -3.0	46	59	1.88	2.48
-3.0 to +3.0	334	47	1.67	2.48
Greater than +3.0	62	52	1.65	1.21

*Central Business District locations only.

TABLE 16. EFFECT OF SPEED LIMIT ON ENDING LOST TIME

SPEED LIMIT (MPH)	NUMBER OF LOADED CYCLES	AVERAGE ENDING LOST TIME (SECONDS)
35	150	1.81
45	108	1.64
55	32	0.88

Note: The analysis was limited to non-CBD locations in Lexington on approaches with grades of -3.0 to +3.0 percent and yellow times of 3.5 to 4.5 seconds.

TABLE 17. STOPPED TIME REQUIRED FOR PASSENGERS TO
ENTER OR EXIT LOCAL BUS

NUMBER OF PASSENGERS ENTERING OR EXITING	SAMPLE SIZE	AVERAGE STOPPED TIME (SECONDS)
1	150	6.3
2	50	10.5
3	29	12.3
4	13	14.7
5	14	14.7
6	5	20.4
7	3	16.7
8	5	25.8
9	3	28.7

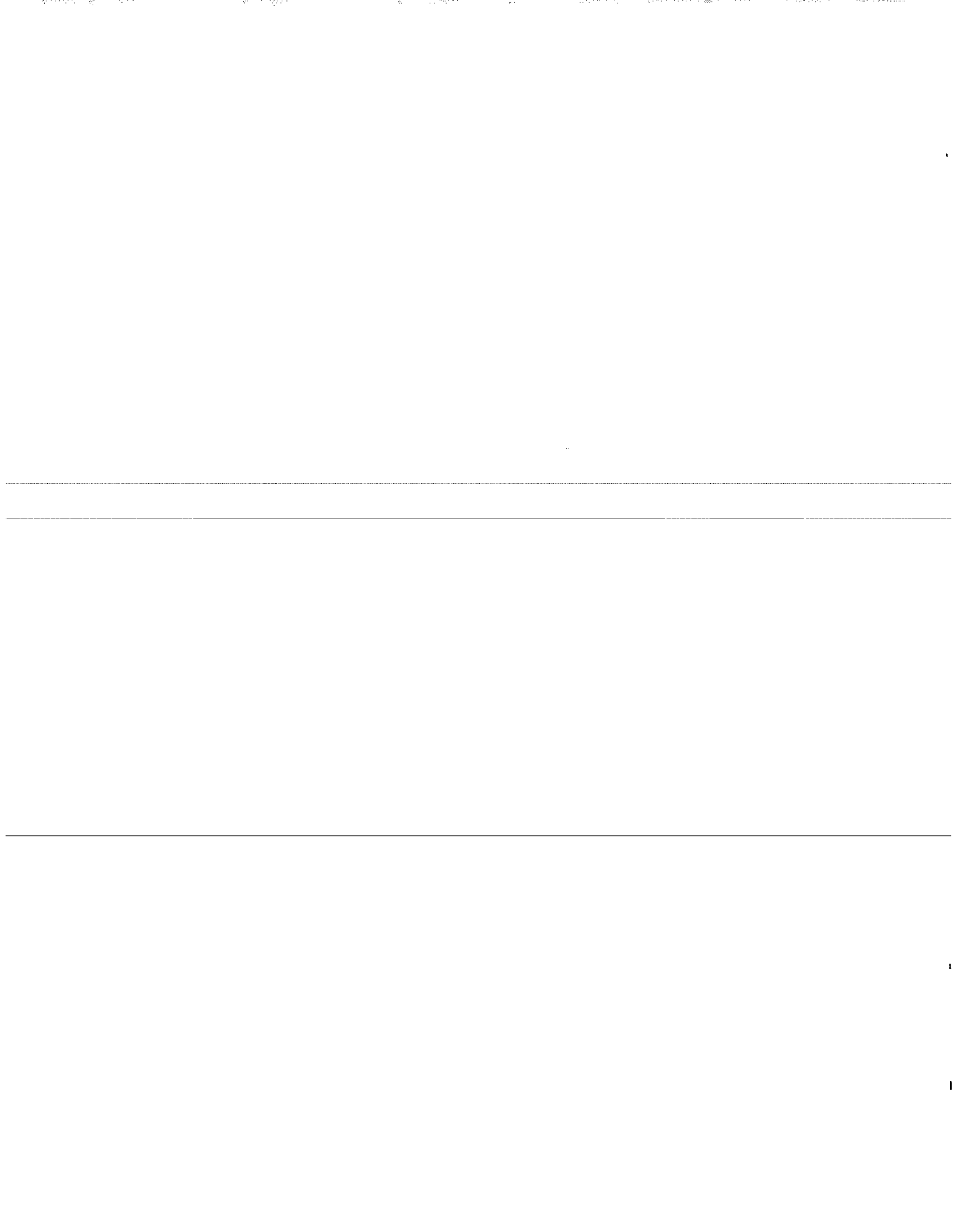


Figure 1. Relationship Between Lost Time per Cycle for Opposed Left-Turning Vehicles and the Opposing Volume per Cycle (Left-Turn-Only Lane)

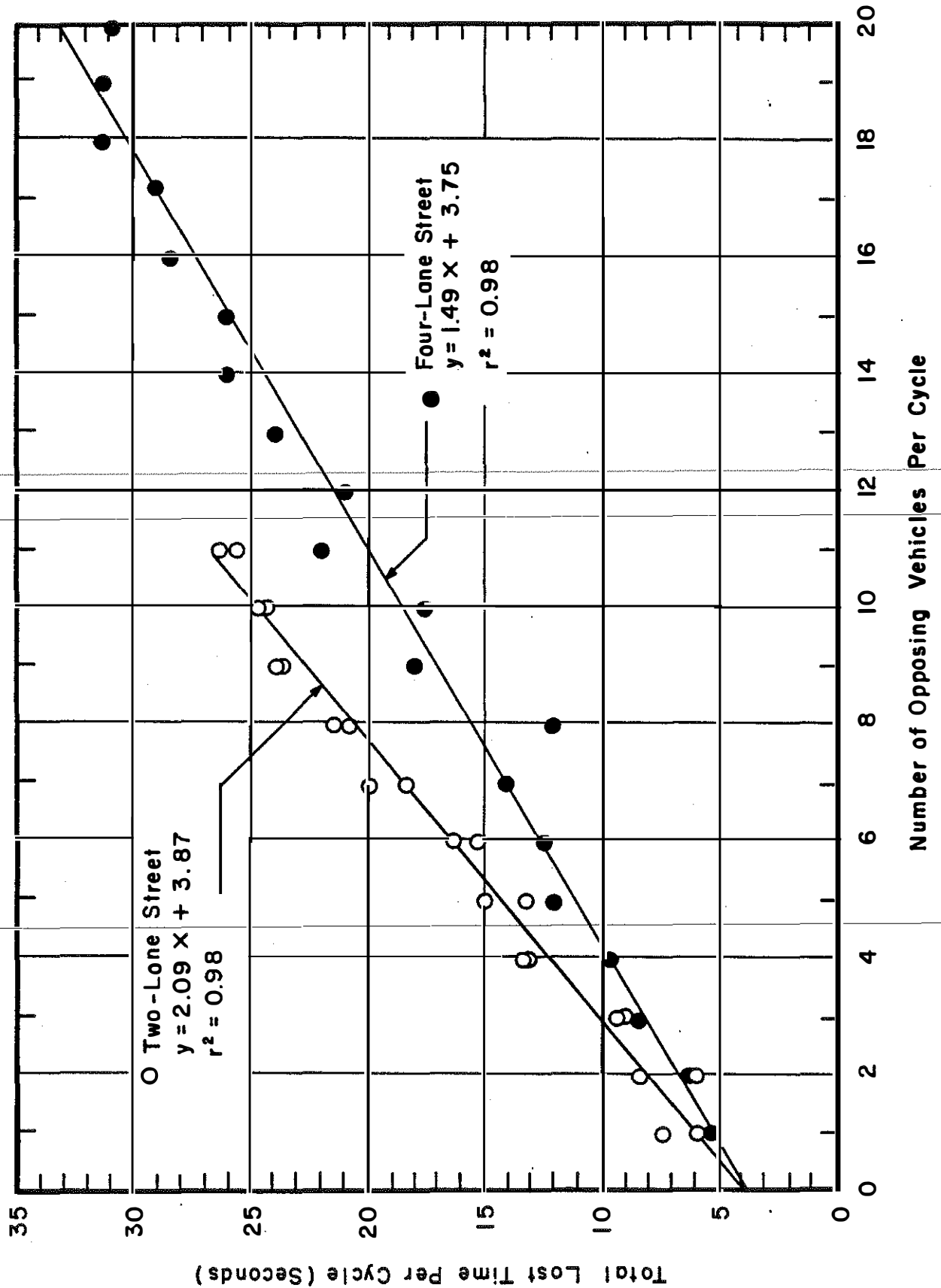
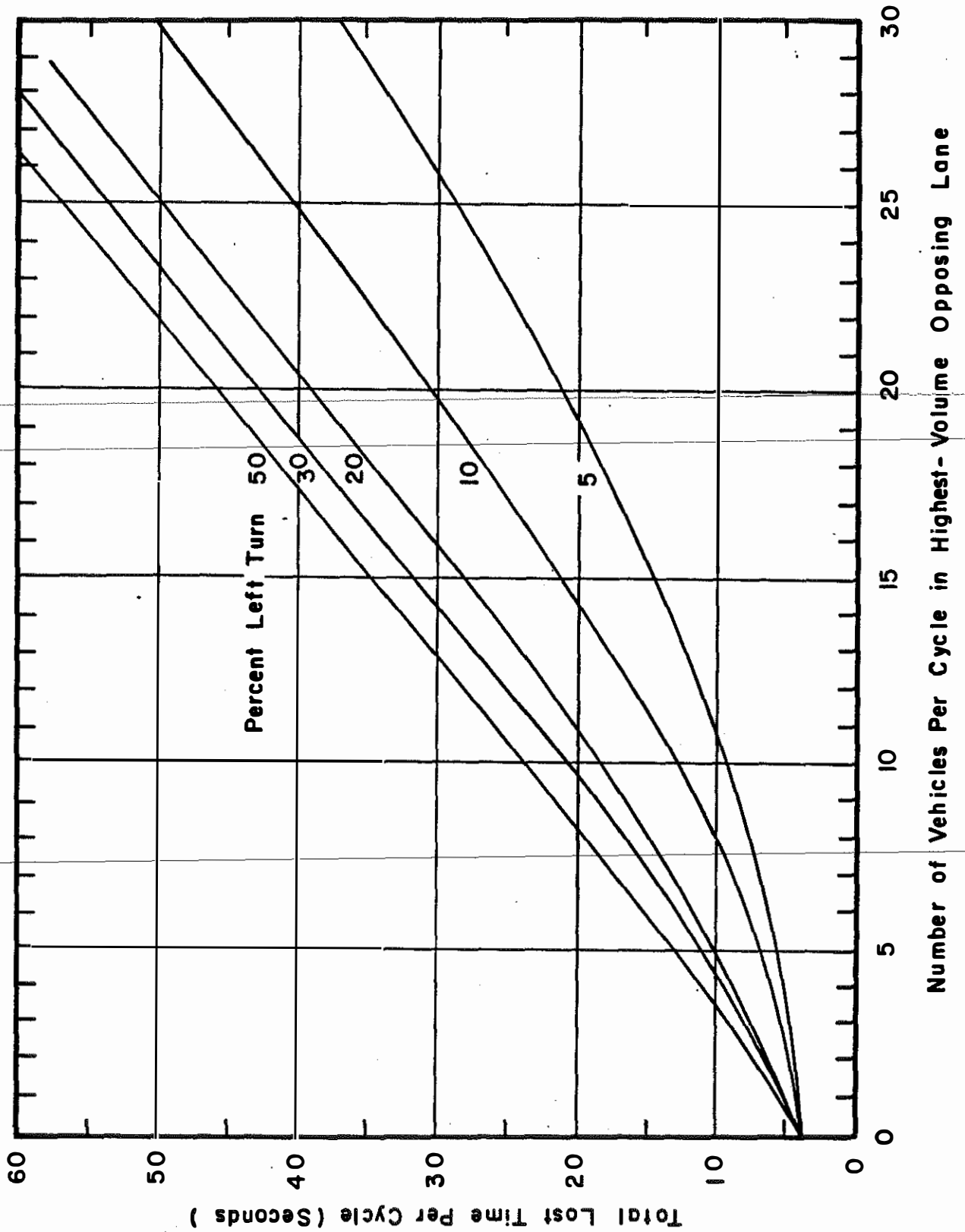


Figure 2. Relationship Between Lost Time per Cycle and the Opposing Volume per Cycle for a Lane with Left-Turning and Through Vehicles



A P P E N D I X

C A S E S T U D I E S

BEGINNING LOST TIMES

To illustrate use of the formula for predicting lost time at the beginning of the phase, three sample locations were selected for case studies. Predicted values for beginning lost time were calculated and compared to measured values, as shown.

Case Study Number 1

Location	-- Broadway northbound at High Street, Lexington
Lane	-- Right lane of two through-only lanes
City Population	-- 204,200
Location in City	-- CBD
Cycle Length	-- 70.0 seconds
Speed Limit	-- 35 mph
Gradient	-- -5.0 percent

Correction Factors:	Cp = 1.00
	Cl = 1.20
	Cc = 1.20
	Cs = 0.90
	Cg = 0.80
	Cr = 1.00

Predicted Value: $L_b = 1.40(1.20)(1.20)(0.90)(0.80) = 1.45$ seconds
Measured Value: $L_b = 1.60$ seconds
Difference = 9 percent

Case Study Number 2

Location -- Euclid Avenue westbound at Rose Street, Lexington
Lane -- Combination through and right-turn lane
City Population -- 204,200
Location in City -- Fringe
Cycle Length -- 70.0 seconds
Speed Limit -- 35 mph
Gradient -- -0.5 percent
Turning Radius -- 24 feet
Percent Turning -- 12 percent

Correction Factors: $C_p = 1.00$
 $C_l = 1.10$
 $C_c = 1.20$
 $C_s = 0.90$
 $C_g = 1.00$
 $C_r = 1.00 + (-0.20)(12/100) = 0.98$

Predicted Value: $L_b = 1.40(1.10)(1.20)(0.90)(0.98) = 1.63$ seconds

Measured Value: $L_b = 1.92$ seconds

Difference = 15 percent

Case Study Number 3

Location -- New Circle Road northbound at Woodhill Drive, Lexington
Lane -- Through-only lane
City Population -- 204,200
Location in City -- Outlying Business District
Cycle Length -- 128.0 seconds
Speed Limit -- 45 mph
Gradient -- +0.5 percent

Correction Factors: $C_p = 1.00$
 $C_l = 1.00$
 $C_c = 0.90$
 $C_s = 1.00$
 $C_g = 1.00$
 $C_r = 1.00$

Predicted Value: $L_b = 1.40(0.90) = 1.26$

Measured Value: $L_b = 1.28$ seconds

Difference = 2 percent

ENDING LOST TIMES

To illustrate the use of the ending lost time prediction formula given in the recommendations, a few case studies were conducted to compare measured and predicted values. Following is a summary of these comparisons. The data necessary to use the prediction formula are given along with the calculations. The measured values are then given and compared to the predicted values.

Case Study Number 1

Location	-- Euclid Avenue at Rose Street, Lexington
Length of Yellow	-- 4.0 seconds
Cycle Length	-- 70 seconds
City Population	-- 204,200
Location in City	-- Fringe
Gradient	-- -0.5 percent
Speed Limit	-- 35 mph
Type of Lane	-- Through or right-turn lane

Adjustment Factors:	Fy = 1.00
	Fc = 1.15
	Fp = 1.00
	F1 = 1.05
	Fg = 1.00
	Fs = 1.00
	Ft = 1.00

Predicted Value: $Le = 1.67(1.15)(1.05) = 2.02$ seconds

Measured Value: $Le = 2.09$ seconds

Difference = 3 percent

Case Study Number 2

Location -- Broadway at High Street, Lexington
Length of Yellow -- 3.6 seconds
Cycle Length -- 70 seconds
City Population -- 204,200
Location in City -- Central Business District
Gradient -- -5.0 percent
Speed Limit -- 35 mph
Type of Lane -- Through lane

Adjustment Factors: $F_y = 1.00$
 $F_c = 1.15$
 $F_p = 1.00$
 $F_l = 1.20$
 $F_g = 1.00$
 $F_s = 1.00$
 $F_t = 1.00$

Predicted Value: $L_e = 1.67(1.15)(1.20) = 2.30$ seconds

Measured Value: $L_e = 2.49$ seconds

Difference = 8 percent

Case Study Number 3

Location -- Nicholasville Road at Reynolds Road, Lexington
Length of Yellow -- 3.0 seconds
Cycle Length -- 153 seconds
City Population -- 204,200
Location in City -- Outlying Business District
Gradient -- -0.5 percent
Speed Limit -- 45 mph
Type of Lane -- Through or right-turn lane

Adjustment Factors: $F_y = 0.70$
 $F_c = 1.00$
 $F_p = 1.00$
 $F_l = 0.95$
 $F_g = 1.00$
 $F_s = 1.00$
 $F_t = 1.00$

Predicted Value: $L_e = 1.67(0.70)(0.95) = 1.11$ seconds

Measured Value: $L_e = 1.03$ seconds

Difference = 8 percent

CAPACITY CALCULATION

The following case study illustrates how saturation flow levels together with beginning, ending, and other lost times, can be used to calculate the capacity of a specific approach to a signalized intersection.

Case Study (Capacity Calculation)

Location -- Euclid Avenue westbound at Rose Street, Lexington
Description -- Two lanes on approach:
One left-turn only, width = 10.7 feet;
One right-turn and through, width = 13.3 feet,
Turning radius = 24 feet

Location in City -- Fringe
Pedestrian Activity -- Heavy
Approach Grade -- -0.5 percent
Speed Limit -- 35 mph
Traffic Composition -- Left-turn lane -- 97.0% passenger cars
2.5% single-unit trucks
~~0.5% combination trucks~~

Opposing Volume = 400 vph

Right-turn and through lane -- ~~82.0%~~ through passenger cars
2.5% through single-unit trucks
0.5% through combination trucks
14.0% right-turning passenger cars
1.0% right-turning single-unit trucks
4 local buses per hour, averaging
5 persons entering or exiting

Signal Timing -- Green time = 26.0 seconds
Yellow time = 4.0 seconds
All-red time = 0.0 seconds
Cycle length = 70.0 seconds

Capacity of Left-Turn-Only Lane

Saturation Flow (from previous report (1))

$$S = 1650(F_{lp})(F_c)(F_{vt})(F_g)(F_w)(F_r)(F_t)(F_s)(F_d)$$

$$F_{lp} = 0.96$$

$$F_c = 1.00$$

$$F_{vt} = (100)/((97(0.98)+(2.5)(1.57)+(0.5)(2.41)) = 1.00$$

$$F_g = 1.00 - 1.1(-0.5/100) = 1.01$$

$$F_w = 1.00$$

$$F_r = 1.00$$

$$F_t = 1.02$$

$$F_s = 1.00$$

$$F_d = 1.00$$

$$S = 1650(0.96)(1.01)(1.02) = 1632 \text{ vphg}$$

Lost Time

For opposed left turns, need opposing volume per cycle

$$\text{Opposing volume per cycle} = 400 \text{ vph}(70 \text{ sec/cycle})/(3600 \text{ sec/hr}) = 7.8 \text{ veh/cycle}$$

From Figure 1, for two-lane road (since left-turning vehicles turn across only one lane of opposing traffic),

$$\text{Lost Time per cycle} = 20.5 \text{ seconds}$$

Therefore,

$$L_b + L_e + L_o = 20.5 \text{ sec}$$

$$\begin{aligned} \text{Effective Green} &= G + Y - L_b - L_e - L_o \\ &= 26.0 + 4.0 - 20.5 \\ &= 9.5 \text{ seconds} \end{aligned}$$

$$\begin{aligned} \text{Capacity} &= (S)(G_e)/(C) \\ &= (1632)(9.5)(70.0) = 221 \text{ vph} \end{aligned}$$

Capacity of Right-Turn and Through Lane

Saturation Flow

$$S = 1650(F_{lp})(F_c)(F_{vt})(F_g)(F_w)(F_r)(F_t)(F_s)(F_d)$$

$$F_{lp} = 0.96$$

$$F_c = 1.00$$

$$F_{vt} = 100 / ((82)(1.00) + (14)(1.12) + (2.5)(1.36) + (1)(1.71) + (0.5)(2.02)) = 0.96$$

$$F_g = 1.01$$

$$F_w = 1.00$$

$$F_r = (85/100) + 0.93(15)/100 = 0.99$$

$$F_t = 0.96$$

$$F_s = 1.00$$

$$F_d = 1.00$$

$$S = 1650(0.96)(0.96)(1.01)(0.99)(0.96) = 1460 \text{ vphg}$$

Lost Time

From Equation 8

$$L_b = 1.40(C_p)(C_l)(C_c)(C_s)(C_g)(C_r)$$

$$C_p = 1.00$$

$$C_l = 1.10$$

$$C_c = 1.20$$

$$C_s = 0.90$$

$$C_g = 1.00$$

$$C_r = 1.00 + (-0.20)(15/100) = 0.97$$

$$L_b = 1.40(1.10)(1.20)(0.90)(0.97) = 1.61 \text{ seconds}$$

From Equation 10

$$Le = 1.67(Fy)(Fc)(Fp)(Fl)(Fg)(Fs)(Ft)$$

$$\begin{aligned}Fy &= 1.00 \\Fc &= 1.15 \\Fp &= 1.00 \\Fl &= 1.05 \\Fg &= 1.00 \\Fs &= 1.00 \\Ft &= 1.00\end{aligned}$$

$$Le = 1.67(1.15)(1.05) = 2.02 \text{ seconds}$$

Pedestrian Interference

For heavy pedestrian activity and 15 percent turning, assume 0.5 case of pedestrian interference per cycle

$$\text{Lost Time} = (0.5 \text{ case/cycle})(5.0 \text{ sec/case}) = 2.5 \text{ sec/cycle}$$

Local Buses

Given an average of 5 entering and exiting passengers per stop, using Equation 7

$$y = 2.50(5) + 4.18 = 16.68 \text{ seconds}$$

(this is lost time per stop)

$$\begin{aligned}\text{Stops per cycle} &= (4 \text{ stops per hour})(70 \text{ sec/cycle})/(3600 \text{ sec/hr}) \\ &= 0.08\end{aligned}$$

$$\text{Lost Time per cycle} = (16.68)(0.08) = 1.33 \text{ seconds}$$

Total Lost Time per Cycle

$$\begin{aligned}L &= 1.61\text{sec} + 2.02\text{sec} + 2.50\text{sec} + 1.33\text{sec} = 7.46 \text{ sec} \\ \text{or } L &= 7.5 \text{ sec}\end{aligned}$$

Effective Green

$$\begin{aligned}Ge &= G + Y - L \\ &= 26.0 + 4.0 - 7.5 \\ &= 22.5 \text{ sec}\end{aligned}$$

Capacity

$$\begin{aligned}C &= S(Ge)/C \\ &= (1460)(22.5)/(70.0) \\ &= 469 \text{ vph}\end{aligned}$$

Total Capacity of Approach

$$\begin{aligned}C &= Cl + Cr \\ &= 221 \text{ vph} + 469 \text{ vph} = 690 \text{ vph}\end{aligned}$$

From Equation 10

$$Le = 1.67(Fy)(Fc)(Fp)(Fl)(Fg)(Fs)(Ft)$$

$$Fy = 1.00$$

$$Fc = 1.15$$

$$Fp = 1.00$$

$$Fl = 1.05$$

$$Fg = 1.00$$

$$Fs = 1.00$$

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