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16. Abstract

The capacity of an intersection is affected significantly by the relative proportion of straight-through and turning vehicles in each approaching lane. In many situations—particularly at signalized intersections—traffic throughput on an approach can be increased by adding auxiliary lanes to accommodate only turning vehicles. Techniques for designing left-turn and right-turn lanes at intersections and evaluating the related traffic performance are needed.

Guidelines for determining the number and length of left-turn lanes needed at signalized intersections have been developed. The guidelines are implemented primarily through a microcomputer program called "Left-Turning Movement Analysis Program" (LTMAP). This program provides the engineer/user with an interactive means for entering descriptive data concerning intersection turn-lane configuration, traffic volumes, vehicle classes, traffic behavior parameters, and signal timing. A range of descriptive quantitative information about expected queue lengths, likely signal-cycle failures, volume-to-capacity statistics, and various delay estimates is produced immediately by the program. Different intersection operational situations can be compared quickly and easily in this way.

Equivalence factors for converting right-turn traffic volumes to equivalent straight-through volumes at stop-sign controlled intersections are presented, and guides for determining the length of right-turn bays at a signalized intersection are shown graphically. These tools aid the engineer in designing and analyzing auxiliary-lane treatments required for various intersection conditions.

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by

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Research Report Number 1111-1F

Research Project 3-18-87-1111

Capacity Improvements for Urban Intersections

conducted for

Texas State Department of Highways and Public Transportation

in cooperation with the

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by the

CENTER FOR TRANSPORTATION RESEARCH

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PREFACE

Auxiliary turn lanes are frequently used as a means of enhancing the quantity and quality of intersection traffic flow. Study efforts described in this report are intended to be an aid to the engineer as decisions about auxiliary lane utilization are made. While the calculation procedures described yield answers to many questions, these answers are certainly not intended as a substitute for experience and sound engineering judgement.

ABSTRACT

The capacity of an intersection is affected significantly by the relative proportion of straight-through and turning vehicles in each approaching lane. In many situations—particularly at signalized intersections—traffic throughput on an approach can be increased by adding auxiliary lanes to accommodate only turning vehicles. Techniques for designing left-turn and right-turn lanes at intersections and evaluating the related traffic performance are needed.

Guidelines for determining the number and length of left-turn lanes needed at signalized intersections have been developed. The guidelines are implemented primarily through a microcomputer program called "Left-Turning Movement Analysis Program" (LTMAP). This program provides the engineer/user with an interactive means for entering descriptive data concerning intersection turn-lane configuration, traffic volumes, vehicle classes, traffic behavior parameters, and signal timing. A range of descriptive quantitative information about expected queue lengths, likely signal-cycle failures, volume-to-capacity statistics, and various delay estimates is produced immediately by the program. Different intersection operational situations can be compared quickly and easily in this way.

Equivalence factors for converting right-turn traffic volumes to equivalent straight-through volumes at stop-sign controlled intersections are presented, and guides for determining the length of right-turn bays at a signalized intersection are shown graphically. These tools aid the engineer in designing and analyzing auxiliary-lane treatments required for various intersection conditions.

SUMMARY

Capacity of a street intersection is affected significantly by the relative number of turning and straight-through vehicles which must be accommodated in each approaching lane. Turning vehicles maneuver more slowly than straight-through vehicles, and they must wait for appropriate gaps in conflicting traffic flows before entering the intersection and clearing a shared lane for use by straight-through vehicles. Left-turning vehicles require more time to clear the intersection than right-turning vehicles. In many situations—particularly at signalized intersections—the overall performance of the intersection can be improved by adding auxiliary turning-traffic lanes adjacent to the through-traffic lanes. These auxiliary lanes provide a designated area in which turning vehicles can decelerate, stop, and enter the intersection with minimal interference to through traffic.

Guidelines for determining the number and length of left-turn lanes needed at signalized intersections have been developed. In this development, it was found that the variables which have the greatest impact on left-turning traffic performance are (1) left-turn volume, (2) left-turn red time, and (3) signal cycle length. The relative impact of each of these variables was studied for single left-turn lanes and for dual left-turn lanes. Measures of performance selected to evaluate the effectiveness of left-turn operations included (1) cycle failure, (2) demand-capacity ratio, and (3) delay. These guidelines are implemented primarily through a microcomputer program called "Left-Turning Movement Analysis Program" (LTMAP). Through screen prompts, this program provides the engineer/user with an interactive means for entering descriptive data concerning intersection turn-lane configuration, traffic volumes, vehicle classes, traffic behavior parameters, and signal timing. A range of descriptive quantitative information about expected queue lengths, likely signal-cycle failures, volume-to-capacity statistics, and various delay estimates is produced immediately by the program. The program will be distributed on a single floppy disk. The disk also includes data files from multiple runs of the TEXAS Model for Intersection Traffic concerning average and maximum queue lengths, and average queue delay for both single and dual left-turn lanes. Different intersection operational situations can be compared quickly and easily by using LTMAP on an IBM-compatible microcomputer.

In Chapter 5, equivalence factors which may be used for converting right-turn traffic volumes to equivalent straight-through volumes at stop-sign-controlled intersections are presented, and guides for determining the length of right-turn bays at a signalized intersection are shown graphically. These tools aid the engineer in designing and analyzing auxiliary-lane treatments required for various intersection conditions.

IMPLEMENTATION STATEMENT

The guidelines presented in this report can be put into immediate use by State Department of Highways and Public Transportation engineers who are responsible for intersection design and modification. The microcomputer software program called "Left-Turning Movement Analysis Program" (LTMAP), along with a copy of this report, should be distributed to these personnel when approved. Transportation engineers in other governmental jurisdictions in Texas and in other states will find the guidelines described herein useful for designing and analyzing auxiliary turning lanes at intersections.

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CHAPTER 1. INTRODUCTION

The overall capacity of an urban street intersection is affected significantly by the relative number of turning vehicles and straight-through vehicles which must be accommodated within each approaching lane. Turning vehicles maneuver more slowly than straight-through vehicles, and they must wait for appropriate gaps in conflicting traffic flows before entering the intersection and clearing a shared lane for use by straight-through vehicles. Conceptually, left-turning vehicles require more time to clear the intersection than right-turning vehicles. In many situations—particularly at signalized intersections—the overall performance of the intersection can be improved by adding auxiliary turning-traffic lanes adjacent to the through-traffic lanes. These auxiliary lanes provide a designated area in which turning vehicles can decelerate, stop, and enter the intersection with minimal interference to through traffic.

The primary objective of the research upon which this report is based was to develop guidelines for using auxiliary lanes at urban intersections. Multiple left-turn lanes at signalized intersections were evaluated extensively in relation to the number of lanes required and to the storage length of each such left-turn lane(s). The assumption was made that a left-turn-only signal phase was justified to control a dedicated auxiliary left-turn lane(s). The number of required left-turn lanes was analyzed by using left-turn performance measures that indicate whether there is a cycle-failure, capacity, or delay problem at the intersection. The left-turn storage-length issue was addressed by utilizing the results of computer simulation with the TEXAS Model for Intersection Traffic (Ref 11). This model incorporates the influence of vehicles arriving at random times on the approach to the intersection. A user-friendly computer software program called LTMAP, for Left-Turning Movement Analysis Program, was developed for use on an IBM-compatible microcomputer. This program, described in Chapter 4, provides the engineer/user with a convenient interactive design and analysis tool for evaluating single and dual left-turn lane configurations.

Techniques for determining the need for right-turn lanes or bays are included in Chapter 5. The TEXAS Model for Intersection Traffic (Ref 11) was the basis for developing equivalence factors that can be used to convert observed right-turn traffic flow rates into equivalent straight-through traffic flow rates when an intersection is controlled by stop signs. These traffic flow rates are helpful in deciding whether traffic signal control is warranted for certain lane configurations at the intersection. The NETSIM Model (Ref 16) was used to estimate the length of queues that might develop at a signalized intersection and block access to a right-turn bay. Decision charts are provided to guide the selection of right-turn bay length.

CHAPTER 2. SINGLE-LANE LEFT-TURN ANALYSIS

This chapter addresses two basic questions: first, does an urban intersection have sufficient capacity, and second, how much storage is needed for the left-turning vehicles? The first question is analyzed by deriving new, or presenting existing, warrants that identify critical capacity conditions at urban intersections. These warrants are grouped into three categories: cycle-failure warrants, demand-capacity warrants and delay warrants. The second question, that of appropriate storage length, is analyzed by using conceptual formulas coupled with simulation results. Chapter three examines the question of whether more than one left-turn lane is needed, and if so, how long this lane should be.

The basic assumption in this single-lane left-turn analysis was that a left-turn bay with a protected phase was required. Additionally, it was assumed that the signal timing had been optimized or that the left-turn green time was fixed. Implicit in this assumption was that when additional capacity is needed for a left-turn movement it is much cheaper and faster to change the signal timing than it is to alter the intersection's geometry. Machemehl's and Mechler's (Refs 1 and 2) publications provide an analysis of left-turn phase sequencing and cycle lengths. Their work coupled with Lin's and Machemehl's study (Ref 2) provide an extensive source of warrants and procedures relating to left-turns.

VARIABLES AND MEASURES OF PERFORMANCE

VARIABLES

The variables that were assumed to influence a left-turning movement most were: traffic volumes, signal timing and intersection geometry. The vast number of combinations of these three variables makes any analysis of this type complex. In addition to the assumptions stated above some additional assumptions were made. First, the cycle length and split were assumed to be appropriate, or optimal, for the given traffic conditions. Equations such as Webster's, Pignataro's, Davidson's and the Canadian method provide procedures for cycle-length and split optimization. Second, it was assumed that the signal was pretimed. An actuated controller makes a left-turn study much more difficult due to the variability of the cycle split. However, when traffic volumes approach the intersection's capacity, the behavior of an actuated controller is essentially pretimed. Because left-turn movements become problematic when traffic volumes approach capacity, the assumption of a pretimed controller is viewed as being valid.

In order to concentrate on conditions where the left-turn movement becomes problematic it was assumed that the left-turn demand volume was approaching its capacity (V/C greater than 0.5). The last major assumption that was made was that, unless otherwise noted all vehicles are expressed in passenger car equivalent units (pcu's).

MEASURES OF PERFORMANCE

Lin (Ref 3) identified five performance measures that are applicable to a left-turn analysis. They are: average delay, ninety-percentile delay, percentage of drivers incurring excessive delay, average queue length, and degree of saturation. He defined and explained the average delay as: "the sum of each driver's delay divided by the total number of drivers. The average value of delay is usually used in both practice and theory for evaluating a queueing system. The average delay represents the delay for an average driver under an average condition" (Ref 3, p 119). The ninety-percentile delay is the delay that ninety percent of the drivers will incur. Implicit in this definition is the assumption that the delay distribution is known, which is not always the case. Because of this limitation the ninety-percentile delay was not chosen as a performance measure in this study. Lin's third measure was the percentage of drivers incurring excessive delay. One or more cycle failures will produce excessive delay and thus an impatient and hazardous driver. This problem is addressed in the cycle failure warrant section of this study. Lin's fourth measure was average queue length. This subject is addressed in the bay length determination section of this study. The last pertinent measure was the degree of left-turn saturation. As is shown in the critical volume-to-capacity ratio section of this report, this is an important factor and should be included in a left-turn analysis. In summary, of the five left-turn performance measures outlined by Lin; average delay, percentage of drivers incurring excessive delay, average queue length and degree of saturation are appropriate for use in this analysis. Ninety-percentile delay was not chosen because of the difficulty associated with its measurement.

LEFT-TURN WARRANTS

The left-turn warrants analyzed in this section are: cycle-failure, demand-capacity, and delay warrants. Each of these is then constrained by several criteria that must be met in order for that warrant to be activated. The cycle failure warrant addresses the probable maximum number of left-turning cycle failures in one hour and the maximum number that any one vehicle should experience. The demand-capacity warrant determines a critical volume-to-capacity ratio at which additional capacity is needed. The delay warrant defines the amount of delay allowed before additional capacity is required.

CYCLE FAILURE WARRANTS

According to Pignataro (Ref 4): "a cycle failure is defined in one of two ways: (1) vehicles arriving in the last cycle time are not cleared in the current green on *at least* one leg, and (2) vehicles so arriving are not cleared on the critical leg." For the purposes of this study it was assumed that the left-turn movement was on the critical leg.

Lin's Method

Lin (Ref 3) has identified two warrants that relate the number of cycle failures to insufficient left-turn capacity. The warrants are:

(1) five percent of left-turners experiencing more than two cycle failures; and,
(2) four left-turners in one hour experiencing more than two cycle failures.

The values used in the above warrants were determined by Lin, and it was assumed the these conditions would provoke impatient and dangerous behavior from the average driver. These warrants, while useful, are hard to use in practice because of the difficulty of determining the distribution of the vehicles experiencing more than two cycle failures. It is for this reason that they were not included in the implementation package outlined in Chapter 4.

Pignataro's Method

Pignataro (Ref 4, p 356) states that, "cycle failure is addressed indirectly by requiring that the peak 15-minute volume for each leg be accommodated in the green time available to that leg in the peak 15 minutes." If it is assumed that the left-turn volume is the critical lane volume for the major street then the equation that Pignataro uses for cycle failures can be used for just the left-turners. The adapted equation is as follows:

$$\frac{N_i S_i}{4(PHF)} \leq \frac{900\,G}{C}$$

where:

N_i = left-turning vehicles in PCU's per hour;
S_i = approximate average headway between the left-turning vehicles, in seconds;
PHF = peak-hour factor, the ratio of the number of leftturning vehicles entering the intersection during the peak hour to four times the number of vehicles entering during the peak 15-minute period;
C = cycle length, in seconds; and
G = left-turn green time, in seconds.

If it is assumed that this movement is operating near capacity, the value of S_i becomes essentially constant. Pignataro uses a value of 2.5 seconds, which is a reasonable estimate of the straight-through minimum headway when the traffic volume is approaching capacity. While this may be adequate for straight-through movements, simulation results have shown that left-turning vehicles have average headways (at saturation) of about 3 seconds. It is therefore recommended that, for left-turn analysis, a value of between 2.5 and 3.0 seconds be used for the average minimum left-turn headway.

The left side of the above inequality is the required left-turning green time based on the demand. The right side of the inequality is the provided left-turn green time based on the predetermined signal timing. Therefore, the equation is a comparison of the left-turn green time required in relation to the amount allocated. Pignataro's use of the peak-hour factor is appropriate because it incorporates the variability of the traffic flow during the peak-hour. A relatively high number of vehicles arriving during one 15-minute interval of the peak hour would result in a low PHF. This in turn would require additional green time, and Pignataro's equation incorporates this effect.

Pignataro uses this equation to address indirectly the probability of an insufficient capacity based on a peak hour with uniform arrivals. However, his equation does not addresses the probability of experiencing a cycle failure based on a random, Poisson-distributed arrival process. Because of this limitation his method was not included in the implementation package. Drew's method does address this random arrival process, and therefore was used to determine the probability of a cycle failure.

Drew's Method

Drew's definition of cycle failure is: "any cycle during which approach arrivals exceed the capacity for departures" (Ref 5, p 139). His equation determines the probability of the capacity being exceeded and includes (the Poisson-distributed) randomness in the arrival stream. The equation is as follows:

$$P(x+1) = \sum_{x+1}^{\infty} \frac{m^{x+1} e^{-m}}{(x+1)!}$$

where:

m = 4 (peak 15-minute critical lane volume)(C/3600),
m = average number of uniform arrivals during one cycle length in the peak 15-minute period,
Ge = effective green,

D = average minimum headway,
D = 3 seconds (assumed),
x = Ge/D, and
x = potential number of vehicles processed during the effective green.

This equation is good because it assumes that the peak period would be the period of most interest to the traffic engineer for design purposes. References 5 (p 140) and 6 (p 504) provide curves which show the probability of a cycle failure in relation to the average number of arrivals per cycle and the amount of green time. Drew suggests a 30 percent chance of cycle failure as being a practical design value. Drew's equation is based on through movements with an average minimum headway, D, of 2 seconds. This value should be increased to account for the additional time required for a left-turn maneuver. As stated earlier, a D value of between 2.5 and 3.0 seconds is recommended.

DEMAND-CAPACITY WARRANTS

The underlying premise in the demand-capacity warrants was that if the left-turn demand is known then the amount of capacity needed to accommodate that demand is also known. By assuming that the signal timing is fixed, the only other variable which will significantly affect the capacity is intersection geometry. With respect to left-turning movements, greater capacity implies a longer storage length, additional left-turn lanes, or both. The questions that are addressed in this section are: what is the left-turn capacity for a given geometry and timing, and is this capacity adequate to handle the (given) demand? If it is determined that the capacity is inadequate for the demand, then additional storage is required. The required left-turn storage length is addressed in the Bay Length Determination section.

Capacity

Capacity analysis focuses on two methods: (1) a method developed using the TEXAS Model (Ref 11) which utilizes an average left-turn processing rate, and (2) the method outlined in Chapter Nine of the 1985 Highway Capacity Manual (Ref 7). Each method will be presented, then a comparative analysis will be made.

TEXAS Model Method

Saturation flow rate can be analyzed in terms of the average left-turn processing rate, R, in terms of protected green time per vehicle. This value is the same as the average minimum departure headway used in Drew's equation. It was assumed that this processing rate was dependent on the driver's and vehicle's characteristics and not on signal timing and geometry. An intersection with more ample geometry will have a larger R-value, but for the purposes of this study intersection geometry was assumed to be constant.

The assumption that signal timing (cycle length and left-turn green time) did not affect the processing rate was tested with the TEXAS Model. Figures 2-1a, b, c, and d show the required green time per vehicle for cycle lengths of 60, 90 and 120 seconds in relation to inadequate, appropriate, and excess left-turn green time. Figure 2-1d shows the value of R for a 60 second cycle length with the three different green times. Each data point on these graphs represents the average of four independent, 30-minute simulation runs. The appropriate-green-time case was calculated as a critical-lane-volume type of cycle split based on a critical lane for each leg. The volumes on all movements other than the left-turners were held constant. The inadequate and excess green times were calculated by respectively subtracting and adding twenty percent of the green time from and to the appropriate case. The green time per vehicle was then calculated as the total available green time divided by the number of vehicles processed. From these graphs it should not be concluded that at lower volumes a left-turning vehicle required more time to make a left-turn. Because the headways between vehicles increased as the volume decreased, so did the value of R. Of greater importance is the processing rate at the higher volumes. At a left-turn demand of 800 vehicles per hour, all cases converged to an R value of approximately 3 seconds per vehicle. This is germane to the determination of a saturation flow value because it implies that when volumes approach saturation the process rate becomes constant. Lin (Ref 3) reached the same conclusion with the same value for R in his permissive left-turn study. At lower volumes it is hard to determine an average headway because of the large variability in vehicle spacing. Because of this, the equations given below are intended to be used only when the traffic volume is approaching capacity.

Once the left-turn processing rate is assumed to be constant, the calculation of saturation flow rate becomes relatively straightforward. By dividing the R-value of 3 seconds per vehicle into 3600 the result is a saturation flow rate (Q_S) of 1200 vehicles per hour. This is the same value that the Australian Road Capacity Guide recommends (see Ref 2).

The calculation of the left-turn capacity for the TEXAS Model method is as follows:

$$Q_l = Q_s \frac{G}{C}$$

$$= \frac{3600}{R} * \frac{G}{C}$$

The TEXAS Model only allows one left-turning vehicle to proceed through a yellow-change interval per cycle. Field data have indicated that the average number of vehicles processed in this interval is 1.5. It was therefore

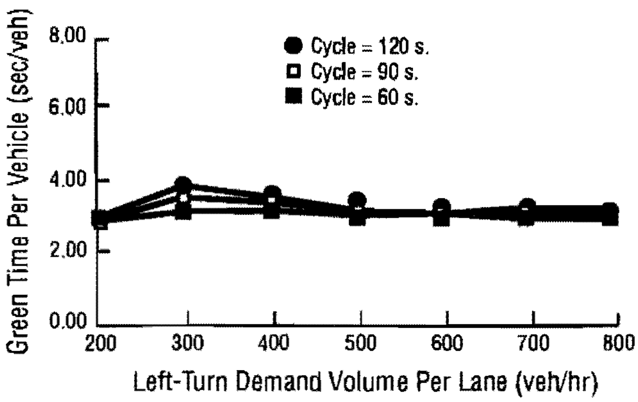

Fig 2-1a. Left-turn processing times for one vehicle given inadequate green time (from TEXAS Model).

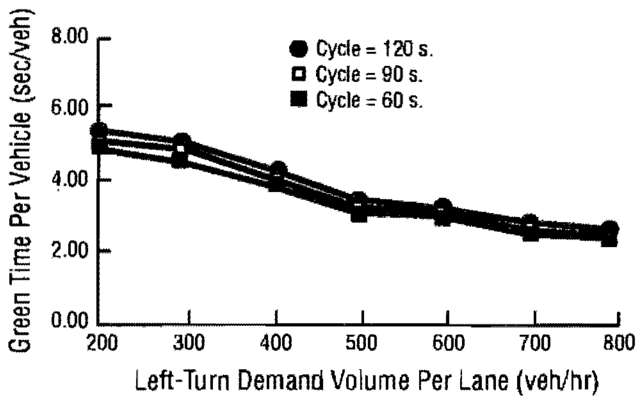

Fig 2-1b. Left-turn processing times for one vehicle given appropriate green time (from TEXAS Model).

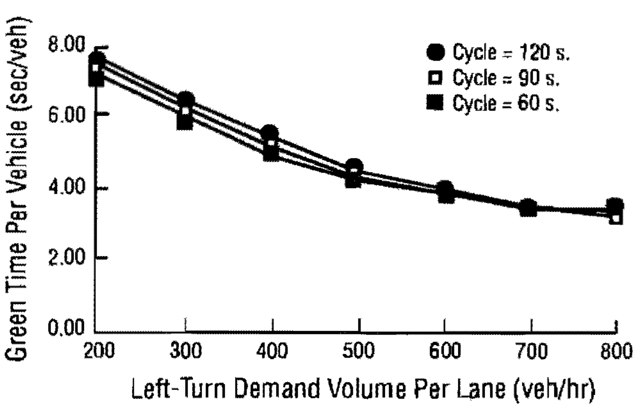

Fig 2-1c. Left-turn processing times for one vehicle given excess green time (from TEXAS Model).

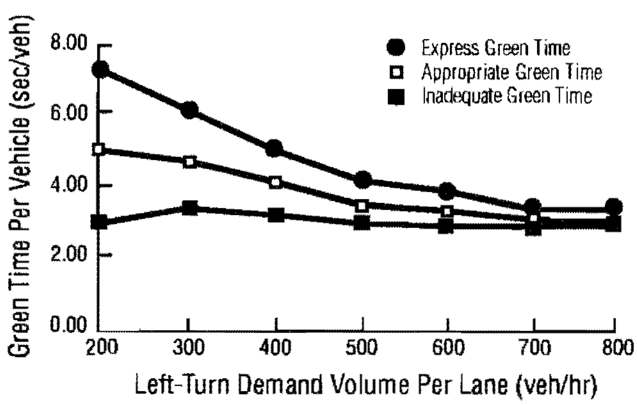

Fig 2-1d. Left-turn processing times for a 60-second cycle length with excess, appropriate, and inadequate green time (from TEXAS Model).

desirable to revise the above equation to account for the extra 0.5 vehicles per phase. The equation then becomes:

$$Q_l = \left[\frac{3600}{R} * \frac{G}{C}\right] + \left[\frac{3600}{C} * 0.5\right]$$

$$= \left[\frac{P}{R} + \frac{0.5}{C}\right] * 3600$$

where:

Q_s = Left-turn saturation flow rate (veh/hour green);
Q_l = left-turn capacity when approaching saturation conditions (veh/hour);
R = protected left-turn processing rate (sec/veh);
G = effective left-turn green time (sec);
C = cycle length (sec); and
P = decimal percentage of cycle for protected green phase.

The 1985 Highway Capacity Manual Method

The 1985 Highway Capacity Manual's (85 HCM) definition of capacity is: "the maximum flow rate (for the subject approach) which may pass through the intersection under prevailing traffic, roadway, and signalization conditions" (Ref 7, p 9-3). Another way of stating this is that capacity is the product of the saturation flow rate times the percent of the cycle that is effectively green (Ge/C). The saturation flow rate is then defined as: "the maximum rate of flow that can pass through a given intersection approach or lane group under prevailing traffic and roadway conditions, assuming that the approach or lane group has 100 percent of real time available as effective green time" (Ref 7, p 9-3). In this study, all saturation flow values are based on one hour of continuous, uninterrupted left-turn green time. The 85 HCM provides a detailed explanation with work sheets for determining the left-turn capacity of an intersection. To avoid redundancy, this left-turn analysis will only focus on the weaknesses of the Highway Capacity Manual approach rather than a step-by-step explanation of left-turn capacity determination as outlined in the manual.

The Capacity Manual (p 9-73) states: "...saturation flow rates have a high degree of variability." A study conducted by JHK & Associates showed that median saturation flow rates for through and turn lanes for fair-to-good geometric and traffic conditions were 1600 and 1500 vphgpl, respectively.

In contrast, the "typical" procedure of using an ideal saturation flow rate of 1800 and multiplying it by a left-turn correction factor, provides a left-turn saturation flow rate of 1710 vphgpl. TEXAS Model simulation runs indicate that this latter value is too high for left-turning traffic. In fact, based on a left-turn processing rate of 3 seconds, the saturation flow value determined from the TEXAS Model was 1200 vphgpl. It is therefore recommended that the range of 1500 to 1710 vphgpl be used as the left-turn saturation flow value in capacity calculations.

In equation form the 1985 Highway Capacity Manual method is:

$$Q_l = Q_s * \frac{G}{C}$$

where:

Q_l = Left-Turn Capacity (veh/hr),
Q_s = Left-Turn Saturation Flow Rate (veh/hr green),
or (Thru Saturation Flow Rate) * (0.95),
G = Effective Green (sec), and
C = Cycle Length (sec).

Comparative Analysis of Capacity Determination Methods

To aid in comparing the two methods presented above, the equation for each method is presented again:

TEXAS Model Method:

$$Q_l = \left[\frac{3600}{R} * \frac{G}{C}\right] + \left[\frac{3600}{C} * 0.5\right]$$

$$= \left[\frac{P}{R} + \frac{0.5}{C}\right] * 3600$$

1985 Highway Capacity Manual Method:

$$Q_l = S * \frac{G}{C}$$

The relationship between the G/C ratio and the capacities discussed above are shown in Fig 2-2a. The cycle length used in this graph is 60 seconds. The graph shows that as the effective green time increases the spread between the two capacities also increases. The HCM 1710 and HCM 1500 lines represent the capacities as determined by the 85 HCM for left-turn saturation flow rates of 1710 and 1500 respectively. Similarly, the TEXAS R=3 and TEXAS R=2.5 lines represent the capacities that were calculated using a left-turn processing rate of 3.0 and 2.5 seconds, respectively. As the graph indicates there is a fairly close match between the 85 HCM 1500 Method and the Texas R=2.5 method. (An R of 2.5 seconds is equivalent to an HLM saturation flow of 1440 vph.) Because the danger of overestimating capacity is more serious than underestimating it, the HCM 1710 Method should be looked at very carefully to determine whether it is appropriate for capacity calculations. This graph also has three horizontal lines representing left-turn demands of 600, 700 and 800 vehicles per hour. These lines have been included to indicate the points at which demand equals capacity for each method. For example, at a demand of 600 ltvph, capacity would be reached at a G/C of: 0.35 for the 85 HCM 1710 Method, 0.4 for the 85 HCM 1500 Method, and 0.42 and 0.5 for the TEXAS 3.0 and 2.5 Methods, respectively.

The left-turn capacities in a Ge/C range of 0.0 to 0.4, are shown in Fig 2-2b. As this graph indicates, the capacities converge as the Ge/C approaches zero. When the 85 HCM 1500 method was compared to the Texas 2.5 method at a Ge/C of 0.3, there was only a 18 vph difference between the calculated capacities.

The minimum left-turn processing rate of 3.0 seconds that was determined in TEXAS Model simulations should serve as a conservative lower bound in making capacity calculations. Capacities calculated using an R value of 2.5 seconds closely matched those of the HCM 1500 method; therefore, the TEXAS 2.5 Method can serve as an upper bound. The HCM 1710 method is considered too liberal relative to the other methods. To reflect local conditions more accurately, a field study should be conducted to determine the left-turn headways, and thus the left-turn processing rate, during peak periods.

The use of a capacity equation that is based on a processing rate rather than a saturation flow rate is significant because for a given intersection it is easier to collect headway data than it is to determine a saturation flow rate. In fact, the 85 HCM suggests field measurements of headways as a means of estimating saturation flow.

Critical Volume to Capacity Ratio

In Lin's study of unprotected left-turn operations he states that there is a "threshold located at M vehicles lower than the left-turn capacity, and once the left-turn demand reaches this threshold, the left-turn operations will become critical" (Ref 3, p 172). Unfortunately, Lin's study does not provide enough data or analysis to aid in determining where this threshold is for protected left-turn movements.

By using some measures of effectiveness such as delay, or the ratio of the left-turn vehicles processed to the left-turn demand, a traffic engineer may be able to determine at what point below capacity the left-turn operation becomes critical. Simulation models provide a valuable tool in determining these measures of effectiveness.

The TEXAS Model was used to investigate whether this critical volume-to-capacity ratio exists. Of the two measures of effectiveness discussed above, delay was chosen to be more appropriate. There were three primary reasons: first, in the TEXAS Model if a left-turn queue backs up to the point where the vehicles log-in (e.g., 1000 feet), the vehicle is eliminated thus altering the (input) left-turn demand; second, the left-turn demand is difficult to determine in the field; and last, delay is a measurable and commonly-accepted indicator of intersection performance.

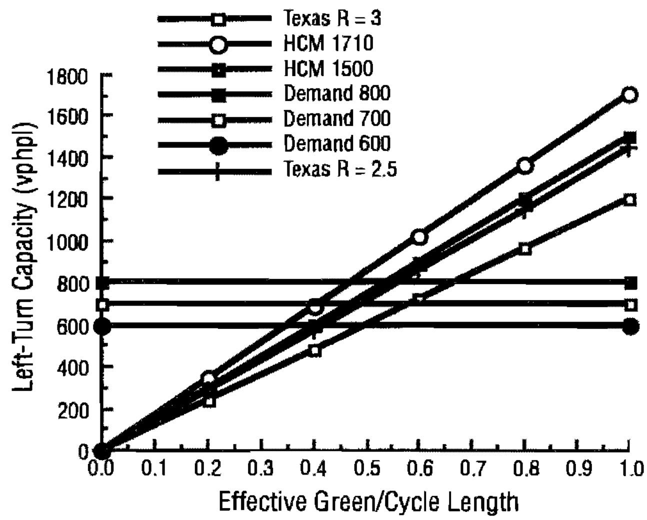

Fig 2-2a. Comparative capacity graph for a 60-second cycle length (effective green/cycle length = 0.0 to 1.0).

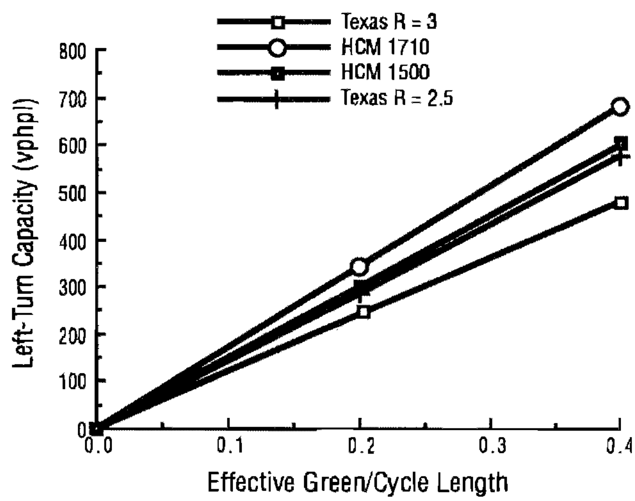

Fig 2-2b. Comparative capacity graph for a 60-second cycle length (effective green/cycle length = 0.0 to 0.4).

Of all the delay statistics generated by the TEXAS Model, average left-turn queue delay was deemed to be the most appropriate for the purposes of this analysis. In the TEXAS Model a vehicle is experiencing queue delay when the distance between it and the preceding vehicle is less than or equal to 30 feet and the vehicle's speed is less than 2 miles per hour.

Figures 2-3a and b show the relationship between the average left-turn queue delay and the volume to capacity ratio for 60 and 120 second cycle lengths respectively. The ratio of the effective green to the cycle length was held constant at 0.3. Each graph is comprised of the results from 28 independent TEXAS Model simulation runs. A fourth-order polynomial was fit to these points to determine whether an inflection point existed at some volume-to-capacity ratio of less than one. It should be stressed that this fourth-order polynomial was not intended to be used in its equation form for prediction purposes, but rather was used as a graphical tool to find any inflection points.

From the data it can be seen that the average queue delay remains fairly constant up to a V/c ratio of 0.90, then increases dramatically above this point. It is important to note that the duration of the cycle length did not significantly affect the location of the inflection point.

The horizontal line at 35 seconds of average delay corresponds to the point at which a left-turn operation becomes critical. This value was determined by Lin. With a cycle length of 60 seconds, the 35-second line meets the curve at a V/c of almost exactly 0.90. This supports the conclusions made by Lin. For the 120-second cycle length, most of the TEXAS Model data points fall above the 35-second line indicating that this cycle length is too long with respect to delay. The inflection point at this cycle length occurs at a V/c of 0.90 as well. It can be concluded that above a V/c of 0.90 the delay should be expected to increase dramatically.

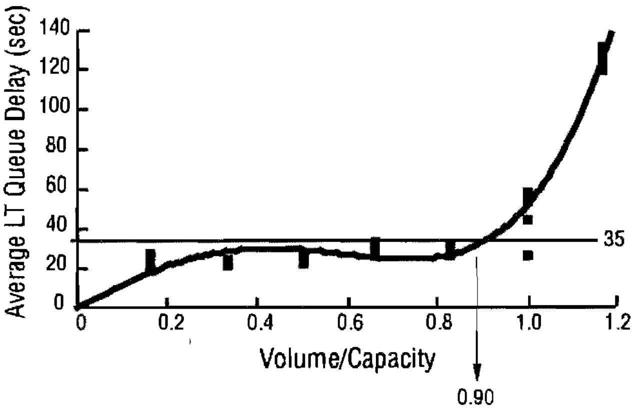

Fig 2-3a. Fourth-order curve showing relationship between V/c and delay for C=60 sec. and Ge/C = 0.3.

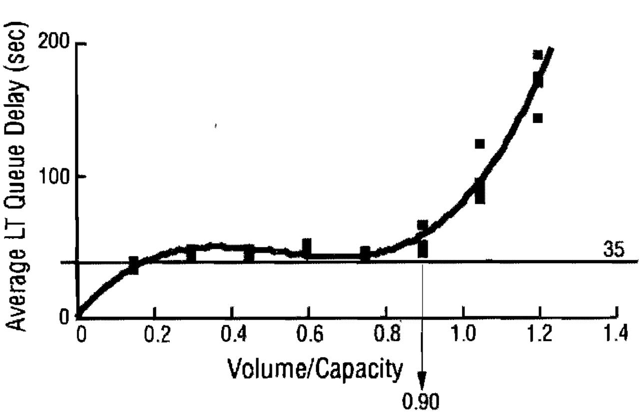

Fig 2-3b. Fourth-order curve showing relationship between V/c and delay for C = 120 sec. and Ge/C = 0.3.

A factor that will be addressed in more detail in the delay warrant section of this study is the determination of delay at V/c ratios of greater than one. Briefly, above a V/c of 1.0 the queue is in an unstable state and the delay value is a function of the duration of the observation period. In essence, when the capacity has been exceeded, the queue grows continuously thus the magnitude of the delay will depend on how long the observer has been watching the queue. From the TEXAS Model runs there is no doubt that delay increases dramatically when capacity is exceeded. The points that are above capacity in the graphs presented here represent an observation period of 30 minutes. This should be taken into consideration before any conclusions are drawn from these graphs regarding delay behavior when V/c is greater than one.

DELAY-BASED WARRANT

There are three commonly-used delay measures: total delay, queue delay, and stopped delay. This delay analysis will use both stopped delay and queue delay as performance measures.

Vehicles incur stopped delay when they move at less than two miles per hour. The average stopped delay is the ratio of the total stopped delay to the number of vehicles experiencing this delay. The 85 HCM delay formula calculates stopped delay, as does the cycle failure equation (CF equation) derived in this section.

Lin (Ref 3) defines queue delay as: "the time duration from when a vehicle joins a queue until it crosses the stop line, and includes stop time and move-up time while in the queue." The warrants presented in this section were derived by Lin and were based on queue-delay measures derived from TEXAS Model simulations. It is for this reason, even though the 85 HCM and CF equations use stopped delay, that all TEXAS Model delay data will use queue delay. This discrepancy should not be problematic because any delay statistics should be used as "ballpark figures" and not as concrete, absolute results. This disclaimer is due to the difficulty in measuring delay accurately.

Lin's research involved looking at and evaluating current critical condition identifiers for an unprotected left-turn movement. From these and simulation results he derived four new identifiers which indicate a critical left-turn movement. One of these can be applied to a protected left-turn movement. This critical condition is when a left-turner experiences at least 35 seconds of left-turn queue delay. It makes no difference to the motorist whether he is in a protected or unprotected phase, the fact that he has experienced 35 seconds or more of delay would make this an undesirable driving condition. Given this critical condition, the following analysis of average left-turn delay focuses on the shortcomings of the 1985 Highway Capacity Manual delay equation, followed by a derivation of a new equation which is tested with the TEXAS Model.

1985 HIGHWAY CAPACITY MANUAL DELAY EQUATION

In Chapter Nine of the 1985 Highway Capacity Manual an equation is presented for determining the average stopped delay per vehicle in each lane group. Used in the level-of-service module, this equation is based on Webster's work (Ref 8). The major problem with Webster's equation, which was corrected in the 85 HCM equation is that it becomes unstable as volume to capacity ratios approach one. As stated earlier, a queue resulting from demands above capacity is in an unstable state and thus the magnitude of the delay is a function of the duration of the observation period. However, a particular movement may be in an oversaturated state for only a short (known) duration and it would be desirable to have an equation that is applicable to this condition. The 85 HCM equation is applicable when volumes are at and above capacity, thereby eliminating the major weakness of Webster's equation. The Capacity Manual's equation does have some other weaknesses which will be addressed in this analysis.

The 85 HCM equation is presented here to highlight its different components. (Ref 7, pp 9-18):

$$d = d_1 + d_2$$

$$d = \left[0.38\, C \frac{[1 - g/C^2]}{[1 - (g/C)(x)]}\right] + \left[173x^2\left[(x - 1) + \sqrt{(x - 1)^2 + (16x/c)}\right]\right]$$

where:

- d = average stopped delay per vehicle for the lane group, in sec/veh;
- C = cycle length in seconds;
- g/C = the effective green time over the cycle length;
- X = the volume to capacity ratio.
- c = capacity of the lane group

The above delay equation can be broken up into uniform arrival d_1, and incremental or random arrival d_2 components. Figure 2-4a shows the linear relationship that exists between the d1 term and an increased cycle length for a volume-to-capacity ratio of 0.5. Figure 2-4b shows that the random component of delay has a much greater impact on the total delay (uniform and random) when the volume approaches capacity.

The underlying assumption in the 85 HCM equation, and in this study, is that the approaching vehicles arrive as a random process that is Poisson distributed. It is important to note that the 85 HCM states "The equation yields reasonable results for values of X (v/c) between 0.0 and 1.0. Where oversaturation occurs for long periods (15 min), it is difficult to accurately estimate delay, because spillbacks may extend to adjacent intersections. The equation may be used with caution for values of X up to 1.2, but delay estimates for higher values are not recommended." (Ref 7, pp 9-19). It is good that this statement was included; however, in an oversaturated condition the effects of spillbacks are of secondary importance when compared to the effect that a long versus a short period of observation may have on the delay.

The 85 HCM provides for a progression adjustment factor that incorporates the effects of good or bad progression into the delay determination. For a left-turn movement the 85 HCM states "Left-turn movement delays are generally unaffected by progression: protected left-turn phases are rarely progressed, and permitted left-

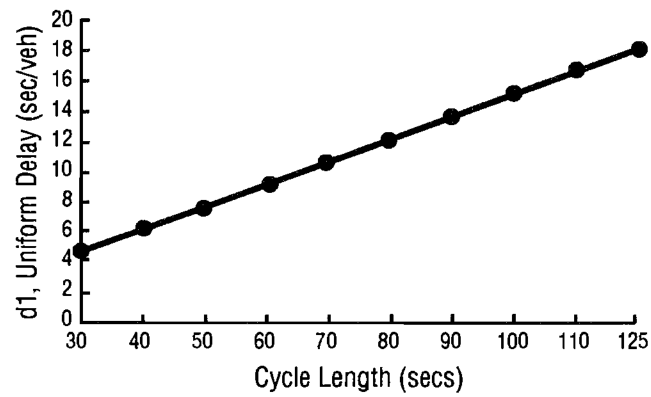

Fig 2-4a. Uniform (d1) component of 85HCM delay equation for varying cycle lengths (G/C = 0.5).

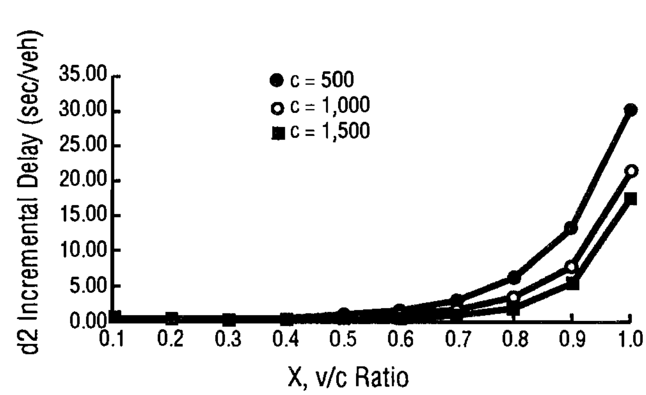

Fig 2-4b. Random (d2) component of 85HCM delay equation for varying volume to capacity ratios.

turn delay is most dependent upon opposing traffic." (Ref 7, pp 9-19) A progression factor was not included in the delay calculations made in this study.

Because the random-delay component of the 85 HCM equation is based on a combination of simulation, observation and adjustment, it is difficult to break the component down into easily understandable parts. For this reason the random part of the capacity manual's equation has been kept as a whole and has been assumed to adequately capture the random variability of an arriving traffic stream. The uniform component was analyzed as a uniform arrival process and is geometrically derived in the next section.

When the 85 HCM equation was compared to TEXAS Model results it became apparent that the 85 HCM equation underestimates the average delay. After careful study it was determined that the equation underestimates the effect that cycle failures have on the average delay. When the uniform component of the 85 HCM equation was derived again allowing for the input of cycle failure data with the random term left unchanged, the results were much closer to those observed with the TEXAS Model.

An additional problem with the 85 HCM manual equation is its inability to adjust to different storage bay lengths. If the left-turn bay is full, some vehicles that would normally be included in left-turn delay calculations are excluded. If there is an adequate storage length, then clearly this is not a problem. However, it is usually the case where there is not enough bay length, not vice versa.

In the following section the derivation of this new uniform component is presented, and a comparison is made between the 85 HCM equation, the CF equation, and the results from TEXAS Model simulations.

THE CYCLE FAILURE EQUATION

A total stopped delay equation that includes the effect of cycle failures, can be derived from the geometric relationships shown in Figs 2-5a, b, and c. The uniform component of the delay can be calculated by determining the area enclosed in the polygons (Fig 2-5a). With respect to this figure, there are four separate cases that may occur at an intersection, they are given here and discussed below.*

Case 1 (Fig 2-5b) is when there are no vehicles arriving during the entire cycle. This case is only of interest if there is an initial queue. With no initial queue there would be no vehicles in or entering the system and therefore no delay. If there is an initial queue, this case calculates the delay encountered by these vehicles while they are waiting and being processed. Clearly this condition would result in low delay values.

More probable cases than Case 1 are Cases 2 and 3 (Figs 2-5b and c). In these cases, where arrival rate A is not equal to zero, there are vehicles arriving but the processing rate is still larger than the arriving rate. This is analogous to a left-turn movement operating below its capacity, which would be considered to be in a stable condition. If an initial queue is present the arrival path would be A. If there was no initial queue this would be path A'. These two arrival rates are not equal due to fact that the queue lengths are identical at the start of the effective green. This was done to simplify the explanation and the figure. It is very likely that these two rates would not be equal, thus the queue resulting from the A' arrival rate would probably be somewhere between the baseline and the N=0 line. Given that N is less than zero, the residual queue will be in either one of two conditions: Case 2, the entire queue may be processed before or at the end (the N<0 line) of the green, or Case 3 where the processing rate may not be high enough to eliminate the queue thus resulting in a residual queue (between the N=0 and the N<0 lines).

Case 4 (Fig 2-5c) is where the processing rate is less than the arrival rate. As outlined earlier this is an unstable condition and the amount of delay is a function of the observation period. This case has been included to allow the traffic engineer to determine what the delay would be if the observation period were known. An example of this would be if the demand exceeded the capacity for 5 minutes during a peak hour. The limiting factor in this, and in all cases, is the maximum storage length of the left-turn bay, Qs.

The random component of delay makes this derivation much more difficult. The problem arises in that it is difficult to quantify at what point during the cycle vehicles arrive. Since vehicle arrivals are assumed to be a random process, they could, and do, arrive at any time during the cycle. The 85 HCM's D2 term attempts to

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* Case 1) $N < 0, A = 0$ $\quad Dt = Q_oR_e + \frac{Q_o^2}{2P}$

Case 2) $N < 0, A > 0, Q_R \leq 0$ $\quad Dt = Q_oR_e + \frac{AR_e^2}{2} + \frac{(AR_e + Q_o)2}{2|N|})$

Case 3) $N \leq 0, A > 0, Q_R > 0$ $\quad Dt = Q_oR_e + \frac{AR_e^2}{2} + \frac{|N| G_e}{2} + (Q_o + AR_e - |N| G_e)G_e$

Case 4) $N > 0, Q_R \leq Q_S$ $\quad Dt = Q_oR_e + \frac{AR_e^2}{2} + (Q_o + AR_e)(G_e) + \frac{N G_e^2}{2}$

where: Dt = Total uniform stopped delay (veh-sec)

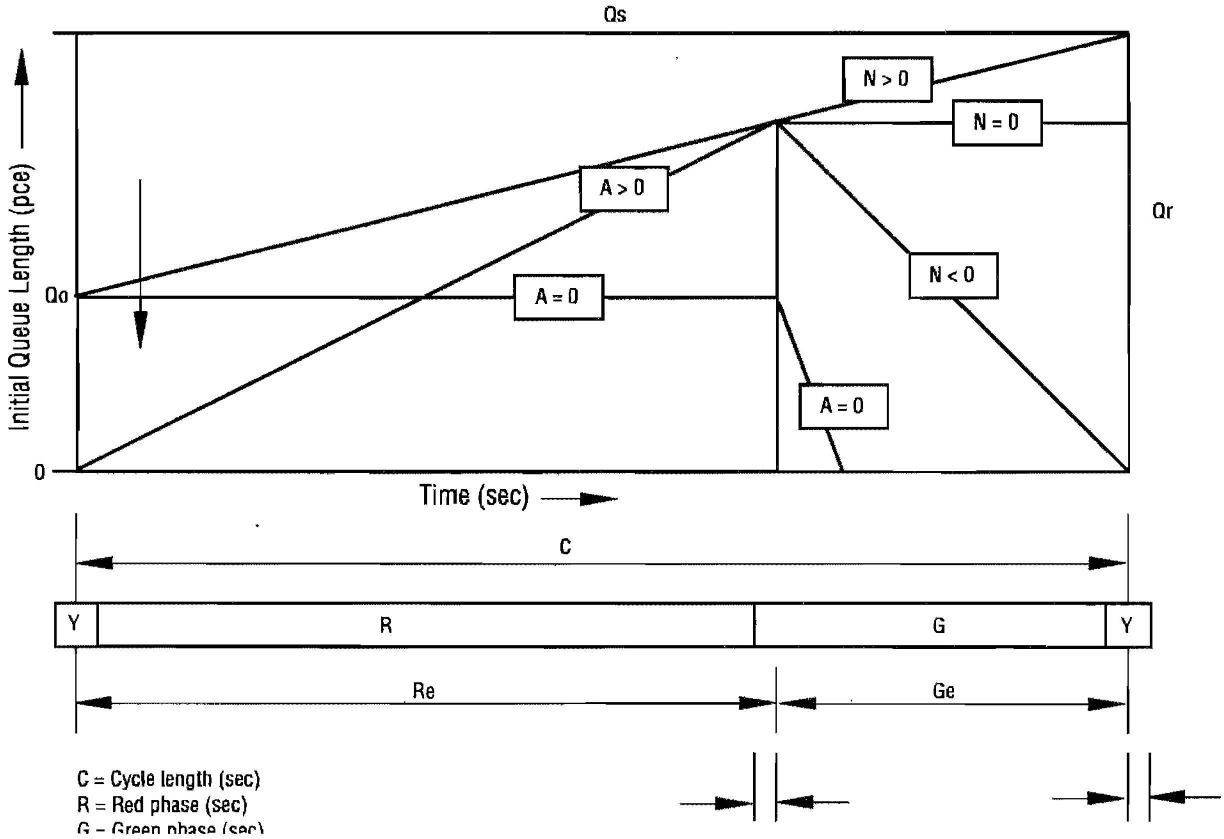

Fig 2-5a. Delay diagram for CF equation — all cases.

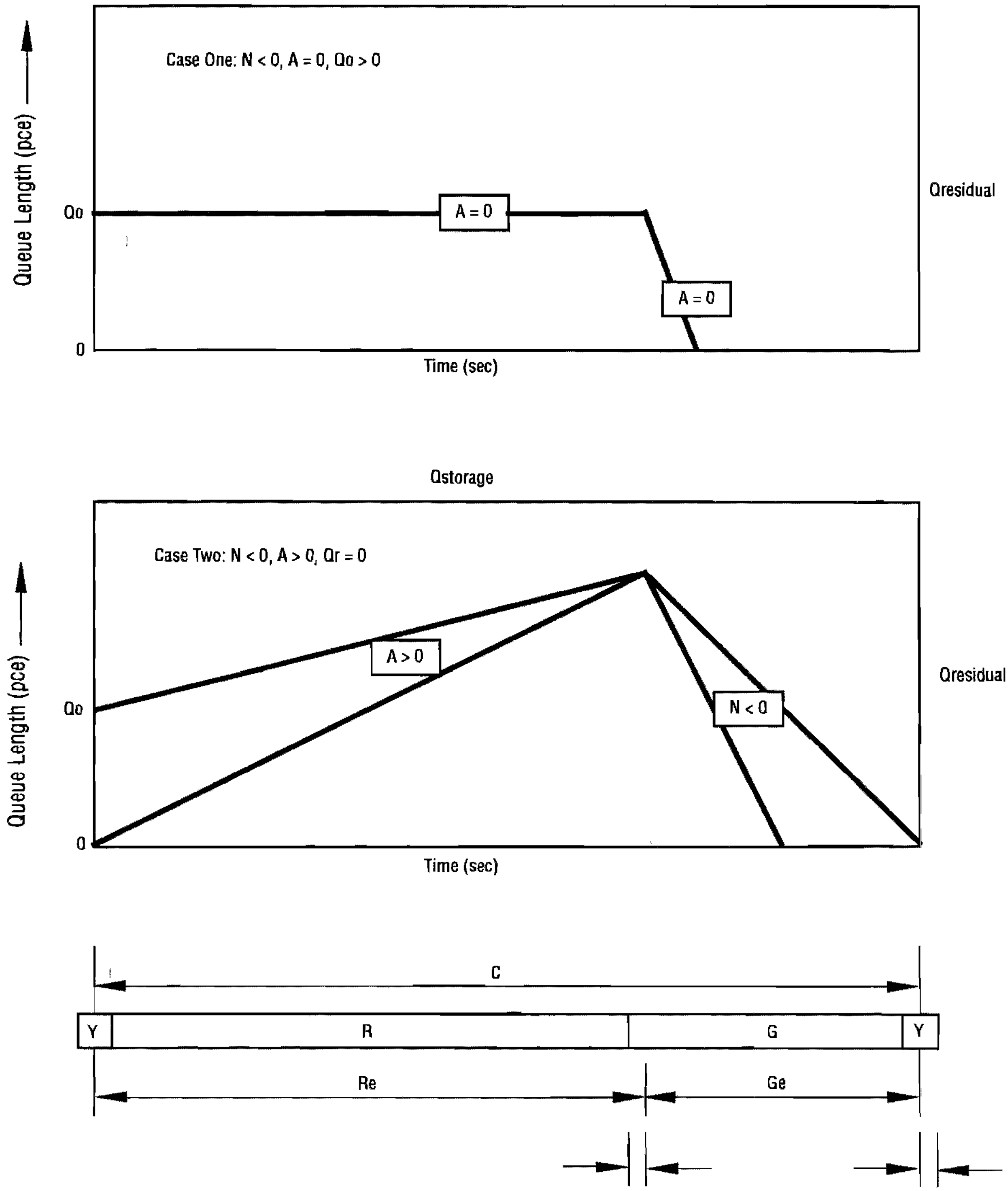

Fig 2-5b. Delay diagrams for CF equation, cases one and two.

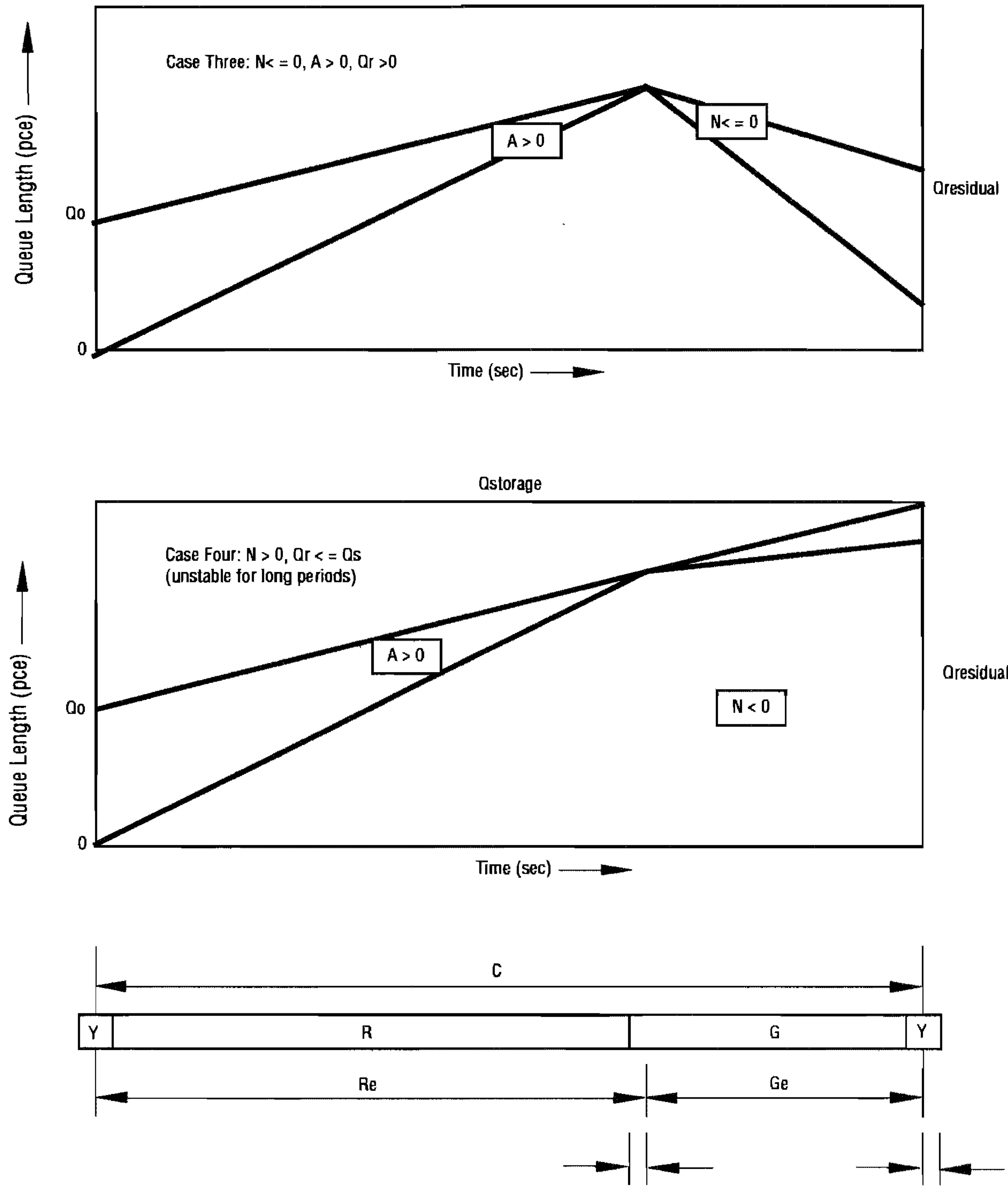

Fig 2-5c. Delay diagrams for CF equation, cases three and four.

capture this randomness.. Because it is beyond the scope of this study to derive an equation of this form it was deemed appropriate to use the D2 term. When the full 85 HCM equation was used and compared to TEXAS Model results, it was found to consistently underestimate the delay. By using the CF equation and the D2 HCM term the results were an overestimate of the delay when compared to the TEXAS Model. After further study it was found that the 85 HCM D2 term incorporated some of the effects that residual queues have on delay. Because the CF equation incorporates this as well, the result was a double counting of the residual queue delays. However, it was found that by inputting the average number of cycle failures per hour as the Qo term rather than the average residual queue length, the results were very close to those obtained from the TEXAS Model. These results are shown in Figs 2-6a and b. For a cycle length of 60 and 120 seconds and a Ge/C of 0.3, if there were a total of 20 cycle failures during a one hour observation period, the value of Qo would be 0.33.

Because most traffic engineering delay-based performance measures are based on the average delay and not the total delay, it is necessary to divide the total stopped delay by the number of vehicles experiencing the delay. The average uniform stopped delay, Da, is calculated as follows:

Da (for Cases 2,3,4) = Dt/(VC/3600)
Da (for Case 1, not valid for Qo = 0)
= Dt/Qo

By combining the uniform component derived above with the random component (D2 term) of the 85 HCM average stopped delay equation (Ref 7, pp 9-18) the result is:

$$D = Da + 173x^2\left[(x-1) + \sqrt{(x-1)^2 + (16x/c)}\right]$$

where:

D = average uniform and random stopped delay (sec),
x = volume to capacity ratio for the lane group, and
c = capacity of the lane group (pce/hr)

Delay Performance Measure

As was stated in the beginning of this section, Lin determined that 35 seconds of average left-turn delay was approximately the point at which drivers become impatient and therefore potentially dangerous. If this value is used as an upper bound on the left-turn delay we can identify critical conditions by using the CF equation. Figures 2-6a and b show the 35-second maximum delay line. From these figures it can be seen that in terms of delay a 60-second cycle length is much more desirable than one that is 120 seconds. The TEXAS Model data points support this conclusion and indicate that a 120 second cycle length is not appropriate at any volume-to-capacity ratio when 35 seconds of delay is used as a upper limit.

SUMMARY OF PERFORMANCE-MEASURE WARRANTS

It would be useful to summarize the warrants that will be used in the Implementation Package, that is outlined in Chapter 4.

The first performance measure that was analyzed was that of cycle failures. Drew's equation provides an

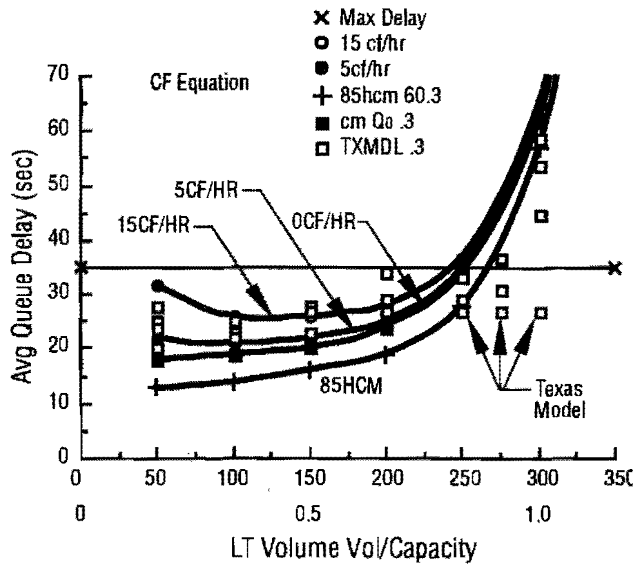

Fig 2-6a. CF, 85HCM equation, and TEXAS Model results for V/c versus delay, cycle length = 60 sec., Ge/C = 0.30.

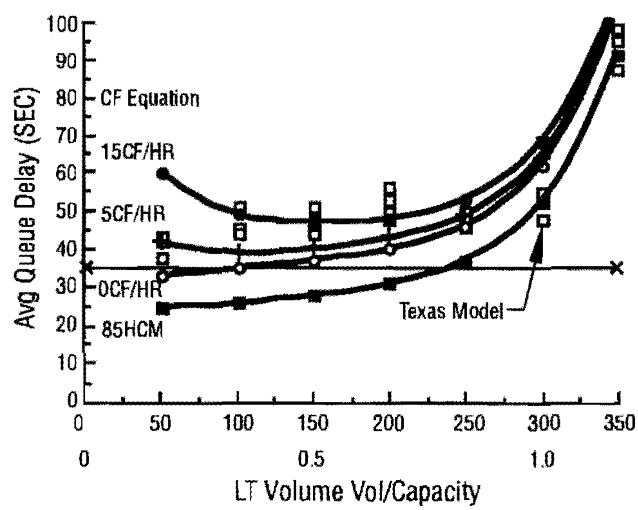

Fig 2-6b. CF, 85HCM equation, and TEXAS Model results for V/c versus delay, cycle length = 120 sec., Ge/C = 0.30.

engineer with a useful tool for determining the probability of experiencing a cycle failure given the peak 15-minute volume, the signal timing, and the average minimum headway.

The second measure was the relationship between demand and capacity. It was shown that at a volume-to-capacity ratio of 0.90 there is dramatically increased delay.

The last performance measure presented was delay. Lin (Ref 3) has shown that a queue-delay value of 35 seconds can be used as an approximate upper limit on the amount of delay a motorist can experience before becoming impatient, and thus potentially dangerous.

BAY-LENGTH DETERMINATION

LEFT-TURN QUEUE LENGTH

Red time and demand volume are the variables that have the greatest impact on the maximum length of a left-turning queue. Where an existing intersection has sufficient storage, a field study should be conducted to determine the maximum queue length. If it is either a proposed intersection or an intersection with insufficient left-turn storage, other methods such as simulations or mathematical models are needed to determine the maximum queue length. By utilizing the TEXAS simulation model, the average and maximum queue lengths can be determined for given traffic and signal conditions. Figures 2-7 a & b provide the maximum queue lengths, in feet, obtained for varying left-turn volumes and red times for a cycle length of 60 seconds. These figures also show the delineation between a left-turn bay and lane at a queue length of 100 feet. Once the maximum queue length has been determined, calculating the required bay length is relatively straightforward.

Assuming that for each vehicle class the average vehicle length and the percentage of vehicles in that class are known, the required bay length can be determined. As shown by Lin (Ref 3) if the maximum queue length is multiplied by adjustment factors to accommodate vehicles other than PCU's, the required bay length becomes:

$$L_{b1} = W_t P_l L_{lm} + W_c (1-P_l) L_{lm}$$

where

- L_{b1} = length of the left-turn bay based on the left-turn queue;
- W_t = feet of bay length occupied by a truck or bus;
- P_l = the percentage of trucks or buses in the left-turn traffic flow (decimal);
- L_{lm} = the maximum left-turn queue length (vehicles);
- W_c = feet of bay length occupied by a passenger car.

If the distribution of the maximum left-turn queue length is known, the traffic engineer may wish to use not the absolute highest value but perhaps the eightieth or ninetieth percentile values. The reason for using a design value (such as 85%) is illustrated in Fig 2-8. This figure is a hypothetical cumulative distribution of maximum queue lengths. This curve shows that there is an inflection point after which the benefit of added storage does not justify the additional cost. Thus a 15-percent increase in the bay length in the 80th percentile region would result in far less additional usage than if this added storage was built in the 50th percentile region. Therefore, in this study, the calculated design values for left turn bays are 85 percent of the maximum queue length value. The engineer may wish to alter this design percentage to suit individual needs and requirements.

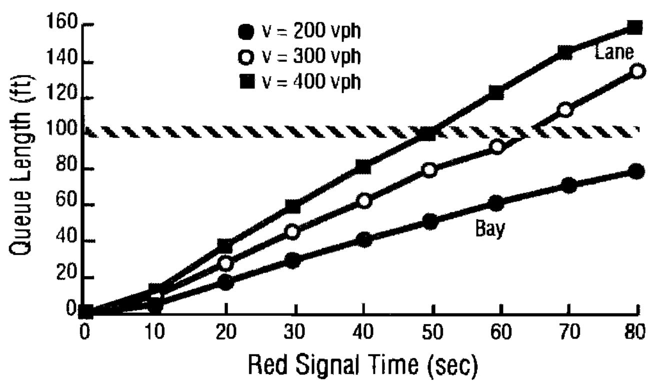

Fig 2-7a. TEXAS Model simulation results showing the left-turn queue length as a function of red time for a left-turn volume of 200, 300, and 400 vph (Ref 15).

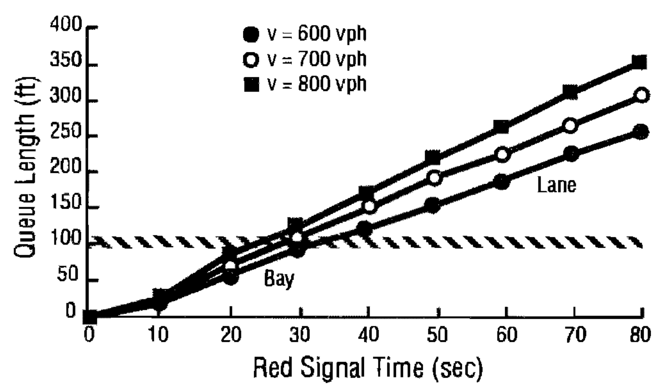

Fig 2-7b. TEXAS Model simulation results showing the left-turn queue length as a function of red time for a left-turn volume of 600, 700, and 800 vph (Ref 15).

THROUGH-TRAFFIC QUEUE LENGTH

Most analyses of left-turn bay lengths focus on the left-turning traffic flow and timing. An important point that also needs to be considered is the length of the through traffic queue. If there is an adequate length of left-turn bay but the through queue is backed up to the point where it is preventing access to the bay then clearly this will lead to an undesirable situation.

The procedure for determining the length of the left-turning bay based on the through-traffic queue length is essentially the same as that of the left-turn queue length. The formula is identical to the previous one but the variables now apply to the through traffic:

$$L_{b2} = W_t P_t L_{tm} + W_c (1-P_t) L_{tm}$$

where

L_{b2} = length of the left-turn bay based on the through queue;

P_t = the percentage of trucks and buses in the through traffic flow (decimal); and

L_{tm} = the maximum through queue length (vehicles).

As was the case for L_{b1} the traffic engineer may wish to use a lower number than the absolute maximum through-traffic queue length. However, this adjustment should be fully justified because the effect of a blocked left-turn lane can be much more detrimental than that of a left-turn lane that is operating at its capacity.

The two equations above both assume that the maximum queue lengths and the vehicle mixes are known. For an existing intersection this assumption may be satisfied with field studies, but for one that is proposed, the queue lengths would have to be derived from other sources such as computer simulation. These equations could also be applied to the average queue length instead of the maximum queue length. Because the maximum is easier to determine in a field study it was assumed to be of more use as a variable in these equations.

THE TEXAS MODEL METHOD

The limiting factor in applying the above equations is that they both assume that the maximum left-turn and through-traffic queue lengths are known. However, this is not the case in solving many traffic engineering problems. Determining the maximum queue length is difficult because of the numerous variables involved. With a random arrival process, it is very difficult to predict how many vehicles will arrive during any given signal cycle. Compounding the solution is the issue of cycle split within the given cycle.

A simulation model that measures the maximum and average queue lengths during several signal cycles provides an excellent tool for evaluating the effects of these variables. The TEXAS Model was used in this study to determine the maximum and average queue lengths for a variety of signal timings, and traffic volumes. Single and dual left-turn lanes were analyzed as described in Chapters 3 and 4.

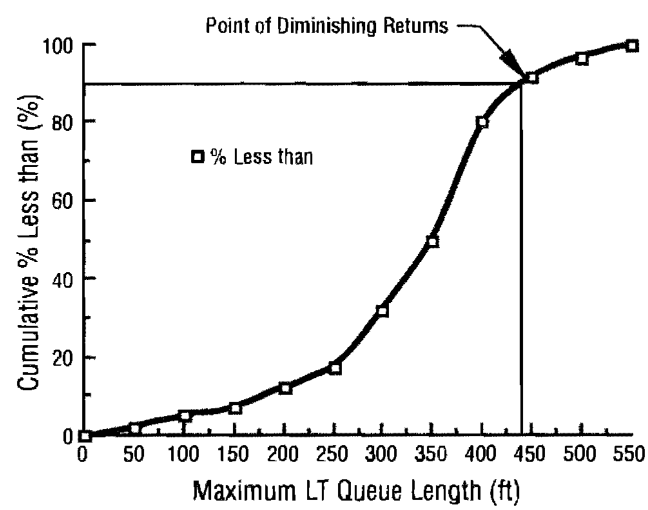

Fig 2-8. Graph showing reasoning behind using a design storage length that is less than the maximum queue length.

CHAPTER 3. DUAL-LANE LEFT-TURN ANALYSIS

This chapter analyzes the performance of a dual-lane left-turn operation in terms of the operational capacity (and saturation flow) and measures of performance. Most of the performance measures that were presented in the previous chapter are applicable to the evaluation of a dual-lane left-turn operation on a per-lane basis. The significant difference is that the saturation-flow value of dual left-turning lanes is not equal to two times that of a single left-turn lane. This chapter describes the previous studies of dual-lane saturation flow, and then verifies these results with data from a field study and with results from the TEXAS Model.

Where previous research results are applicable to single as well as dual left-turn lanes, it will be stated. This chapter focuses on aspects that are dual left-turn lane specific, which consist primarily of the saturation-flow-value determination.

DUAL-LANE LEFT-TURN SATURATION FLOW DETERMINATION

This section will show, through the use of past publications, simulation models, and current field studies, that the capacity of a dual-lane left-turn operation is not equal to twice that of a single left-turn lane. The pertinent variable in any capacity determination is the saturation-flow value for a given movement.

This analysis of dual-lane left-turn saturation flow is divided into three parts: first, a literature review is made of existing work; second, results from simulations utilizing the TEXAS Model are presented; and last, findings from a field study are presented. A summary is then made of the findings from these three sources of information.

LITERATURE REVIEW OF DUAL-LANE-LEFT-TURN SATURATION FLOW DETERMINATION

There are two excellent references that address the question of dual left-turn saturation flow rather extensively. The first is a master's thesis completed by William E. Assmus at Northwestern University in April of 1970 (Ref 9). His work, entitled *Operational Performance of Exclusive Double Left-Turn Lanes*, is a study of dual-lane left-turns that includes an appendix with a large amount of field data. The second reference is a Ph.D. dissertation completed in December of 1984 by Robert Stokes of Texas A&M University and is entitled *Saturation Flows of Exclusive Double Left-Turn Lanes* (Ref 10). This extensive study relies heavily upon field measurements at numerous locations in Texas.

Due to the extent to which both of these studies have addressed dual-lane left-turn saturation flow, this study has attempted to validate their findings rather than extensively re-examine the topic. This validation includes the use of the TEXAS Model and one field study.

Northwestern University Study

Assmus' study (Ref 9) was conducted in June and July of 1969 and utilized time-lapse photography as the means of data collection. Seven Chicago area intersections with exclusive dual left-turn lanes were examined. These intersections were then grouped into three groups each possessing similar geometries. Assmus makes the assumption that all of these intersections are independent. He states: "The flow conditions at each site were not affected directly or noticeably by conditions at adjacent intersections" (Ref 9, p 24). Due to the impracticality of checking this assumption, it is assumed to be valid. This assumption is important because all validations of this work were based on the same premise. The chosen intersections were photographed during the peak periods. One limitation of this study is that there were no duplicate observations of any of the intersections during the same time period.

Assmus points out that the driver mix is an important aspect of this study and should be considered. The mix in this study was assumed to be made up of 90 to 95 percent "commuter" and "sophisticated" drivers. These drivers know how a dual left-turn operation works, and generally traverse the same intersection on a regular basis (Ref 9, p 40).

The vehicle mix is perhaps one of the most important non-timing aspects of any saturation-flow analysis. Assmus recognized this and adjusted his vehicle counts to reflect the differences in vehicle performance. The adjustment factor that was used was that one commercial vehicle was equivalent to three passenger-car units. He also adjusted the counts to reflect the fact that most of the commercial vehicles used the outside left-turn lane. No distinction was made between different classes of non-commercial vehicles (Ref 9, p 53).

By computing the adjusted average headway in seconds per vehicle, Assmus was able to determine the saturation flow in vehicles per hour of green. In addition to the adjustments outlined above, an adjustment for starting delay was included. This adjustment was made by starting the timing and counting after the third vehicle had crossed the stop line, thereby minimizing the effect of starting time delay. The lost time at the end of the cycle was addressed by determining the average number of vehicles that were processed through the yellow-change phase. Once this value was determined, an adjustment was made to the vehicle counts so as to assign a correct volume processed during the yellow-change phase.

The results from this study are summarized as follows (Lane #1 is the median left-turn lane) (Ref 9, p 103):

Vehicles Per Hour of Green - Loaded Cycles Only			
Intersection	**Lane #1**	**Lane #2**	**Both Lanes**
Type 1	1260	1810	3070
Types 2&3	1540	1530	3070
All Types	1420	1650	3070

Assmus defines the intersection types as follows: Type 1 installations are "used primarily to handle moderate turning volumes with very short green phases (approximately 8 to 10 seconds long). The savings in required G/C's using two turning lanes are then available to increase the capacity of other movements. Type 2 and 3 exclusive double left-turn lanes are used to handle very large turning volumes, with the left movements being dominant maneuvers at the intersections" (Ref 9, p 117).

The results of this study are useful in that they point out that the total saturation flow of both lanes is independent of the type of intersection. The distribution of vehicles in each of the two lanes was more evenly distributed in the Type-2 intersection which handles a much larger left-turn demand.

Texas A&M Study

A more recent study of dual left-turn saturation flow rates was completed by Robert Stokes of Texas A&M University in December of 1984 (Ref 10). This study provides a detailed literature review combined with a field study utilizing time-lapse photography.

Stokes selected fourteen dual-lane left-turn sites to study. All the sites were located in Texas with the location and number of sites as follows: Austin had two sites, College Station had six, and the remaining six were located in Houston. This study was considered better than the Northwestern study due to the duplication of most of the observations. An extensive filming schedule allowed for 30 independent observation periods.

This study focused on gathering three principal data sets. The first set was to determine the number and type of vehicles that entered the intersection during the yellow-change and red phases on each: approach, lane, and phase. The second data set contained the headway and lane-blockage information for each: approach, lane, and phase. The last set documented the observed queue length at the start of each green phase for each: approach, lane, and phase, and by vehicle type (Ref 10, p 87).

The saturation flow estimates that were determined in the Texas A&M study are summarized below for a 95 percent confidence interval (Ref 10, p 147):

95% Confidence Intervals for Average Left-Turn Saturation Flows (vphlg)			
Lane	**Austin**	**College Station**	**Houston**
1	1565 - 1714	1636 - 1800	1714 - 1895
2	1565 - 1714	1565 - 1714	800 - 2000

The Texas A&M study concludes that: "Based on the results of this study, and a review of the data from a limited number of related studies, average double left-turn saturation flow rate on the order of 1600 vphlg would appear to be a reasonable value for most planning applications" (Ref 10, p 156).

The study also notes that the intersections in Houston had saturation flow values of approximately of 1800 vphlg. This higher value was attributed to the urban driver being more aggressive and accustomed to this type of operation.

As indicated in the beginning of this section, there has been a substantial amount of research done in the area of dual left-turn saturation flow determination. The remaining part of this section focuses on validating the findings that have been presented above. This validation was done by utilizing the TEXAS Model, and with one field study that was conducted in Austin, Texas, in August of 1987.

TEXAS MODEL DUAL-LANE LEFT-TURN SATURATION FLOW DETERMINATION

The geometry used for the dual left-turn saturation flow study is shown in Fig 3-1(a,b). This dual-lane left-turn intersection was the same intersection used to collect data for the implementation package outlined in Chapter 4. The simulation (SIM) input files are the same files that were used for the dual-lane left-turn part of the implementation package outlined in Chapter 4.

Four runs were made at each cycle length of 60, 80, 100, and 120 seconds. The (G+Y)/(Cycle Length) ratio was equal to 0.50 for all the cycle lengths. The Y, or clearance interval, was 3 seconds for all these runs. The TEXAS Model does not allow for a separation of the volume processed into individual lanes within each turning movement; thus the statistics reflect only the total dual left-turn volume processed per hour. All of the simulations consisted of a 5-minute start-up interval and a 30-minute simulation during which statistics were gathered. As with all TEXAS Model runs done in this study, four simulations runs were made with the random number seed being changed on each run. Although additional runs are always desirable, the results were consistent enough to satisfy the validation purposes of the runs.

The pertinent flow statistics are shown in Table 3-1. The TEXAS Model Yellow-Change Factor is a factor that adjusts the single-lane left-turn volume upward by 0.5 vehicles per cycle. This is done to compensate for the TEXAS Model's limit of only one vehicle per yellow-change phase. Field observations have shown that, when approaching capacity, the average number of vehicles processed during this phase is 1.5. The effect of this adjustment factor is more pronounced at a shorter cycle length. If this factor had not been included, the difference in dual left-turn saturation flow at 60 and 120 seconds would be 134 vehicles instead of 204 vehicles.

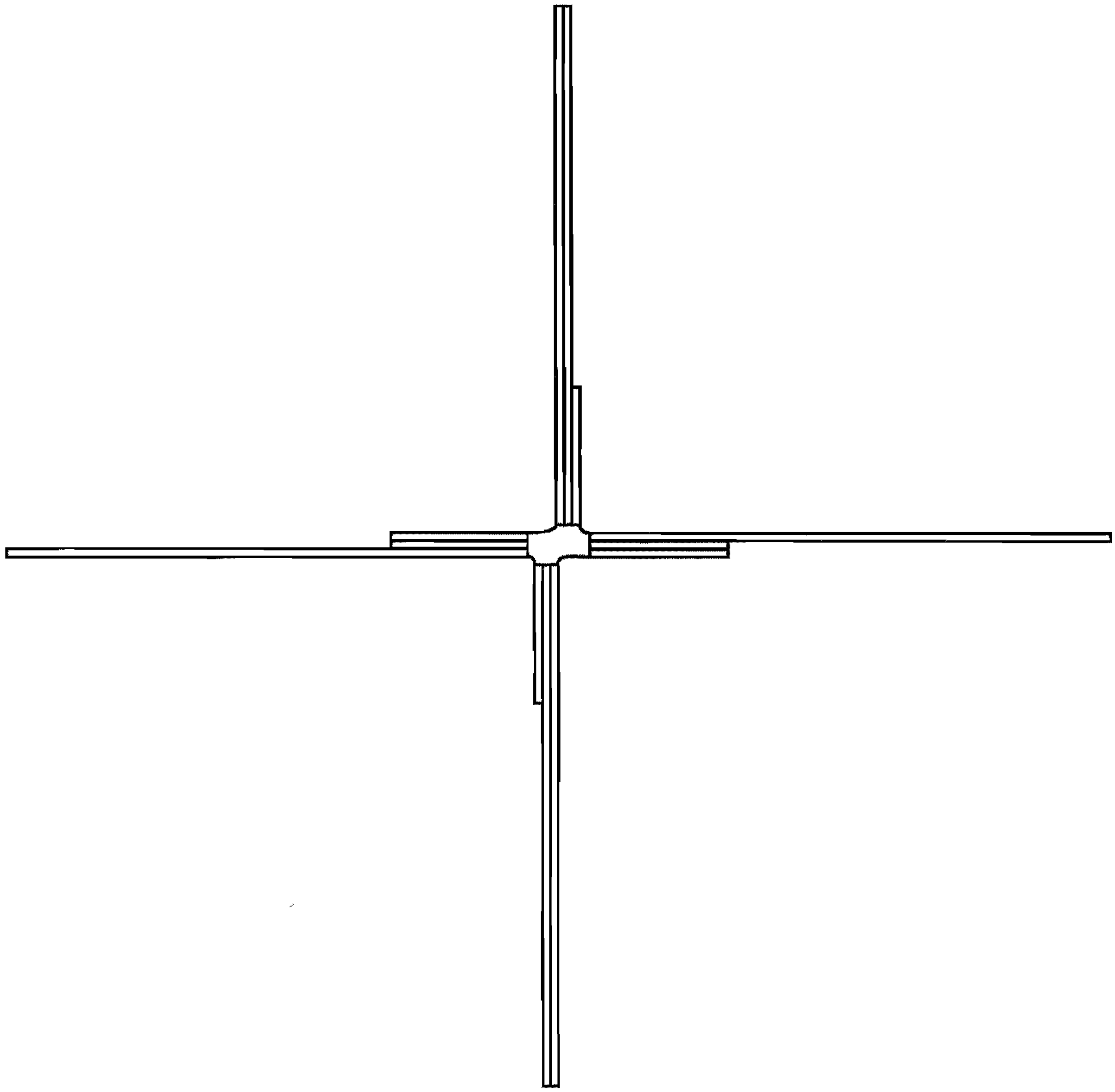

Fig 3-1a. Dual-lane left-turn geometry used for TEXAS Model runs—inbound lanes.

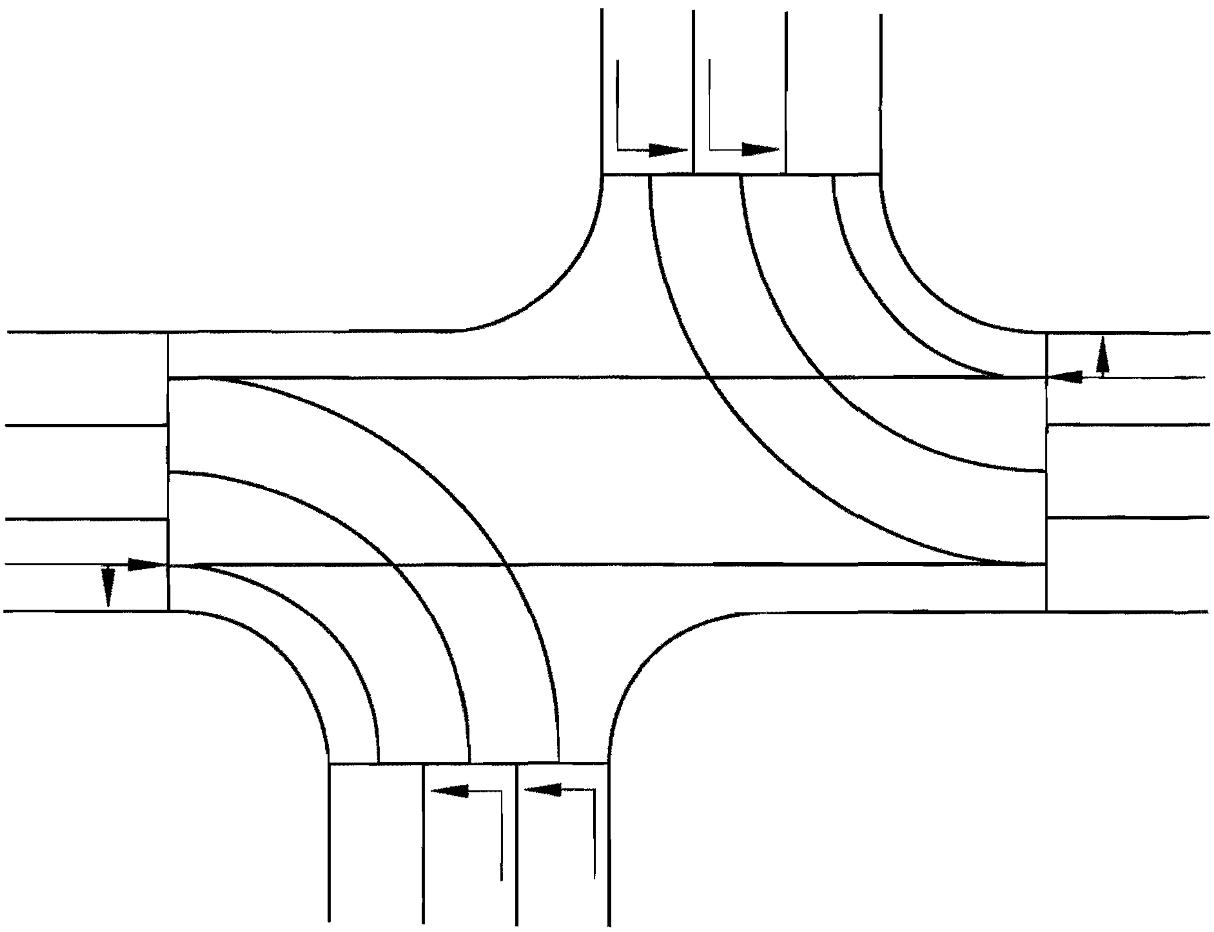

Fig 3-1b. Dual-lane left-turn geometry used for TEXAS Model runs—intersection with paths for turning movements.

Although this discrepancy is of concern, it is not large enough to invalidate the TEXAS Model results. The final averages of these runs will be presented in summary form at the end of this chapter (with all other saturation flow data).

CONGRESS AND RIVERSIDE TRAFFIC COUNTS

The dual left-turn movements at Congress Avenue and Riverside Drive in Austin, Texas, were chosen for this study because of the high-volume left-turning traffic, the pretimed signal, and the low number of heavy vehicles. A traffic count was made on Wednesday, August 5th, 1987, during the peak period from 6:58 A.M. to 8:03 A.M. Unfortunately, no data were gathered to determine the distribution of vehicles in the two different left-turning lanes. In retrospect, this would have been a very good statistic to obtain; however, previous studies have addressed this question rather extensively. Consideration of the distribution is important and will be addressed further in the dual left-turn demand-capacity warrant section of this study. Only one field study was done because, as outlined earlier, the purpose of this part of the study was only to validate other researchers' findings rather than reexamine the entire dual-lane left-turn saturation flow question.

The traffic count data and the signal timing sheet from the Congress and Riverside field study are presented in Appendices A and B, respectively. The TEXAS Model was used to simulate the same geometry and signal timing as observed in the field. The resulting averages of three TEXAS Model simulations in relation to the observed data for each turning movement are shown below:

The high ratio of hourly traffic volume processed by the TEXAS Model to the volumes observed in the field indicates adequate simulation, given the parameters stated above. Because the Congress and Riverside intersection operated under signal controller a pretimed intersection, the amount of effective green time available to the dual-lane left turners could be determined from the signal timing sheet obtained from the City of Austin. This sheet is shown in its original form in Appendix B. The dual-lane left-turning northbound traffic on Congress Avenue is the only movement of interest because the volumes on the southbound leg did not approach the saturation flow. A summary of the three peak 5 and 15-minute periods for this dual-lane left-turning movement is shown below:

5-Minute Peaks		15-Minute Peaks	
Total Dual LT Vehicles	End Time (a.m.)	Total Dual LT Vehicles	End Time (a.m.)
31	7:48	81	7:53
27	7:53	78	7:48
24	7:38	75	7:58

From the signal timing sheet, under Plan 2, the amount of left-turn green time for the movement of interest is 9 seconds. The yellow-change interval under Plan 2 is 4 seconds. If the lost time is assumed to be 3 seconds, then the effective green time becomes the left-turn green time of 9 seconds plus the yellow interval of 4 seconds minus the lost time of 3 seconds, resulting in 10 seconds of effective green. With a 90-second cycle length, the resulting peak average headway and saturation flow values for 5-minute and 15-minute intervals are as follows:

Period Length	Flow (veh)	Avg Headway of Single Veh in Dual Lt (sec)	Dual LT Saturation (vphlg)
5 min	31	2.15	3349
15 min	81	2.47	2914

Congress and Riverside
Observed Versus Simulated Hourly Volumes

Direction	Leg #	Movement	Hourly Volumes (vph) Observed	TX Mdl (15 min)	TX Mdl (40 min)
Northbound	3	Left	204	228	209
		Through	795	764	794
		Right	93	100	104
Southbound	1	Left	94	80	88
		Through	253	264	254
		Right	28	32	27
Eastbound	4	Left	42	52	48
		Through	420	436	416
		Right	94	112	95
Westbound	2	Left	71	56	71
		Through	630	648	630
		Right	130	100	129
		Grand Total	2,854	2,872	2,865
		Simulation/Observed (%)		100.6	100.4

TABLE 3-1. STATISTICS FROM DUAL-LANE LEFT-TURN SATURATION FLOW DETERMINATION USING THE TEXAS MODEL

Cycle Length (sec)	Effective Green (sec)	Run	Total Dual LT Vol Processed (vph)	Total Dual LT Vol Per Cycle (veh)	Single LT Vol Per Cycle (veh)	TX Model Amber Factor (veh)	Avg Single LT Headway (sec)	Single LT Saturation Flow (vphlg)	Total Dual LT Saturation Flow (vphlg)
60	27	Run 1	1102	18.37	9.18	0.50	2.79	1,291	2,582
		Run 2	1092	18.20	9.10	0.50	2.81	1,280	2,560
		Run 3	1098	18.30	9.15	0.50	2.80	1,287	2,573
		Run 4	1090	18.17	9.08	0.50	2.82	1,278	2,556
		Average	1095.5	18.26	9.13	0.50	2.80	1,284	2,568
80	37	Run 1	1080	24.00	12.00	0.50	2.96	1,216	2,432
		Run 2	1084	24.09	12.04	0.50	2.95	1,221	2,441
		Run 3	1088	24.18	12.09	0.50	2.94	1,225	2,450
		Run 4	1086	24.13	12.07	0.50	2.94	1,223	2,445
		Average	1084.50	24.10	12.05	0.50	2.95	1,221	2,442
100	47	Run 1	1096	30.44	15.22	0.50	2.99	1,204	2,409
		Run 2	1090	30.28	15.14	0.50	3.01	1,198	2,396
		Run 3	1094	30.39	15.19	0.50	2.99	1,202	2,404
		Run 4	1094	30.39	15.19	0.50	2.99	1,202	2,404
		Average	1093.50	30.38	15.19	0.50	3.00	1,202	2,403
120	57	Run 1	1096	36.53	18.27	0.50	3.04	1,185	2,371
		Run 2	1092	36.40	18.20	0.50	3.05	1,181	2,362
		Run 3	1096	36.53	18.27	0.50	3.04	1,185	2,371
		Run 4	1088	36.27	18.13	0.50	3.06	1,177	2,354
		Average	1093.00	36.43	18.22	0.50	3.05	1,182	2,364

TABLE 3-2. A SUMMARY OF DUAL-LANE LEFT-TURN SATURATION FLOW RESEARCH RESULTS (ADAPTED FORM STOKES—REF 10)

Source and Conditions	Dual Left-Turn Saturation Flow: Inside Lane	Outside Lane	Average	Ratio of Inside to Outside Lane	Efficiency Factor Relative to Single LT Flow* sat = 1710**	Efficiency Factor Relative to Through Flow* sat = 1800**
Capelle & Pinnell (1961)						
Permissive Dual Left-Turn	1,500	1,636	1,568	0.92	0.92	0.87
Ray (1965)						
Permissive Dual Left-Turn	1,240	1,230	1,235	1.01	0.72	0.69
Exclusive Dual Left-Turn	1,375	1,315	1,345	1.05	0.79	0.75
Assumus (1970)						
Exclusive Dual Left-Turn	1,420	1,650	1,535	0.86	0.90	0.85
Kunzman (1978)						
Queue <= 4 veh/lane	-	-	1,439		0.84	0.80
Queue >= 5 veh/lane	-	-	1,581		0.92	0.88
All Queue Lengths	-	-	1,523		0.89	0.85
Texas A & M (1984)						
Exclusive Dual Left-Turn						
Austin	1,639.5	1,639.5	1,640	1.00	0.96	0.91
College Station	1,718	1,639.5	1,679	1.05	0.98	0.93
Houston	1,804.5	1,900	1,853	0.95	1.08	1.03
Congress & Riverside (1987)						
Exclusive Dual Left-Turn	-	-	1,675		0.98	0.93
Texas Model (1988)						
Exclusive Dual Left-Turn	-	-	1,222		0.71	0.68
Overall Averages			1,524	0.98	0.89	0.85

* Ratio of Average Dual Saturation Flow (single lane) to given movement

** Saturation flow values for these movements as per 85 HCM

These results are consistent with the results obtained in the studies that were reviewed in the beginning of this chapter. The following section reviews the saturation flow data that has been presented thus far and makes recommendations based on this data.

SUMMARY OF DUAL-LANE LEFT-TURN SATURATION FLOW DATA

Stokes (Ref 10) provides an important table that lists the results of many of the dual-lane left-turn saturation flow studies that have been conducted over the past 27 years. His table has been adapted and updated and is shown as Table 3-2. The overall averages that are shown in this table are not intended to be used as design values, but rather to provide a general indication of the mean values. Of more concern for design values are the overall statistics that are presented in Table 3-3. This table is comprised of the data that was deemed to be the most realistic and accurate. The overall saturation flow average of 1615 is very close to Stokes's recommended value of 1600. It should also be noted that the average of the dual-to-through-lane saturation flow values suggests that for a given intersection, the dual-lane left-turn saturation flow value may be estimated by multiplying the through-lane value by 0.90. The difference in the ratios of inside to outside dual left-turn lanes is not sufficient to make any conclusions regarding the vehicle distributions between these lanes. This supports the fact that when drivers see a shorter queue in the other left-turn lane, they will change lanes so as to perform the turning maneuver in a shorter amount of time. Therefore, this study concurs with Stokes's recommendation of using 1600 as a per-lane saturation flow value for a dual-lane left-turn operation. Additionally, the dual-lane left-turn saturation flow may be estimated by adjusting the through saturation flow value downwards by 10 percent.

DUAL-LANE LEFT-TURN PERFORMANCE MEASURES AND BAY-LENGTH DETERMINATION

CYCLE-FAILURE WARRANTS

For the purposes of this warrant, the distribution of vehicles between the two left-turn lanes and the processing time in each of these lanes, is assumed to be equal. With these assumptions, the determination of the probability of a cycle failure is essentially the same as that for a single-lane left-turn movement. For this reason, the same equation and recommendations that were outlined in the single-lane left-turn analysis will be utilized for this analysis. The input volume will be the dual-lane left-turning volume on a per lane basis. This dual-lane left-turn performance measure has been included in the implementation package outline in Chapter 4.

TABLE 3-3. DUAL-LANE LEFT-TURN SATURATION FLOW RESULTS—DESIGN VALUES

Source and Conditions	Dual Left-Turn Saturation Flow: Inside Lane	Dual Left-Turn Saturation Flow: Outside Lane	Dual Left-Turn Saturation Flow: Average	Ratio of Inside to Outside Lane	Efficiency Factor Relative to Single LT Flow* sat = 1710**	Efficiency Factor Relative to Through Flow* sat = 1800**
Assumus (1970)						
Exclusive Dual Left-Turn	1,420	1,650	1,535	0.86	0.90	0.85
Kunzman (1978)						
Queue <= 4 veh/lane	-	-	1,439		0.84	0.80
Queue >= 5 veh/lane	-	-	1,581		0.92	0.88
All Queue Lengths	-	-	1,523		0.89	0.85
Texas A & M (1984)						
Exclusive Dual Left-Turn						
Austin	1,639.5	1,639.5	1,640	1.00	0.96	0.91
College Station	1,718	1,639.5	1,679	1.05	0.98	0.93
Houston	1,804.5	1,900	1,853	0.95	1.08	1.03
Congress & Riverside (1987)						
Exclusive Dual Left-Turn	-	-	1,675		0.98	0.93
Overall Averages			1,615	0.96	0.94	0.90

* Ratio of Average Dual Saturation Flow (single lane) to given movement
** Saturation flow values for these movements as per 85 HCM

DEMAND-CAPACITY WARRANT

This warrant differs from the single-lane left-turn warrant in that the saturation flow values are not the same. As outlined above, a recommended design value for a dual-lane left-turn movement is 1600 vehicles per lane, or 90 percent of the straight-through value. This warrant will use 1600 vehicles per lane per hour for saturation flow when determining the capacity of a dual-lane left-turn movement.

All other assumtions made for the single-lane left-turn movement are assumed to be valid for the dual left-turners as well. Therefore, the determination of the dual-lane left-turn capacity also remains the same as that of a single-lane left-turn with the exception of the new saturation flow value indicated above.

The demand-to-capacity ratio of 0.90 will also be used to identify the point at which a left-turn operation reaches a critical level. This was not investigated in further detail because the primary focus of this study has been on queue length determination and not on determining exact performance measures. This 0.90 figure is intended to be a general indicator of critical performance and not an exact, rigid limit. This should be kept in mind when using the implementation package.

DELAY WARRANT

As with cycle failure and demand-capacity warrants, the assumption has been made that the behavior of either lane in a dual left-turn operation is similar to that of single left-turn operation in terms of the respective performance measures. With respect to delay, because the distribution of the vehicles between the two lanes has been assumed to be approximately equal, and the signal timing is the same, then the delay experienced in either of the two lanes should not be drastically different from that experienced by a vehicle in a single-lane left-turn operation. The above assumptions are supported by the conclusion made in the saturation-flow section of this chapter which indicated that there is not enough evidence to show that more vehicles are processed in either the inside or in the outside lane in a dual-lane left-turn operation. Therefore, as with the above warrants, the delay performance measures outlined in the single-left-turn analysis are assumed to be appropriate for measuring the performance of a dual-lane left-turn operation. This warrant has been included in the implementation package and will be addressed in more detail in Chapter 4.

BAY-LENGTH DETERMINATION

The key assumption in this study's determination of dual left-turn bay length is that, as stated above, the performance of either of the lanes in a dual operation is essentially the same as that of a single left-turn lane. For this reason the equations that were applicable in the single left-turn analysis are also applicable in the dual left-turn analysis. Instead of re-stating all the equations, if interested, the reader should consult the bay-length-determination section of Chapter 2.

SUMMARY

The TEXAS Model provides an excellent tool for determining the average and the maximum bay length needed for a dual-lane left-turn operation. The data for these values that were obtained from TEXAS Model runs with many different left-turn volumes and signal timings, are shown in Appendix C. The next chapter, outlining the implementation package, explains in detail the parameters used in these simulation runs.

The above warrants and bay-length determinations rely heavily upon the material presented in the single-lane left-turn analysis chapter of this study. The assumptions made regarding the similarity between the performance of either lane in a dual-lane left-turn operation and a single-lane left-turn operation do not imply that there are no differences. However, the assumptions do imply that these differences do not alter the results enough to warrant further time and effort in their investigation. Given the multivariate nature of turning-movement analysis, the major effort of this study has been to focus on the variables that influence a left-turn operation the most, and not to include every possible variable. The following chapter outlines the relationship between three of these important variables and their effect on delay, average queue length, and maximum queue length. The three variables are (1) the time during which left-turns are prohibited or left-turn red time, (2) cycle length, and (3) left-turn volume.

CHAPTER 4. IMPLEMENTATION PACKAGE

The Left-Turning Movement Analysis Program (LTMAP) is an IBM-compatible Turbo Pascal program that has been developed to aid engineers in analyzing existing or proposed left-turning movements at urban intersections. The LTMAP relies heavily upon the information that has been presented in the previous two chapters. The program also acts as a database program in that it accesses TEXAS Model simulation results that are based on user-specified inputs.

This chapter first presents the pertinent equations and concepts that were used in the implementation program. This part of the chapter is essentially a review of the pertinent equations and concepts that were presented in Chapters 2 and 3. Next, a description of all TEXAS Model simulation runs is made, including a discussion of the pertinent variables and parameters that were used in the LTMAP. The last section of this chapter presents the LTMAP and includes a description of the required hardware, input values, and cautions for users.

LTMAP: PERTINENT EQUATIONS AND CONCEPTS

The program allows for the determination of cycle failures, volume to capacity relationships, average delays, and queue lengths for single and dual left-turn lanes. This summary of the pertinent equations and concepts that have been used in the LTMAP will focus on these four areas. The summary is brief because the derivation and justification of the equations and concepts has been addressed in the previous two chapters.

CYCLE FAILURES

The cycle failures output table in the LTMAP is divided into five parts:

(1) the average number of uniform arrivals per lane during one signal cycle length in the peak period;
(2) the average minimum departure headway;
(3) the number of vehicles processed per lane during the effective green phase;
(4) the probability of having more vehicles arriving than being processed (during the effective green period); and
(5) the ratio of the arrival rate to the processing rate, or percent arrival rate to processing rate.

The average number of uniform arrivals per lane during one cycle in the peak period is expressed in equation form as follows:

\# UNIFORM. ARR. = 4 (Peak 15-Minute Volume)*(Cycle Length / 3600)

The average minimum departure headway is a user-defined input, and is used in the next performance measure.

The number of vehicles processed per lane during the effective green phase is equal to the effective green divided by the average minimum departure headway.

The probability of having more vehicles arriving than are being processed during the effective green period is based on Drew's work (Ref 5) with Poisson arrival distributions given that the arrival and processing parameters are known (derived above). As noted by Drew, the suggested upper limit for this probability is 30 percent. The function is as follows:

$$P(x+1) = \sum_{x+1}^{\infty} \frac{m^{x+1} e^{-m}}{(x+1)!}$$

where:

- m = 4 (peak 15-minute critical lane volume)(C/3600);
- m = average number of uniform arrivals during one cycle length in the peak 15-minute period;
- Ge = effective green;
- D = average minimum headway;
- D = 3 seconds (assumed); and
- x = Ge/D
  = number of vehicles processed during the effective green.

The percent of the arrival rate to the processing rate is simply the ratio of m to x.

VOLUME-TO-CAPACITY RELATIONSHIPS

There are two different capacities that were derived in this performance measure. The first was the TEXAS Model method, which utilizes a left-turn processing rate that was derived from TEXAS Model simulation runs. The TEXAS Model capacity equation is as follows:

$$Q_l = \left[\frac{3600}{R} * \frac{G}{C}\right] + \left[\frac{3600}{C} * 0.5\right]$$

$$= \left[\frac{P}{R} + \frac{0.5}{C}\right] * 3600$$

where:

- Q_s = Left-turn saturation flow rate (veh/hour green);
- Q_l = left-turn capacity when approaching saturation conditions (veh/hour);

R = protected left-turn processing rate (sec/veh);
G = effective left-turn green time (sec);
C = cycle length (sec); and
P = decimal percentage of cycle for protected green phase.

The 1985 Highway Capacity Manual equation for capacity is as follows:

$$Q_l = S * \frac{G}{C}$$

where:

Q_l = left-turn capacity (veh/hr);
Q_s = left-turn saturation flow rate (veh/hr green);
= (thru saturation flow rate) * (0.95); and
G = Effective Green (sec).

The key to the 85HCM equation is the left-turn saturation flow rate. Because of the importance of this value and its variability, it has been included as a user-specified input. The default value for single left-turns is 1,710 vphlg, as recommended by the 85HCM (assumes a through saturation flow value of 1,800). The LTMAP uses a default of 1,600 vphlg per dual left-turn lane. This saturation flow value was determined in Chapter 3.

Two capacity measures have been included so that the engineer may have a resulting volume to capacity ratio that is in a range, rather that one specific answer.

The suggested upper limit for the volume to capacity ratio for either method is 90 percent. The justification for using this value was addressed in Chapter 2.

AVERAGE DELAYS

The average delay output table in the LTMAP is comprised of three different methods for determining delay:

(1) average queue delay from TEXAS Model simulations;
(2) the cycle failure delay equation;
(3) the 85HCM delay equation.

The average queue delay results from the TEXAS Model simulations were obtained from the same set of runs that were used for determining the queue lengths. The input parameters, variables, and description of these runs is given in the next section of this chapter (TEXAS Model Simulations).

The cycle failure delay equation is broken up into four cases*

where:

D_t = total uniform stopped delay (veh/sec);
C = cycle length (sec);
R = red phase length (sec);
G = green phase length;
Y = clearance interval (sec);
G_e = effective green (sec);
R_e = effective red (sec);
A = left-turn arrival rate (pce/sec);
P = left-turn processing rate (pce/sec);
N = net left-turn processing rate (pce/sec);
Q_s = maximum left-turn storage capacity (pce);
Q_o = initial queue length (pce);
= average number of cycle failures per cycle, based on the peak hourly volume, or 4 X peak 15-minute (pce); and
Q_R = residual queue length (pce).

Da (for cases 2,3,4) = Dt/(VC/3600)
Da (for case 1, not valid for Qo=0) = Dt/Qo

The 85HCM delay equation is:

$$d = \left[0.38\,C \frac{[1 - g/C^2]}{[1 - (g/C)\,(x)]}\right] + \left[173x^2\left[(x-1) + \sqrt{(x-1)^2 + (16x/c)}\right]\right]$$

where:

d = average stopped delay per vehicle for the lane group, in sec/veh;
C = cycle length, in seconds;
g/C = the effective green time over the cycle length;
x = the volume to capacity ratio; and
c = capacity of the lane group.

---

* Case 1) $N < 0, A = 0$ $\quad D_t = Q_oR_e + \frac{Q_o^2}{2P}$

Case 2) $N < 0, A > 0, Q_R \le 0$ $\quad D_t = Q_oR_e + \frac{AR_e^2}{2} + \frac{(AR_e + Q_o)^2}{2|N|}$

Case 3) $N \le 0, A > 0, Q_R > 0$ $\quad D_t = Q_oR_e + \frac{AR_e^2}{2} + \frac{|N|G_e}{2} + (Q_o + AR_e - |N|G_e)G_e$

Case 4) $N > 0, Q_R \le Q_S$ $\quad D_t = Q_oR_e + \frac{AR_e^2}{2} + (Q_o + AR_e)(G_e) + \frac{NG_e^2}{2}$

The suggested upper limit as defined by Lin (Ref 3) is 35 seconds of average left-turn queue delay. There is not a problem with the fact that the CF and 85HCM equations determine the average stopped delay and the TEXAS Model and the upper limit are defined in terms of the average queue delay. Because of the inherent variability of any delay measurement, any suggested upper limit should only be used as a "rule of thumb" and not as a definite and inflexible upper bound. As was the case with the volume to capacity performance measures, more than one delay measure has been included in this program to give the engineer a range of values to use when evaluating turning movement performance.

QUEUE LENGTHS

The average, maximum, and design queue lengths were derived solely from the results of TEXAS Model simulation results. Due to the multitude of variables involved and the randomness of any vehicle arrival process, it was difficult to derive any reliable equation that would determine the queue lengths of an arriving traffic stream. For this reason the TEXAS Model provided an ideal solution to solving the multivariate and random nature of this problem.

The average and maximum queue lengths in vehicles were obtained directly from the results of the TEXAS Model runs that are outlined in the next section of this chapter. By prompting the user for information about the percentages and lengths of vehicles in each class, the queue length in feet was determined. To the length of each vehicle was added the user- specified average clear space between stopped vehicles in the stopped queue. This allowed the user to define the "packing" of the queue, which has a direct effect on the length of the queue. The total queue length in feet was obtained by weighting each vehicle class by its percentage, then summing the weighted lengths (which included the addition of the clear space between stopped vehicles to each vehicle). The design queue length is 85 percent of the maximum queue length (in vehicles and feet).

TEXAS MODEL SIMULATIONS

The three primary input variables that were analyzed were: left-turn red time, cycle length, and the left-turn volume for single and dual left-turn movements. Because of the large number of combinations of these three primary variables it became apparent that the TEXAS Model runs should be limited to a specified range of these combinations. The cycle lengths of 60, 80 ,100, and 120 seconds were chosen as appropriate cycle lengths because they represent short, medium, and long cycle lengths. Because the typical left-turn movement operates in a G+Y/C range of 0.2 to 0.6, the left-turn red time was limited to increments of 10 seconds within these G+Y/C bounds. The left-turn volume was difficult to limit because of the variable nature of the traffic stream. Therefore, left-turn volumes of 200, 300, 400, 500, 600, 700, and 800 vehicles per hour were chosen for each timing configuration that fell within the stated bounds. Table 4-1 shows the relationship between the cycle length, left-turn red time, left-turn green + yellow, and the G+Y/C ratio. Outlined cells fell within the specified range of the input variables, and simulations were done with these signal timing configurations. Each of these signal timing schemes had the above mentioned volumes simulated. With each combination of red time, cycle length and volume, four independent simulation runs were performed for both single and dual left-turn operations. An independent simulation is one in which the random numbers used are different from those used in other runs. The averages of each of the four runs is shown in Table 4-2. The results from all of the simulation runs are shown in Appendix C.

The geometry and input files that were used for the dual left-turn runs were presented in Chapter 3 in the dual left-turn saturation flow section. Figures 4.1a and b show the geometry that was used for the single left-turn simulation runs. Appendix D shows examples of the TEXAS Model geometry and driver-vehicle (GDV) and simulation (SIM) input files that were used in the single and dual left-turn analysis.

LEFT-TURNING MOVEMENT ANALYSIS PROGRAM

The Left-Turning Movement Analysis Program (program listing in Appendix E) provides engineers with an interactive intersection design and evaluation tool. The IBM-compatible program requires that the host machine have a math coprocessor and a color graphics adapter.

LTMAP prompts the user for input and then allows movement within the program by selecting the next-desired action. The input and desired-action screen prompts are shown in Figs 4.2a, b, and c. LTMAP is relatively user-friendly, and all input values are checked to determine whether they are within the specified ranges. A review of these ranges is presented here:

Input Variable	Range or Correct Response
Cycle Length	60, 80, 100, or 120 (seconds)
Left-Turn Red Time	30, 40, 50, 60, 70, 80, or 90 (seconds)
	0.2 <= (G+Y/C) <= 0.6
Single or Dual Left-Turns	s, d
Left-Turn Volume	200, 300, 400, 500, 600, 700, or 800 (lt vph, per lt lane)
Peak 15 Minute Volume	0 to 300 lt vph
Number of Vehicle Classes	Integer >= 1
% In Each Vehicle Class	Integer Percentage (sum must = 100)

Some of the input prompts have been excluded from checking because either there is no required range (saturation flow) or the range is not viewed as being a potential problem (length of vehicles). All the prompts specify in what form the response should be.

After the data have been input, the desired-action screen appears. This screen is self-explanatory, but all inputs must be in lower case letters. This lower case requirement is true for all yes or no responses as well.

Also included on the floppy disk with the program are six data files. These files (labeled *.DAT) are read by the program in the format specified in the program's read section. These files contain the TEXAS Model simulation results and include the data for the average queue lengths, the maximum queue lengths, and the average queue delay for both single and dual left-turn lanes. The data contained in these files are the same as those presented in Table 4-2.

All files labelled *.BGI are the appropriate drivers (or device-specific files) that are required for most graphics adapter packages. As stated above, the program requires a color graphics adapter. The drivers that are present are for AT&T, CGA, EGA, VGA, Hercules, and PC3270 color graphics cards.

Because of the large number of floating point calculations that this program performs, a math coprocessor chip (Intel 8087) is also required for the program to run correctly.

The LTMAP program was written on an IBM-compatible machine and was intended to be used on similar machines. One limitation with all IBM-compatible programs is that it is difficult to encompass all possible hardware configurations; thus problems may arise if the hardware differs substantially from the machine it was written on (COMPAQ 386). It is recommended that the program be used on a IBM XT or AT compatible, or PS2, with a Variable Graphics Adapter or Enhanced Graphics Adapter.

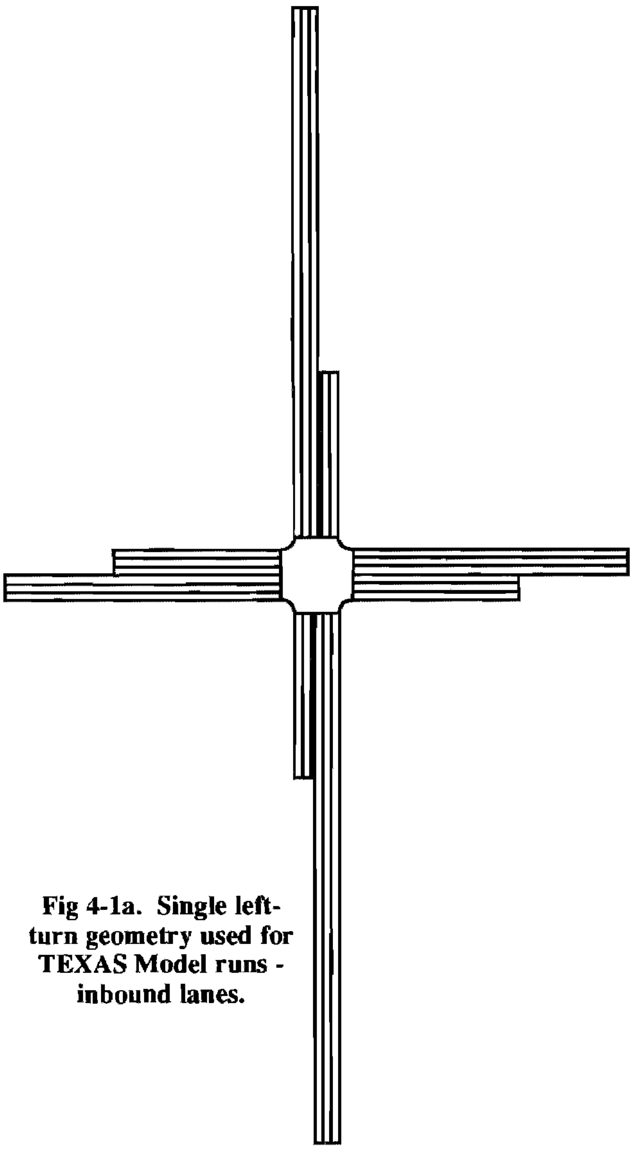

Fig 4-1a. Single left-turn geometry used for TEXAS Model runs - inbound lanes.

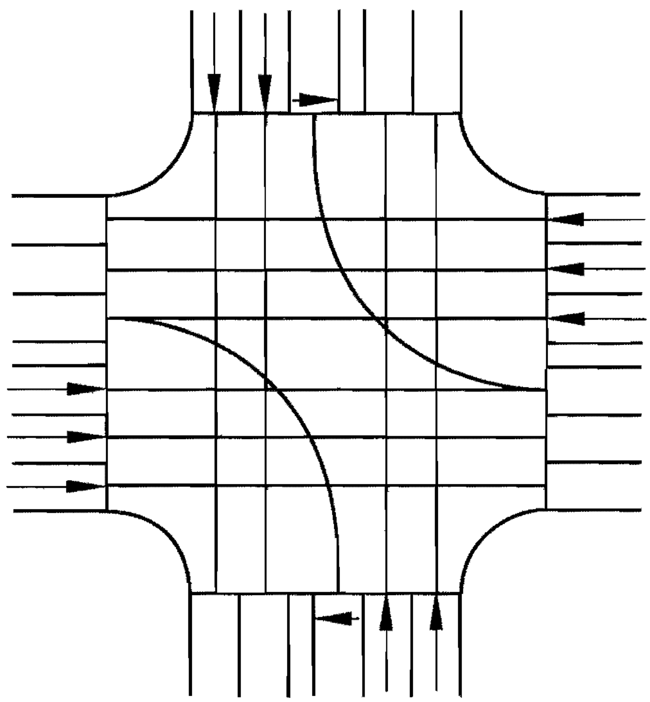

Fig 4-1b. Single left-turn geometry used for TEXAS Model runs - intersection with turning movements.

```
**************************************************************
THIS SECTION IS FOR DEFINING SIGNAL TIMING CHARACTERISTICS.
**************************************************************

Enter the desired cycle length (60,80,100 or 120 seconds).
100

Enter the left turn red phase length (30,40,50,60,70,80, or 90 secs.).
The G+Y/CL ratio must be between 0.2 & 0.6.
80

PRESS RETURN TO ENTER VEHICLE CHARACTERISTICS
```

Fig 4-2a. LTMAP, signal timing input prompts.

```
*********************************************************
THIS SECTION IS FOR DEFINING THE VEHICLE CHARACTERISTICS.
*********************************************************
Do you want to analyze a single or dual left-turn operation (s or d)?
d

Enter the dual left-turn volume
on a per lane basis (200,300,400,500,600,700 or 800 vph).
345
THE PER LANE LEFT TURN VOLUME MUST BE 200,300,400,500,600,700, OR 800 VPH,
PLEASE REENTER THE THE PER LANE LEFT TURN VOLUME.
500


Enter the peak 15 minute dual left-turn volume
on a per lane basis (must be less than or equal to 300 vehicles).
200

Do you want to use 1600 vph per lane as the saturation flow
value for a dual left-turn operation (y or n)?
y

Do you want to use 2.5 seconds as the average minimum
departure headway in the left-turning queue (y or n)?


Do you want to use 6 feet as the average
headway in the stopped queue (y or n)?
y

How many different classes of vehicles are there?
2

Input the percentage of vehicles in class 1
(integer percentage, i.e. 52).
50
Input the length of vehicles in class 1
(integer feet, i.e. 24).
34

Input the percentage of vehicles in class 2
(integer percentage, i.e. 52).
50
Input the length of vehicles in class 2
(integer feet, i.e. 24).
24

                    PRESS RETURN TO CONTINUE
```

Fig 4-2b. LTMAP, vehicle characteristics input prompts.

```
ENTER THE FOLLOWING LETTERS TO CONTINUE:

i = review of the INPUT values

q = average, maximum, and design QUEUE lengths table

c = CYCLE failure statistics table

v = VOLUME to capacity statistics table

d = DELAY statistics table

n = starts NEW data entry section again

e = EXITS program
```

Fig 4-2c. LTMAP, desired action input prompts.

TABLE 4-1. G-OVER-C RATIOS FOR DIFFERENT SIGNAL TIMING COMBINATIONS

Left-Turn	Left-Turn Red Time (sec)										
G + Y	10	20	30	40	50	60	70	80	90	100	110
10	0.50	0.33	0.25	0.20	0.17	0.14	0.13	0.11	0.10	0.09	0.08
20	0.67	0.50	0.40	**0.33**	0.29	**0.25**	0.22	**0.20**	0.18	0.17	0.15
30	0.75	0.60	**0.50**	0.43	**0.38**	0.33	**0.30**	0.27	**0.25**	0.23	0.21
40	0.80	0.67	0.57	**0.50**	0.44	**0.40**	0.36	**0.33**	0.31	0.29	0.27
50	0.83	0.71	0.63	0.56	**0.50**	0.45	**0.42**	0.38	0.36	0.33	0.31
60	0.86	0.75	0.67	**0.60**	0.55	**0.50**	0.46	0.43	0.40	0.38	0.35
70	0.88	0.78	0.70	0.64	**0.58**	0.54	0.50	0.47	0.44	0.41	0.39
80	0.89	0.80	0.73	**0.67**	0.62	0.57	0.53	0.50	0.47	0.44	0.42
90	0.90	0.82	0.75	0.69	0.64	0.60	0.56	0.53	0.50	0.47	0.45
100	0.91	0.83	0.77	0.71	0.67	0.63	0.59	0.56	0.53	0.50	0.48
110	0.92	0.85	0.79	0,73	0.69	0.65	0.61	0.58	0.55	0.52	0.50

☐ - Texas Model runs = cells that fall within the range of:
1) Cycle length = 60, 80, 100, or 120 seconds
2) (0.2 <= ((green + yellow)/cycle length) <= 0.6)

TABLE 4-2. AVERAGES OF TEXAS MODEL RUNS FOR SPECIFIED SIGNAL TIMINGS AND LEFT-TURN VOLUMES

Single Left-Turn

Cycle Length	LT Red Time	Average Left-Turn Queue Delay (sec) Left-Turn Volume (vph per lane) 200	300	400	500	600	700	800
60	30	18.75	18.88	20.60	27.55	71.23	105.90	118.63
	40	26.28	35.45	154.05	207.65	260.33	282.35	288.00

Cycle Length	LT Red Time	Average Left-Turn Queue Length (veh) Left-Turn Volume (vph per lane) 200	300	400	500	600	700	800
60	30	0.60	0.95	1.48	3.05	11.40	17.28	19.40
	40	1.23	2.80	16.80	23.05	29.10	30.78	32.05

Cycle Length	LT Red Time	Maximum Left-Turn Queue Length (veh) Left-Turn Volume (vph per lane) 200	300	400	500	600	700	800
60	30	4.50	5.50	6.75	10.50	22.50	27.25	27.50
	40	6.50	9.50	27.50	31.00	36.25	36.50	36.75

Single Left-Turn

Cycle Length	LT Red Time	Average Left-Turn Queue Delay (sec) Left-Turn Volume (vph per lane) 200	300	400	500	600	700	800
80	40	22.85	24.85	26.68	32.88	71.08	106.13	121.93
	50	28.15	32.78	63.63	131.38	192.68	214.65	226.73
	60	39.85	145.48	348.18	376.93	421.68	444.78	450.05

Cycle Length	LT Red Time	Average Left-Turn Queue Length (veh) Left-Turn Volume (vph per lane) 200	300	400	500	600	700	800
80	40	0.70	1.13	1.95	3.58	11.50	17.35	19.98
	50	1.10	2.20	7.03	16.38	24.25	26.53	27.60
	60	1.95	12.88	30.75	33.08	37.10	38.38	37.75

Cycle Length	LT Red Time	Maximum Left-Turn Queue Length (veh) Left-Turn Volume (vph per lane) 200	300	400	500	600	700	800
80	40	5.00	6.25	9.00	12.75	23.25	27.25	29.50
	50	6.00	8.75	17.50	25.00	32.50	33.50	34.25
	60	7.75	25.50	40.00	41.25	43.75	43.50	42.50

TABLE 4-2 (CONTINUED). AVERAGES OF TEXAS MODEL RUNS FOR SPECIFIED SIGNAL TIMINGS AND LEFT-TURN VOLUMES

Single Left-Turn

		Average Left-Turn Queue Delay (sec) Left-Turn Volume (vph per lane)						
Cycle Length	**LT Red Time**	**200**	**300**	**400**	**500**	**600**	**700**	**800**
100	40	23.05	25.45	25.03	26.15	32.70	46.25	65.75
	50	27.93	29.95	31.53	35.33	70.25	107.78	121.53
	60	32.68	36.68	52.75	97.93	165.90	182.75	191.23
	70	38.73	57.08	205.80	251.55	308.20	319.35	328.80
	80	66.60	325.70	476.63	497.93	538.28	557.00	562.90

		Average Left-Turn Queue Length (veh) Left-Turn Volume (vph per lane)						
Cycle Length	**LT Red Time**	**200**	**300**	**400**	**500**	**600**	**700**	**800**
100	40	0.65	1.25	1.77	1.75	3.65	8.18	12.68
	50	0.90	1.43	2.35	3.60	11.48	17.70	19.85
	60	1.23	2.20	5.33	12.95	22.53	24.60	25.45
	70	1.73	4.53	21.68	26.48	32.15	32.98	33.50
	80	3.63	25.53	36.48	37.80	40.08	40.58	40.33

		Maximum Left-Turn Queue Length (veh) Left-Turn Volume (vph per lane)						
Cycle Length	**LT Red Time**	**200**	**300**	**400**	**500**	**600**	**700**	**800**
100	40	4.75	6.75	7.25	8.25	12.50	20.75	24.50
	50	5.50	7.00	10.25	12.50	23.50	28.75	30.25
	60	6.50	8.50	15.00	23.25	32.00	33.00	33.00
	70	7.75	12.75	33.00	36.50	39.50	40.00	39.50
	80	10.25	40.25	43.50	44.50	45.50	45.50	44.75

Single Left-Turn

		Average Left-Turn Queue Delay (sec) Left-Turn Volume (vph per lane)						
Cycle Length	**LT Red Time**	**200**	**300**	**400**	**500**	**600**	**700**	**800**
120	50	29.58	29.70	31.63	31.83	38.28	56.58	75.95
	60	34.88	36.25	37.38	41.55	75.33	112.68	125.53
	70	39.58	42.98	50.63	98.35	154.85	174.70	184.93
	80	45.90	50.58	137.10	198.75	253.85	267.88	277.35
	90	54.68	146.25	331.28	374.80	405.53	432.20	438.28

		Average Left-Turn Queue Length (veh) Left-Turn Volume (vph per lane)						
Cycle Length	**LT Red Time**	**200**	**300**	**400**	**500**	**600**	**700**	**800**
120	50	0.75	1.23	1.80	2.28	4.75	10.00	14.13
	60	1.05	1.85	2.73	4.20	11.85	18.38	20.40
	70	1.38	2.55	4.85	13.08	21.53	24.03	25.20
	80	1.85	3.68	15.00	22.40	28.63	30.03	30.73
	90	2.55	12.63	29.75	32.73	36.00	37.33	37.60

		Maximum Left-Turn Queue Length (veh) Left-Turn Volume (vph per lane)						
Cycle Length	**LT Red Time**	**200**	**300**	**400**	**500**	**600**	**700**	**800**
120	50	5.50	7.00	8.75	10.00	15.50	22.75	28.00
	60	6.75	8.25	10.25	13.50	24.50	30.00	31.25
	70	7.25	10.00	14.00	24.50	32.50	33.50	33.25
	80	8.25	11.75	26.50	33.00	38.00	37.75	37.50
	90	9.00	25.25	40.25	41.25	43.50	43.25	43.00

TABLE 4-2 (CONTINUED). AVERAGES OF TEXAS MODEL RUNS FOR SPECIFIED SIGNAL TIMINGS AND LEFT-TURN VOLUMES

Dual Left-Turn

		Average Left-Turn Queue Delay (sec) Left-Turn Volume (vph per lane)						
Cycle Length	**LT Red Time**	**200**	**300**	**400**	**500**	**600**	**700**	**800**
60	30	17.30	18.13	19.43	22.73	92.45	130.08	144.18
	40	23.78	27.80	170.83	272.88	302.48	319.25	323.00

		Average Left-Turn Queue Length (veh) Left-Turn Volume (vph per lane)						
Cycle Length	**LT Red Time**	**200**	**300**	**400**	**500**	**600**	**700**	**800**
60	30	0.58	0.88	1.40	2.53	15.00	20.73	22.65
	40	1.05	2.08	19.48	30.38	32.98	34.45	34.85

		Maximum Left-Turn Queue Length (veh) Left-Turn Volume (vph per lane)						
Cycle Length	**LT Red Time**	**200**	**300**	**400**	**500**	**600**	**700**	**800**
60	30	3.75	4.25	5.75	7.25	26.75	28.00	28.00
	40	5.00	6.25	35.75	38.00	38.75	38.75	39.25

Dual Left-Turns

		Average Left-Turn Queue Delay (sec) Left-Turn Volume (vph per lane)						
Cycle Length	**LT Red Time**	**200**	**300**	**400**	**500**	**600**	**700**	**800**
80	40	23.40	24.03	25.18	27.80	92.03	132.45	145.13
	50	29.53	30.75	52.90	193.88	233.50	245.60	253.95
	60	37.65	181.20	381.43	441.75	457.25	472.03	479.00

		Average Left-Turn Queue Length (veh) Left-Turn Volume (vph per lane)						
Cycle Length	**LT Red Time**	**200**	**300**	**400**	**500**	**600**	**700**	**800**
80	40	0.75	1.18	1.75	2.80	14.90	21.10	23.00
	50	1.18	2.00	6.03	24.30	28.78	30.33	31.13
	60	1.85	15.55	33.80	37.75	38.95	39.75	39.78

		Maximum Left-Turn Queue Length (veh) Left-Turn Volume (vph per lane)						
Cycle Length	**LT Red Time**	**200**	**300**	**400**	**500**	**600**	**700**	**800**
80	40	4.25	5.25	6.25	8.75	27.00	29.00	29.00
	50	5.25	6.50	12.75	34.25	35.00	35.50	36.25
	60	6.25	25.00	43.25	43.75	44.50	44.00	44.00

TABLE 4-2 (CONTINUED). AVERAGES OF TEXAS MODEL RUNS FOR SPECIFIED SIGNAL TIMINGS AND LEFT-TURN VOLUMES

Dual Left-Turns

Average Left-Turn Queue Delay (sec)
Left-Turn Volume (vph per lane)

Cycle Length	LT Red Time	200	300	400	500	600	700	800
100	40	23.20	23.38	24.78	25.38	27.90	59.05	72.15
	50	28.93	29.50	30.88	33.25	98.40	133.28	145.25
	60	34.23	35.08	40.55	150.20	203.08	218.68	226.03
	70	40.20	49.35	229.23	316.68	343.48	352.63	358.53
	80	70.18	397.60	506.58	554.13	576.78	588.93	601.13

Average Left-Turn Queue Length (veh)
Left-Turn Volume (vph per lane)

Cycle Length	LT Red Time	200	300	400	500	600	700	800
100	40	0.58	0.90	1.33	1.82	2.65	11.83	14.63
	50	0.85	1.40	2.15	3.25	16.03	21.55	23.33
	60	1.23	2.03	3.88	20.50	26.95	28.63	29.30
	70	1.73	3.85	25.03	33.33	35.58	36.20	36.10
	80	3.83	31.08	37.80	40.45	41.13	41.73	41.48

Maximum Left-Turn Queue Length (veh)
Left-Turn Volume (vph per lane)

Cycle Length	LT Red Time	200	300	400	500	600	700	800
100	40	4.25	5.25	6.25	7.25	9.25	21.00	25.00
	50	5.25	6.00	8.00	9.50	28.50	29.50	30.50
	60	6.00	7.25	10.50	33.25	34.00	34.25	35.00
	70	7.00	10.25	39.25	40.75	41.25	42.00	41.75
	80	9.50	44.00	45.75	45.75	45.25	46.25	45.50

Dual Left-Turns

Average Left-Turn Queue Delay (sec)
Left-Turn Volume (vph per lane)

Cycle Length	LT Red Time	200	300	400	500	600	700	800
120	50	27.70	29.68	30.60	31.63	34.45	78.43	95.35
	60	33.60	35.10	36.98	39.53	109.68	140.68	148.58
	70	39.40	41.08	44.03	152.95	192.70	210.33	213.35
	80	44.50	48.70	160.80	267.45	292.20	307.00	311.60
	90	51.83	158.70	363.07	427.00	449.43	455.65	471.30

Average Left-Turn Queue Length (veh)
Left-Turn Volume (vph per lane)

Cycle Length	LT Red Time	200	300	400	500	600	700	800
120	50	0.75	1.15	1.73	2.35	3.68	14.53	17.53
	60	1.00	1.63	2.58	3.95	17.50	22.15	23.66
	70	1.38	2.35	3.88	20.75	25.75	28.10	28.58
	80	1.83	3.23	17.90	29.75	32.35	34.03	34.20
	90	2.48	13.40	32.45	37.33	38.38	38.95	39.10

Maximum Left-Turn Queue Length (veh)
Left-Turn Volume (vph per lane)

Cycle Length	LT Red Time	200	300	400	500	600	700	800
120	50	4.75	6.25	7.50	8.25	11.50	24.25	28.75
	60	5.25	7.50	9.00	11.50	29.50	30.75	31.25
	70	6.25	8.75	11.25	33.50	34.00	35.00	35.00
	80	7.50	9.50	33.00	38.75	39.00	40.25	40.00
	90	8.50	24.00	42.50	44.25	44.50	44.75	44.25

CHAPTER 5. RIGHT-TURN TREATMENTS

Currently, the Manual on Uniform Traffic Control Devices (MUTCD) does not provide a means for distinguishing between the operational effects of turning traffic and straight-through traffic when applying the volume warrants for signalization given in Section 4c (Texas MUTCD). Turning and straight traffic volumes are normally summed to produce the total approach volumes which are referenced within the warrants. However, it is intuitively obvious that maximum flow rates are not the same for turning and for straight movements. The times needed for making a turning and for making a straight movement are different. Therefore, the evaluation of an approach volume in terms of its need for signalization should include some means of accounting for the effects of turning movements. The relative effect of right-turning traffic on intersection capacity is of particular interest.

DEVELOPMENT OF AN EQUIVALENCE RELATIONSHIP

The maximum flow rate from a lane into an intersection is affected by the proportion of turning vehicles and straight-through vehicles in the lane. In order to evaluate the effects of various ratios of right-turning to straight-through vehicles on maximum flow rate, a series of experiments was designed to develop an equivalency relationship. A variety of geometric and traffic-control conditions were included.

If the equivalence relationship was to be used in warrant studies, it was reasoned that the traffic control conditions which should be studied were those that would most likely be in effect prior to signalization. This consideration led to the inclusion of 2-way and all-way stop as the most likely traffic control features. Street geometry should likely also affect the relative performance of straight and right-turn maneuvers. Therefore, intersections with 4 X 4 and 4 X 2 lane geometries were included. The TEXAS Model for Intersection Traffic (Ref 17), which is a microscopic traffic simulation model, was configured with these basic geometric and traffic control features. For each test condition, essentially infinite queues of traffic were generated for the stop-controlled approaches while traffic volumes on the cross street were varied from zero to as much as 2,300 vehicles per hour (expressed as the sum of both cross-street approach volumes). Specifications utilized in the simulation included 600-foot intersection approach lengths and 20-foot curb return radii.

Results of the 2-way and all-way stop experiments for 4 X 4 and 4 X 2 lane geometries are presented in Tables 5-1 and 5-2. Each of the maximum flow rates presented in the tables represents the arithmetic mean of four replicate observations of 30 minutes of simulated observation time. Graphical presentation of the data for the 4 X 4 lane geometry type under 2-way stop control is shown in Fig 5-1. The figure indicates that the stop-controlled straight movement has a slightly higher flow rate until the total volume of traffic being crossed reaches approximately 800 vehicles per hour. As the uncontrolled crossing traffic volume increases above 800 vehicles per hour, the maximum right-turn flow rate exceeds the straight flow rate by an increasing margin.

A similar graphical comparison of maximum flow rates for stop-controlled straight and right maneuvers with 4 X 2 lane geometrics is presented in Fig 5-2. In this case, the maximum flows are not discernibly

TABLE 5-1. MAXIMUM STOP SIGN FLOW RATES PER LANE FOR TWO-WAY STOP CONTROL

Total Uncontrolled Crossing Traffic (Total Both Approaches (vph))	Maximum Per Lane Stop Sign Flow (vph/lane) — Intersection Geometry/Movement: 4 x 4/ Straight	4 x 4/ Right	4 x 2/ Straight	4 x 2/ Right
0	380	361	382	392
100	392	364	376	386
300	366	353	348	348
500			327	331
700	333	321	304	302
900			286	285
1100	288	306	262	268
1300			248	247
1500	245	292	210	216
1700			176	196
1900	198	274		
2300	144	253		

TABLE 5-2. MAXIMUM STOP SIGN FLOW RATES PER LANE FOR ALL-WAY STOP CONTROL

Total Uncontrolled Crossing Traffic (Total Both Approaches (vph))	Maximum Per Lane Stop Sign Flow (vph/lane) — Intersection Geometry/Movement: 4 x 4/ Straight	4 x 4/ Right	4 x 2/ Straight	4 x 2/ Right
100	389	377	377	380
200			369	375
400	365	367	360	366
600			357	360
700			358	360
800	346	347		
1200	340	339		
1350	339	335		

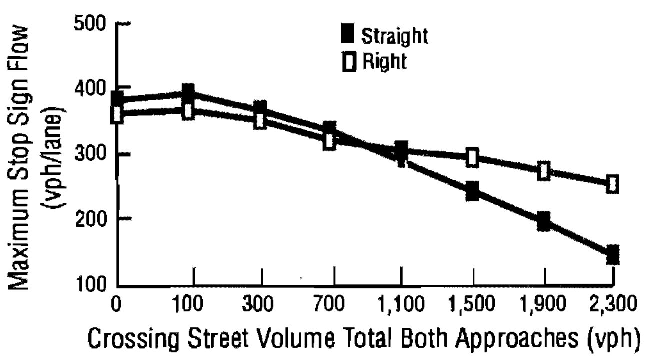

Fig 5-1. Maximum flow rate per lane, 4 X 4 geometry, 2-way stop control.

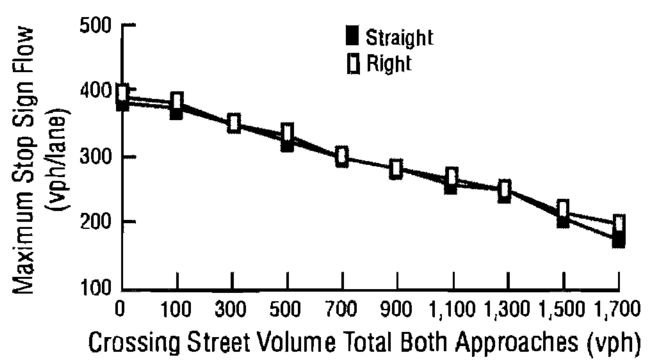

Fig 5-2. Maximum flow rate per lane, 4 X 2 geometry, 2-way stop control.

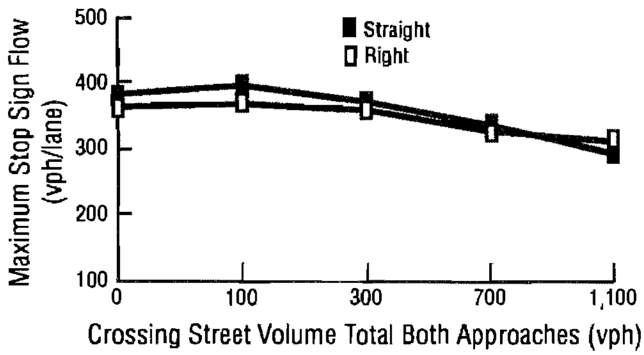

Fig 5-3. Maximum flow rate per lane, 4 X 4 geometry, all-way stop control.

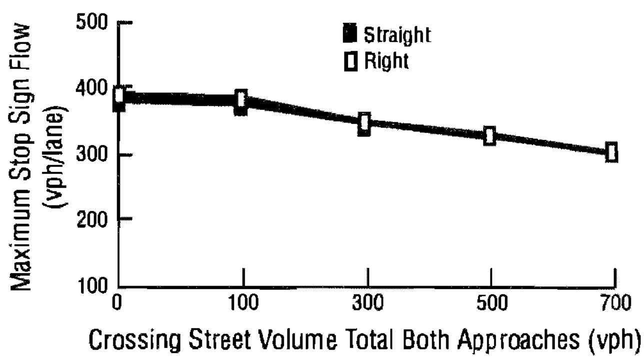

Fig 5-4. Maximum flow rate per lane, 4 X 2 geometry, all-way stop control.

different until the "to be crossed" flows exceed approximately 1,500 vehicles per hour. This is probably true because the crossing traffic is confined to one lane in each direction. This means that the straight and right-turn flows on the four-lane street must utilize the same gaps in the crossing street traffic for executing their maneuvers. The right-turn flows do not have an opportunity to turn into a curb lane which may serve as a "free" right-turn lane in the 4 X 4 case.

The graphical comparisons are further extended to the all-way stop case through Figs 5-3 and 5-4. The trends indicated in the two figures are structurally similar to the cases for 2-way stop control. However, differences in maximum flow rates are generally less significant, due to the very orderly sharing of right-of-way which normally occurs at all-way stop intersections.

As noted previously, one means of equating right and straight movements is in terms of their equivalent maximum flow rates. The data of the previous sections have been utilized to form such equivalence factors, which are presented in Figs 5-5 and 5-6. The factors presented here consist of the maximum straight flow rate divided by the corresponding maximum right-turn flow rate. Therefore, the factors should be multiplied by right-turn flow rates to yield equivalent straight flows. As evidenced by the figures, the magnitudes of the factors are significantly different from 1.0 for 2-way stop control but approximately 1.0 for the all-way stop control cases.

Equivalence factors graphically described in Figs 5-5 and 5-6 provide the capability of equating right-turn and straight movements in terms of their relative maximum flow rates. As presented in these figures, the factors should be multiplied by measured right-turn flow rates in order to convert them to equivalent straight flows. Use of these factors, when evaluating an intersection for possible signal installation, can, in certain volume and control conditions, have a rather significant impact.

RIGHT-TURN BAYS VERSUS RIGHT-TURN LANES

If a right-turn lane is considered to be a turn bay with a speed-change area, the basic issue becomes the distance from the intersection to the entrance of the turn bay. The length of traffic queue that would typically be created on the intersection approach needs to be estimated, because this queue can block entry by right-turn traffic to the turn bay.

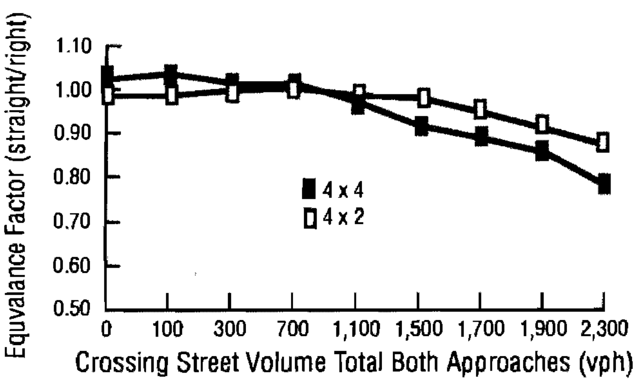

Fig 5-5. Equivalence factors, 2-way stop control, 4 X 4 and 4 X 2 intersection geometry.

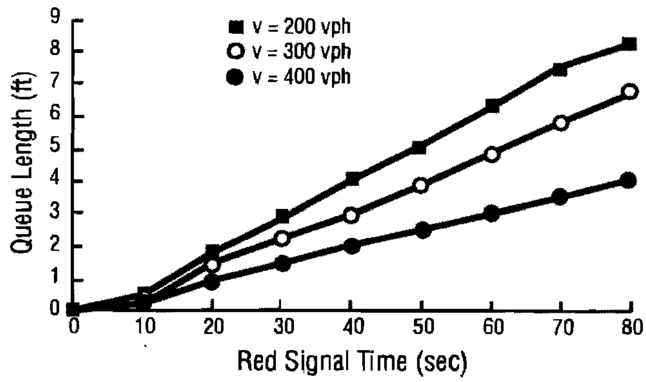

Fig 5-7. Queue lengths versus red signal time (low demand).

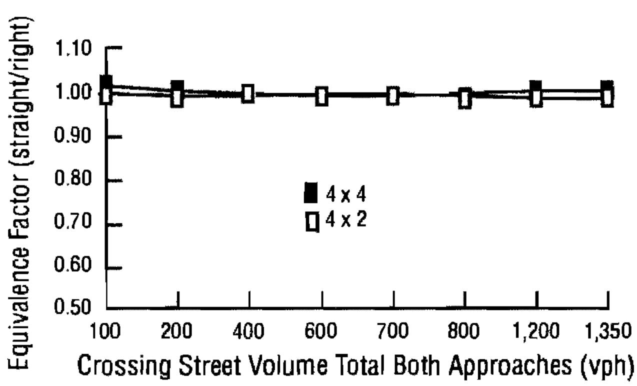

Fig 5-6. Equivalence factor, all-way stop control, 4 X 4 and 4 X 2 intersection geometry.

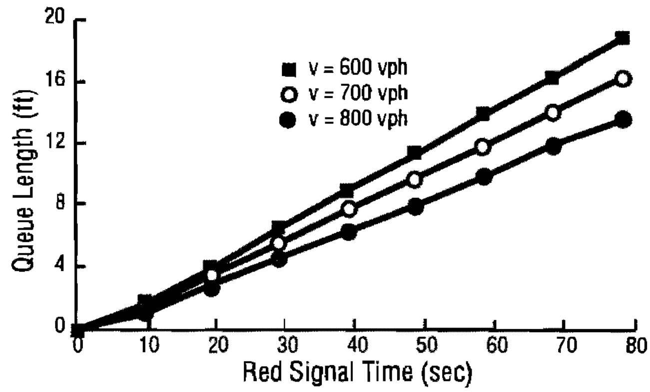

Fig 5-8. Queue lengths versus red signal time (high demand).

An experimental testing program was designed using the NETSIM (Ref 16) model to estimate average queue lengths. Traffic volumes of 200 to 800 vehicles per hour per lane were selected as encompassing the usual range of demands. Red signal phases ranging from 10 to 80 seconds were utilized along with a pre-timed signal control scheme.

Optimal cycle lengths were not used for the various demand levels in order to get average queue lengths for long red phases and to allow queues to completely clear before the beginning of each red phase. Twenty samples were taken at each volume level over the length of the red phase and then averaged to produce a relatively stable statistic. At least 10 minutes of initialization time were specified for each simulation run to attain the network equilibrium state before collecting data.

Average maximum queue lengths as measured from the modeling are presented in Figs 5-7 and 5-8. Graphical results have been presented in two charts in order to enhance the resolution for the lower-volume conditions. In all cases the queue lengths tend to increase almost linearly with red time.

Another view of the simulation results is presented in Figs 5-9 and 5-10 in which the average maximum queue lengths of Figs 5-7 and 5-8 are presented in units of feet instead of vehicles. This conversion utilized an assumed vehicle length plus a clear space of 19 feet. The ordinates of Figs 5-9 and 5-10 might be interpreted as the minimum distances from the intersection approach stopline at which the opening to a right turn bay or lane must occur if the opening is to not be blocked by through traffic queues.

Figures 5-9 and 5-10 have been termed decision charts since they can assist in making two decisions. First, as noted in the previous paragraph, they can be used to estimate the required distance from the intersection stopline to the entrance to a right-turn bay or lane. Second, they may be used in deciding whether the treatment should be a turn bay or lane. The answer to the bay versus lane question is really dependent upon how one defines each of these treatments. For purposes of the presentation in these figures, a bay has been considered to be a geometric treatment having an entrance less than 100 feet from the intersection stopline. This definition means

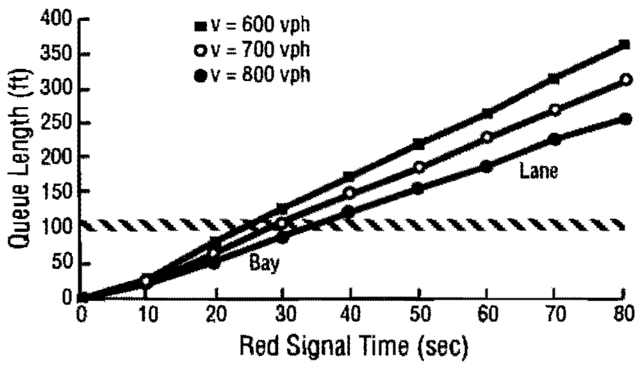

Fig 5-9. Decision chart for turn bays versus lanes (high volumes, 600-800 vph/lane).

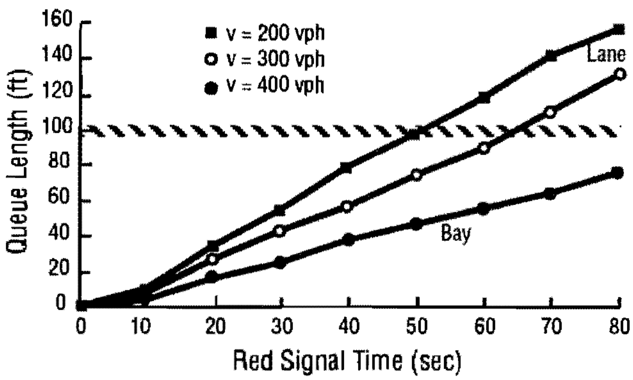

Fig 5-10. Decision chart for bays versus lanes (low volumes, 200-400 vph/lane).

that a treatment consisting of a short (less than 100 feet) deceleration and storage lane in the vicinity of the intersection would be termed a bay. Although the bay versus lane terminology may not be significant, as a practical matter, if the nose of the right-turn feature must be more than approximately 100 feet from the intersection stopline, it must include a significant length of parallel lane. The 100-foot distance has been used in Figs 5-9 and 5-10 as a more or less arbitrary definition of the difference between a right-turn bay and a lane.

SUMMARY

Analyses presented in this chapter have approached two rather different problems which are both related to right-turn operations through at-grade intersections.

(1) Equivalence relationships have been developed for converting magnitudes of measured right-turn flows into equivalent straight-through flows. The relationships are based on the relative maximum flow rates of straight and right-turn movements through stop controlled approaches under 2-way and all-way traffic control and 4 X 2 and 4 X 4 intersection lane configurations. The relationships are intended for use in pre-signalization warrant analyses, although they may be used in a variety of other ways.

(2) Design guidelines have been provided for determining the required lengths of right-turn bays or lanes. These guidelines have been developed for use at signalized intersections where per lane through traffic volumes range from 200 to 800 vehicles per hour.

CHAPTER 6. SUMMARY AND CONCLUSION

In the study of left-turn lanes, the starting assumption was that a dedicated left-turn phase and lane are warranted. Based on this assumption, the primary objective was to determine the number and length of left-turn lanes required at urban intersections.

It was found that the variables which have the greatest impact on the performance of a left-turn operation are: traffic volume, signal timing, and intersection geometry. Because one of the goals was to determine the optimum storage length, intersection geometry was held constant. The signal timing encompassed two variables that significantly affected left-turn performance; they were cycle length and left-turn red time. The left-turning volume obviously has a direct influence on a left-turn operation, but in some instances it was found that the through-traffic volume also affected the left-turning movement. Cross-street traffic was excluded from the left-turn analysis due to its minor impact on this movement. The three variables which have the greatest impact on a left-turn operation are: left-turn volume, left-turn red time, and cycle length. These are the primary input variables that are used in the Left-Turning Movement Analysis Program (LTMAP) outlined in Chapter 4.

The impact of the above-mentioned variables on single left-turn movements is discussed in Chapter 2. Pertinent performance measures and corresponding warrants are identified. A method for using results from selected TEXAS Model simulation runs to determine maximum and average queue lengths is described.

Chapter 3 addresses dual left-turn lane geometry. Of the three primary performance measures presented in Chapter 2 (cycle-failure, demand-capacity, and delay-based warrants), only the demand-capacity warrant needed to be revised in order to be used for dual left-turn evaluation. The primary reason for this revision was that the dual-lane left-turn saturation flow, on a per-lane basis, was found to be 90 percent of the through-traffic saturation flow, while the single-lane left-turn value is 95 percent of the through-traffic saturation flow.

The microcomputer program called LTMAP that is presented in Chapter 4 is intended to aid engineers in designing and evaluating left-turning movements at urban intersections. This program incorporates many of the analysis considerations described in Chapters 2 and 3. The warrants, or "suggested upper limits," that are presented in LTMAP allow the engineer/user to develop a feeling for how close the defined intersection left-turn operation is to reaching a critical level. These warrants are intended to be used as general guidelines and not as rigid, inflexible upper bounds.

The appendices at the end of this report include all the data that were obtained from the TEXAS Model simulation runs as well as a hard-copy listing of the computer code for the Left-Turning Movement Analysis Program (LTMAP).

Chapter 5 addresses two issues related to right-turn auxiliary lanes. Equivalence factors which may be used for converting observed right-turn flows into equivalent straight-through flows when interpreting warrants for traffic signalization are presented in a graphical form. Also, guidelines for determining the required length of a right-turn bay or lane at a signalized intersection are presented. These tools provide the engineer with means for evaluating the effectiveness of existing or proposed right-turn bays under various traffic and traffic-control conditions.

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APPENDIX A. CONGRESS AVENUE AND RIVERSIDE DRIVE, AUSTIN, TEXAS, WEDNESDAY, AUGUST 5, 1987

TRAFFIC COUNT DATA

Location: Congress Ave and Riverside Drive
Start Time: T 6:58 am

Counted by: Chris Marcus and Allen Hoffman
Interval Length: 5 min

		Northbound			Southbound			Eastbound			Westbound		
Int. #	Time	Left	Thru	Right	Left	Thru	Right	Left	Thru	Right	Left	Thru	Right
1	7:03	9	31	4	8	15	0	3	10	4	4	28	3
2	7:08	11	41	7	7	24	2	1	23	2	1	28	3
3	7:13	7	47	4	3	14	2	1	23	6	3	29	8
4	7:18	6	45	8	7	12	2	3	34	6	10	39	10
5	7:23	14	61	8	5	9	1	5	40	3	9	38	8
6	7:28	16	56	6	10	24	1	2	31	10	5	49	9
7	7:33	15	58	7	10	18	0	2	49	8	6	66	17
8	7:38	24	91	8	7	11	4	4	27	3	4	52	9
9	7:43	23	96	7	10	29	1	4	30	6	3	65	20
10	7:48	31	67	14	9	21	3	5	38	6	7	76	9
11	7:53	27	89	11	4	27	9	8	41	9	8	61	14
12	7:58	17	78	11	10	37	1	3	44	23	7	55	12
13	8:03	13	66	2	12	27	2	4	40	12	8	72	11
						Hourly Totals							
12	7:58	200	760	95	90	241	26	41	390	86	67	586	122
13	8:03	204	795	93	94	253	28	42	420	94	71	630	130

TRAFFIC COUNT DATA (CONTINUED)

Hourly Traffic Volumes

		Total Hourly Volume by Leg				% Traffic from Specified Leg: NB Leg to			SB Leg to			EB Leg to			WB Leg to		
Int	Time	NB	SB	EB	WB	SB	EB	WB	NB	EB	WB	NB	EB	WB	NB	EB	WB
12	7:58	1055	357	517	775	72	19	9	68	7	25	17	8	75	9	16	76
13	8:03	1092	375	556	831	73	19	9	67	7	25	17	8	76	9	16	76

15 Minute Traffic Volumes

		Total Hourly Volume by Leg				% Traffic from Specified Leg: NB Leg to			SB Leg to			EB Leg to			WB Leg to		
Int	Time	NB	SB	EB	WB	SB	EB	WB	NB	EB	WB	NB	EB	WB	NB	EB	WB
3	7:13	161	75	73	107	74	17	9	71	5	24	16	7	77	7	13	79
4	7:18	176	73	99	131	76	14	11	68	8	23	14	5	81	11	16	73
5	7:23	200	55	121	154	77	14	10	64	9	27	12	7	80	14	17	69
6	7:28	220	71	134	177	74	16	10	63	6	31	14	7	78	14	15	71
7	7:33	241	78	150	207	73	19	9	65	3	32	14	6	80	10	16	74
8	7:38	281	85	136	217	73	20	7	62	6	32	15	6	79	7	16	77
9	7:43	329	90	133	242	74	19	7	64	6	30	13	8	80	5	19	76
10	7:48	361	95	123	245	70	22	8	64	8	27	12	11	77	6	16	79
11	7:53	365	113	147	263	69	22	9	68	12	20	14	12	74	7	16	77
12	7:58	345	121	177	249	68	22	10	70	11	19	21	9	69	9	14	77
13	8:03	314	129	184	248	74	18	8	71	9	20	24	8	68	9	15	76

TRAFFIC COUNT DATA (CONTINUED)

15 min Totals

		Northbound			Southbound			Eastbound			Westbound		
Int. #	Time	Left	Thru	Right	Left	Thru	Right	Left	Thru	Right	Left	Thru	Right
3	7:13	27	119	15	18	53	4	5	56	12	8	85	14
4	7:18	24	133	19	17	50	6	5	80	14	14	96	21
5	7:23	27	153	20	15	35	5	9	97	15	22	106	26
6	7:28	36	162	22	22	45	4	10	105	19	24	126	27
7	7:33	45	175	21	25	51	2	9	120	21	20	153	34
8	7:38	55	205	21	27	53	5	8	107	21	15	167	35
9	7:43	62	245	22	27	58	5	10	106	17	13	183	46
10	7:48	78	254	29	26	61	8	13	95	15	14	193	38
11	7:53	81	252	32	23	77	13	17	109	21	18	202	43
12	7:58	75	234	36	23	85	13	16	123	38	22	192	35
13	8:03	57	233	24	26	91	12	15	125	44	23	188	37

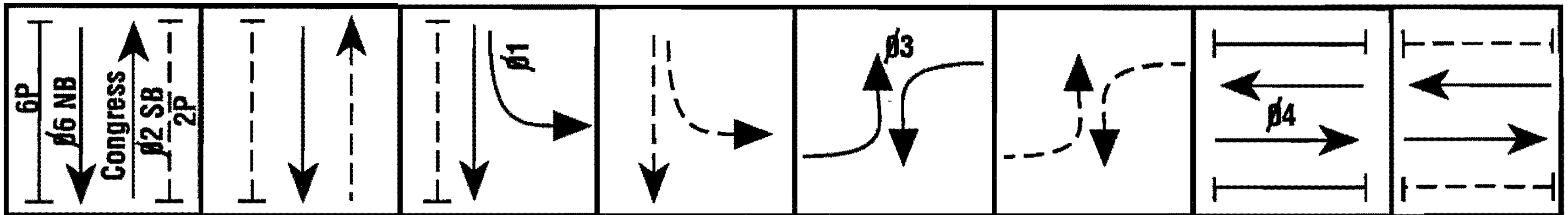
Total Volume (15 min intervals)

Int #	Total
3	416
4	479
5	530
6	602
7	676
8	719
9	794
10	824
11	888
12	892
13	875

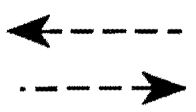
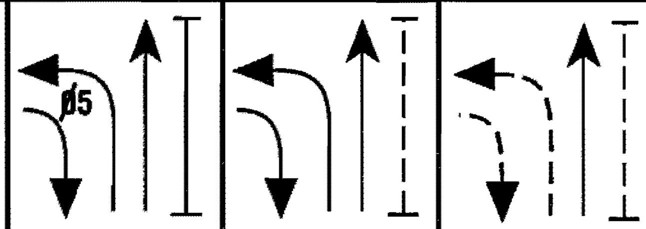
Total Hourly Volume

Int #	Total
12	2,704
13	2,854

APPENDIX B. CONGRESS AVENUE AND RIVERSIDE DRIVE SIGNAL TIMING SHEET



PL 1 9	4	8	4	5	4	4	21
PL 2 11		9		8			
PL 3 15		11		9			
PL 4							

	ALL RED	 ø5			*Actuated* – !!* →	w/other intersections along Congress Pretired w/i Itself	
PL 1 4	1	5	6	4			
PL 2			10				
PL 3			3				
PL 4							

CYCLE LENGTHS		OFF 1	OFF 2	OFF 3	OFF 4
PLAN 1	80	30			
PLAN 2	90		2		
PLAN 3	90			21	
PLAN 4					

MASTER: CONGRESS & 1st STREET
COMPUTOR SYNC:

START-UP PHASES:	2,6	1,3,4,5
START-UP COLORS:	GREEN	RED

TIME OF DAY OPERATION:			DAYS OMITTED
FLASH:	01:00	06:00	
PLAN 1			
PLAN 2	07:00	08:30	SAT, SUN
PLAN 3	16:30	18:30	SAT, SUN
PLAN 4			

FLASH: ALL	FLASH: ALL
UCF: RED	MAN/CONF.: RED
SYSTEM NAME:	INTERSECTION ID #: 24 SHEET: 1 OF 2
INTERSECTION: CONGRESS & RIVERSIDE	DATE: 7/15/87

APPENDIX C. TEXAS MODEL SIMULATION RESULTS FOR SINGLE AND DUAL LEFT-TURN LANES

		Single Left-Turn					
		Cycle Length 60 sec					
		LT Red 30 sec			LT Red 40 sec		
LT Volume (vph)		Avg Queue Del (sec)	Avg Queue (veh)	Max Queue (veh)	Avg Queue Del (sec)	Avg Queue (veh)	Max Queue (veh)
200	Run 1	21.2	0.7	5	28.3	1.3	7
	Run 2	18.7	0.6	5	25.3	1.2	6
	Run 3	17.4	0.6	4	24.3	1.1	6
	Run 4	17.7	0.5	4	27.2	1.3	7
	Average	18.75	0.60	4.50	26.28	1.23	6.50
300	Run 1	17.3	0.8	5	27.9	1.9	7
	Run 2	18.7	0.9	4	32.8	2.7	10
	Run 3	20.4	1.2	8	41.1	3.4	11
	Run 4	19.1	0.9	5	40	3.2	10
	Average	18.88	0.95	5.50	35.45	2.80	9.50
400	Run 1	21.8	1.7	8	196.1	20.2	30
	Run 2	20.4	1.5	6	147.7	16.7	28
	Run 3	20	1.4	7	103.4	12	25
	Run 4	20.2	1.3	6	169	18.3	27
	Average	20.60	1.48	6.75	154.05	16.80	27.50
500	Run 1	23.4	2.5	9	210.8	23.5	30
	Run 2	28	3.1	12	211.1	23.8	30
	Run 3	37.9	4.9	14	237.2	25.6	33
	Run 4	20.9	1.7	7	171.5	19.3	31
	Average	27.55	3.05	10.50	207.65	23.05	31.00
600	Run 1	77.7	12.1	22	249.9	28.1	36
	Run 2	45.1	7.2	21	252.7	28.9	38
	Run 3	64.6	10.7	21	260.3	28.8	34
	Run 4	97.5	15.6	26	278.4	30.6	37
	Average	71.23	11.40	22.50	260.33	29.10	36.25
700	Run 1	112.3	18.3	27	286.6	30.9	36
	Run 2	99.1	16.5	27	289.7	31.6	37
	Run 3	107.5	17.5	29	276.8	30.3	37
	Run 4	104.7	16.8	26	276.3	30.3	36
	Average	105.90	17.28	27.25	282.35	30.78	36.50
800	Run 1	116.2	19.2	27	289	31.3	36
	Run 2	118.9	19.8	29	275	30.3	35
	Run 3	125.5	20	27	292	32.1	37
	Run 4	113.9	18.6	27	296	34.5	39
	Average	118.63	19.40	27.50	288.00	32.05	36.75

		Single Left-Turn					
		Cycle Length 80 sec					
		LT Red 40 sec			LT Red 50 sec		
LT Volume (vph)		Avg Queue Del (sec)	Avg Queue (veh)	Max Queue (veh)	Avg Queue Del (sec)	Avg Queue (veh)	Max Queue (veh)
200	Run 1	21.9	0.8	5	26.3	1.1	6
	Run 2	20.8	0.6	4	26.8	1	6
	Run 3	24	0.7	6	29.1	1.1	6
	Run 4	24.7	0.7	5	30.4	1.2	6
	Average	22.85	0.70	5.00	28.15	1.10	6.00
300	Run 1	26	1.2	6	31	1.8	8
	Run 2	25.2	1.3	7	33.1	2.3	9
	Run 3	23.7	1.2	7	34.5	2.5	10
	Run 4	24.5	0.8	5	32.5	2.2	8
	Average	24.85	1.13	6.25	32.78	2.20	8.75
400	Run 1	27.5	2.1	10	96.6	11.3	22
	Run 2	26.2	2	10	61.3	6.8	17
	Run 3	26.2	1.8	8	45.8	4.9	14
	Run 4	26.8	1.9	8	50.8	5.1	17
	Average	26.68	1.95	9.00	63.63	7.03	17.50
500	Run 1	28.5	2.7	10	141.3	17.7	26
	Run 2	34.5	4.1	15	153	19.1	28
	Run 3	42.8	5.4	17	155.1	19	27
	Run 4	25.7	2.1	9	76.1	9.7	19
	Average	32.88	3.58	12.75	131.38	16.38	25.00
600	Run 1	67.9	10.7	25	181.2	22.7	31
	Run 2	54.2	8.3	21	196.2	24.5	33
	Run 3	64.3	10.8	22	192	24.1	31
	Run 4	97.9	16.2	25	201.3	25.7	35
	Average	71.08	11.50	23.25	192.68	24.25	32.50
700	Run 1	119.3	19.2	28	219.3	27	32
	Run 2	94.7	15.9	26	206.9	26.1	34
	Run 3	98	16.2	28	212.5	26.2	34
	Run 4	112.5	18.1	27	219.9	26.8	34
	Average	106.13	17.35	27.25	214.65	26.53	33.50
800	Run 1	121.4	19.9	29	222.3	27.1	34
	Run 2	120.6	19.7	29	220.6	27.6	35
	Run 3	124.6	20	29	229.4	27.6	34
	Run 4	121.1	20.3	31	234.6	28.1	34
	Average	121.93	19.98	29.50	226.73	27.60	34.25

Single Left-Turn				
		Cycle Length 80 sec		
		LT Red 60 sec		
LT Volume (vph)		Avg Queue Del (sec)	Avg Queue (veh)	Max Queue (veh)
200	Run 1	34.1	1.8	7
	Run 2	37.8	1.8	7
	Run 3	39	1.8	8
	Run 4	48.5	2.4	9
	Average	39.85	1.95	7.75
300	Run 1	75.5	6	16
	Run 2	159.1	14.2	25
	Run 3	152.9	14.7	30
	Run 4	194.4	16.6	31
	Average	145.48	12.88	25.50
400	Run 1	369	32.2	41
	Run 2	323.6	29.3	40
	Run 3	334.1	29.5	41
	Run 4	366	32	38
	Average	348.18	30.75	40.00
500	Run 1	389.3	34.1	42
	Run 2	390.5	33.9	42
	Run 3	394.4	34.2	41
	Run 4	333.5	30.1	40
	Average	376.93	33.08	41.25
600	Run 1	408	36.1	43
	Run 2	417.1	37.1	43
	Run 3	433	37.6	45
	Run 4	428.6	37.6	44
	Average	421.68	37.10	43.75
700	Run 1	452.2	38.8	44
	Run 2	442.7	38.4	43
	Run 3	441.1	37.8	43
	Run 4	443.1	38.5	44
	Average	444.78	38.38	43.50
800	Run 1	444.9	37.7	43
	Run 2	444.7	37.7	42
	Run 3	466.1	38	43
	Run 4	444.5	37.6	42
	Average	450.05	37.75	42.50

		Single Left-Turn					
		Cycle Length 100 sec					
		LT Red 40 sec			LT Red 50 sec		
LT Volume (vph)		Avg Queue Del (sec)	Avg Queue (veh)	Max Queue (veh)	Avg Queue Del (sec)	Avg Queue (veh)	Max Queue (veh)
200	Run 1	25.1	0.9	6	29.5	0.9	6
	Run 2	22.7	0.6	5	28.2	1	6
	Run 3	23.4	0.5	3	29.8	0.9	4
	Run 4	21	0.6	5	24.2	0.8	6
	Average	23.05	0.65	4.75	27.93	0.90	5.50
300	Run 1	24.7	1	6	29.9	1.2	6
	Run 2	26.3	1.7	8	31.3	1.5	7
	Run 3	25.7	1.2	7	28.7	1.6	8
	Run 4	25.1	1.1	6	29.9	1.4	7
	Average	25.45	1.25	6.75	29.95	1.43	7.00
400	Run 1	23.4	1.4	8	31.6	2.6	10
	Run 2	25.8	2.8	7	31.5	2.5	12
	Run 3	26.4	1.1	7	31.9	2.2	10
	Run 4	24.5	1.8	7	31.1	2.1	9
	Average	25.03	1.77	7.25	31.53	2.35	10.25
500	Run 1	25.8	1.6	8	34.9	3.4	13
	Run 2	25.4	1.8	8	34.2	3.7	11
	Run 3	27.2	1.9	8	39.4	4.5	16
	Run 4	26.2	1.7	9	32.8	2.8	10
	Average	26.15	1.75	8.25	35.33	3.60	12.50
600	Run 1	30	3.4	12	71.6	11.1	22
	Run 2	26.6	2.5	10	56.7	9	23
	Run 3	26.9	2.3	10	56.5	9.7	22
	Run 4	47.3	6.4	18	96.2	16.1	27
	Average	32.70	3.65	12.50	70.25	11.48	23.50
700	Run 1	52.2	9.9	22	116.8	18.9	30
	Run 2	32.5	5	18	101.2	17.1	28
	Run 3	40.5	6.7	19	104.3	17.2	29
	Run 4	59.8	11.1	24	108.8	17.6	28
	Average	46.25	8.18	20.75	107.78	17.70	28.75
800	Run 1	78.2	14.9	27	121.6	19.8	30
	Run 2	58.8	11.3	22	126.3	20.2	31
	Run 3	62.2	12.1	24	119	19.5	29
	Run 4	63.8	12.4	25	119.2	19.9	31
	Average	65.75	12.68	24.50	121.53	19.85	30.25

		Single Left-Turn					
		Cycle Length 100 sec					
		LT Red 60 sec			LT Red 70 sec		
LT Volume (vph)		Avg Queue Del (sec)	Avg Queue (veh)	Max Queue (veh)	Avg Queue Del (sec)	Avg Queue (veh)	Max Queue (veh)
200	Run 1	33.1	1.3	6	40.2	2	8
	Run 2	31.8	1.3	7	37.4	1.7	8
	Run 3	35.8	1.2	6	40.8	1.6	7
	Run 4	30	1.1	7	36.5	1.6	8
	Average	32.68	1.23	6.50	38.73	1.73	7.75
300	Run 1	36.5	1.8	8	47.8	3.3	9
	Run 2	38.8	2.5	9	53.3	4.4	11
	Run 3	34.9	2.4	8	66.6	5.7	15
	Run 4	36.5	2.1	9	60.6	4.7	16
	Average	36.68	2.20	8.50	57.08	4.53	12.75
400	Run 1	85.8	9.6	20	210.3	21.7	32
	Run 2	44	4.5	15	188.8	20.4	33
	Run 3	39.2	3.4	10	190.1	20.4	35
	Run 4	42	3.8	15	234	24.2	32
	Average	52.75	5.33	15.00	205.80	21.68	33.00
500	Run 1	105.8	14.1	27	255.3	27	34
	Run 2	108.7	14.9	27	243.5	26.2	38
	Run 3	127	16.7	25	269.2	27.7	38
	Run 4	50.2	6.1	14	238.2	25	36
	Average	97.93	12.95	23.25	251.55	26.48	36.50
600	Run 1	157.1	21.5	33	307.8	31.9	39
	Run 2	163.2	22.3	31	298.6	31.4	40
	Run 3	165.7	22.3	31	314.7	32.4	39
	Run 4	177.6	24	33	311.7	32.9	40
	Average	165.90	22.53	32.00	308.20	32.15	39.50
700	Run 1	193	25.6	33	320	32.8	40
	Run 2	174.2	24.2	32	324	33.5	40
	Run 3	178.5	23.9	33	309.9	32.3	39
	Run 4	185.3	24.7	34	323.5	33.3	41
	Average	182.75	24.60	33.00	319.35	32.98	40.00
800	Run 1	193.5	25.6	34	331.2	33.6	40
	Run 2	185.6	25.1	32	332.9	33.9	40
	Run 3	187.9	25.1	33	317.8	33	39
	Run 4	197.9	26	33	333.3	33.5	39
	Average	191.23	25.45	33.00	328.80	33.50	39.50

Single Left-Turn				
		Cycle Length 100 sec		
		LT Red 80 sec		
LT Volume (vph)		Avg Queue Del (sec)	Avg Queue (veh)	Max Queue (veh)
200	Run 1	64.9	3.8	10
	Run 2	57.7	3.2	9
	Run 3	67.9	3.5	9
	Run 4	75.9	4	13
	Average	66.60	3.63	10.25
300	Run 1	192.7	15.8	37
	Run 2	377.6	29.6	41
	Run 3	335.3	27.2	42
	Run 4	397.2	29.5	41
	Average	325.70	25.53	40.25
400	Run 1	461.8	36.3	43
	Run 2	435.8	35.1	44
	Run 3	489.4	36.6	44
	Run 4	519.5	37.9	43
	Average	476.63	36.48	43.50
500	Run 1	495.8	38.1	43
	Run 2	525.3	38.8	45
	Run 3	512.5	38.5	45
	Run 4	458.1	35.8	45
	Average	497.93	37.80	44.50
600	Run 1	544.1	39.8	44
	Run 2	518.4	39.5	46
	Run 3	555.7	40.6	45
	Run 4	534.9	40.4	47
	Average	538.28	40.08	45.50
700	Run 1	561	40.4	46
	Run 2	545.3	40.3	44
	Run 3	555.2	40.5	46
	Run 4	566.5	41.1	46
	Average	557.00	40.58	45.50
800	Run 1	582.7	40.6	44
	Run 2	559.9	40.8	47
	Run 3	555.8	39.9	44
	Run 4	553.2	40	44
	Average	562.90	40.33	44.75

		Single Left-Turn					
		Cycle Length 120 sec					
		LT Red 50 sec			LT Red 60 sec		
LT Volume (vph)		Avg Queue Del (sec)	Avg Queue (veh)	Max Queue (veh)	Avg Queue Del (sec)	Avg Queue (veh)	Max Queue (veh)
200	Run 1	29.8	0.8	6	33.5	1	6
	Run 2	30.3	0.8	6	38.2	1.3	8
	Run 3	27.8	0.7	5	32.9	0.9	6
	Run 4	30.4	0.7	5	34.9	1	7
	Average	29.58	0.75	5.50	34.88	1.05	6.75
300	Run 1	28.7	1.1	7	32.5	1.5	8
	Run 2	31.2	1.2	7	38.4	1.9	9
	Run 3	29.3	1.3	7	37	2	8
	Run 4	29.6	1.3	7	37.1	2	8
	Average	29.70	1.23	7.00	36.25	1.85	8.25
400	Run 1	32.3	1.9	10	38	2.9	11
	Run 2	30.3	1.8	9	36.4	2.8	11
	Run 3	31.6	1.8	8	37	2.6	9
	Run 4	32.3	1.7	8	38.1	2.6	10
	Average	31.63	1.80	8.75	37.38	2.73	10.25
500	Run 1	31.8	2.2	10	39.2	3.8	14
	Run 2	31.3	2.3	10	40.7	4	15
	Run 3	33.5	2.8	11	49.6	6.2	16
	Run 4	30.7	1.8	9	36.7	2.8	9
	Average	31.83	2.28	10.00	41.55	4.20	13.50
600	Run 1	37.8	4.4	14	85	13.1	25
	Run 2	33.6	3.9	13	55.8	8.1	22
	Run 3	33.2	3.1	12	61.2	10.1	23
	Run 4	48.5	7.6	23	99.3	16.1	28
	Average	38.28	4.75	15.50	75.33	11.85	24.50
700	Run 1	67.2	12.6	24	124.9	20.4	32
	Run 2	42.8	6.6	22	104.6	17.2	28
	Run 3	52.8	9.3	21	106.3	17.3	30
	Run 4	63.5	11.5	24	114.9	18.6	30
	Average	56.58	10.00	22.75	112.68	18.38	30.00
800	Run 1	75.4	13.9	28	124.9	20.1	30
	Run 2	71.6	13.4	27	133	21.4	32
	Run 3	79.3	14.7	28	123.5	20.1	32
	Run 4	77.5	14.5	29	120.7	20	31
	Average	75.95	14.13	28.00	125.53	20.40	31.25

		Single Left-Turn					
		Cycle Length 120 sec					
		LT Red 70 sec			LT Red 80 sec		
LT Volume (vph)		Avg Queue Del (sec)	Avg Queue (veh)	Max Queue (veh)	Avg Queue Del (sec)	Avg Queue (veh)	Max Queue (veh)
200	Run 1	37.2	1.2	6	45.1	1.7	7
	Run 2	41	1.5	9	45.8	2	10
	Run 3	39.1	1.4	6	46.3	1.9	7
	Run 4	41	1.4	8	46.4	1.8	9
	Average	39.58	1.38	7.25	45.90	1.85	8.25
300	Run 1	42.8	2.4	9	47	3.1	10
	Run 2	43.8	2.5	11	53.5	4	13
	Run 3	43.4	2.7	10	53.1	4.1	12
	Run 4	41.9	2.6	10	48.7	3.5	12
	Average	42.98	2.55	10.00	50.58	3.68	11.75
400	Run 1	68	7.6	18	184.6	19.8	32
	Run 2	43.6	4	13	127.1	14.2	24
	Run 3	44.9	3.9	13	88.6	9.8	24
	Run 4	46	3.9	12	148.1	16.2	26
	Average	50.63	4.85	14.00	137.10	15.00	26.50
500	Run 1	99.6	13.3	26	214.9	24.1	33
	Run 2	102.9	14.1	24	203.6	23	33
	Run 3	115.7	15.6	27	220.3	24.4	35
	Run 4	75.2	9.3	21	156.2	18.1	31
	Average	98.35	13.08	24.50	198.75	22.40	33.00
600	Run 1	150.4	20.8	32	252.6	28.2	38
	Run 2	151	21.1	35	247.9	28.5	39
	Run 3	151.8	21.2	29	251	28.3	37
	Run 4	166.2	23	34	263.9	29.5	38
	Average	154.85	21.53	32.50	253.85	28.63	38.00
700	Run 1	181.8	24.6	34	272	30.1	38
	Run 2	166.6	23.5	33	261	29.8	37
	Run 3	173.9	23.9	33	262.2	29.4	37
	Run 4	176.5	24.1	34	276.3	30.8	39
	Average	174.70	24.03	33.50	267.88	30.03	37.75
800	Run 1	187.2	25.4	35	267.5	30.1	37
	Run 2	180.8	24.8	33	278.4	30.9	37
	Run 3	190.2	25.8	33	291.4	31.2	37
	Run 4	181.5	24.8	32	272.1	30.7	39
	Average	184.93	25.20	33.25	277.35	30.73	37.50

		Single Left-Turn		
		Cycle Length 120 sec		
		LT Red 90 sec		
LT Volume (vph)		Avg Queue Del (sec)	Avg Queue (veh)	Max Queue (veh)
200	Run 1	55.4	2.6	9
	Run 2	54.3	2.6	10
	Run 3	51.9	2.3	7
	Run 4	57.1	2.7	10
	Average	54.68	2.55	9.00
300	Run 1	67.9	5.2	16
	Run 2	175.8	15.4	25
	Run 3	164.6	15	31
	Run 4	176.7	14.9	29
	Average	146.25	12.63	25.25
400	Run 1	333.2	29.9	40
	Run 2	295.7	28	41
	Run 3	340.6	29.7	41
	Run 4	355.6	31.4	39
	Average	331.28	29.75	40.25
500	Run 1	378.9	33.2	41
	Run 2	378.4	33.1	42
	Run 3	385.8	33.3	42
	Run 4	356.1	31.3	40
	Average	374.80	32.73	41.25
600	Run 1	400	35.3	43
	Run 2	396	36	45
	Run 3	413.8	36.3	43
	Run 4	412.3	36.4	43
	Average	405.53	36.00	43.50
700	Run 1	427.5	37	43
	Run 2	426.9	37.5	43
	Run 3	437.6	37.1	43
	Run 4	436.8	37.7	44
	Average	432.20	37.33	43.25
800	Run 1	431.7	37	43
	Run 2	440.7	37.4	42
	Run 3	437.2	37.9	43
	Run 4	443.5	38.1	44
	Average	438.28	37.60	43.00

		Single Left-Turn					
		Cycle Length 60 sec					
		LT Red 30 sec			LT Red 40 sec		
LT Volume (vph)		Avg Queue Del (sec)	Avg Queue (veh)	Max Queue (veh)	Avg Queue Del (sec)	Avg Queue (veh)	Max Queue (veh)
200	Run 1	16.6	0.5	3	23.7	1	5
	Run 2	18.5	0.7	4	25.8	1.3	6
	Run 3	16.1	0.5	4	20.9	0.8	4
	Run 4	18	0.6	4	24.7	1.1	5
	Average	17.30	0.58	3.75	23.78	1.05	5.00
300	Run 1	17.9	0.8	4	25.3	1.6	6
	Run 2	18.1	0.9	4	27.2	1.9	6
	Run 3	18.5	1	5	31	2.7	7
	Run 4	18	0.8	4	27.7	2.1	6
	Average	18.13	0.88	4.25	27.80	2.08	6.25
400	Run 1	19.7	1.4	7	190	21.6	35
	Run 2	18.9	1.4	5	201.7	22.7	38
	Run 3	20.2	1.5	6	154	18	35
	Run 4	18.9	1.3	5	137.6	15.6	35
	Average	19.43	1.40	5.75	170.83	19.48	35.75
500	Run 1	21.6	2.1	6	256.5	28.6	38
	Run 2	22.7	2.4	8	282.6	31.4	39
	Run 3	22.4	2.5	7	274.4	30.6	37
	Run 4	24.2	3.1	8	278	30.9	38
	Average	22.73	2.53	7.25	272.88	30.38	38.00
600	Run 1	85.7	14.2	28	308.8	33.6	39
	Run 2	105.3	16.6	27	308.6	32.8	39
	Run 3	87.9	14.5	25	306.2	33.6	38
	Run 4	90.9	14.7	27	286.3	31.9	39
	Average	92.45	15.00	26.75	302.48	32.98	38.75
700	Run 1	134.4	21.1	28	323.7	34.7	39
	Run 2	128	20.9	28	312.5	34.5	39
	Run 3	130	20.8	28	319.9	34.1	38
	Run 4	127.9	20.1	28	320.9	34.5	39
	Average	130.08	20.73	28.00	319.25	34.45	38.75
800	Run 1	149.4	23.7	28	321.9	35.5	39
	Run 2	143.4	22.4	28	323.7	34.6	39
	Run 3	140.9	22.1	28	324.1	34.4	40
	Run 4	143	22.4	28	322.3	34.9	39
	Average	144.18	22.65	28.00	323.00	34.85	39.25

LT Volume (vph)		Dual Left-Turn, Cycle Length 80 sec, LT Red 40 sec: Avg Queue Del (sec)	Avg Queue (veh)	Max Queue (veh)	LT Red 50 sec: Avg Queue Del (sec)	Avg Queue (veh)	Max Queue (veh)
200	Run 1	23.9	0.7	4	30.4	1.2	5
	Run 2	24.4	0.9	5	29.8	1.3	6
	Run 3	22.4	0.6	4	29	1	5
	Run 4	22.9	0.8	4	28.9	1.2	5
	Average	23.40	0.75	4.25	29.53	1.18	5.25
300	Run 1	23.6	1	5	30	1.7	5
	Run 2	23.7	1.1	5	30.8	2	7
	Run 3	25.1	1.4	6	31.8	2.4	7
	Run 4	23.7	1.2	5	30.4	1.9	7
	Average	24.03	1.18	5.25	30.75	2.00	6.50
400	Run 1	24.6	1.7	6	45.8	5.4	12
	Run 2	25.5	1.8	6	60.2	7.3	15
	Run 3	25.9	1.8	7	61.2	6.8	13
	Run 4	24.7	1.7	6	44.4	4.6	11
	Average	25.18	1.75	6.25	52.90	6.03	12.75
500	Run 1	26.6	2.4	8	174.3	21.7	34
	Run 2	27.9	2.6	8	198.7	25	34
	Run 3	27.3	3	8	199.4	25.1	35
	Run 4	29.4	3.2	11	203.1	25.4	34
	Average	27.80	2.80	8.75	193.88	24.30	34.25
600	Run 1	81.1	13.3	27	229.9	28.7	35
	Run 2	104	16.5	28	237.5	28.7	35
	Run 3	89.4	14.7	27	237.5	29.1	35
	Run 4	93.6	15.1	26	229.1	28.6	35
	Average	92.03	14.90	27.00	233.50	28.78	35.00
700	Run 1	133.7	21.3	29	244.5	30.2	36
	Run 2	135.6	21.4	30	243.6	30.2	35
	Run 3	131.3	21.2	28	243.8	30.4	35
	Run 4	129.2	20.5	29	250.5	30.5	36
	Average	132.45	21.10	29.00	245.60	30.33	35.50
800	Run 1	148.3	23.6	29	255.5	31	36
	Run 2	148.7	23.4	29	249.7	30.8	36
	Run 3	138.1	22	29	254.2	30.9	36
	Run 4	145.4	23	29	256.4	31.8	37
	Average	145.13	23.00	29.00	253.95	31.13	36.25

		Dual Left-Turn		
		Cycle Length 80 sec		
		LT Red 60 sec		
LT Volume (vph)		Avg Queue Del (sec)	Avg Queue (veh)	Max Queue (veh)
200	Run 1	38.5	1.9	6
	Run 2	39.6	2.2	8
	Run 3	37.6	1.6	6
	Run 4	34.9	1.7	5
	Average	37.65	1.85	6.25
300	Run 1	108.6	8.5	14
	Run 2	183.2	15.2	25
	Run 3	228.4	21.6	34
	Run 4	204.6	16.9	27
	Average	181.20	15.55	25.00
400	Run 1	394.9	35.4	43
	Run 2	407.8	35.4	44
	Run 3	380.5	33.5	43
	Run 4	342.5	30.9	43
	Average	381.43	33.80	43.25
500	Run 1	419.3	36.2	44
	Run 2	450.9	38.2	44
	Run 3	449.6	38.2	43
	Run 4	447.2	38.4	44
	Average	441.75	37.75	43.75
600	Run 1	452.7	39.1	45
	Run 2	464.1	39	44
	Run 3	456.8	38.9	45
	Run 4	455.4	38.8	44
	Average	457.25	38.95	44.50
700	Run 1	471.7	39.9	44
	Run 2	469.2	40.2	45
	Run 3	476.9	39.7	44
	Run 4	470.3	39.2	43
	Average	472.03	39.75	44.00
800	Run 1	490.4	40	44
	Run 2	475.3	40.1	44
	Run 3	463.7	39.6	44
	Run 4	486.6	39.4	44
	Average	479.00	39.78	44.00

		Dual Left-Turn					
		Cycle Length 100 sec					
		LT Red 40 sec			LT Red 50 sec		
LT Volume (vph)		Avg Queue Del (sec)	Avg Queue (veh)	Max Queue (veh)	Avg Queue Del (sec)	Avg Queue (veh)	Max Queue (veh)
200	Run 1	23	0.6	4	29.4	0.9	6
	Run 2	23.3	0.6	5	29.3	1	5
	Run 3	22.6	0.5	4	27.5	0.7	5
	Run 4	23.9	0.6	4	29.5	0.8	5
	Average	23.20	0.58	4.25	28.93	0.85	5.25
300	Run 1	22.3	0.8	5	28.8	1.2	6
	Run 2	22.6	0.9	5	28.9	1.4	6
	Run 3	24.8	1	6	30.3	1.6	7
	Run 4	23.8	0.9	5	30	1.4	5
	Average	23.38	0.90	5.25	29.50	1.40	6.00
400	Run 1	24.6	1.3	6	30.7	2.2	8
	Run 2	24.6	1.4	6	30.3	2.2	8
	Run 3	24.4	1.3	6	31.3	2.1	8
	Run 4	25.5	1.3	7	31.2	2.1	8
	Average	24.78	1.33	6.25	30.88	2.15	8.00
500	Run 1	25.6	1.9	7	32.6	3	8
	Run 2	25	1.7	7	32.8	3.1	10
	Run 3	25	1.8	7	33.4	3.2	10
	Run 4	25.9	1.9	8	34.2	3.7	10
	Average	25.38	1.82	7.25	33.25	3.25	9.50
600	Run 1	28.3	2.8	10	94.3	15.7	29
	Run 2	28	2.6	9	108	17.2	29
	Run 3	27.6	2.6	9	98.5	15.9	28
	Run 4	27.7	2.6	9	92.8	15.3	28
	Average	27.90	2.65	9.25	98.40	16.03	28.50
700	Run 1	62.2	12	22	129.8	20.7	29
	Run 2	58.7	11.7	20	132	21.9	30
	Run 3	56.4	11.3	21	137	22.2	30
	Run 4	58.9	12.3	21	134.3	21.4	29
	Average	59.05	11.83	21.00	133.28	21.55	29.50
800	Run 1	77	15.1	25	149	23.8	31
	Run 2	68.4	14.3	26	144.9	23.4	31
	Run 3	70.5	14.5	24	142	23.1	30
	Run 4	72.7	14.6	25	145.1	23	30
	Average	72.15	14.63	25.00	145.25	23.33	30.50

		Dual Left-Turn					
		Cycle Length 100 sec					
		LT Red 60 sec			LT Red 70 sec		
LT Volume (vph)		Avg Queue Del (sec)	Avg Queue (veh)	Max Queue (veh)	Avg Queue Del (sec)	Avg Queue (veh)	Max Queue (veh)
200	Run 1	34.5	1.2	6	41.5	1.8	7
	Run 2	35.5	1.5	6	41.3	2	8
	Run 3	32.8	1	6	37.6	1.4	6
	Run 4	34.1	1.2	6	40.4	1.7	7
	Average	34.23	1.23	6.00	40.20	1.73	7.00
300	Run 1	34	1.8	6	40.7	2.6	8
	Run 2	33.1	1.9	7	49.8	3.8	10
	Run 3	36.8	2.4	9	60.6	5.6	12
	Run 4	36.4	2	7	46.3	3.4	11
	Average	35.08	2.03	7.25	49.35	3.85	10.25
400	Run 1	40.5	3.8	11	260.5	27.9	40
	Run 2	41.3	4.2	11	252.3	27.1	40
	Run 3	40.9	4	10	230.7	25.4	39
	Run 4	39.5	3.5	10	173.4	19.7	38
	Average	40.55	3.88	10.50	229.23	25.03	39.25
500	Run 1	116.9	16.2	31	306	32.5	40
	Run 2	154.7	21.1	34	323	33.8	42
	Run 3	156.8	21.5	34	315.5	33.2	40
	Run 4	172.4	23.2	34	322.2	33.8	41
	Average	150.20	20.50	33.25	316.68	33.33	40.75
600	Run 1	205.8	27.4	36	335.7	35.7	40
	Run 2	208.6	27.3	34	358	36	42
	Run 3	200.8	26.8	32	340	35.4	41
	Run 4	197.1	26.3	34	340.2	35.2	42
	Average	203.08	26.95	34.00	343.48	35.58	41.25
700	Run 1	221.1	29.2	34	356.3	36.5	43
	Run 2	218.5	28.5	35	343	35.6	42
	Run 3	219.2	28.7	34	351	36.1	41
	Run 4	215.9	28.1	34	360.2	36.6	42
	Average	218.68	28.63	34.25	352.63	36.20	42.00
800	Run 1	225.2	29.1	35	357.6	36.4	42
	Run 2	224.2	29.2	35	359.7	35.6	41
	Run 3	226.9	29.4	35	355.2	36.1	42
	Run 4	227.8	29.5	35	361.6	36.3	42
	Average	226.03	29.30	35.00	358.53	36.10	41.75

Single Left-Turn				
		Cycle Length 100 sec		
		LT Red 80 sec		
LT Volume (vph)		Avg Queue Del (sec)	Avg Queue (veh)	Max Queue (veh)
200	Run 1	54.1	2.9	7
	Run 2	110	6.7	13
	Run 3	61.1	2.7	10
	Run 4	55.5	3	8
	Average	70.18	3.83	9.50
300	Run 1	356.4	27.8	43
	Run 2	407.7	31.6	44
	Run 3	419.7	33.3	45
	Run 4	406.6	31.6	44
	Average	397.60	31.08	44.00
400	Run 1	526.2	38.8	47
	Run 2	519.7	38.8	45
	Run 3	502.3	37.1	45
	Run 4	478.1	36.5	46
	Average	506.58	37.80	45.75
500	Run 1	561.9	40.5	46
	Run 2	549.6	40.6	46
	Run 3	550.3	40.5	46
	Run 4	554.7	40.2	45
	Average	554.13	40.45	45.75
600	Run 1	580.9	41.4	45
	Run 2	582.3	41.2	46
	Run 3	579.3	40.8	45
	Run 4	564.6	41.1	45
	Average	576.78	41.13	45.25
700	Run 1	585.1	41.4	46
	Run 2	574.5	41.3	45
	Run 3	590.8	42	47
	Run 4	605.3	42.2	47
	Average	588.93	41.73	46.25
800	Run 1	597.9	41.1	46
	Run 2	598.6	41.7	46
	Run 3	600	41.3	45
	Run 4	608	41.8	45
	Average	601.13	41.48	45.50

		Dual Left-Turn					
		Cycle Length 120 sec					
		LT Red 50 sec			LT Red 60 sec		
LT Volume (vph)		Avg Queue Del (sec)	Avg Queue (veh)	Max Queue (veh)	Avg Queue Del (sec)	Avg Queue (veh)	Max Queue (veh)
200	Run 1	29.4	0.8	4	33.8	1	5
	Run 2	27.6	0.8	5	33.7	1.1	5
	Run 3	24.5	0.6	5	33	0.9	6
	Run 4	29.3	0.8	5	33.9	1	5
	Average	27.70	0.75	4.75	33.60	1.00	5.25
300	Run 1	29.7	1	6	35	1.4	8
	Run 2	30.8	1.2	6	35.9	1.7	7
	Run 3	29.1	1.3	7	35.1	1.9	8
	Run 4	29.1	1.1	6	34.4	1.5	7
	Average	29.68	1.15	6.25	35.10	1.63	7.50
400	Run 1	30.9	1.8	8	37.7	2.7	9
	Run 2	31.3	1.9	8	36.7	2.7	9
	Run 3	30.9	1.7	7	36.8	2.5	9
	Run 4	29.3	1.5	7	36.7	2.4	9
	Average	30.60	1.73	7.50	36.98	2.58	9.00
500	Run 1	31.4	2.2	8	38.2	3.7	10
	Run 2	31.9	2.2	8	39.5	3.7	10
	Run 3	31.8	2.4	8	38.8	3.5	12
	Run 4	31.4	2.6	9	41.6	4.9	14
	Average	31.63	2.35	8.25	39.53	3.95	11.50
600	Run 1	34.6	3.8	12	105.4	16.9	30
	Run 2	36.5	4.2	12	119.7	18.9	30
	Run 3	33.5	3.3	11	105.4	16.8	29
	Run 4	33.2	3.4	11	108.2	17.4	29
	Average	34.45	3.68	11.50	109.68	17.50	29.50
700	Run 1	77.9	14.6	23	143	22.5	31
	Run 2	79.3	14.6	24	138.1	21.7	31
	Run 3	82.6	15.6	25	139.4	21.9	30
	Run 4	73.9	13.3	25	142.2	22.5	31
	Average	78.43	14.53	24.25	140.68	22.15	30.75
800	Run 1	95.2	17.5	29	149.2	23.9	31
	Run 2	96.2	18	28	149.6	23.7	31
	Run 3	92.4	16.6	28	147.7	23.32	32
	Run 4	97.6	18	30	147.8	23.7	31
	Average	95.35	17.53	28.75	148.58	23.66	31.25

		Dual Left-Turn					
		Cycle Length 120 sec					
		LT Red 70 sec			LT Red 80 sec		
LT Volume (vph)		Avg Queue Del (sec)	Avg Queue (veh)	Max Queue (veh)	Avg Queue Del (sec)	Avg Queue (veh)	Max Queue (veh)
200	Run 1	39.7	1.4	5	43	1.7	7
	Run 2	39.6	1.4	7	46.8	2	9
	Run 3	37.4	1.2	6	41.7	1.5	7
	Run 4	40.9	1.5	7	46.5	2.1	7
	Average	39.40	1.38	6.25	44.50	1.83	7.50
300	Run 1	40.7	2.1	9	48	3	9
	Run 2	41.6	2.4	8	49.7	3.2	10
	Run 3	41.4	2.8	10	49.1	3.7	10
	Run 4	40.6	2.1	8	48	3	9
	Average	41.08	2.35	8.75	48.70	3.23	9.50
400	Run 1	43.7	3.9	12	170.3	19.4	35
	Run 2	44.5	4.1	12	193.6	21.6	36
	Run 3	43.8	3.7	11	142.6	16.1	32
	Run 4	44.1	3.8	10	136.7	14.5	29
	Average	44.03	3.88	11.25	160.80	17.90	33.00
500	Run 1	148	20	33	256.3	28.8	40
	Run 2	157.9	21.5	34	272.2	30	38
	Run 3	148	20	33	270.2	29.8	39
	Run 4	157.9	21.5	34	271.1	30.4	38
	Average	152.95	20.75	33.50	267.45	29.75	38.75
600	Run 1	193	25.7	34	291.4	32.4	40
	Run 2	194.5	25.9	34	293.2	32.2	39
	Run 3	193.7	26	34	299.3	32.8	39
	Run 4	189.6	25.4	34	284.9	32	38
	Average	192.70	25.75	34.00	292.20	32.35	39.00
700	Run 1	210.5	28.1	35	304.2	34	41
	Run 2	210.9	28.3	35	309.4	34.5	40
	Run 3	207.8	28	35	308.9	33.8	40
	Run 4	212.1	28	35	305.5	33.8	40
	Average	210.33	28.10	35.00	307.00	34.03	40.25
800	Run 1	214.1	28.6	35	312.9	34.4	40
	Run 2	216.3	29	35	307.8	34	40
	Run 3	210.2	28.1	35	309.7	33.6	40
	Run 4	212.8	28.6	35	316	34.8	40
	Average	213.35	28.58	35.00	311.60	34.20	40.00

Single Left-Turn				
		Cycle Length 120 sec		
		LT Red 90 sec		
LT Volume (vph)		Avg Queue Del (sec)	Avg Queue (veh)	Max Queue (veh)
200	Run 1	50	2.3	8
	Run 2	55.2	2.9	10
	Run 3	47	1.9	8
	Run 4	55.1	2.8	8
	Average	51.83	2.48	8.50
300	Run 1	84.9	6.5	13
	Run 2	161.3	13.1	21
	Run 3	233.6	21.2	42
	Run 4	155	12.8	20
	Average	158.70	13.40	24.00
400	Run 1	379.5	34.2	44
	Run 2	382.3	33.8	43
	Run 3	356.4	31.9	42
	Run 4	334.1	29.9	41
	Average	363.07	32.45	42.50
500	Run 1	419	36.9	45
	Run 2	435.8	37.5	44
	Run 3	415.6	37.3	44
	Run 4	437.6	37.6	44
	Average	427.00	37.33	44.25
600	Run 1	443.6	38.1	44
	Run 2	450.2	38.5	44
	Run 3	455.1	38.8	45
	Run 4	448.8	38.1	45
	Average	449.43	38.38	44.50
700	Run 1	452	38.8	45
	Run 2	462.3	39.3	45
	Run 3	459.2	38.6	44
	Run 4	449.1	39.1	45
	Average	455.65	38.95	44.75
800	Run 1	477.4	38.9	45
	Run 2	466.1	39.8	44
	Run 3	469.1	38.6	44
	Run 4	472.6	39.1	44
	Average	471.30	39.10	44.25

APPENDIX D. EXAMPLES OF TEXAS MODEL GEOMETRY, DRIVER-VEHICLE, AND SIMULATION INPUT FILES USED IN SINGLE AND DUAL LEFT-TURN LANE ANALYSES

```
         1         2         3         4         5         6         7
1234567890123456789012345678901234567890123456789012345678901234567890123456789
5X6 INTERSECTION, SINGLE LEFT, 2 THRU LANES      6D1L.300         REP01

IS TITLE TEXT OK ?
Y

PARAMETER-OPTION DATA:
F(1) - TOTAL NUMBER OF LEGS.  <3 TO 6> [4]
F(2) - SIMULATION TIME IN MINUTES.  [20]
F(3) - MINIMUM HEADWAY IN SECONDS.  <1.0 TO 3.0> [1.0]
F(4) - NUMBER OF VEHICLE CLASSES.  <12> [12]
F(5) - NUMBER OF DRIVER CLASSES.  <3> [3]
F(6) - PERCENT OF LEFT TURNING VEHICLES TO ENTER IN MEDIAN LANE.<50 TO 100>[80]
F(7) - PERCENT OF RIGHT TURNING VEHICLES TO ENTER IN CURB LANE. <50 TO 100>[80]
EDIT EXAMPLE: "F(2)=15" CHANGES FIELD 2 TO "15", OTHER FIELDS REMAIN UNCHANGED
KEYIN "HELP" FOR ADDITIONAL ASSISTANCE

  DATA FIELDS:      4   35  1.0   12    3   80   80
FIELD NUMBERS:    \.1/ \.2/ \.3/ \.4/ \.5/ \.6/ \.7/

IS PARAMETER-OPTION DATA OK ?
Y

CURB RETURN RADII:
EACH FIELD - CURB RETURN RADIUS BETWEEN OUTERMOST INBOUND LANE AND THE ADJACENT
             (COUNTERCLOCKWISE) LEG.  <INTEGER, 0 TO 200>  [20]

  DATA FIELDS:     20   20   20   20
FIELD NUMBERS:    \.1/ \.2/ \.3/ \.4/

ARE CURB RETURN RADII OK ?
```

Fig D-1. TEXAS model example geometry and driver vehicle input file used for single left-turn analysis.

```
Y

LEG 1 GEOMETRY DATA:
F(1) - LEG NUMBER.  WILL BE RESET TO THE NUMBER OF THE LEG BEING PROCESSED.
F(2) - LEG ANGLE.  POSITIVE IS CLOCKWISE FROM NORTH = 0 (ZERO) DEGREES.
       <0 TO 359, IN INCREASING ORDER>  [EQUAL ANGLES]
F(3) - LENGTH OF INBOUND LANES.  <400 TO 1000>  [800]
F(4) - LENGTH OF OUTBOUND LANES.  [250]  (SUGGEST 250 FOR LOW TRAFFIC VOLUME,
       400 FOR HIGH VOLUME. FOR EMISSIONS, MUST BE SAME AS INBOUND LANE LENGTH)
F(5) - NUMBER OF INBOUND LANES.  <0 TO 6>  [2]
F(6) - NUMBER OF OUTBOUND LANES.  <0 TO 6>  [2]
F(7) - SPEED LIMIT ON INBOUND LANES IN MPH.  <10 TO 80>  [30]
F(8) - SPEED LIMIT ON OUTBOUND LANES IN MPH.  <10 TO 80>  [30]
F(9) - LEG CENTERLINE OFFSET FROM INTERSECTION CENTER. POSITIVE IS TO THE RIGHT
       WHEN FACING IN DIRECTION OF INBOUND TRAFFIC.  <-200 TO 200>  [0]
F(10) - MEDIAN WIDTH, WILL BE CENTERED ON LEG CENTERLINE.  <0 TO 100>  [0]
F(11) - LIMITING ANGLE FOR STRAIGHT MOVEMENT.  <0 TO 45 DEGREES>  [20]
F(12) - LIMITING ANGLE FOR U-TURN.  <0 TO 45 DEGREES>  [10]

  DATA FIELDS:      1    0 1000  250    2    1   30   30  -24    0  20  10
FIELD NUMBERS:    \.1/ \.2/ \.3/ \.4/ \.5/ \.6/ \.7/ \.8/ \.9/ \10/ \11 \12

IS LEG 1 GEOMETRY DATA OK ?



F(12) - LIMITING ANGLE FOR U-TURN.  <0 TO 45 DEGREES>  [10]

  DATA FIELDS:      1    0 1000  250    2    1   30   30  -24    0  20  10
FIELD NUMBERS:    \.1/ \.2/ \.3/ \.4/ \.5/ \.6/ \.7/ \.8/ \.9/ \10/ \11 \12

IS LEG 1 GEOMETRY DATA OK ?
Y

F(1) - WIDTH OF LANE.  <8 TO 15>  [12]
F(2) - MOVEMENT CODE. ANY OF"U"(U-TURN),"L"(LEFT),"S"(STRAIGHT) AND "R"(RIGHT).
F(3) - LENGTH OF USABLE LANE FROM LANE TERMINAL.  [0, FOR OPEN LANE]
F(4) - LENGTH OF USABLE LANE FROM OUTER END.  [0, FOR OPEN LANE]
F(5) - OFFSET OF LANE TERMINAL.  POS. IS TOWARD INTERSECTION. <-350 TO 100> [0]
F(6) - PERCENT OF INBOUND TRAFFIC TO ENTER IN THIS LANE.
       <0 TO 100, SUM FOR LEG = 100, 0 FOR LANE NOT USABLE AT OUTER END>
EDIT EXAMPLE: "LANE(3,1)=8" CHANGES FIELD 1 OF LANE 3 TO "8", OTHERS UNCHANGED
KEYIN "HELP" FOR ADDITIONAL INFORMATION
LANE DATA FOR LEG 1:
 1  (INBOUND 1)      12 L      0    0    0   50
 2  (INBOUND 2)      12 L      0    0    0   50
 3  (OUTBOUND 1)     12 LR     0    0    0
                   \.1/ \.2/ \.3/ \.4/ \.5/ \.6/
IS LANE DATA FOR LEG 1 OK ?
```

```
F(1) - NAME FOR INBOUND TRAFFIC HEADWAY FREQUENCY DISTRIBUTION:
       "CONSTAN", "ERLANG", "GAMMA", "LOGNRML", "NEGEXP","SNEGEXP" OR "UNIFORM"
       MAY BE ABBREVIATED TO THE FIRST CHARACTER.
F(2) - TOTAL HOURLY VOLUME ON LEG, VPH. <0 TO 4000> [200 PER INBOUND LANE]
F(3) - PARAMETER FOR HEADWAY FREQUENCY DISTRIBUTION:
         CONSTANT - NONE.
         ERLANG - INTEGER VALUE (ROUNDED) FOR MEAN**2/VARIANCE.<GREATER THAN 1>
         GAMMA - MEAN**2/VARIANCE. <GREATER THAN 1>
         LOGNORMAL - STANDARD DEVIATION.
         NEGATIVE EXPONENTIAL - NONE.
         SHIFTED NEGATIVE EXPONENTIAL - MINIMUM HEADWAY IN SECONDS. <LESS THAN
                                        OR EQUAL MEAN HEADWAY>
         UNIFORM - STANDARD DEVIATION
F(4),F(5)- MEAN,85 PERCENTILE SPEED OF ENTERING VEHICLES, MPH.<10 TO 80>[29,31]
F(6) - TRAFFIC MIX DATA TO FOLLOW ? <"YES" OR "NO">  ["NO"]
F(7) - SEED FOR RANDOM NUMBERS (0 FOR AUTO. SELECTION).  <0 TO 99999> [0]
EDIT EXAMPLE: "F(4)=29,32" CHANGES FIELD 4 TO "29" AND FIELD 5 TO "32"
KEYIN "HELP" FOR ADDITIONAL ASSISTANCE

  DATA FIELDS:   SNEGEXP   316   1.50  29.0  31.0 YES     0
FIELD NUMBERS:   \..1../ \.2./ \..3./ \.4./ \.5./ \6/ \.7./

IS INBOUND TRAFFIC HEADWAY FREQUENCY DISTRIBUTION DATA FOR LEG 1 OK ?
,

MIX (PERCENTAGES) OF VEHICLE CLASSES IN INBOUND TRAFFIC FOR LEG 1:
EACH FIELD - PERCENT OF INBOUND VEHICLES IN THE SPECIFIED (BY FIELD NUMBER)
             VEHICLE CLASS.  <0 TO 100 AND SUM = 100>
EDIT EXAMPLE: "F(2)=3*20" CHANGES FIELDS 2 THRU 4 TO "20", OTHERS UNCHANGED
KEYIN "HELP" FOR ADDITIONAL ASSISTANCE


  DATA FIELDS:     0   0 100   0   0   0   0   0   0   0   0   0
FIELD NUMBERS:   \1/ \2/ \3/ \4/ \5/ \6/ \7/ \8/ \9/ \10 \11 \12

IS MIX (PERCENTAGES) OF VEHICLE CLASSES IN INBOUND TRAFFIC FOR LEG 1 OK ?
```

```
         1         2         3         4         5         6         7
1234567890123456789012345678901234567890123456789012345678901234567890123456789
5X6 INTERSECTION, SINGLE LEFT, 2 THRU LANES      SIM40.60

IS TITLE TEXT OK ?


SIMULATION PARAMETER-OPTION DATA:
F(1) - START-UP TIME IN MINUTES. (STATISTICS NOT GATHERED)  <2.0 TO 5.0> [5.0]
F(2) - SIMULATION TIME IN MINUTES.  <10.0 TO 60.0> [FROM G&D-V REF. FILE]
F(3) - TIME INCREMENT FOR SIMULATION, "DT". (SUGGEST 1.0 FOR SIGNAL,
       0.5 FOR NON-SIGNAL)  <0.50 TO 1.00> [0.50]
F(4) - TYPE OF INTERSECTION CONTROL: <"U", "Y", "ST", "A", "P", "SE" OR "F">
       "U" - UNCONTROLLED.
       "Y" - YIELD.
       "ST" - STOP, LESS THAN ALL WAY.
       "A" - ALL-WAY STOP.
       "P" - PRETIMED SIGNAL.
       "SE" - SEMI-ACTUATED SIGNAL.
       "F" - FULL-ACTUATED SIGNAL.
F(5) - STATISTICAL SUMMARY BY TURNING MOVEMENT ?  <"YES" OR "NO"> ["YES"]
F(6) - STATISTICAL SUMMARY BY INBOUND APPROACH ?  <"YES" OR "NO"> ["YES"]
F(7) - COMPRESSED OUTPUT OF STATISTICS ?  <"YES" OR "NO"> ["NO"]
F(8) - VEHICLE POSITION (POLLUTION/DISPLAY) DATA ?  <"YES" OR "NO"> ["NO"]
KEYIN "HELP" FOR ADDITIONAL ASSISTANCE.

DATA: 5.00 30.00 1.00 PRETIMED YES YES NO  NO
 FLD: \.1/ \.2./ \.3/ \...4../ \5/ \6/ \7/ \8/

IS SIMULATION PARAMETER-OPTION DATA OK ?

Y

SIMULATION PARAMETER-OPTION DATA 2:
F(1) - SPEED BELOW WHICH A SPECIAL DELAY STATISTIC IS COLLECTED. <0 TO 40> [10]
F(2) - MAXIMUM CLEAR DISTANCE FOR BEING IN A QUEUE.  <4 TO 40> [30]
F(3) - CAR FOLLOWING EQUATION PARAMETER LAMBDA.  <2.300 TO 4.000> [2.800]
F(4) - CAR FOLLOWING PARAMETER MU.  <0.600 TO 1.000> [0.800]
F(5) - CAR FOLLOWING PARAMETER ALPHA.  <0 TO 10000> [ 4000]
F(6) - TIME FOR LEAD ZONE USED IN CONFLICT CHECKING.  <0.50 TO 3.00> [1.30]
F(7) - TIME FOR LAG ZONE USED IN CONFLICT CHECKING.  <0.50 TO 3.00> [.50]
KEYIN "HELP" FOR ADDITIONAL ASSISTANCE.

DATA: 10  30 2.800 0.800  4000 1.30 0.50
 FLD: \1 \2/ \.3./ \.4./ \.5./ \.6/ \.7/

IS SIMULATION PARAMETER-OPTION DATA 2 OK ?
```

Fig D-2. TEXAS model example simulation input file used for single left-turn analysis.

```
Y

LANE CONTROL DATA:
EACH FIELD - TYPE OF CONTROL FOR THE INDICATED INBOUND LANE:
 "BL" - BLOCKED LANE. LANE ENDS BEFORE THE INTERSECTION.
 "UN" - UNCONTROLLED. <ONLY IF INTER. CONTROL = "NONE", "YIELD" OR "STOP">
 "YI" - YIELD SIGN. <NOT IF INTERSECTION CONTROL = "NONE">
 "ST" - STOP SIGN. <ONLY IF INTERSECTION CONTROL = "STOP" OR "ALL-WAY">
 "SI" - SIGNAL WITHOUT LEFT OR RIGHT TURN ON RED. <SIGNALIZED INTER. ONLY>
 "LT" - SIGNAL WITH LEFT TURN ON RED. <SIGNALIZED INTERSECTION ONLY>
 "RT" - SIGNAL WITH RIGHT TURN ON RED. <SIGNALIZED INTERSECTION ONLY>
KEYIN "HELP" FOR ADDITIONAL ASSISTANCE.

 LEG: /---1--\ /---2--\ /---3--\ /---4--\
LANE:  1  2  3  1  2  3  1  2  3  1  2  3
DATA: SI SI SI SI SI SI SI SI SI SI SI SI
 FLD: \1 \2 \3 \4 \5 \6 \7 \8 \9 10 11 12

IS LANE CONTROL DATA OK ?
Y

SIGNAL CONTROLLER IS PRETIMED.  THERE ARE 3 CONTROLLER PHASES.

PRETIMED SIGNAL TIMING DATA:
F(1) - GREEN INTERVAL.  <1.0 TO 99.0, SECONDS> [30.0]
F(2) - YELLOW-CHANGE INTERVAL.  <1.0 TO 9.0, SECONDS> [3.0]
F(3) - ALL RED-CLEARANCE INTERVAL.  <0.0 TO 9.0, SECONDS> [0.0]
*** EACH TIME INTERVAL IS AUTOMATICALLY ROUNDED TO THE NEAREST "DT".

CYCLE LENGTH IS 60.0 SECONDS.

P(A): 17.0 3.0 0.0
 (B): 22.0 3.0 0.0
 (C): 12.0 3.0 0.0
 FLD: \.1/ \2/ \3/

IS PRETIMED SIGNAL TIMING DATA OK ?
```

```
Y

GREEN INTERVAL SEQUENCE DATA:
EACH FIELD -GREEN SIGNAL INDICATION FOR THE CONTROLLER PHASE AND LANE:
"C" - CIRCULAR GREEN. ALL PERMITTED MOVEMENTS MAY MOVE.
"L" - LEFT GREEN ARROW, PROTECTED LEFT TURN.
"S" - STRAIGHT GREEN ARROW.   "R" - RIGHT GREEN ARROW.
*** ANY TWO OF THE ABOVE MAY BE USED TOGETHER, EXCEPT "LS" OR "LR".
"UN" - UNSIGNALIZED, SIGN CONTROL OR BLOCKED LANE, PER LANE CONTROL DATA.
BLANK - IMPLIED RED.
*** "LC" IS LANE CONTROL DATA.   "MC" IS MOVEMENT CODE FROM GEOMETRY REF. DATA.

 LEG: /---1--\ /---2--\ /---3--\ /---4--\
LANE:  1  2  3  1  2  3  1  2  3  1  2  3
  MC: L  S  S  S  S  S  L  S  S  S  S  S
  LC: SI SI SI SI SI SI SI SI SI SI SI SI
P(A): L                 L
 (B):    C  C              C  C
 (C):          C  C  C              C  C  C
 FLD: \1 \2 \3 \4 \5 \6 \7 \8 \9 10 11 12

IS GREEN INTERVAL SEQUENCE DATA OK ?
```

```
         1         2         3         4         5         6         7
1234567890123456789012345678901234567890123456789012345678901234567890123456789
DUAL LEFT-TURNS   300 LT VEHS PER HR PER LANE                        REP01

IS TITLE TEXT OK ?
Y

PARAMETER-OPTION DATA:
F(1) - TOTAL NUMBER OF LEGS.  <3 TO 6> [4]
F(2) - SIMULATION TIME IN MINUTES.  [20]
F(3) - MINIMUM HEADWAY IN SECONDS.  <1.0 TO 3.0> [1.0]
F(4) - NUMBER OF VEHICLE CLASSES.  <12> [12]
F(5) - NUMBER OF DRIVER CLASSES.  <3> [3]
F(6) - PERCENT OF LEFT TURNING VEHICLES TO ENTER IN MEDIAN LANE.<50 TO 100>[80]
F(7) - PERCENT OF RIGHT TURNING VEHICLES TO ENTER IN CURB LANE. <50 TO 100>[80]
EDIT EXAMPLE: "F(2)=15" CHANGES FIELD 2 TO "15", OTHER FIELDS REMAIN UNCHANGED
KEYIN "HELP" FOR ADDITIONAL ASSISTANCE

  DATA FIELDS:      4   35  1.0   12    3   60   80
FIELD NUMBERS:    \.1/ \.2/ \.3/ \.4/ \.5/ \.6/ \.7/

IS PARAMETER-OPTION DATA OK ?



Y

CURB RETURN RADII:
EACH FIELD - CURB RETURN RADIUS BETWEEN OUTERMOST INBOUND LANE AND THE ADJACENT
             (COUNTERCLOCKWISE) LEG.  <INTEGER, 0 TO 200>  [20]

  DATA FIELDS:     20   20   20   20
FIELD NUMBERS:    \.1/ \.2/ \.3/ \.4/

ARE CURB RETURN RADII OK ?
```

Fig D-3. TEXAS Model example geometry and driver-vehicle input file used for dual left-turn analysis.

```
Y

LEG 1 GEOMETRY DATA:
F(1) - LEG NUMBER.  WILL BE RESET TO THE NUMBER OF THE LEG BEING PROCESSED.
F(2) - LEG ANGLE.  POSITIVE IS CLOCKWISE FROM NORTH = 0 (ZERO) DEGREES.
       <0 TO 359, IN INCREASING ORDER>  [EQUAL ANGLES]
F(3) - LENGTH OF INBOUND LANES.  <400 TO 1000>  [800]
F(4) - LENGTH OF OUTBOUND LANES.  [250]  (SUGGEST 250 FOR LOW TRAFFIC VOLUME,
       400 FOR HIGH VOLUME. FOR EMISSIONS, MUST BE SAME AS INBOUND LANE LENGTH)
F(5) - NUMBER OF INBOUND LANES.  <0 TO 6>  [2]
F(6) - NUMBER OF OUTBOUND LANES.  <0 TO 6>  [2]
F(7) - SPEED LIMIT ON INBOUND LANES IN MPH.  <10 TO 80>  [30]
F(8) - SPEED LIMIT ON OUTBOUND LANES IN MPH.  <10 TO 80>  [30]
F(9) - LEG CENTERLINE OFFSET FROM INTERSECTION CENTER. POSITIVE IS TO THE RIGHT
       WHEN FACING IN DIRECTION OF INBOUND TRAFFIC.  <-200 TO 200>  [0]
F(10) - MEDIAN WIDTH, WILL BE CENTERED ON LEG CENTERLINE.  <0 TO 100>  [0]
F(11) - LIMITING ANGLE FOR STRAIGHT MOVEMENT.  <0 TO 45 DEGREES>  [20]
F(12) - LIMITING ANGLE FOR U-TURN.  <0 TO 45 DEGREES>  [10]

  DATA FIELDS:      1    0 1000  250    3    2   30   30    3    6  2
FIELD NUMBERS:   \.1/ \.2/ \.3/ \.4/ \.5/ \.6/ \.7/ \.8/ \.9/ \10/ \11 \12

IS LEG 1 GEOMETRY DATA OK ?
Y

F(1) - WIDTH OF LANE.  <8 TO 15>  [12]
F(2) - MOVEMENT CODE. ANY OF"U"(U-TURN),"L"(LEFT),"S"(STRAIGHT) AND "R"(RIGHT).
F(3) - LENGTH OF USABLE LANE FROM LANE TERMINAL.  [0, FOR OPEN LANE]
F(4) - LENGTH OF USABLE LANE FROM OUTER END.  [0, FOR OPEN LANE]
F(5) - OFFSET OF LANE TERMINAL.  POS. IS TOWARD INTERSECTION. <-350 TO 100> [0]
F(6) - PERCENT OF INBOUND TRAFFIC TO ENTER IN THIS LANE.
       <0 TO 100, SUM FOR LEG = 100, 0 FOR LANE NOT USABLE AT OUTER END>
EDIT EXAMPLE: "LANE(3,1)=8" CHANGES FIELD 1 OF LANE 3 TO "8", OTHERS UNCHANGED
KEYIN "HELP" FOR ADDITIONAL INFORMATION
LANE DATA FOR LEG 1:
 1  (INBOUND 1)      12 L      0    0    0   70
 2  (INBOUND 2)      12 S      0    0    0   20
 3  (INBOUND 3)      12 S      0    0    0   10
 4  (OUTBOUND 1)     12 LS     0    0    0
 5  (OUTBOUND 2)     12 S      0    0    0
                   \.1/ \.2/ \.3/ \.4/ \.5/ \.6/
IS LANE DATA FOR LEG 1 OK ?
```

```
F(1) - NAME FOR INBOUND TRAFFIC HEADWAY FREQUENCY DISTRIBUTION:
       "CONSTAN", "ERLANG", "GAMMA", "LOGNRML", "NEGEXP","SNEGEXP" OR "UNIFORM"
       MAY BE ABBREVIATED TO THE FIRST CHARACTER.
F(2) - TOTAL HOURLY VOLUME ON LEG, VPH. <0 TO 4000> [200 PER INBOUND LANE]
F(3) - PARAMETER FOR HEADWAY FREQUENCY DISTRIBUTION:
         CONSTANT - NONE.
         ERLANG - INTEGER VALUE (ROUNDED) FOR MEAN**2/VARIANCE.<GREATER THAN 1>
         GAMMA - MEAN**2/VARIANCE. <GREATER THAN 1>
         LOGNORMAL - STANDARD DEVIATION.
         NEGATIVE EXPONENTIAL - NONE.
         SHIFTED NEGATIVE EXPONENTIAL - MINIMUM HEADWAY IN SECONDS. <LESS THAN
                                        OR EQUAL MEAN HEADWAY>
         UNIFORM - STANDARD DEVIATION
F(4),F(5)- MEAN,85 PERCENTILE SPEED OF ENTERING VEHICLES, MPH.<10 TO 80>[29,31]
F(6) - TRAFFIC MIX DATA TO FOLLOW ? <"YES" OR "NO">  ["NO"]
F(7) - SEED FOR RANDOM NUMBERS (0 FOR AUTO. SELECTION).  <0 TO 99999> [0]
EDIT EXAMPLE: "F(4)=29,32" CHANGES FIELD 4 TO "29" AND FIELD 5 TO "32"
KEYIN "HELP" FOR ADDITIONAL ASSISTANCE

  DATA FIELDS:   SNEGEXP   600   1.80  29.0  31.0 YES    0
FIELD NUMBERS:   \..1../ \.2./ \..3./ \.4./ \.5./ \6/ \.7./

IS INBOUND TRAFFIC HEADWAY FREQUENCY DISTRIBUTION DATA FOR LEG 1 OK ?

MIX (PERCENTAGES) OF VEHICLE CLASSES IN INBOUND TRAFFIC FOR LEG 1:
EACH FIELD - PERCENT OF INBOUND VEHICLES IN THE SPECIFIED (BY FIELD NUMBER)
             VEHICLE CLASS.  <0 TO 100 AND SUM = 100>
EDIT EXAMPLE: "F(2)=3*20" CHANGES FIELDS 2 THRU 4 TO "20", OTHERS UNCHANGED
KEYIN "HELP" FOR ADDITIONAL ASSISTANCE


  DATA FIELDS:     0   0 100   0   0   0   0   0   0   0   0   0
FIELD NUMBERS:   \1/ \2/ \3/ \4/ \5/ \6/ \7/ \8/ \9/ \10 \11 \12

IS MIX (PERCENTAGES) OF VEHICLE CLASSES IN INBOUND TRAFFIC FOR LEG 1 OK ?
```

```
SIMULATION PARAMETER-OPTION DATA:
F(1) - START-UP TIME IN MINUTES. (STATISTICS NOT GATHERED)  <2.0 TO 5.0> [5.0]
F(2) - SIMULATION TIME IN MINUTES.  <10.0 TO 60.0> [FROM G&D-V REF. FILE]
F(3) - TIME INCREMENT FOR SIMULATION, "DT". (SUGGEST 1.0 FOR SIGNAL,
       0.5 FOR NON-SIGNAL)  <0.50 TO 1.00> [0.50]
F(4) - TYPE OF INTERSECTION CONTROL: <"U", "Y", "ST", "A", "P", "SE" OR "F">
       "U" - UNCONTROLLED.
       "Y" - YIELD.
       "ST" - STOP, LESS THAN ALL WAY.
       "A" - ALL-WAY STOP.
       "P" - PRETIMED SIGNAL.
       "SE" - SEMI-ACTUATED SIGNAL.
       "F" - FULL-ACTUATED SIGNAL.
F(5) - STATISTICAL SUMMARY BY TURNING MOVEMENT ?  <"YES" OR "NO"> ["YES"]
F(6) - STATISTICAL SUMMARY BY INBOUND APPROACH ?  <"YES" OR "NO"> ["YES"]
F(7) - COMPRESSED OUTPUT OF STATISTICS ?  <"YES" OR "NO"> ["NO"]
F(8) - VEHICLE POSITION (POLLUTION/DISPLAY) DATA ?  <"YES" OR "NO"> ["NO"]
KEYIN "HELP" FOR ADDITIONAL ASSISTANCE.

DATA: 5.00 30.00 1.00 PRETIMED YES YES NO  NO
 FLD: \.1/ \.2./ \.3/ \...4../ \5/ \6/ \7/ \8/

IS SIMULATION PARAMETER-OPTION DATA OK ?


Y


SIMULATION PARAMETER-OPTION DATA 2:
F(1) - SPEED BELOW WHICH A SPECIAL DELAY STATISTIC IS COLLECTED. <0 TO 40> [10]
F(2) - MAXIMUM CLEAR DISTANCE FOR BEING IN A QUEUE.  <4 TO 40> [30]
F(3) - CAR FOLLOWING EQUATION PARAMETER LAMBDA.  <2.300 TO 4.000> [2.800]
F(4) - CAR FOLLOWING PARAMETER MU.  <0.600 TO 1.000> [0.800]
F(5) - CAR FOLLOWING PARAMETER ALPHA.  <0 TO 10000> [ 4000]
F(6) - TIME FOR LEAD ZONE USED IN CONFLICT CHECKING.  <0.50 TO 3.00> [1.30]
F(7) - TIME FOR LAG ZONE USED IN CONFLICT CHECKING.  <0.50 TO 3.00> [.50]
KEYIN "HELP" FOR ADDITIONAL ASSISTANCE.

DATA: 10  30 2.800 0.800  4000 1.30 0.50
 FLD: \1 \2/ \.3./ \.4./ \.5./ \.6/ \.7/

IS SIMULATION PARAMETER-OPTION DATA 2 OK ?
```

Fig D-4. TEXAS Model example simulation input file used for dual left-turn analysis.

```
DATA: 10  30 2.800 0.800  4000 1.30 0.50
 FLD: \1 \2/ \.3./ \.4./ \.5./ \.6/ \.7/

IS SIMULATION PARAMETER-OPTION DATA 2 OK ?
Y

LANE CONTROL DATA:
EACH FIELD - TYPE OF CONTROL FOR THE INDICATED INBOUND LANE:
 "BL" - BLOCKED LANE. LANE ENDS BEFORE THE INTERSECTION.
 "UN" - UNCONTROLLED. <ONLY IF INTER. CONTROL = "NONE", "YIELD" OR "STOP">
 "YI" - YIELD SIGN. <NOT IF INTERSECTION CONTROL = "NONE">
 "ST" - STOP SIGN. <ONLY IF INTERSECTION CONTROL = "STOP" OR "ALL-WAY">
 "SI" - SIGNAL WITHOUT LEFT OR RIGHT TURN ON RED. <SIGNALIZED INTER. ONLY>
 "LT" - SIGNAL WITH LEFT TURN ON RED. <SIGNALIZED INTERSECTION ONLY>
 "RT" - SIGNAL WITH RIGHT TURN ON RED. <SIGNALIZED INTERSECTION ONLY>
KEYIN "HELP" FOR ADDITIONAL ASSISTANCE.

 LEG: /-1-\ /2 /-3-\ /4
LANE:  1  2  1  1  2  1
DATA: SI SI SI SI SI SI
 FLD: \1 \2 \3 \4 \5 \6

IS LANE CONTROL DATA OK ?


SIGNAL CONTROLLER IS PRETIMED.  THERE ARE 2 CONTROLLER PHASES.

PRETIMED SIGNAL TIMING DATA:
F(1) - GREEN INTERVAL.  <1.0 TO 99.0, SECONDS> [30.0]
F(2) - YELLOW-CHANGE INTERVAL.  <1.0 TO 9.0, SECONDS> [3.0]
F(3) - ALL RED-CLEARANCE INTERVAL.  <0.0 TO 9.0, SECONDS> [0.0]
*** EACH TIME INTERVAL IS AUTOMATICALLY ROUNDED TO THE NEAREST "DT".

CYCLE LENGTH IS 60.0 SECONDS.

P(A): 17.0 3.0 0.0
 (B): 37.0 3.0 0.0
 FLD: \.1/ \2/ \3/

IS PRETIMED SIGNAL TIMING DATA OK ?
```

```
GREEN INTERVAL SEQUENCE DATA:
EACH FIELD -GREEN SIGNAL INDICATION FOR THE CONTROLLER PHASE AND LANE:
"C" - CIRCULAR GREEN. ALL PERMITTED MOVEMENTS MAY MOVE.
"L" - LEFT GREEN ARROW, PROTECTED LEFT TURN.
"S" - STRAIGHT GREEN ARROW.   "R" - RIGHT GREEN ARROW.
*** ANY TWO OF THE ABOVE MAY BE USED TOGETHER, EXCEPT "LS" OR "LR".
"UN" - UNSIGNALIZED, SIGN CONTROL OR BLOCKED LANE, PER LANE CONTROL DATA.
BLANK - IMPLIED RED.
*** "LC" IS LANE CONTROL DATA.   "MC" IS MOVEMENT CODE FROM GEOMETRY REF. DATA.

 LEG: /-1-\ /2 /-3-\ /4
LANE:  1  2  1  1  2  1
  MC: L  L  S  L  L  S
  LC: SI SI SI SI SI SI
P(A): L  L     L  L
 (B):       C        C
 FLD: \1 \2 \3 \4 \5 \6

IS GREEN INTERVAL SEQUENCE DATA OK ?
```

APPENDIX E. LEFT-TURNING MOVEMENT ANALYSIS PROGRAM—(LTMAP) HARDCOPY LISTING OF COMPUTER CODE

```
{$R-}    {Range checking off}
{$B+}    {Boolean complete evaluation on}
{$S+}    {Stack checking on}
{$I+}    {I/O checking on}
{$N+}    {Yes numeric coprocessor}
{$M 65500,16384,655360} {Turbo 3 default stack and heap}


program  project;
uses
   Graph;
label
       StartAgain, ReEnter;
type
    RedType = 3..9;
    GaCType = 2..7;
    VolType = 2..8;
    IntegerTypeArray= array [RedType,GaCType,VolType] of integer;

var
   Red: RedType;
   GaC: GaCType;
   Vol: VolType;

   AavgQ, AmaxQ,  AQDelay,
        DualAavg, DualAmax, DualDel: IntegerTypeArray;
        InputCycle, InputRed, InputGaC,InputVol, NumVehClasses,
   i,TotalAvgQFt, TotalMaxQFt,TotalDesQFt, Avg,
   Max, Des, IntPercent, Length, CarBodyLength, Gd, Gm,
        AvgQueHeadway, Num, count, PercentTotal,
        TableX, Delay, LTSatFlow, Cse  : Integer;

   TempChk, NumVehAvgClass, NumVehMaxClass, NumVehDesClass,
   TempTotalAvgQFt, TempTotalMaxQFt, TempTotalDesQFt,
        AvgQFt, MaxQFt, DesQFt, AvgMinQSecs, CycFailM,
        Base, ProbCF, CumProbCF, Basehcm, Expon,
        GoChcm, VChcm, VCtexas, Qhcm, Qtexas, GOC, CycFailX, TempInputGreen,
   D1hcm, D2hcm, HCMTotDel, InitQue, Ge, Re, A, P, N, Qr, Dt,
        Da, Qo, DelayCFTot, NumVehs, TempInputVol,
        TempInputRed, TempInputCycle, Peak15MinVol : real;

   QLenUnit : text;

   AvgQStr, MaxQStr, DesQStr, TotalAvgQFtStr,TotalMaxQFtStr, TotalDesQFtStr,
        InputCycleStr,InputGaCStr,InputRedStr,InputVolStr,
        CycFailMStr, AvgMinQSecsStr,TableXStr, CumProbCFStr,
        RatioArrToProcStr, DelayStr, D1hcmstr, D2hcmstr, HCMTotDelStr,
        Dastr, DelayCFTotStr, Peak15MinVolStr, AvgQueHeadwayStr,
        Qostr, LtSatFlowStr: string[6];
```

```
   OpType : string [200];

   PercentageStr,LengthStr, CarBodyLengthStr : array [1..6] of string[6];

   Percentage : array[1..6] of integer;

   answer : Char;


Procedure InputTable; FORWARD;
Procedure QueLenTable; FORWARD;
Procedure CycleFailureTable; FORWARD;
Procedure VolToCapTable; FORWARD;
Procedure DelayTable; FORWARD;

{************************************************************}
{This procedure opens the AavgQ input file.                   }
{************************************************************}

procedure Open_AavgQ_Input_File (var QLenUnit:text);
   begin
       assign (QLenUnit, 'AavgQ.Dat');
       reset (QLenUnit);
   end;


{************************************************************}
{This procedure opens the AmaxQ input file.                   }
{************************************************************}

procedure Open_AmaxQ_Input_File (var QLenUnit:text);
   begin
       assign (QLenUnit, 'AmaxQ.Dat');
       reset (QLenUnit);

   end;




{************************************************************}
{This procedure opens the AQDelay input file.                   }
{************************************************************}

procedure Open_AQDelay_Input_File (var QLenUnit:text);
   begin
       assign (QLenUnit, 'AQDelay.Dat');
       reset (QLenUnit);

   end;
```

```
{*************************************************************}
{This procedure opens the DualAavgQ input file.              }
{*************************************************************}

procedure Open_DualAavg_Input_File (var QLenUnit:text);
   begin
        assign (QLenUnit, 'DualAavg.Dat');
        reset (QLenUnit);
   end;


{*************************************************************}
{This procedure opens the DualAmax input file.               }
{*************************************************************}

procedure Open_DualAmax_Input_File (var QLenUnit:text);
   begin
        assign (QLenUnit, 'DualAmax.Dat');
        reset (QLenUnit);

   end;




{*************************************************************}
{This procedure opens the DualDel input file.                }
{*************************************************************}

procedure Open_DualDel_Input_File (var QLenUnit:text);
   begin
        assign (QLenUnit, 'DualDel.Dat');
        reset (QLenUnit);

   end;


{*************************************************************}
{This procedure is used for reading avg que input file.           }
{*************************************************************}

procedure Read_AavgQ_Line (var QLenUnit :text);
   begin
         readln (QLenUnit, AavgQ[Red,GaC,2],
          AavgQ[Red,GaC,3], AavgQ[Red,GaC,4],
          AavgQ[Red,GaC,5], AavgQ[Red,GaC,6],
          AavgQ[Red,GaC,7], AavgQ[Red,GaC,8]);
  end;
```

```
{************************************************************}
{This procedure is used for reading max que input file.           }
{************************************************************}

procedure Read_AmaxQ_Line (var QLenUnit:text);
   begin
         readln (QLenUnit, AmaxQ[Red,GaC,2],
          AmaxQ[Red,GaC,3], AmaxQ[Red,GaC,4],
          AmaxQ[Red,GaC,5], AmaxQ[Red,GaC,6],
          AmaxQ[Red,GaC,7], AmaxQ[Red,GaC,8]);

   end;

{************************************************************}
{This procedure is used for reading the avg. queue delay input file.}
{************************************************************}

procedure Read_AQDelay_Line (var QLenUnit:text);
   begin
         readln (QLenUnit, AQDelay[Red,GaC,2],
          AQDelay[Red,GaC,3], AQDelay[Red,GaC,4],
          AQDelay[Red,GaC,5], AQDelay[Red,GaC,6],
          AQDelay[Red,GaC,7], AQDelay[Red,GaC,8]);

   end;

{************************************************************}
{This procedure is used for reading dual avg que input file.            }
{************************************************************}

procedure Read_DualAavg_Line (var QLenUnit :text);
   begin
         readln (QLenUnit, DualAavg[Red,GaC,2],
          DualAavg[Red,GaC,3], DualAavg[Red,GaC,4],
          DualAavg[Red,GaC,5], DualAavg[Red,GaC,6],
          DualAavg[Red,GaC,7], DualAavg[Red,GaC,8]);
  end;

{************************************************************}
{This procedure is used for reading  Dual max que input file.            }
{************************************************************}

procedure Read_DualAmax_Line (var QLenUnit:text);
   begin
         readln (QLenUnit, DualAmax[Red,GaC,2],
          DualAmax[Red,GaC,3], DualAmax[Red,GaC,4],
          DualAmax[Red,GaC,5], DualAmax[Red,GaC,6],
          DualAmax[Red,GaC,7], DualAmax[Red,GaC,8]);

   end;
```

```
{****************************************************************}
{This procedure is used for the Dual avg. queue delay input file.}
{****************************************************************}

procedure Read_DualDel_Line (var QLenUnit:text);
   begin
        readln (QLenUnit, DualDel[Red,GaC,2],
         DualDel[Red,GaC,3], DualDel[Red,GaC,4],
         DualDel[Red,GaC,5], DualDel[Red,GaC,6],
         DualDel[Red,GaC,7], DualDel[Red,GaC,8]);

   end;


{*********************************************************}
{This procedure clears the screen.                        }
{*********************************************************}


procedure ClearS;
var Gd,Gm: integer;
begin
  Gd := Detect;
  InitGraph(Gd,Gm, ' ');
  if GraphResult <> grOk then
  Halt(1);
  ClearViewPort;
  CloseGraph;
end;


{********************************************************************}
{This procedure is for the user to input what the next step should be.}
{********************************************************************}

procedure NextStep;

  begin
  ClearS;
  repeat
  begin
         writeln;
         writeln;
     writeln (' ENTER THE FOLLOWING LETTERS TO CONTINUE:');
     writeln;
         writeln;
         writeln (' i = review of the INPUT values');
     writeln;
         writeln (' q = average, maximum, and design QUEUE lengths table');
     writeln;
         writeln (' c = CYCLE failure statistics table');
```

```
    writeln;
        writeln (' v = VOLUME to capacity statistics table');
    writeln;
        writeln (' d = DELAY statistics table');
    writeln;
    writeln (' n = starts NEW data entry section again');
    writeln;
        writeln (' e = EXITS program');
    writeln;
        readln (answer);
        if (answer = 'i') then
                    begin
       InputTable;
                    end
               else if (answer = 'q') then
             begin
       QueLenTable;
             end
              else if (answer = 'c')then
             begin
                    CycleFailureTable;
             end
        else if (answer = 'v')then
             begin
                    VolToCapTable;
             end
        else if (answer = 'd')then
             begin
                    DelayTable;
             end
        else if (answer = 'n') or (answer = 'e') then
             begin
             end
        else
                    begin
                    writeln ('ANSWER MUST BE EITHER i, l, c, v, d, n, or e PLEASE REENTER.');
                    end;
  end;
until ((answer = 'i') or (answer = 'c') or (answer = 'v') or (answer = 'd')
      or (answer = 'n') or (answer = 'e') or (answer = 'l'));
end;


{**********************************************************************}
{This procedure presents the starting screen.                          }
{**********************************************************************}


procedure StartScreen;
```

```
begin
  Gd := Detect;
  InitGraph(Gd,Gm, ' ');
  if GraphResult <> grOk then
   Halt(1);


  Line(25,15,605,15);
  Line(605,15,605,120);
  Line(25,120,25,15);
  Line(25,120,605,120);
  OutTextXY(145,30, 'TURNING MOVEMENT ANALYSIS PACKAGE (TMAP)');
  OutTextXY(145,45, '   The University of Texas at Austin');
  OutTextXY(145,110,'      - press return to continue -');
  readln;
  ClearViewPort;
  CloseGraph;
end;


{******************************************************************}
{This procedure presents the input values.                         }
{******************************************************************}



procedure InputTable;

var
   Gd, Gm, Space : Integer;
   Qtexasstring, Qhcmstring, InputVolString,
        VCtexasstring, VChcmstring : String[15];


begin
  Gd := Detect;
  InitGraph(Gd,Gm, ' ');
  if GraphResult <> grOk then
   Halt(1);

{This section draws the input summary and queue length tables.}

  Line(25,15,605,15);
  Line(605,15,605,185);
  Line(605,185,25,185);
  Line(25,185,25,15);
  Line(25,185,605,185);
  Line(25,25,605,25);
  OutTextXY(28,7,'INPUT SUMMARY                        Press return to continue');
  OutTextXY(28,17,OpType);
  OutTextXY(28,32,'CYCLE LENGTH  (60,80,100 OR 120 seconds) ' );
```

```
  OutTextXy(455,32, InputCycleStr);
  OutTextXY(28,47,'LEFT TURN RED TIME (sec.)          ');
  OutTextXy(455,47, InputRedStr);
  OutTextXY(28,62,'LEFT TURN VOLUME PER LEFT-TURN LANE (vph)     ');
  OutTextXy(455,62, InputVolStr);
  OutTextXY(28,77,'PEAK 15 MINUTE VOLUME PER LEFT-TURN LANE (vph)');
  Str(round(Peak15MinVol), Peak15MinVolStr);
  OutTextXY(455,77,Peak15MinVolStr);
  OutTextXY(28, 92 ,'SATURATION FLOW PER LEFT-TURN LANE (vphltg)');
  Str(LtSatFlow,LtSatFlowStr);
  OutTextXY(455, 92 ,LtSatFlowStr);
  OutTextXY(28,107,'VEHICLE MIX =');
  OutTextXY(28,122,'AVERAGE MINIMUM DEPARTURE HEADWAY (sec.)');
  OutTextXY(450,122,AvgMinQSecsStr);
  OutTextXY(28,137,'AVERAGE HEADWAY IN STOPPED QUEUE (ft.)');
  Str(AvgQueHeadway, AvgQueHeadwayStr);
  OutTextXY(455,137,AvgQueHeadwayStr);
  OutTextXY(28,152,'AVERAGE NUMBER OF CYCLE FAILURES PER CYCLE');
  Str(Qo,Qostr);
  OutTextXY(450,152,QoStr);

Space :=39;
For i :=1 to NumVehClasses do
  Begin
             Space :=Space+110;
             OutTextXY(Space,107, PercentageStr[i]);
             OutTextXY(Space+26,107, '% @');
             OutTextXY(Space+59,107,CarBodyLengthStr[i]);
             OutTextXY(Space+75,107, 'ft');
         end;
  readln;
CloseGraph;
NextStep;
end;


{******************************************************************}
{This procedure presents the queue lengths table.                  }
{******************************************************************}

procedure QueLenTable;

const
  Table2: array[1..13] of PointType =
  ((x:25; y:58),(x:25; y:130),(x:605; y:130),(x:605; y:58), (x:25; y:58),
  (x: 25; y:68), (x:605; y:68),
  (x: 218; y:68), (x:218; y:130),(x:218; y:68),
  (x:411; y:68), (x:411; y:130), (x:411; y:68));

var
   Gd, Gm, Space : Integer;
```

```
   Qtexasstring, Qhcmstring, InputVolString,
        VCtexasstring, VChcmstring : String[15];

begin
  Gd := Detect;
  InitGraph(Gd,Gm, ' ');
  if GraphResult <> grOk then
   Halt(1);

  DrawPoly(SizeOf(Table2) div SizeOf(PointType), { 4 }
          Table2);
  OutTextXY (29,60,OpType);
  OutTextXY(140,35, '             LEFT TURN QUEUE LENGTHS');
  OutTextXY(140,45,'   (obtained from TEXAS MODEL simulation runs)');
  OutTextXY(43,85,'AVG. LT QUEUE LENGTH    MAX. LT QUEUE LENGTH   DESIGN LT QUEUE LENGTH');
  OutTextXY(41,100,'              Feet                    Feet                    Feet');
  OutTextXY(112,100, TotalAvgQFtStr);
  OutTextXY(41,115,'              Vehicles                Vehicles                Vehicles ');
  OutTextXY(112,115, AvgQStr);
  OutTextXY(295,100, TotalMaxQFtStr);
  OutTextXY(295,115, MaxQStr);
  OutTextXY(490,100, TotalDesQFtStr);
  OutTextXY(490,115, DesQStr);
  OutTextXY(30,150,'Note: the maximum queue possible with the TEXAS MODEL is approximately');
  OutTextXY(30,160,'     45 vehicles.');
  OutTextXY(90,187,'Press return to continue.');
  readln ;
ClearViewPort;
CloseGraph;
NextStep;
end;

{*********************************************************************}
{This procedure presents the cycle failure table.                     }
{*********************************************************************}



procedure CycleFailureTable;

begin
  Gd := Detect;
  InitGraph(Gd,Gm, ' ');
  if GraphResult <> grOk then
   Halt(1);

begin;
  Line(25,15,605,15);
  Line(605,15,605,120);
  Line(605,120,25,120);
  Line(25,120,25,15);
```

```
  Line(25,120,605,120);
  Line(25,25,605,25);
  OutTextXY(222,5, '      CYCLE FAILURES');
  OutTextXY(28,17,OpType);
  OutTextXY(33,27,'Average number of uniform arrivals per lane during');
  OutTextXY(33,35,'one cycle length in the peak period. ');
  OutTextXY(520,32,CycFailMStr);
  Line(25,44,605,44);
  OutTextXY(33,47,'Average minimum departure headway (sec.).');
  OutTextXY(510,47,AvgMinQSecsStr);
  Line(25,58,605,58);
  OutTextXY(33,62,'Number of vehicles processed per lane during');
  OutTextXY(33,71,'effective green phase.');
  OutTextXY(520,66,TableXStr);
  Line(25,80,605,80);
  OutTextXY(33,83,'Probability of having more vehicles');
  OutTextXY(33,92,'arriving than being processed.*');
  OutTextXY(520,87,CumProbCFStr);
  OutTextXY(546,87,'%');
  Line(25,103,605,103);
  OutTextXY(33,109,'Percent of arrival rate to processing rate.');
  OutTextXY(520,109,RatioArrToProcStr);
  OutTextXY(546,109,'%');
  OutTextXY(300,135,'* SUGGESTED UPPER LIMIT');
  OutTextXY(380,145,'30%   ');
  OutTextXY(90,187,'Press return to continue.');

  readln;
  ClearViewPort;
  CloseGraph;
  NextStep;
  end;
end;
{*********************************************************************}
{This procedure presents the volume to capacity table.               }
{*********************************************************************}


procedure VolToCapTable;

var
   Gd, Gm, Space : Integer;
   Qtexasstring, Qhcmstring, InputVolString,
        VCtexasstring, VChcmstring : String[15];
begin
  begin
  Gd := Detect;
  InitGraph(Gd,Gm, ' ');
  if GraphResult <> grOk then
   Halt(1);
```

```
  end;

  Line(25,15,605,15);
  Line(605,15,605,120);
  Line(605,120,25,120);
  Line(25,120,25,15);
  Line(25,120,605,120);
  Line(25,25,605,25);
  OutTextXY(222,5, '     VOLUME:CAPACITY');
  OutTextXY(28,17,OpType);
  Line(25,40,(round(Qtexas*0.4)),40);
  Line((round(Qtexas*0.4)),40,(round(Qtexas*0.4)),50);
  Line((round(Qtexas*0.4)),50,25,50);
  Line(25,66,(round(TempInputVol*0.4)),66);
  Line((round(TempInputVol*0.4)),66,(round(TempInputVol*0.4)),76);
  Line((round(TempInputVol*0.4)),76,25,76);
  Line(25,93,(round(Qhcm*0.4)),93);
  Line((round(Qhcm*0.4)),93,(round(Qhcm*0.4)),103);
  Line((round(Qhcm*0.4)),103,25,103);
  OutTextXY(29,31,'Capacity-Texas Model Method (vph)');
  OutTextXY(29,57,'Left-Turn Volume (vph)');
  OutTextXY(29,84,'Capacity-85 HCM Method (vph)');
  Str(round(Qtexas), Qtexasstring);
  Str(round(Qhcm),Qhcmstring);
  Str(round(TempInputVol),InputVolstring);
  Str(round(100*VCtexas), VCtexasstring);
  Str(round(100*VChcm),VChcmstring);
  OutTextXY(29,42,Qtexasstring);
  OutTextXY(29,68,InputVolstring);
  OutTextXY(29,95,Qhcmstring);
  OutTextXY(475,42,'V/C texas*');
  OutTextXY(495,54,VCtexasstring);
  OutTextXY(521,54,'%');
  OutTextXY(475,77,'V/C hcm*');
  OutTextXY(495,89,VChcmstring);
  OutTextXY(521,89,'%');
  OutTextXY(300,135,'* SUGGESTED UPPER LIMIT');
  OutTextXY(300,146,'        V/C <= 90%      ');
  OutTextXY(90,187,'Press return to continue.');
  readln;

  ClearViewPort;
  CloseGraph;
  NextStep;
end;


{*********************************************************************}
{This procedure presents the delay table.                             }
{*********************************************************************}
```

```
procedure DelayTable;

begin
  Gd := Detect;
  InitGraph(Gd,Gm, ' ');
  if GraphResult <> grOk then
   Halt(1);



  Line(25,15,605,15);
  Line(605,15,605,120);
  Line(605,120,25,120);
  Line(25,120,25,15);
  Line(25,120,605,120);
  Line(25,25,605,25);
  OutTextXY(222,5, '     AVERAGE DELAY');
  OutTextXY(28,17,OpType);
  OutTextXY(28,30,'Average queue delay* from Texas Model simulations.');
  OutTextXY(520,30,DelayStr);
  OutTextXY(549,30,'secs.');
  Line(25,40,605,40);
  OutTextXY(28,45,'Cycle Failure Delay Equation:');
  OutTextXY(33,55,'Uniform component of CF delay equation.');
  str(round(Da),Dastr);
  OutTextXY(520,55,Dastr);
  OutTextXY(555,55,'secs.');
  OutTextXY(33,65,'Random component (= D2 component of 85HCM delay equation).');
  OutTextXY(520,65,D2hcmstr);
  OutTextXY(555,65,'secs.');
  str(round(DelayCFTot),DelayCFTotStr);
  OutTextXY(33,75,'Total CF equation delay equation value.');
  OutTextXY(520,75,DelayCFTotStr);
  OutTextXY(555,75,'secs.');
  Line(25,85,605,85);
  OutTextXY(28,90,'Uniform (D1) component of 85HCM delay equation.');
  OutTextXY(520,90,D1hcmstr);
  OutTextXY(555,90,'secs.');
  OutTextXY(28,100,'Random (D2) component of 85HCM delay equation.');
  OutTextXY(520,100,D2hcmstr);
  OutTextXY(555,100,'secs.');
  OutTextXY(28,110,'Total 85HCM delay equation value.');
  OutTextXY(520,110,HCMTotDelStr);
  OutTextXY(555,110,'secs.');
  OutTextXY(300,125,'* SUGGESTED UPPER LIMIT');
  OutTextXY(300,136,' 35 seconds average delay   ');
  OutTextXY(50,150,'Note: When operating above capacity, the delay becomes a');
  OutTextXY(50,160,'      function of the length of time the queue is observed, therefore');
  OutTextXY(50,170,'      the above statistics should be used with caution in this range.');
```

```
  OutTextXY(200,185,'Press return to continue.');
  readln;
  ClearViewPort;
  CloseGraph;
  NextStep;
end;


{**************************************************************}
{This procedure is for inputting single lt specific data.    }
{**************************************************************}

procedure SLtInput;

begin
writeln;
writeln ('Enter the single left-turn volume (200,300,400,500,600,700 or 800 vph).');

readln (TempInputVol);
while not ((TempInputVol = 200) OR
    (TempInputVol = 300) OR
    (TempInputVol = 400) OR
    (TempInputVol = 500) OR
    (TempInputVol = 600) OR
    (TempInputVol = 700) OR
    (TempInputVol = 800)) DO
    begin
      writeln ('THE LEFT TURN VOLUME MUST BE 200,300,400,500,600,700, OR 800 VPH,');
      writeln ('PLEASE REENTER THE THE LEFT TURN VOLUME.');
      readln (TempInputVol);
      writeln;
    end;

InputVol :=round(TempInputVol / 100);
TempInputGreen:= (TempInputCycle-TempInputRed-3.0);

writeln;
writeln ('Enter the peak 15 minute single left-turn critical lane volume');
writeln ('(must be less than or equal to 300 vehicles).');
readln (Peak15MinVol);
while ((Peak15MinVol < 0) OR (Peak15MinVol > 300)) do
   begin
     writeln ('PEAK 15 MINUTE VOLUME IS NOT WITHIN SPECIFIED RANGE, PLEASE REENTER.');
          readln (Peak15MinVol);
        end;

writeln;

repeat
writeln ('Do you want to use 1710 vph as the saturation flow');
writeln('value for a single left-turn lane (y or n)?');
```

```
readln (answer);
  begin
        if (answer = 'y') then
                      begin
                      LTSatFlow :=1710;
                      end
        else if (answer = 'n')then
                  begin
       writeln ('Input the single left-turn saturation flow value (integer).');
                      readln (LTSatFlow);
                      end
        else
                      begin
                      writeln ('ANSWER MUST BE EITHER y or n, PLEASE REENTER.');
                      end;
  end;
until ((answer = 'y') or (answer = 'n'));
Avg := AavgQ [InputRed,InputGaC,InputVol];
Max := AmaxQ [InputRed,InputGaC,InputVol];
Des  := round( Max * 0.85);
Delay := AQDelay [InputRed,InputGaC,InputVol];
end;

{************************************************************}
{This procedure is for inputting dual lt specific data.     }
{************************************************************}

procedure DLtInput;

begin
writeln;
writeln ('Enter the dual left-turn volume');
writeln('on a per lane basis (200,300,400,500,600,700 or 800 vph).');
readln (TempInputVol);
while not ((TempInputVol = 200) OR
    (TempInputVol = 300) OR
    (TempInputVol = 400) OR
    (TempInputVol = 500) OR
    (TempInputVol = 600) OR
    (TempInputVol = 700) OR
    (TempInputVol = 800)) DO
    begin
      writeln ('THE PER LANE LEFT TURN VOLUME MUST BE 200,300,400,500,600,700, OR 800 VPH,');
      writeln ('PLEASE REENTER THE THE PER LANE LEFT TURN VOLUME.');
      readln (TempInputVol);
      writeln (' ');
    end;

InputVol :=round(TempInputVol / 100);
TempInputGreen:= (TempInputCycle-TempInputRed-3.0);
```

```
writeln;
writeln ('Enter the peak 15 minute dual left-turn volume');
writeln ('on a per lane basis (must be less than or equal to 300 vehicles).');
readln (Peak15MinVol);

while ((Peak15MinVol < 0) OR (Peak15MinVol > 300)) do
   begin
     writeln ('PEAK 15 MINUTE VOLUME IS NOT WITHIN SPECIFIED RANGE, PLEASE REENTER.');
          readln (Peak15MinVol);
        end;

writeln;

repeat
writeln ('Do you want to use 1600 vph per lane as the saturation flow');
writeln('value for a dual left-turn operation (y or n)?');
  readln (answer);
  begin
         if (answer = 'y') then
                       begin
                       LTSatFlow :=1600;
                       end
         else if (answer = 'n')then
               begin
                       writeln('Input the dual left-turn saturation flow per lane (integer).');
                       readln (LTSatFlow);
                       end
         else
                       begin
                       writeln ('ANSWER MUST BE EITHER y or n, PLEASE REENTER.');
                       end;
  end;
until ((answer = 'y') or (answer = 'n'));
Avg := DualAavg [InputRed,InputGaC,InputVol];
Max := DualAmax [InputRed,InputGaC,InputVol];
Des  := round( Max * 0.85);
Delay := DualDel [InputRed,InputGaC,InputVol];
end;


{***************************************************************}
{This function calculates factorials.                           }
{***************************************************************}

function Factorial (num : extended): Extended;


var
        r : extended;
```

```
        i,intnum : integer;

begin
   intnum := round(num);
   r := 1;
        for i := 2 To intnum Do
                r := r * i;
        Factorial := r;
end;

{***********************************************************}
{This function calculates powers.                           }
{***********************************************************}

function Power (Base:extended; Expon:extended): extended;


begin
        Power := exp(Expon*ln(Base));
end;

{***********************************************************}
{This function converts integer types to strings.           }
{***********************************************************}

function IntToStr(j :longint):string;
var
        s: string[6];

begin
        Str(i,s);
        IntToStr := s;
end;



{***********************************************************}
{Main Program                                               }
{***********************************************************}

begin

{FIRST READ OF DATA IS FOR Average Queue Length             }


{READING DATA FOR CYCLE LENGTH = 60 SEC.                    }
   Open_AavgQ_Input_File(QLenUnit);
   For Red:= 3 TO 4 DO
       begin
           GaC := (6-Red);
```

```
            Read_AavgQ_Line (QLenUnit);
        end;
  {READING DATA FOR CYCLE LENGTH = 80 SEC                    }
     For Red:=4 TO 6 DO
        begin
            GaC := (8-Red);
            Read_AavgQ_Line (QLenUnit);
        end;
  {READING DATA FOR CYCLE LENGTH =100 SEC.                   }
     For Red:= 4 TO 8 DO
        begin
            GaC := (10-Red);
            Read_AavgQ_Line (QLenUnit)
        end;
  {READING DATA FOR CYCLE LENGTH =120 SEC                    }
     For Red:= 5 TO 9 DO
        begin
            GaC := (12-Red);
            Read_AavgQ_Line (QLenUnit);
        end;



  {SECOND READ OF DATA IS FOR Maximum Queue Length     }
     Open_AmaxQ_Input_File(QLenUnit);

  {READING DATA FOR CYCLE LENGTH = 60 SEC.                   }
     For Red:= 3 TO 4 DO
        begin
            GaC := (6-Red);
            Read_AmaxQ_Line (QLenUnit);
        end;
  {READING DATA FOR CYCLE LENGTH = 80 SEC                    }
     For Red:=4 TO 6 DO
        begin
            GaC := (8-Red);
            Read_AmaxQ_Line (QLenUnit);
        end;
  {READING DATA FOR CYCLE LENGTH =100 SEC.                   }
     For Red:= 4 TO 8 DO
        begin
            GaC := (10-Red);
            Read_AmaxQ_Line (QLenUnit)
        end;
  {READING DATA FOR CYCLE LENGTH =120 SEC                    }
     For Red:= 5 TO 9 DO
        begin
            GaC := (12-Red);
            Read_AmaxQ_Line (QLenUnit);
        end;
```

```
{THIRD READ OF DATA IS FOR Average Queue Delay   }
  Open_AQDelay_Input_File(QLenUnit);

{READING DATA FOR CYCLE LENGTH = 60 SEC.                 }
  For Red:= 3 TO 4 DO
     begin
         GaC := (6-Red);
         Read_AQDelay_Line (QLenUnit);
     end;
{READING DATA FOR CYCLE LENGTH = 80 SEC                  }
  For Red:=4 TO 6 DO
     begin
         GaC := (8-Red);
         Read_AQDelay_Line (QLenUnit);
    end;
{READING DATA FOR CYCLE LENGTH =100 SEC.                 }
  For Red:= 4 TO 8 DO
     begin
         GaC := (10-Red);
         Read_AQDelay_Line (QLenUnit)
     end;
{READING DATA FOR CYCLE LENGTH =120 SEC                  }
  For Red:= 5 TO 9 DO
     begin
         GaC := (12-Red);
         Read_AQDelay_Line (QLenUnit);
     end;



begin

{FOURTH READ OF DATA IS FOR Dual Average Queue Length            }


{READING DATA FOR CYCLE LENGTH = 60 SEC.                 }
  Open_DualAavg_Input_File(QLenUnit);
  For Red:= 3 TO 4 DO
     begin
         GaC := (6-Red);
         Read_DualAavg_Line (QLenUnit);
     end;
{READING DATA FOR CYCLE LENGTH = 80 SEC                  }
  For Red:=4 TO 6 DO
     begin
         GaC := (8-Red);
```

```
            Read_DualAavg_Line (QLenUnit);
        end;
{READING DATA FOR CYCLE LENGTH =100 SEC.                        }
    For Red:= 4 TO 8 DO
        begin
            GaC := (10-Red);
            Read_DualAavg_Line (QLenUnit)
        end;
{READING DATA FOR CYCLE LENGTH =120 SEC                         }
    For Red:= 5 TO 9 DO
        begin
            GaC := (12-Red);
            Read_DualAavg_Line (QLenUnit);
        end;


{FIFTH READ OF DATA IS FOR Dual Maximum Queue Length      }
    Open_DualAmax_Input_File(QLenUnit);

{READING DATA FOR CYCLE LENGTH = 60 SEC.                        }
    For Red:= 3 TO 4 DO
        begin
            GaC := (6-Red);
            Read_DualAmax_Line (QLenUnit);
        end;
{READING DATA FOR CYCLE LENGTH = 80 SEC                         }
    For Red:=4 TO 6 DO
        begin
            GaC := (8-Red);
            Read_DualAmax_Line (QLenUnit);
        end;
{READING DATA FOR CYCLE LENGTH =100 SEC.                        }
    For Red:= 4 TO 8 DO
        begin
            GaC := (10-Red);
            Read_DualAmax_Line (QLenUnit)
        end;
{READING DATA FOR CYCLE LENGTH =120 SEC                         }
    For Red:= 5 TO 9 DO
        begin
            GaC := (12-Red);
            Read_DualAmax_Line (QLenUnit);
        end;




{SIXTH READ OF DATA IS FOR Dual Average Queue Delay    }
    Open_DualDel_Input_File(QLenUnit);
```

```
{READING DATA FOR CYCLE LENGTH = 60 SEC.                }
  For Red:= 3 TO 4 DO
     begin
        GaC := (6-Red);
        Read_DualDel_Line (QLenUnit);
     end;
{READING DATA FOR CYCLE LENGTH = 80 SEC                 }
  For Red:=4 TO 6 DO
     begin
        GaC := (8-Red);
        Read_DualDel_Line (QLenUnit);
    end;
{READING DATA FOR CYCLE LENGTH =100 SEC.                }
  For Red:= 4 TO 8 DO
     begin
        GaC := (10-Red);
        Read_DualDel_Line (QLenUnit)
     end;
{READING DATA FOR CYCLE LENGTH =120 SEC                 }
  For Red:= 5 TO 9 DO
     begin
        GaC := (12-Red);
        Read_DualDel_Line (QLenUnit);
     end;
end;

ClearS;
StartScreen;
CloseGraph;


StartAgain:

writeln ('******************************************************************');
writeln ('THIS SECTION IS FOR DEFINING SIGNAL TIMING CHARACTERISTICS.');
writeln ('******************************************************************');
writeln;
writeln ('Enter the desired cycle length (60,80,100 or 120 seconds).');
readln (TempInputCycle);
while not((TempInputCycle = 60) OR
   (TempInputCycle = 80) OR
   (TempInputCycle = 100) OR
   (TempInputCycle = 120)) DO
     begin
       writeln ('THE CYCLE LENGTH IS NOT 60,80,100 OR 120 SECS. PLEASE REENTER THE CYCLE LENGTH.');
       readln (TempInputCycle);
       writeln (' ');
     end;
InputCycle :=round(TempInputCycle / 10.00);
writeln;
```

```
writeln ('Enter the left turn red phase length (30,40,50,60,70,80, or 90 secs.).');
writeln ('The G+Y/CL ratio must be between 0.2 & 0.6.');
readln (TempInputRed);
tempchk := round(((TempInputCycle-TempInputRed) / (TempInputCycle))*100);
      writeln (' ');
repeat
begin
                        if (TempChk < 2.0E+01) then
                                begin
                          writeln ('THE G+Y/CL RATIO MUST BE >= 0.2 AND <= 0.6.');
                     writeln ('PLEASE REENTER THE RED PHASE LENGTH SO THIS IS SATISFIED.');
                          readln (TempInputRed);
                                  writeln (' ');
                                        end;
                                        tempchk := round(((TempInputCycle-TempInputRed) / (TempInputCycle))*100);
         if (TempChk > 6.0E+01) then
                                begin
                          writeln ('THE G+Y/CL RATIO MUST BE >= 0.2 AND <= 0.6.');
                     writeln ('PLEASE REENTER THE RED PHASE LENGTH SO THIS IS SATISFIED.');
                          readln (TempInputRed);
                                  writeln (' ');
                                        end;

           while not
                           ((TempInputRed = 30) OR
                           (TempInputRed = 40) OR
                      (TempInputRed = 50) OR
                      (TempInputRed = 60) OR
                      (TempInputRed = 70) OR
            (TempInputRed = 80) OR
            (TempInputRed = 90)) DO
         begin
         writeln ('THE LEFT TURN RED PHASE LENGTH MUST BE 30,40,50,60,70,80, OR 90 SECONDS.');
         writeln ('PLEASE REENTER THE RED PHASE LENGTH SO THIS IS SATISFIED.');
                readln (TempInputRed);
           end;
end;
tempchk := round(((TempInputCycle-TempInputRed) / (TempInputCycle))*100);
until      ((TempChk >= 2.00E01) AND (TempChk <= 6.00E01)) AND
                                (((TempInputRed = 30) OR
                           (TempInputRed = 40) OR
                      (TempInputRed = 50) OR
                      (TempInputRed = 60) OR
                      (TempInputRed = 70) OR
            (TempInputRed = 80) OR
            (TempInputRed = 90)));

TempInputGreen :=(TempInputCycle-TempInputRed-3);

InputRed :=round (TempInputRed / 10);
InputGaC :=(InputCycle - InputRed);
```

```
writeln;
writeln ('PRESS RETURN TO ENTER VEHICLE CHARACTERISTICS');
readln;

ClearS;

writeln ('************************************************************');
writeln ('THIS SECTION IS FOR DEFINING THE VEHICLE CHARACTERISTICS.');
writeln ('************************************************************');

repeat
begin
writeln('Do you want to analyze a single or dual left-turn operation (s or d)?');
         readln (answer);
         if (answer <> 's') and (answer <> 'd') then
                      begin
                      writeln ('ANSWER MUST BE EITHER s or d, PLEASE REENTER.');
                      end;
end;
until ((answer = 's') or (answer = 'd'));
     if (answer = 's') then
        begin
        OpType:= 'SINGLE LEFT-TURN OPERATION';
                      SLtInput;
                      end
         else
              begin
                      OpType:= 'DUAL LEFT-TURN OPERATION - ALL STATISTICS ON PER LEFT-TURN LANE BASIS';
                      DLtInput;
                      end;


writeln;



{This section does the calcuations for the prob. of cycle failure table.}
repeat
   writeln ('Do you want to use 2.5 seconds as the average minimum ');
         writeln ('departure headway in the left-turning queue (y or n)?');
         readln (answer);
         if (answer = 'y') then
                      begin
                      AvgMinQSecs := 2.5;
                      end
         else if (answer = 'n')then
              begin
        writeln ('Input the average minimum departure headway in the left-turning queue.');
                      writeln ('(real seconds, i.e. 2.15).');
                      readln (AvgMinQSecs);
                      end
```

```
          else
                      begin
                      writeln ('ANSWER MUST BE EITHER y or n, PLEASE REENTER.');
                      end;
until ((answer = 'y') or (answer = 'n'));


ProbCF :=1.0;
CumProbCF :=0;
CycFailM := (((4.0) * (Peak15MinVol) * (TempInputCycle))/(3600.00));
CycFailX := (TempInputGreen) / (AvgMinQSecs);
TableX :=round(CycFailX);
while (ProbCF > 1.0E-07) do
        begin
   CycFailX := CycFailX + 1.0;
        ProbCF := (((Power(CycFailM,CycFailX)) *
                                  ( EXP(-CycFailM))/(Factorial(CycFailX))));
        CumProbCF := ProbCF + CumProbCF;
        end;




{This section calculates the delays used in the delay performance table.}

  begin
        GoC :=((TempInputGreen)/TempInputCycle);
   Qtexas := ((((GoC/3.0)+(0.5/TempInputCycle))*3600.00));
        Qhcm :=(LTSatFlow)*(GoC);
   VCtexas := (((TempInputVol/Qtexas)));
        VChcm := (((TempInputVol)/Qhcm));
  end;



{This section calculates the 85HCH delay term.}

D1hcm := (((0.38*TempInputCycle)*((1.0-GoC)*(1.0-GoC)))/
          (1.0-((GoC)*(VChcm))));
Basehcm :=  (((VChcm-1.0)*(VChcm-1.0))+((16.0*VChcm)/Qhcm));
D2hcm := ((173.0*(Sqr(VChcm)))*(((VChcm-1.0) + (Sqrt(Basehcm)))));
HCMTotDel := (round(D2hcm) + round(D1hcm));
Str(round(D1hcm),D1hcmstr);
Str(round(D2hcm),D2hcmstr);
Str(round(HCMTotDel), HCMTotDelStr);

writeln;

{This section calculates the Cycle Failure equation delay term.}
```

```
writeln('The number of cycle failures has a significant impact');
writeln('on the average queue delay.  Do you want to input any cycle');
writeln('failure information (y or n)?');
repeat
         readln (answer);
  begin
         if (answer = 'n') then
                      begin
                      Qo := 0;
                      end
         else if (answer = 'y')then
                begin
        writeln ('Input the average number of cycle failures per cycle');
                      writeln( 'per left-turn lane (real number, i.e. 3.2).');
                      readln (Qo);
                      end
         else
                      begin
                      writeln ('ANSWER MUST BE EITHER y or n, PLEASE REENTER.');
                      end;
  end;
until ((answer = 'y') or (answer = 'n'));
Cse :=0;
Ge:=TempInputGreen;
Re:=TempInputRed;
A:=((TempInputVol)/(3600));
P:=(LTSatFlow)/(3600);
N :=(A-P);
Qr :=(Qo+(A*Re)+(N*Ge));
NumVehs := ((TempInputVol*TempInputCycle) / (3600));
if (N<0) and (A=0) and (Qo<>0) then
       begin
   Dt :=((Qo*Re)+((Sqr(Qo))/(2*P)));
   Cse :=(1);
   Da :=(Dt/Qo);
       end

else if (N<0) and (A>0) and (Qr<=0) then
       begin
   Dt := ((Qo*Re)+((A*(Sqr(Re)))/2)+((Sqr((A*Re)+Qo))/(2*(Abs(N)))));
   Da :=(Dt/NumVehs);
   Cse :=(2);
       end

else if (N<=0) and (A>0) and (Qr>0) then
       begin
   Dt := (((Qo*Re)+((A*(Sqr(Re)))/2)+(((Abs(N))*(Sqr(Ge)))/2)
                      +((Qo+(A*Re)-((Abs(N))*Ge))*Ge)));
   Cse :=(3);
       Da :=(Dt/((TempInputVol*TempInputCycle)/3600));
```

```
else if (N>0) then
        begin
   Dt :=((Qo*Re)+((A*(Sqr(Re)))/2)+((Qo+(A*Re))*Ge)+((N*(Sqr(Ge)))/2));
        end
   Cse :=(A);
        Da :=(Dt/((TempInputVol*TempInputCycle/3600)));
        end

else
        begin
        end;

DelayCFTot :=(Da+D2hcm);
  repeat
  begin
         writeln;
     writeln ('Do you want to use 6 feet as the average ');
         writeln ('headway in the stopped queue (y or n)?');
         readln (answer);
         if (answer = 'y') then
                    begin
                    AvgQueHeadway := 6
                    end
         else if (answer = 'n')then
              begin
        writeln ('Input the average headway in the stopped queue');
                    writeln ('(integer feet, i.e. 4).');
                    readln (AvgQueHeadway);
                    end
         else
                    begin
                    writeln ('ANSWER MUST BE EITHER y or n, PLEASE REENTER.');
                    end;
  end;
until ((answer = 'y') or (answer = 'n'));


ReEnter:
PercentTotal:=0;
begin
writeln;
writeln ('How many different classes of vehicles are there?');

readln (NumVehClasses);
  TempTotalAvgQFt := 0;
  TempTotalMaxQFt := 0;
  TempTotalDesQFt := 0;
  for i := 1 to NumVehClasses do
     begin
                    writeln;
```

```
        writeln ('Input the percentage of vehicles in class ',i);
                 writeln ('(integer percentage, i.e. 52).');

        readln (Percentage[i]);
        IntPercent :=round(Percentage[i] * 100);
        Str(Percentage[i],PercentageStr[i]);
        writeln ('Input the length of vehicles in class ',i);
                 writeln ('(integer feet, i.e. 24).');
        readln (CarBodyLength);
        Length :=(CarBodyLength + AvgQueHeadway);
                 Str(CarBodyLength,CarBodyLengthStr[i]);
        AvgQFt := ((Percentage[i]/100.0) * Avg)*(Length);
        TempTotalAvgQFt :=  (AvgQFt + TempTotalAvgQFt);
                 MaxQFt := ((Percentage[i]/100.0) * Max)*(Length);
        TempTotalMaxQFt := (MaxQFt + TempTotalMaxQFt);
        DesQFt := (MaxQFt * 0.85);
        TempTotalDesQFt := (DesQFt + TempTotalDesQFt);
        PercentTotal := (PercentTotal + (Percentage[i]));
         end;

end;
while (PercentTotal <> 100) do
     begin
     writeln('THE TOTAL PERCENTAGE OF ALL VEHICLE CLASSES IS NOT EQUAL TO 100%,');
          writeln('PLEASE REENTER THE DATA.');
     goto ReEnter;
          end;

        TotalAvgQFt := round(TempTotalAvgQFt);
    TotalMaxQFt := round(TempTotalMaxQFt);
        TotalDesQFt := round(TempTotalDesQFt);

    writeln;
    writeln;
    writeln ('                        PRESS RETURN TO CONTINUE');
    readln;

        Str(Avg, AvgQStr);
    Str(Max,MaxQStr);
        Str(Des,DesQStr);
    Str(Delay,DelayStr);
        Str(TotalAvgQFt,TotalAvgQFtStr);
    Str(TotalMaxQFt,TotalMaxQFtStr);
    Str(TotalDesQFt,TotalDesQFtStr);
    Str(round(TempInputCycle),InputCycleStr);
    Str(round(TempInputRed),InputRedStr);
        Str(round(TempInputVol),InputVolStr);
    Str(round(CycFailN),CycFailNStr);
        Str(AvgMinQSecs,AvgMinQSecsStr);
        Str(round(TableX),TableXStr);
        Str(round(CumProbCF*100),CumProbCFStr);
        Str(round((round(CycFailN)/round(TableX)*100)),RatioArrToProcStr);
```

```
    NextStep;
         if (answer = 'n') then
                     begin
                     ClearS;
        Goto StartAgain;
                     end;
    close (QLenUnit);
ClearS;
end.
```