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Yellow and Red Intervals to Improve Signal Timing Plans for Left-Turn Movements

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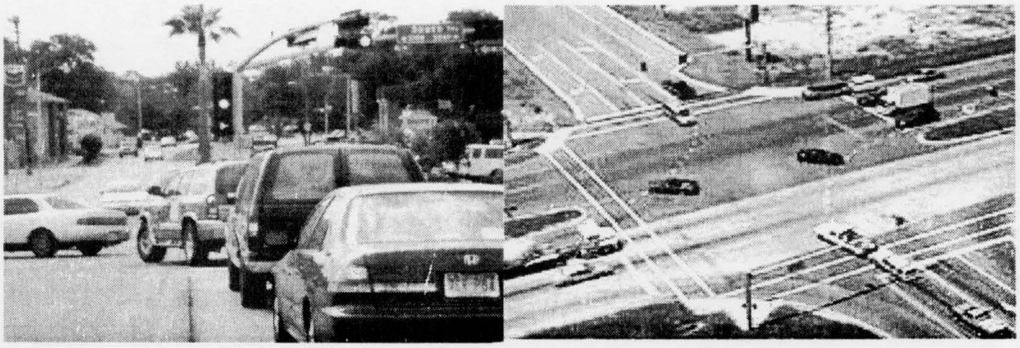

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16. Abstract

This project intends to develop and test a framework for setting yellow change and red clearance intervals for the left-turn movement, which can be used directly by the field traffic engineers in selecting the appropriate values for parameters in the proposed framework. The framework is designed to incorporate a comprehensive set of parameters related to intersection geometry, perception, human comfort, driver's behavior, safety issues, and traffic related laws. The application of this proposed framework is expected to improve both the left-turn movement safety and the efficiency at the intersection. This is the interim report for the project, which summarizes the work that has been performed during the first year (2001-2002) of this two-year project.

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SUMMARY

The signal interval between conflicting traffic movements has long been an important operational problem, in which the human comfort and perception factors, the traffic safety, the vehicle's driving behavior, the interpretation of the traffic laws, and the signal timing settings are all framed together. For years, the stop/proceed dilemma for motorists approaching a signal-controlled intersection has been studied, and the appropriate method for setting the yellow change and red clearance intervals for straight movements has been developed. However, the yellow change and red clearance intervals for turning movements are yet understood in both theory and practice. The lack of an appropriate method in determining the left-turn yellow change and red clearance intervals results in signal timings, which are either unsafe for left-turn vehicles or inefficient for the intersection.

This project intends to develop and test a comprehensive framework for setting yellow change and red clearance intervals for the left-turn movement, which can be used directly by the field traffic engineers in selecting the appropriate values for parameters in the proposed framework.

During the time period covered by this interim report (from September 2001 to August 2002), a review of the state-of-the-art and the state-of-the-practice was firstly conducted. As for the state-of-the-art, a number of mathematical formulas have been proposed for the calculation of yellow change interval in the past years by scientists and engineers. More updated researches are reflected on the evolution of ITE equations and guidance. However, most of these formulas are too simple to tell any differences among intersections, and few and fuzzy parameters are involved in the calculation, which could result in low accuracy. Furthermore, almost all of them were developed based on through-movement, and then the research specifically for left-turn movement is very scare.

Compared with yellow change interval, the red clearance interval is more involved with geometry parameters rather than human factors. Again, most of the relevant published researches

are for the through-movement, which incorporated the red clearance interval with the yellow change interval as a single one interval called yellow interval. The key point that existing methodologies suggest is how to determine the length of vehicles' moving curve and the speed, which will be left to the field engineers to fix. Liu, et.al. (2001) studied the calculation of the red clearance interval and considered much more parameters. But their methodology does not encourage including the red clearance deduction by considering the distance between potential conflict point and the other conflicting movement. This might make the red clearance a little longer than necessary.

As for the state-of-the-practice regarding yellow change and red clearance intervals, no nationwide techniques exist till now. The case of city of Lewisville, Texas provides an Excel spreadsheet that was developed to calculate vehicle clearances (yellow change and red clearance) and pedestrian clearance for a single intersection. Some engineers would like to choose an empirical time, or calculate based on the width of intersection, or use the ITE recommendation.

In order to identify major parameters that can be included in the proposed framework for determining yellow change and red clearance intervals for left-turn movement, a survey to transportation engineers, researchers, and executives was conducted. A review of the top 10 prioritized factors based on the survey analysis reveals that the number one concern of users was related to accident. Other factors include geometry, visibility and impeding factors, design, speed, traffic law and signal phasing.

The proposed framework for calculating the yellow change and red clearance includes two steps. Step 1 is to calibrate the model parameters using the field collected data. Step 2 calculates the yellow change and red clearance intervals based on the calibrated parameters.

To better collect the field data needed for model calibration and calculation, a data collection plan was developed in which a total of 20 intersections will be collected during peak and off-peak periods. There are two alternative data collection methods. The first method is to video tape each selected intersection and then to extract the data from these video tapes. The second data collection alternative is to collect the data in real time in the field using the appropriate measuring equipment.

The on-going work will be to continue the literature review so as to capture the state-of-the-art/practice. By fully establishing the steps and equations to calculate the yellow change and red clearance intervals, the development of the analytical framework will be completed. Then the data collection work will be conducted according to the data collection plan. Subsequently, the model will be calibrated based on the collected field data. Finally, the research report documenting the research findings and recommendations will be prepared.

CHAPTER 1 INTRODUCTION

1.1 Background of Research

Yellow change and red clearance intervals have been used to provide an orderly traffic transition by clearing an intersection of one traffic stream before allowing another conflicting stream to proceed. A yellow interval, definition of the sum of a "yellow change" interval and a following "red clearance" interval, is essentially put into the traffic light cycle to allow drivers to safely and efficiently make decisions to stop or proceed at stop line and to allow time for clearing the intersection. The signal interval calculation has long been an important operational problem, in which human comfort and perception factors, interpretation of the traffic ordinances, and signal timing, intertwine. These factors may not be compatible with each other in practice for all situations. This dilemma problem is very complex. The bottom line is that it is important to provide yellow change and red clearance sufficiently long enough for drivers approaching an intersection to eliminate or mitigate the dilemma.

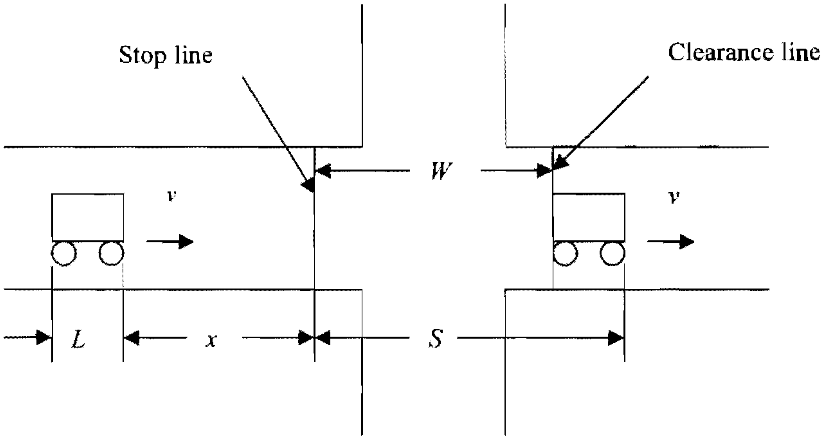


FIGURE 1 Through Movement in a Signal-Controlled Intersection

Figure 1 illustrates a motorist moving toward an intersection with speed v. When the yellow signal commences at a distance x, if he cannot make a comfortable full stop before the stop line, the yellow interval must be able to provide enough time to cover the distance of x and S, in other wards, clear the intersection. In Figure 1, W is the intersection width, L is the vehicle length, and S is the sum of W and L.

In the above case, if the distance x and S are too long for the motorist to cover before the onset of the green for conflicting traffic, a dilemma zone exists. This problem was examined in details by Liu, *el. al.* (1996). Their examination has shown that the dilemma zone associated with a speed less than the speed limit when the yellow indication commences can be eliminated, provided that the driver accelerates with an acceleration rate larger than, or equal to, a required critical acceleration, or accelerates with an available acceleration of linear functional form. However, it would be dangerous to advise drivers to follow the proverbial interpretation of the yellow indication as an instruction to "accelerate with caution." For this reason, the only sensible approach is to provide yellow change and red clearance intervals consistent with the reasonable human behavior. In this case, the required yellow change or red clearance interval is usually longer than what is being used in practice.

The above discussions are for the straight movement in general. Although some of these discussions could also be applied to left-turn movement, the unique characteristics of the left-turn movement make it essentially different from and more complex than the straight movement. The left-turn movement involves more dimensions and parameters that the straight movement does not. For convenience, a left-turn movement at a signal-controlled intersection can be conceptually divided into two stages. The first stage occurs when a motorist proceeds into an intersection during the yellow change; and the second stage takes place when the motorist makes a left-turn while experiencing a relatively high magnitude of acceleration on the left-turn curve.

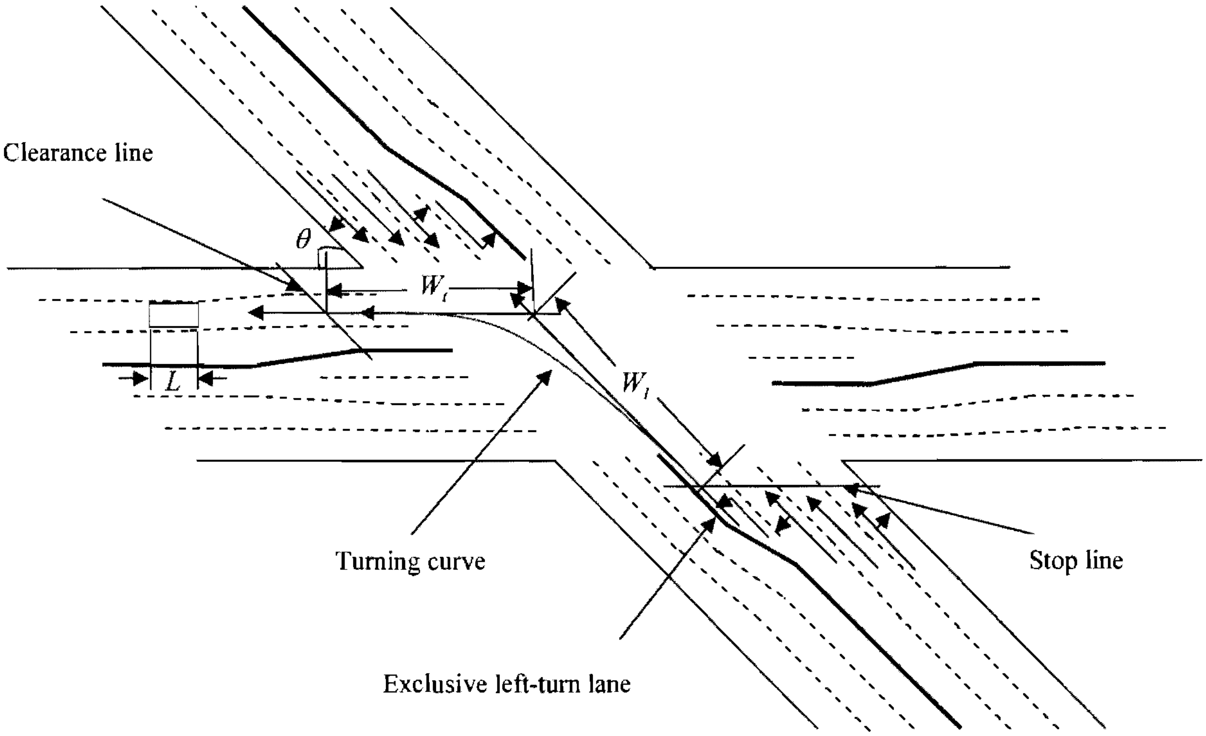


FIGURE 2 A Schematic Drawing of the Left-Turn Movement in a Signal-Controlled Intersection

The left-turn movement is symbolically sketched in Figure 2 for an intersection with a simple geometry. As show in Figure 2, the basic control parameters related with the left-turn movement include the length W_l, which depends on the number of crossing lanes; the width W_t, which depends on the number of opposing lanes; the vehicle length L; and the turning angle θ, which could be either an acute angle or an obtuse angle. Other factors that affect the left-turn movement include the speed limits on the approaching and crossing streets; left-turn curve entering speed; average speed along the curve; driver perception and reaction time; comfortable deceleration rate; driving behavior (type of turning curve); tolerable acceleration rate on the curve; and drivers' toleration of centrifugal force on the curve. Factors that also need to be considered include the distances between the stop lines of crossing and opposing streets and the potential conflicting points within the intersection, and the interpretation of the traffic ordinance.

As described above, the setting of yellow change and red clearance intervals for the left-turn movement is clearly more complex than the straight movement because of the number of controlling factors involved. As an example, simply consider the potential curve that each vehicle may follow in making the left turn. There are numerous possible curves that drivers may follow depending on the geometry of the intersection and each driver's driving behavior. Different types of curves make the required red clearance different. In another example, the approaching street and the crossing street may have different speed limits, which will complicate the driving behavior of vehicles making the left-turn movement. To maximize the operational efficiency of the intersection, the yellow change and the red clearance for the left-turn movement must be determined using a reliable method on an intersection-by-intersection basis.

The yellow interval problem is an example of the incompatibility of man-made laws and physically attainable human behavior. Longer yellow change or red clearance interval is viewed as undesirable by many traffic engineers because of delay it causes the traffic waiting along the cross-street. When insisting on using a short interval, one must combine it with a vehicle code that is compatible with the characteristics of drivers, vehicles, roads and signal operations. Although the Uniform Vehicle Code (National Committee on Uniform Traffic Laws and Ordinance, 1968) and the recent Institute of Transportation Engineers (ITE) report (ITE Technical Council Task Force, 1994) allow approaching vehicles to enter an intersection during yellow interval, they do not provide a solution for a driver in dilemma zone. For the safety concern, the yellow change and red clearance intervals must be long enough to guarantee that most of the drivers approaching an intersection at a reasonable speed within the speed limit will be able to not only enter the intersection before the onset of the red clearance interval, but also clear the intersection before the red clearance ends. Therefore, how to balance the trade-off between safety and efficiency concerns becomes an important problem in setting the yellow change and red clearance intervals, especially for left-turn movement.

1.2 Objectives of Research

The primary objective of this project is to develop and test a framework for setting yellow change and red clearance intervals for the left-turn movement, which can be used directly by the field traffic engineers in selecting the appropriate values for parameters in the proposed framework.

The framework will incorporate a comprehensive set of parameters related to intersection geometry, perception, human comfort, driver's behavior, safety issues, and traffic related law. The application of this proposed framework is expected to improve both the left-turn movement safety and the efficiency at the intersection.

1.3 Outline of This Report

This is the interim report of the project covering the work that has been done during the first year. In the following chapters of this report, the major existing methodologies proposed or adopted by different US agencies, especially those by state of Texas will be firstly presented. Then, the procedure of the survey for identifying the parameters and the analyses of the survey will be provided. Subsequently, a data collection for calibrating the framework will be presented. Finally, the on-going works of this project will be given.

CHAPTER 2 LITERATURE REVIEW

2.1 Review of State-of-the-Art

2.1.1 Yellow Change

The yellow change in traffic signal cycles at intersections is used to alert drivers of the imminent change in the direction of traffic flow. Upon observing the onset of yellow, the driver of a car approaching an intersection must make the decision of either stopping or continuing to cross the intersection. Among drivers who decide to enter the intersection, some will clear the intersection before the onset of the green for conflicting traffic flow, but others unable to do so. Vehicles that cannot clear the intersection can block the paths of cross-street traffic that have right of way. This kind of blockings and the accidents because of them could be reduced by adjusting the traffic signal timing. Specifically, changing the yellow change is to ensure every vehicle can stop safely before stop line or clear the stop line before the onset of the red phase, (the red clearance, the second stage of the left-turn movement, will ensure that the vehicles that pass the stop line can clear the intersection during the all-red clearance), in another way, eliminate the "dilemma zone."

Previous Studies

Table 1 is summary of previous studies by Stimpson, *et al.* (1980) on yellow change or yellow interval. Before we describe the equations in Table 1, Figure 3 as well as a description of symbols are provided in the following.

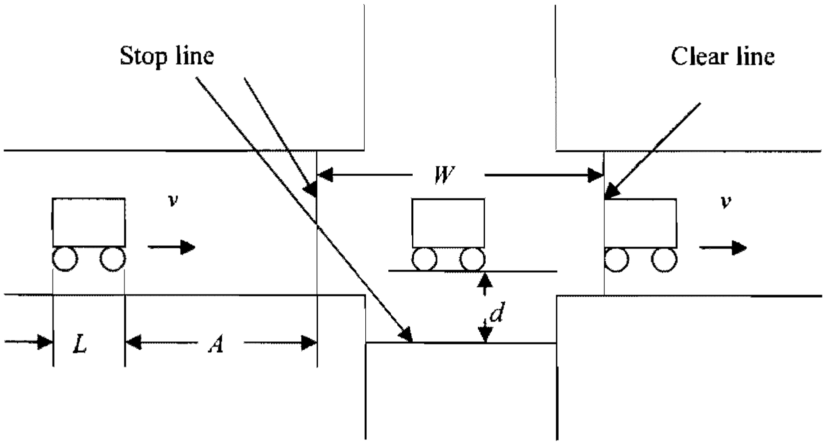


FIGURE 3 Symbols Used in Table 1

δ_{-} , t^*	Driver reaction times for stopping and starting
V, $V_{.85}$	Mean approach speed, 85th percentile of approach speed
W	Intersection width
L	Vehicle length
A	Distance from stop line at which desired percentile for stopping occurs
a, $a_{-0.85}$, a_{+}	Deceleration rate, 85th percentile of deceleration accepted, maximum acceleration of cross-flow traffic
d	Distance between vehicle and cross-flow stopline

The concept of "dilemma zone" was introduced in a quantitative form by Gazis *et al.* in 1960. The drivers who would neither stop safely nor clear the intersection before the onset the green for conflicting traffic flow are called "in the dilemma zone," if the yellow signal time duration is below a threshold value. Gazis *et al.* calculated the dilemma zone boundary in terms of speed of travel and distance from intersection at yellow signal onset and calculated the yellow signal time duration threshold at which the dilemma zone disappears. The formula in the paper is listed in Table 1 (Stimpson, *et al.* 1980).

What drivers do when caught in the dilemma zone has been investigated in several research projects. Crawford and Taylor (1961) observed driver decisions using eight subjects in repeated runs. In this experiment subjects faced onset of yellow at varying speed (20-60 mph) and at varying distances from the traffic signal (50-350 ft.). There were no other vehicles interfering with driver decisions and yellow interval was fixed at 3 seconds. At given speeds, the percentage of drivers that stopped was found to increase linearly with the distance from the intersection.

TABLE 1 Proposed Timing Formulae for Yellow Change or Yellow Interval (Source: Stimpson, *et al.* 1980)

Source	Year	Formula	Comment
1. Gazis, *et al.*	1960	$\delta_- + \frac{1}{2} \cdot \frac{V}{a} + \frac{W+L}{V}$	Velocity and deceleration assumed same for all drivers.
2. Crawford and Taylor	1961	$0.68 \cdot \left[\frac{W}{V} + KV^{3/5}\right]$	Constant K depends on proportion of responses; value of K obtained from one experiment and was not further validated.
3. Olson and Rothery	1962	$(A+W+L)/V$	No explicit rule for determining A is given.
4. Olson and Rothery	1972	5.5 sec.	... Amber periods of about 5.5 seconds are realistic... they provide a clearing time that allows all or nearly all motorists to clear an intersection. The limits of the applicability of the recommendation are unclear.
5. MUTCD	1971	3 ~ 6 sec.	Too unspecific to be useful.
6. Williams	1977	$\delta_- + \frac{V}{2a_{-0.85}} + \frac{W+L}{V_{0.85}} - \left(t^* + \sqrt{\frac{2d}{a_+}}\right)$	Cross street start-up and acceleration time is subtracted; traffic and pavement conditions are not accounted for.
(1) Transportation and Traffic Engineering Handbook 7 use same formula as 1.			
(2) Equations in source 1, 3, 4, and 5 are yellow interval, which includes red clearance.			

In 1962, Olson and Rothery determined the percentages of drivers stopping after yellow onset as a function of deceleration needed for stopping. He compared results between pairs of intersections that had different yellow durations but were otherwise similar. A formula for determining the duration of yellow in terms of approach speed, intersection width and "distance from intersection at which desired percentile cutoff (for stopping probability) occurs" was also derived (listed in Table 1). Olson and Rothery repeated some of their observations in 1972 and found that the percentages of drivers stopping increased at one and decreased at the other intersections during the intervening stage.

In 1977, Williams proposed a yellow interval formula which was proposed in terms of deceleration rate accepted by pre-assigned driver percentage, maximum acceleration rate of cross flow traffic, and other variables.

The equations listed in the Table 1 consider few factors of the intersection and drivers, therefore lacking accuracy. Most of the equations are too simple to tell any differences between intersections. To simplify the calculation, all of them just consider the lump sum of the yellow change and red clearance – yellow interval. Furthermore, all of these equations were developed based on through movement. The research specifying for left-turn movement is very scare although the left-turn movement has its unique characteristics. Along with the increasing traffic volume and development of the intersection, for instance, multiple left-turn lanes appear in more and more intersections, and further researches are required to incorporate more parameters related to the yellow interval into the setting of the yellow change and red clearance. It should be noted that the calculations listed in this section are either for the through movements and they might incorporate red clearance or not, or specific for left-turn movement and independent on red clearance. Nevertheless, all of them have the same methodology in the yellow change calculation. The specific red clearance calculation for left turn is reviewed in the next section.

More updated researches are reflected on the following ITE equations and guidance.

ITE Equations and Guidance

In addition to the above studies, ITE constantly updates its equation for calculating the yellow change based on a variety of researches. From the executive summary in Table 2 by Eccles and McGee (2001), newest guidance for determining the yellow interval length is provided in the *Traffic Engineering Handbook* (ITE, 1999). The equation for calculating the yellow interval, $y + r$ is as follows:

$$y + r = \delta_{-} + \frac{V}{2a + 64.4g} + \frac{W + L}{V} \qquad (1)$$

The principal factors that are taken into account in the development of the change period are:

- $\delta\_$ = perception-reaction time of the motorist
- V = speed of the approaching vehicle
- a = comfortable deceleration rate of the vehicle
- W = width of the intersection, as shown in Figure 4
- L = length of vehicle, as shown in Figure 4
- g = grade of the intersection approach

Still this equation is for through movement and does not consider sufficient parameters, such as speed limit, intersection angle, etc. This equation also gives no information about how to determine the approaching speed and why it is the most appropriate speed for calculating yellow change. The adopted speed here will largely affect the setting of the yellow change and need further research. Another drawback is the equation does not incorporate any information about the distance between the potential conflicting points and the stop line of the conflicting traffic flow. Disregard of the distance might result in unnecessary long yellow interval, thus decrease the efficiency.

Following Figure 4 shows a schematic intersection illustrating the symbols used by ITE equations.

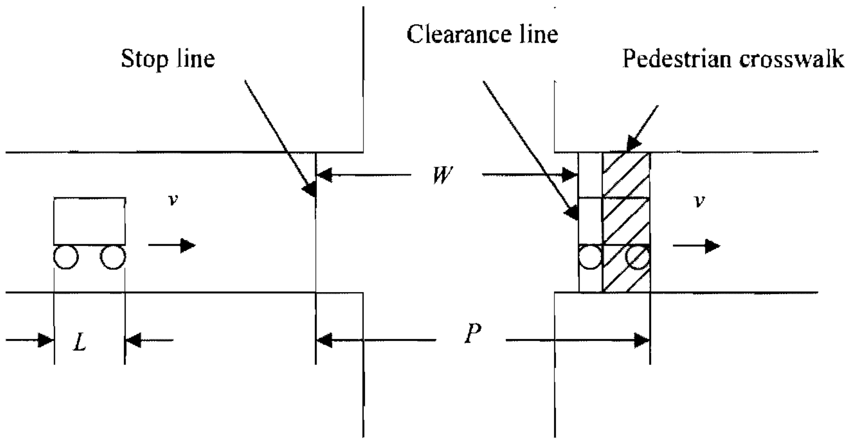


FIGURE 4 Intersection illustrating the symbols

The history of the suggested practices by ITE is summarized in Table 2 (Eccles and McGee, 2001). Comparing with early researches, current equation considers more characteristics of the traffic and the roadway environment. If there is a grade on the approach to the intersection, the equation adjusts the time needed for the vehicle to decelerate. In all of these equations, the most notable change in the suggested values involved a decrease in the assumed deceleration rate. The lower deceleration rate reflected a more realistic estimate of the time needed to comfortably stop a vehicle. The assumed approach speed (e.g. average speed, 85th percentile speed, posted speed limit) used to calculate the yellow change and any all-red clearance has also changed over the last sixty years. Presently the speed at which 85% of the vehicles are traveling at or below is used in the calculation. Consideration of the needs of vehicles traveling at slower speeds is also suggested (i.e. if additional time is required for them to traverse the intersection).

TABLE 2 Summary of History of ITE Equations and Guidance
(Eccles and McGee, 2001)

Year	Source	Equations	Discussion
1982	ITE Manual of Traffic Signal Design	$y = \delta\_ + \frac{1}{2}\frac{V}{a} + \frac{W+L}{V}$ $y = \delta\_ + \frac{V}{2a+64.4g} + \frac{W+L}{V}$	Equation calculates 'yellow change', as yellow change plus red clearance. 1st equation is same as 1965 and 1976. 2nd of the equations includes effect of grade on stopping ability. Some use first two terms rounded up to nearest 1/2 sec. as yellow change.
1985	ITE "Determining Vehicle Change Intervals: A Proposed Recommended Practice"	$y = \delta\_ + \frac{V}{2a+64.4g}$ $r = \frac{W+L}{V}, r = \frac{P}{V}, r = \frac{P+L}{V}$	1982 equation divided into 2 equations. First is yellow change. If used, second is red clearance, first becomes yellow change.
1992	ITE Traffic Engineering Handbook, 4th ed.	Same equations as 1985	Same equations and procedure as 1985
1999	ITE traffic Engineering Handbook, 5th ed.	$y = \delta\_ + \frac{V}{2a+64.4g} + \frac{W+L}{V}$	Third term of the kinematic equation is added back to the equation as it was in 1982. Application requires exercise of engineering judgment.

Notes: The equations are all represented in U.S. standard units. For ease of presentation, they have all been expressed with a uniform set of variables. The variables in the equations represent the following parameters: a=deceleration rate, ft/sec^2 ; g=grade of approach expressed as a decimal; L=length of the vehicle, feet; P=width of intersection, in feet, measured from the near side stop line to the far side of the farthest conflicting pedestrian crosswalk along the actual vehicle path; r=length of the all-red, seconds; $\delta\_$ *=perception-reaction time, seconds; W=width of the intersection; and V=approach velocity, feet/sec.*

An Analytical Approach

In the most recent work, Liu, *et al.* (2002) presents a research about the setting of the yellow change and red clearance intervals for left-turn movement. In the paper, the distance beyond which a vehicle approaching intersection at a speed v_0 cannot stop comfortably is given by:

$$x_a = v_0\delta_- + v_0^2 / 2a \qquad (2)$$

where δ_- and a are defined as the same ones as in ITE equations. When the driver makes the turn, the entering speed v_i is expressed by:

$$v_i = \begin{cases} \alpha v_t + (1-\alpha)v & \text{if} \quad v \le v_t \\ v_t & \text{otherwise} \end{cases} \qquad (3)$$

where v_t is the speed limit of approaching street, and v is the average approaching speed. Quantity α is a parameter, which depends on driver's behavior and decision. The yellow change interval is determined by:

$$y = 2(\delta_- + \frac{v_t}{2a})/(1 + \frac{v_i}{v_t}) \qquad (4)$$

2.1.2 Red Clearance

Red clearance, setting of the interval of the second stage of the left-turn movement has experienced considerable change over the past years. Comparing with the setting of the yellow change, red clearance is more involved with geometry parameters rather than human factors.

Previous Studies

Most of the published researches on red clearance are about the through movement and incorporated with the yellow change as yellow interval. Depending on the policy of the local agency, the red clearance for through movement is determined by one of the following expression:

$$r = \frac{W + L}{V} \qquad (5)$$

or $$r = \frac{P}{V} \quad (6)$$

or $$r = \frac{P + L}{V} \quad (7)$$

Where:

- r = length of red clearance interval, to the nearest 0.1 sec
- W = width of intersection, in feet, measured from the near-side stop line to the far edge of the conflicting traffic lane along the actual vehicle path, as shown in Figure 4
- P = width of intersection, in feet, measured from the near-side stop line to the far side of the farthest conflicting pedestrian crosswalk along the actual path, as shown in Figure 4
- L = length of vehicle, recommended as 20 ft
- V = speed of the vehicle through the intersection, in ft/sec

In the above Table 2, the summary about ITE equation and guidance on the yellow interval also includes the red clearance computation for through movement.

All of these equations suggest the key point in setting the red clearance which is how to determine the length of vehicles' moving curve and the speed. The equations here are left these problems to the field engineers to fix. However, problems in left-turn movement are much more complex, involving much more characteristics of intersections and drivers' behave, and cannot just leave them to be fixed according to the engineers' experience.

It currently has three basic categories of signal phasing for left-turn movement, varying on the local traffic demand and system progression needs.

- Unprotected left-turn phasing
- Protected-only left-turn phasing, and
- Protected/permissive left-turn phasing

Unprotected left-turn phasing: Left turns are made through gaps in the opposing traffic flow. Separate left-turn lanes may or may not be provided.

Protected-only left-turn phasing: When a separate interval is provided to accommodate a left-turn without conflicting traffic, and left turns are prohibited during the rest of the cycle, protected-only left-turn phasing occurs. Although the MUTCD (Manual of Uniform Traffic Control Devices, 1988) provides no left-turn phasing warrants, the Traffic Control Devices Handbook (Federal Highway Administration, 1999) offers suggested guidelines for setting separate left-turn phasing:

- Volumes. Consider further studies for separate left-turn phasing when the product of left-turning vehicles and opposing volumes during peak hours exceeds 100,000 on a four-lane street or 50,000 on a two-lane street, and the left-turn volume is greater than two vehicles per cycle.
- Accident experience. Install left-turn phasing if the critical number of left-turn accidents has occurred. For one approach, the critical number is four left-turn accidents in 1 year or six in 2 years. For both approaches, the critical number is six left-turn accidents in 1 year or 10 in 2 years.
- The delay is also a factor to consider for setting left-turn phase.

Protected/permissive left-turn phasing: Protected/ permissive left-turn phasing provides a protected phase during one interval and allows unprotected turns (on green) to be made through gaps in the opposing traffic flow during another intervals. One of the basic intentions of protected/permissive technique is that the protected green arrow is displayed only when needed in traffic demand condition

For setting the all-red clearance in protected left-turn movement, some researches, like Butler, J (1983) adopted equations similar to the ITE Guideline for through movement phases. Rather than specify a travel distance for each left-turn movement, the equations use a conservative estimate based on the length of the pedestrian turning movement, from curb to curb, to simplify the analysis. For example, the methodology taken by city of Lewisville (Black, 2001), the turning distance is simply given by:

$$S = \sqrt{W_l^2 + W_t^2} \cdot \mu \qquad (8)$$

Where W_l , W_t are the widths of the crossing street and approaching street, and parameter μ is given according to the geometry characteristics and traffic engineers' estimation. Again, the equation gives no information about how to set μ . These practices leave many factors to the wild guess, and are not accurate enough for both efficiency and safety.

The detail of a left-turn movement can be complex. In general, the expression for a red clearance interval can be expressed as:

$$r = S / V_c \tag{9}$$

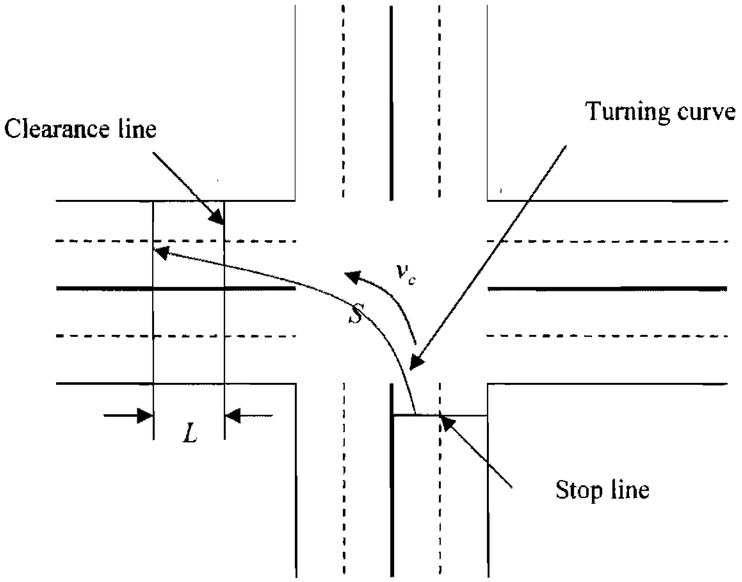


FIGURE 5 Calculation of the Red Clearance

The quantity S is the length of the curve measured from the stop line to L feet ahead of the clearance line, where quantity L is the length of an approaching vehicle. The quantity V_c is the average speed of the vehicle on the turning curve. In order to apply the equation, numerical values of the average speed V_c and the length of a curve S must be determined. Both numbers depend on the characteristics of the curve which a motorist chooses.

An Analytical Approach

Liu, *et.al.* (2002) studied the calculation of the red clearance. First, they assumed the turning angle be θ (in the unit of radian), the angle between the direction of the approaching and that of the clearing movements. The average curvature of the turning curve is found to be θ / S. Note that angle θ does not have to be $\pi/2$. It can be shown that the following relation holds for the curve so long as a motorist is not making several zigzag movements within the triangle of intersection (need not be a right triangle):

$$S_{\min} = [W_K{}^2 + W_l{}^2 + 2W_K W_l \cos\theta]^{1/2} \le S \le S_{\max} = W_K + W_l \qquad (10)$$

Quantity W_K equals $W_t + L$. The trajectory of a moving vehicle at an intersection is not well defined and the detail of the maneuver is almost up to the motorist's driving habit and perception about a driving environment. Thus, the length of the turning curve may be parameterized as

$$S = \beta S_{\max} + (1-\beta) S_{\min} \qquad (11)$$

Quantity $\beta \in (0,1)$. The curve could be a spiral, a circular curve, or a complex compound curve. By selecting a certain type of curve, one can estimate the exact value of parameter β. In general, a driver is willing to experience relatively high acceleration when taking parameter β to be close to zero; and the driver prefers a smoother ride when taking parameter β close to one. The average curvature for the turning curve is $k = \theta/S$; and its upper bound is $\theta / S_{\min}$. In the limit of θ approaching zero, the movement becomes straight. As mentioned earlier, driver behavior, size of vehicles, markers for left turns, and various other factors have effects on the characteristics of left-turn curves. Nevertheless, the magnitude of average centrifugal acceleration experienced by motorists is an important indicator in determining the duration that a vehicle spends in an intersection. The detailed evaluation of acceleration and speed along a turning curve is complex. However, adopting a dimensional type of analysis, we may calculate the average turning speed by imposing that:

$$k V_c^2 \le \gamma g \qquad (12)$$

Quantity γ may be selected in the interval [0.3, 0.8] (Liu, *et al*, 2001). Gazis (1960) and Stimpson (1980) indicate the number 0.3 has been selected as an 'alarming' acceleration rate; and Hammond (1941) indicates the number 0.8 has been used before to represent a large deceleration rate. The average speed on turning curves may be set according to

$$V_c = Min\{[\gamma g S / \theta]^{1/2}, \lambda V_l + (1-\lambda) V_{lt}\} \qquad (13)$$

Where: parameters V_{lt} and V_l are the speed limits for the crossing and straight (approaching) movements, respectively. Parameter λ, in the interval [0, 1], is to be chosen for a turning movement. If both speed limits V_{lt} and V_l are the same, the second term in the right hand side of the equation will be independent of λ. Introducing the parameter λ is necessary for establishing a bound value for the average speed along a turning curve. For most signal-controlled intersections, the first term at the right hand side of the equation is less than the second term. The average speed V_c along a turning curve should not exceed max $[V_{lt}, V_l]$ for all cases according to the equation. A possible choice is to approximate α by:

$$(W_l / V_l) \cdot [W_l / V_l + W_K / V_{lt}]^{-1} \qquad (14)$$

It is corresponding to a situation in which a vehicle is moving at speed limit along both side, approaching street and crossing street of the intersection.

Therefore, time duration needed for a motorist to clear off an intersection, red clearance, may be estimated using the following equation:

$$r = [\beta S_{\max} + (1-\beta) S_{\min}] / V_c \qquad (15)$$

The upper bound given by the equation is usually larger than the red clearance interval for through movement for most intersections if not for all. This result complies with the real situation in the intersection.

The equations here consider much more parameters related to the red clearance, and can be put into practice in some intersections after getting enough information to set the quantities. But this methodology does not encourage including the red clearance deduction by considering the distance between potential conflict point and the other conflict movement. This might make the red clearance a little longer than necessary.

2.2 Review of State-of-the-Practice

2.2.1 Case of City of Lewisville, Texas

The equation and method described below is a practice in the city of Lewisville, Texas, provided by Mr. John R. Black. The procedures are provided with an Excel spreadsheet that was developed to calculate vehicle clearances (yellow change and red clearance) and pedestrian clearance times (flashing don't walk) for a single intersection. Each user and agency must customize the spreadsheet equations to follow local policies and procedures. Please note that the application of this spreadsheet might have some restricts, for instance, it can only be applied in the intersection of right angle. Other restricts include that it incorporates very few parameters.

The spreadsheet compares clearance times in a traffic signal controller with calculated yellow change, red clearance and pedestrian clearance times to check compliance with the MUTCD and ITE guidelines. The methods used in the spreadsheet follow the recommended practice of The Institute of Transportation Engineers (ITE Technical Committee 4A-16, May 1985). In order to provide the complete information for the left-turn yellow change calculation adopted by this spreadsheet, the yellow change for through movement is provided for reference, while other documents about the red clearance for through movement and pedestrian clearance are not provided here.

Through Movement Yellow Change

City of Lewisville uses the latest ITE equation for setting yellow change:

$$y = \delta_{\_} + V_l \cdot \frac{1.467}{2a_{\_} + 2Gg} \qquad (16)$$

Where:

- y = length of the yellow change to the nearest .1 sec.
- $\delta_{\_}$ = driver perception reaction time, the city uses 1.1 sec
- V_l = proper speed limit of the approach (miles/hour)
- $a_{\_}$ = acceleration/deceleration rate, the city uses 10 ft/sec^2
- G = acceleration due to gravity, the city uses 32.2 ft/sec^2
- g = grade of the approach in %/100 (negative is downhill)

The equation is the same as listed in the Table 2, except City of Lewisville separate the second part as red clearance while ITE just included that as yellow interval.

Protected Left-Turn Yellow Change

There is no consensus for using yellow change and red clearance times applied to protected left-turns. The City of Lewisville uses a left-turn yellow change of 3". Calculated values of left-turn yellow change are usually lower than 3 seconds because left-turn approach speeds are so low.

Protected Left-Turn Red Clearance

The calculation of red clearance in the spreadsheet for protected left-turn phases is similar to the ITE Guideline for through movement phases. Rather than specify a travel distance for each left-turn movement, the spreadsheet uses a conservative estimate to simplify the analysis:

The distance traversed by the left-turning vehicle is estimated by:

$$S = 0.8\sqrt{XDIST^2 + YDIST^2} \qquad (17)$$

Where:

- $XDIST = XWALK$ for the adjacent through movement – W (width of 1 lane)
- $YDIST = XWALK/2$ for the through movement approaching from the right (left-turns point of view)
- $XWALK$ = width of the pedestrian x-walk, ft. curb to curb (lane line)

Then, the formula used in the spreadsheet to calculate the red clearance is:

$$r = \frac{S}{1.417 V_c} - \%tRl \cdot \delta_{-} \qquad (18)$$

Where:

- r (left) = red clearance interval rounded to the nearest .1"
- S = path of the left-turn vehicle, ft
- V_c = velocity (miles/hour) of the left-turn clearing vehicle
- $\%tRl$ = percentage of perception-reaction time to deduct from the red clearance.

- L = length of the vehicle (ft.) – assumed to be 20 ft
- δ_{-} = perception-reaction time

The practice here also has the same methodology as the one by ITE, simply using the 0.8 as μ value [Eq (8)], and gives no information to explain why. The practice also contains no information about how to get the velocity of left-turn clearing vehicle. The setting of μ and velocity are the two key points to set accurate red clearance both safely and efficiently.

2.2.2 General Case of US

Although a large majority of the traffic engineers are in favor of the establishment of a national technique for establishing the length of left-turn phase change intervals, and a significant proportion of these engineers wish to have any proposed national technique be able to take into account variations in local conditions, such national technique does not exist. The current techniques adopted by various cities in US can be summarized as follows.

Choosing an Empirical Time

According to a nationwide survey in the technical committee report by Colorado/Wyoming section, ITE in March 1985, the empirical time can be chosen such as:

- 3 s. yellow change; 1 s. red clearance at all locations
- 4 s. yellow change plus no red clearance
- 3 s. yellow change + 1.5 seconds red clearance
- 3 s. yellow interval for speeds less than 40mph; 4 s. yellow interval for speeds 40 to 50 mph; 5 s. yellow interval for speeds greater than 50 mph
- 3 s. yellow change with "appropriate" red clearance
- 3.5 s. yellow interval for 1-2 opposing lanes; 4.0 s. interval for 3 or more opposing lanes
- 3.5 s. (4 s. on multilane) yellow change; 0.5-1 s. red clearance for skewed intersection
- y=3 s. yellow change+ red clearance

Where: red clearance = 0.5 s. for 1 opposing lane
= 1.0 s. for 2 opposing lanes
= 1.5 s. for 3 or more opposing lanes

Based on Width of Intersection

Also in the same technical committee report, following equations were indicated, but the red clearances are not specified. They might have been incorporated into the equations, which makes the equations yellow intervals (yellow change plus red clearance), or just don't set red clearance in the field. The formulas are:

$$y = \delta_- + \frac{3v}{2a} + \frac{W + L}{v} \tag{19}$$

or

$$y = \delta_- + \frac{v}{2a} + \frac{W + L}{v} \tag{20}$$

- δ_- = 3 s. reaction time
- v = speed, ft/s. (assumed to be 20 mph for left turn vehicles)
- a = deceleration rate (assumed to be 12 ft/s^2)
- W = distance of vehicle travel from the stop bar turning into the nearest lane
- L = the vehicle length (assumed to be 20 ft)

The Other Methods

The method ITE recommended is also put into practice in many US cities:

Yellow change:
$$y = \delta_- + \frac{v}{2a + 64.4g} \tag{21}$$

Red clearance:
$$r = \frac{W + L}{v} \tag{22}$$

Where:

- y = yellow change
- g = percent approach grade/100 (add for upgrade, subtract for downgrade)
- r = red clearance

All kinds of methods have been currently adopted in various intersections, and all of these are based on the methodologies listed above. Generally, minimum yellow change for traffic should be based upon the critical speed, or determined from the prevailing speed or speed limit, if possible. The critical speed for a turn lane should be determined from the actual approach speed. Red clearance from one half to three seconds may be used. Red clearances are typically used to clear unusually wide intersections and at locations where heavy left turn traffic demand requires additional time to clear the intersection. A red clearance should only be used where applicable, in accordance with a traffic engineering study conducted to determine need.

CHAPTER 3 SURVEY TO IDENTIFY MAJOR PARAMETERS

In order to identify the major parameters that can be included in the proposed framework for determining yellow change and red clearance intervals for left-turn movement, a survey to the transportation engineers, researchers, and executives was designed. The parameters and their priorities can be determined from the analyses of the survey results. The purpose of this survey is to seek technical personnel's help in identifying and prioritizing all possible parameters that would potentially be included in the framework to be developed. The survey identified all pertinent factors deemed important, and assessed their relative priorities. The survey form is attached in Appendix I. Each parameter listed in the survey is given numbers from "1" to "5" with "5" having the highest priority and "1" having the lowest priority. The respondents circled a number that they think represents the level of importance of the parameter in determining the yellow change and red clearance intervals for left-turn movement.

The survey was conducted in November 2001 and mailed through e-mails to Texas Chapter ITE mailing list. Most of the responses were received by fax and some by e-mail. The names of the respondents are listed in Appendix II. Of all the 27 respondents, 13 are engineers, 5 are researchers and 9 are executives (Figure 6).

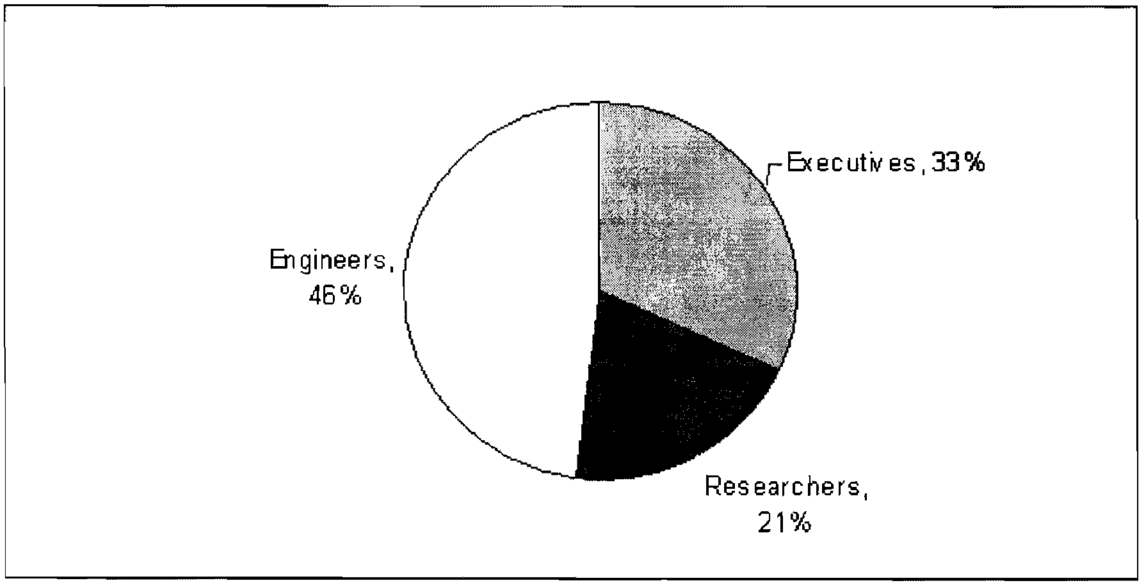


FIGURE 6 Illustration of Survey Respondents

From the responses, the prioritizations of the parameters evaluated by engineers, researchers, and executives were obtained. Engineers prioritized the top 10 parameters as:

1. Historical accident data due to left-turn movement
2. Visibility of traffic signals
3. Drivers' perception-reaction time
4. Average driving speed on the curve
5. Historical accident data at intersection
6. Intersection signal phasing structure
7. Numbers of approaching and crossing lanes and streets
8. Location of stop line and clearance line for left –turn movement
9. Curve entering speed, and Speed limits on approaching and crossing streets

Researchers prioritized the top 10 parameters as:

1. Numbers of approaching and crossing lanes and streets
2. Speed limits on approaching and crossing streets
3. Historical accident data due to left-turn movement

4. Average driving speed on the curve
5. Traffic laws related to signal controlled intersections
6. Drivers' perception-reaction time
7. Drivers' comfortable deceleration rate
8. Historical accident data at intersection
9. Deceleration and acceleration on the left-turn curve
10. Curve entering speed

Executives prioritized the top 10 parameters as:

1. Historical accident data due to left-turn movement
2. Number of total left-turn lanes
3. Numbers of approaching and crossing lanes and streets
4. Number of shared lanes for left-turn movement
5. Speed limits on approaching and crossing streets
6. Left-turn traffic volumes on approaching street
7. Visibility of traffic signals
8. Widths of approaching and crossing lanes and streets
9. Historical accident data at intersection
10. Turning angle (or angle between approaching and crossing streets)

The results of the scores and ranking from engineers, researchers, executives are listed in Tables 3 - 5. From the three tables we can see that engineers, researchers and executives provide different prioritization of parameters. For example, the engineers and the executives regard "Historical accident data due to left-turn movement" as the top one parameter, while the researchers think "Numbers of approaching and crossing lanes and streets" should be the top one parameter.

In order to give better and unique prioritization for the candidate parameters, one of the best ways is to prioritize the parameters based on the weighted sum of the scores from the three different sources.

Table 6 lists the results of one of the possible weighted scores. In this table, the weights chosen for engineers, researchers and executives are 40%, 30% and 30%, respectively. The reason why we give higher weight to engineers is not only because the number of the responded surveys from engineers is higher (46%), but also we think engineers should have more practical experiences, which is very important in the prioritization of the parameters. Based on these weighted scores, the prioritized top 10 parameters are determined as:

1. Historical accident data due to left-turn movement
2. Numbers of approaching and crossing lanes and streets
3. Visibility of traffic signals (traffic signal position, etc.)
4. Speed limits on approaching and crossing streets
5. Average driving speed on the curve
6. Historical accident data at intersection
7. Traffic laws related to signal controlled intersections
8. Drivers' perception-reaction time
9. Widths of approaching and crossing lanes and streets
10. Intersection signal phasing structure

A review of these top 10 prioritized factors from this table reveals that the number one concern of users was related to accident (#1 and #6). Other factors include geometry (#2 and #9), visibility and impeding factors (#3 and #8), design (posted) speed (#4 and #5), traffic law (#7) and signal phasing (#10).

TABLE 3 Parameters' Average Scores and Ranking from Engineers

Parameter Name	Ranking	Score
Historical accident data due to left-turn movement	1	4.38
Visibility of traffic signals (traffic signal position, etc.)	2	4.08
Drivers' perception-reaction time	3	3.85
Average driving speed on the curve	4	3.77
Historical accident data at intersection	5	3.77
Intersection signal phasing structure	6	3.77
Numbers of approaching and crossing lanes and streets	7	3.54
Location of stop line and clearance line for left –turn movement	8	3.54
Curve entering speed	9	3.46
Speed limits on approaching and crossing streets	10	3.46
Widths of approaching and crossing lanes and streets	11	3.38
Drivers' comfortable deceleration rate	12	3.38
Turning angle (or angle between approaching and crossing streets)	13	3.31
Trajectory of left-turn curve	14	3.23
Traffic laws related to signal controlled intersections	15	3.15
Left-turn traffic volumes on approaching street	16	3.08
Traffic volumes on approaching and crossing streets	17	3.00
Vehicle types	18	3.00
Drivers' toleration of centrifugal acceleration force	19	2.92
Vehicle sizes	20	2.92
Distances between potential conflicting points and stop lines	21	2.92
Number of total left-turn lanes	22	2.77
Deceleration and acceleration on the left-turn curve	23	2.77
Number of shared lanes for left-turn movement	24	2.15
Lane assignment on approaching street	25	2.15

TABLE 4 Parameters' Average Scores and Ranking from Researchers

Parameter Name	Ranking	Score
Numbers of approaching and crossing lanes and streets	1	4.20
Speed limits on approaching and crossing streets	2	4.20
Historical accident data due to left-turn movement	3	4.20
Average driving speed on the curve	4	4.00
Traffic laws related to signal controlled intersections	5	4.00
Drivers' perception-reaction time	6	3.80
Drivers' comfortable deceleration rate	7	3.80
Historical accident data at intersection	8	3.80
Deceleration and acceleration on the left-turn curve	9	3.60
Curve entering speed	10	3.60
Distances between potential conflicting points and stop lines	11	3.60
Visibility of traffic signals (traffic signal position, etc.)	12	3.60
Widths of approaching and crossing lanes and streets	13	3.40
Turning angle (or angle between approaching and crossing streets)	14	3.40
Number of total left-turn lanes	15	3.40
Trajectory of left-turn curve	16	3.40
Drivers' toleration of centrifugal acceleration force	17	3.20
Left-turn traffic volumes on approaching street	18	3.20
Intersection signal phasing structure	19	3.20
Location of stop line and clearance line for left –turn movement	20	3.00
Number of shared lanes for left-turn movement	21	3.00
Traffic volumes on approaching and crossing streets	22	3.00
Lane assignment on approaching street	23	3.00
Vehicle types	24	3.00
Vehicle sizes	25	2.60

TABLE 5 Parameters' Average Scores and Ranking from Executives

Parameter Name	Ranking	Score
Historical accident data due to left-turn movement	1	4.13
Number of total left-turn lanes	2	4.00
Numbers of approaching and crossing lanes and streets	3	3.75
Number of shared lanes for left-turn movement	4	3.75
Speed limits on approaching and crossing streets	5	3.75
Left-turn traffic volumes on approaching street	6	3.63
Visibility of traffic signals (traffic signal position, etc.)	7	3.63
Widths of approaching and crossing lanes and streets	8	3.50
Historical accident data at intersection	9	3.50
Turning angle (or angle between approaching and crossing streets)	10	3.38
Average driving speed on the curve	11	3.38
Traffic laws related to signal controlled intersections	12	3.38
Traffic volumes on approaching and crossing streets	13	3.25
Lane assignment on approaching street	14	3.25
Vehicle types	15	3.25
Vehicle sizes	16	3.25
Location of stop line and clearance line for left –turn movement	17	3.13
Curve entering speed	18	3.00
Drivers' toleration of centrifugal acceleration force	19	3.00
Intersection signal phasing structure	20	3.00
Drivers' comfortable deceleration rate	21	2.88
Distances between potential conflicting points and stop lines	22	2.88
Deceleration and acceleration on the left-turn curve	23	2.75
Drivers' perception-reaction time	24	2.63
Trajectory of left-turn curve	25	2.50

TABLE 6 Parameters' Weighted Scores from All Respondents and Their Ranking

Parameter Name	Weighted-score	Ranking
Historical accident data due to left-turn movement	4.25	1
Numbers of approaching and crossing lanes and streets	3.80	2
Visibility of traffic signals (traffic signal position, etc.)	3.80	3
Speed limits on approaching and crossing streets	3.77	4
Average driving speed on the curve	3.72	5
Historical accident data at intersection	3.70	6
Traffic laws related to signal controlled intersections	3.47	7
Drivers' perception-reaction time	3.47	8
Widths of approaching and crossing lanes and streets	3.42	9
Intersection signal phasing structure	3.37	10
Curve entering speed	3.36	11
Drivers' comfortable deceleration rate	3.36	12
Turning angle (or angle between approaching and crossing streets)	3.36	13
Number of total left-turn lanes	3.33	14
Left-turn traffic volumes on approaching street	3.28	15
Location of stop line and clearance line for left –turn movement	3.25	16
Distances between potential conflicting points and stop lines	3.11	17
Traffic volumes on approaching and crossing streets	3.08	18
Vehicle types	3.08	19
Trajectory of left-turn curve	3.06	20
Drivers' toleration of centrifugal acceleration force	3.03	21
Deceleration and acceleration on the left-turn curve	3.01	22
Vehicle sizes	2.92	23
Number of shared lanes for left-turn movement	2.89	24
Lane assignment on approaching street	2.74	25

CHAPTER 4 DEVELOPMENT OF ANALYTICAL FRAMWORK

This chapter will present the development of the analytical framework for calculating the yellow change and red clearance for left turn movement. The block diagram of the framework will be firstly introduced. Then the field data that will be used to calibrate the parameters will be explained individually. After that, the process of parameter calibration will be given and the formulas for calculating the yellow change and red clearance will be provided. Finally, the flowchart of the computer program is presented.

4.1 Block Diagram of Analytical Framework

The framework for calculating the yellow change and red clearance includes two steps. In step 1, the raw field data will be used in calibrating three quantities α, β and γ, which will be incorporated directly into the model. These parameters will be described in detail later. After calibration, the recommended values for the three parameters will be given according to the specific field environment. In step 2, the yellow change and red clearance intervals will be calculated based on the calibrated parameters.

Figure 7 shows the block diagram of the analytical framework to calculate the yellow change and red clearance. From the block diagram we can see that the raw field data are to be used for the calibration of parameters. Both the raw field data and the calibrated parameters will be used for the calculation of yellow change and red clearance.

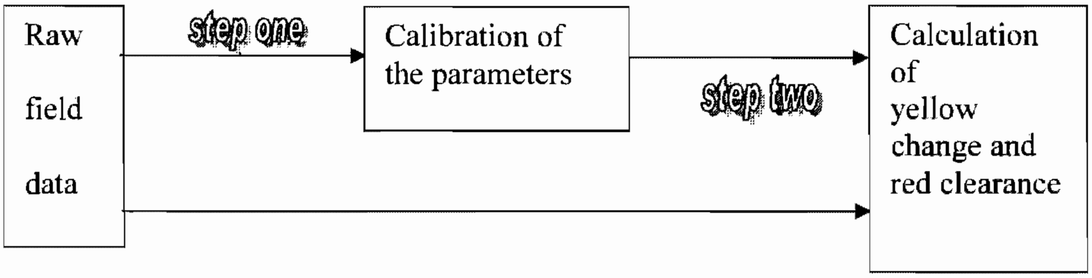


FIGURE 7 Block Diagram of Analytical Framework

4.2 Notation

The following symbols are used in the framework:

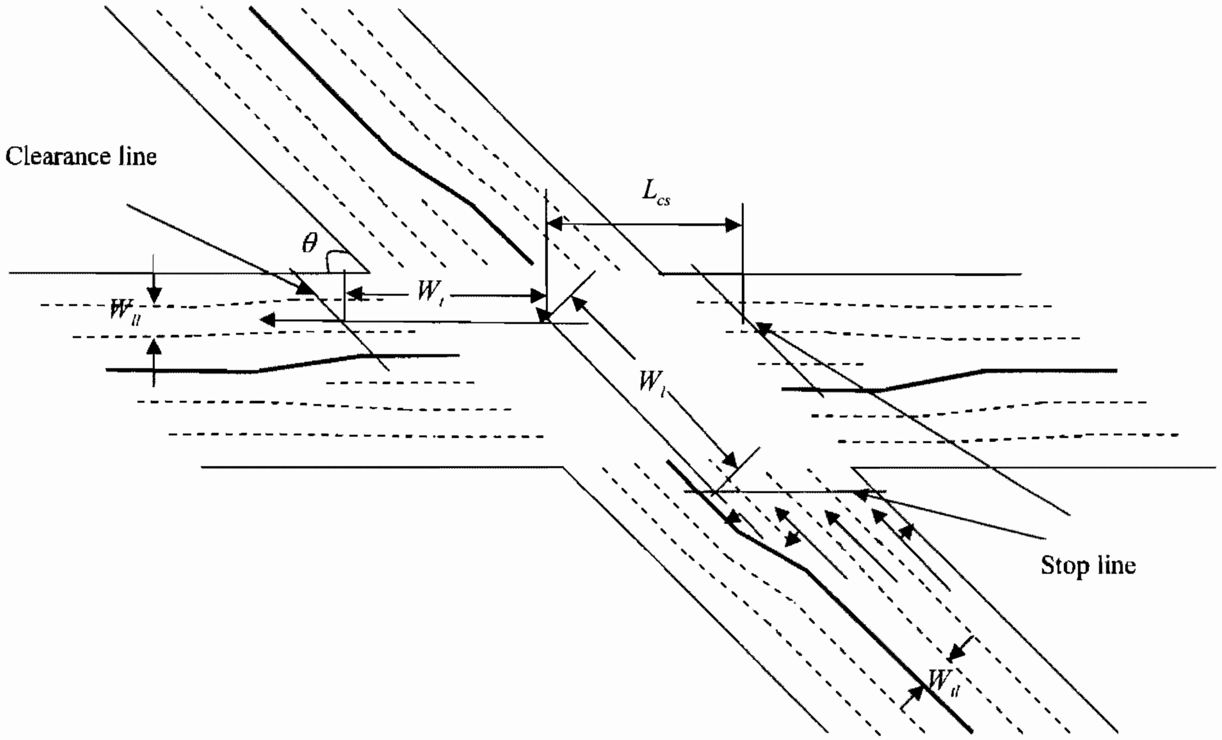


FIGURE 8 Symbols used in the framework

a_- / a_+ = comfortable deceleration/acceleration rate (feet/s^2)

g = gravity acceleration rate on Earth (feet/s^2)

L = vehicle length (feet)

S = length of turning curve for left-turn movement (feet)

δ_{-} = drivers' perception-reaction time (s)

$L_{threshold}$ = threshold distance of comfortable signal visibility (feet)

L_{vi} = distance of signal visibility (feet)

W_t = width of approaching street, as in Figure 8 (feet)

W_l = width of crossing street, as in Figure 8 (feet)

W_{tl} =width of approaching lanes, as in Figure 8 (feet)

W_{ll} = width of crossing lanes, as in Figure 8 (feet)

t = number of crossing lanes

l = number of left-turn or shared lanes in approaching street

ξ = correction factor for multiple left-turn lanes or crossing lanes

$V_{0.85}$ = 85% percentile driving speed (miles/h)

T_{vi} = additional time in yellow change for short visibility of signals

α = dimensionless quantity range from 0 to 1

β = dimensionless quantity range from 0 to 1

γ = dimensionless quantity range from 0 to 1

λ = dimensionless quantity range from 0 to 1

V_t = speed limit on the approaching street (miles/h)

V_l = speed limit on the crossing street (miles/h)

V_i = speed when entering intersection for making left turn (miles/h)

V_c = average speed of vehicle on turning curve (miles/h)

θ = intersection angle between approach and departure direction (radians)

T_{cs} = time deducted from red clearance (s)

L_{cs} = distance between conflict point and (opposite/ cross street's) stop line (feet), (L_{cs} in Figure 8 is the one in left-turn lag scenario)

y = yellow change (s)

r = red clearance (s)

4.3 Field Data

Field data is the source of information for calibration and calculation process. Most of the field data are to be collected directly from target intersections. Some of these data are used to calculate the parameters that can be incorporated into the calculation model, while the others will be used for the calibration of parameters. Some empirical values, such as comfortable acceleration or deceleration rate, and drivers' reaction time, are also treated as raw field data, although they might not be collected from each intersection. The field data are listed in the following with brief descriptions:

1. **Drivers' perception-reaction time.** Drivers' perception-reaction time, which is the time drivers need to capture any signal change and make a reaction to the change, is one of the major reasons for setting yellow change interval. This value directly affects the calculation of the yellow change interval.

2. **Visibility of traffic signals (traffic signal position, etc).** When a vehicle approaches an intersection, the position of traffic signal obviously influences the driver's decision on whether to go ahead to go through the intersection or stop. Then, if derivers cannot clearly discern the red signal or green from a reasonable distance, the drivers' decisions will be delayed and affect the yellow change they need. From the above analysis, visibility of traffic signals is defined as the maximum distance between signal stand and the vehicle where its driver can see the signal clearly while driving.

3. **Widths of approaching and crossing lanes and streets.** Widths of approaching street and crossing street are defined as shown in Figure 8. It's a major factor that decides the distance a vehicle should pass for clearing the intersection.

4. **Left-turn traffic volumes on approaching street.** In intersections with high left-turn volumes, the distances between the vehicles might be too short to let the vehicles have relatively high speed. Under these circumstances, vehicles may enter the intersection with lower speed. Further analysis, however, finds that for the vehicles approaching an intersection at a speed lower than the calculated entering speed, (which is a parameter that is used as standard speed to calculate the yellow change and will be discussed later), the yellow change needed to eliminate dilemma zone is always shorter. Therefore, the yellow change adopted should always satisfy these situations.

5. **Vehicle types.** Generally, since different types of vehicles have different accelerate/decelerate abilities, all vehicle types should be considered in the interval calculation. However, too many vehicle types make it impossible to give specific consideration to each vehicle type. For the convenience of calculation, a "general" vehicle type considering every type of vehicles has been used in the research. Nevertheless we might consider some particular intersections where trucks have a significant percentage. In the intersection where truck percentage against total volume increases to a certain level, a correction factor might be given for their special speed, acceleration/deceleration ability and length.

6. **Lane assignment on approaching street.** There are different types of lane assignment on approaching street, including left-turn lanes and shared lanes. The different assigned lanes will be numbered separately in the research. The number of the lanes as well as the lane assignment might affect the turning curve length.

7. **Drivers' comfortable deceleration rate.** At the onset of yellow, if the driver decides to stop before stop line, time the vehicle needs from the enforcement of brake and complete stop is partly decided by deceleration rate. This time is the other part in the yellow change interval other than drivers' perception-reaction time. Mostly, the comfortable deceleration rate is set as $10\ \text{feet/sec}^2$, as in the Recommended Practice by ITE in 1985.

8. **Drivers' toleration of centrifugal acceleration force.** Clearly, centrifugal acceleration force is totally dependent on the turning speed, given a certain turning curve. Therefore, this will be a major factor in setting the red clearance.
9. **Historical accident data.** Historical accident data also belong to the field data. However, the causes for accidents vary very much, such as geometry problems, signal timing problems. Beside that, accurate accident data are very difficult, if not impossible to obtain. So, it is hard to incorporate historical accident data directly into calculation model. For considering this important factor, the historical accident data, together with the current yellow change and red clearance setting, can be used to judge the effectiveness of the model. In the situation that has high historical accident rate, it might imply potential problems of too short yellow change and/or red clearance.
10. **Traffic laws**. Traffic law may or may not allow a vehicle to enter the intersection in the yellow phase. In some cases, it creates a portion before the intersection called dilemma zone. This model is intended to eliminate this dilemma zone through proper setting of yellow change and red clearance.
11. **The other field data**. The field data may also include some data about the physical characteristics of intersections and vehicles:
    - Distances between potential conflicting points and stop lines
    - Turning angle (or angle between approaching and crossing streets)
    - Numbers of approaching and crossing lanes and streets
    - Speed limits on approaching and crossing streets
    - Number of total left-turn lanes
    - Number of shared lanes for left-turn movement
    - Vehicle sizes

4.4 Parameters Calibrated From the Field Data

After the preparation of the field data, several parameters can be calibrated and/or calculated from the field data. Setting of yellow change and red clearance intervals are directly based on these parameters. The calculation of some parameters might involve more than one field data, while some might be related to the other parameters.

Correction factor for numbers of approaching and crossing lanes

In the intersection of multiple approaching lanes and/or crossing lanes, vehicles at the outer left turn curve might take more time to clear the intersection than vehicles in the inner curve. Thus, red clearance may be decided based on the outer curve. These time gaps are solely caused by the curve length (Figure 9, curve AB and $A'B'$). Considering the fact that the curves are somewhat in parallel, a correction factor is given to red clearance model for the single left-turn approaching and crossing lane, which is always the insider lane.

In the intersection where the number of crossing lanes is t and the number of the approaching left-turn exclusive and shared lanes is l, correction factor is calculated by the distance of circles of the outside left-turn lanes, according to the intersection width and lane width. The formula is:

$$\xi = \sqrt{(W_t + (l-1)W_{tl})^2 + (W_l + (t-1)W_{ll})^2} \,/\, \sqrt{W_t^{\,2} + W_l^{\,2}} \qquad (23)$$

where, ξ is the intended correction factor.

For the case of multiple approaching left-turn lanes and crossing lanes, this factor is defined as the ratio of the length of the outside curve to the length of the inside curve, which are illustrated in Figure 9 as curve $A'B'$ and curve AB. Because actual left-turn curves are always unavailable, this ratio is estimated by the length of line $A'B'$ and AB. When the turning angle is not the right one, the length of line $A'B'$ and AB may involve angle θ. But because the lines themselves are used to estimate the ratio of curves, we can also use the above equation to approximate the real case.

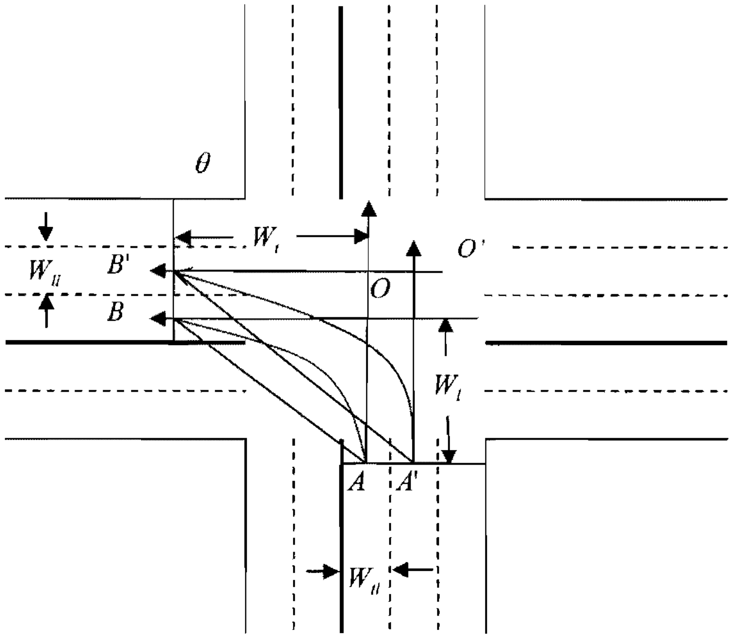


FIGURE 9 Turning Curve for Different lanes

Time delay from low visibility of traffic signals (traffic signal position, etc)

As mentioned before, visibility of traffic signals is defined as the maximum distance between the signal stand and the vehicle where its driver can see the signal clearly while driving. Yellow change interval might be affected by insufficient visibility.

In some situation, visibility of traffic signals may delay the driver's perception. If the drivers cannot see the signals clearly from a certain distance when approaching the intersection, it might take time to discern the signals and then react in a location where is too close to the intersection. When the visibility distance is longer than a threshold within which the drivers begin to make the decision, it has no effect on the calculation of yellow change and red clearance. In the intersection where visibility distance is shorter than the threshold, a time T_{vi} should be incorporated into yellow change. The time T_{vi} will be the additional time for driver to cover the loss because of the short visibility of signals.

$$T_{vi} = Max\left[0, 0.6820(L_{threshold} - L_{vi}) / V_{0.85}\ \right] \qquad (24)$$

where, 0.6820 is set for different units in the equation, $V_{0.85}$ is 85% percentile speed on the approaching lanes, in miles/h. L_{vi} is the distance of visibility of traffic signals, in feet. $L_{threshold}$ is the threshold distance, in feet, which will be determined after the calibration.

If the L_{vi} is longer than $L_{threshold}$, T_{vi} should be zero.

Entering speed calculated from speed limits on approaching and crossing streets

For yellow change interval, the speed limit on approaching street will affect vehicle's entering speed. When entering the intersection, a motorist can either decelerate or accelerate toward the intended entering speed that can be less or equal to the speed limit on the approaching street. The entering speed V_i might be expressed in terms of speed limit of the approaching street V_t and 85% percentile speed $V_{0.85}$:

$$\begin{cases} V_i = \alpha V_t + (1-\alpha)V_{0.85} & \text{If } V_{0.85} \le V_t \\ V_i = V_t & \text{Otherwise} \end{cases} \qquad (25)$$

Quantity α, located in the interval [0, 1], is to be chosen for a turning movement from the calibration of the model. If $V_{0.85}$ and V_t are equal, the second term in the right hand side of the equation will be independent of α.

For red clearance setting, speed limits will also affect the calculation of average driving speed on the curve V_c, which will be described in detail later.

Length of turning curve based on the widths of approaching and crossing lanes and streets

The actual turning curve, which can be estimated as $\sqrt{W_l^2 + W_t^2 + 2W_lW_t\cos\theta}$, is always unavailable, but which should be somewhere between the two extremes, which are the longest distance, $W_l + W_t$, and the shortest cut distance.

The following equation calculates the length of actual turning curve.

$$S = \beta(W_l + W_t) + (1-\beta)\sqrt{W_l^2 + W_t^2 + 2W_lW_t\cos\theta} + L \qquad (26)$$

where, the quantity β is used to adjust and simulate the actual curve and will be calibrated by the field data and L is the vehicle length.

Average driving speed on the curve

There are two factors that will affect the average driving speed on the curve. First one is the comfortable centrifugal acceleration. The turning speed may not be limited by the comfortable centrifugal force for driver. According to the centrifugal force law, given "comfortable" centrifugal force as γg, the speed should not exceed the $0.6820\sqrt{\gamma g S/\theta}$. The other factor is speed limits on the approaching street and crossing street. We might consider the average speed to be $\lambda V_t + (1-\lambda)V_l$, for either accelerating from V_t to V_l, or decelerating from V_t to V_l.

Average driving speed V_c will be calculated as:

$$V_c = Min[0.6820\sqrt{\gamma g S/\theta},\ \lambda V_t + (1-\lambda)V_l] \qquad (27)$$

Where S is the length of actual turning curve, and θ is the angle of the intersection. In the equation, Quantity λ may be selected in an interval decided by calibration of the model.

Time deduction for distances between potential conflicting points and stop lines

When the green signal is given to the conflicting traffic, it takes time for vehicles to reach the conflicting point. Portion of the time can be deducted from the red clearance. The time can be the one that vehicles take from full stop to accelerate and to reach the conflicting point (in case of driver's anticipating green in this situation, the time calculated below does not include the perception-reaction time), or the time for a driving vehicle to take from stop line to conflicting point, which ever is less.

Here, the L_{cs} is the distance between conflict point and opposite stop line if the signal phase is left-turn before through movement (left-turn lead scenario), or the distance between conflict point and crossing stop line if the signal phase is left-turn after through movement (left-turn lag scenario). For the safety consideration, the percentage of the time used to deduct from red clearance is set as 90%, as recommended by City of Lewisville (2001).

It will reduce the red clearance by deducting a deduction factor- T_{cs} , which is calculated as follows:

$$T_{cs} = \%tRl * Min[\frac{2L_{cs}}{a_+^2},\ 0.6820\frac{L_{cs}}{V_{0.85}} + \delta_-] \qquad (28)$$

where $\%tRl$ is the percentage of perception – reaction time to deduct from the red clearance – default value might be 90%, and δ_- is drivers' perception-reaction time.

Trajectory of left-turn curve

The value of quantity β in the calculation of length of the actual turning curve (Equation 26) will affect the trajectory of the left-turn curve.

4.5 Calculation of Yellow Change and Red Clearance

Calculations of the yellow change and red clearance intervals are based on the parameters above and the raw field data. The value of quantities α, β and γ involved in the parameters' calculation need to be determined in the stage of model calibration. The equation used for setting yellow change interval is as follows.

Yellow change is set as: $y = 2(\delta_- + \frac{V_t}{2a_-})/(1+\frac{V_i}{V_t}) + T_{vi}$ (29)

In the equation, $\delta_- + \frac{V_t}{2a_-}$ is normally used as yellow change calculation. And for $2/(1+\frac{V_i}{V_t})$, it is an adjustment factor of the entering speed. Clearly, the adjustment factor would be 1 if V_i=V_t; while the factor would be large than 1 if V_i is less than V_t,. This agrees with the description above.

The equation used for setting the red clearance interval is as follows.

Red clearance is set as: $r = 0.6820\frac{\xi S}{V_c} - T_{cs}$ (30)

4.6 Proposed Computer Program

After establishing the complete model for calculating and calibrating the yellow change and red clearance intervals, a computer program will be developed for implementation of the model. Using the proposed model and programs, the users can calculate the yellow change and red clearance intervals by simply entering the necessary field data about the intersection. The function of calibration in the program is to determine values of the three quantities α, β and γ in the calculation of the parameters.

The flow chart of the computer program is shown in the Figure 10. The interface of a preliminary computer program is illustrated in Figures 11 – 15. Figure 11 illustrates the above analytical framework. From the equation number, all the equations in Figure 11 can be found in the above analyses.

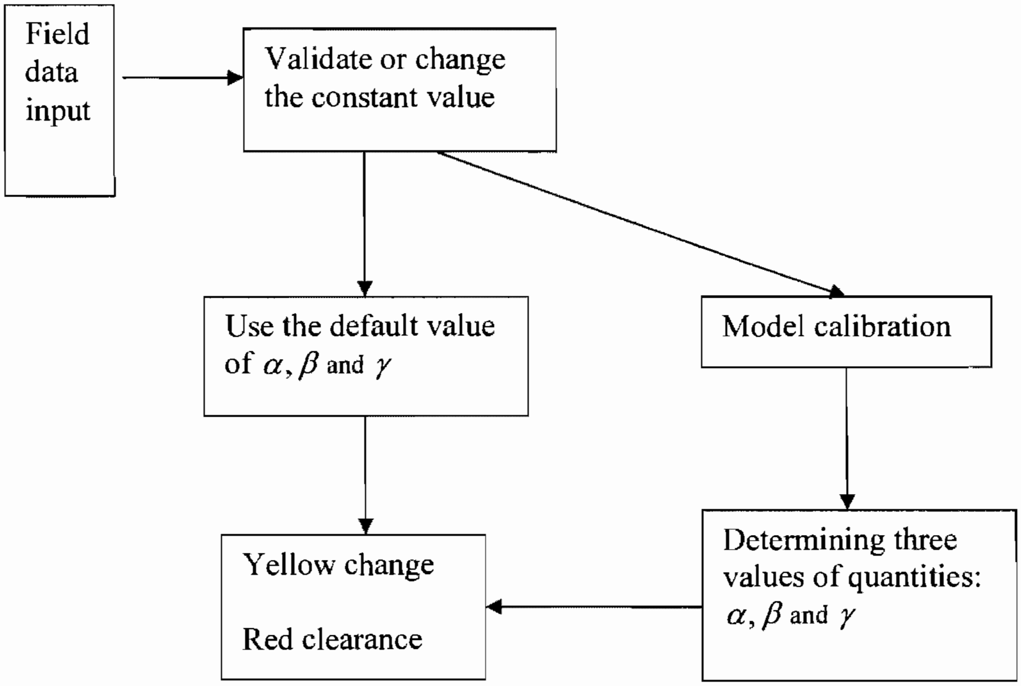
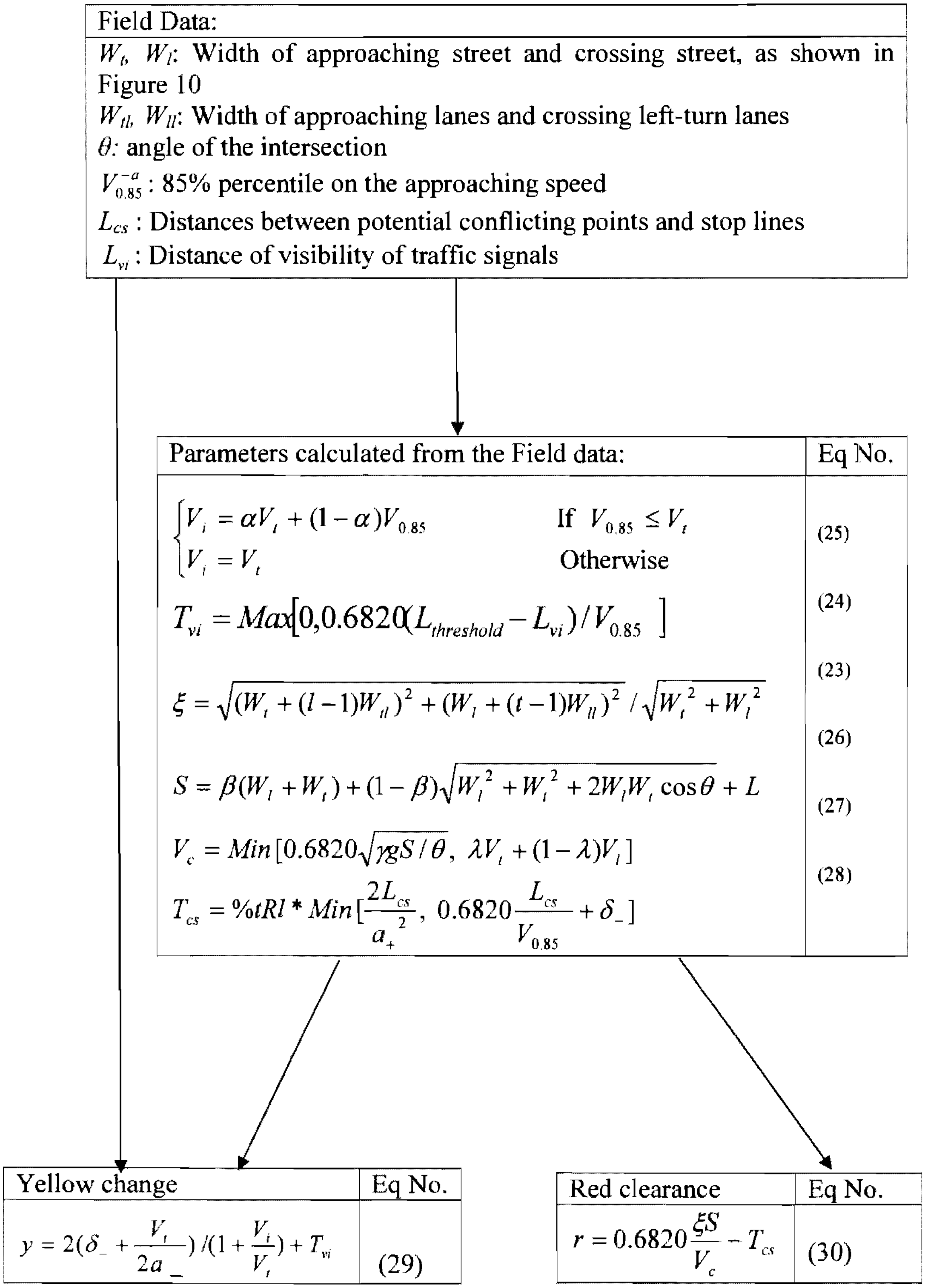


FIGURE 10 Flow Chart of Computer Program



Field Data:

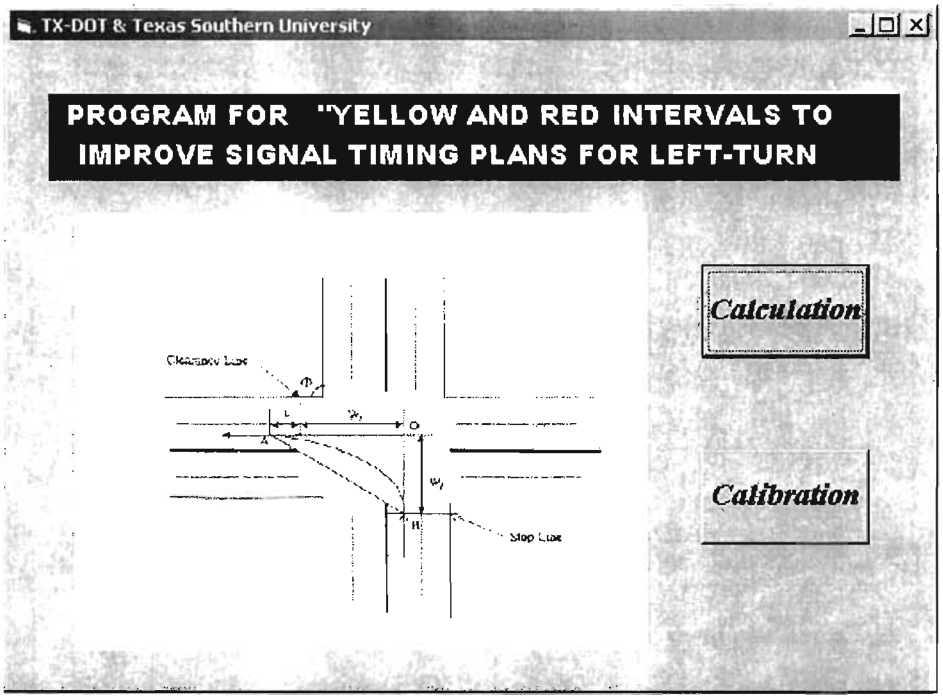
W_t, W_l: Width of approaching street and crossing street, as shown in Figure 10
W_{tl}, W_{ll}: Width of approaching lanes and crossing left-turn lanes
θ: angle of the intersection
$V_{0.85}^{-a}$: 85% percentile on the approaching speed
L_{cs} : Distances between potential conflicting points and stop lines
L_{vi} : Distance of visibility of traffic signals

Parameters calculated from the Field data:	Eq No.
$\begin{cases} V_i = \alpha V_t + (1-\alpha)V_{0.85} & \text{If } V_{0.85} \le V_t \\ V_i = V_t & \text{Otherwise} \end{cases}$	(25)
$T_{vi} = Max[0, 0.6820(L_{threshold} - L_{vi}) / V_{0.85}]$	(24)
$\xi = \sqrt{(W_t + (l-1)W_{tl})^2 + (W_l + (t-1)W_{ll})^2} / \sqrt{W_t^2 + W_l^2}$	(23)
$S = \beta(W_l + W_t) + (1-\beta)\sqrt{W_l^2 + W_t^2 + 2W_l W_t \cos\theta} + L$	(26)
$V_c = Min[0.6820\sqrt{\gamma g S / \theta},\ \lambda V_t + (1-\lambda)V_l]$	(27)
$T_{cs} = \%tRl * Min[\frac{2L_{cs}}{a_+^2},\ 0.6820\frac{L_{cs}}{V_{0.85}} + \delta_-]$	(28)

Yellow change	Eq No.
$y = 2(\delta_- + \frac{V_t}{2a_-}) / (1 + \frac{V_i}{V_t}) + T_{vi}$	(29)

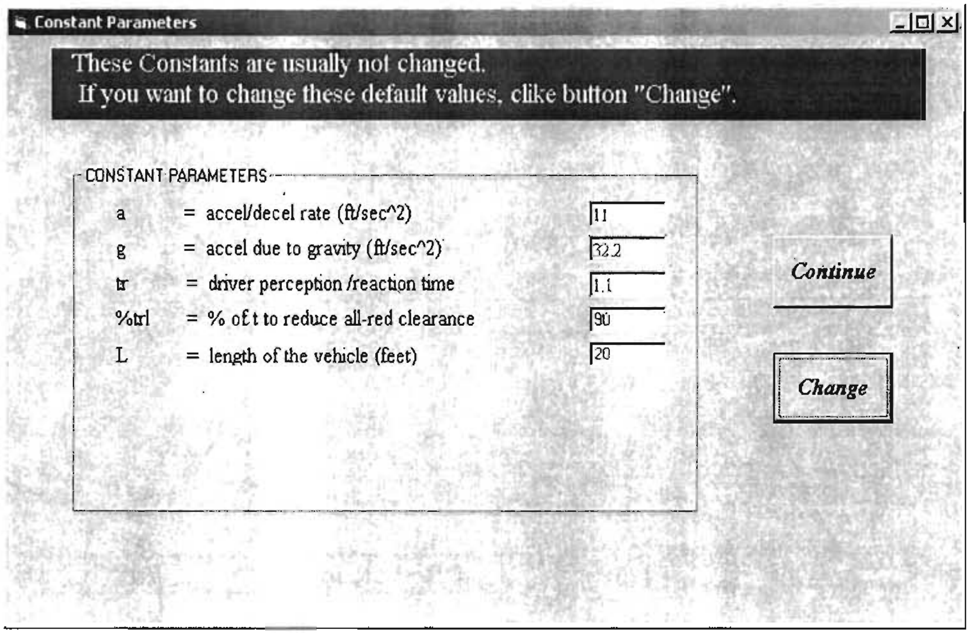
Red clearance	Eq No.
$r = 0.6820\frac{\xi S}{V_c} - T_{cs}$	(30)

FIGURE 8 Preliminary Framework for Calculating Two Intervals



PROGRAM FOR "YELLOW AND RED INTERVALS TO IMPROVE SIGNAL TIMING PLANS FOR LEFT-TURN

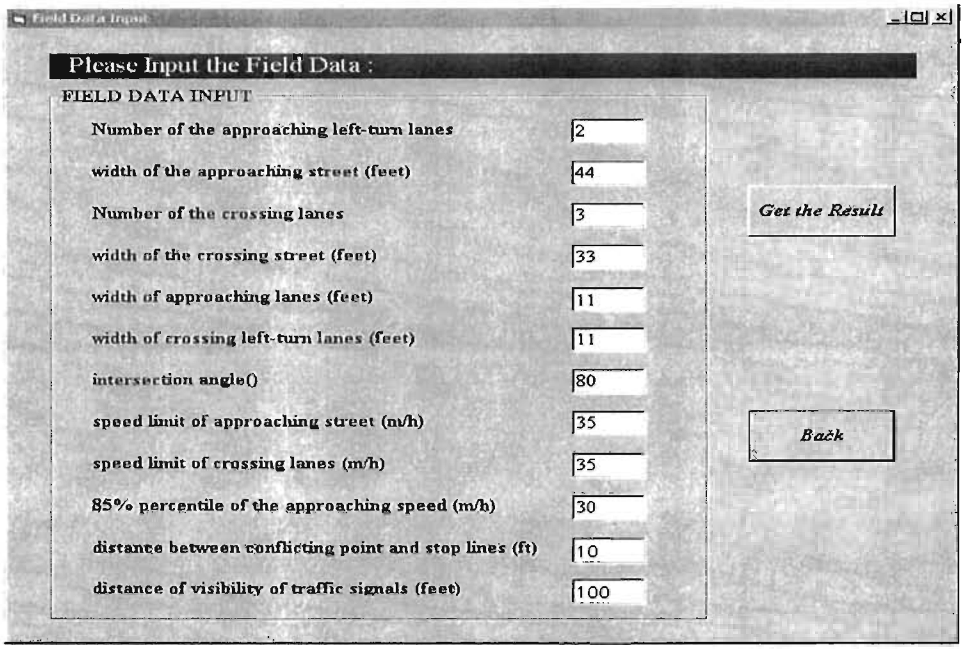
FIGURE 9 Illustration of Conceptual Computer Program – Intersection Geometry



These Constants are usually not changed.
If you want to change these default values, clike button "Change".

a = accel/decel rate (ft/sec^2) 11
g = accel due to gravity (ft/sec^2) 32.2
tr = driver perception /reaction time 1.1
%trl = % of t to reduce all-red clearance 90
L = length of the vehicle (feet) 20

FIGURE 10 Illustration of Conceptual Computer Program – Constant Parameter

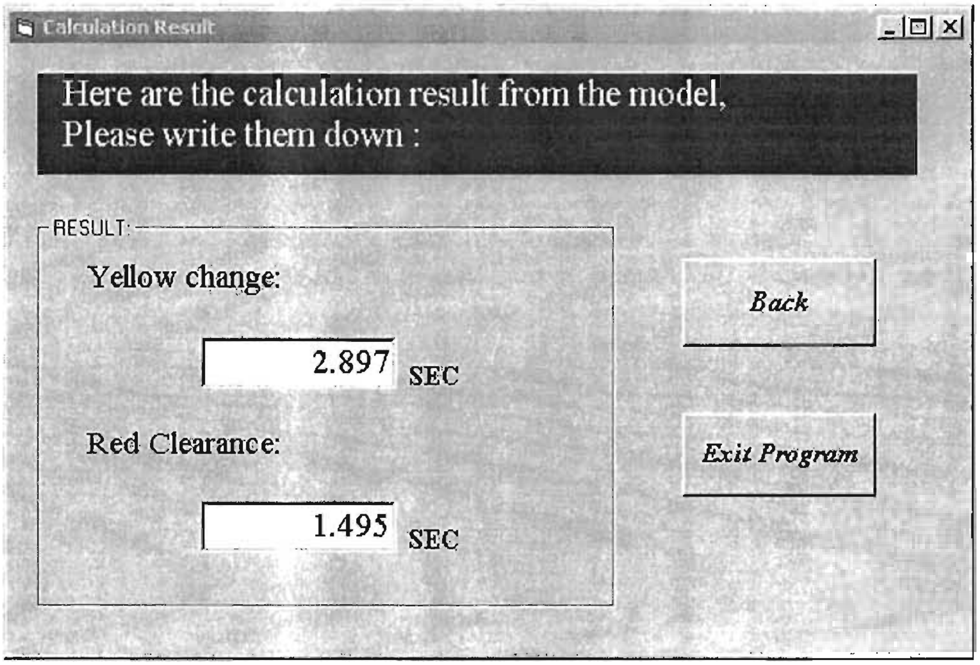


Please Input the Field Data :

FIELD DATA INPUT

Number of the approaching left-turn lanes	2
width of the approaching street (feet)	44
Number of the crossing lanes	3
width of the crossing street (feet)	33
width of approaching lanes (feet)	11
width of crossing left-turn lanes (feet)	11
intersection angle()	80
speed limit of approaching street (m/h)	35
speed limit of crossing lanes (m/h)	35
85% percentile of the approaching speed (m/h)	30
distance between conflicting point and stop lines (ft)	10
distance of visibility of traffic signals (feet)	100

FIGURE 11 Illustration of Conceptual Computer Program – Parameter Inputting



Here are the calculation result from the model,
Please write them down :

RESULT:

Yellow change: 2.897 SEC

Red Clearance: 1.495 SEC

FIGURE 12 Illustration of Conceptual Computer Program – Outputs

CHAPTER 5 DATA COLLECTION

5.1 Background

Data collection plan is the work documented in Tasks #5 in the original project proposal submitted to TxDOT in August 2001 where TTI was specified as the leading agency. Under Task #5, TTI will develop field data collection plan, which will specify the data collection methods and the required devices, the number of intersections under each category, the time duration of each site, and the related traffic flow and site characteristics. Once the data collection plan is submitted to TxDOT for review and get approved, work will be initiated for detailed site selection, which was described under Task #6.

Design of data collection plan is to make sure that all the data needed to calibrate the model will be collected, and the requirements on the sites for collecting the field data will be satisfied.

5.2 Data Requirements

All the data needed to calibrate the model and the requirements of the sites for collecting the field data should be satisfied.

5.2.1 General Requirements on the Intersection

Based on discussions within the research team and recommendations from the project panel members, data at 21 intersections will be collected. These intersections should cover a broad range of geographic locations as well as different traffic flow, traffic operations and geometric conditions.

5.2.2 Geometry Parameters

The geometry parameters to be considered may include:

1. Angle of intersection (please draw a simple intersection layout).

2. Distance between stop line at each direction and the center point of the intersection.
3. Distance between clearance line at each direction and the center point of the intersection.
4. Number of lanes at each direction, and their widths.
5. Number of left-turn lanes at each direction.
6. Number of shared left-turn at each direction.
7. Grade of intersection approaches.

5.2.3 Traffic Parameters

The traffic parameters to be considered may include:

1. Time that a left-turn vehicle spends from entering the stop line to leaving the clearance line.
2. Approaching volumes and left-turn volumes at each direction.
3. Vehicles mix: percentage of trucks within left-turn vehicles.
4. Approaching speed of each left-turn vehicle.
5. Speed limits on each street.
6. Traffic signal visibility distance from signal stand.

5.2.4 Historical Parameters

The historical parameters to be considered may include:

1. Historical accident rate.
2. Historical accident rate due to the left-turn movement.

5.2.5 Yellow Change and Red Interval Related Parameters

The yellow change and red interval related parameters to be considered may include:

1. Current yellow change and red clearance intervals.
2. Number of left-turn vehicles that enter the intersection after the signal turns to yellow

on each signal circle.

3. Number of vehicles that make a sharp stop before stop line after the signal turns to yellow on each signal circle.
4. Number of vehicles that make a forcing left-turn during red clearance on each signal circle.
5. Number of turning vehicles that cannot complete the left-turn at the end of red clearance on each signal circle.
6. Time from the first left-turn vehicle's complete stop before the stop line during the yellow interval to the end of the yellow light on each signal circle.
7. Time from the last vehicle that completes left-turn movement to the end of red clearance on each signal circle.

5.3 Data Collection Plan

Even though the safety related elements (e.g., accident data, visibility) are important, it may prove very difficult to collect some useful data for the purpose of this project. For example, accidents have to be associated with the left turn movements, and somehow occurred during the clearance interval. Such information may not be available. Nevertheless it is important to identify/select sites for which some historical data exists, rather than those for which no accident data have been maintained. In preparing our data collection plan, we need to make sure that enough data is collected for each particular category. It is also recognized that too diversified data may not be good for model validation and calibration.

A total of 21 intersections are to be collected during peak and off-peak periods. Where appropriate, two approaches (including a main street approach and a side street approach) of an intersection will be collected, with a minimum of 3 hours for each approach. Table 7 shows a preliminary data collection plan with the required number of intersections in each category.

As shown in Table 7, the intersections are classified based on speed group, the number of left turn lanes, and the left turn control type. Two speed groups are identified, with the low speed group of speed limits less than 45 mph, and the high speed group of speed limits greater than or equal to 45 mph. The two left turn control types include protected and protected/permitted control. Permitted left turn is not a subject of this study, since the yellow and all-red clearance intervals are normally determined based on the through movement. We believe that such a data collection plan would cover the majority of the intersection types and would establish a good database for model calibration and validation.

TABLE 7 Number of Sites for Each Category

L: Speed Limit < 45 mph (11)		**H: Speed Limit ≥ 45 mph (10)**	
One LT Lane (6)	Protected (PT) (2)	One LT Lane (5)	Protected (PT) (2)
	Protected/Permitted (PM) (4)		Protected/Permitted (PM) (3)
> One LT Lanes (5)	Protected (PT) (4)	> One LT Lanes (5)	Protected (PT) (5)
	Protected/Permitted (PM) (1)		-

Summary by Category:

1. By Speed:	L: 11;	H: 10
2. By # LT Lanes:	1: 11;	2: 10
3. By Control:	PT: 13;	PM: 8

Table 8 shows the number of sites in each category and the geographic region. Table 9 lists the name of the intersections, the location, the associated category, and general comments on the site characteristics. As can be seen that the sites cover 3 major geographic regions consisting of 8 different jurisdictions with a balanced distribution among different speed, geometry, and left turn control types.

TABLE 8 Number of Sites for Each Category and Region

Summary by Category:

1. By Speed:	**L: (11);**	**H: (10)**
College Station:	4	2
Houston:	2	4
Dallas/Forth Worth:	5	4
2. By # LT Lanes:	**1: (11);**	**>1: (10)**
College Station:	4	2
Houston:	3	3
Dallas/Forth Worth:	4	5
3. By Control :	**PT: (13);**	**PM: (8)**
College Station:	3	3
Houston:	5	1
Dallas/Forth Worth:	5	4

Total: College Station: 6

Houston: 6

Dallas/Fort Worth: 9

TABLE 9 Candidate Sites for Data Collection in College Station and Houston

Site Location	Geometry Group	Comments
College Station		
1. University Dr./Texas Avenue	L2PT	High volume
2. Texas Ave./Holleman Dr.	L1PT	Grade
3. Wellborn Rd./George Bush Dr.	L1PM	Standard Geometry
4. Wellborn Rd./Rock Prairie Rd.	H1PM	High Speed (55 mph)
5. FM 2818/Wellborn Rd.	H1PM	Angel, high left turn
6. FM 2818/Texas Avenue	H1PM	Standard Geometry
Houston		
7. Scott St./ N MacGregor Way.	L1PT	Angle, High volume
8. Richmond Ave./Buffalo Rd.	L2PT	High volume
9. Bellaire Blvd./Gessner Rd.	H1PT	High volume
10. Richmond Ave./Rice Rd.	H1PM	High volume
11. Bellaire Blvd and Bissonett	H2PT	Angle
12. Bellaire Blvd./I-8.	H2PT	High speed
Arlington		
13. Arbrook/Matlock	L1PM	Angle, High accident
14. Pleasant Ridge/Cooper	H2PT	High accident
15. Pioneer/Cooper	H2PT	High accident
Grapevine		
16. SH121/GV Mills Blvd.	L2PM	High accident
Dallas		
17. Abrams/Skillman	L2PT	Angle
Lewisville		
18. Corporate/SH121	L1PM	High accident
19. FM1171/Old Orchard	L1PM	High accident
The Colony		
20. SH121/FM423	H2PT	High accident
Fort Worth		
21. 377/FM167	H1PT	+55 mph speed

Note: PT – Protected; PM – Permitted; L – Low Speed; H – High Speed;
1 – 1 Left-turn Lane; 2 – More than 1 Left-turn Lanes

5.4 Data Collection Methods

Several data collections are proposed depending on the type of data to be collected. These different data collection methods and the data to be collected are discussed below.

5.4.1 Request from Responsible City and Jurisdictions

The following data are to be collected through contacting city and jurisdictions that are responsible for maintaining and operating the intersections.

1. Existing signal timing
2. Accident data for the past three years
3. Intersection drawing (in scale) for obtaining geometric data, such as angle, lane width.

5.4.2 Video Taping

Video taping is proposed to collect detailed traffic flow data and vehicle maneuvers while approaching the intersection and moving within the intersection. Video tape will provide a permanent record of the data, which can be reviewed at a later time to verify the data or to get more information. However, this method requires an optimal camera location to ensure that information can be clearly recorded. We have conducted a pilot study by using TTI's video trailer that allows a video camera to be mounted on top of a 35-foot raised pole. Based on our preliminary results, it was found that for small intersections (e.g., 2 by 2 lanes), the signal indication as well as the vehicle movements within the intersection can be recorded and viewed from the video tapes. The time events including time leaving the stop line, time reaching the center of the intersection, time leaving the intersection can be accurately extracted from the video tapes using a computer software. To obtain a good field of view, it is necessary to locate the video trailer approximately 40 to 60 feet away from the intersection. At larger intersections, the setback distance may even be longer in order to cover the entire intersection. However, the signal indication may not be viewed clearly from the video tape. In this case, vehicle movements within the intersection may only roughly estimated. Nevertheless, the research team strongly favors such a data collection method.

5.4.3 Speed Measurement

Speed for the left turn vehicles will be collected at the same time of video taping. Radar gun will be used to collect sample speed data for the left-turn vehicles. Speed at the beginning of the left turn bay will be recorded, which is assumed to be the approaching speed for potential dilemma zone calculations. At least 125 samples or a 2-hour time period will be collected for each left-turn movement, which comply with TxDOT's requirements on the sample size.

5.4.4 Other Field Measurements

Other data that cannot be obtained directly from the video tapes or the city need to be measured in the field during the same time of video taping. These data may include grades (to be estimated), number of lanes, lane widths, sight distance, and left turn phasing.

CHAPTER 6 CONCLUSION AND ON-GOING WORK

6.1 Conclusion

In this interim report, the following works have been conducted. As the first step, state-of-the-art and state-of-the-practice were reviewed including both theoretical approaches and practical methodologies. Then, methodologies being used in Texas have been identified. Literature review shows that most of the approaches and methodologies are for through movement only with little and fuzzy parameters considered.

In order to identify parameters that are important to the determination of yellow change and red clearance intervals, a survey was conducted to engineers and executives. Based on the analysis of the survey results, the major parameters involved in developing framework for determining left-turn yellow change and red clearance intervals have been identified with a prioritized order. The field data needed to calibrate the model have also been identified and a data collection plan has been designed.

Based on the literature review, methodologies related to calculating yellow change and red clearance intervals have been identified and a preliminary analytical framework has been designed, where two steps are included. In order to apply the framework, a computer program for this research has been conceptually developed.

6.2 On-going works

The on-going work will focus on the following steps according to the work plan of the project:

- Further modify the final analytical framework by establishing steps and equations to calculate the yellow change and red clearance intervals;

- Collect field data according to approved data collection plan. Accident history and engineering drawings for the candidate intersections will also be acquired. The on-site video taping of the intersections will be conducted;
- Extract field data from video tapes and analyze all the surveyed data preparing all the information needed for model calibration;
- Calibrate the model based on the analytical framework and the collected field data. and then calculate the yellow change and red clearance for the surveyed intersections; and
- Document the final research report summering research performed, findings and recommendations.

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APPENDIX I SURVEY FORM

Texas Department of Transportation Research Project 0-4273

"Yellow and Red Intervals to Improve Signal
Timing Plans for Left-Turn Movement"

Survey of model parameters

Description: Texas Southern University (TSU) and Texas Transportation Institute (TTI) are jointly conducting a research project for Texas Department of Transportation (Tx-DOT), which is to develop and test a framework for setting yellow change and red clearance intervals for the left-turn movement. The objective of this research is to integrate a comprehensive set of parameters related to geometry, driving behavior, perception and comfort, traffic and vehicles, safety, traffic ordinances, and others.

The purpose of this survey is to seek your help in identifying and prioritizing all possible parameters that would potentially be included in the framework. Each parameter listed in the following is given numbers from "1" to "5" with "5" having the highest priority and "1" having the lowest priority. Please circle a number that you think represents the level of importance of the parameter in determining the yellow change and red clearance intervals. Please either e-mail your response to yu_lx@tsu.edu or fax to (713) 313-1856. Your cooperation in this survey is highly appreciated.

Parameter category 1: Intersection geometry related parameters
Widths of approaching and crossing lanes and streets
Priority: 1 2 3 4 5

Numbers of approaching and crossing lanes and streets
Priority: 1 2 3 4 5

Turning angle (or angle between approaching and crossing streets)
Priority: 1 2 3 4 5

Location of stop line and clearance line for left -turn movement
Priority: 1 2 3 4 5

Number of total left-turn lanes
Priority: 1 2 3 4 5

Number of shared lanes for left-turn movement
Priority: 1 2 3 4 5

Others (please specify. If you have more than two additional parameters, please attach a separate sheet)
Parameter Name: ____________________
Priority: 1 2 3 4 5

Parameter Name: ____________________
Priority: 1 2 3 4 5

Parameter category 2: Driving behavior related parameters
Trajectory of left-turn curve
Priority: 1 2 3 4 5

Deceleration and acceleration on the left-turn curve
Priority: 1 2 3 4 5

Curve entering speed
Priority: 1 2 3 4 5

Average driving speed on the curve
Priority: 1 2 3 4 5

Others (please specify. If you have more than two additional parameters, please attach a separate sheet)
Parameter Name: ____________________
Priority: 1 2 3 4 5

Parameter Name: ____________________
Priority: 1 2 3 4 5

Parameter category 3: Drivers' perception and comfort related parameters
Drivers' perception-reaction time
Priority: 1 2 3 4 5

Drivers' comforTable 4eceleration rate
Priority: 1 2 3 4 5

Drivers' toleration of centrifugal acceleration force
Priority: 1 2 3 4 5

Others (please specify. If you have more than two additional parameters, please attach a separate sheet)
Parameter Name: ____________________
Priority: 1 2 3 4 5

Parameter Name: ____________________
Priority: 1 2 3 4 5

Parameter category 4: Traffic and vehicle related parameters
Speed limits on approaching and crossing streets
Priority: 1 2 3 4 5

Traffic volumes on approaching and crossing streets
Priority: 1 2 3 4 5

Left-turn traffic volumes on approaching street

Priority: 1 2 3 4 5

Lane assignment on approaching street
Priority: 1 2 3 4 5

Vehicle types
Priority: 1 2 3 4 5

Vehicle sizes
Priority: 1 2 3 4 5

Others (please specify. If you have more than two additional parameters, please attach a separate sheet)
Parameter Name: ____________________
Priority: 1 2 3 4 5

Parameter Name: ____________________
Priority: 1 2 3 4 5

Parameter category 5: Traffic safety related parameters
Distances between potential conflicting points and stop lines
Priority: 1 2 3 4 5

Historical accident data at intersection
Priority: 1 2 3 4 5

Historical accident data due to left-turn movement
Priority: 1 2 3 4 5

Others (please specify. If you have more than two additional parameters, please attach a separate sheet)
Parameter Name: ____________________
Priority: 1 2 3 4 5

Parameter Name: ____________________
Priority: 1 2 3 4 5

Parameter category 6: Traffic ordinances related parameters
Traffic laws related to signal controlled intersections
Priority: 1 2 3 4 5

Others (please specify. If you have more than two additional parameters, please attach a separate sheet)
Parameter Name: ____________________
Priority: 1 2 3 4 5

Parameter Name: ____________________
Priority: 1 2 3 4 5

Parameter category 7: Other parameters
Visibility of traffic signals (traffic signal position, etc.)
Priority: 1 2 3 4 5

Intersection signal phasing structure
Priority: 1 2 3 4 5

Others (please specify. If you have more than five additional parameters, please attach a separate sheet)

Parameter Name: ____________________
Priority: 1 2 3 4 5

Parameter Name: ____________________
Priority: 1 2 3 4 5

Parameter Name: ____________________
Priority: 1 2 3 4 5

Parameter Name: ____________________
Priority: 1 2 3 4 5

Parameter Name: ____________________
Priority: 1 2 3 4 5

Acknowledgement

We appreciate your valuable time to take part in this survey for its success. Please fill the following information for further contact:

Name of the person who filled this survey: ____________________________________
Title: ____________________ Name of the Organization: ____________________
Address: ____
____
Telephone: (____) ____________________ Fax: (____) ____________________
E-mail: ____
Website: ____

Please mail/fax/e-mail this competed form using the following information:

Dr. Lei Yu, P.E.

Department of Transportation Studies, Texas Southern University
3100 Cleburne Avenue, Houston, Texas 77004

Telephone: (713) 313-7182; Fax: (713) 313-1856
E-mail: yu_lx@tsu.edu; Website: http://transportation.tsu.edu/

APPENDIX II LIST OF RESPONDEDENTS

No.	Responser's name	Title	Organization
1	Bancroft, Bill	Engineer Assistant	Tx-DOT
2	Bean, Jonanthan	Engineering Assistant	TxDOT-Bryan
3	Black, John.R., P.E	ITS manager/ system engineer	Naztec, Inc, Lewisville, TX
4	Brewer, Marcus A	Assistant Trans. Researcher	TTI
5	Burris, Mark		TAMU
6	Choy, Sek	Engineering Associate	City of San Antonio
7	Dedeitch, Boro	Senior Transportation Eng.	Parsons Transportation Group
8	Denholm, John III	Engineering Designer	Lee Engineering
9	Gates, Tim	Assistant Trans Researcher	TTI
10	Hallimore, Angie, P.E.	Project Engineer	Montgomery Associates
11	Henk, Russell	Program Manager	TTI
12	Hillje, Mark	Project Manage	Epsilon Engineering
13	Jenkes, Stuart	Traffic System Manager	TX-DOT Paarr
14	Kelly, A. B.	P.E.	TCB Inc.
15	Larkins, Rich	Dic of Transportation	City of Grand Prairie
16	Luedtke, Paul	Assistant Director of Transportation	City of Garland
17	Mendoza, Federico	Traffic Engineer	Brown & Gay Engineers
18	Nuckles, Nelson B., P.E.	Discipline Leader Streets and Highways	Freese and Nichols, Inc.
19	Rzmirer, Aronulte	Dist Traf Engineer	Transguide Transportation Center
20	Sanders, Sandra	Research Associate	TTI
21	Saycor, Robert	P.E. Traffic Operation Engineer	City of Richardson
22	Schultz, Grant	Graduate Student	Texas A&M
23	Squire, James R, P.E.	President	Sylva Engineering Corp.
24	Sunkari, Srinivasa	Assistant Research Engineer	TTI
25	Wayne, Gisler	Manager - Traffic Management and Operations	Houston TranStar
26	Webster, Chuck	Signal Shop Supervisor	TX-DOT
27	Williams, Donna H.	Business Development Director	Parsons Transportation Group