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16. Abstract

This project developed and tested 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. The framework was 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 can improve both the safety and the efficiency of the left-turn movement at the intersection. The field data collected from 21 intersections in 8 Texas cities was used for the preliminary calibration of three essential parameters within the improved framework. The three essential parameters are related to *drivers' entering driving behavior*, *drivers' behavior on left-turn curve*, and *drivers' tolerable centrifugal force*, respectively. After the preliminary calibration, a systematic calibration approach was designed to extend the improved framework to a wider range of intersection configurations associated with different approaching speed limits, number of left-turn lanes, control types, and truck percentages. Through this research it is found that the existing yellow change intervals for the left-turn movement should be shorter, and the existing red clearances longer. However, the existing total change intervals need not to be changed. This means that the safety of left-turn can be greatly improved without decreasing the efficiency of the entire intersection operation.

This is the final report for the project, which summarizes the work that has been performed during the two-year project research.

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

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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 the straight movement has been developed. However, the yellow change and red clearance intervals for the left turn movement are yet understood in neither theory nor 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 is intended 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.

During the time period covered by this project (from September 2001 to August 2003), a review of the state-of-the-art and the state-of-the-practice was conducted first. As for the state-of-the-art, a number of mathematical formulas have been proposed for the calculation of the yellow change interval in the past years by scientists and engineers. More updated studies are reflected in the evolution of ITE equations and guidance. However, most of these formulas are too simple to compute different configurations of intersections and very few parameters are

considered in the calculation. Furthermore, almost all of them were developed based on the through-movement, and the research specifically designed for left-turn movement is scare.

Compared with the yellow change interval, the red clearance interval is more related to 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 interval called the change interval. The key point that existing methodologies suggest is how to determine the length of vehicles' moving curve and the speed, which is left to the field engineers to figure out. Liu, et.al. (2001) proposed an approach for the calculation of the red clearance interval, which considered many parameters. But their methodology did not include the red clearance deduction by considering the distance between the conflict point and the conflicting stopline. This might result in the red clearance interval 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 the yellow change and red clearance intervals for the 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 was related to accident. Other factors include geometry design (number and width of lanes), visibility and impeding factors, speed, traffic law, perception-reaction time, and signal phasing.

With the prioritized parameters, the key to the framework development would be how to address or incorporate these parameters into the framework. The proposed framework used two categories to group the parameters identified in the survey, raw data that could be collected directly from the sites, and calibrated parameters from the raw data. Therefore, the proposed framework for calculating the yellow change and red clearance intervals includes two steps. In Step 1, the raw field data are used in calibrating parameters. In Step 2, the yellow change and red clearance intervals are calculated based on the calibrated parameters and some of the raw data.

The framework development is the basis for the calibration, calculation, and analysis. In the framework development, a process was defined to calculate the parameters and intervals. Every calculation was defined in the mathematic equation. By the literature review, the framework proposed by Liu *et al* (2001), to be described in Chapter 2, forms the basis for the proposed framework. The proposed framework was described in the way that new parameters were introduced, and several existing parameters were revised. The improvement improved both the safety and the efficiency at the intersection.

After the development of framework, the calibration, calculation and analysis were conducted. Data collected from field sites were used to calibrate the parameters in the framework, and recommended yellow change and red clearance intervals for the surveyed sites were generated.

The calibration and calculation began with the data collection. The project committee helped to select the intersections for the data calibration. These intersections covered a broad range of geographic locations as well as different traffic flow, traffic operations and geometric conditions. Data from the intersections were collected during peak and off-peak periods. Where appropriate, the left-turn movement on both the main street approach and the side street approach were collected, with a minimum of 3 hours for each approach. Various methods were used in the data collection process, including requesting information, videotaping, manual measuring and radar guns. The data collection included the data related to the yellow change and red clearance intervals, and historical accidents. These data were not intended to be directly incorporated in the framework or to be used to calibrate the framework. However, they are very important in verifying the framework's effectiveness.

After the data collection, a method was developed to retrieve the data from original data collection sources, such as engineering drawings, videotapes, and radar gun. The data retrieving was to process the data for being directly used in the calibration and calculation. Data came from different sources. Geometry parameters data were directly obtained from the engineering drawings. Human factor parameters were derived from the ITE/MUTCD manuals. Law related parameters were stipulated by traffic regulations on the intersection. There were also some data that were requested directly from juridical agencies. Most important data are those related to the left-turn movement behavior, which were retrieved from the video tapes. A computer program was coded to process and standardize the data.

In order to consider the data accuracy, a sensitivity analysis was conducted before the calibration task. This analysis is intended to determine how the inaccurate data would affect the calibration results. The sensitivity analysis was conducted by tentatively calculating the parameters in the framework, and ultimately the yellow change and red clearance intervals, based on the proposed framework.

With all the necessary data from the engineering drawings, tapes and radar guns, the calibration of the framework was carried out. The calibration and calculation were conducted in two steps. The first step was to preliminarily calibrate the parameters and calculate the intervals for surveyed intersections only. Several parameters in the framework, including entering speed, turning speed, and turning curve were preliminarily calibrated. These parameters are very important in setting the intervals and are related to the drivers' behavior. The sec step was to further calibrate the framework for any target intersections. Target intersections were grouped by intersections' characteristics, including speed limits, control types, number of left-turn lanes, and vehicle types.

Based on the calibration and calculation results it is found that in the surveyed 21 Texas intersections, the existing yellow change intervals are longer than the calculated ones, while the existing red clearance intervals are shorter. However, the total change intervals (including both the yellow changes and red clearance intervals) are about the same as the calculated ones. Validation in terms of accident analysis shows that, the left-turn accident rates at intersections, with longer yellow changes and shorter red clearances than the calculated ones by the framework, are higher than the others.

The above conclusions are meaningful since they imply that the adjusted yellow change and red clearance can increase the safety for left-turn with no reduction of the total green time in intersections.

In order to implement the proposed framework, it is suggested to collect filed data from more intersections in Texas and to further calibrate the parameters. Based on the internal computer program used in this research, a more user-friendly and engineer-oriented software should be further developed.

CHAPTER 1

INTRODUCTION

1.1 Background of Research

The traffic signal intervals' calculation has long been an important operational problem, in which the 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. Among the intervals, the 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 change is introduced into the traffic light cycle to allow drivers to make decisions to either stop or proceed at the stop line, and a red clearance is to give the vehicle sufficient time for clearing the intersection. In some situations, the yellow interval, defined as the sum of a "yellow change" interval and a following "red clearance" interval, is studied as a single problem.

Figure 1 illustrates a motorist moving toward an intersection at speed v. When the yellow interval commences at a distance x, if the motorist cannot make a comfortable full stop before the stop line, the yellow interval must provide enough time for the motorist to go through the distance of x plus S, in other words, to clear the intersection before the conflicting vehicles enter the intersection. Here, the time for vehicle to going through x is yellow change, and the time for going through S is red clearance. Please note that this is for the through movement situation. In Figure 1, W is the intersection width, L is the vehicle length, and S is the sum of W and L.

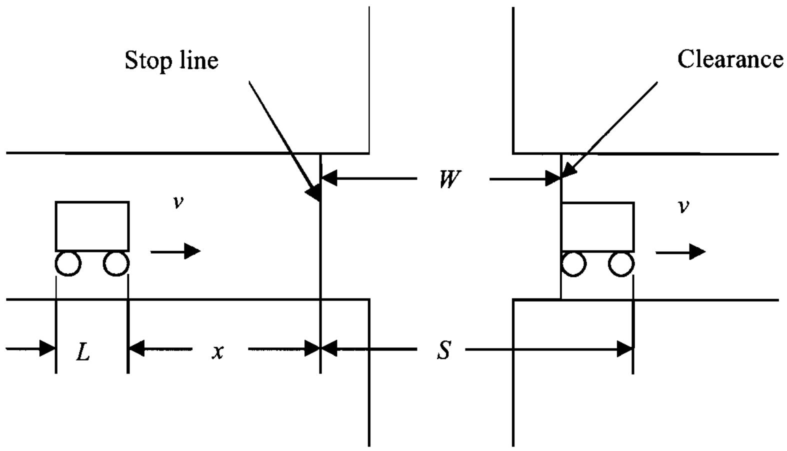

FIGURE 1: Illustration of Through Movement at a Signal-Controlled Intersection

In the above case, if the distance x plus S is too long for the motorist to cover before the onset of the green for the conflicting traffic, a dilemma zone exists. A vehicle is in called in the "dilemma zone" when the yellow change commences, if it can neither stop comfortably before the stop line, nor can it clear the intersection safely before the conflicting traffic enters the intersection. When the yellow change and red clearance intervals are set appropriately at an intersection, the dilemma zone can be eliminated technically. This problem was examined in details by Liu, *et al.* (1996). Their study showed that the dilemma zone associated with a speed less than the speed limit when the yellow indication commences could be eliminated, provided that the driver accelerates with an acceleration rate larger than, or equal to, a required critical acceleration rate (this acceleration rate is the lowest one for drivers to clear the intersection before the green signal begins for the conflicting traffic) or accelerates with an available acceleration in a 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 the 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 through movement. Although some of the discussion could also be applied to the left-turn movement, the unique characteristics of the left-turn movement make it essentially different from and more complex than the through movements.

A left-turn movement at a signal-controlled intersection can be conceptually divided into two phases. The first phase occurs when a motorist proceeds into the intersection during the yellow change interval; and the sec phase takes place when the motorist makes a left-turn while experiencing a relatively high acceleration rate on the left-turn curve.

A left-turn movement is symbolically sketched in Figure 2 for an intersection with a general geometry. Basic control parameters related to the left-turn movement include the crossing street length W_l, which is a function of the number of crossing lanes, the street 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, the left-turn curve entering speed, the average speed along the curve, the driver perception and reaction time, the comfortable deceleration rate, the driving behavior (type of turning curve), the tolerable acceleration rate on the curve, and the driver's toleration of centrifugal force on the curve. The values of those comfortable, tolerable rates or force are decided based on the ergonomic engineering. Additional 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 the 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. For example, when the potential curve that each vehicle may follow in making the left turn is considered, 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 some cases, the approaching street and the crossing street may have different speed limits, which will further complicate the driving behaviors of vehicles during the left-turn movement. To maximize the operational efficiency of the intersection, the yellow change and red clearance intervals for the left-turn movement must be determined with a reliable and consistent method on an intersection-by-intersection basis.

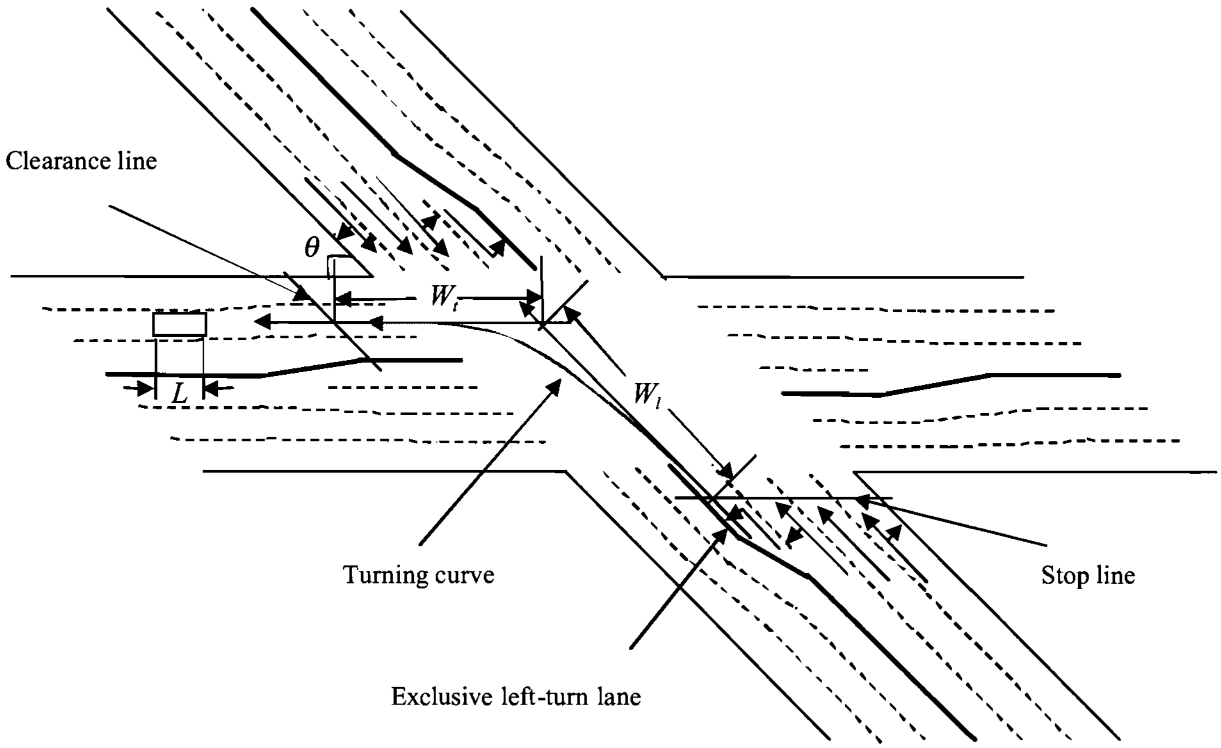

FIGURE 2: A Schematic Drawing of the Left-Turn Movement at a Signal-Controlled Intersection

The yellow interval problem is an example of the incompatibility of man-made laws and physically attainable human behavior. A longer yellow change or red clearance interval is viewed as undesirable by many traffic engineers because of the delay it may cause. When a short interval is used, it may create safety problems. In addition, it must be combined 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 the yellow interval, they do not, however, provide a solution for the drivers in the dilemma zone. For the safety concern, the yellow change and red clearance intervals must be long enough to guarantee that most drivers approaching an intersection 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 safety and efficiency issues becomes an important problem in setting the yellow change and red clearance intervals, especially for the left-turn movement.

1.2 Objectives of Research

The above background description has provided a general technical picture of the issues related to the yellow change and red clearance intervals for both through movement and left-turn movement. It is necessary to develop a reliable and consistent model for setting the yellow change and red clearance intervals for the left-turn movement. In response, this research intends to conduct a comprehensive study on the setting of the yellow change and red clearance intervals for the left-turn movement, both theoretically and practically. Specific objectives are:

- to develop a framework for setting the yellow change and red clearance intervals for the left-turn movement, which incorporates a comprehensive set of parameters, which will improve both the safety and efficiency of the intersections;
- to systematically calibrate the developed framework with the field collected data; and
- To validate the framework by analyzing the accident data on the surveyed intersections.

1.3 Outline of This Report

This is the project report covering all tasks during the research period. 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 presented first. Then, the procedure of the survey for identifying the parameters and the analyses of the survey will be provided. After that, the framework determining the yellow change and red clearance interval is proposed. Subsequently, a data collection for calibrating the framework, and the calibration, calculation and result analysis will be presented. After that, the process of the calibration of the framework will be presented. Finally, conclusions and recommendations will be given.

CHAPTER 2

LITERATURE REVIEW

2.1 Review of State-of-the-Art

This section summarizes the previous studies related to the setting of the yellow change and red clearance intervals. The reviews of the research for the yellow change and red clearance intervals are presented separately. However, since most of the previous studies have considered the yellow change and red clearance intervals jointly as the yellow interval, it is sometimes hard to separate the yellow change and red clearance intervals. Therefore, the research about the yellow interval is discussed along with the yellow change interval. In one of the latest studies, the analytical approach proposed by Liu, *et al.* (2002) provided a systematic analysis on the yellow change and red clearance intervals for left-turn movement. Since this approach is selected as the basis for the framework development in the project, it is discussed separately in the review.

2.1.1 Yellow Interval and Yellow Change Interval

The yellow change interval in traffic signal cycles is used to alert drivers of the imminent change in the direction of traffic flow. Upon observing the onset of the yellow, the driver of a vehicle 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 the conflicting traffic flow, but others may not be able to do so. Vehicles that cannot clear the intersection will block the paths of the cross-street traffic that have the right of way. This kind of blockings and accidents could be reduced by adjusting the traffic signal timing. Specifically, changing the yellow change interval is to ensure that every vehicle can stop safely before the stop line or clear the stop line before the onset of the red signal.

Previous Studies. The yellow interval problem has long been an issue for traffic engineers and researchers. In the past years, many mathematical approaches or suggested values have been proposed for the yellow interval. Table 1 is a summary of previous studies conducted by Stimpson, *et al.* (1980) on the yellow interval. Some of the descriptions of these studies follow the table.

Figure 3 provides the description of symbols used in Table 1.

There is a concept called "dilemma zone" which should be discussed here as it relates to the setting of the yellow interval directly, this concept was first introduced in a quantitative form by Gazis, *et al.* (1960). The drivers who could neither stop safely nor clear the intersection before the onset of the green signal for the conflicting traffic flow are called "in the dilemma zone." This occurs when the yellow interval is below a threshold value. Gazis, *et al.* calculated the dilemma zone boundary in terms of the speed of travel and the distance from the intersection at the onset of the yellow interval and calculated the yellow interval threshold at which the dilemma zone disappears.

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

TABLE 1: Proposed Timing Formula for the Yellow Interval

(Source: Stimpson, *et al.* 1980)

Source	Yr	Formula	Comment
1. Gazis, *et al.*	1960	$\delta_{-} + \frac{1}{2} \cdot \frac{V}{a} + \frac{W+L}{V}$	Speed and deceleration assumed the same for all drivers.
2. Crawford and Taylor	1961	$0.68 \cdot \left[\frac{W}{V} + KV^{3/5}\right]$	Parameter K is a constant, whose value was obtained from an experiment by author.
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.	Too unspecific to be useful.
5. Manual of Uniform Traffic Control Devices (MUTCD)	1971	3 ~ 6 sec.	Too unspecific to be useful.
6. Williams	1977	$\delta_{-} + \frac{V}{2a_{-0.85}} + \frac{W+L}{V_{0.85}} - \left(\delta_{-} + \sqrt{\frac{2d}{a_{+}}}\right)$	Cross street perception reaction time and acceleration time is subtracted.
(1) Transportation and Traffic Engineering Handbook 7 use the same formula as 1.			
(2) Equations in source 1, 3, 4, and 5 are yellow interval, which includes red clearance.			

FIGURE 3: Symbols Used in Table 1

δ_{-}	Driver reaction times for the stopping and starting, in sec
V, $V_{.85}$	Mean approach speed, 85th percentile of the approach speed, feet/sec
W	Intersection width, feet
L	Vehicle length, feet
A	Distance from the stop line at which the desired percentile for stopping occurs, feet
a, $a_{-0.85}$, a_{+}	Deceleration rate, 85th percentile of deceleration accepted, maximum acceleration of cross-flow traffic, feet/sec^2
d	Distance between the vehicle and the cross-flow stop line, feet

In 1962, Olson and Rothery determined the percentages of drivers stopping after the yellow onset as a function of the deceleration needed for stopping. He compared results between pairs of intersections that had different yellow intervals but otherwise were similar. A formula for determining the yellow interval in terms of the approach speed, the intersection width and the "distance from the intersection at which the 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 some intersections and decreased at the others during the intervening stage.

In 1971, MUTCD recommended the yellow interval as 3 sec to 6 sec. This recommendation is too unspecific to be useful for the research purpose.

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

All of these equations were developed based on through movements. There is very little research that specifies the left-turn movement, although the movement has its unique characteristics from the through movement. It seems that the yellow interval for through movement is simply used for left-turn movement in practice.

In addition to the above studies, the ITE has constantly updated its equation for calculating the yellow interval based on a variety of studies. From the summary in Table 2 by Eccles and McGee (2001), a latest guidance for determining the yellow interval was provided in the Traffic Engineering Handbook (ITE, 1999). The equation for calculating the yellow interval, a sum of the yellow change and red clearance intervals, $y+r$, is as follow:

$$y + r = \delta\_ + \frac{V}{2a + 64.4g} + \frac{W + L}{V} \tag{1}$$

where

a = comfortable deceleration rate of the vehicle, feet/sec^2

W = width of the intersection, as shown in Figure 4, feet

g = grade of the intersection approach

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 plus red clearance intervals. 1st equation is the same as 1965 and 1976. 2nd of the equations includes effect of grade on stopping ability. Some use the 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. The first is for the yellow change. The second is for the red clearance.
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 kinematical equation is added back to the equation as it was in 1982. Application requires exercise of engineering judgment.

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

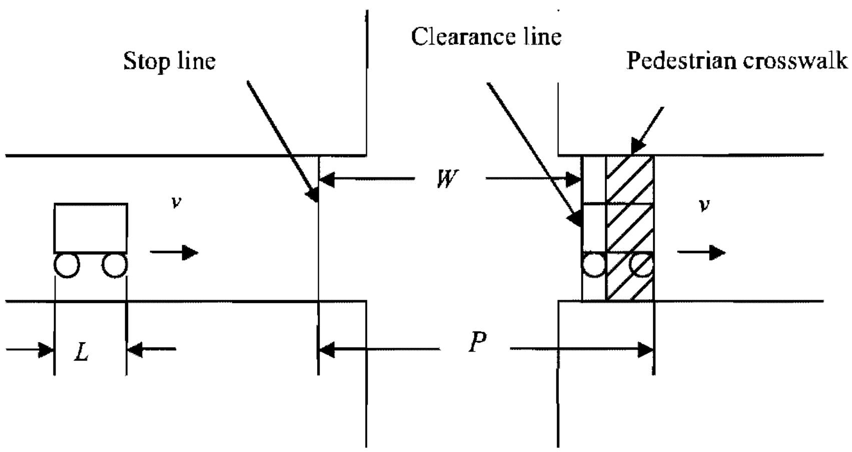

FIGURE 4: Intersection Symbols for ITE Equations

Again, this equation is for the through movement only without considering any parameters related to the left-turn movement. Another drawback is that 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 an unnecessary long yellow interval, thus decreasing the efficiency.

Compared with the early ITE equations, the current ITE equation considers more characteristics of the traffic and the roadway environment. If there is a grade on the approach street to the intersection, the equation adjusts the time needed for the vehicle to decelerate. 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, and posted speed limit) is used to calculate the yellow change and red clearance intervals, which has also changed over the last sixty years. Presently, 85% percentile speed, the speed at or below which 85% of the vehicles are traveling, is used in the calculation.

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 for the left-turn movement specifically. This work developed a comprehensive framework that incorporated a comprehensive set of variables for setting the yellow change and red clearance intervals. In the paper, the distance beyond which a vehicle approaching an intersection at a speed v_0 cannot stop comfortably is given by:

$$x_a = v_0\delta_- + v_0^2 / 2a \tag{2}$$

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

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

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

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

This analytical approach gives systematical analysis about the determination of the left-turn yellow change interval, and is chosen for the further improvement in the project.

2.1.2 Red Clearance

The red clearance interval has experienced considerable changes over the past years. Compared with the setting of the yellow change, the red clearance interval is involved with many geometry parameters as well as human factors.

Previous Studies. Most published research on the red clearance interval is for the through movement. It is always combined with the yellow change interval to form the yellow interval. In most of cases as shown in Table 2, the red clearance interval for the through movement is determined by one of the following expressions:

$$r = \frac{W + L}{V} \tag{5}$$

or

$$r = \frac{P}{V} \tag{6}$$

or

$$r = \frac{P+L}{V} \tag{7}$$

Where

r = red clearance interval, to the nearest 0.1 sec.

P = width of the intersection, feet, measured from the near-side stop line to the far side of the farthest conflicting pedestrian crosswalk along the actual path.

All the above Equation (5), (6), and (7) suggest that a key point in setting the red clearance interval is how to determine the length of vehicles' movement in intersection and the speed. The equations here leave these problems to the field engineers to solve. While the equations for determining the red clearance interval for the through movement seems very simple and straightforward. Problems for determining the red clearance interval for the left-turn movement are much more complex than for the through movement, involving both characteristics of intersections and drivers' behavior, which cannot be easily resolved according to the engineers' experience.

For setting the red clearance interval for left-turn movement, Butler (1983) adopted equations similar to the ITE Guideline for the through movement phases. Rather than specifying 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. In the methodology taken by the city of Lewisville (Black, 2001), the turning distance is simply given by:

$$S = \sqrt{W_l^2 + W_t^2} \cdot \mu \tag{8}$$

where, W_l and 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. This equation gives no information about how to set μ. These practices leave many factors to unsound estimation, and are not accurate enough for 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:

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

As shown in Figure 5, S is the length of the curve measured from the stop line to L feet ahead of the clearance line, where 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.

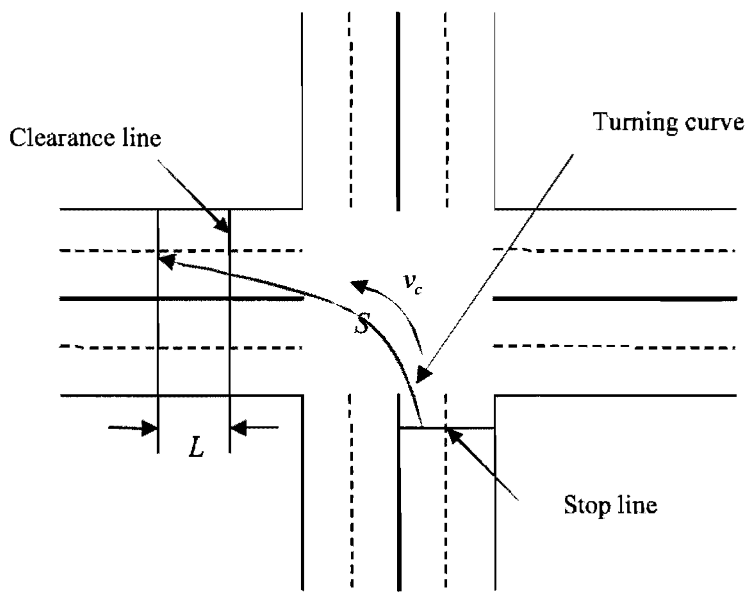

FIGURE 5: Calculation of the Red Clearance Interval

<u>An Analytical Approach</u>. Liu, *et al.* (2002) studied the calculation of the red clearance interval through an analytical approach. The following is a detail description of the approach proposed by Liu, *et al.* (2002).

First, they assumed the turning angle was 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. It can be shown that the following relation holds for the curve as long as a motorist is not making several zigzag movements within the triangle of the intersection (need not be a right triangle):

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

Where, the Parameter W_K equals $W_l + L$, as shown in Figure 6. The $S_{\max}$ and $S_{\min}$ are defined as shown in the Figure 6.

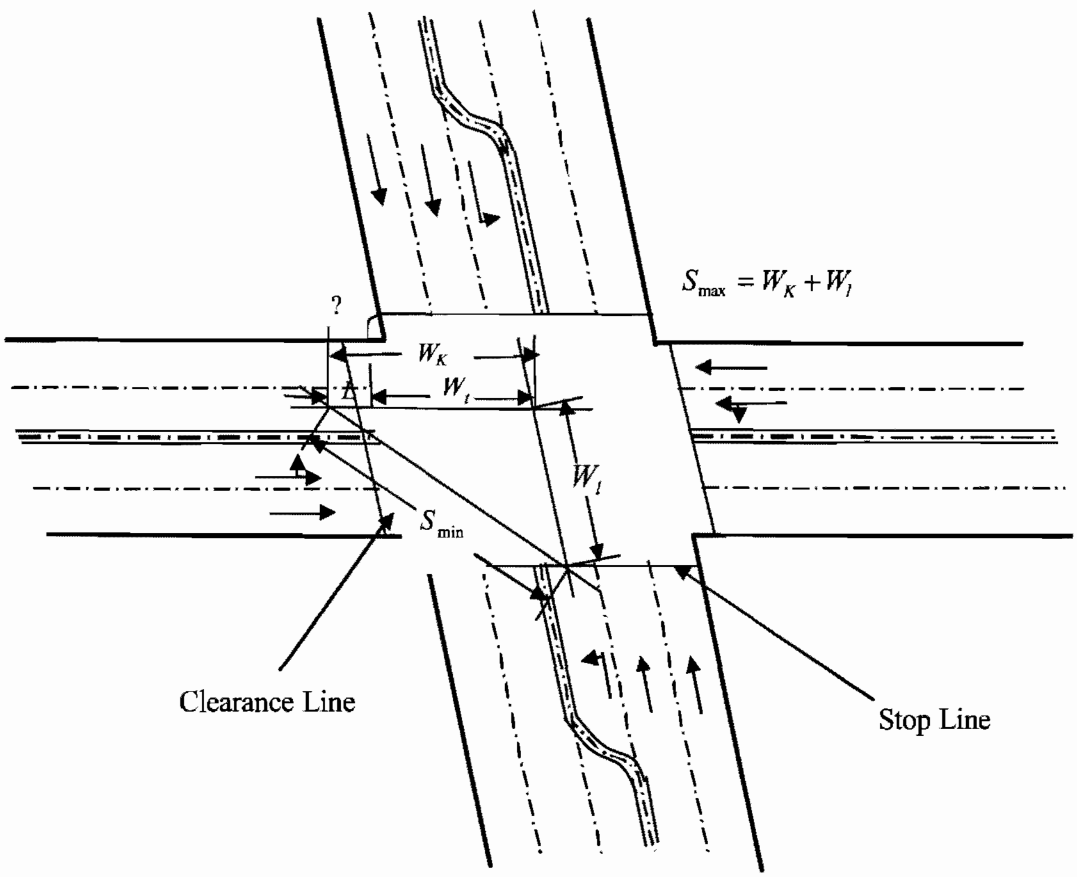

FIGURE 6: Illustration of the Calculation of the Turning Curve

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

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

where, parameter $\beta \in (0,1)$. The curve of the left-turn 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 the parameter β to be close to zero, and the driver prefers a smoother ride when taking the 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, the driver's behavior, the size of vehicles, the markers for the left turn vehicles and various other factors have effects on the characteristics of the left-turn curves. Nevertheless, the magnitude of the average centrifugal acceleration experienced by motorists is an important indicator in determining the duration that a vehicle spends within an intersection. The detailed evaluation of the acceleration and the speed along a turning curve is complex. However, adopting a dimensional type of analysis, the average turning speed is calculated by imposing that:

$$k V_c^2 \leq \gamma g \tag{12}$$

Parameter γ may be selected in the interval [0.3, 0.8] (Liu, *et al*, 2002). Gazis (1960) and Stimpson (1980) indicated that the number 0.3 had been selected as an "alarming" acceleration rate; and Hammond (1941) indicated that the number 0.8 had been used before to represent a large deceleration rate. The average speed on turning curves may be set according to:

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

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 the max $[V_{lt}, V_l]$ for all cases according to the equation. A possible choice is to approximate λ 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 the speed limit along sides, approaching street and crossing street of the intersection.

Therefore, the time duration needed for a motorist to clear off an intersection, the red clearance interval, 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 the through movement for most intersections if not for all.

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 Black (2001). The procedures are provided with an Excel spreadsheet that was developed to calculate vehicle clearances (the yellow change and red clearance intervals) and pedestrian clearance times (flashing don't walk) for a single intersection.

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 ITE (ITE Technical Committee 4A-16, 1985). The yellow change and red clearance interval for the through movement and left-turn movement adopted by The City of Lewisville are provided here.

Through Movement Yellow Change and Red Clearance Intervals. The City of Lewisville uses the latest ITE equation for setting the yellow change interval:

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

Where:

V_l = proper approach speed limit, miles/hour

G = acceleration due to gravity, the city uses 32.2 feet/sec^2

g = grade of the approach in % (negative is downhill)

The equation is similar to the latest ITE equation. The difference is that the City of Lewisville uses the approach speed limit, while ITE uses the mean approach speed. The City of Lewisville also separated the second part of the ITE latest equation as the red clearance interval, while ITE just included that as the yellow interval.

Protected Left-Turn Yellow Change. There is no consensus for using the yellow change and red clearance intervals applied to protected left-turns. The City of Lewisville uses a left-turn yellow change of 3 sec. Calculated values of the left-turn yellow change interval are usually lower than 3 sec because the left-turn approach speeds are usually very low.

Protected Left-Turn Red Clearance. The calculation of the red clearance in the spreadsheet for the protected left-turn phases is similar to the ITE Guideline for the through movement phases. Rather than specifying 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:

$$S = 0.8\sqrt{W_K^{\ 2} + W_l^{\ 2}} \tag{17}$$

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

$$r = \frac{S}{1.417\, V_c} - \%tRl \cdot \delta\_ \tag{18}$$

where

$\%tRl$ = percentage of perception-reaction time to deduct from the red clearance.

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

2.2.2 General Case of US

Although a large majority of traffic engineers is in favor of the establishment of a national technique for determining the yellow intervals and a significant proportion of these engineers wishes that some proposed national techniques takes into account variations in local conditions, such a 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 conducted by the technical committee of Colorado/Wyoming section, ITE (1985), the empirical time is chosen for the yellow change and red clearance interval for left-turn movement as:

3 sec. yellow change; 1 sec. red clearance at all locations

4 sec. yellow change plus no red clearance

3 sec. yellow change + 1.5 sec red clearance

3 sec. yellow interval for speeds less than 40 miles/hour; 4 sec. yellow interval for speeds 40 to 50 miles/hour; 5 sec. yellow interval for speeds greater than 50 miles/hour

3 sec. yellow change with "appropriate" red clearance

3.5 sec. yellow interval for 1-2 opposing lanes; 4.0 sec. interval for 3 or more opposing lanes

3.5 sec. (4 sec. on multilane) yellow change; 0.5-1 sec. red clearance for skewed intersection

y=3 sec. yellow change+ red clearance

Where: red clearance = 0.5 sec. for 1 opposing lane

= 1.0 sec. for 2 opposing lanes

= 1.5 sec. for 3 or more opposing lanes

Based on Width of Intersection. Also in the same technical committee report by Colorado/Wyoming section, ITE (1985), the following equations were indicated for both through and left-turn movement, and the red clearances have been incorporated into the equations, making those equations for yellow intervals (yellow change plus red clearance).

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

or

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

where

v = speed, feet/sec. (assumed to be 20 miles/hour for left turn vehicles)

W = intersection width, the distance of vehicle travel from the stop bar turning into the nearest lane is used for left-turn movement, feet

Other Methods. The method recommended by ITE is also put into practice in many US cities for both through and left-turn movement:

Yellow change:

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

Red clearance:

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

2.3 Observations

By reviewing the state-of-the-art and state-of-the-practice regarding the yellow change and red clearance intervals, it is shown that the existing methods have the following limitations:

Most of methodologies were developed based on the through movement, without considering the left-turn movement, which is more complex with unique characteristics;

The frameworks for setting intervals incorporated a limited number of parameters, thus, considering little specific for each individual intersection;

By comparison of the state-of-the-art versus the state-of-the-practice, it is found that although some studies about the left-turn yellow change and red clearance intervals were conducted, engineers still prefer to use a simple methodology to set the intervals in practice. A lot of cities adopted the empirical times for yellow change and red clearance intervals. This is due to the fact that there is no nationally accepted methodology about determining the left-turn yellow change and red clearance intervals.

Compared with the left-turn red clearance interval, the yellow change interval was studied by more researchers from earlier time. The reason is that researchers have long been studying the yellow change interval issues for the through movement. The dilemma zone problem was first introduced back to 1960. Some of issues studied for through movement can also be applied to the left-turn movement.

When conducting the study about determining the intervals for the through movement, the red clearance interval is always integrated with the yellow change interval as a yellow interval. However, the red clearance interval for left-turn is much more complex than that for through movement. The study for left-turn movement yellow change and red clearance should be conducted separately.

In the previous analytical studies about the left-turn red clearance intervals, most of them used the parameters of the left-turn curve and the average turning speed. However, they gave little information on how to appropriately calculate these parameters.

In this chapter, the analytical approach by Liu, *et al.* (2002) was studied in detail. This approach considered much more parameters, and can be put into practice in some intersections after getting enough information to set the parameters. The approach can serve as a quite reasonable framework if further improvement of some parameters can be provided.

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 7).

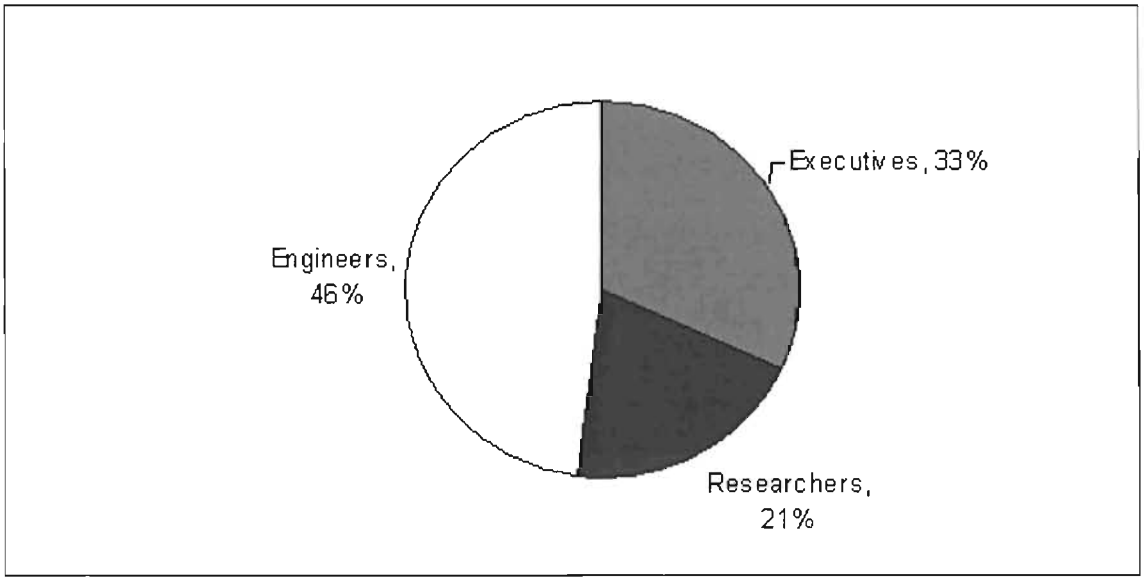

FIGURE7: Illustration of Survey Respondents

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 parameters 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 8 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.

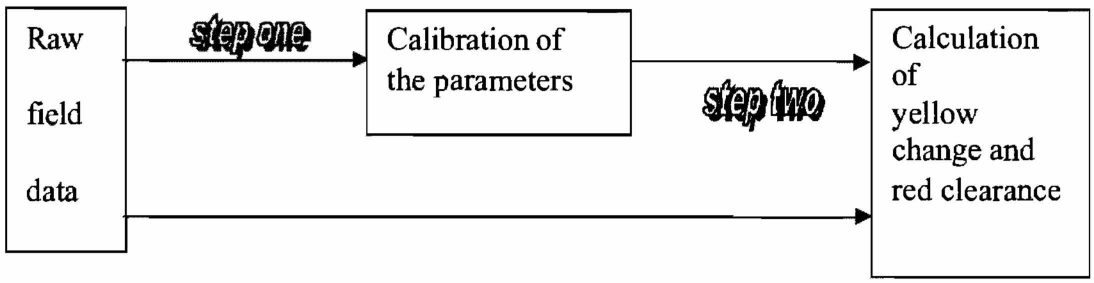

FIGURE8: Block Diagram of Analytical Framework

4.2 Notation

The following symbols are used in the framework:

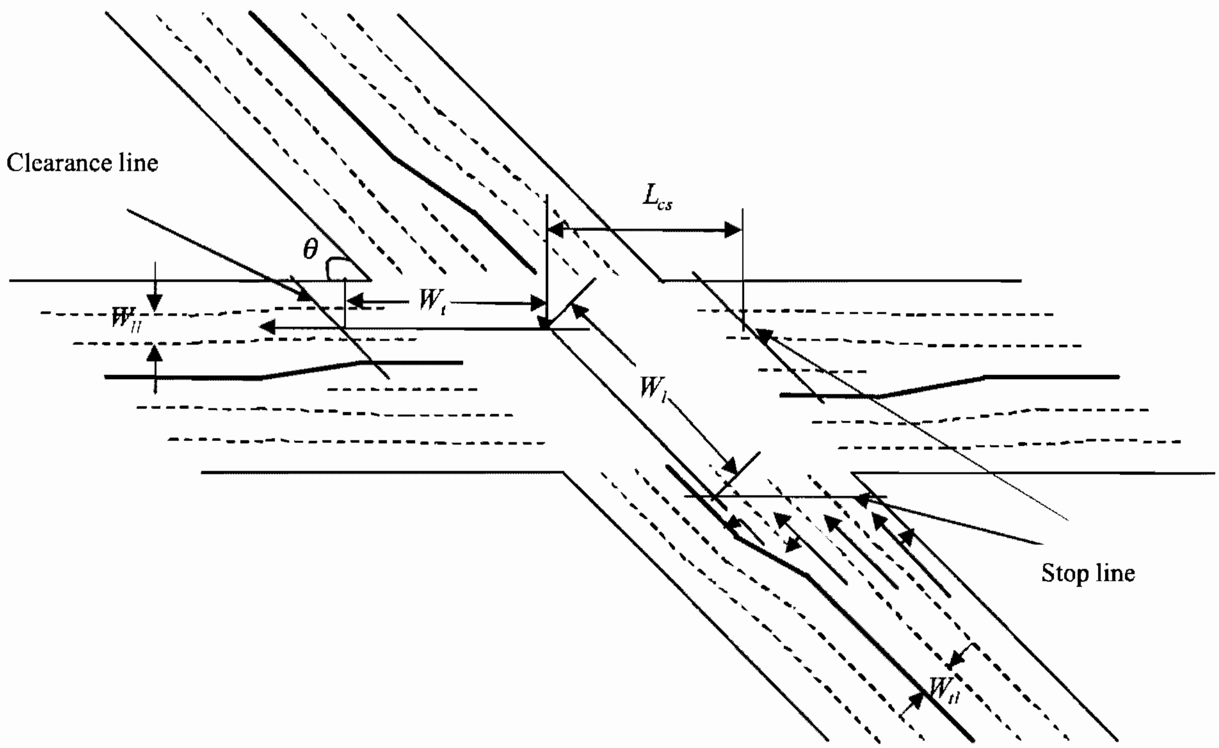

FIGURE 9: Symbols used in the framework

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

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

L = vehicle length (feet)

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

$\delta\_$ = drivers' perception-reaction time (sec)

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

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

W_t = width of approaching street, as in Figure 9 (feet)

W_l = width of crossing street, as in Figure 9 (feet)

W_{tl} =width of approaching lanes, as in Figure 9 (feet)

W_{ll} = width of crossing lanes, as in Figure 9 (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/hour)

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

α = dimensionless parameter range from 0 to 1

β = dimensionless parameter range from 0 to 1

γ = dimensionless parameter range from 0 to 1

λ = dimensionless parameter range from 0 to 1

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

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

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

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

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

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

L_{cs} = distance between conflict point and (opposite/ cross street's) stop line (feet), (L_{cs} in Figure 9 is the one in left-turn lag scenario)

y = yellow change (sec)

r = red clearance (sec)

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:

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.

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.

Widths of approaching and crossing lanes and streets. Widths of approaching street and crossing street are defined as shown in Figure 9. It's a major factor that decides the distance a vehicle should pass for clearing the intersection.

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.

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.

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.

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 feet/sec^2, as in the Recommended Practice by ITE in 1985.

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.

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.

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.

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.

4.4.1 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 10, 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:

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

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 10 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 ?. 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.

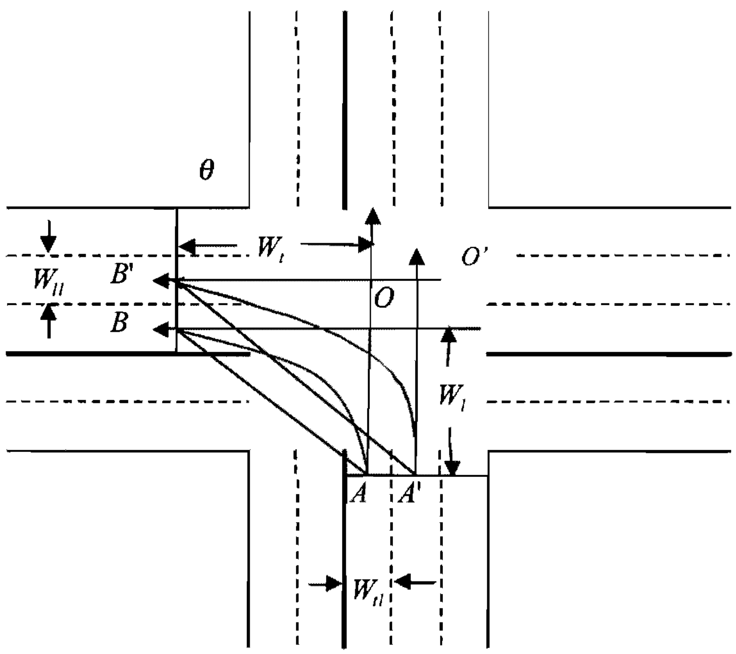

FIGURE 10: Turning Curve for Different lanes

4.4.2 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.

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

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

4.4.3 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 $V_{0.85}$:

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

Parameter 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 sec 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.

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

The actual turning curve, which can be estimated as $\sqrt{W_l^2 + W_t^2 + 2W_l W_t \cos\theta}$, 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.

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

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

4.4.5 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:

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

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

4.4.6 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:

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

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.

4.4.7 Trajectory of left-turn curve

The value of parameter 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 parameters 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 set as:

$$y = 2(\delta_- + \frac{V_t}{2a_-})/(1 + \frac{V_i}{V_t}) + T_{vi} \tag{29}$$

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 set as:

$$r = 0.6820\frac{\xi(S+L)}{V_c} - T_{cs} \tag{30}$$

CHAPTER 5

DATA COLLECTION

5.1 Background

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

5.2 Data Requirements

Data to be collected includes the geometry data, the traffic information, the historical accident information and current yellow change and red intervals.

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 were collected. These intersections covered 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 included:

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 included:

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 included:

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 considered included:

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) were important, it proved 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 was not 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 made sure that enough data was collected for each particular category. It was also recognized that too diversified data were not good for model validation and calibration.

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

As shown in Table 7, the intersections were classified based on speed group, the number of left turn lanes, and the left turn control type. Two speed groups were 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 included protected and protected/permitted control. Permitted left turn was not a subject of this study, since the yellow and all-red clearance intervals were normally determined based on the through movement. We believe that such a data collection plan covered the majority of the intersection types and established 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. The selected sites covered 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

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	Angle, high left turn
6. FM 2818/Texas Avenue	H1PM	Standard Geometry
Houston		
7. Richmond/Sage Rd.	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 Bissonet	H2PT	Angle
12.Bellaire Blvd./Toll Rd 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. FM3040/MAcArthur Dr.	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 were conducted depending on the type of data. These different data collection methods to be collected are discussed below.

5.4.1 Request from Responsible City and Jurisdictions

The following data were collected through contacting city and jurisdictions that were 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 was conducted to collect detailed traffic flow data and vehicle maneuvers while approaching the intersection and moving within the intersection. Video tape provided a permanent record of the data, which could 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 conducted a pilot study by using the video trailer that allowed 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 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 be estimated. Nevertheless, the research team strongly favored such a data collection method.

5.4.3 Speed Measurement

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

5.4.4 Other Field Measurements

Other data that could not be obtained directly from the video tapes or the city needed to be measured in the field during the same time of video taping. These data included number of lanes, lane widths, sight distance, and left turn phasing.

5.5 Data Retrieval

With all the data collected and tapes recorded, next step was extracting the field data from various sources, such as video tapes, engineering drawings, and analyzing the surveyed data for each intersection.

5.5.1 Data Groups

Since in analytical framework, the intervals were calculated from several parameters, all the information for preparing the parameters was needed to calibrate the model. The parameters were grouped according to the different resources as following.

Geometry Parameters

Geometry parameters data were directly obtained from the engineering drawings. The group has the parameters of Numbers of Lanes, Width of Lanes and Streets, Turning Angle, Distance between Potential Conflict Point and Stop Line, Lane Assignments, and Traffic Signal Position/Visibility.

Human Factor Parameters

Human factor parameters are some parameters whose values are decided by human engineering knowledge. The most acknowledged values were found in transportation manuals or other researches. The following are the human factor parameters and their respective value range:

Drivers' Perception-Reaction Time (1.0 - 1.5 sec)

Drivers' Comfortable Acceleration Rate (10 - 11 feet/sec^2)

Drivers' Tolerable Centrifugal Force (0.5 – 0.6*g*, *g* is gravity)

Law Related Parameters

Law related parameters are stipulated by traffic regulations on the intersection. Traffic laws or regulations were assumed to be always obeyed in the yellow intervals setting process. The law related parameters are Speed Limits on Approaching Lane, Speed Limit on Crossing Lane, and Traffic Laws Related to Signal Controlled Intersections.

Some parameters were provided by governmental agencies. They were Historical Accident Data Due to Left-Turn Movement, Historical Accident Data at Intersection, Signal Phasing Structure, Vehicle Length, and Vehicle Types.

Other than these parameters, there were some calculated and calibrated parameters as well.

Calculated Parameters

Calculated parameters were used as interims to calculate the yellow change and red clearance. They are Correction Factor for Multiple Left-Turn Lanes, Time Deduction for Distance between Conflicting Points and Stoplines, Time Delay from Low Visibility of Traffic Signals.

Calibrated Parameters

The calibrated parameters are those parameters which value should be decided first to get yellow intervals. The calibration process is giving a value table, from which the value of each parameter in this group can be chosen according to the different types of target intersection, and applied directly to the intersection. The parameters needed to be calibrated are Drivers' Approaching Behavior (α), Drivers' Behavior on Left-Turn Curve (ß), Drivers' Tolerable Centrifugal Force (?).

5.5.2 Data from Tapes

The tapes were used to retrieve the data needed to calibrate the parameters. According to the analytical framework, in order to calibration, following data in each intersection were required: 85% approaching speed, time and distance to get the entering speed, and the turning time and turning curve. The process to get these data was based on a MATLAB program which recording the timings of vehicle's positions.

The following figure sketch (Figure 11) shows five points that were supposed to be set in each surveyed intersection in the TV screen. The MATLAB program records the time when each vehicle reaches the five positions in Figure 11.

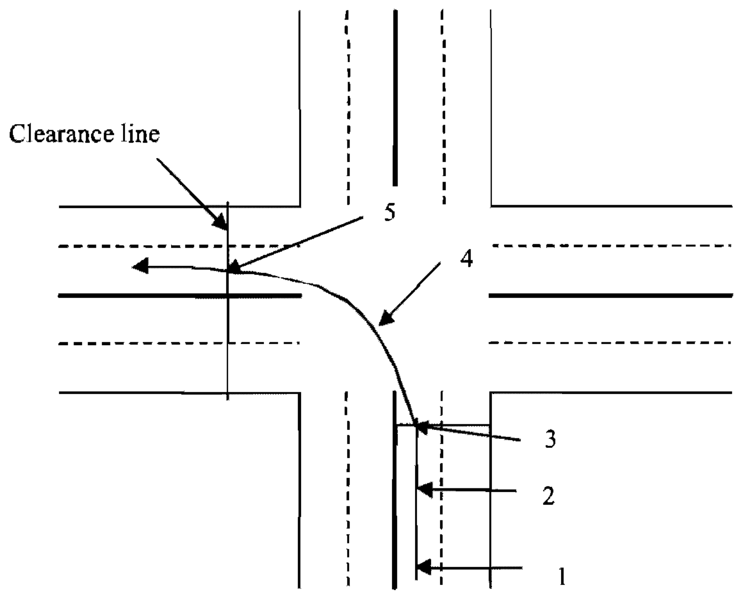

FIGURE 11: Data Retrieving from Tapes

With these times, the driving interval between each two points can be calculated. The time interval between the third position and fifth position is the turning time. For calculating the entering speed, the distance between the first point and the third point must be measured first. With the help of the corresponding engineering drawings, the scale of the screen picture and actual distance can be gotten by measuring the street width on the screen and reading the actual width on the drawing. Then, the distance from the first position to third position is measured on the screen, and the actual distance based on the scale. Then, average entering speed would be calculated from the driving distance and time interval.

For recording the turning curve, the MATLAB program records the three different curves according to which point of the three points the vehicle passed. The following sketch illustrates the thinks. When vehicle completes the left-turn, the turning curve is estimated as one of the three different curve types, which represent the longest curve, middle curve and shortest curve.

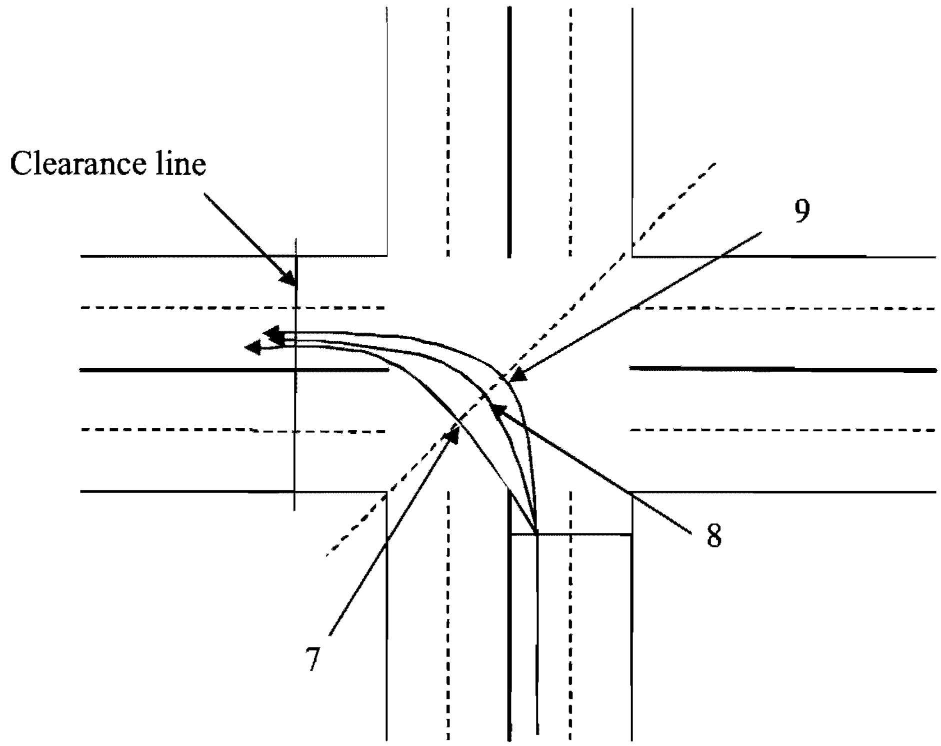

FIGURE 12: Turning Curves Retrieving from Tapes

After indicating the specific curve and recording the time interval of turning time from the third point and fifth point in Figure 12, the actual curve length is required to get the turning speed. The actual lengths of three curves are estimated form the engineering drawings. As we indicated in the analytical framework, the longest possible driving distance is assumed to be the sum of distance from the point A to O, and Point O to B as the points indicated in the Figure 13, and the shortest one should be the short cut, distance from the point A to B. The normal curve, or the middle curve passes on the point 8 indicated in the Figure 12 is assumed to be circle, because of its constant radii, then radial force. For determining the circle, three positions on the circle are needed. Point A and B are the two natural positions. Since the normal curve passes somewhat between the short cut and position O, the third position is set in the middle of the point O to the short cut which is the position C indicated in the Figure 13. Then the normal curve can be get form the geometric calculation. For the curves pass on the point 7 or 9, they are assumed to be the average of the normal curve and short cut, and normal curve and longest possible driving distance respectively.

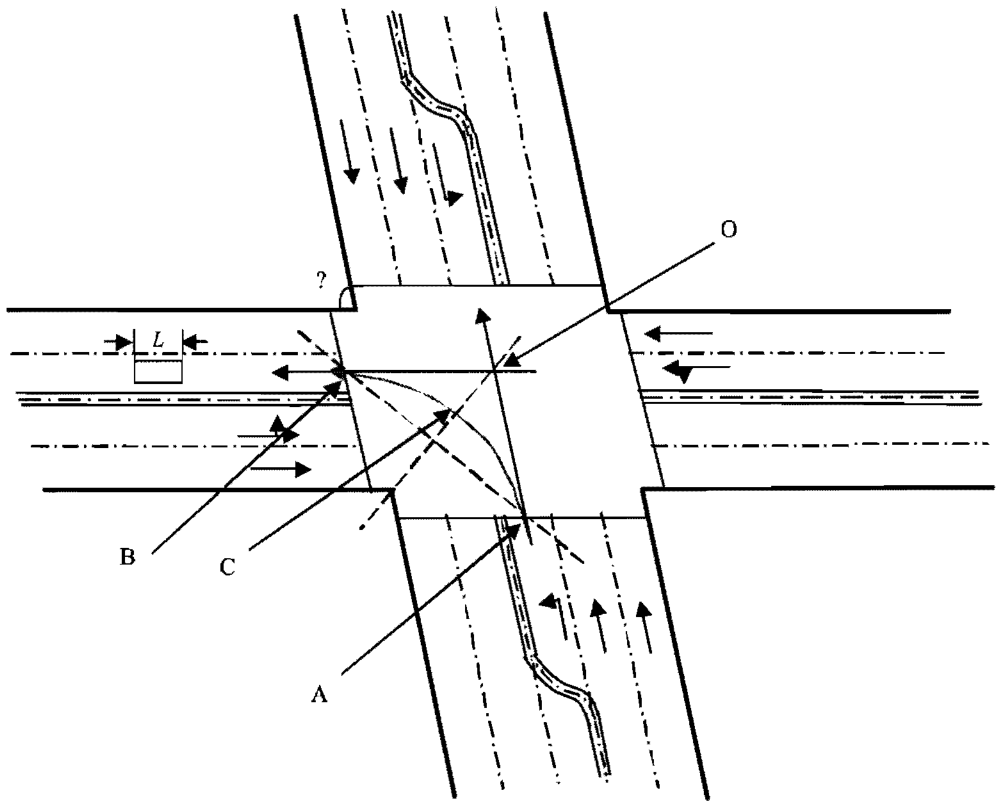

FIGURE 13: Calculate Simulated Turning Curves

All the information was recorded by the MATLAB in txt format. The following Table 10 is a data stream from the intersection of Georgebush Dr @ Wellborn in College Station, Texas. The first column is the number for vehicles; the sec column to the sixth column is the time of each vehicle passing the 5 positions illustrated in the Figure 14. The seventh column is the choosing of turning curve shown in Figure 15, with 1, 2, and 3 to indicate the three types of curve respectively. The eighth column is the record of vehicle types, with 1 and 2 to indicate whether it's a truck or not. The last column is the record of whether the vehicle stops or not before making left-turn.

TABLE 10: Data Retrieved from Tapes in Matlab Format

```
**************************************************************
*    This is the data from the survey tape    *
**************************************************************

The name of the intersection is:  Georgebush Dr.@wellborn

1 0.0000 2.9150 7.1110 20.2300 21.9220  2 1 0
2 0.0000 2.4540 5.9990 7.8710  9.0330   1 0 1
3 0.0000 2.0430 4.3960 39.8670 41.6700  2 0 0
4 0.0000 1.7630 3.6660 16.4340 18.3970  2 1 0
5 0.0000 2.5740 4.4770 17.1350 18.8970  3 1 0
6 0.0000 2.1230 4.0150 21.0500 22.9730  2 1 0
```

5.6 Sensitivity Analysis of Data Accuracy

The sensitivity analysis tested the effect on the calibration and intervals setting of the possible inaccuracy of the field data from the tapes, in another words, data quality. In the framework, the yellow change setting was based on the parameter α, and red clearance setting was based on the parameter β and γ. Therefore, in the sensitivity analysis, we first analyzed the data's effect on the parameter, then on the ultimate intervals setting.

The first type of data measured from the tapes that affect the parameter α is the distance from the position 1 to position 3 (Figure 11). This distance was measured from the TV screen. The intersection used for sensitivity analysis has the setting as in the following table (Table 11), which was based on a real intersection. Other parameters assumed for analysis are also listed in the same table. The largest possible on-screen measuring error in length was within ± 0.5 inch. By scaling, the estimated distance from position 1 to position 3 lies between 126ft to 138ft. Based on this estimation, the calibrated parameter α is between 0.10 and 0.26. Accordingly, the calculated yellow change fluctuates from 3.11 sec to 3.00 sec, with a relative error of 1.80%.

TABLE 11: Intersection Configurations 1

Intersection type	H1PM
Parameter β	0.4
Parameter γ	0.5
Approaching Speed Limit	50 miles/hour
85 Percentile Speed	36 miles/hour
Number of Crossing Lanes	2
Number of Approaching Lanes	2
Number of Left-Turn Lanes	1
Intersection Angle	60

The complete trend of the effect about accuracy of the field data is shown in the Figure 14. The figure gives the parameter α value and respective yellow change to each possible distance. From the figure, even the largest inaccuracy from the field data only swung the yellow change a 0.055s, with parameter α can up and down about 44%.

The field data from the tapes that affect the red clearance are curve length. Similar analysis was given about the red clearance. One different between the yellow change and red clearance was that setting of red clearance is involving two parameters β and γ, and the two parameters swung to different direction for the same accuracy of the curve length. The two parameters can also make the red clearance to the different directions, thus neutralizes the effect of the inaccuracy of the field data. The separate analysis about relationship between the two parameters and red clearance will be given in the next chapter (Chapter 6). However, the effect the accuracy of the curve length on the two parameters and red clearance can be analyzed here. Intersection used for this sensitivity analysis has the setting as in Table 12.

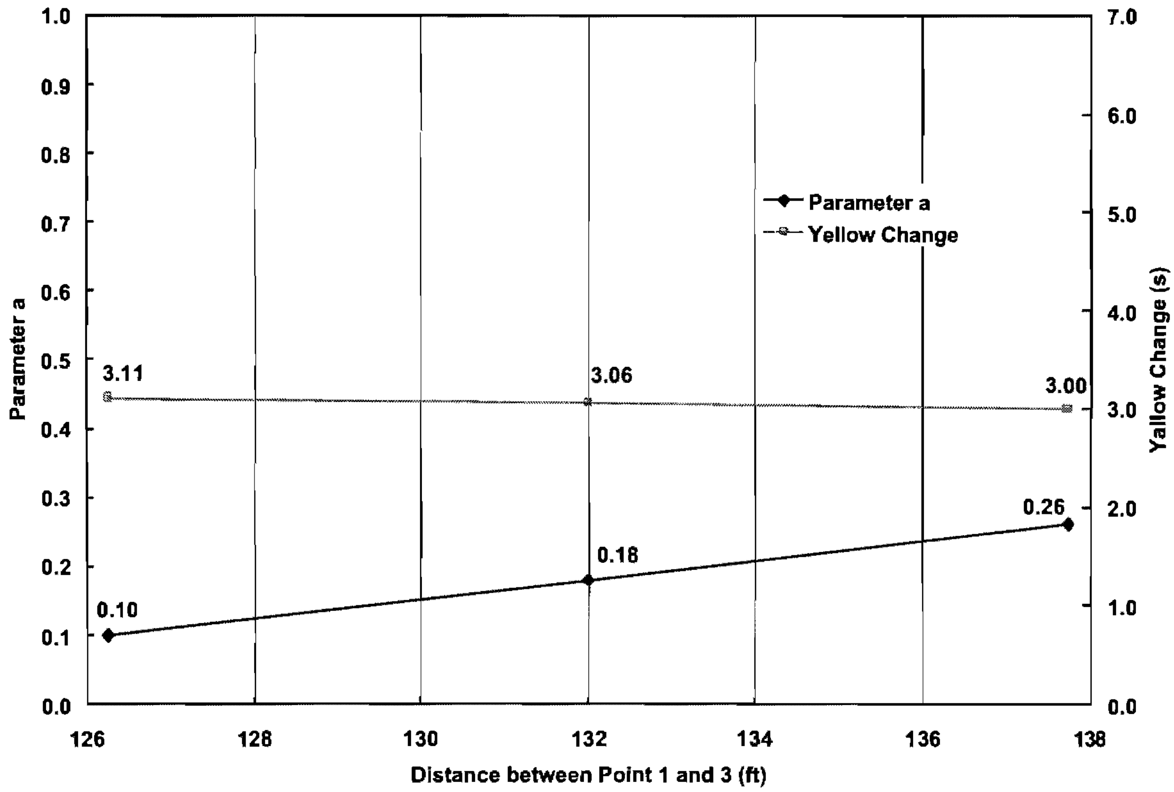

FIGURE 14: Data Accuracy Analysis for Yellow Change

TABLE 12 Intersection Configurations 2

Intersection type	H1PM
Parameter α	0.5
Approaching Speed Limit	40 miles/hour
85 Percentile Speed	32 miles/hour
Number of Crossing Lanes	3
Number of Approaching Lanes	3
Number of Left-Turn Lanes	1
Intersection Angle	90

The data needed for calibration or red intervals calculation is the curve. From the data retrieve plan, we noted that the curves were decided by three position 7, 8 and 9 (Figure 12). The three positions are in area between the longest curve, sum of approaching street width and cross street width, and the shortest curve, shortcut. In the previous description about the positions, the three curves are set as intermediate curve from the shortcut to the longest driving distance. Therefore, largest possible inaccuracy about the curve is 25% of the difference of longest driving distance (sum of the approaching street width and crossing street width) and the shortcut. In the case used to do the analysis, the shortcut curve is 150 feet; while the curve passes position 9 (Figure 12) is 195 feet. From the definition of parameter β, the parameter vary from 0 to 0.75. Parameter γ varies from the 0.49 to 0.64; therefore γ fluctuates 0.05 every 25% variation of curve. Finally, red clearance fluctuates from 3.16 sec to 3.03 sec; that equals about less than 4.2%.The detail result is shown in the following figure 15.

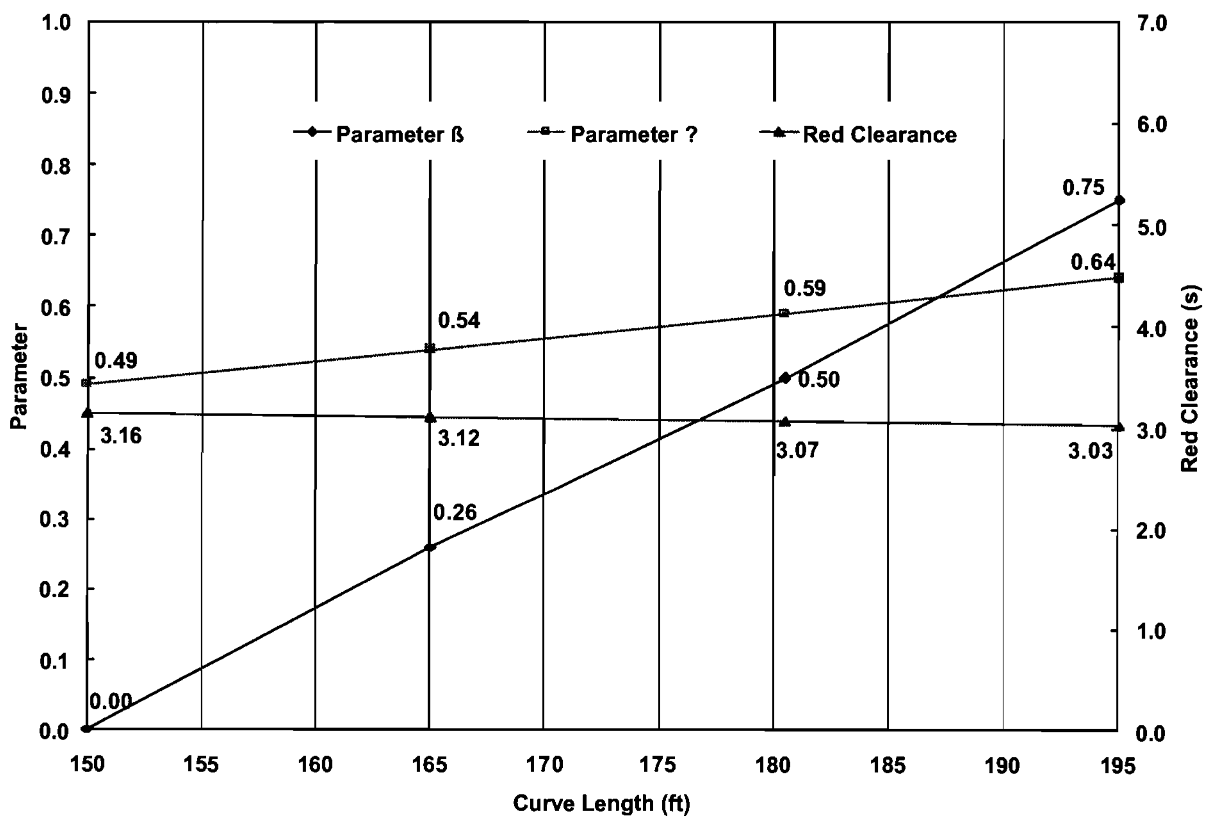

FIGURE 15: Data Accuracy Analysis for Red Clearance

CHAPTER 6

MODEL CALIBRATION

With all the necessary data from the engineering drawings and tapes, the calibration of model, the calibration of the model can be done by getting the parameters α, β, and γ's values. The three parameters are in Equation 25, 26, and 27. Each parameter stands for an undecided driver's behavior to be calibrated. Drivers are intended to slow down before making the left turn Therefore, entering speed is determined by the average driving speed and turning speed. The parameter α in the Equation 25 was used for the calculation of the entering driving behavior before making the left-turn. As described in the model, the turning curve should be less than the sum of the width of approaching street and cross street, and be longer than the shortcut from the approaching street to cross street. The exact curve depends on the driver's drive behavior. Parameter β in the Equation 26 was used to calculate the driver's behavior on left-turn curve. Vehicle's speed in the turning curve depends on the human's tolerable centrifugal force by which drivers still feel comfortable and can maneuver safely. The last parameter in the Equation 27 was used to calibrate driver's tolerable centrifugal force during left-turn.

6.1 Preliminary Calibrating Drivers' Entering Driving Behavior

In the Equation (25), the parameter α value affects the calculation of the parameter entering speed. Because the parameter entering speed is ultimately used in the calculation of the yellow change interval in Equation (29), the parameter α value can affect the determination of the yellow change interval, through the entering speed. In order to analyze the effect of the parameter α on the yellow change interval and the entering speed, the yellow change interval and the entering speed are calculated by giving a whole range of the parameter α value, from 0 to 1, based on an example intersection. The configurations of the example intersection used to analyze the effect of parameter α are shown in Table 13.

TABLE 13: Configurations of the Intersection Used for Analyzing the Effect of the Parameter α

Intersection type	H1PM
Parameter β	0.4
Parameter γ	0.5
Approaching Speed Limit	50 miles/hour
85 Percentile Speed	36 miles/hour
Number of Crossing Lanes	2
Number of Approaching Lanes	2
Number of Left-Turn Lanes	1
Intersection Angle	60°

By inputting different parameter α values, from 0 to 1, different yellow change intervals and entering speeds can be obtained. The calculation results of the yellow change interval and entering speed are presented in Figure 16.

Figure 16 illustrates that yellow change interval and the parameter entering speed are not very sensitive to the parameter α. The yellow change intervals vary from 2.7 sec to 2.4 sec, even though this analysis is conducted based on the whole range of the parameter α value, 0 to 1. This means that possible inaccuracy of parameter α will not affect the determination of the yellow change interval very much.

From the Figure 16, it is also known that, if the entering speed can be obtained from the data retrieved from the tapes, the value of the parameter α can be calculated. The preliminary calibration is intended to calculate the value of parameter α by obtaining the entering speed based on the collected data on 21 surveyed intersections.

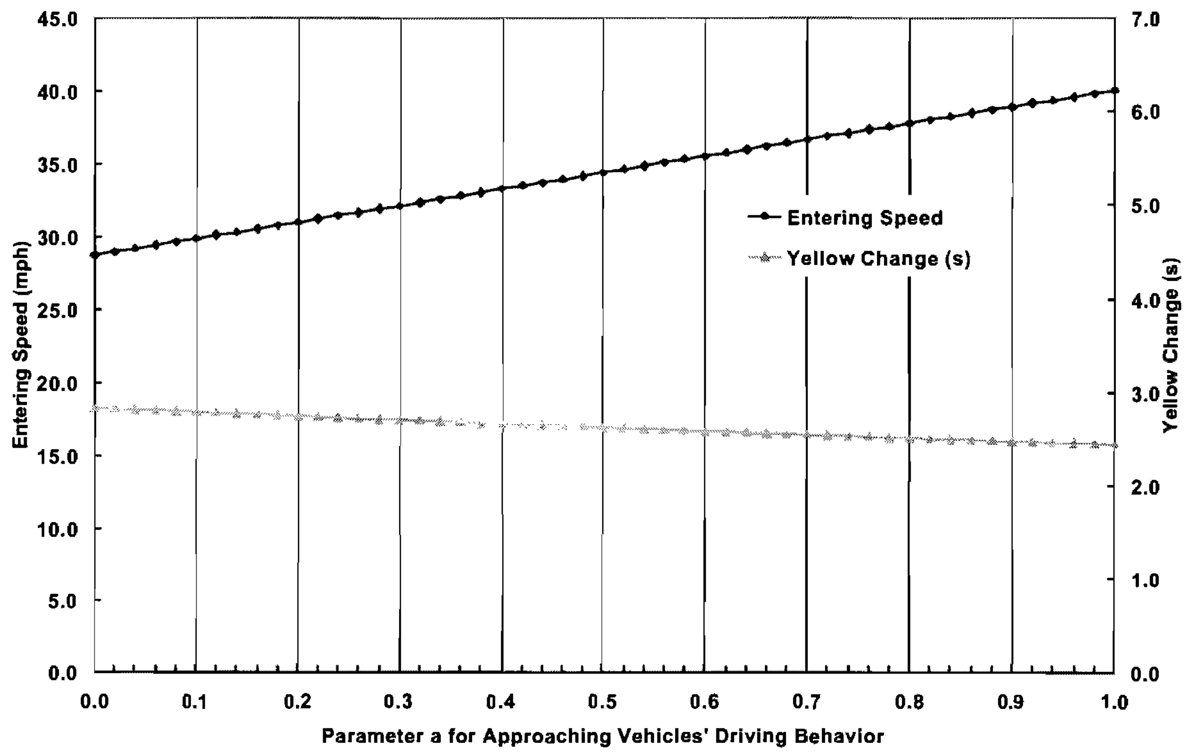

FIGURE 16: Analysis of the Effect of the Parameter α

The calibration was conducted based on data from the 21 intersections. In Equation (25), the parameter α can be calculated after obtaining the entering speed, the approaching speed limit, and the 85% percentile approaching speed. Both the approaching speed limit and the 85% percentile approaching speed were collected from the sites. The entering speed can be obtained based on the data retrieved from the tapes, as the distance of between the position 1 and the position 3 (as shown in Figure 11) divided by the time elapsed.

For each surveyed intersection, every vehicle's entering speed in the tapes can be obtained. Then, the results of the parameter α values are calculated respectively. The average of the calculated parameter α values was adopted for each intersection.

The average values of the parameter α for 21 surveyed intersections are summarized in Table 16.

6.2 Preliminary Calibrating Drivers' Behavior on Left-Turn Curve

In the Equation (26), the parameter β value affects the calculation of the parameter turning curve. Since the parameter turning curve is ultimately used in the red clearance interval calculation in Equation (30), the parameter β value can affect the determination of the red clearance interval, through the parameter turning curve. In order to analyze the effect of the parameter β on the red clearance interval and the turning curve, the red clearance interval and the turning curve are calculated by giving a whole range of the parameter β value, from 0 to 1, based on an example intersection. The configurations of the example intersection used to analyze the effect of parameter β are shown in Table 14.

TABLE 14: Configurations of the Intersection Used for Analyzing the Effect of the Parameter β

Intersection type	H1PM
Parameter β	0.4
Parameter γ	0.5
Approaching Speed Limit	50 miles/hour
85 Percentile Speed	36 miles/hour

Number of Crossing Lanes	2
Number of Approaching Lanes	2
Number of Left-Turn Lanes	1
Intersection Angle	60°

By inputting different parameter β values, from 0 to 1, different red clearance intervals and turning curves can be obtained. The calculation results of the red clearance interval and turning curve are presented in Figure 17.

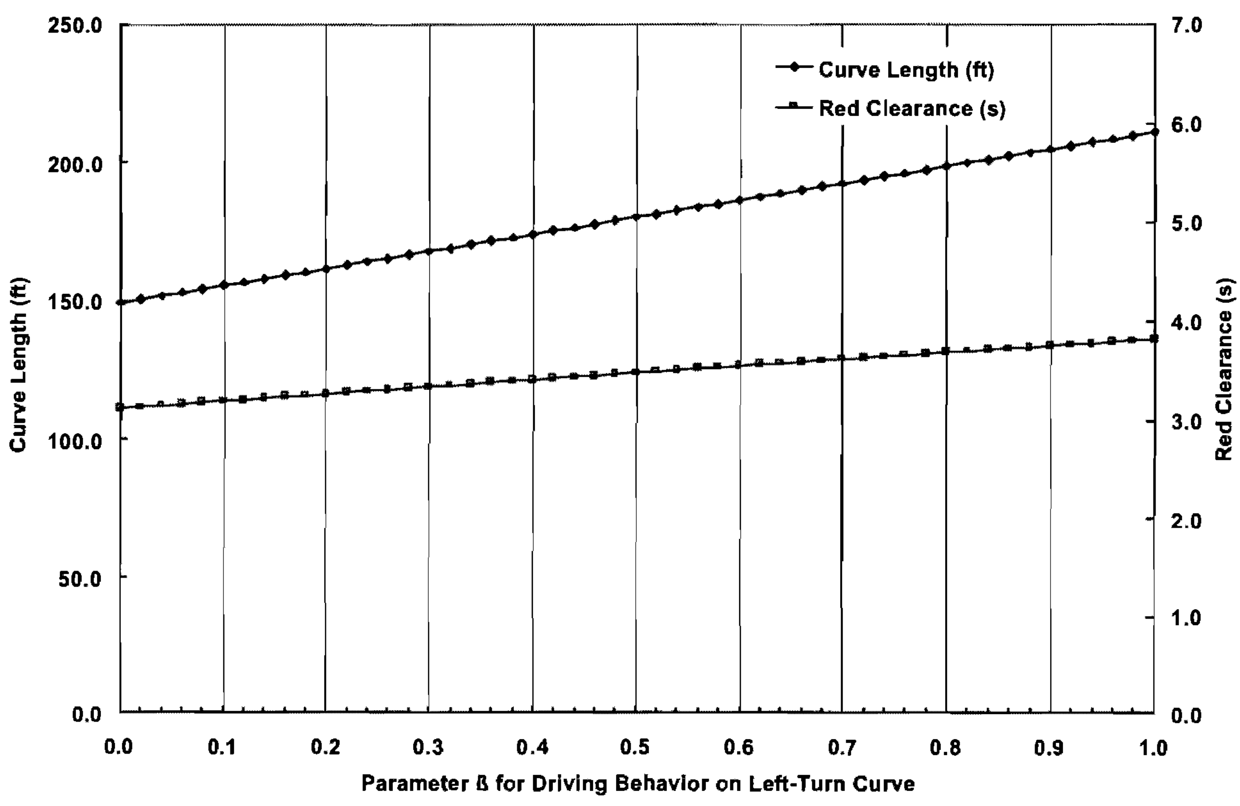

FIGURE 17: Analysis of the Effect of the Parameter β

Figure 17 illustrates that the red clearance intervals vary from the 3.2 sec to 3.8 sec. By the Figure 17 and Equation (26), if the turning curve is obtained based on the data retrieved from the tapes, the value of the parameter β can be calculated. It is noted that, in the Figure 12, all three turning curves should be between the S_{max}, and S_{min}, defined in the Figure 6. Therefore, length difference between the two neighbor turning curves should be about 25% of the distance of (S_{max} - S_{min}). It is assumed that the turning curve a vehicle travel close can be correctly judged during the data collection. This means that possible inaccuracy of parameter β is only within 25% of its range, because the parameter β is used to determine whether the actual curve is more influenced by the S_{max} or S_{min}. Within the 25% range of the parameter β, the red clearance interval varies only about 1.5 sec.

The preliminary calibration is intended to calculate the value of parameter β based on the Equation (26) by obtaining the turning curve based on the collected data on 21 surveyed intersections.

For each surveyed intersection, every vehicle's turning curve in the tapes can be obtained. Then, the results of the parameter β values are calculated respectively. The average of the calculated parameter β values was adopted for each intersection.

The average values of the parameter β for 21 surveyed intersections are summarized in Table 16.

6.3 Preliminary Calibrating Drivers' Tolerable Centrifugal Force

In the Equation (27), the parameter γ value affects the calculation of a major parameter, the turning speed. Because the parameter turning speed is used in the red clearance interval calculation in Equation (30), the parameter γ value can affect the determination of the red clearance interval, through the parameter turning speed. In order to analyze the effect of the parameter γ on the determination of the red clearance interval and the turning speed, the red clearance interval and the turning speed are calculated by giving the largest possible values of the parameter γ value, from 0.2 to 1.0, based on an example intersection. The configurations of the example intersection used to analyze the effect of parameter γ are shown in Table 15.

TABLE 15: Configurations of the Intersection Used for Analyzing the Effect of the Parameter γ

Intersection type	H1PM
Parameter β	0.4
Parameter γ	0.5
Approaching Speed Limit	50 miles/hour
85 Percentile Speed	36 miles/hour
Number of Crossing Lanes	2
Number of Approaching Lanes	2
Number of Left-Turn Lanes	1
Intersection Angle	60^{o}

By inputting different parameter γ values, from 0.2 to 1.0, different red clearance intervals and turning speeds can be obtained. The calculation results of the red clearance interval and turning speed are presented in Figure 18.

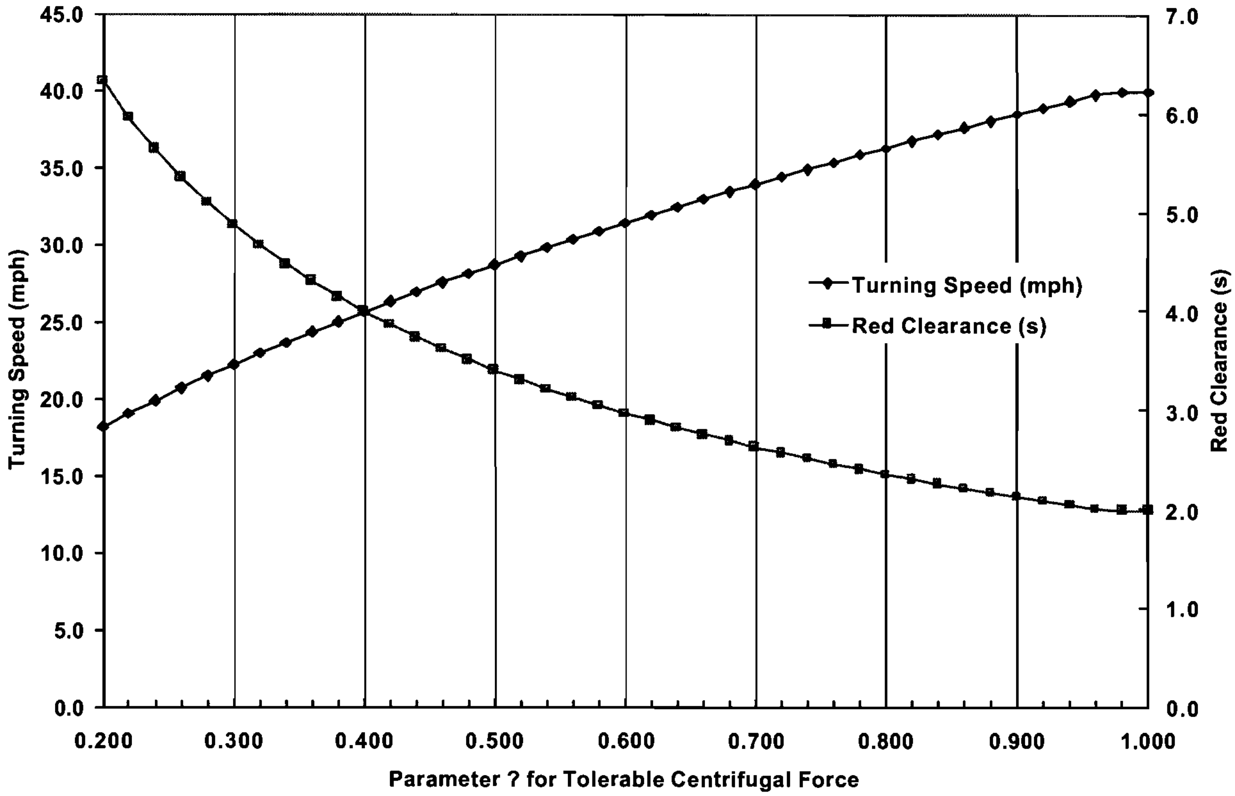

FIGURE 18: Analysis of the Effect of the Parameter γ

Figure 18 illustrates that the red clearance intervals vary from the 2.0 sec to 4.1 sec. Both the red clearance interval and the turning speed are very sensitive to the parameter γ. Fortunately, the turning speed is confined by the centrifugal force experienced by the driver. Therefore, the parameter γ value range can be determined by theatrical study. As noted in the Literature Review, the parameter γ should be between the 0.3 and 0.8.

The preliminary calibration is intended to calculate the value of parameter γ based on the Equation (27) by obtaining the turning speed based on the collected data on 21 surveyed intersections. In Equation (27), the parameter γ can be calculated after obtaining the turning speed, turning curve, speed limits, and intersection angle. The limits and the intersection angle collected from the sites. The turning speed can be obtained based on the data retrieved from the tapes, as the turning curve divided by the time elapsed between the position 3 and the position 5 (as shown in Figure 11). For each surveyed intersection, every vehicle's turning speed in the tapes can be obtained. Then, the results of the parameter γ values are calculated respectively. The average of the calculated parameter γ values was adopted for each intersection.

The average values of the parameter γ for 21 surveyed intersections are summarized in Table 16.

The typical parameter value can be obtained from the preliminary calibration. Typical α value is from 0.18 to 0.42; typical β value is from 0.2 to 0.43; and typical γ value is from 0.50 to 0.89. The typical parameter α value illustrates that the entering speed is more influenced by the approaching speed than the approaching speed limit. The typical parameter β value illustrate the turn curve is more influenced by the shortest curve, S_{min} as shown in Figure 6. This means that the drivers prefer a shorter turning curve. The typical parameter γ value obtained from preliminary calibration illustrate that the drivers tend to drive at a relatively high speed during the left-turn movement.

After obtaining all three parameters values, the yellow changes and red clearances on the surveyed intersections were calculated. The results are also listed in Table 16, along with the calibration results of the three parameters.

TABLE 16: Calibration and Calculation Results

Intersection	Type	α	β	γ	y	r	Actual
2818 & Wellborn Dr. NB	H1PM	0.18	0.2	0.49	3.1	3.4	3.6
Texas Ave & University Dr. SB	L2PT	0.171	0.39	0.492	3.0	3.8	4.7
Wellborn Rd. & Rock Prairie SB	H1PM	0.082	0.385	0.298	4.1	3.9	5.1
Texas Ave & 2818 SB	H1PM	0.277	0.325	0.715	3.4	2.5	3.7
Texas Ave & Holleman Dr. NB	L1PT	0.354	0.292	0.812	2.9	1.8	2.6
Wellborn & George Bush Dr. SB	L1PM	0.265	0.374	0.861	2.8	2.3	3.2
377 & FM 167 SB	H1PT	0.301	0.407	0.735	2.7	2.1	2.8
Cooper & Pleasant Ridge SB	H2PT	0.411	0.413	0.89	3.0	2.4	3.6
Skillman & Abrians EB	L2PM	0.291	0.234	0.648	2.6	2.7	3.8
3040 & MacArther Dr. WB	L2PM	0.252	0.316	0.736	2.8	2.3	3.7

Main St. & Old Orchard WB	L1PM	0.296	0.279	0.701	2.5	2.1	3.8
Bellaire & Toll Rd 8 WB	H2PT	0.350	0.357	0.568	2.5	2.7	3.7
Bellaire & Gessner EB	H1PT	0.342	0.374	0.503	2.7	3.0	4.0
Bellaire & Bissonet EB	H2PT	0.307	0.292	0.869	2.3	2.6	4.1
Richmond & Buffalo Speedway EB	L2PT	0.299	0.286	0.71	2.8	2.5	4.0
Richmond & Sage Rd. EB	L1PT	0.273	0.335	0.636	2.5	2.8	4.1
Richmond Ave. & Rice Rd. WB	H1PM	0.406	0.217	0.484	2.6	2.6	3.5
SH 121 & Corporatave Dr. NB	L1PM	0.148	0.386	0.796	3.1	1.8	3.5
Cooper & Pioneer SB	H2PT	0.427	0.434	0.897	2.3	2.6	4.0
Arbrook & Matlock WB	L1PM	0.326	0.290	0.769	2.7	1.9	3.7
SH 121 & 423 EB	H2PT	0.274	0.343	0.799	3.7	2.7	3.9

From the preliminary calibration results, the red clearances are somehow between 0.5 sec to 1.5 sec less than the actual left-turn time. It is because of the time lag of the conflicting traffics for reaching the potential collision point. Factors affecting the time lag include the perception reaction time, the driving speed, and the distance between the conflict point and the opposing stop line. A comparison of calculated and existing yellow changes and red clearances are illustrated in Figure 19. The mean calculated yellow change interval from 21 intersections is 2.9 sec, with a standard deviation of 0.4 sec. The mean calculated red clearance interval is 2.6 sec, with a standard deviation of 0.6 sec.

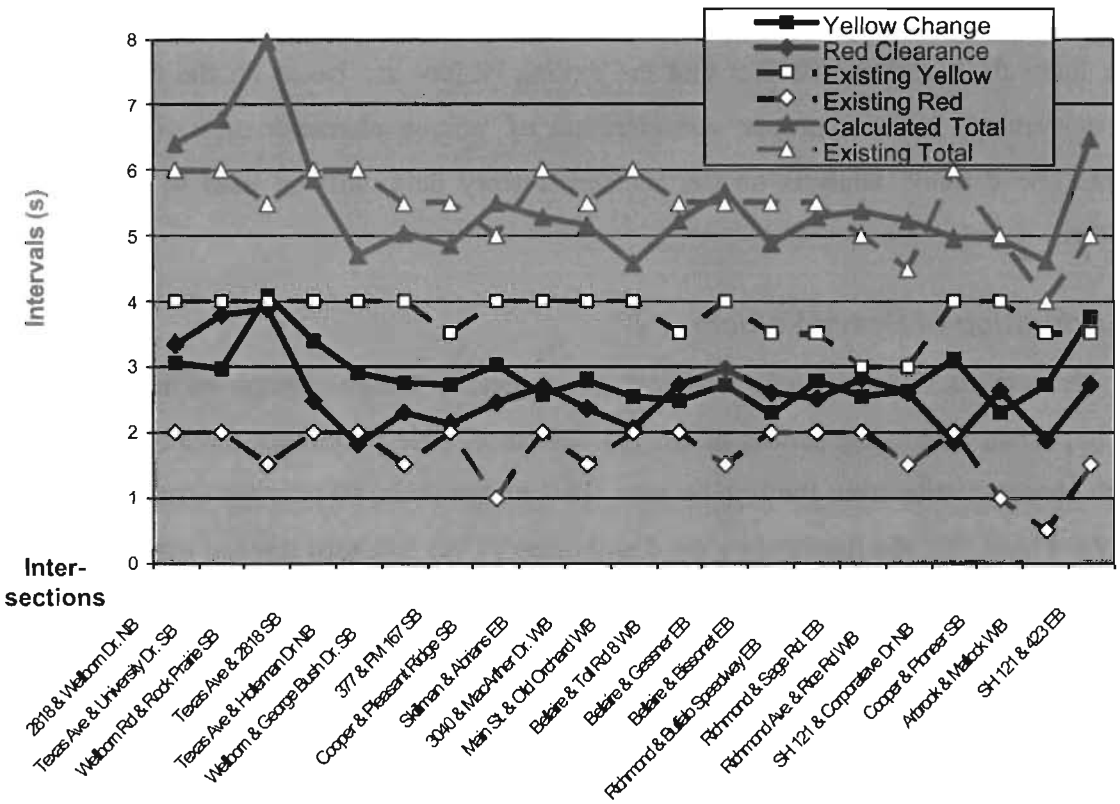

FIGURE 19: Comparison of Calculated and Existing Yellow Change and Red Clearance Intervals

Figure 19 also illustrates a comparison of the calculated and existing yellow change and red clearance intervals on each intersection.

By the comparison, it is found that the calculated yellow change intervals by proposed framework are generally shorter than the existing ones. The average existing yellow change interval is 3.8 sec, which is about 0.9 sec longer than the average of the calculated ones. It is also found that the calculated red clearance intervals by proposed framework are generally longer than the existing ones. The average existing red clearance is only 1.7 sec, which is about 1.0 sec shorter than the average of the calculated ones. While the calculated yellow change intervals are shorter and the calculated red clearance intervals are longer, the sum of calculated yellow change and red clearance intervals are about the same as the sum of the existing yellow change and red clearance intervals. The average sum of the calculated yellow change and red clearance intervals is only 0.2 sec longer than the sum of the existing ones.

The reason for the discrepancy in the calculated and existing yellow change and red clearance intervals is due to the fact that the exiting values are based on the theory for the through movement, without proper consideration of unique characteristics of the left-turn movement. The detailed analysis on the accident history data will be used to find possible explanations.

6.4 Consideration of Heavy Vehicle

In the analytical framework, vehicle type, especially the percentage of heavy vehicles, plays an important role in the setting of the red clearance. Heavy vehicles have different speed and length characteristics from the regular cars. This makes them take longer time to make left-turns. In the Figure 20, the data shows the distribution of the left-turn turning time by cars and trucks in the surveyed 21 intersections. Averagely, car took 4.2 sec to complete the movement, while truck took 4.7 sec. The standard deviations for them were 0.9 sec and 1.1 sec respectively. The data indicates trucks took about average 0.5 sec more to make turn than the regular vehicles do.

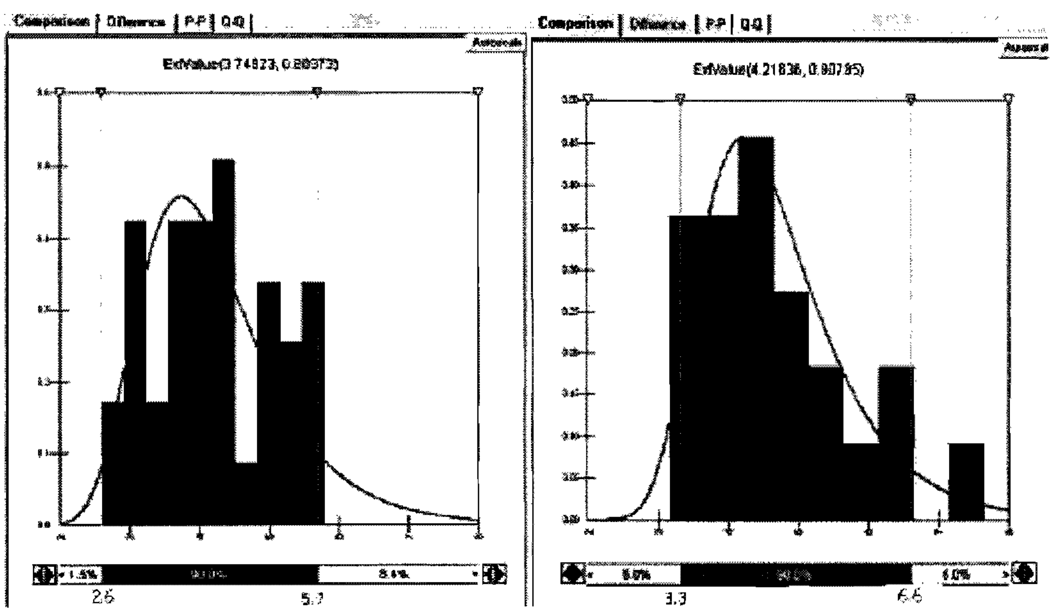

Figure 20: Field Data: Left-Turn time of Regular Vehicles and Trucks

Therefore, special consideration should be given to the particular intersections with high percentage of the heavy vehicles. Because of the independence of heavy vehicle percentage from the intersections' geometry characteristics, human factor, or law related raw data, it can be incorporated into the model by giving extra time to the red clearance in the intersection at different percentages periods. Linear regression method was used to estimate the red clearance and actual turn time ratio at different percentage of heavy vehicles based on the field data. On our surveyed intersections, the percentages of trucks are presented in the Figure 21.

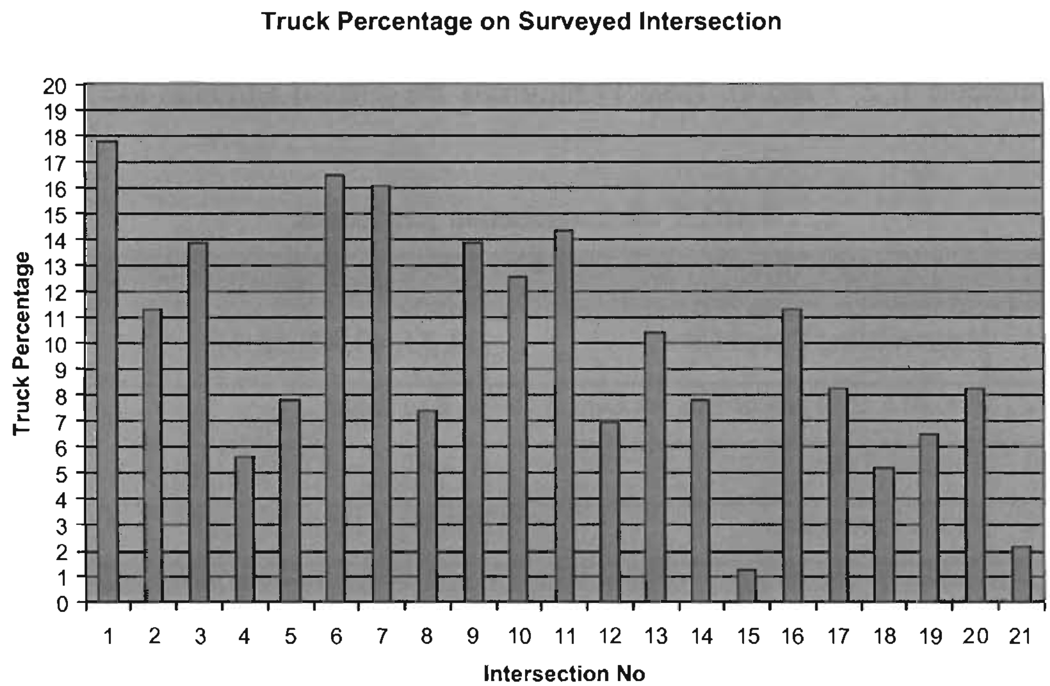

Figure 21: Percentage of Trucks on 21 Intersections

In our surveyed intersections, each intersection only had one percentage. For considering this factor into the other intersections, a method to find different parameters values on different percentages is necessary, because the parameters are the media to the yellow change and red clearance. Further calibration of model, which calibrates the parameters based on four attributes, addressed this issue. Six groups were proposed to represent the intersections with different percentage of trucks. Intersections with no trucks go to group 1 with 0% trucks; intersections with 0% to 5% go to group 2 with 5% trucks; intersections with 5% to 10% trucks go to group 3 with 10% trucks; and so on, till the intersections with more than 15% trucks go to group 5 with 20% or more trucks.

6.5 Further Calibration Results

The further calibration is intended to extend the preliminary calibration results to applications for a wider range of intersection configurations and traffic conditions. The further calibration is to use the results from the preliminary calibration to develop a generalized approach, which can output the values of critical parameters (α, ß and γ) in the proposed framework for any intersection with the inputs of the attributes for that particular intersection. The attributes to be calibrated in the further calibration include the approaching speed limit, the number of left-turn lanes, the control type, and the percentage of trucks making the left-turns (titled as attribute 1, 2, 3 and 4). Table 17 illustrates the selected attributes and their possible values.

TABLE 17: Intersection Attributes

n	Attributes: x_{ij}	Possible attribute Value
1	Approaching Speed Limit	30, 35, 40, 45, 50, 55
2	No. of Left-Turn or Shared Lanes	1, 2 or more
3	Control Type	1 – PT, 2 – PT/PM
4	Truck Percentage	0%, 5%, 10%, 15%, 20% or More,

X_{ji} – attribute, i – subscriptions of the attribute, stands for each type of intersection,
j – subscription of the attributes, stands for the intersection No. for 21 surveyed intersections

Attribute 1, the approaching speed limit has six possible values, from 30 to 55miles/hour. Attribute 2, the number of left-turn or shared lanes has two possible values, 1 and 2 or more. The third attribute, the control type has two values, 1 for the protected left turn and 2 for the protected/permitted left turn control. The fourth attribute is the truck percentage, which has values of 0%, 5%, 10%, 15%, and 20% or More. In combination, there are 24 types of intersections under each percentage of trucks. The following Equation (31) was used to further calibrate the parameters value. The Equation (31) is a typical regression model. This model is adopted because the further calibrated parameters values based on the model are adjusted from the average preliminary calibrated parameter values. Therefore, the unreasonable further calibrated parameter values can be avoided. In the equation, $[b_0, b_1, b_2 ... b_N]$ are interim parameters to be calibrated. After inputting average parameters values for the 21 surveyed intersections, and the intersection's attributes, $[b_0, b_1, b_2 ... b_N]$ can be derived using any regression tool.

$$\alpha_i = \overline{\alpha} \times e^{b_0 + \sum_{j=1}^{N} b_j x_{ij}} \tag{31}$$

The results of $[b_0, b_1, b_2 \ldots b_N]$ and intersection types are then input into Equation (32) to derive parameters values for each type of intersection.

$$\hat{\alpha}_i = \overline{\alpha} \times e^{\hat{b}_0 + \sum_{j=1}^{N} \hat{b}_j x_{ij}} \tag{32}$$

In summary, the further calibration process is shown in Figure 22:

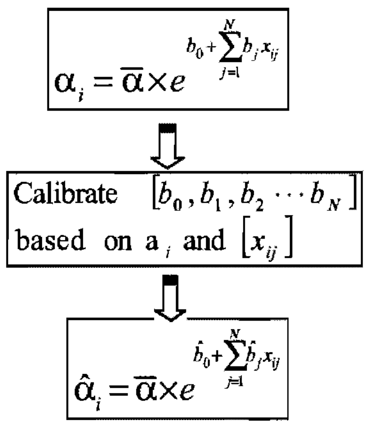

FIGURE 22: Process of Further Calibration

A MATLAB program is coded for the parameter derivation computation. Tables 18 to Table 22 provide the resulting parameter values for each type of intersection with different percentages of trucks.

TABLE 18: Recommended Parameters' values for Each Type of Intersections with 0% trucks

Intersection Types			α	β	γ
Speed Limit	No of LT and Shared Lanes	Control			
30	1	1	0.3774	0.3535	0.9067
30	1	2	0.2865	0.2905	0.8137
30	2	1	0.3888	0.3451	0.9761
30	2	2	0.2952	0.2836	0.8759
35	1	1	0.3584	0.355	0.8198
35	1	2	0.2721	0.2917	0.7357
35	2	1	0.3693	0.3465	0.8824
35	2	2	0.2803	0.2848	0.7919
40	1	1	0.3404	0.3564	0.7411
40	1	2	0.2584	0.2929	0.6651
40	2	1	0.3507	0.348	0.7978
40	2	2	0.2662	0.286	0.7159
45	1	1	0.3233	0.3579	0.67
45	1	2	0.2454	0.2941	0.6013
45	2	1	0.3331	0.3494	0.7212
45	2	2	0.2529	0.2871	0.6473
50	1	1	0.307	0.3594	0.6057
50	1	2	0.2331	0.2953	0.5436
50	2	1	0.3164	0.3508	0.6521
50	2	2	0.2401	0.2883	0.5852
55	1	1	0.2916	0.3608	0.5476
55	1	2	0.2214	0.2965	0.4915
55	2	1	0.3005	0.3523	0.5895
55	2	2	0.2281	0.2895	0.529

TABLE 19: Recommended Parameters' values for Each Type of Intersections at with 5% trucks

Intersection Types			α	β	γ
Speed Limit	No of LT and Shared Lanes	Control			
30	1	1	0.3604	0.3544	0.874
30	1	2	0.2736	0.2912	0.7844
30	2	1	0.3713	0.346	0.9409
30	2	2	0.2819	0.2843	0.8443
35	1	1	0.3423	0.3558	0.7902
35	1	2	0.2598	0.2924	0.7091
35	2	1	0.3526	0.3474	0.8506
35	2	2	0.2677	0.2855	0.7633
40	1	1	0.3251	0.3573	0.7144
40	1	2	0.2467	0.2936	0.6411
40	2	1	0.3349	0.3488	0.769
40	2	2	0.2542	0.2867	0.6901
45	1	1	0.3087	0.3587	0.6458
45	1	2	0.2343	0.2948	0.5796
45	2	1	0.3181	0.3502	0.6952
45	2	2	0.2415	0.2878	0.6239
50	1	1	0.2932	0.3602	0.5839
50	1	2	0.2226	0.296	0.524
50	2	1	0.3021	0.3517	0.6285
50	2	2	0.2293	0.289	0.5641
55	1	1	0.2785	0.3617	0.5279
55	1	2	0.2114	0.2973	0.4737
55	2	1	0.2869	0.3531	0.5682
55	2	2	0.2178	0.2902	0.5099

TABLE 20: Recommended Parameters' values for Each Type of Intersections with 10% trucks

Intersection Types			α	β	γ
Speed Limit	No of LT and Shared Lanes	Control			
30	1	1	0.3441	0.3552	0.8425
30	1	2	0.2612	0.2919	0.7561
30	2	1	0.3546	0.3468	0.9069
30	2	2	0.2691	0.285	0.8139
35	1	1	0.3268	0.3567	0.7617
35	1	2	0.2481	0.2931	0.6835
35	2	1	0.3367	0.3482	0.8199
35	2	2	0.2556	0.2862	0.7358
40	1	1	0.3104	0.3581	0.6886
40	1	2	0.2356	0.2943	0.618
40	2	1	0.3198	0.3496	0.7413
40	2	2	0.2428	0.2873	0.6652
45	1	1	0.2948	0.3596	0.6226
45	1	2	0.2238	0.2955	0.5587
45	2	1	0.3037	0.3511	0.6702
45	2	2	0.2306	0.2885	0.6014
50	1	1	0.28	0.3611	0.5628
50	1	2	0.2125	0.2967	0.5051
50	2	1	0.2885	0.3525	0.6059
50	2	2	0.219	0.2897	0.5437
55	1	1	0.2659	0.3626	0.5088
55	1	2	0.2018	0.298	0.4566
55	2	1	0.274	0.3539	0.5477
55	2	2	0.208	0.2909	0.4916

TABLE 21: Recommended Parameters' values for Each Type of Intersections with 15% trucks

Intersection Types			α	β	γ
Speed Limit	No of LT and Shared Lanes	Control			
30	1	1	0.3286	0.3561	0.8121
30	1	2	0.2494	0.2926	0.7288
30	2	1	0.3386	0.3476	0.8742
30	2	2	0.257	0.2857	0.7845
35	1	1	0.3121	0.3575	0.7342
35	1	2	0.2369	0.2938	0.6589
35	2	1	0.3216	0.349	0.7903
35	2	2	0.2441	0.2869	0.7093
40	1	1	0.2964	0.359	0.6638
40	1	2	0.225	0.295	0.5957
40	2	1	0.3054	0.3505	0.7145
40	2	2	0.2318	0.288	0.6412
45	1	1	0.2815	0.3605	0.6001
45	1	2	0.2137	0.2962	0.5385
45	2	1	0.29	0.3519	0.646
45	2	2	0.2202	0.2892	0.5797
50	1	1	0.2674	0.3619	0.5425
50	1	2	0.2029	0.2975	0.4869
50	2	1	0.2755	0.3533	0.584
50	2	2	0.2091	0.2904	0.5241
55	1	1	0.2539	0.3634	0.4905
55	1	2	0.1927	0.2987	0.4402
55	2	1	0.2616	0.3548	0.528
55	2	2	0.1986	0.2916	0.4738

TABLE 22: Recommended Parameters' values for Each Type of Intersections with 20% or more trucks

Intersection Types			α	β	γ
Speed Limit	No of LT and Shared Lanes	Control			
30	1	1	0.3138	0.3569	0.7828
30	1	2	0.2382	0.2933	0.7025
30	2	1	0.3233	0.3484	0.8427
30	2	2	0.2454	0.2864	0.7562
35	1	1	0.298	0.3584	0.7077
35	1	2	0.2262	0.2945	0.6351
35	2	1	0.3071	0.3499	0.7618
35	2	2	0.2331	0.2875	0.6837
40	1	1	0.283	0.3598	0.6398
40	1	2	0.2149	0.2957	0.5742
40	2	1	0.2916	0.3513	0.6887
40	2	2	0.2214	0.2887	0.6181
45	1	1	0.2688	0.3613	0.5785
45	1	2	0.2041	0.297	0.5191
45	2	1	0.277	0.3527	0.6227
45	2	2	0.2102	0.2899	0.5588
50	1	1	0.2553	0.3628	0.523
50	1	2	0.1938	0.2982	0.4693
50	2	1	0.263	0.3542	0.5629
50	2	2	0.1997	0.2911	0.5052
55	1	1	0.2425	0.3643	0.4728
55	1	2	0.1841	0.2994	0.4243
55	2	1	0.2498	0.3556	0.5089
55	2	2	0.1896	0.2923	0.4567

6.6, Validation in Terms of Accident Analysis

In order to examine the effectiveness of the proposed framework, a comparison of calculated versus observed yellow change and red clearance intervals should be conducted. Intersections with either longer or shorter observed intervals should be further examined. This section uses the historical accident data to identify the potential problem intersections for this kind of examination.

To this end, the historical accident data from 2000 to 2002 on each surveyed intersection are organized into two categories: the number of total crashes (NTC) and the number of crashes due to the left-turn (NCLT). From the two categories, the percentage of crashes due to the left-turn (PCLT) is calculated. For each of the three categories, for example NCLT, several ranges are partitioned from 0 to the largest NCLT, such as range one, intersections with NCLT of 0 to NCLT of 5, range two, intersections with NCLT of 6 to NCLT of 10, and so forth, till to the last range, intersections with largest NCLT among the 21 surveyed intersections. Then, the number of intersections falling under each range is summed for statistic analysis. In order to identify the problem intersections, two figures about the accident data are plotted: the number of intersections vs. NCLT, and the number of intersections vs. PCLT.

Figure 23 illustrates the distribution of the NCLT when the confidence level is set to 90%. The intersections that may have problems are those with 30 to 35 crashes related to the left-turn movement. From this analysis, the intersection which meets this criterion is Texas Ave @ University Dr, which had 34 accidents due to the left-turn movement.

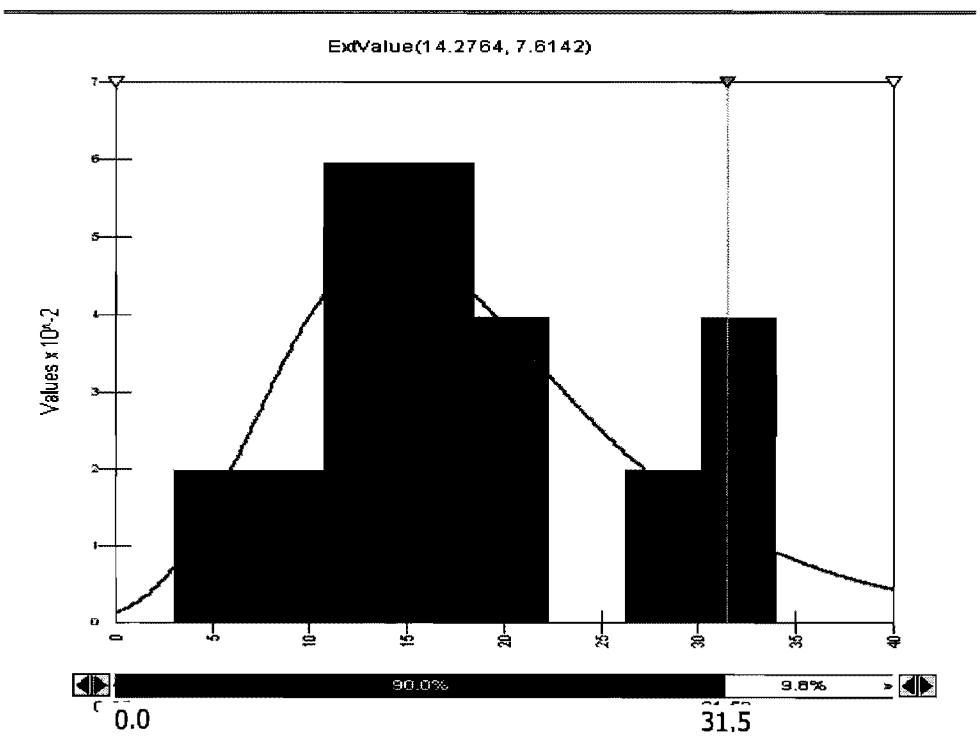

FIGURE 23: Distribution of the Number of Crashes due to the Left-Turn

FIGURE 24 illustrates the distribution of the PCLT. When the confidence level is set to 90% again based on the distribution of the PCLT, the intersections of Arbrook @ Matlock and Cooper @ Pioneer meet the criterion. The intersection of Arbrook @ Matlock had a record of the 50% PCLT, and the Cooper @ Pioneer had 38%.

In order to compare the three selected problem intersections based on the above accident analysis with other sites, two other intersections, Texas Ave @ 2818, which had 13 NCLT AND 13.8% PCLT, and Texas Ave @ Holleman Dr., which had 17 NCLT and 8.7% PCLT, are selected.

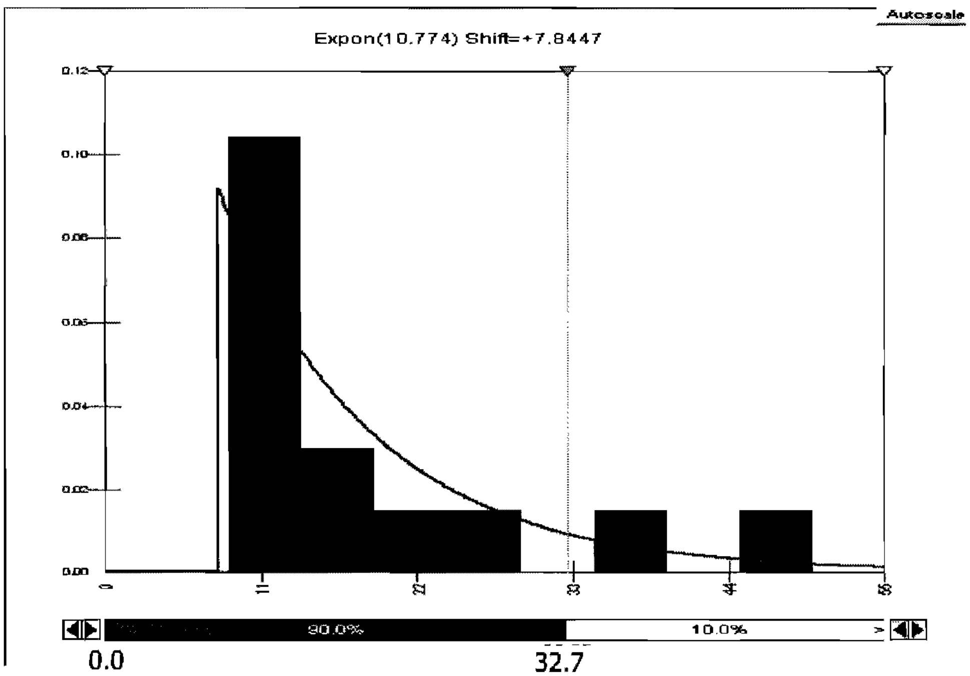

FIGURE 24: Distribution of the Percentage of Crashes due to the Left-Turn

Table 23 illustrates the calculated versus existing yellow change and red clearance intervals for both the problem intersections and non-problem intersections. By comparing the calculated versus the existing ones, it is found that the yellow change interval is shorter and the red clearance interval is longer for the proposed framework than the existing ones. This is understandable considering the fact that drivers are usually less comfortable during the left-turn movement due to the centrifugal force than the through movement. The fact that those who forcibly enter and clear intersections with a high speed clearly bear a larger risk of losing control and having accident makes the drivers prefer a lower speed. The lower turning speed also makes the drivers always decelerate before preceding the intersection to make the left-turn movement. The lower speed before entering the intersection and during left-turn movement explains that a shorter yellow change is needed to eliminate the dilemma zone and a longer red clearance interval to clear the intersection. Another reason for a longer red clearance interval is that vehicles take a longer trajectory on the left-turn curve than the through movement.

TABLE 20: Comparison of Problem Intersections vs. Non-Problem Intersections

Intersection	Type	Yellow		Red Clearance		Actual Turn Time
		Calculated	Existing	Calculated	Existing	
Texas Ave & University Dr. SB	L2PT	3.0	4	3.8	2	4.7
Arbrook & Matlock WB	L1PM	2.7	3.5	1.9	0.5	3.7
Cooper & Pioneer SB	H2PT	2.3	4	2.6	1	4.0
Texas Ave & 2818 SB	H1PM	3.4	4	2.5	2	3.7
Texas Ave & Holleman Dr. NB	L1PT	2.9	4	1.8	2	2.6

The general findings about the shorter yellow change and red clearance intervals are from both the problem intersections and non-problem intersections. Furthermore, by the comparison of the intervals for the problem intersections versus non-problem intersections in Table 23, it is also found that the problem intersections had much larger differences between the existing and calculated yellow change and red clearances than that of non-problem intersections.

First, the problem intersections are examined. For the intersection of Texas Ave @ University Dr., the yellow change interval on this intersection is 4.0 sec and the red clearance interval is 2.0 sec. The calculated results from the framework are 3.0 sec for the yellow change interval, and 3.8 sec for red clearance interval, with the 4.7 sec actual left-turn time retrieved from the tape. According to the results of the framework, the existing red clearance interval is

1.8 sec shorter than what it should be, based on the proposed framework, and the yellow change interval is 1.0 sec longer. One explanation is that the yellow change interval allows more vehicles to enter the intersection during the left-turn phase, while the red clearance interval is too short for all of them to clear the intersection. This effect is even clearer when considering the two intersections with the highest PCLT, 50% and 38% respectively. The red clearances on the two intersections are 1.4 sec, and 1.6 sec shorter than what they should be, and the intersection of Arbrook @ Matlock has the shortest red clearance of 0.5 sec.

For the two intersections with the normal accident records, Texas Ave @ 2818 and Texas Ave @ Holleman Dr., both red clearances are set at 2.0 sec. The red clearance on the intersection of Texas Ave @ Holleman Dr is only 0.2 sec shorter than what it should be. On Texas Ave @ 2818, however, the red clearance is 0.5 sec shorter than the calculated one, and its yellow change is only 0.4 sec longer than the calculated one.

Based on the above analysis, the proposed framework for determining the yellow change and red clearance intervals can improve the safety of the left-turn, because the intersections with larger deviation of the existing yellow change and red clearance intervals form the calculated ones had higher risk for left-turn movement.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

In this research, a comprehensive framework has been developed for determining the yellow change and red clearance intervals for the left-turn movements. The proposed framework was built by incorporating significant improvement to the original work conducted by Liu, *et al.* (2002). This framework integrated a comprehensive set of parameters related to the safety, perception, human comfort, driver's behavior, traffic ordinances, and intersection geometric characteristics. The framework has been systematically calibrated, and is flexible to be implemented to different types of intersections.

Based on the developed framework and its calibration based on the data collected from 21 surveyed intersections in Texas, the following conclusions are provided:

(1) Existing yellow change intervals for the left-turn are too long;

(2) Existing red clearances are too short; and

(3) Existing total change intervals (including both the yellow change and the red clearance) are about the same as the calculated ones.

The primary reason for the above conclusions is because the existing yellow change and red clearance intervals are either the empirical ones or determined based on the through movement.

By validating the framework in terms of the accident analysis, it is found that the left-turn accident rate is higher for those intersections with longer existing yellow changes and shorter red clearances. Therefore, the proposed framework can improve the safety without decreasing the efficiency of the intersections.

7.2 Recommendations

It is recommended to implement the proposed framework in Texas. Based on the calibration from 21 Texas intersections, the suggested yellow changes and red clearances for typical intersections are listed in Table 24.

Table 24: Suggested Intervals for Intersections with Angle of 90

Approach Speed	No of Lanes		Depth							
			70ft		90ft		110ft		130ft	
			Yellow	Red	Yellow	Red	Yellow	Red	Yellow	Red
30	1	PT	3.0	**2.2**	3.0	**2.9**	3.0	**3.6**	3.0	**4.3**
		PM	3.0	**2.2**	3.0	**2.8**	3.0	**3.5**	3.0	**4.2**
	2	PT	3.0	**2.5**	3.0	**3.2**	3.0	**3.9**	3.0	**4.6**
		PM	3.0	**2.4**	3.0	**3.1**	3.0	**3.8**	3.0	**4.5**
40	1	PT	3.0	**2.4**	3.0	**2.9**	3.0	**3.6**	3.0	**4.3**
		PM	3.0	**2.6**	3.0	**2.8**	3.0	**3.5**	3.0	**4.2**
	2	PT	3.0	**2.6**	3.0	**3.2**	3.0	**3.9**	3.0	**4.6**
		PM	3.0	**2.8**	3.0	**3.1**	3.0	**3.8**	3.0	**4.5**
50	1	PT	3.0	**2.9**	3.0	**3.1**	3.0	**3.6**	3.0	**4.3**
		PM	3.0	**3.1**	3.0	**3.3**	3.0	**3.5**	3.0	**4.2**
	2	PT	3.0	**3.1**	3.0	**3.2**	3.0	**3.9**	3.0	**4.6**
		PM	3.0	**3.3**	3.0	**3.5**	3.0	**3.8**	3.0	**4.5**
55 or above	1	PT	3.0	**3.1**	3.0	**3.3**	3.0	**3.6**	3.0	**4.3**
		PM	3.4	**3.5**	3.3	**3.7**	3.3	**3.9**	3.2	**4.2**
	2	PT	3.3	**3.5**	3.2	**3.6**	3.1	**3.8**	3.1	**4.5**
		PM	3.4	**3.7**	3.3	**3.8**	3.2	**4.0**	3.2	**4.2**

Note: for trucks, yellow change remains same, red clearance increases 0.1s for 5%-10% trucks in the traffic; 0.3 for 10%-15% trucks; 0.4s for 15%-20% trucks; and 0.5s for 20% or above trucks.
PT: Protected; PM: Protected/Permitted

It should be noted that the 21 intersections from 8 cities are not sufficient enough for obtaining the state-wide standard of change intervals. It is suggested to further calibrate the parameters of the framework based on field data from more intersections following the same procedures as proposed in this report.

Based on the internal computer program used in this research, a more user-friendly and engineer-oriented software can be further developed.

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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	Department 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