2008 OTC Research Project Report

Characterize Dynamic Dilemma Zone and Minimize its Effect at Signalized Intersections

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Submitted by

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PREFACE

Dilemma zone at signalized intersection has been recognized as a major potential causing rear-end crashes, and has been widely studied by researches since it was initially proposed as the GHM model in 1960. However, concepts conventionally defined to represent yellow phase dilemma lack integrity. This research conducts a comprehensive literature review with attempt to clarify the interrelationship among dilemma zone, option zone, and indecision (decision) zone, and to develop a heuristic framework to present the contributing factors in dilemma zone modeling. A new method for modelling the locations and lengths of the dilemma zone using video-capture techniques and vehicle trajectory data is presented in this report. First, dilemma zone is mathematically modeled based on the literature review. Then, field-observed trajectory data extracted by the video-capturing-based approach are used to calibrate the contributing factors involved in the dilemma zone models. The high accuracy of the time-based trajectory data has significantly enhanced the accuracy of the calibrated dilemma zone models. Two sets of trajectories are explored for calibrating the dilemma zone contributing factors. One is concerned with maximum yellow-onset safe passing distance and minimum yellow-onset stopping distance. The other is concerned with X^{th} percentile yellow-onset passing distance and stopping distance for the prevailing travel behaviors. The latter alternative actually precludes “too conservative” and “too aggressive” behaviors in response to yellow indications.

One critically important result is the dilemma zone look-up charts that are developed based on the calibrated dilemma zone models. Such charts provide a convenient tool to identify locations and lengths of dilemma zones for any speed and yellow duration conditions. Additionally, impact of arrival type and vehicle types are also explored. Results reveal that traffic in a good progression (*Arrival Type* ≥ 4) has a further option zone. It is also discovered that the length of option zone decreases as vehicle size increases, while the downstream boundary of option zone is further from the stop line as vehicle size increases. In overall, the project provides primary study results and solid basis for future study of the optimum signal detection placement and related dilemma zone protection problems with consideration of multi-speed protection.

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CHAPTER 1:

PROBLEM STATEMENT

The report “National Agenda for Intersection Safety” (USDOT, 2002) quotes that in the year 2000, more than 2.8 million intersection related crashes occurred, which amounts to 44 percent of all reported crashes (USDOT, 2002). In Ohio, intersection crashes account for 24 percent of the fatalities and 37 percent of the disabling injuries (ODOT, 2006). The National Highway Traffic Safety Administration has estimated that aggressive drivers cause two-thirds of all fatal crashes and are responsible for nearly 35 percent of all crashes (ACEP, 2006). Among all possible factors contributing to the traffic-signal-related crashes, intersection dilemma zone is one of major causes and critical issues that have not been fully solved yet.

According to ITE handbook (ITE, 1985), a dilemma zone is a (length) range within which a vehicle approaching an intersection during its yellow phase can neither safely clear the intersection, nor stop comfortably at the stop-line. With existence of dilemma zone, the drivers are actually exposed to a potentially hazardous condition in which a rear end accident may occur if the front vehicle stops abruptly during the yellow period. An angle accident may occur if the driver attempts to cross the intersection at the onset of the red interval (ODOT & FHWA, 2005). To minimize the safety problems caused by dilemma zone, protection strategies, such as detection-based control systems, are implemented at high-speed intersections to clear vehicles out of dilemma zone at the onset of the yellow indication. Therefore, the accurate and exact location of dilemma zone is of great importance for those dilemma zone protection systems. However, the range and location of a dilemma zone is dynamic featured because of variations in vehicle approach speed, driving behaviors, vehicle break performance, intersection geometry, and duration of yellow interval. The standard practice of using the average driver data with traditional method for computing the dilemma zone is likely to reach misleading conclusions (MDOT, 2006).

Recent study conducted by Maryland DOT (MDOT, 2004 2006) indicates that systematically modeling dynamic dilemma zones is quite difficult without accurate trajectory data. Traditional traffic counting methods that were used in data collection in old studies are difficult to obtain the trajectory data that describe the dynamic natures of dilemma zone and the interrelations between dynamic dilemma zone and critical impact factors. The trajectory data applied in MDOT’s study (MDOT, 2006) describe the times when an individual vehicle passes fixed reference lines perpendicular to the roadway (termed as “fixed-spatial-point trajectory data in this report). In order to more accurately reflect vehicles’ speed and acceleration/deceleration changes in responding to yellow indication, it could be another alternative to use the data that describe the track of a moving vehicle over a small time interval (termed as “time-based trajectory data”). Time-based trajectory data can well relate the instant speed at any time step (30 steps per second maximum). This feature makes it valuable to obtain the data from which the interrelations between driving behaviors (e.g., speed, acceleration, stop/pass decision), duration of yellow interval, distribution of dilemma zone ranges, and speed distribution can be well represented. This research uses VEVID (Vehicle Video-Capture Data Collector) (Wei et al., 2000 2005), which is a software program developed by the authors and can extract time-based trajectory data from digital videos, to study the dynamic nature of dilemma zone.

Another important concept, option zone, is defined as a zone within which at the onset of yellow indication, the driver could choose either to clear the intersection or stop at the stop line before the end of yellow interval. According to the review of literature, option zone has less been studied and in particular distinguished from the so called dilemma zone. The option zone commonly exists at high speed intersections. Existence of the option zone also has great potential to cause drivers' hesitation either to stop or pass the intersection during the yellow indication, and it is also one of contributing factors to rear-end collisions at high speed intersections. This research project puts much effort on identifying the existence of dilemma zone, option zone and their inherent relationship.

CHAPTER 2:

GOAL AND OBJECTIVES

The goal of the project is to provide proof of concept about the methodology for extracting dilemma zone vehicle trajectory data and quantitatively modeling locations and lengths of the dilemma zone under various classifications of approaching speeds and yellow durations. Through this study, we use a case study of one signalized intersection to demonstrate the feasibility of applying the trajectory data to investigate effect of traffic features and travel behaviors on the formation of the dilemma zone and calibrate dilemma zone models, so as to provide a solid basis for preparing further research on analysis of more locations in Ohio and dilemma zone detectors layout problems. The specific objectives are:

1) Conduct comprehensive literature review covering topics about concurrent research on dilemma zone;
2) Conduct field data collection through videotaping and traffic counting techniques, and extract vehicle trajectory data related to yellow dilemma behaviors with VEVID;
3) Develop models to more accurately measure the location and length of the dilemma zone, and calibrate the model parameters with observed trajectory data; and
4) Tentatively develop dilemma zone look-up chart to provide accurate dilemma zone locations for helping layout design of dilemma zone protection detectors.

CHAPTER 3:

RELATED WORK AND LITERATURE REVIEW

3.1 Existing Definitions of Dilemma and Option Zones

The concept of dilemma zone was initially proposed by Gazis, Herman and Maradudin (1960), which is usually referred as GHM model by acronym of the authors' names. A dilemma zone is defined by the authors as a zone within which a driver can neither bring his/her car to a stop safely nor go through the intersection before the signal turns red. The concept of dilemma zone is illustrated by **Figure 1**.

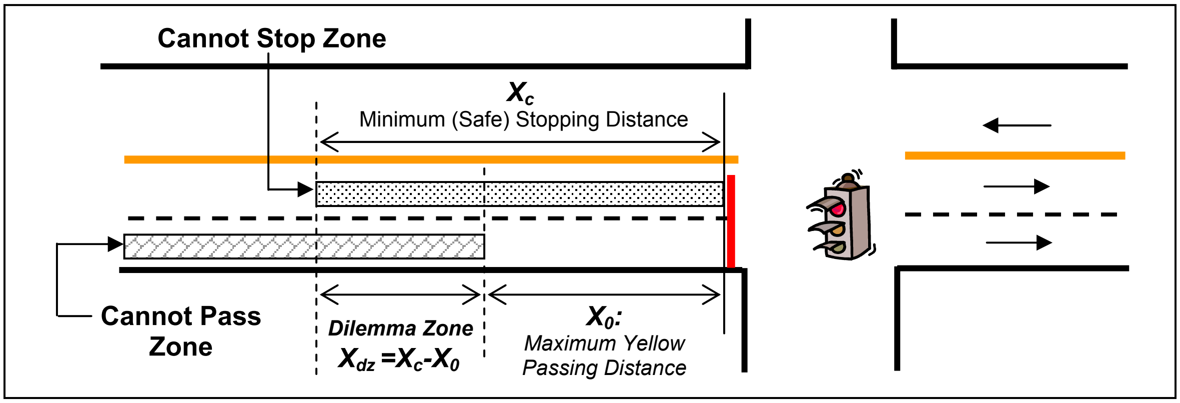


Figure 1: Formation of a Dilemma Zone

In Figure 1, X_c is referred as to the critical distance or the *minimum (possible) stopping distance* from stop line. At a closer distance from the stop line than X_c, a vehicle cannot safely stop before the stop line. X_0 is the maximum distance a vehicle can travel during the entire yellow interval and clear the intersection before the end of yellow interval. Thus, X_0 is usually referred as to the *maximum yellow passing distance* from the stop line for the entire yellow interval. When $X_c > X_0$, the vehicle physically located somewhere between X_c and X_0 is actually within a "dilemma situation" in which the vehicle can not safely stop before the stop line and is also incapable to safely pass the intersection during the yellow interval. The physical zone between X_c and X_0 when $X_c > X_0$ forms the dilemma zone. In other words, a driver within dilemma zone is at a position shorter than the minimum stopping distance, which means he/she can hardly come to a full stop before the stop line, and is also at a position at which no enough yellow time available for the driver to pass the stop line before the end of yellow interval. In this situation, the word "dilemma" exactly represents such a circumstance, although he/she might not be aware of it. X_c and X_0 can be expressed mathematically by **Equations (1)** and **(2)** (Gazis 1960), respectively.

$$X_c = V_0\delta_2 + \frac{V_0^2}{2a_2} \tag{1}$$

$$X_0 = V_0\tau - W + \frac{1}{2}a_1(\tau - \delta_1)^2 \tag{2}$$

Where, V_0 = the vehicle's approach speed (ft/s);
δ_2 = the driver's perception-reaction time for stopping (sec);
a_2 = the maximum vehicle's deceleration rate (ft^2/s);
δ_1 = the driver's perception-reaction time for running (sec);
a_1 = the constant vehicle's acceleration rate (ft^2/s);
τ = the duration of yellow interval (sec);
W = the summation of intersection width and the length of vehicle.

When $X_c > X_0$, i.e., as maximum yellow passing distance is greater than the minimum stopping distance, the vehicle within the "zone" between X_c and X_0 at the onset of the yellow time faces two options: either pass the intersection or slow down and stop before the stop line during the yellow time. The "zone" between X_c and X_0 ($X_c > X_0$) is termed as option zone, as shown by **Figure 2**.

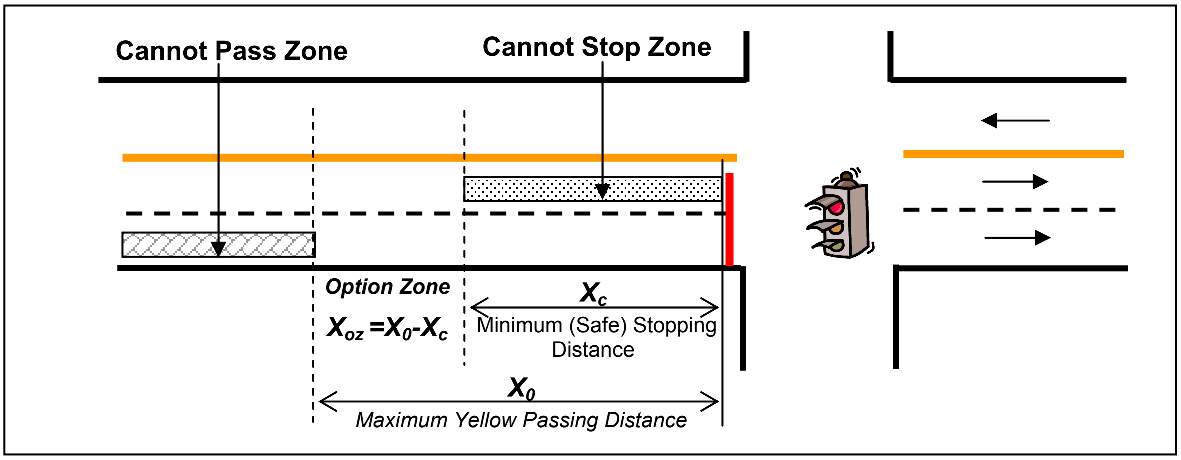


Figure 2: Formation of an Option Zone

Therefore, an option zone is defined as a zone within which at the onset of yellow indication, the driver can either come to a stop safely or proceed through the intersection before the end of yellow interval. The word "option" means that the driver's final decision of whether to pass or to stop is optional. Whatever passing or stopping is chosen, he/she could finally make it.

The dilemma zone is also modeled by probabilistic approaches based on probability of drivers' decision to stop during a yellow interval. Zegeer (1977) defined a dilemma zone as "the road segment where more than 10% and less than 90% of the drivers would choose to stop." The upstream boundary of the dilemma zone is the distance beyond which more than 90 percent of all drivers would stop if presented with a yellow indication. Sheffi and Mahmassani (1981) used speed and distance from stop line to estimate the probability of stopping during the yellow interval. Dilemma zone curves (probability of stopping vs. distance from stop line) were developed to determine the boundaries of dilemma zones at various speed classifications.

El-Shawarby et al. (2006) summarized the above two definitions of the dilemma zones from stopping distance and drivers' choice of stopping perspectives, respectively, which likely caused somewhat confusion to the researchers. Typically, those two definitions are represented by one initially defined by GHM model (Gazis et al. 1960) and the probabilistic dilemma zone definition (Zegeer, 1977).

Parsonson (1992) indicated in his research report that the probabilistic definition of the dilemma zone is actually about an option zone -- a length of an approach in advance of an intersection where an individual driver may experience indecisiveness upon seeing the indication of the yellow signal. And the calculation of the boundaries of the option zone follows "10% to 90%" rule based on Zegeer's study (1977). According to Parsonson's definition, this kind of option zone is also interpreted as "indecision zone" or "decision zone". Si et al. (2007) concurred with Parsonson's definition of the option zone. They stated that the dilemma zone and option zone are fundamentally different issues, although the boundaries of the dilemma zone and the option zone may overlap to a certain extent. The dilemma zone can be eliminated by appropriate yellow and red clearance times, whereas the option zone always exist as a result of varied travel decision-making choices of stop or go behaviors.

Urbanik and Coonce (2007) recently conducted a comprehensive literature review on the definitions of dilemma zone, with intention to clarify the "the dilemma" with dilemma zones. They believe that there is a lack of rigor with regard to defining terminology and the documenting of assumptions when discussing dilemma zones. They termed the dilemma zone, which was originally defined and formulated by Gazis (1960) as Type I dilemma zone, and the other one initially defined by Zegger (1977) as Type II dilemma zone. They also indicated that Type I dilemma zone could be eliminated when yellow interval is long enough. And driver's exposure to the Type II dilemma zone can be minimized through the design of detection system and the associated signal timing parameters.

3.2 Driver's Response to Yellow Indication

Driving behavior in response to yellow signal indication has been recognized as one of contributors to the dynamic natures of dilemma zones. Olson and Rothery (1962) continued Gazis et al.'s study, seeking possible behavioral trends in this decision-making problem at the onset of yellow indication. Their research came to a significant conclusion that driver's behavior does not seem to change as a function of different yellow interval durations. Liu, et al (1996) investigated the incompatibilities of the yellow-light phase duration and traffic ordinances, a problem raised from the GHM Model. They also made a significant progress in uncovering the complex interrelationships between dilemma zone, driver response, and the yellow interval duration.

El-Shawarby et al (2006) conducted an experiment to study driver's behavior during the yellow interval. 60 drivers with various ages and sex were hired to driver a test vehicle at a test roadway system. Real-time speeds and distances from stop line were collected through a communication and computer system. They observed driver's stopping at five predetermined distances, and made a diagram representing the relationship of probability of stopping vs. distance from the stop line. By identifying the locations where 10% and 90% drivers would choose to stop, rough location of the option zone was estimated. The research results indicated that at the speed of 45 mph, the dilemma zone lies between around 108 ft to 253 ft from stop line. Also, male drivers are less likely to stop when compared to female drivers. Old drivers are more likely to stop at the onset of yellow indication, while younger drivers are approximately 20% more likely to attempt to run yellow compared to older drivers. The research conducted by Shinar and Compton (2004) also reached a similar conclusion. Based on observations of more than 2000 drivers' responses to the yellow indication, they found male drivers are more aggressive than female drivers, and senior drivers are less likely to take aggressive action than young drivers. Maryland DOT (2006) comprehensively studied driver's behavior over yellow intervals by using fixed spatial-point trajectory data. In this study, driver types were defined based on aggressiveness. Their research results also concord with Shinar and Compton's (2004) conclusions.

Papaioannou (2006) conducted a similar study in Greece. Practical vehicle data were collected at a T intersection. Yellow onset speeds were obtained using radar guns, while the yellow onset distances from the stop line were approximately determined by means of a scale drawn on the roadway pavement with markings every 5 meters. Only the platoon leading vehicle and the first following vehicle were recorded as sampling data. Given a constant maximum deceleration rate and a minimum drivers' reaction time, length of the dilemma zone or option zone for each vehicle was **calculated** by using GHM model with the yellow onset speed as an input. Thus, spatial relationship between the location of dilemma zone or option zone and the position of vehicle at the onset of yellow interval was established. Drivers were then classified into three groups by their aggressiveness, namely, aggressive, normal and conservative. The results indicated that a large percentage of vehicles are within dilemma zone rather than option zone. And the percentage of aggressive drivers among all the drivers is as high as more than 50%.

A key issue that is related to the driver's behavior during the yellow interval is driver's perception–reaction time (PRT), which directly influences the location of a dilemma zone base on GHM model. PRT is the time interval from the onset of the yellow indication to the instant when the brake pedal is applied (Rakha et. al, 2007). Usually, PRT data are recorded as the time elapsed from the onset of the yellow indication until the brake light is observed. Previous study (Taoka, 1989) has demonstrated that the 85th-percentile PRT falls into the range of 1.5–1.9 sec at low speed intersection approaches, and is shorter at high speed intersection approaches (greater than 40 mph), with the 85th-percentile PRTs in the range of 1.1-1.3 sec. Chang et al.'s (1985) study results revealed that speed effectively influences the median PRT, which converges to 0.9 sec at speeds equal to or greater than 45 mph. Caird et al. (2005) found through 77 drivers' driving behavior by using a driving simulator that yellow onset distance from stop line also influences the PRT, which is ranging from 0.86 sec for drivers closest to the intersection stop line to 1.03 sec for drivers farthest from it. The recent research on PRT conducted by Rakha et al (2007) summarized that at a high speed intersection approach (45 mph) the average PRT from 351 observed samples is ranging from 0.3 sec to 1.7 sec, with a mean equals to 0.742 sec, a median of 0.700 sec, and a standard deviation of 0.189 sec. Maryland DOT (2006) indicated in their research report that average PRT of drivers is in the range between 0.93 sec and 1.16 sec.

3.3 Impact of Yellow Duration on Dilemma/Option Zone

The impact of yellow duration on dilemma and option zones has been studied in previous efforts. Saito et al. (1990) conducted a research to study the characteristics of dilemma zones and option zones using video technique. Video-taping techniques were utilized in their research to gain the speed, distance, driver's PRT and deceleration rate of vehicles at the onset of yellow interval. Only the first stopped and the last passing vehicles during the yellow intervals were studied in their research. The result revealed that as duration of yellow interval increases, the rate of vehicles in the dilemma zone decreases while the rate of vehicles in the option zone increases; and the size of the dilemma zone decreases while the size of the option zone increases. Their research also indicated that drivers within the dilemma zone and option zone are greatly dependent on the travel behaviors relevant to drivers' decisions on whether to pass or to stop during a very short time period.

Koll et al.'s (2004) research also indicated that prolonging the yellow interval will not improve the intersection safety, because it will create longer option zones and drivers within option zone will still experience uncertainties about whether to pass or to stop, which may contribute to rear-end accidents.

3.4 Dilemma Zone Protection

Although the dilemma and option zone could not be fully eliminated due to varying and unpredictable driver's behaviors during the yellow intervals, safety problems caused by the dilemma zones could be reduced by taking strategic countermeasures, which are usually referred to as dilemma zone protection.

Ohio DOT (2005) conducted a field testing of implementation of dilemma zone protection and signal coordination at closely-spaced high-speed intersections. Traditional traffic counting methods were applied to collect data related to three types of conflicting vehicles, namely, running red light, stopping abruptly and accelerating through yellow times. Those three types of conflicts were used to identify vehicles that experience dilemma zone problems. The "conflict percentage," which was calculated as the "total conflict volume" over "total volume," was considered a good measure of effectiveness for dilemma zone protection in the study. The study also revealed that accelerating through yellow was the major conflict for all intersections of study. To address the formation of dilemma zones, clearance distance assuming acceleration equals to 10 ft/s^2 were theoretically identified. The detector placement was based on this assumption. The study indicated that different intersection has its unique best extension of green, and there is no one "universal" rule for dilemma zone protection of extending the green time.

Moon et al. (2002, 2003) developed and field-tested an in-vehicle dilemma zone warning system, which provides real-time visual and audible warnings for drivers before the onset of yellow indications. McCoy and Pesti (2003) also proposed a detection and advance warning flasher system to inform drivers of stopping before the onset of yellow indications.

Another sophisticated detection-based dilemma zone protection system, i.e., detection–control system (D–CS), was developed by Zimmerman et al. (2003; 2004; 2005; 2007). It uses dual loops in a speed-trap configuration installed about 1000 ft upstream of the intersection to detect the presences of approaching vehicles and to measure the speed of individual vehicles, so as to provide appropriate green extensions. It differs from the traditional multiple advance detector system because it employs a computerized algorithm that uses vehicle speed and length information to predict when each vehicle arrives in its dilemma zone, where a fixed dilemma zone range is assumed. It attempts to identify the best time to end the major-road through phase based on the number of vehicles in the dilemma zone, the number of trucks in the dilemma zone, and the waiting time of vehicles in conflicting phases. The result of the field implementation showed that D-CS has significantly improved both operations and safety of the concerned intersection.

CHAPTER 4:

METHODOLOGY

4.1 New Understanding of Dilemma Zone

According to the literature, the location of the dilemma zone can be expressed as a function of critical (or minimum) safe brake stopping distance $\boldsymbol{X_c}$ and maximum safe yellow passing distance $\boldsymbol{X_0}$. Two scenarios are refereed to the dilemma zone: Type I dilemma zone as $X_c > X_0$, and Type II dilemma zone as $X_c < X_0$. Based on the mathematical expressions of X_c and X_0 (**Equations (1)** and **(2)**), it is not hard to recognize that the location of a dilemma zone depends on the following factors: approaching speed at onset of yellow indication, driver's perception-reaction time (i.e., PRT), maximum deceleration for safe stopping or acceleration for safe passing, yellow duration, as well as intersection width and vehicle's length. In this research, the intersection width and vehicle's length are not considered in calculating X_0. It is assumed that once a vehicle passes the stop line before the end of yellow interval, it is regarded as a yellow passing vehicle. Based on field observations, when a driver perceives the yellow indication, he/she does not consider whether he/she could clear the intersection completely during the yellow interval. Actually, his/her concern is whether he/she could pass the stop line before the onset of red indication.

To better prepare the research tasks and field data collection and analysis, hierarchy of contributing factors analysis for dilemma zone modeling is developed as shown by **Figure 3**. Contributing factors which are theoretically assumed and can be observed in field are also related through the illustration by **Figure 3**. However, because of variations in drivers' characteristics (such as age, sex, and driving aggressiveness), vehicles' characteristics (such as allowable maximum deceleration), and impact of speed limit as well as intersection size, some parameters such as speeds, PRTs, maximum accelerations or decelerations vary with drivers, vehicles, and driving environments in reality. While these factors (e.g., maximum deceleration for safe stopping or acceleration for safe passing) can be quantitatively assumed with infrastructure design experience, it's actually uncertain of the range of the parameter values that are really matching with real-world travel behaviors. In other words, field observations should be conducted to identify the most appropriate range of the associated parameter values that can be effectively applied into dilemma zone modeling and protection.

As a result of dynamic human traveling and driving behaviors as well as diverse maneuver characteristics of different vehicles, the dilemma zone is actually featured with "dynamic" characteristics. Referring to each individual driver, values of X_c and X_0 may be different and the length or range of the dilemma zone varies; however, statistical method can be used to identify the distribution of the dilemma zone from sampling vehicle trajectory data under scenarios of possible yellow durations and the speed classification for the intersection approach. The dynamics are therefore featured through statistically quantified distributions of the dilemma zones in terms of location and length for each speed classification. Concept of percentile (e.g., 85th percentile yellow passing distance) can be used to define an <u>Xth-percentile dilemma zone</u> under the prevailing traffic conditions.

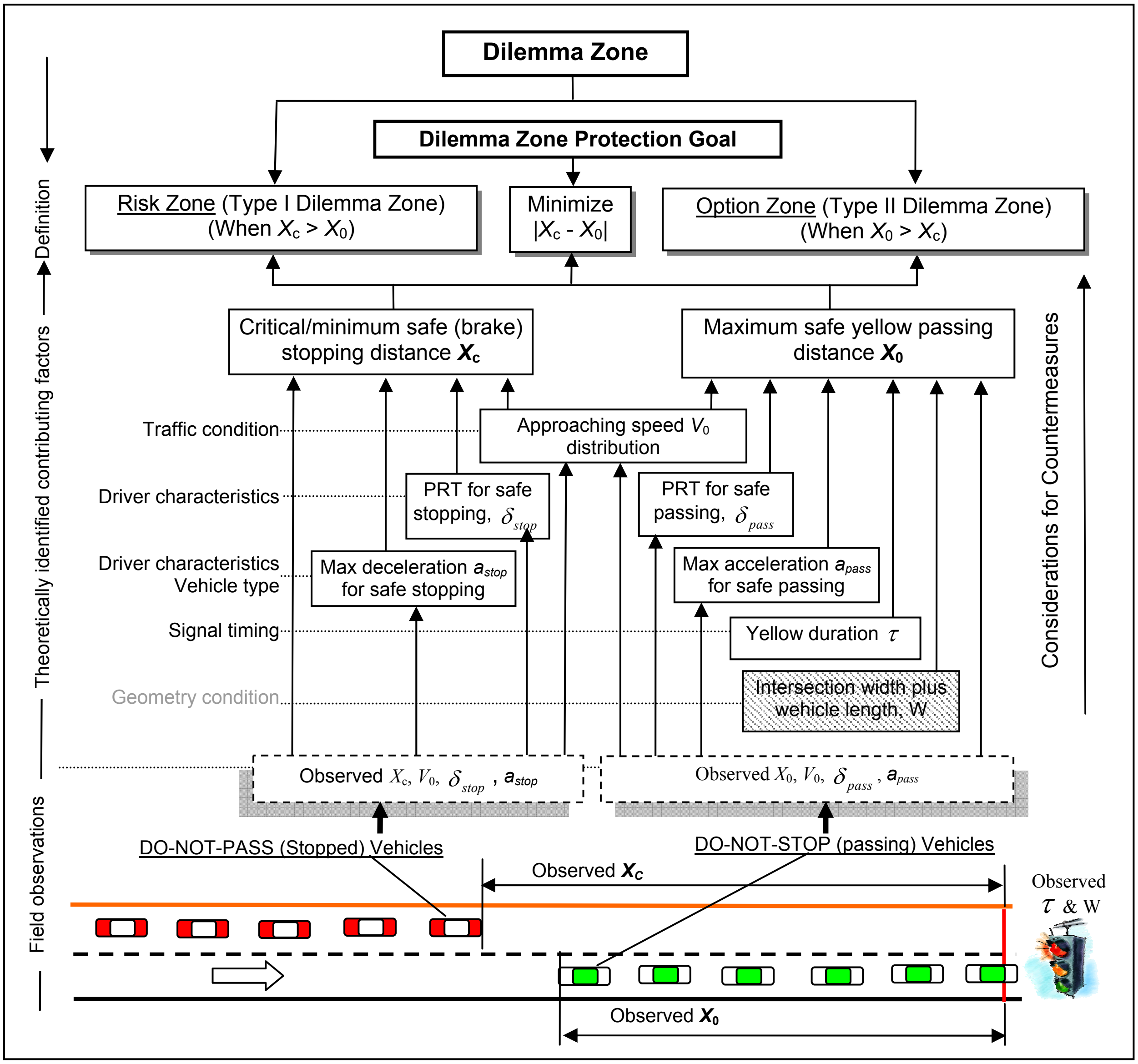


Figure 3: Hierarchy of Contributing Factors Analysis for Dilemma Zone Modeling

As discussed earlier, two types of the dilemma zones (Type I – dilemma zone and Type II – option zone) are a result of theoretically calculating X_c and X_0. If the calculation results in $X_c > X_0$ given a yellow duration τ and approaching speed V_0, the physical zone between X_c and X_0 is traditionally defined as the dilemma zone or Type I dilemma zone (**Figure 1**). A vehicle located within such a zone at the onset of the yellow indication, the vehicle can neither safely stop before the stop line, nor safely pass the stop line during the yellow interval. However, *vehicles within in such a defined dilemma zone are quite difficult to be observed or identified in real-world* *observations*. We can only use the observed locations of vehicles at the onset of yellow indications, which actually stopped before and/or passed the stop line during the yellow period, to statically analyze possible distribution of X_c and X_0 (as illustrated by **Figure 3**), and calculate the length of the Type I dilemma zone with values of X_c and X_0.

On the other hand, if the calculation results in $X_c < X_0$ given a yellow duration τ and approaching speed V_0, the physical zone between X_c and X_0 is traditionally defined as the option zone or Type II dilemma zone (**Figure 2**). A vehicle located within the option zone at the onset of the yellow indication, the vehicle is facing two choices: either passing the intersection or slowing down and stopping before the stop line during the yellow time. Unlike Type I dilemma zone, *vehicles falling into the option zone are observable with ease by observed trajectory data*, as shown by **Figure 4**.

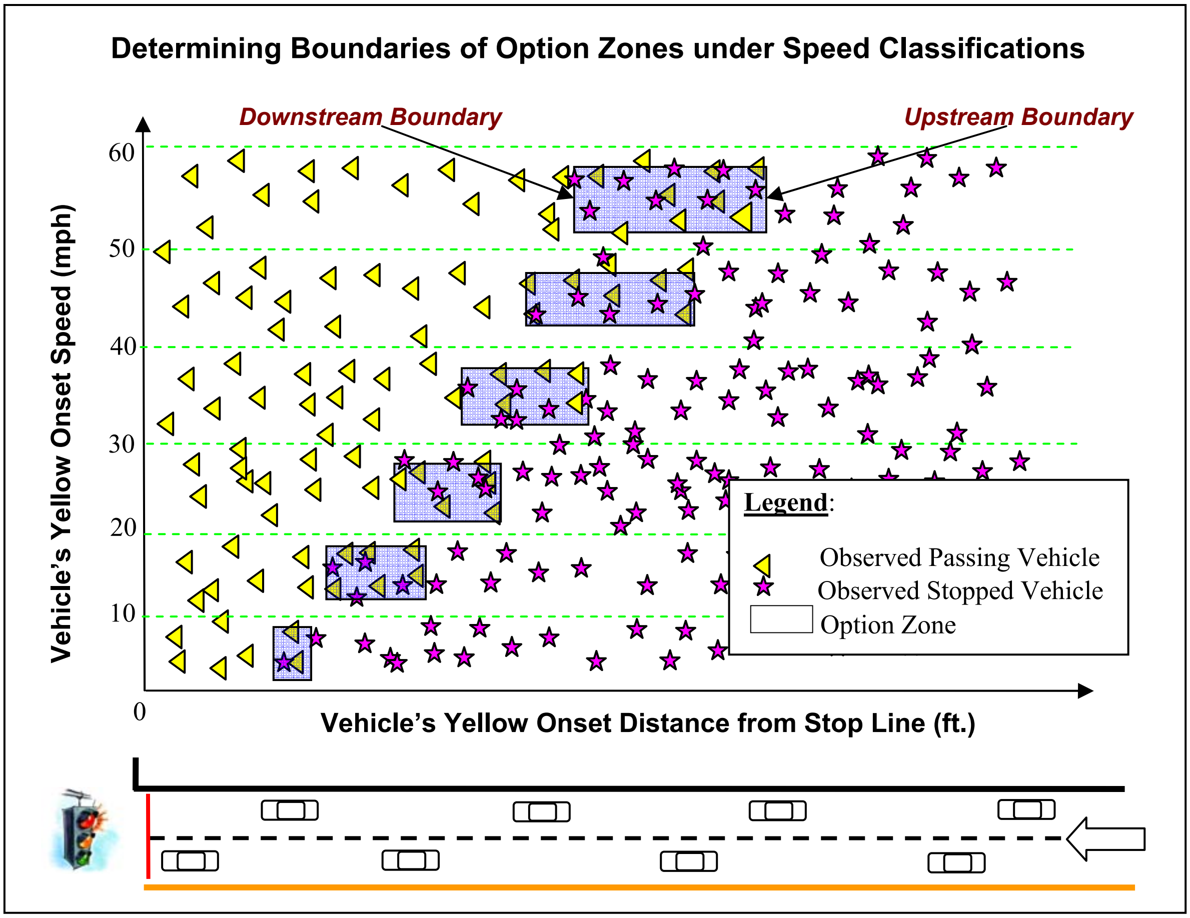


Figure 4: Modeling Boundaries of Option Zones using Observed Trajectory Data

According to the literature review, an <u>indecision zone</u> is defined as a length of a roadway in advance of the intersection where a driver may experience indecisiveness upon seeing the indication of the yellow signal (Parsonson, 1992). Usually it is modeled as the road segment where more than 10% and less than 90% of the drivers would choose to stop, as shown by

Figure 5. Indecision zone is a concept that measures the indecisiveness of drivers in a probabilistic and statistical way. To some extent, indecision zone should be a segment within the option zone, and most parts of them should overlap each other.

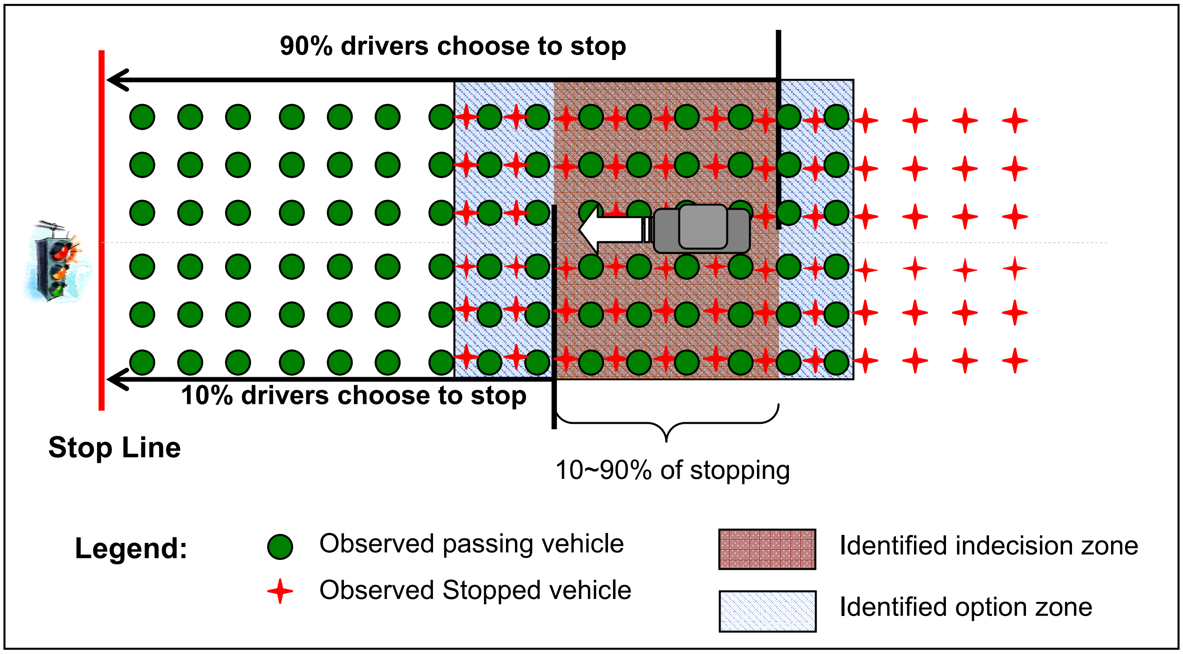


Figure 5: Illustration of Relationship between Option Zone and Indecision Zone

The existence of Type I dilemma zone (when $X_c > X_0$) provides a risky chance for any vehicles happening to be located within this zone to run red, because the yellow duration is insufficient for the vehicle to safely pass the stop line while not sufficient distance for the vehicle to comfortably stop before the stop line. Therefore, the Type I dilemma zone should be eliminated at all possible. Although not so risky as the Type I dilemma zone, the option zone (Type II dilemma zone) potentially leads the driver's hesitation in the decision-making process to decide pass or stop. The option zone is also a dilemma situation to some extent. Whatever Type I or Type II exists, drivers are forced to make a judgment and decision about whether to pass or to stop within a very short period of yellow time. Any hesitation during that time period could potentially result in a rear-end accident if the front vehicle stops abruptly during the yellow interval or an angle accident if the driver attempts to cross the intersection at the onset of the red interval. Therefore, the dilemma zone is understood to be composed of two types, i.e., Type I and Type II. To avoid any confusion of these concepts in descriptions of the report, Type I dilemma zone is termed as "Risk Zone" and Type II dilemma zone is still referred to "Option Zone" in this report.

Regarding the above analysis, dilemma zone protection aims to minimize the effect of dilemma zones. According to the literature review and above discussions, risk zone can not be fully eliminated by a longer duration of yellow interval because of dynamic driving behaviors. Option zone could be even harder to be removed because longer yellow duration yields longer option zone. Nevertheless, the dilemma zone protection with appropriate detection functionality can be helpful to reducing the potentials of forming the dilemma zone and its effect. Dilemma zone modeling through analysis of observed trajectory data could help reveal true dynamic characteristics of dilemma zones and provide basis for figuring out the methods for optimum placement of detectors and yellow durations. The hierarchy of contributing factors to dilemma zone and their associations with observable parameters is illustrated by **Figure 3** to provide a navigator for developing field data collection and dilemma zone modeling work, as described below.

4.2 Extraction of Dilemma Zone Vehicular Trajectory Data

A vehicle trajectory describes the vehicle's path over a period of time, as shown by **Figure 6**. Other parameters, such as velocity, acceleration/deceleration and headway, can be simply derived from vehicle trajectory data. A low-cost method using video-capturing technology for extracting vehicle trajectory data over the yellow interval was developed by using VEVID. This method consists of five basic steps.

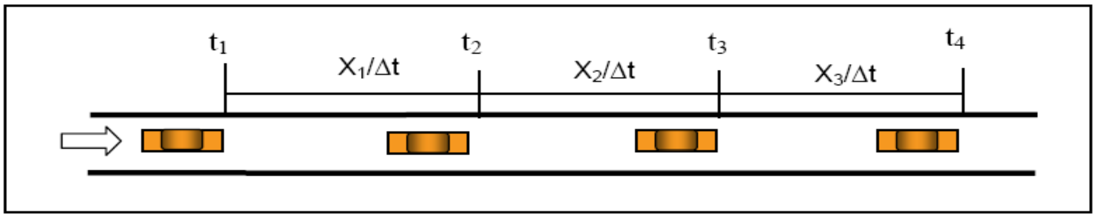


Figure 6: Illustration of Vehicle Trajectory

First, one approach of the mainline street of a signalized intersection is videotaped from an elevated position from which the vehicle responding traffic lights can be fully viewed. After the video is digitized, the screen-measured distance between a vehicle's position and the stop line could be obtained from rectangular coordinates. However, for the sake of perspective effect and the angle between the line of sight of the camcorder and the surface of pavement, screen-measured distance does not represent the real world distance. In order to convert screen-measured distance into real world distance, reference points must be set up in field from stop line to the position of the camcorder at a fixed space like 15 or 20 ft along curbs of both sides and with no interruption to traffic. With the help of those reference points, screen distance from the vehicle position to the stop line can be converted to real world distance (Wei et al., 2005). In field, a chalk is used to mark those points on curbs on both sides of the approach or median. Then, a surveyor steps on each mark for a short while (e.g., 5 seconds) and all these actions are recorded by video camcorder. After back to office, the marked reference points are established into the database of VEVID by identifying the surveyor's feet locations when he steps on the marks in the video, as shown by **Figure 7**. In this way, traffic is neither interfered nor disturbed during the survey.

Second, video is digitized using video-capturing equipment, segments containing yellow interval for each cycle, including 5 second before and after the yellow indication, are exported to an AVI digital video file at a frame rate of 30 fps (frame/sec), which can guarantee the accuracy of identifying the exact time of the onset of yellow.

Third, those video segments are registered in VEVID by assigning established reference points to each video segment.

Fourth, in each frame, real world distance from the targeted vehicle to stop line can be obtained by simply clicking the mouse over the touching point between the rear tire (or front tire) and pavement. VEVID can record every distance generated by every click. With the distance, speed can be derived by dividing the distance interval between two consecutive frames by the time interval. (e.g., time interval between two consecutive frames at frame rate of 30 fps is 1/30 second). Acceleration/deceleration can be derived by dividing the speed difference between two consecutive frames by the time interval.

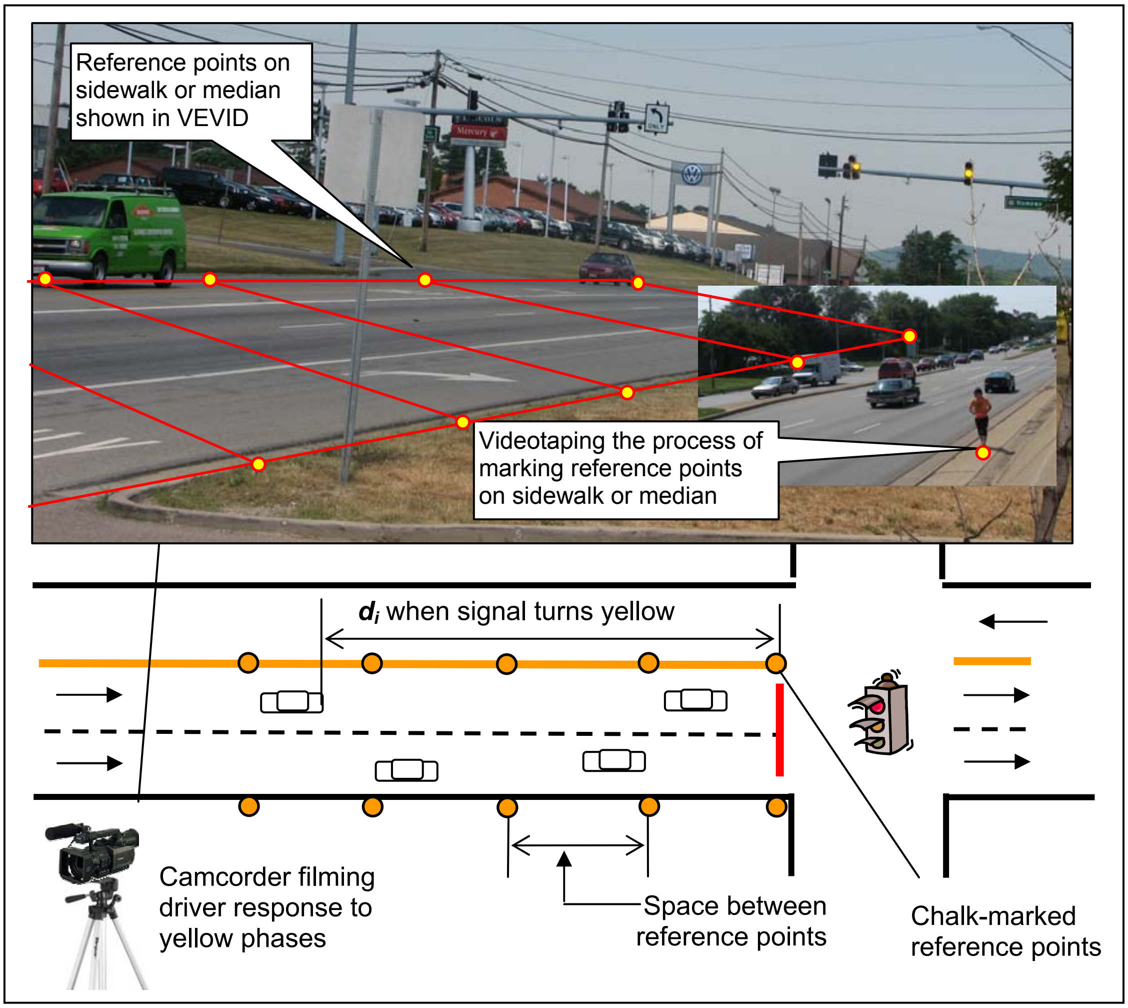
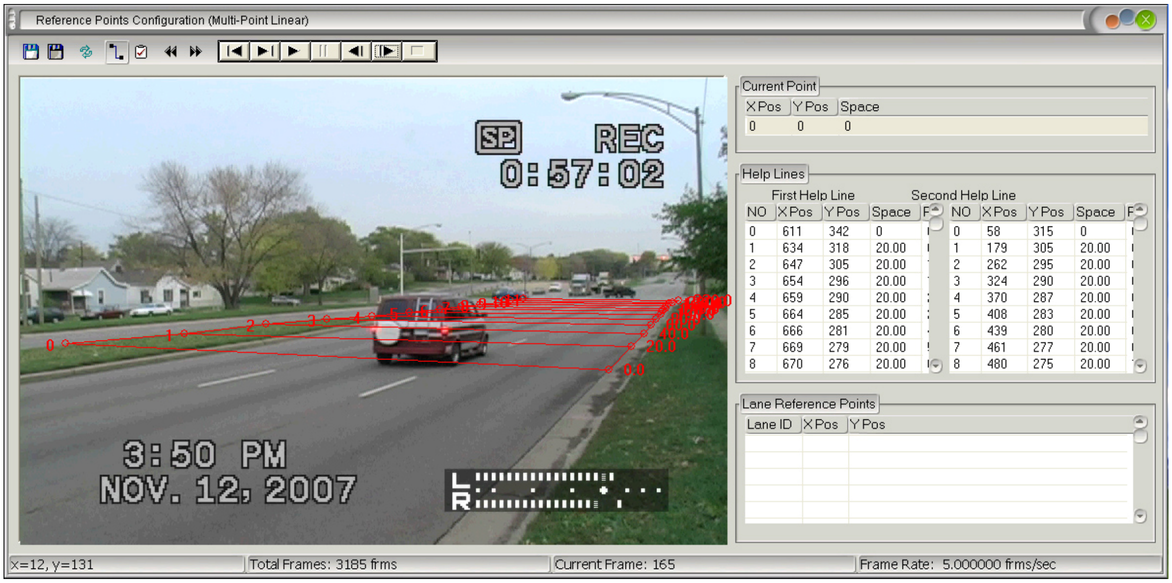


Figure 7: Illustration of Setting up Field Reference Points and Camcorders

Fifth, VEVID can generate an output data file containing vehicle's trajectory over the entire yellow interval, which includes distance, speed, and acceleration/deceleration changing profiles. The output file can be imported into common analytical tools such as Microsoft Excel or Microsoft Access. **Figure 8** shows the interface of the upgraded version of VEVID for extracting vehicular trajectory data over yellow intervals. The whole procedure of the trajectory data extraction is illustrated by a flowchart as shown by **Figure 9**.



Reference Points Configuration (Multi-Point Linear)

Current Point

XPos	YPos	Space
0	0	0

Help Lines

First Help Line

NO	XPos	YPos	Space
0	611	342	0
1	634	318	20.00
2	647	305	20.00
3	654	296	20.00
4	659	290	20.00
5	664	285	20.00
6	666	281	20.00
7	669	279	20.00
8	670	276	20.00

Second Help Line

NO	XPos	YPos	Space
0	58	315	0
1	179	305	20.00
2	262	295	20.00
3	324	290	20.00
4	370	287	20.00
5	408	283	20.00
6	439	280	20.00
7	461	277	20.00
8	480	275	20.00

Lane Reference Points

Lane ID	XPos	YPos

x=12, y=131 | Total Frames: 3185 frms | Current Frame: 165 | Frame Rate: 5.000000 frms/sec

Figure 8: Extracting Vehicular Trajectory Data over Yellow Interval by Using VEVID

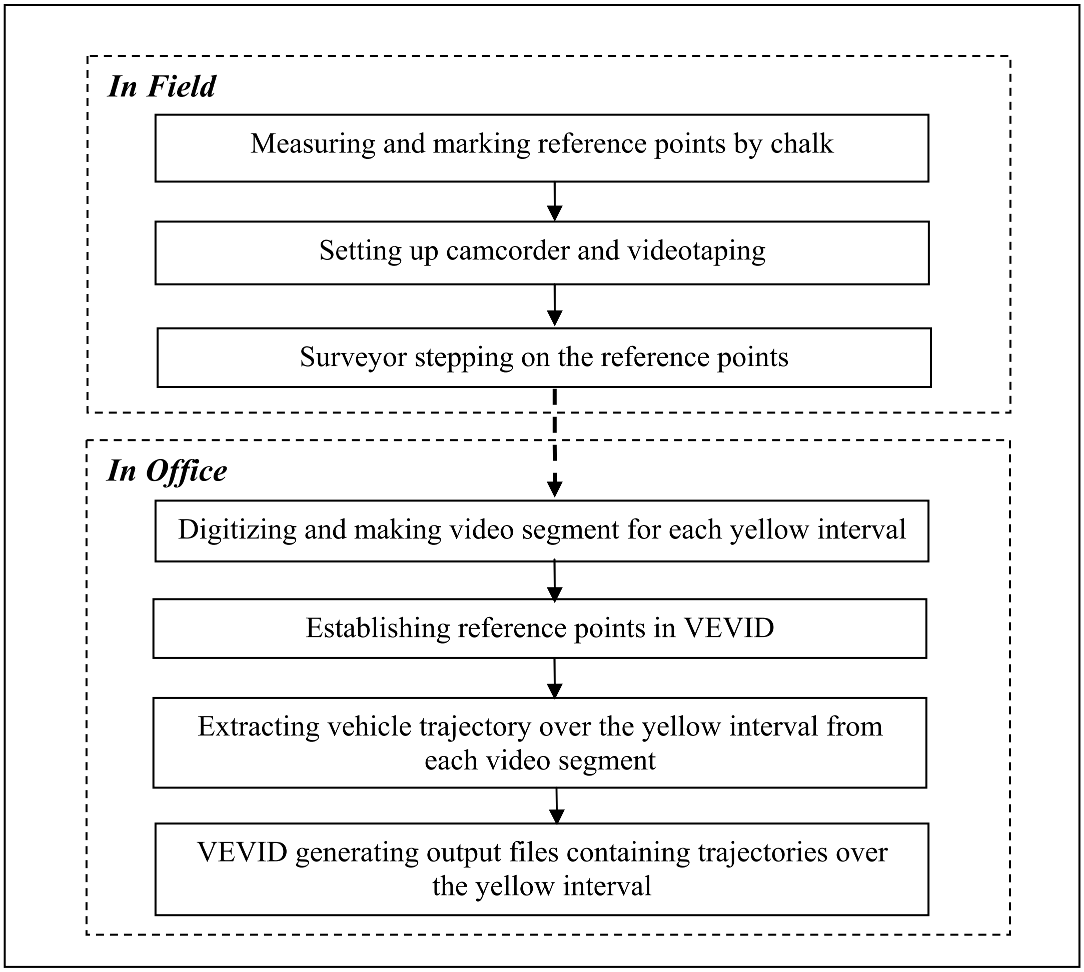


Figure 9: Illustration of Procedure of Vehicular Trajectory Data Extraction

4.3 Sampling Site for Colleting Dilemma Zone Trajectory Data

The intersection of OH-4 and Seward Rd. was selected as the study site where the speed limit is 50 mph on the OH-4 (Dixie Highway) approaches (see **Figure 10**). There is an intersection closely located in the upstream of eastbound traffic, where progression is set up between these two intersections. In order to guarantee the full coverage of the risk zone and option zone, two camcorders were placed along the right side of eastbound approach of OH-4 at the distances of 300 and 500 ft from stop line, respectively. They were synchronized before videotaping. 6.5-hour period of traffic operation was videotaped at this location.

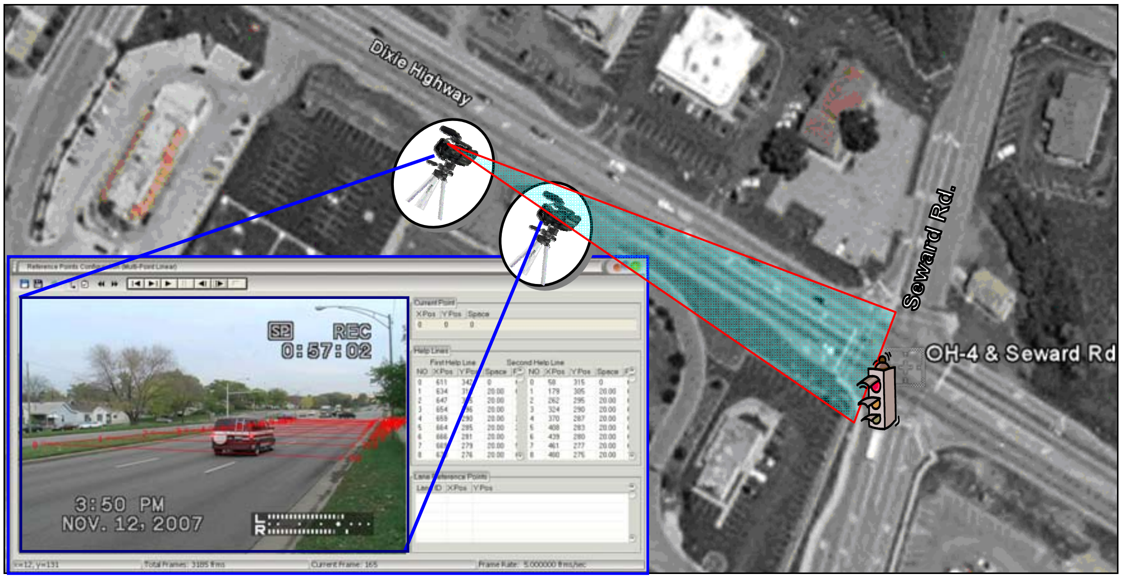


Figure 10: Site of Data Collection and Case Study (OH-4 & Seward Rd)

Trajectory data of vehicles over the yellow intervals were extracted using VEVID with the user's interface showing in the lower-left corner of **Figure 10**. During each yellow interval, every running yellow and running red vehicle was targeted for extracting trajectory data. For those stopped vehicles, only the first vehicle of a platoon in each lane was targeted for trajectory data. It's because the decision made by the drivers of the following vehicle and other later vehicles is totally affected by the manoeuvre of the first stopped vehicle in the platoon. Those drivers usually can do nothing but slow down and stop following the first queuing vehicle. Therefore, those vehicles do not directly contribute to the formation of dilemma zone or option zone and are therefore not included in the samples. Totally 679 vehicle samples were obtained. Vehicle category is recorded for each sample vehicle. Traffic volumes and signal timings of each cycle were also counted and recorded through replaying the videos.

4.4 Modeling Dilemma Zones using Trajectory Data

Based on GHM model (Gazis et al, 1960) and principle of kinetics, the minimum stopping distance X_c and the maximum yellow passing distance X_0 given the vehicle approaching speed V_0 can be expressed in the following equations, respectively.

$$X_c(V_0) = V_0\delta_{stop} + \frac{V_0^2}{2a_{stop}} \qquad (3)$$

$$X_0(V_0) = V_0\tau + \frac{1}{2}a_{pass}(\tau - \delta_{pass})^2 \qquad (4)$$

Where, V_0 = Vehicle approaching speed (ft/s);
$X_c(V_0)$ = Minimum stopping distance from stop line given speed V_0 (ft);
$X_0(V_0)$ = Maximum yellow passing distance from stop line given speed V_0 (ft);

δ_{stop} = Driver's minimum PRT for safe stopping (sec);

a_{stop} = Vehicle's maximum deceleration rate for safe stopping (ft^2/sec);

δ_{pass} = Driver's minimum PRT for safe passing (sec);

a_{pass} = Vehicle maximum acceleration rate for safe passing (ft^2/sec);

τ = Duration of the yellow interval (sec).

As discussed in **Section 4.1**, *the intersection width and vehicle's length are not taken into the account in calculating X_0.* It is assumed that once a vehicle passes the stop line before the end of yellow interval, it is regarded as a yellow passing vehicle. This assumption is from the driver's perspective. When a driver perceives the yellow indication, he/she does not consider whether he/she could clear the intersection completely during the yellow interval. Actually, his/her concern is whether he/she could pass the stop line before the onset of red indication. That's the reason why we made this minor modification compared to the original GHM model.

The length of the risk zone can be modeled by **Equation (5)**, when $X_c > X_0$, while the length of the option zone can be modeled by **Equation (6)**, when $X_0 > X_c$.

$$L_{RZ}(V_0) = X_c(V_0) - X_0(V_0) = V_0\delta_{stop} + \frac{V_0^2}{2a_{stop}} - [V_0\tau + \frac{1}{2}a_{pass}(\tau - \delta_{pass})^2] \tag{5}$$

$$L_{OZ}(V_0) = X_0(V_0) - X_c(V_0) = V_0\tau + \frac{1}{2}a_{pass}(\tau - \delta_{pass})^2 - (V_0\delta_{stop} + \frac{V_0^2}{2a_{stop}}) \tag{6}$$

From these equations, it is not hard to find that values of X_c and X_0 are greatly dependent on the values of the parameters, a_{stop}, a_{pass}, δ_{pass}, and δ_{stop}, which are used to represent the driving behaviors over the yellow interval. To complete the modeling of the location and length of the risk/option zone, appropriate values of these parameters need to be calibrated by using observed vehicle trajectories (e.g. observed X_c and X_0). However, before the calibration process, the observed X_c and X_0 could be statistically analyzed by applying Xth percentile concept (e.g. 85th or 95th percentile X_0), and the Xth percentile X_c and X_0 are used as observed value to calibrate those parameters. From the engineering viewpoints, the percentile concepts are usually employed to represent the range of X_c and X_0 values at a considerably confident level and extremely conservative or aggressive driving behaviors are precluded. Accordingly, locations and lengths of the risk or option zones based on this rational are assumed to be applicable to the prevailing traffic conditions.

CHAPTER 5:

SAMPLE DATA ANALYSIS AND RESULTS

5.1 Calibrating Dilemma Zone Contributing Factors using Observed Trajectory Data

As discussed in Chapter 4, the locations and lengths of the dilemma zone are directly identified by the locations of X_0 and X_c. Based on **Equations (3)** and **(4)**, the value of X_0 is determined by the duration of yellow interval (τ), vehicle approaching speed (V_0), minimum PRT for passing (δ_{pass}), and maximum passing acceleration (a_{pass}), while the value of X_c has nothing to do with the duration of yellow interval τ, but is associated with vehicle approaching speed (V_0), minimum PRT for stopping (δ_{stop}), and the maximum stopping deceleration (a_{stop}). Therefore, the key contributing factors in modeling the dilemma zone are the variables, a_{stop}, a_{pass}, δ_{pass}, and δ_{stop}, and determining their values plays a critical role in application of the models.

It is assumed that values of the maximum stopping deceleration (a_{stop}), maximum passing acceleration (a_{pass}), minimum PRT for passing (δ_{pass}) and minimum PRT for stopping (δ_{stop}) vary with different vehicle approaching speeds. Based on the common sense, we assume vehicles with a higher speed need higher deceleration to stop than vehicles with a lower speed, while vehicles with a lower speed need higher acceleration to pass the stop line before the end of yellow interval than vehicles with a higher speed. We also assume that drivers of stopped vehicles with a higher speed use more PRT to make a stop decision than those drivers with a lower speed. And drivers of the passing vehicles with a higher speed use less PRT to make a passing decision than those drivers with a lower speed. These assumptions are based for calibrating the values of a_{stop}, a_{pass}, δ_{pass}, and δ_{stop} with observed trajectory data.

In order to prepare for the calibration, observed trajectory data are plotted on a coordinate system with the yellow onset speeds on the vertical axis and the yellow onset distances from the stop line on the horizontal axis (See **Figure 11**). Totally, 679 trajectory samples were observed at OH-4 and Seward Road and classified into passing, stopped, and running red vehicles.

Figure 12 shows the locations at yellow onset of observed stopping vehicles, which are referred to stopping distance in response to yellow-onset stopping distance. Minimum yellow-onset stopping distances are regressively modelled using the observed minimum values under different speed ranges. Similarly, **Figure 13** shows locations at yellow onset of observed passing vehicles, which are referred to yellow-onset passing distance in response to yellow indications on the observation basis. Maximum yellow-onset passing distances are regressively modelled using the observed maximum values under different speed ranges.

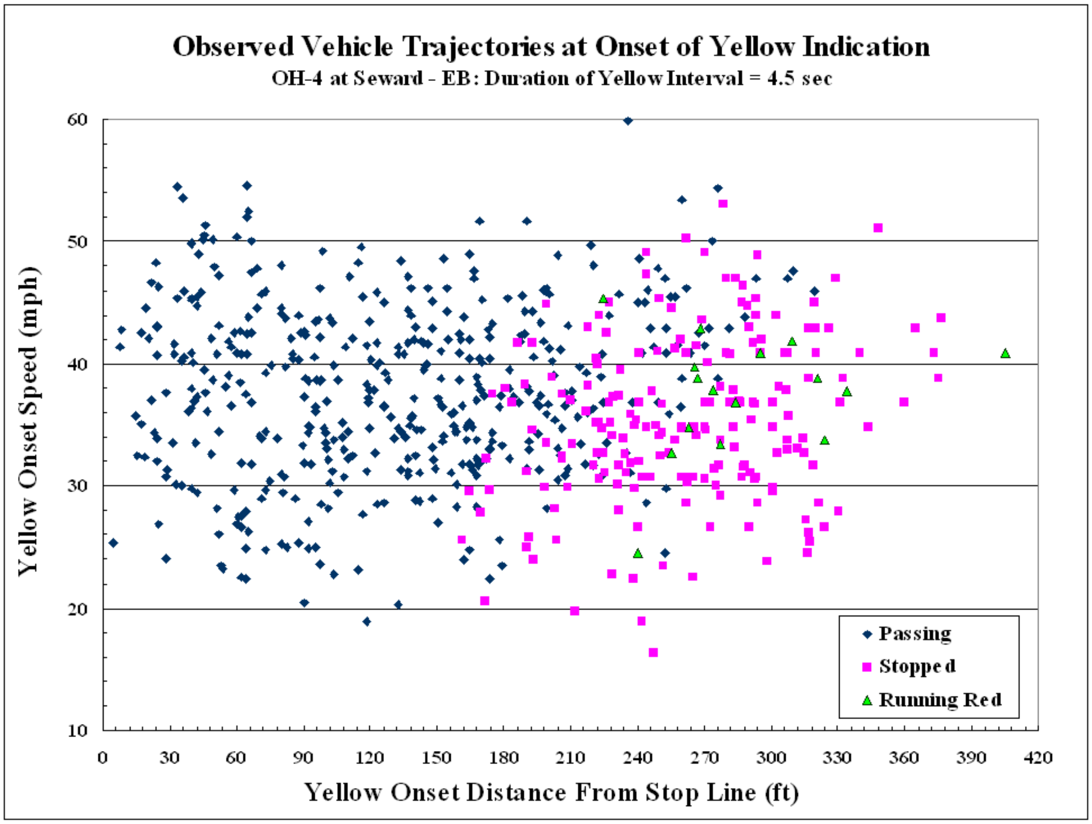


Figure 11: Observed Vehicle Trajectories at the Onset of Yellow Indication

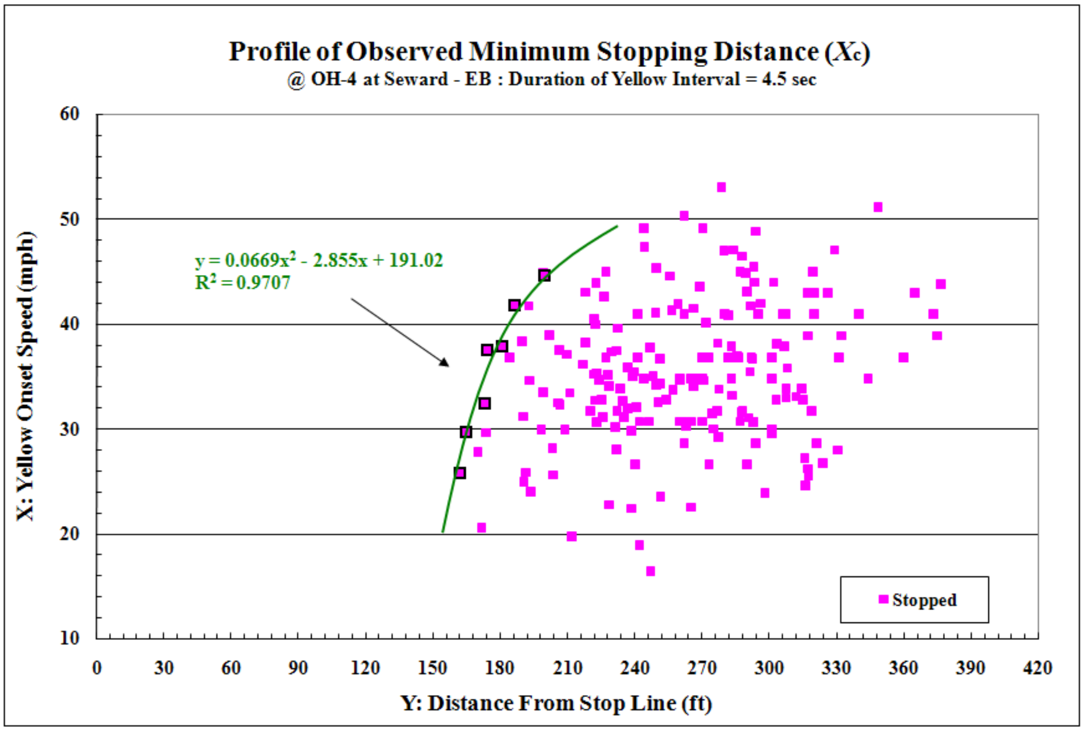


Figure 12: Profile of Observed Minimum Yellow-Onset Stopping Distance

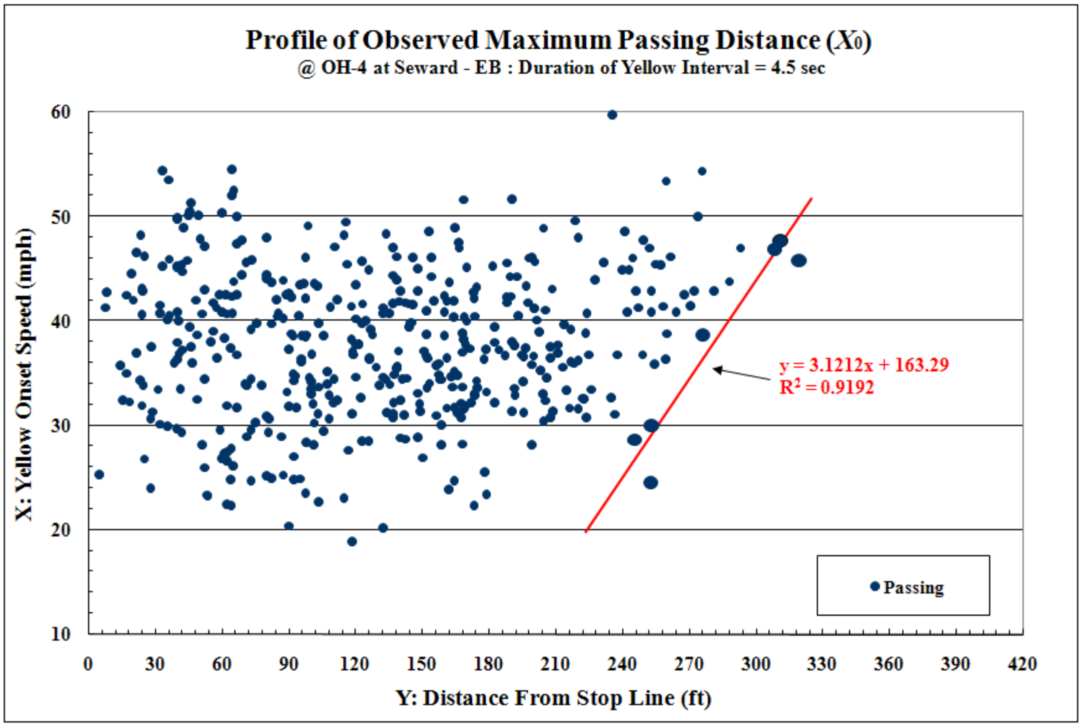


Figure 13: Profile of Observed Maximum Yellow-Onset Passing Distance

In case of no sufficient data to exactly determine the values of concerned variables, namely, a_{stop}, a_{pass}, δ_{pass}, and δ_{stop}, a process of trial-and-fit method can be employed for the calibration. Appropriate values of are obtained through fitting the theoretically calculated X_c and X_0 values (based upon **Equations (3)** and **(4)**) to the observed X_c and X_0 values for various speed inputs from 24 mph to 50 mph. The calibration process and results are illustrated by **Figure 14**, where the goodness-of-fit analysis shows that the correlation coefficient R^2 is 0.9976 for calculated and observed X_c, while the number is 0.9995 for calculated and observed X_0. Both of the R^2 values indicate a good fitting. Through the calibration, values of a_{stop}, a_{pass}, δ_{pass}, and δ_{stop} for various speed inputs are finally obtained and shown in **Table 1**.

As mentioned in **Section 4.3**, X^{th}-Percentile observed X_c and X_0 need to be used in this calibration process in order to consider the prevailing behaviors. If 95th percentile observed X_0 and 10th percentile observed X_c are analyzed as calibration reference values, drivers of the stopped vehicles with yellow-onset distance < 10th percentile X_c are viewed as "extreme conservative" drivers. Meanwhile, drivers of passing vehicles with yellow-onset distance > 95th percentile X_0 are viewed as "extreme aggressive" drivers. Both "extreme" driving behaviors are precluded in such an X^{th}-Percentile analysis. To prepare for the calibration, the profiles of the 95th percentile X_0 and 10th percentile X_c should be identified in advance, which requires the following three steps.

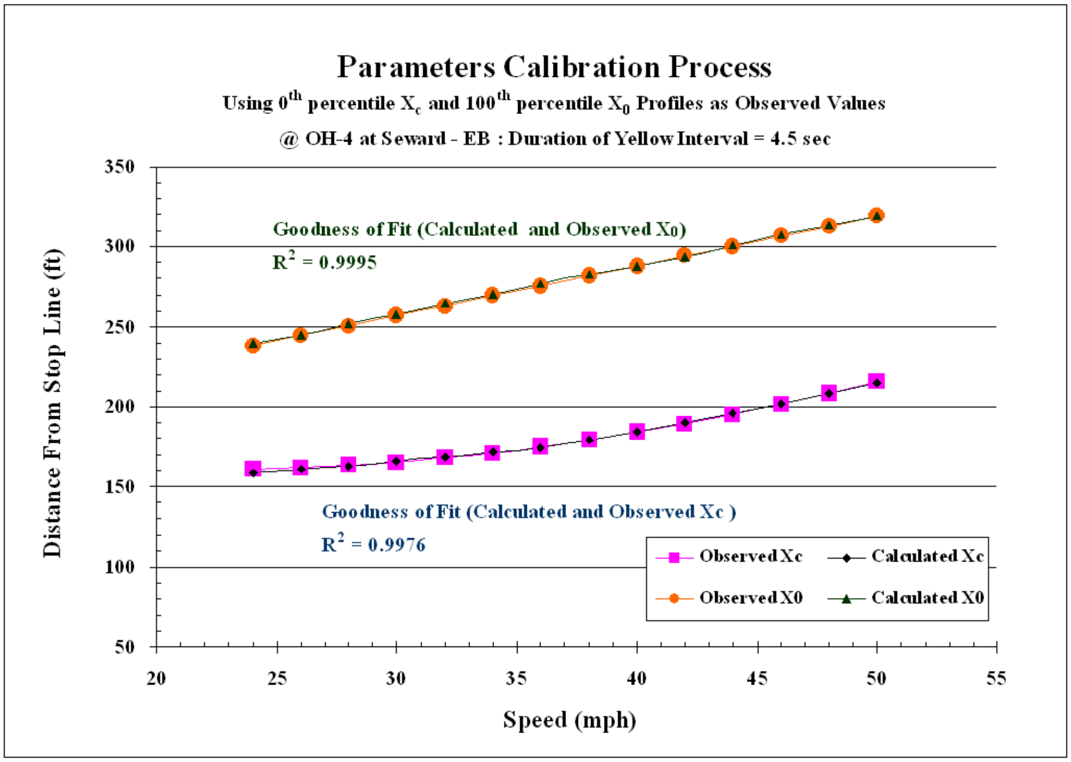


Figure 14: Calibration by Maximum X_c and Minimum X_0 as Reference Values

Table 1: Obtained Parameters Values (Based on Maximum X_c & Minimum X_0) ($\tau = 4.5$ s)

Speed V_0 (mph)	δ_{stop} (s)	a_{stop} (ft/s^2)	δ_{pass} (s)	a_{pass} (ft/s^2)	$X_{c\text{-Calc}}$ (ft)	$X_{c\text{-Obs}}$ (ft)	$X_{0\text{-Calc}}$ (ft)	$X_{0\text{-Obs}}$ (ft)
24	0.4	4.3	0.68	11.1	158	161	239	238
26	0.415	5	0.65	9.9	161	162	245	244
28	0.43	5.8	0.62	9	163	164	253	251
30	0.445	6.6	0.59	7.9	166	166	258	257
32	0.46	7.5	0.56	6.9	168	168	265	263
34	0.475	8.4	0.53	5.8	172	171	270	269
36	0.49	9.4	0.5	4.9	174	175	277	276
38	0.505	10.3	0.47	4	179	179	283	282
40	0.52	11.2	0.44	2.9	184	184	288	288
42	0.535	12.1	0.41	2	190	189	294	294
44	0.55	13	0.38	1.3	196	195	301	301
46	0.565	13.9	0.35	0.5	202	201	308	307
48	0.58	14.8	0.32	-0.4	208	208	313	313
50	0.595	15.7	0.29	-1.2	215	216	319	319

Step 1: Determine the 95th percentile X_0 by identifying the cumulative 95% X_0 for each of the three speed classifications at interval of 10 mph from 20 mph to 50 mph. As an example, **Figure 15** illustrates how to identify the 95th percentile X_0 from all the observed X_0s within the speed classification of 30-40 mph.

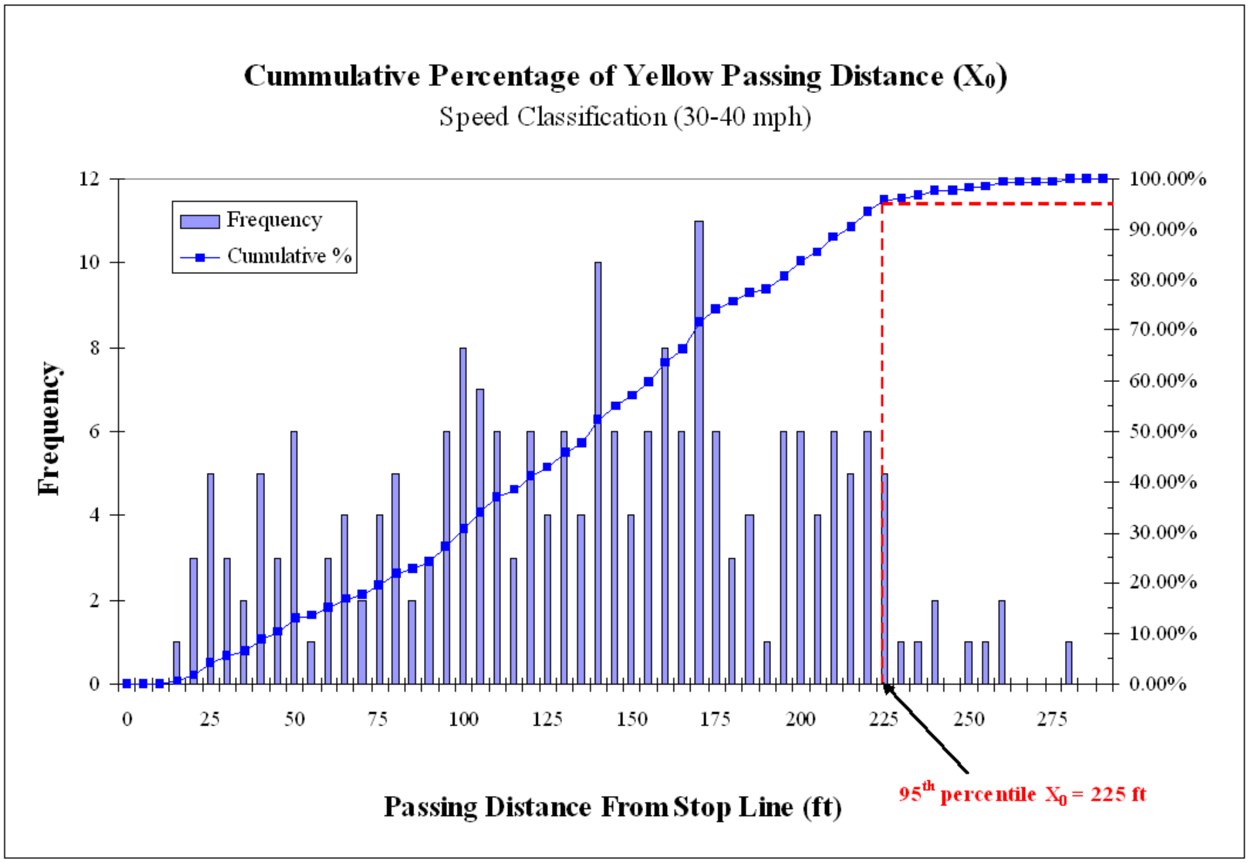


Figure 15: Determination of the 95th Percentile X_0 for Speed Classification of 30-40 mph

Step 2: Determine the 10th percentile X_c by identifying the cumulative 10% X_c for each of the three speed classifications at interval of 10 mph from 20 mph to 50 mph. If $X_0 > X_C$, those X_cs within the range $[X_C, X_0]$ are considered the sample for calculating 10th percentile X_c, a value smaller than the furthest X_0 within that speed classification. **Figure 16** illustrates how to identify the sampling range. X_cs of those stopped vehicles within the highlighted rectangle area constitute the sample. If $X_0 \leq X_C$, the second or third shortest X_c among all observed X_c will be viewed as the applicable values of X_C.

After Step 1 and Step 2, the 10th percentile X_c and 95th percentile X_0 for each speed classification are identified and illustrated by **Figure 17**.

Step 3: Use the mid-point speed of each speed classification (e.g. use 35mph for the speed classification 30-40 mph) as independent variable x, and the corresponding 10th percentile X_c and 95th percentile X_0 as dependant variable y, respectively, profiles that represent the observed 10th percentile X_c and 95th percentile X_0 under continuous speed inputs are obtained through regression, as illustrated by **Figure 18**.

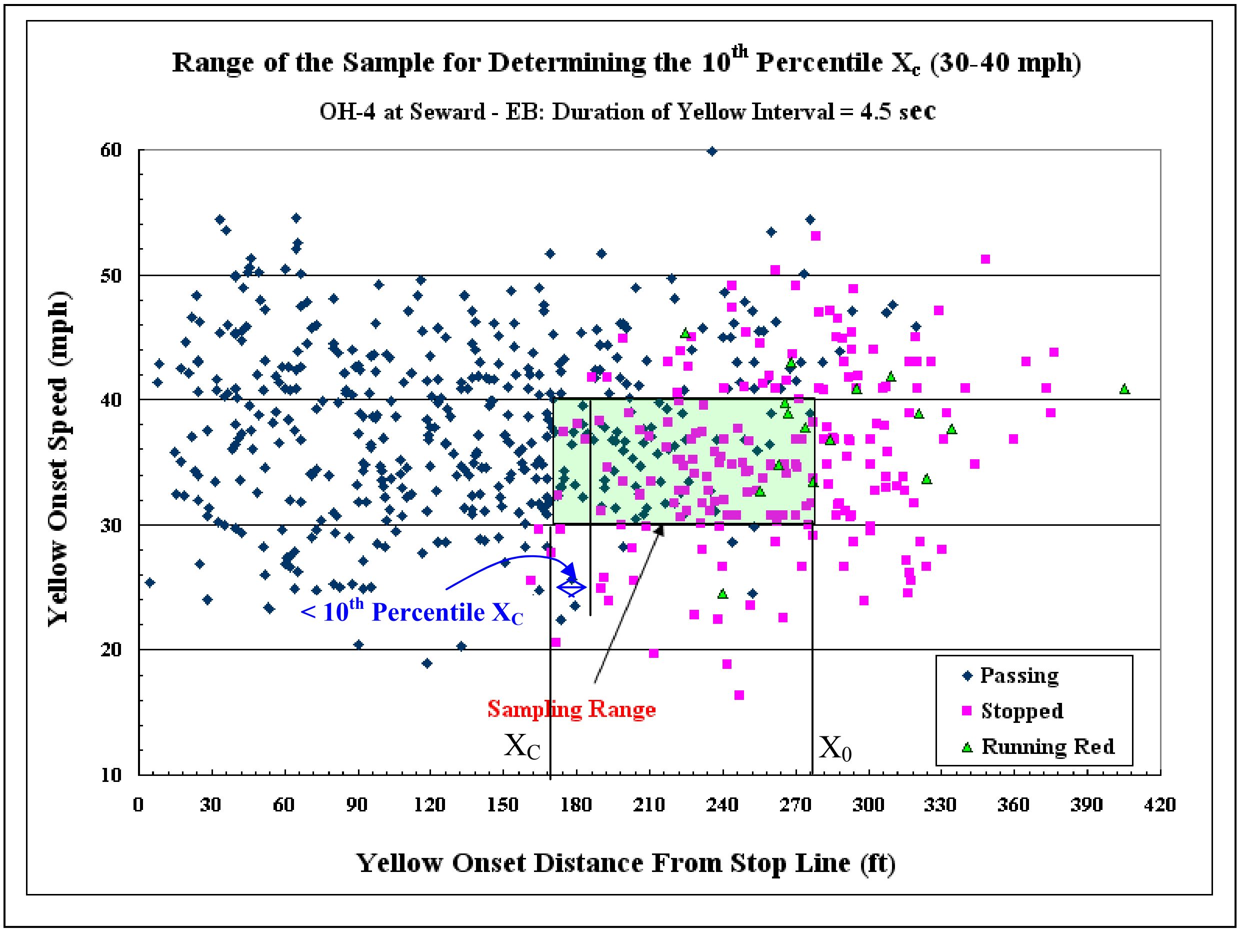


Figure 16: Sampling Range for 10th Percentile X_c for Speed Class of 30-40 mph

Figure 19 shows an example of modeling X_c and X_0 using the 10th percentile X_c and the 95th percentile X_0 as reference values (observed values). **Table 2** contains values of a_{stop}, a_{pass}, δ_{pass}, and δ_{stop} that result in good fits to the 10th percentile X_c and the 95th percentile X_0 values under various speed inputs.

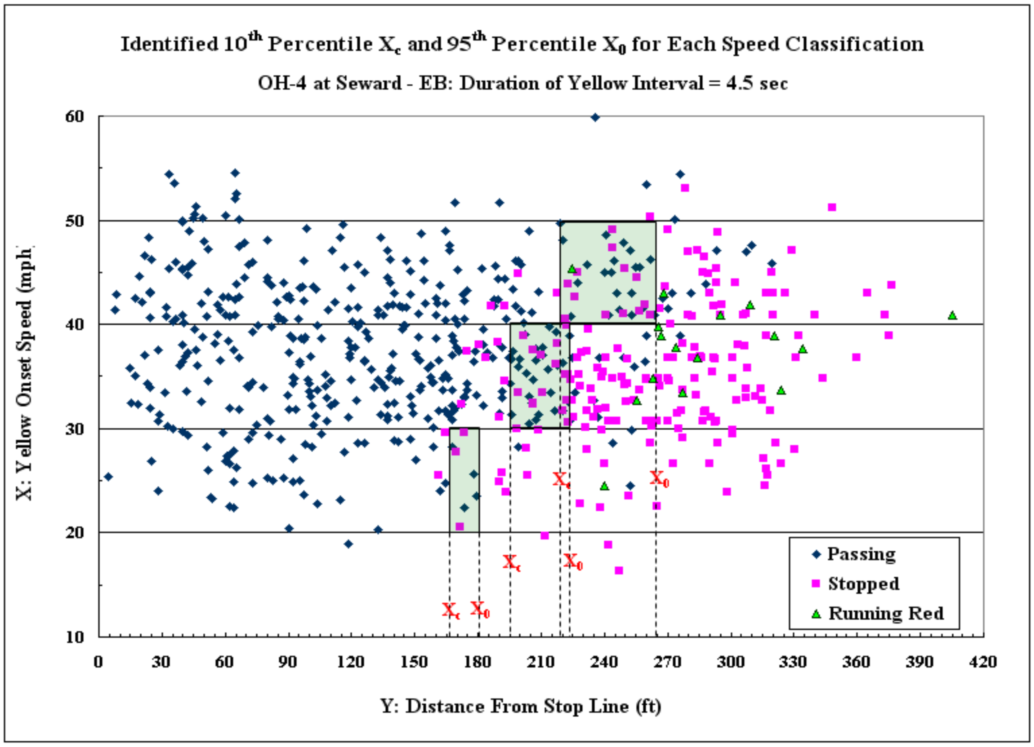


Figure 17: Identified 10th Percentile X_c and 95th Percentile X_0 for Each Speed Classification

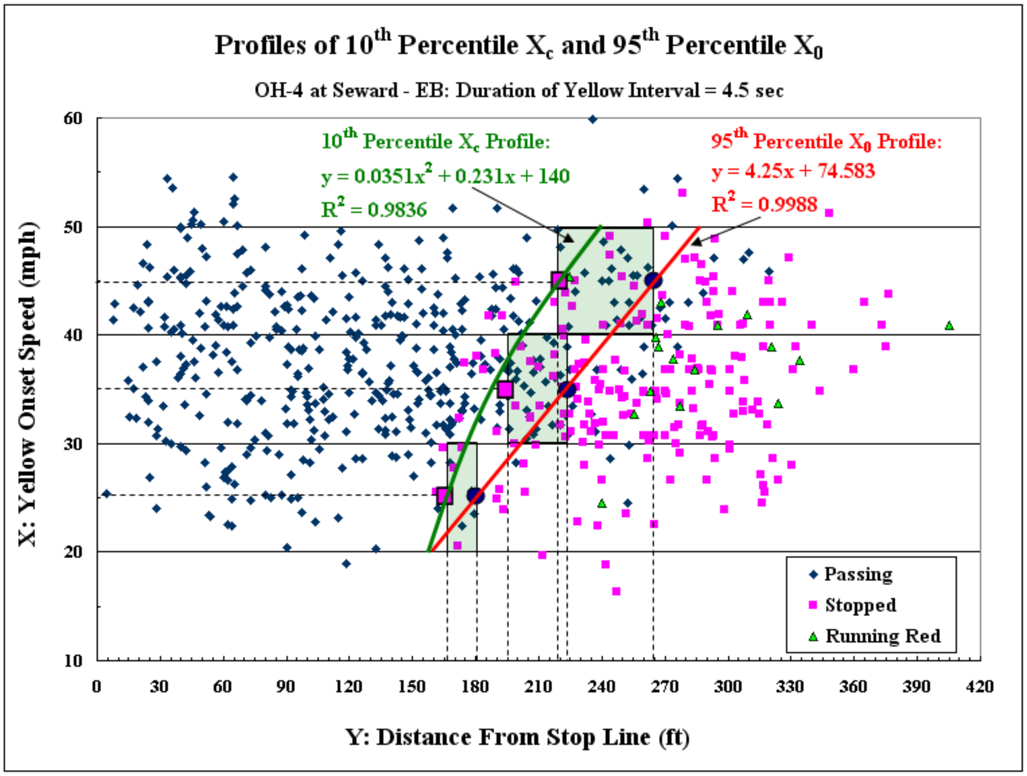


Figure 18: Profiles of 10th Percentile X_c and 95th Percentile X_0

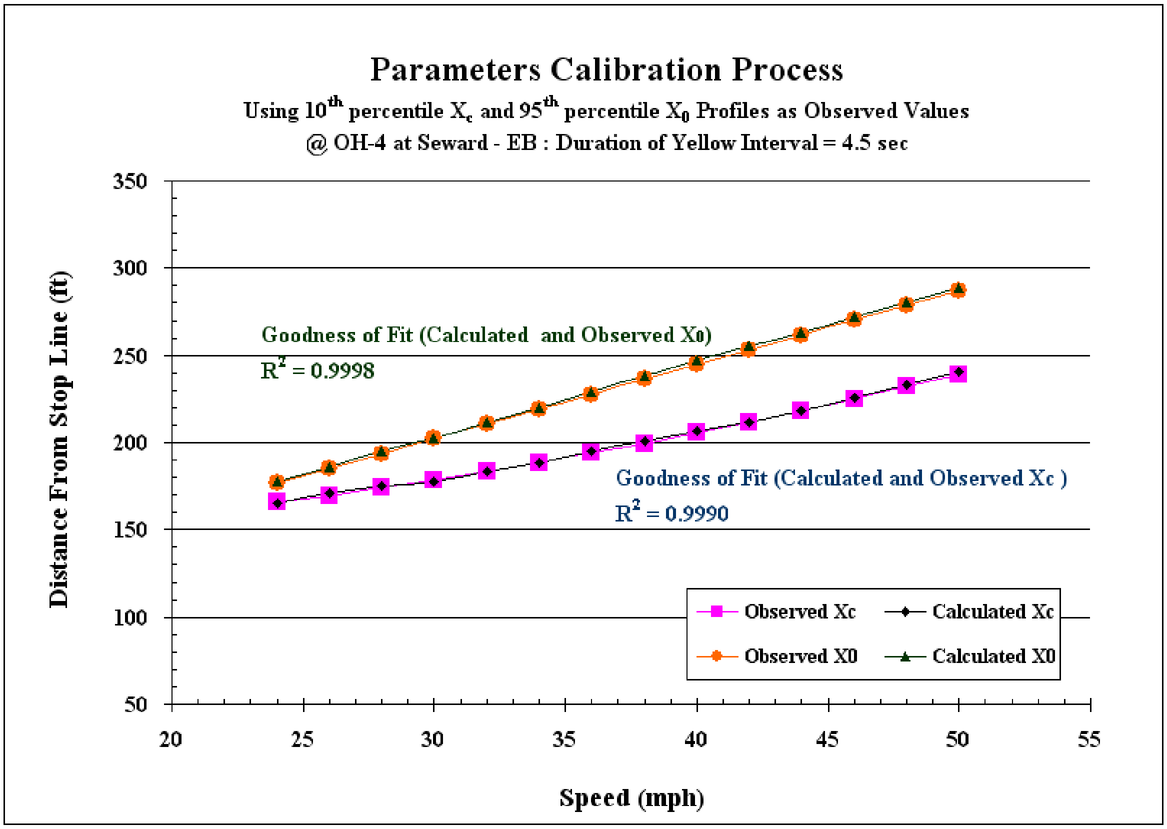


Figure 19: Calibration by 10th Percentile X_c and 95th Percentile X_0 as Reference Values

Table 2: Parameters Values based on 10th percentile X_c and 95th percentile X_0 ($\tau = 4.5$ s)

Speed V_0 (mph)	δ_{stop} (s)	a_{stop} (ft/s^2)	δ_{pass} (s)	a_{pass} (ft/s^2)	$X_{c\text{-Calc}}$ (ft)	$X_{c\text{-Obs}}$ (ft)	$X_{0\text{-Calc}}$ (ft)	$X_{0\text{-Obs}}$ (ft)
24	0.5	4.17	0.6	2.5	165	165	177	177
26	0.515	4.85	0.585	1.9	171	171	186	185
28	0.53	5.55	0.57	1.3	175	175	195	194
30	0.545	6.28	0.555	0.6	178	178	203	202
32	0.56	7	0.54	0.1	184	184	212	211
34	0.575	7.8	0.525	-0.6	188	188	220	219
36	0.59	8.57	0.51	-1.1	195	195	229	228
38	0.605	9.36	0.495	-1.6	201	201	238	236
40	0.62	10.16	0.48	-2.1	207	207	247	245
42	0.635	11	0.465	-2.7	212	212	255	253
44	0.65	11.8	0.45	-3.3	218	218	263	262
46	0.665	12.65	0.435	-3.8	225	225	272	270
48	0.68	13.44	0.42	-4.4	233	233	280	279
50	0.695	14.26	0.405	-4.9	240	240	289	287

5.2 Development of Dilemma Zone Look-up Chart

A dilemma zone look-up chart can be developed based on **Equations (3)** and **(4)**, as well as the values of a_{stop}, a_{pass}, δ_{pass}, and δ_{stop} obtained from calibration process discussed in **Section 5.1**. It tells you whether risk zone or option zone exists, and what the location and length of dilemma zone are, for a specific input of speed and duration of yellow interval. **Figure 20** is a dilemma zone look-up chart developed by using the parameter values in **Table 2**, which considers the majority of drivers.

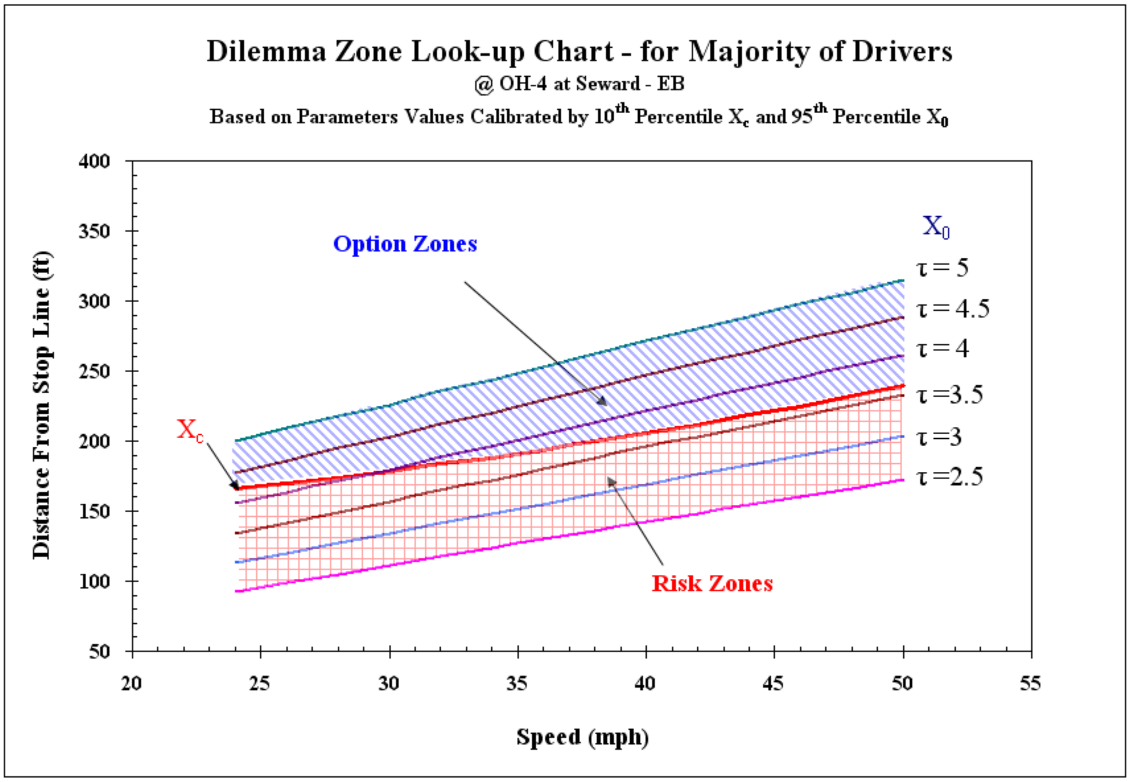


Figure 20: Dilemma Zone Look-up Chart for Majority of Drivers

In **Figure 20**, there is only one X_c profile, because the value of X_c does not change with the yellow durations. And the feasibility of putting those X_0 profiles together is based on the research result that change of yellow duration does not affect the driving behavior (Olson and Rothery, 1962). In this figure, it is not hard to identify that when the yellow duration set to 4 seconds, risk zone is almost eliminated for higher speed inputs and the absolute value $|X_c - X_0|$ is meanwhile minimized.

Figure 21 is a dilemma zone look-up chart that considers all possible driving behaviors, including extreme aggressive and extreme conservative behaviors, which is developed by using the parameter values in **Table 1**. In this figure, when the yellow duration is set to 3 seconds, the absolute value $|X_c - X_0|$ is minimized.

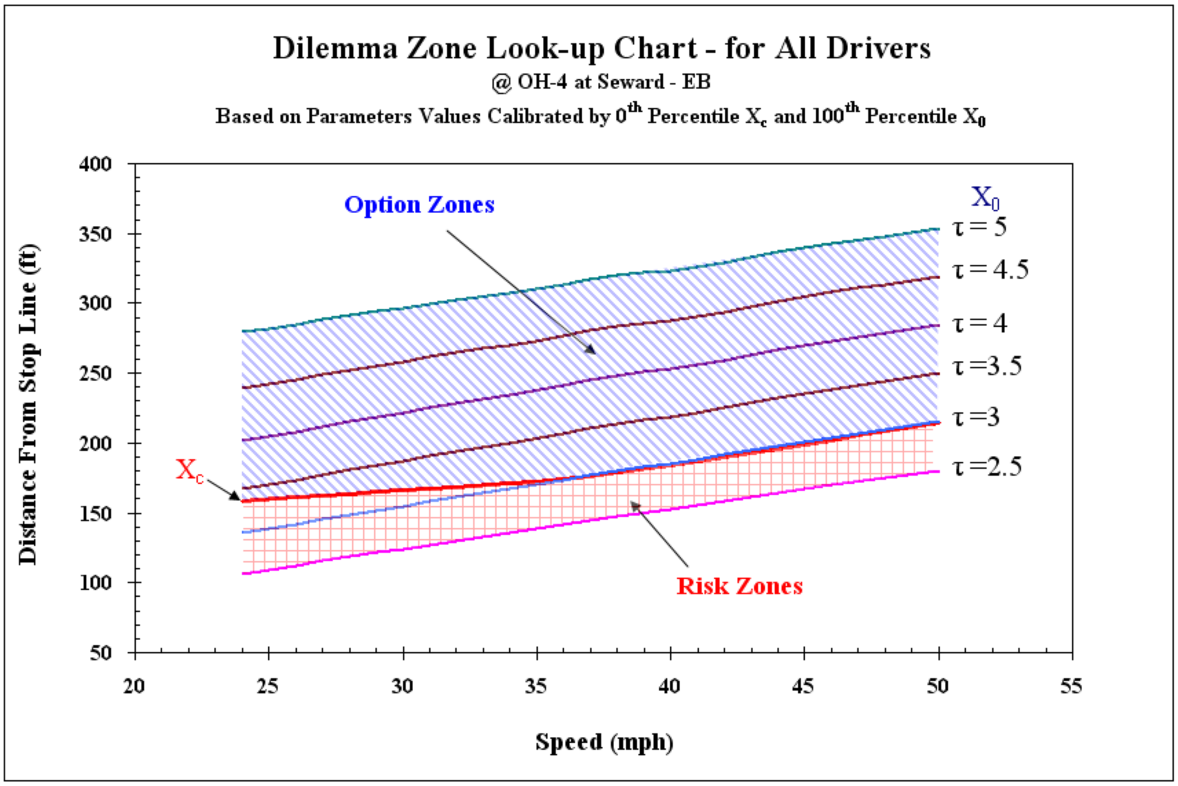


Figure 21: Dilemma Zone Look-up Chart for All Driving Behaviors

From **Figure 20** and **Figure 21**, it can be identified from both charts that the length of option zone becomes longer as yellow duration increases, while the length of risk zone becomes longer as yellow duration decreases. Both of the results are in accordance with other researchers' results (Saito et al, 1990) (Koll et al, 2004). It also can be identified that in the case of 4.5-second yellow duration, there is always option zone and no risk zone with speed ranging from 24 to 50 mph, whatever all the drivers or the majority of the drivers is considered. Therefore, it can be concluded that option zone dominates this case study site (OH-4 at Seward EB with 4.5-second yellow duration).

5.3 Distributions of Option Zones under Different Vehicle Arrival Types

Besides modeling the dilemma zone, some discovering researches are also conducted in this project, including identifying the relationship between option zone and vehicle arrival types, and option zone distribution for various vehicle categories. In this section, how arrival type influences the length of option zone is studied.

Vehicle Arrival Type (TRB, 2000) describes the quality of progression at a definite approach. Base on Highway Capacity Manual 2000 (TRB, 2000), vehicle arrival type of each cycle can be estimated from Platoon Ration, which is calculated as:

$$R_p = \frac{P}{(g/c)} \tag{7}$$

Where, R_p is platoon ratio;
P is proportion of vehicles arriving on green;
g is effective green time, s;
c is cycle length, s.

The relation between platoon ratio and arrival type is described in Table 6.

Table 3: Description of Vehicle Arrival Types (*TRB, 2000*)

Arrival Type	**Range of Platoon Ration, R_p**	**Progression Quality**
1	$\leq$ 0.50	Very Poor
2	> 0.5-0.85	Unfavorable
3	> 0.85-1.15	Random Arrivals
4	> 1.15-1.50	Favorable
5	> 1.50-2.00	Highly Favorable
6	$\geq$ 2.00	Exceptional

Figure 22 illustrates the arrival type distribution resulted from totally 267 observed signal cycles. It is apparent that *Arrival Type 4* dominates the arrivals and the progression is favorable to the operation as assessed by **Table 3**.

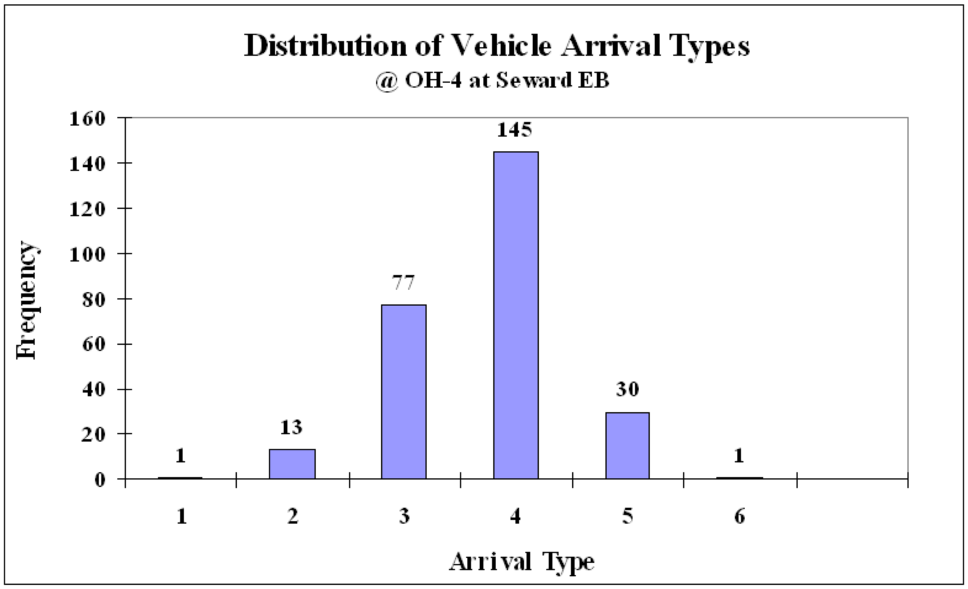


Figure 22: Distributions of Vehicle Arrival Types at Eastbound OH-4 at Seward

For the arrival types, we classify them into two categories, which are good progression and poor progression. Good progression refers to *Arrival Types* $\geq$ 4, while poor progression refers to *Arrival Types* $\leq$ 3. Comparisons are made between the option zone locations under the two arrival type categories. Results indicate that traffic in a good progression (*Arrival Type* ≥ 4) has a further option boundary and longer option zone length than traffic in a poor progression (*Arrival Type* ≤ 3). **Figures 23** and **24** illustrate the option zone locations and lengths under different arrival type categories for the speed classifications of 30-40 mph and 40-50 mph, respectively.

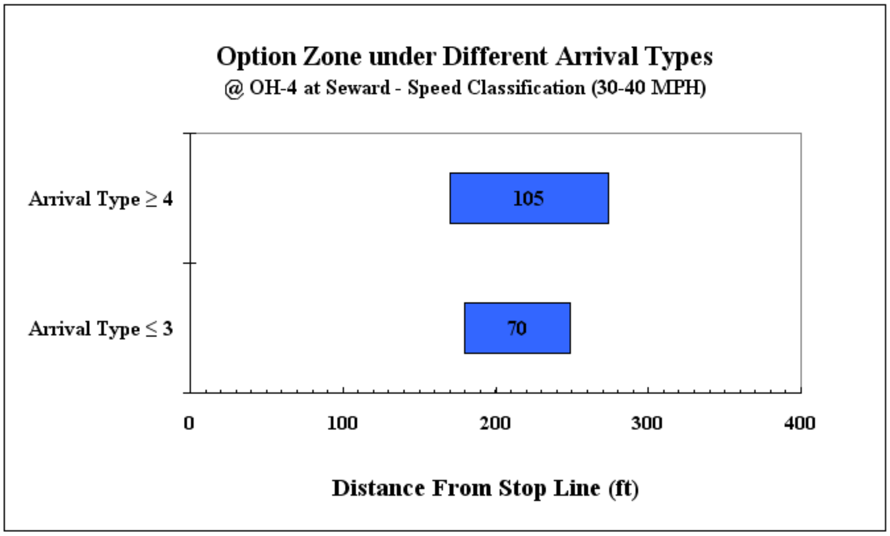


Figure 23: Option Zones under Different Arrival Types (Speed Classification 30-40 mph)

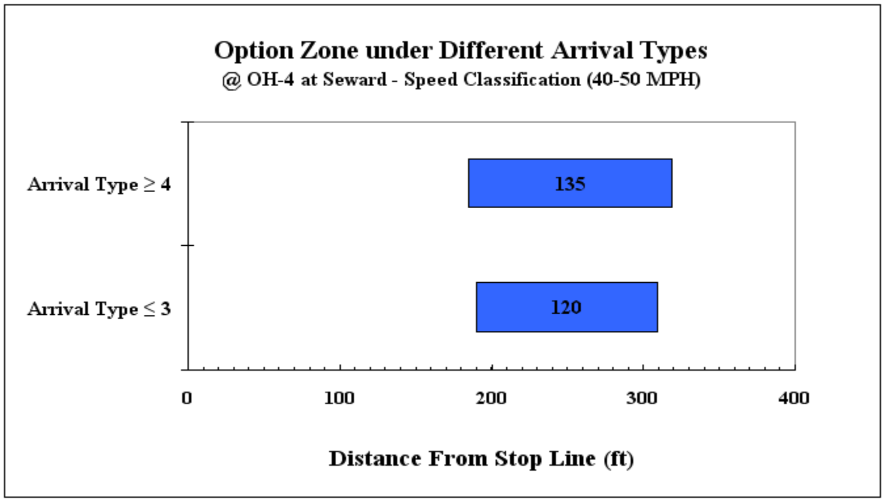


Figure 24: Option Zone under Different Arrival Types (Speed Classification 40-50 mph)

5.4 Distributions of Option Zones for Different Vehicle Categories

The distribution of the option zones are found out variable with different types of vehicles. In this analysis, the locations and lengths of the option zones are identified by the same method as described in **Section 5.3**. As illustrated by **Figure 25**, the result indicates that *Car* has the longest length of the option zone, while *Truck* has the shortest length. It shows that the length of option zone decreases as vehicle size increases, while the downstream boundary of option zone is further from the stop line as vehicle size increases. These findings reveal that the formation of the option zone is highly related to the maneuverability of vehicles. Vehicles with a more flexible maneuverability cause a longer option zone.

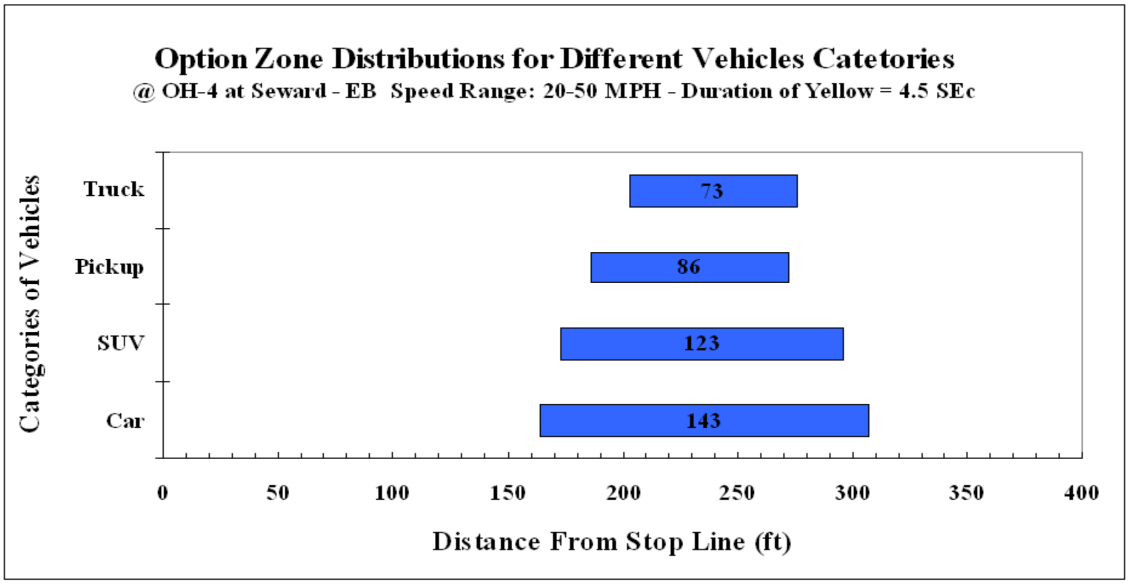


Figure 25: Option Zone Distributions by Vehicle Categories (Speed Range 20-50 mph)

CHAPTER 6:

CONCLUSIONS AND FUTURE RESEARCH

6.1 Conclusions

Since the concept of dilemma zone was proposed in 1960 (Gazis et al, 1960), it has been widely studied by researchers. However, terms conventionally defined to represent yellow phase dilemma lack integrity, and are somewhat confusing in concepts. This research conducts a comprehensive literature review attempting to clarify the relationship among the dilemma zone, option zone, and indecision (decision) zone. A hierarchy diagram (**Figure 3**) is developed to help better understand the distinctions among different concepts and clearly identify the contributing factors to be targeted in the study. Some relevant key findings are summarized as follows:

- *Dilemma Zone (DZ)* is a general concept representing a range (length) of roadway, vehicles within which at the onset of yellow indication may experience yellow dilemma problem.
- There are two types of dilemma zones. Type I dilemma zone is formed when $X_c > X_0$. Vehicles within the Type I dilemma zone at the onset of yellow indication can neither manage to pass the stop line before the end of yellow interval, nor safely stop before the stop line. Regardless passing or stopping decision is made by the driver, it is risky. So the Type I dilemma zone is termed as *Risk Zone (RZ)*. The Type II dilemma zone is formed when $X_0 > X_c$. Vehicles within the Type II dilemma zone at the onset of yellow indication can choose either to pass the stop line before the end of yellow interval, or to safely stop before the stop line. The driver has two options to choose. So the Type II dilemma zone is termed as *Option Zone (OZ)*.
- *Indecision Zone (IZ)* measures yellow dilemma indecisiveness from the probabilistic perspective. It overlaps with the option zone to some extent.

In this project, the dilemma zone is mathematically modeled, and its location and length are determined by the values of minimum (yellow-onset) safe stopping distance X_c and maximum (yellow-onset) safe passing distance X_0, which are represented by **Equations (3)** and **(4)**, respectively. X^{th}-percentile observed X_c and X_0 derived from the vehicle trajectory data are used to calibrate the dilemma zone contributing factors a_{stop}, a_{pass}, δ_{pass}, and δ_{stop}. Dilemma zone look-up chart is developed with the calibrated dilemma zone models and provides a convenient way to identify locations and lengths of dilemma zones for any speed and yellow duration inputs. Unlike traditional equations with constant values of parameters (a_{stop}, a_{pass}, δ_{pass}, and δ_{stop}), the method presented in this study uses a more realistic assumption that values of those parameters vary with vehicle approaching speeds. Those values are determined through the calibration process using real-world observed trajectory data. Results from the look-up dilemma zone chart prove that as yellow duration increases, the length of risk zone decreases while the length of the option zone increases.

Besides the modeling work, relationship between vehicle arrival types and option zone locations, as well as option zone distributions with various vehicle categories are also explored in this project. Key findings are summarized as follows.

- Traffic in a good progression (*Arrival Type* ≥ 4) has a further option zone boundary and longer option zone length than the traffic in a poor progression (*Arrival Type* ≤ 3).
- The length of option zone decreases as vehicle size increases, while the downstream boundary of option zone becomes further from the stop line as the vehicle size increases.

6.2 Discussion and Future Research

As a case study, this project proved the feasibilities of using trajectory-based X^{th} percentile X_c and X_0 profiles to calibrate dilemma zone contributing factors and develop dilemma zone look-up chart. It provides solid basis for future study of optimal signal detection placement and related dilemma zone protection problem with consideration of the protection for multiple speed ranges. However, there are still some aspects that need to be improved in future research.

First, future research will be expanded to more intersections to cover more categories of study site, such as

- High-Speed Mainline vs. Large-Volume Side Street;
- Mainline vs. Ramp/T Intersection; and
- High-Speed Mainline vs. Low-Speed Side Street.

Each category needs at least two study intersections to develop the specific dilemma zone look-up chart and table for it.

Second, more sample data are required at each study site. **Equation (8)** calculates the required sample size for conduct the statistical analysis.

$$\mathrm{N} = (t_{\alpha/2}\frac{\delta}{\mu\varepsilon})^2 \tag{8}$$

Where, μ and δ are the mean and standard deviation of the performance measures; ε is the allowable error specified as a fraction of the mean μ; and $t_{\alpha/2}$ is the critical value of the t-distribution at the confidence interval of $1-\alpha$.

Based on the means and standard deviations of X_0 and X_c for each speed classification we obtained through observation in this project, and by taking the allowable error as 0.05 while the confidence interval as 95%, 900 observations of X_0 and 380 observations of X_c are calculated through **Equation (8)** as required sample size for getting robust statistical results.

Third, complete trajectory over the entire yellow interval is to be extracted for each vehicle, so that more accurate values of the dilemma zone contributing factors a_{stop} , a_{pass} , δ_{pass} , and δ_{stop} will be derived from trajectory data. Statistical analysis will be performed on those values in order to obtain more accurate ranges of those parameters.

Fourth, the following assumptions are made in this project: (1) a vehicle with a higher speed needs more PRT to make a stop decision and higher deceleration to stop; (2) a vehicle with a lower speed needs more PRT to make a passing decision and higher passing acceleration to pass the stop line. These assumptions need to be further proved with the real observed and derived a_{stop} , a_{pass} , δ_{pass} , and δ_{stop} values.

Fifth, the optimal selection of the percentile values of X_0 and X_c for developing the dilemma zone look-up charts needs to be further investigated in future research.

Sixth, impact of vehicle arrival type on the location and length of the option zone needs to be further investigated and the results obtained in this project that high arrival types yields longer option zone needs to be validated by more observations at more study sites.

The most significant contribution of the dilemma zone look-up charts and tables developed by observed trajectory dada is that accurate dilemma zone locations and lengths under specific speed ranges could be easily obtained and provide solid basis for the optimized deployment of loops for multi-speed dilemma zone protection at high speed intersections.

In future research, multiple loops would be placed based on the boundaries of dilemma zones in order to provide multi-speed protection at high speed intersections. For each speed range (e.g. 30-40 mph), a point loop detector would be placed at the corresponding upstream boundary of dilemma zone for this speed range. For example, if three speed ranges are considered for dilemma zone protection, totally three dilemma zone detectors would be placed at this approach, as illustrated by **Figure 26**. Proper unit extension (UE) between two consecutive detectors is determined by the specific protected speed range. And the passage time (PT) of most downstream detector should be measured by the travel time from this detector to the nearest point of conflict.

This loops layout design would be evaluated and calibrated in a microscopic simulation environment (e.g. VISSIM) in order to achieve a balance between dilemma zone protection performance (evaluated by vehicle numbers in dilemma zone, max-out frequency and gap-out frequency) and operational efficiently (evaluated by overall delay). Results of this loops layout design will also be compared to other popular layout designs, such as Single-Detector configuration, Beirele configuration, SDITE configuration, and Bonneson configuration.

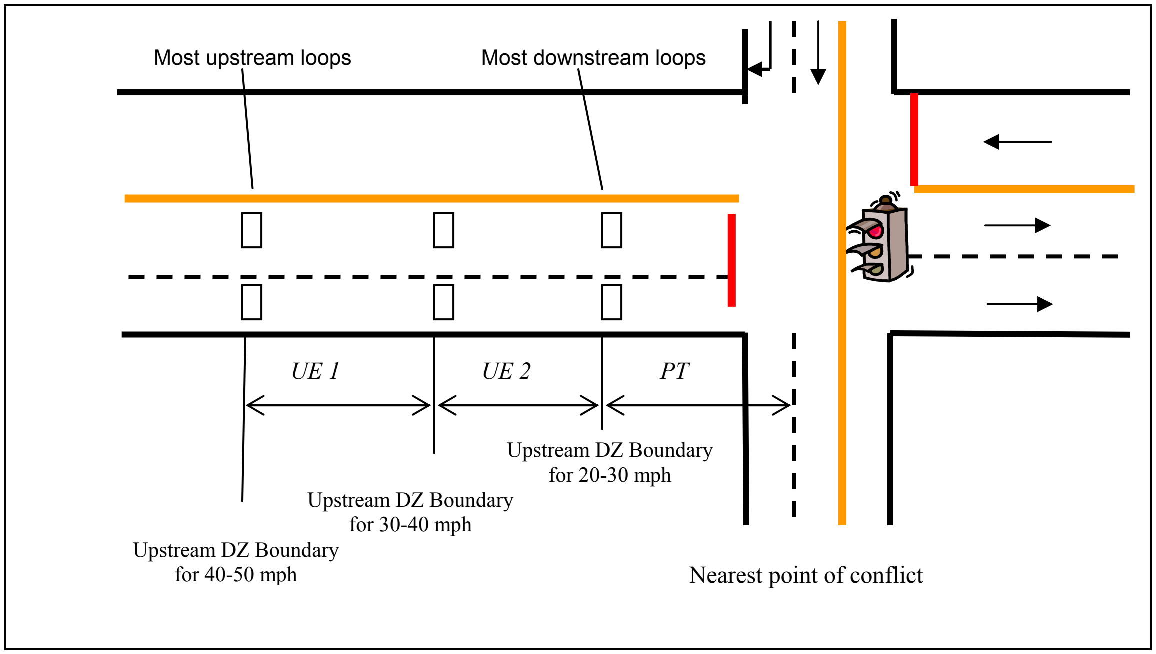


Figure 26: Illustration of Relations between Modeled DZ and Loops Placement

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