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Assessing the Risk of Crash for Trucks on Onset Yellow

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16. Abstract

Each day, millions of signal changes to the yellow phase occur at isolated high speed intersections, when erroneous driver decisions to stop or go may often lead to a crash. Dilemma zone protection systems are typically used to control these intersections in order to ensure the safe and efficient movement of vehicles. However, traditional dilemma zone protection systems show deterioration in performance during medium to heavy traffic volume conditions, jeopardizing both the safety and efficiency of intersections. The performance of these control systems for heavy vehicles is even more greatly affected, as traditional dilemma zone boundaries were developed for passenger vehicles. Research conducted by the authors found that to have the same level of protection as passenger vehicles, heavy vehicles needed to be protected for twice as long. The traditional surrogate measure of safety, the dilemma zone, marks the region of risk at high speed intersections, but does not quantify the level of risk, which is essential from an economic framework. In the current study, an improved surrogate measure of safety, the dilemma hazard function, was developed by expanding the existing measure of safety, utilizing the concept of traffic conflict. The probability of traffic conflict defined the dilemma hazard function, which was used to quantify safety benefits for high speed intersections. A behavioral model was used to develop the dilemma hazard function for passenger vehicles and heavy vehicles using data collected at a typical high speed intersection site in Noblesville, Indiana. The advent of advanced wide area detector technology made it feasible to assume that the dilemma hazard function could be developed for each site, hence, barring the need for a search for a universal dilemma hazard function.

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List of Abbreviations

American Society of Civil Engineers (ASCE)
Dilemma Zone Protection (DPZ)
Mid-America Transportation Center (MATC)
National Highway Traffic Safety Administration (NHTSA)
Red Light Running (RLR)
Root Mean Square Error (RMSE)
Time to Intersection (TTI)
Traffic Conflict Technique (TCT)
Wide Area Detector (WAD)

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Abstract

Each day, millions of signal changes to the yellow phase occur at isolated high speed intersections, when erroneous driver decisions to stop or go may often lead to a crash. Dilemma zone protection systems are typically used to control these intersections in order to ensure the safe and efficient movement of vehicles. However, traditional dilemma zone protection systems show deterioration in performance during medium to heavy traffic volume conditions, jeopardizing both the safety and efficiency of intersections. The performance of these control systems for heavy vehicles is even more greatly affected, as traditional dilemma zone boundaries were developed for passenger vehicles. Research conducted by the authors found that to have the same level of protection as passenger vehicles, heavy vehicles needed to be protected for twice as long. The traditional surrogate measure of safety, the dilemma zone, marks the region of risk at high speed intersections, but does not quantify the level of risk, which is essential from an economic framework. In the current study, an improved surrogate measure of safety, the dilemma hazard function, was developed by expanding the existing measure of safety, utilizing the concept of traffic conflict. The probability of traffic conflict defined the dilemma hazard function, which was used to quantify safety benefits for high speed intersections. A behavioral model was used to develop the dilemma hazard function for passenger vehicles and heavy vehicles using data collected at a typical high speed intersection site in Noblesville, Indiana. The advent of advanced wide area detector technology made it feasible to assume that the dilemma hazard function could be developed for each site, hence, barring the need for a search for a universal dilemma hazard function.

Chapter 1 Introduction and Research Objectives

The cost of motor vehicle collisions in 2006 in the United States totaled nearly $230.6 billion (NHTSA 2007). According to data from the National Highway Traffic Safety Administration (NHTSA) Fatality Analysis Reporting System, crashes caused by red light running (RLR) resulted in an estimated 805 fatalities in 2005 (NHTSA 2006). A survey conducted by the U.S. Department of Transportation and the American Trauma Society indicated that 56% of Americans admit to running red lights (FHWA 2002).

At rural intersections, drivers sometimes travel at high speeds with the expectation of proceeding through them without stopping. A driver approaching isolated intersections must decide whether to stop or go at the onset of the yellow phase. An erroneous decision to go can possibly lead to a right angle crash, and the wrong decision to stop could lead to a severe rear-end crash. The “dilemma zone” is the area where the risk of stop or go decision making error is high (Parsonson 1978).

There are approximately 300,000 signalized intersections in the United States (National Impact Assessment Link 2007), of which about 16% are classified as operating with dilemma zone protection (ITS Deployment Statistics 2004) to avoid drivers being present in the dilemma zone at the onset of yellow. A typical intersection has approximately 700-800 instances of main-street phase terminations for each approach per day. Therefore, 68 million instances occur per day where a potentially incorrect driver decision can be made at the onset of yellow. To mitigate the risk associated with dilemma zones, many intersections employ specialized traffic control systems called dilemma zone protection systems. The two systems currently in place are the green extension and green termination systems.

In green extension systems, the green phase of the high speed approach is extended until there is no vehicle in the dilemma zone. An upper threshold, maximum green time, is provided for this operation to avoid excessive delays to the cross street traffic. Engineering judgment is used to determine the value of the maximum green time. This is an “all-or-nothing” approach: high speed vehicles are provided complete protection against dilemma zone incursions before the maximum green is reached, but if the maximum green is reached, no protection is provided. Green extension systems have been widely implemented in the field for the past four decades. These systems operate efficiently during low volume conditions, but are inefficient and unsafe during medium to heavy volume conditions because of an increased number of max-outs. A detailed discussion of the operation of a green extension system is provided in chapter 2.

Green termination systems are relatively new, and they exist at only a few intersections as a proof of concept and for evaluation purposes. These systems attempt to identify an appropriate time to end the green phase by predicting the value of a performance function for the near future. This performance function is based on the number of vehicles present in the dilemma zone and the opposing queue. The objective is to minimize the number of vehicles in the dilemma zone. These systems have not been implemented on a large scale; therefore, limited quantitative data exists regarding the trade-off between efficiency, cost, and sensor requirements.

The dilemma zone protection systems currently in place at high speed intersections were designed around the passenger vehicle dilemma zone. Passenger vehicles braking systems are required by federal law to sustain a deceleration rate of a minimum of 14 ft/s^2, while braking systems for trucks are required to have a deceleration rate of 21 ft/s^2, meaning that trucks require 50% more stopping distance (Federal Motor Carrier Safety Regulations 2005) and take more time to stop. Moreover, trucks require more time to accelerate at the onset of green. These performance characteristics are a possible influence on driver stop/go decision making at the onset of the yellow phase.

The literature reveals flaws in approaches that are designed solely upon measuring the dilemma zone boundaries for trucks. Using real-time simulation to analyze an extended truck dilemma zone, Karl Zimmerman (2007) demonstrated that an addition of 1.5 s of upstream time to the dilemma zone of passenger vehicles (resulting in a dilemma zone 2.5-5.5 s from the stop line) was associated with a reduction of the number of heavy vehicles in the dilemma zone. Zimmerman also found a dilemma zone boundary of 3-8.2 s from the stop line for heavy vehicles—nearly twice the 3.5-6 s dilemma zone boundary for passenger vehicles.

Though dilemma zone boundaries are determined using a sound stochastic concept, the definition of dilemma zone boundaries is limited in that it is inherently deterministic. It implies a binary conceptualization in which drivers are deemed either at-risk or risk free—specifically, vehicles within a probability of stopping range of 10-90% are automatically considered to be unsafe, while any vehicle outside this area is deemed safe.

The dilemma zone is the traditional surrogate measure of intersection safety; yet, while the dilemma zone marks the region of risk, it does not quantify the level of risk. Sharma and colleagues recently developed and proposed a new and improved surrogate measure of safety, the dilemma hazard function (Sharma et al. 2007). This stochastic function estimates the probability of traffic conflict of varying levels of severity at a specific spatial location. The current research presents the results of an effort to develop a dilemma hazard function for heavy vehicles.

Following the current introductory chapter, chapter 2 reviews research pertaining to dilemma zone definitions as they have developed over time, as well as methods of dilemma hazard mitigation. Presented are historical and current methods utilized in attempts to model driver behavior at high speed intersections upon the onset of yellow. Also described are the current practices involved in assessing vehicle safety at approaching intersections. The limitations of these practices are discussed.

In chapter 3, the different data collection sites and data collection setups are detailed. This study used a combination of radar-based detection and video to monitor and track vehicles as they approached a high speed intersection. In addition, this chapter discusses the steps used in processing the video collected. The current theory underlying driver behavior at the approach of a high speed intersection is also discussed. Using the probit modeling technique, the decision process of drivers at the onset of yellow was modeled. As previously mentioned, traditional surrogate measures of safety such as the dilemma zone denote the region of risk but do not quantify the level of risk. A marginal cost-benefit approach for implementing the dilemma hazard function to improve the safety and efficiency of intersection operation is also presented in this chapter.

Chapter 4 summarizes the research findings and proposes future research steps.

Chapter 2 Literature Review

2.1 Introduction

This chapter reviews previous research on the development and progress of dilemma zone definitions and mitigation methods. Previous and current methods utilized to model driver behavior at high-speed intersections upon the onset of yellow are described, as are current practices used in the assessment of vehicle safety upon approaching an intersection.

2.2 Defining Dilemma Zone Boundaries

Historically, the dilemma zone has been defined as the area where the driver can neither stop comfortably nor clear the intersection safely at the onset of yellow. This approach (Gazis et al. 1960; May 1968) uses deterministic design values, such as perception reaction time, comfortable deceleration or acceleration rates, length of the yellow interval, etc., to determine the location of the dilemma zone. The stopping and clearing distances for a vehicle can be calculated using equations 2.1 and 2.2, respectively.

Any vehicle satisfying the criteria for stopping distance can come to a stop using a comfortable deceleration as represented by the following equations.

$$Xs \geq \frac{V_0^2}{2d} + V_0 t_2 \qquad (2.1)$$

Any vehicle satisfying the criterion for clearing distance can cross the stop line using comfortable acceleration,

$$Xc \le V_0 T + \frac{a}{2}(T - t_1)^2 - L \qquad (2.2)$$

where,

Xs , Xc is the distance from stop line to when the amber phase commences, in ft;

V_0 is the approach speed in ft/s;

T is the amber phase duration in seconds;

L is the length of the vehicle in ft;

a is the acceleration rate in ft/s^2;

d is the deceleration rate in ft/s^2;

t_1,t_2 are the reaction times to accelerate and decelerate respectively, in seconds.

There are three possible scenarios based on the values of the stopping distance and clearing distance.

- Xs > Xc: There exists a dilemma zone (Xs > X > Xc) where a driver can neither stop comfortably nor clear safely.
- Xs = Xc: There exists no dilemma zone.
- Xs < Xc: There exists an option zone (Xs < X < Xc) where a driver can both stop comfortably or proceed safely.

One drawback of this approach is that it assumes a perfect knowledge of all variables. Drivers, lack perfect knowledge, and only perceive variables, such as the distance from the stop bar, yellow duration, etc. Another drawback is that there is no conversion metric that can convert the presence of a vehicle in its dilemma zone to the magnitude of the risk of a crash. As a result, this surrogate measure cannot effectively be used to compare the trade-off between safety and efficiency of operations at intersections.

2.3 Surrogate Measure of Safety using Stop and Go Probabilities

Researchers characterized the surrogate measure of safety as the “decision dilemma zone,” taking into account the variability in human perception. The decision dilemma zone is defined as the approach area within which the probability of deciding to stop at the onset of yellow is within the range of 10-90%. This zone is considered to have a higher risk for rear-end collisions and red light violations, since drivers are not sure whether to proceed through the intersection or to attempt to stop. Zeeger (1977) observed a 54% reduction in total crashes and a 75% reduction in rear-end crashes after implementing traffic control logic that prevented the presence of any vehicle in the decision dilemma zone at the onset of the yellow phase.

There have been several attempts to characterize the dilemma zone boundaries (Olson and Rothery 1962; Webster and Ellson 1965; ITE Technical Committee 1974; Zeeger 1977; Sheffi and Mahmassani 1981; Chang et al. 1985; Bonneson et al. 1994). Initially, a frequency-based approach was used to obtain the probability of stopping. The percentage of drivers stopping at a given distance and speed was used to develop the cumulative distribution function. Typically, distance and speed or time was used as a measure for decision dilemma zone boundaries. Zeeger (1977) found that approximately 90% of traffic would stop if the passage time to the stop line was 4.5-5 s or greater, while only 10% of traffic stopped when the passage time to the stop line was less than 2-2.5 s. Bonneson et al. (1994) found that the beginning of the dilemma zone was 5.0-6.0 s upstream, while the end was approximately 3.0 s upstream. Researchers have observed significant variation in the dilemma zone boundaries obtained from frequency-based methods. Table 2.1 (below) presents the observed ranges of dilemma zone boundaries as reported by different researchers.

Binary discrete choice models were proposed to determine the probability of stopping at a given distance and speed to provide a better understanding of the underlying human decision models, and to explain the variation in the observed dilemma zone boundaries (Sheffi and Mahmassani 1981; Chang et. al. 1985; Gates et al. 2007).

Table 2.1 Dilemma zone boundaries

Speed (mph)	Distance of stop line, ft						
	Olson and Rothery (1962)	Herman et al. (1963)	Webster and Ellson (1965)	ITE (1974)	Zeeger (1977)	Chang et al. (1985)	Bonneson et al. (1994)
35	212*	218*	170*	212*	254	288	245
40	255	260	205	250	283	307	293
45	315*	315*	252*	300	325	326	343
50	375	370	300	350	350	345	396
55	-	-	370*	400*	384	364	452

a) Beginning of dilemma zone (probability of stopping = 0.9)

Table 2.2 (cont'd.) Dilemma zone boundaries

Speed (mph)	Distance of stop line, ft						
	Olson and Rothery (1962)	Herman et al. (1963)	Webster and Ellson (1965)	ITE (1974)	Zeeger (1977)	Chang et al. (1985)	Bonneson et al. (1994)
35	103*	100*	103*	105*	103	128	145
40	110	110	125	110	121	147	178
45	165*	165*	155*	165	152	166	213
50	220	220	185	220	170	185	252
55	-	-	230*	240*	232	204	294

* Interpolated values

b) End of dilemma zone (probability of stopping = 0.1)

Sheffi and Mahmassani (1981) used a probit construct to model driver decisions to stop or go at the onset of yellow, hypothesizing that the travel time to the stop bar, *T*, as perceived by a driver randomly selected from the population, was a random variable given by,

$$T = t + \xi \tag{2.3}$$

where,

t is the measured time to reach the stop bar at a constant current speed. The error term ξ is a random variable assumed to be normally distributed, $\xi \sim N(0, \sigma_{\xi}^{2})$.

If T is less than a critical value, T_{cr}, then the driver would choose to go. Critical time, T_{cr}, was also modeled as a random variable to account for drivers' levels of experience and aggressiveness.

$$T_{cr} = t_{cr} + \varepsilon \tag{2.4}$$

where,

$\varepsilon \sim N(0, \sigma_{\varepsilon}^{2})$ across the driver population and t_{cr} is the mean critical time.

The probability of stopping is then given by the probit equation:

$$P_{STOP} = \Pr\{T_{cr} < T\} = \Phi\left(\frac{t - t_{cr}}{\sigma}\right) \tag{2.5}$$

where,

$\sigma = \sqrt{\sigma_{\xi}^{2} + \sigma_{\varepsilon}^{2} - 2\sigma_{\xi,\varepsilon}}$, and $\Phi(\bullet)$ is the standard cumulative normal function, while $\sigma_{\xi,\varepsilon}$ denotes the covariance of the error terms (ξ, ε).

Note that, although inferences are made based on frequency-based estimates, the error terms ξ, ε not only encompass those errors that occur due to non-homogenous drivers, but also account for the perception errors occurring at the level of the individual driver.

There are drawbacks to the approach presented above. First, although the approach determined dilemma zone boundaries using a sound stochastic concept, the definition that the dilemma zone is based upon is still deterministic on the basis of its binary interpretation: a driver in the area where the probability of stopping ranges from 10-90% is considered to be unsafe while anyone outside this area is considered to be safe. This does not account for the variation in level of risk based upon location. This suggests the need for a traffic hazard function, which would quantify the risk of a crash at a certain location.

2.4 Surrogate Measure Using Fuzzy Based Approach

A possibilistic approach to quantifying anxiety has been proposed as a surrogate measure of safety at signalized intersections (Zadeh et al. 1974; Wang 1983; Klir and Folger 1988; Zimmermann 1990). Possibility theory is a relatively new concept for representing uncertainty. Yager (1982) defined tranquility as the emotional or psychological ease with which the best alternative could be selected from a set of competing ones. Anxiety can then be defined as the lack of tranquility. If all competing alternatives are nearly equal in terms of their feasibility of being selected as the best, then the selection of one alternative for implementation would lead to high anxiety.

Consider a situation in which it is necessary to select from d_i alternatives the one which best satisfies a set of criteria, defined by fuzzy set D. The fuzzy set D can be represented as:

$$\left\{\frac{\gamma_1}{d_1}, \frac{\gamma_2}{d_2}, \frac{\gamma_3}{d_3} \ldots\ldots\right\} \tag{2.6}$$

where,

γ_i is the degree of membership in set D for decision alternative d_i.

The anxiety associated with the decision is defined as:

$$Ant(D) = 1 - \int_0^{\alpha_{\max}} \frac{1}{CardD_\alpha} d\alpha \tag{2.7}$$

where,

$Ant(D)$ is the degree of anxiety associated with the decision function D;

$\alpha_{\max}$ is the largest degree of membership in D; and

$CardD_\alpha$ is the cardinality of the α -level set of D. This is the number of alternatives whose membership grade is greater than or equal to α .

Some typical properties of quantitative measures of anxiety are highlighted hereafter through example. Anxiety is low if a single best alternative is available. If one alternative satisfies the necessary criteria perfectly and all other alternatives are not fit for selection, then $CardD_\alpha$ = 1 for all α , and anxiety for the selection would be zero. Higher anxiety would arise from deciding between several alternatives having equal support (or, when none of the alternatives have high support). For a binary choice, the above expression is reduced to equation 2.7 (Yager and Kikuchi 2004):

$$Ant(D) = 1 - Max(a_1, a_2) + \frac{1}{2} Min(a_1, a_2) \quad (2.8)$$

where,

a_1 and a_2 correspond to the membership grade for choices 1 and 2, respectively.

Yager and Kikuchi (2004) also proposed a principle of maximum anxiety. A decision-maker chooses the time to act as the time of highest anxiety.

Kikuchi et al. (1993) used the measure of anxiety defined above to quantify the level of ease with which drivers made the decision to stop or go when faced with a yellow phase. The authors commented that, regardless of the timing of the yellow phase, driver will experience anxiety during the signal change interval. It was suggested that the only method of alleviating anxiety would be to implement intelligent transportation systems to provide drivers with external commands to stop or go. The lack of near-term feasibility is a key drawback of this approach. Another drawback is that when the driver receives an external command that is contradictory to his or her perception, anxiety levels may increase further.

Apart from implementation issues, there are other shortcomings of the use of anxiety as a surrogate measure of safety. In the United States, safety is measured in terms of the number of crashes occurring at a facility. The conversion function which converts the measure of anxiety to the risk of crash is not available, and will need to be developed prior to using this theory as a surrogate measure of safety. Another unaddressed issue is the dynamic nature of human decision-making, which implies that, even if a person makes a decision at a given instance in time, he or she may change the decision in the near future based on feedback from the system. For example, a common traffic conflict observed at the onset of the yellow phase occurs when a driver initially presses the brake, then decides to proceed; or conversely, when a driver decides to proceed, then suddenly brakes. These types of conflicts are not addressed within the proposed measure of anxiety.

2.5 Yellow Phase Duration and Driver Behavior

Researchers have also studied change in driver behavior as a function of the length of the yellow interval. For example, increases in the duration of yellow were found to correspond to decreased incidents of right-angle crashes in a study of intersections equipped and not equipped with a flashing green signal (Knoflacher 1973). In a study by Van der Horst and Wilmink (1986), lengthy yellow intervals led to premature stopping (stopping before the onset of red when the light was still yellow) among last-to-stop drivers at intersections. This indecision influenced drivers to proceed through the intersection at their next approach. The probability of stopping 4 s from the intersection decreased from 0.5 for a yellow length of 3 s to 0.34 for a yellow length of 5 s (Van der Horst and Wilmink 1986). Bonnenson et al. (2002), in a study of multiple intersections in Texas, also found that driver behavior was responsive to increases in the duration of yellow; in their (2002) study, RLR decreased up to half upon increases in yellow duration ranging between 0.5-1.5 s among instances when yellow duration did not exceed 5.5 s. As determined by Koll et al. (2004), early stops should have a negative effect on the frequency of right-angle collisions.

On the other hand, other research (e.g., Olson and Rothery 1962) has concluded that varying yellow phase durations did not change driver behavior. Further, studies have demonstrated that end-of-phase signal duration that is too long is associated with greater variability in driver decision making and a potential increase in the risk of rear-end collisions (Olson and Rothery 1962; May 1968; Mahalel and Prashker 1987). For example, Mahalel and Prashker (1987) witnessed an expansion of the indecision among zone among intersections equipped with a 3 s yellow that was preceded by a 3 s flashing green signal. The indecision zone increased from 2-5 s to 2-8 s with the addition of a flashing green interval. Evidence linked the lengthened indecision zone to an increase in the frequency of rear-end crashes.

2.6 Dilemma Zone Mitigation

2.6.1 The Green Extension Method

Green extension systems are deployed at rural high-speed signalized intersections to reduce the number of red light violations and rear-end crashes. These systems use simultaneous gap-out logic in the signal controller to decide the allotment of green to each phase. The basic logic is:

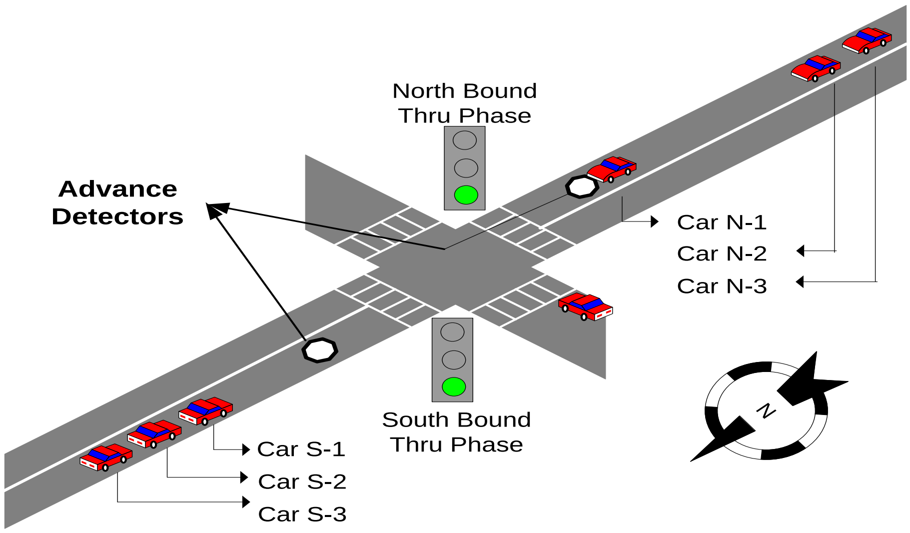
1. All phases are allotted green until they discharge at saturation.
2. The main street green is extended beyond saturation until there is no vehicle in the dilemma zone or the max-out time is reached.

The first objective of this signal control logic is to minimize the occurrence of high-speed vehicles in the dilemma zone; this objective governs the length of the green phase at the main approach. The second objective of the logic is to keep the wait time for any vehicle at the intersection within acceptable limits; this objective governs the max-out time for the main street green. All side-street phases are allotted green as long as they are discharging at saturation flow, thereby reducing the total delay at the intersection.

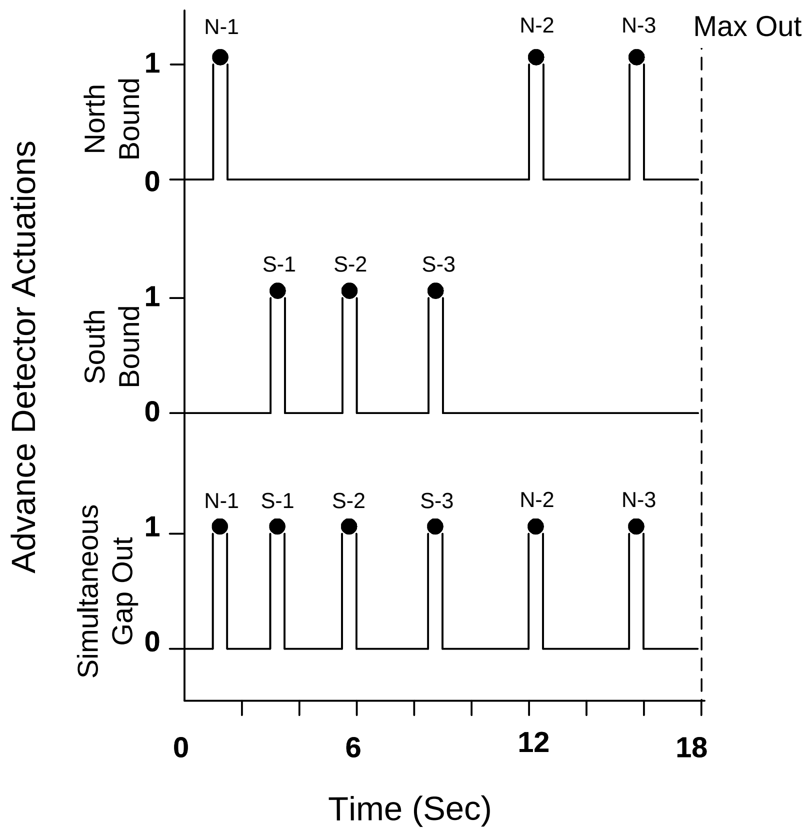
Engineering judgment are used to determine the value of the maximum green time. However, as previously noted, this is an “all-or-nothing” approach in which high-speed vehicles are provided complete protection against dilemma zone incursions before the maximum green is reached, but the protection is withdrawn after maximum green is reached. Consequently, there exists no intermediate level of protection; the signal logic either provides 100% protection against the dilemma zone in the case of gap-out, or drops to 0% in the case of max-out.

The operation of simultaneous gap-out logic for the green extension is illustrated in figure 2.1. A hypothetical traffic signal is shown in figure 2.1a. This intersection has high-speed through movement running north-south. The advance detectors present on the high-speed arterial mark the beginning of the dilemma zone. The advance detectors on both the northbound and southbound arterial are connected in a series. The northbound and southbound through phases are simultaneously extended for a pre-specified green extension time upon the detection of a vehicle. The green extension time is sufficient to carry the detected vehicle through the dilemma zone. So, the green through phase for the northbound and southbound movements is terminated when there is no vehicle present in the dilemma zone on either of the two approaches. Such a termination of the phase is called "gap-out." The through phase can also be terminated if the traffic controller is unable to find a gap before the maximum green time has expired. Such a termination of the green phase is called "max-out." Figure 2.1b shows the actuation time diagram for the hypothetical traffic flow shown in 2.1a. A green extension time of 3 s and a maximum green time of 18 s are assumed in this example.

In figure 2.1a, the signal is resting in green for the northbound and southbound through movements at time 0. Upon arrival of the first vehicle on the cross-street, the maximum green timer starts. The green phase for the through movement is extended for 3 s at t = 1 s by car N-1, and is again extended by the arrival of car S-1. This process is continued until the last car, N-3, arrives at t = 16 s. The phase would have terminated as a "gap-out" at t = 19 s, but the maximum green time is set to be 18 s; hence the phase "max-out" occurs at t = 18 s, leaving a vehicle in its dilemma zone.



a) Example intersection



b) Example detector inputs

Figure 2.1 Illustration of simultaneous gap-out logic

This simple example illustrates a major drawback in the simultaneous gap-out logic. If only the northbound traffic were present, the through phase would have gap-out at t = 4 s; and if only the southbound traffic were present, the phase would have gap-out at t = 12 s. The increase in the number of lanes decreases the probability of gap-out. This problem becomes worse when the high-speed arterial carries medium to heavy traffic volumes. The safety benefits are negated when the high-speed through phase is arbitrarily terminated by max-out. A detailed analysis of this problem is described later in this chapter. It is shown that the implementation of the simultaneous gap-out logic led to max-outs ranging from 3.5-40% of the cycles per hour during the peak traffic flow periods and around 200 dilemma zone incursions per day at the study intersection in Noblesville, Indiana.

In an actuated control, phases 2 and 6 (main street through phases) are most often linked for gap-out purposes, which impose an additional constraint on the control system. The constraint requires that when crossing the barrier, phases 2 and 6 must gap-out together in order to terminate the green interval. In the absence of a simultaneous gap-out logic, if phase 2 gaps out prior to phase 6, both phases proceed to clearance as soon as a gap is found in phase 6, regardless of any new call placed on phase 2. With simultaneous gap-out enabled, the new call will extend phase 2, even though it would have otherwise already gapped out. In this example, phase 2 and phase 6 need to gap-out simultaneously to end the phases. Therefore, the simultaneous gap-out logic inherently increases the likelihood of max-out scenarios.

The above example illustrates that simultaneous gap-out logic can be problematic under conditions of medium to high traffic volumes; in such scenarios, it will reduce the efficiency of the intersection without improving any dilemma zone protection when the phases max-out. The maxing-out of phases leads to increases in the cycle lengths, which results in increased delay on the intersection and subsequent increases in travel times and vehicle operating costs.

Though some advanced green extension systems do exist, such as Texas Transportation Institute truck priority system (Middleton et al. 1997) and LHORVA (Kronborg 1992), to date, none explicitly consider the marginal trade-offs between safety and delay.

2.6.2 The Green Termination Algorithm Method

The green termination algorithm is currently in the early phases of implementation and can be found at only a few intersections. Green termination algorithm systems attempt to identify the correct time to end the green signal phase by predicting the correct value of a performance function for the near future, with the objective of minimizing the performance function. The performance function is based upon the quantity of vehicles present in the dilemma zone and the length of the opposing queue. At this time, only limited empirical data exists regarding the performance of green termination algorithms in terms of efficiency, cost, and detector requirements.

2.6.3 The D-CS System

Detection-Control System, or D-CS, is a state-of-the-art system developed by the Texas Transportation Institute (Bonneson et. al. 2002). DC-S has been implemented at eight intersections in Texas, as well as three intersections in Ontario, Canada (Zimmerman, 2007). The system uses a green termination algorithm, and consists of two components: vehicle status and phase status. It collects data from a speed trap located sufficiently far from the intersection (approximately 800-1,000 ft), as well as data on vehicle length. Based on this data, the system projects the arrival and departure time of a vehicle in the dilemma zone, using this data to maintain a “dilemma zone matrix” that is updated every 0.05 s. The phase status component, which is also updated every 0.5 s, utilizes the dilemma-zone matrix, maximum green time, and number of calls registered on opposing phases to control termination of the main street green phase.

The phase end decision can be summarized as follows:

1. Stage 1: D-CS operates similarly to simultaneous gap-out logic. The main street green phase is terminated only if there are no vehicles in their dilemma zone in any of the main-street lanes. This stage lasts for 70% of the maximum green time.
2. Stage 2: D-CS terminates the main street green phase if all of the following conditions are true:
   a. All of the main street lanes have one or fewer passenger cars in their dilemma zone.
   b. There are no trucks in the dilemma zone in any of the main street lanes.
   c. There is not a time in next few seconds when there will be a lesser number of projected vehicles in the dilemma zone.
3. Stage 3: D-CS terminates the main street green once the maximum green time has elapsed.

Bonneson and Zimmerman (2005), found that DC-S intersections displayed a reduced frequency of red light violations at nearly every approach, with a 58% overall reduction in the frequency of red light running violations. The reduction for heavy vehicles, specifically, was approximately 80%. When DC-S replaced systems that used multiple advance loop detection or no advance detection, the system reduced violations by 53% and 90%, respectively.

2.6.4 The Self-Optimizing Signal Control (SOS) Method

Developed in Sweden, the SOS system is a green termination algorithm system designed for use at isolated intersections. Similarly to D-CS, the SOS system utilizes detectors in each lane to project vehicles that are approaching the intersection. The Miller algorithm performs calculations for different lengths of t (e.g., 0.5 s-20 s) and determines the cost of terminating the green phase immediately versus in t seconds (Kronborg 1997). SOS evaluates three different factors: the reduction of stops and delays for vehicles via the green extension, increased stops and delays for the opposing traffic, and increased stops and delays for vehicles void of the green extension that must wait for the next green phase. In evaluating SOS, Kronborg et al. (1997) found that the percentage of vehicles in the dilemma zone decreased by 38%, while the number of vehicles at-risk of rear-end collisions decreased by 58%.

2.6.5 Wavetronix SmartSensor Advance

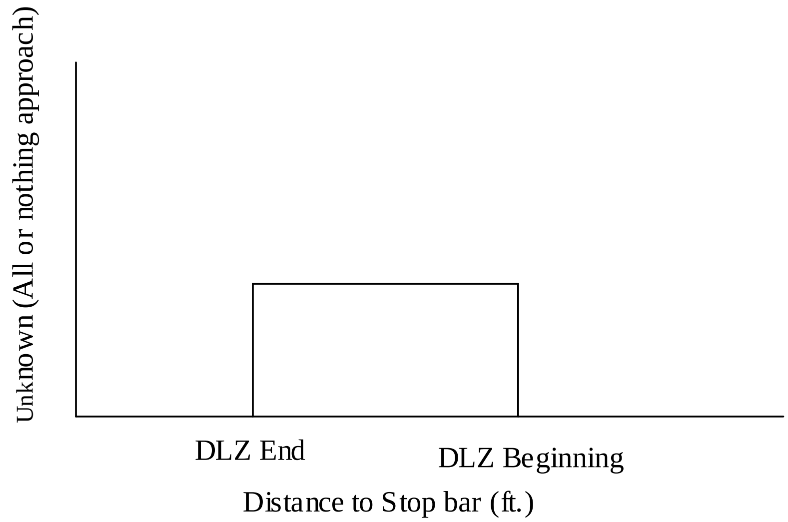
The Wavetronix SmartSensor Advance with SafeArrival technology is one of the most modern vehicle detection-based dilemma zone protection systems (Wavetronix 2011). The system uses digital wave radar to track vehicle ranges and speeds, in order to provide an accurate estimate of the arrival time to the stop bar. The system also determines the position and size of gaps in the flowing traffic to extend the green time to allow for safe passage if necessary. In a comparison study conducted by Knodler and Hurwitz (2009), SmartSensor reduced the number of vehicles in the Type II dilemma zone in more effectively than inductive loops, decreasing red light running more than threefold in comparison to that system. The system also shows promise in the early detection of heavy vehicles, making it potentially useful toward the development of variable dilemma zones that are based on vehicle type.

2.7 Quantifying the Risk of Traffic Conflict

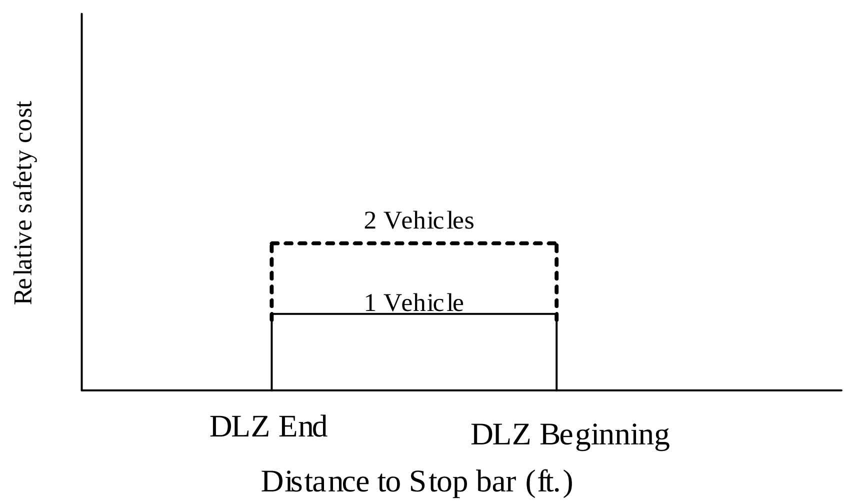
While traditional surrogate measures of safety (e.g., the dilemma zone vehicle count) are unable to quantify crash risk, traffic conflicts have demonstrated utility as a tool for indirectly measuring the safety of a given intersection. Figures 2.6a-c illustrate the contrast between the currently utilized surrogate measure of intersection safety and the proposed measure presented in this evaluation.

Current green extension systems represent an all-or-nothing approach in which all vehicles at a high speed approach are cleared until maximum green time is reached, and vehicles are not provided protection at the end of maximum green time. As shown in figure 2.6a, green extension systems do not incorporate a metric for measuring the cost associated with crash risk. Green termination systems use rank-ordered assessment of the number of vehicles in the dilemma zone as a surrogate measure to quantify the cost of risk, where the cost of one vehicle in the dilemma zone is lower than the cost of two, but this measurement is independent of the positions of vehicles in the dilemma zone. There is also only limited research on the relationship between dilemma zones and associated safety-related monetary costs of dilemma zone incursion.

The dilemma zone model devised by Sharma et al. (2011) utilized the observed probability of stop and go at the onset of the yellow light. In this model, the probability of traffic conflict was based upon the probability of driver decision making error. The dilemma hazard function for vehicles traveling at 45 mph at the data collection site in Noblesville, Indiana is shown in figure 2.6c. The analysis conducted by Sharma et al. (2011) developed probability of conflict curves for single passenger vehicles. The current research aims to develop the dilemma hazard function for heavy vehicles. The dilemma hazard function can be enhanced even further with the addition of severe conflict boundaries using acceleration and deceleration thresholds.

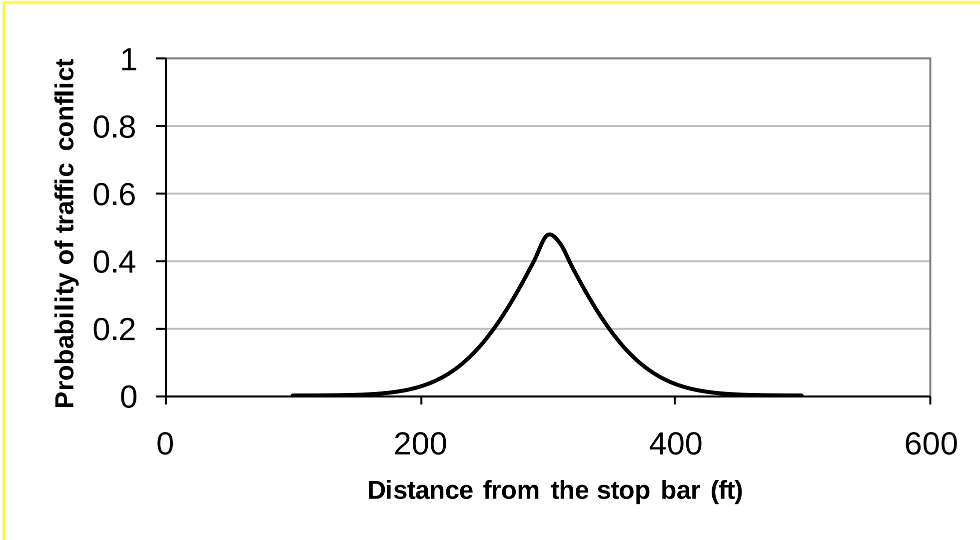


a) Evaluating the cost of safety in current green extension systems



b) Evaluating the cost of safety in advanced green termination systems

Figure 2.2 Comparison of traditional and proposed surrogate methods of safety



c) Proposal for the evaluation of safety cost

Figure 2.2 (cont'd.) Comparison of traditional and proposed surrogate methods of safety

2.7.1 The Traffic Conflict Technique as a Surrogate Measure of Safety

The traffic conflict technique (TCT) was first proposed by Perkins and Harris (1968), who defined a conflict as "the occurrence of evasive actions, such as braking or weaving, which are forced on the driver by an impending crash situation or a traffic violation." The conflicts were categorized as left-turn conflicts, weave conflicts, rear-end conflicts, and cross-traffic conflicts.

This technique gained wide popularity as a surrogate for measuring traffic safety for two main reasons: first, traffic conflicts are more frequently observed than are crashes, implying that a large amount of information regarding intersection safety can be collected quickly using conflict data. Cooper and Ferguson (1976) reported that, on average, the ratio of the rate of crashes to the rate of serious conflicts lies in the range of 1:2000; in other words, 10 hours of conflict observation at a particular site can provide information that is equivalent to two to three years of reported crash records. Second, TCT provides an opportunity for traffic engineers to proactively improve the safety of a site, instead of waiting for the crash history to evolve. Due to these advantages, the traffic conflict technique has been used by several agencies to investigate the crash potential and operational deficiencies of intersections. Numerous research efforts have attempted to establish a direct relationship between crashes and conflicts (Baker 1972; Spicer 1972; Cooper 1973; Paddock 1974). A review by Glauz and Migletz (1980) identified 33 previous studies that at least partially dealt with the conflict-crash relationship.

Some concerns have been raised regarding TCT techniques (e.g., Glennon et al. 1977), due to the fact that the initial approach to this technique was, generally, to compare observed crashes with the observed surrogate measure; since both conflict and crashes are randomly distributed events, it is highly improbable that the exact number of crashes at a site could be predicted. Glauz et al. (1985) proposed a new approach that compared the expected crash rate as predicted by conflict ratios to the expected crash rate as predicted by crash histories, concluding that estimates of the expected crash rates could be computed from traffic conflict history with nearly the same accuracy as predicted by crash history. Fazio et al. (1993) also advocated the use of traffic conflicts as a surrogate measure for traffic safety. Further, Gettman and Head (2003) provided a detailed use-case analysis for using traffic conflicts as a surrogate measure for safety in a micro-simulation package.

2.7.2 Defining Traffic Conflicts at the Onset of Yellow

Zeeger (1977) identified six conflicts that can occur at the onset of yellow.

- Red light runner (RLR): Defined as occurring when the front of the vehicle was behind the stop line at the onset of the red signal.
- Abrupt stop: Occurs when a vehicle stops instead of clearing the intersection, when it would be more appropriate to clear the intersection. These conflicts can

be calculated mathematically based on onset yellow distance and speed; they can also be observed visually.

- Swerve-to-avoid collision: An erratic swerve-out-of-lane maneuver conducted to avoid collision with a vehicle in front stopped at the light.
- Vehicle skidded: A more severe abrupt stop that is audible to the observer. The vehicle wheels lock-up in order to stop.
- Acceleration through yellow: The vehicle successfully crosses the stop bar, but only by accelerating; based on calculated distance and speed, the vehicle's constant speed trajectory would not have been adequate for successful crossing. Acceleration through yellow can be heard audibly or identified through numerical calculation.
- Brakes applied before passing through: The driver applies the brakes before traversing the intersection. Indicates driver indecisiveness. This conflict can be observed visually.

2.8 Modeling the Dilemma Zone Hazard Model for Passenger and Heavy Vehicles

Researchers have recently developed dilemma hazard models to quantify the level of risk associated with vehicle presence in the dilemma zone. The recently developed dilemma hazard model is a potential traffic conflict measure that calculates the dilemma zone hazard based on driver decisions and actual vehicle capability as a function of time-to-intersection (TTI) at onset yellow. The dilemma zone hazard model was calibrated and validated by Li (2009) utilizing a methodology developed by the American Society of Civil engineers (ASCE). Li used the Monte Carlo method to simulate collected data (driver stop/go decisions, vehicle kinematics, acceleration/deceleration rates) in order to establish dilemma zone hazard values within the boundaries of 2-5 s. Models were created for single- and two-vehicle scenarios. Results are shown below in figure 2.8, and illustrate the effect of signal timing on the dilemma hazard.

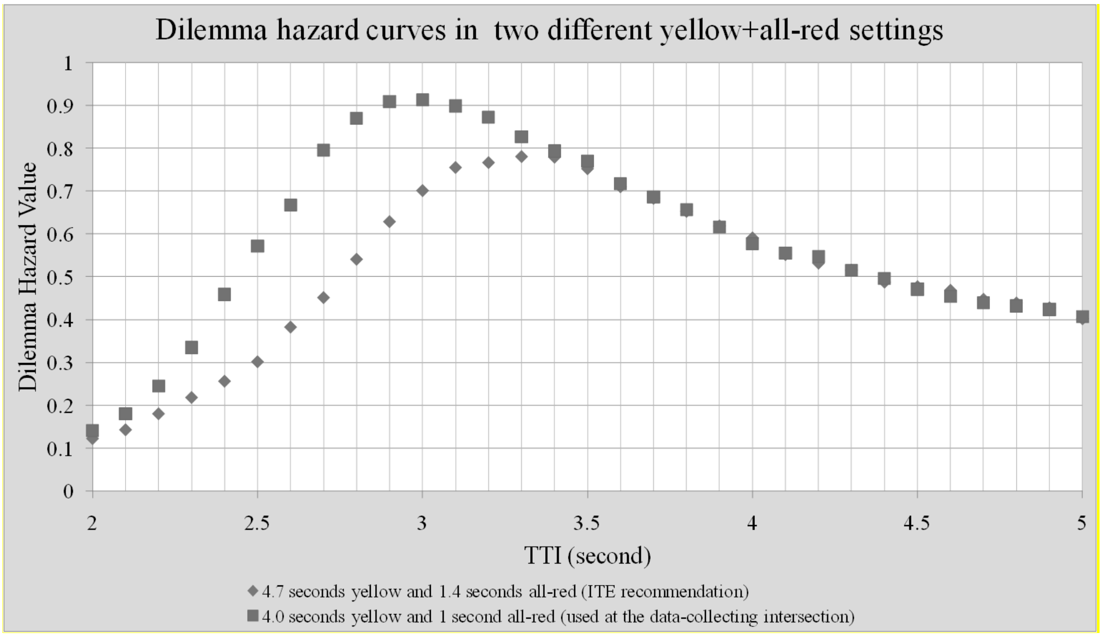


Figure 2.3 Dilemma hazard curves for various yellow and all-red clearance intervals (Li 2009)

Sharma et al. (2011) outlined a theoretical justification for utilizing probability of stopping to estimate probability of conflict at high speed intersections for single vehicles, discussed in detail in the following chapter.

2.9 Summary

The traditional surrogate measure of intersection safety—the dilemma zone—denotes the region of risk but fails to quantify the level of risk. The dilemma zone hazard model and dilemma zone hazard function have recently been used in attempts to quantifying the level of safety risk upon onset yellow. The dilemma hazard function was recently developed for single passenger vehicles (Sharma et al. 2011). The goal of the current research was to develop a dilemma zone hazard function for heavy vehicles.

Chapter 3 Development of Vehicle Based Dilemma Hazard Function

This chapter develops a dilemma zone hazard function estimation for passenger cars and heavy vehicles. This approach is an extension of the current approach which uses dilemma zone boundaries to determine the risk of traffic conflict for an individual vehicle in the case of a dilemma zone incursion. Field data collected from the intersection of SR 37 and SR 32 at Noblesville, Indiana were used to generate a binary choice model that best explained the underlying criteria for driver decisions at the onset of yellow. The probability of making an erroneous decision was used as the probability of a traffic conflict. Conflict severity was determined using the observed acceleration and deceleration ranges used by drivers at the intersection. Although the data were specific to one intersection, the procedures are readily transferable, and demonstrate how a sensor providing richer data than that provided via an inductive loop detector can be used to incorporate safety into signal operations.

3.1 Traffic Conflict at the Onset of Yellow

A conceptualized order of events occurring at the onset of yellow is shown in figure 3.1. A driver makes a decision to stop or go based on his/her environment, the signal settings, and adjacent vehicles. Let us assume a driver observes a yellow light at time t and decides to stop or go at time $t+\Delta t_1$. An erroneous decision could be made at time $t+\Delta t_1$ due to an error in perceiving the surroundings. The driver would realize his/her error after receiving feedback from the surrounding system, called “perceived conflict.” The driver then tries to rectify the error by taking evasive action at time $t+\Delta t_1+\Delta t_2$. If the evasive action is successful, then normal traffic resumes. However, an unsuccessful evasive action results in a crash. The probability of a traffic conflict would therefore be the same as the probability of having a “perceived conflict.” Some perceived conflicts may require severe evasive action (e.g., in the case of a higher degree of perception error), while others may require minor evasive action. Compared to a minor conflict, the probability of a crash is much higher in the case of a severe conflict.

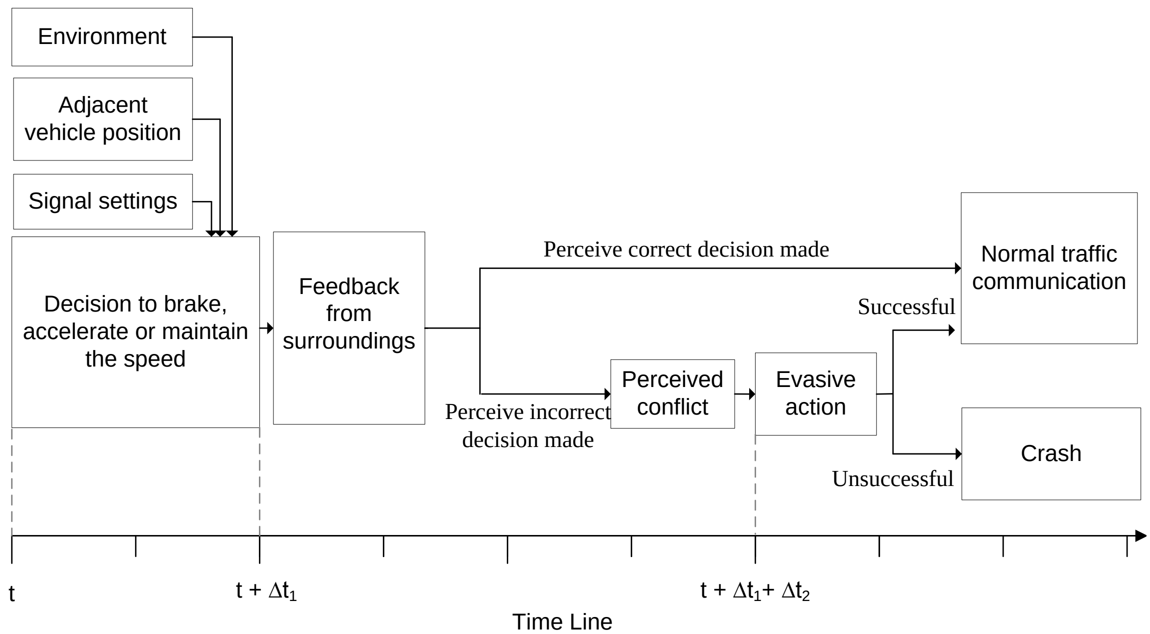


Figure 3.1 Driver decision processes at the onset of yellow

For example, traffic conflicts caused by the onset of the yellow light—such as acceleration through yellow, brakes applied before passing through, and abrupt stops—are minor conflicts. However, running a red light, swerving to avoid a collision, and vehicle skidding fall in the category of severe conflicts. Traffic conflicts can further be sub-divided into two categories based on the (a) presence or (b) absence of another vehicle in close proximity in the same lane. A driver's decision when faced with the yellow phase may depend on the presence of another vehicle in the lane. In the absence of another vehicle, the factors affecting the decision of the driver will be the distance from the stop-bar, velocity, weather conditions, length of yellow, etc. In the presence of another vehicle, the decision model of each driver can become complicated, as the decision of one driver may affect the other, and the correlated perception errors of both drivers would lead to a complex decision model. In this report, we restrict our discussion to single vehicle conflict. Multiple vehicle conflict is a topic we propose for future investigation and research. Note that recasting the dilemma zone design as a marginal costs-benefit problem (Sharma et al. 2007), presented in the previous chapter, allows the designer to considerably enhance the efficiency and safety at the intersection, even when a single vehicle dilemma zone hazard function is used.

The high-speed intersection of SR37 and SR32 in Noblesville, Indiana was used to study the decision process of drivers for the development of driver decision models and the dilemma zone hazard function. The following section describes the data collection and validation processes.

3.2 Field Data Collection and Validation

The data collection site at the signalized intersection of SR 37 and SR 32 in Noblesville, Indiana is shown in figure 3.2a. This instrumented intersection logs wide area detector (WAD) individual vehicle tracks and signal states. A simultaneous video of the existing traffic conditions was recorded for manual ground-truthing. Figure 3.2b illustrates the data collection environment used for the evaluation.

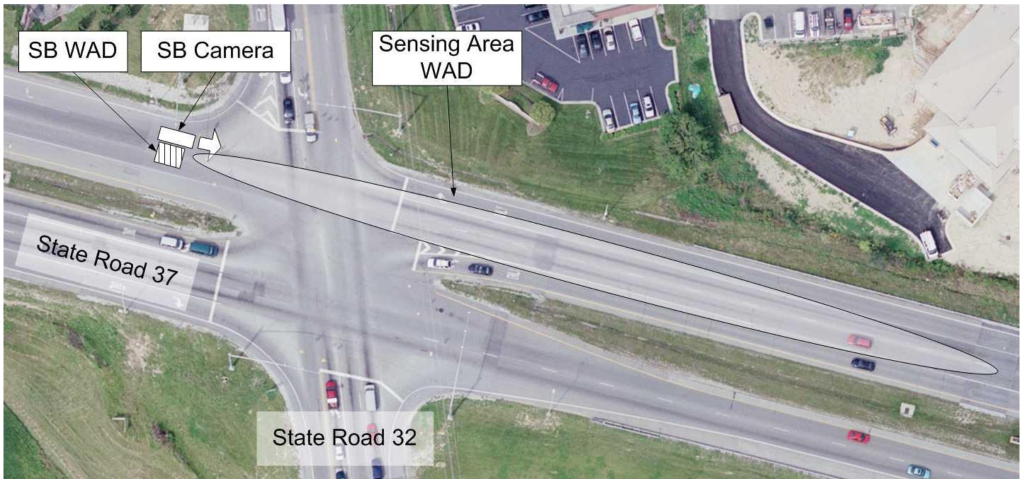
The equipment used for data collection included:

- Southbound (SB) WAD: SmartSensor Advance by Wavetronix was used as the WAD. This sensor uses a patented digital wave radar technology to track all vehicles, with a stated accuracy of 5 ft. The SB WAD was mounted on a mast arm 155 ft behind the stop bar at a height of 32 ft.

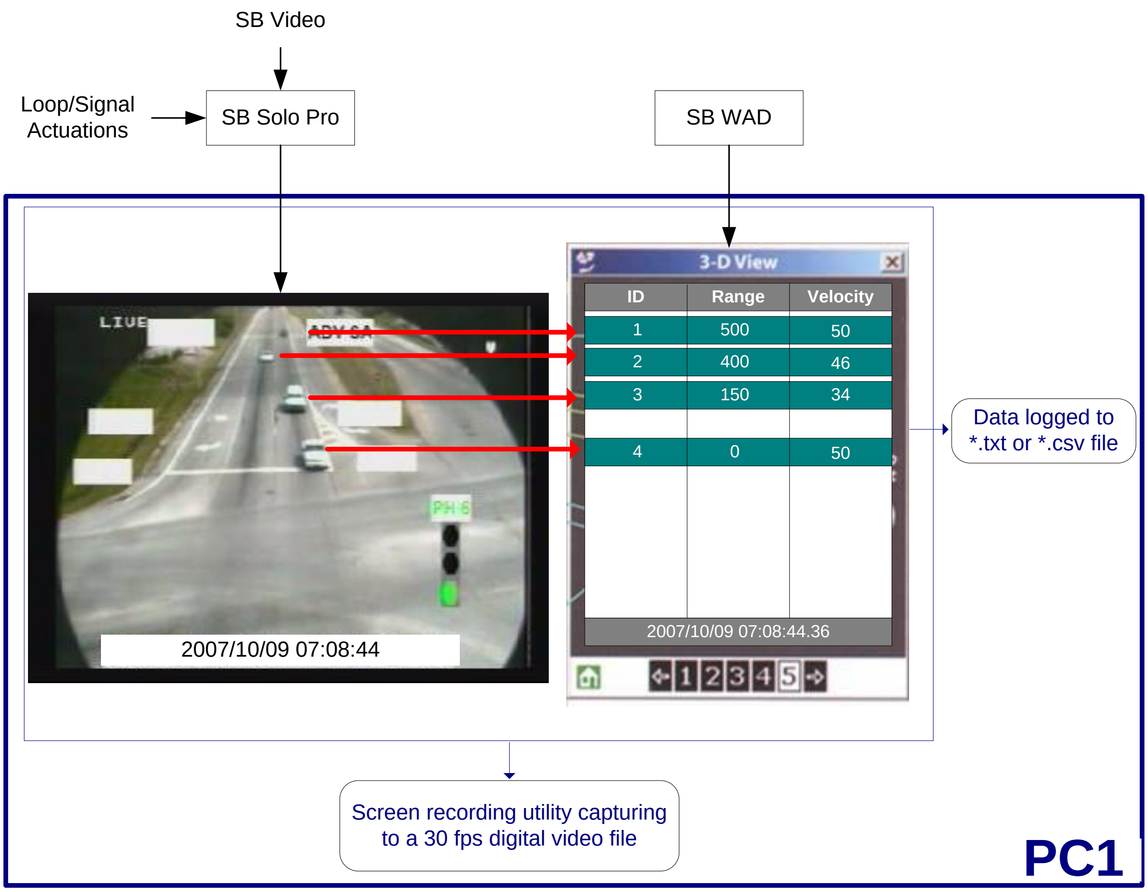
- SB Video: A video camera mounted on the SB mast arm was used for visual validation. The camera had the capability to overlay signal actuations over the video captured by the video sensor.

This setup was used to estimate the speed and position of the vehicle entering the SB approach. Vehicles up to a distance of 450 ft were detected by the WAD, and the WAD track files with the distance, speed, and identification numbers of the reported detections were logged. Also, the video output and the WAD output were displayed on a PC, and were recorded by a screen capture device at a rate of 30 frames/s, as shown in figure 3.2b.

After installation of the WAD, it was validated against a handheld GPS device. Three vehicle types: a sedan, a pickup truck, and an eight-passenger van, were used as probe vehicles to collect data. Ten runs were conducted for each vehicle type. The time was dynamically synchronized to 0.01 s precision across the data collection computer and GPS device. The root mean square error (RMSE) in distance was reported as 7.3 ft. An example of vehicle tracking by GPS and WAD is shown in figure 3.3. A detailed analysis of the performance of the WAD can be found in Sharma et al. (2008).



a) Intersection layout



b) Data collection environment

Figure 3.2 Data collection at SR 37 and SR 32 in Noblesville, Indiana

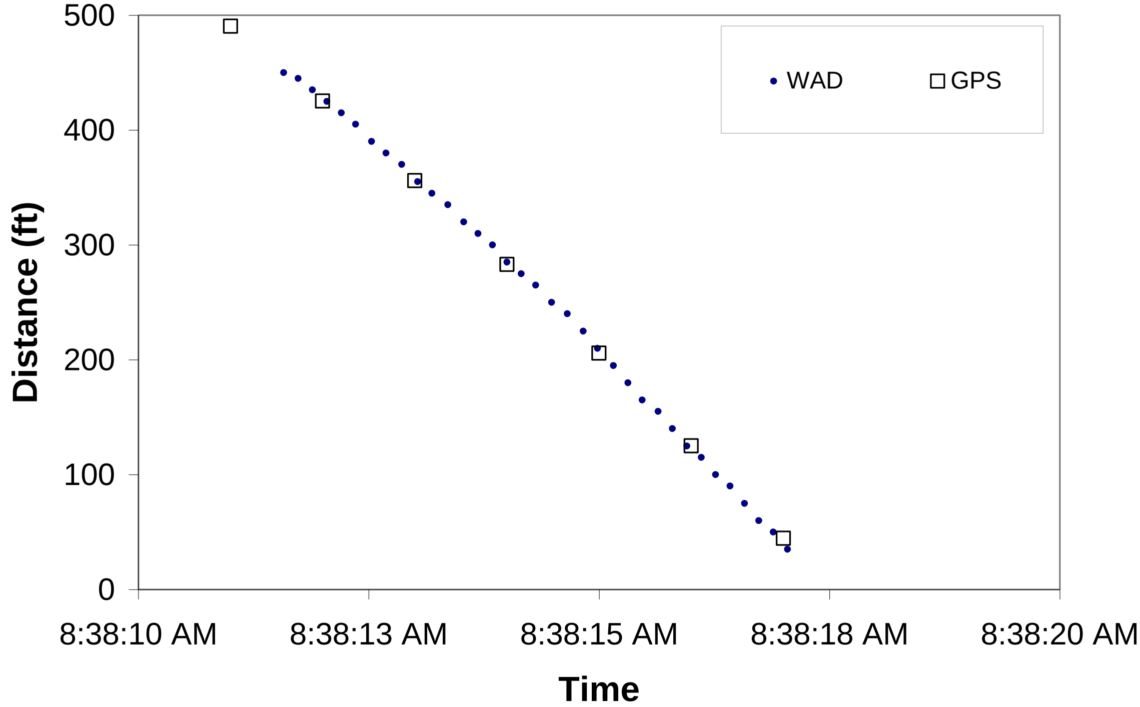


Figure 3.3 Example comparison between WAD and GPS

Data was collected on the southbound approach of SR 37 beginning in September 2007 and ending in April 2008; data was recorded between 6:00 am and 8:00 pm. The recorded video, with WAD and video input, was analyzed manually to reduce 102 days of data. The data were collected during good weather conditions and in the absence of any special event. The time of the onset of yellow, the vehicle Id number, driver decisions to stop or go, vehicle velocity, and the distance from the stop bar as given by the WAD, were noted. Only cases having one car in a lane at the onset of yellow were kept for the analysis of single vehicle conflict. Instances where the WAD performed erratically were deleted to maintain a high degree of accuracy. A total of 2,349 vehicles were observed, of which there were 252 heavy and 2,097 passenger vehicles. Figure 3.4 shows the cumulative speed distribution of speed for heavy vehicles and passenger vehicles. The 85th percentile speed for passenger vehicles was 56 mph, and was 51 mph for heavy vehicles; the 15th percentile speed for passenger vehicles was 40.4 mph and 34 mph for heavy vehicles. Figure 3.5 presents a histogram for the frequency of observation of passenger vehicles and heavy vehicles at a certain time to the stop bar. It can be seen that the data encompasses the typical range of dilemma zone boundaries. The peak hour through volume on the two south bound approach lanes varied between 600-900 vehicles per hour.

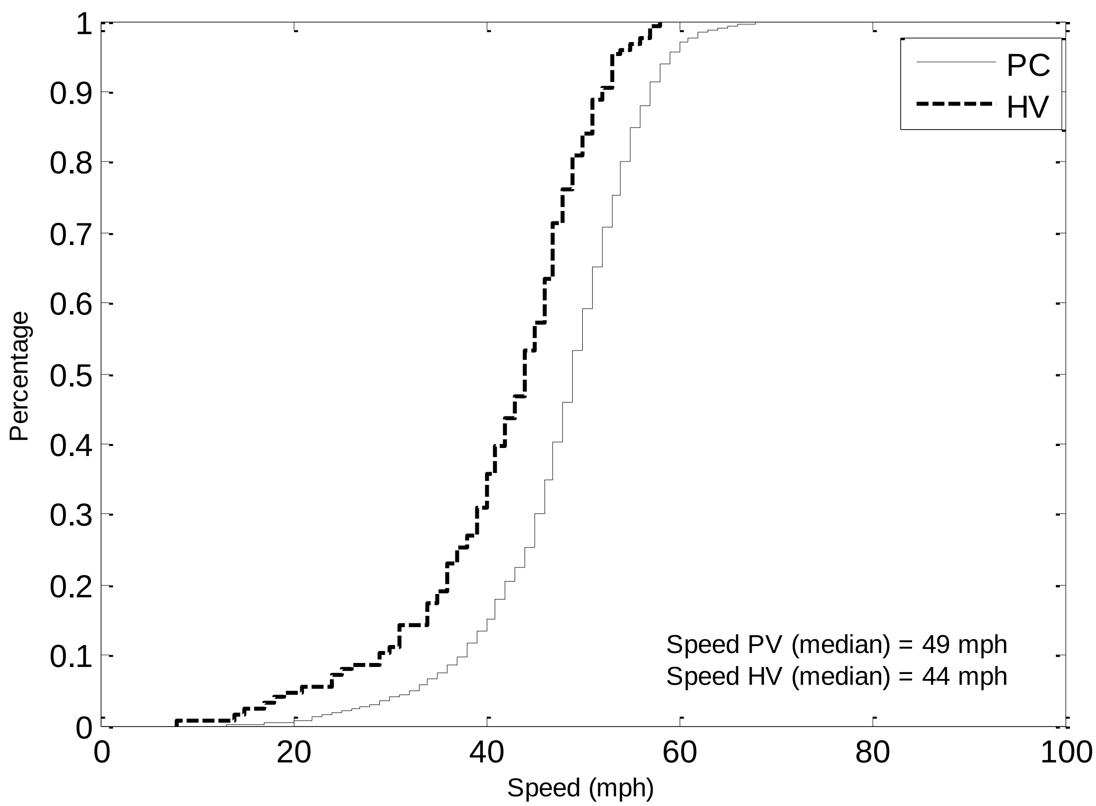


Figure 3.4 Cumulative speed distribution of heavy vehicles and passenger vehicles at the onset of yellow

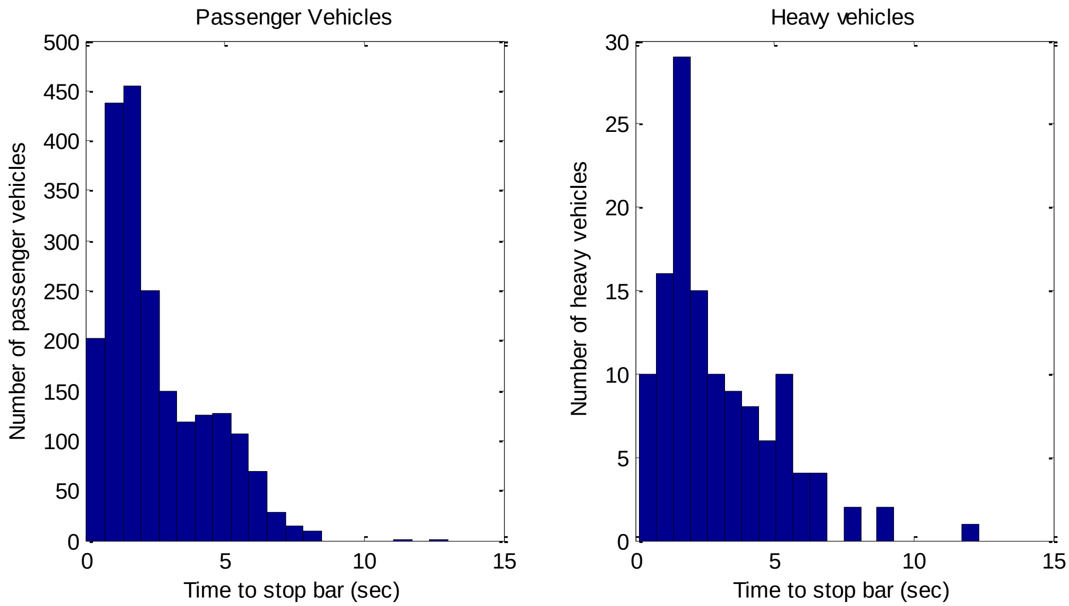


Figure 3.5 Histogram of passenger vehicles and heavy vehicles observed at a given time from the stop bar

3.3 Driver Decision Making at the Onset of Yellow

At the onset of yellow, a driver can choose from two mutually exclusive courses of action: stop or go. Therefore, driver behavior can be modeled as a binary choice process. Recalling the approach developed by Sheffi and Mahmassani (1981), let T_{p} be a driver's perceived time to reach the stop bar, randomly chosen from a population. As a result of the variance in driver behavior based on several independent factors such as perception of the yellow interval based on past experience, perception of the distance from the stop bar, perception reaction time, comfortable deceleration rate, etc., T_p can be modeled as a normally distributed random variable, as shown below in equation 3.1.

$$T_p = T_{req} + \xi \tag{3.1}$$

where,

T_{req} is the required time to safely enter the intersection based on the vehicle's onset distance and speed.

ξ: is a random variable is assumed to be normally distributed.

Figure 3.6 illustrates the resulting probability density function. If the perceived time, T_p, is greater than the critical time threshold, T_t, for the driver, a driver will decide to stop; otherwise, they decide to go.

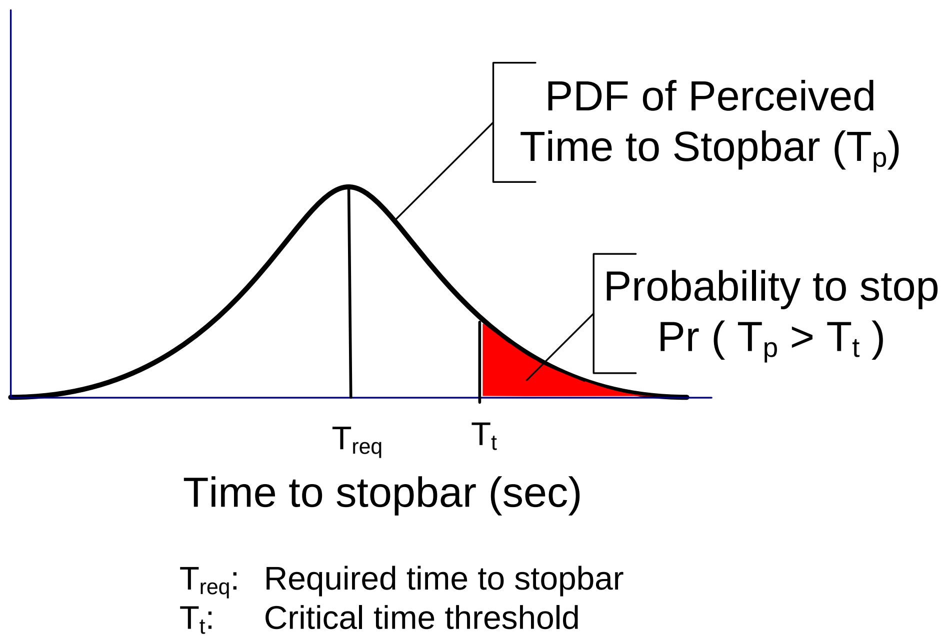


Figure 3.6 Probability density function for perceived time to stop bar

Therefore, the probability of stopping can then be calculated as:

$$P_{Stop} = \Pr\{T_p > T_t\} \tag{3.2}$$

$$P_{Stop} = \Pr\{T_{req} + \xi - T_t > 0\} \tag{3.3}$$

$$P_{Stop} = \Pr\{\xi > -(T_{req} - T_t)\} \tag{3.4}$$

$$P_{Stop} = \Pr\left\{\frac{\xi}{\sigma_\xi} < (\frac{T_{req}}{\sigma_\xi} - \frac{T_t}{\sigma_\xi})\right\} \tag{3.5}$$

$$P_{Stop} = \Pr\left\{z < \left(\frac{T_{req} - T_t}{\sigma_\xi}\right)\right\} = \Phi\left(\frac{T_{req} - T_t}{\sigma_\xi}\right) = \Phi\left(\mathrm{T_{req}} \cdot \mathrm{a} + \mathrm{b}\right) \tag{3.6}$$

In addition, the estimates of a and b represent,

$$a = \frac{1}{\sigma_\xi} \; ; \; b = -\frac{T_t}{\sigma_\xi} \tag{3.7}$$

where,

Φ(●) represents the standard normal cumulative normal function and equation 3.7 is a probit construct.

Estimates a and b from equation 3.7 are imperative to the formation of the probability of stopping curve, as they represent the slope and intercept. The two proceeding figures are illustrations of this significance.

Table 3.1 presents the probit model developed for the data obtained from the test site. The model had 93.38% correct prediction accuracy. Figure 3.7 presents the probability of stopping plots for passenger vehicles and heavy vehicles. Table 3.2 presents the important statistics from the two models. The dilemma zone boundaries were found to be between 3.5-6 s and 3-8.2 s for passenger vehicles and heavy vehicles, respectively. It can be seen that the dilemma zone boundary for trucks was 2.7 s longer. The longer boundaries show that heavy vehicles had higher variability in decision making at the onset of yellow. A provision of providing information to truck drivers, such as advance warning flashers, to aid in decision making could help reduce this variability. The other important observation to be noted is that the critical threshold for passenger vehicles (4.7 s) was very close to the yellow time at the intersections, a finding consistent with Sheffi and Mahmassani (1981). The critical threshold for trucks (5.6 s) was higher than the passenger vehicle threshold, as well as the yellow duration. A significant number of truck drivers decided to go through the intersection, despite the risk of running the red light; this could be due to the fact that heavy vehicles try to avoid heavy deceleration to avoid jack-knife crashes. This also signifies the need to provide special dilemma zone protection when the trucks are detected. Wide area detectors with the capability to identify heavy vehicles could provide site-specific and vehicle specific protection, thus significantly improving safety at high speed intersections.

Table 3.1 Probit model for probability of stopping

Number of observations: 2223 Unrestricted log likelihood: -352.25 Restricted log likelihood: -1000.79 Prob$\left[X^2 > 275.69\right]$= 0.00 AIC: 0.32		
Variable Name	**Value**	**T-stats**
Constant	4.83	20.02
Required Acceleration	-1.022	-19.65
HV_addConst	-2.04	-4.53
HV_Acc	0.52	5.52

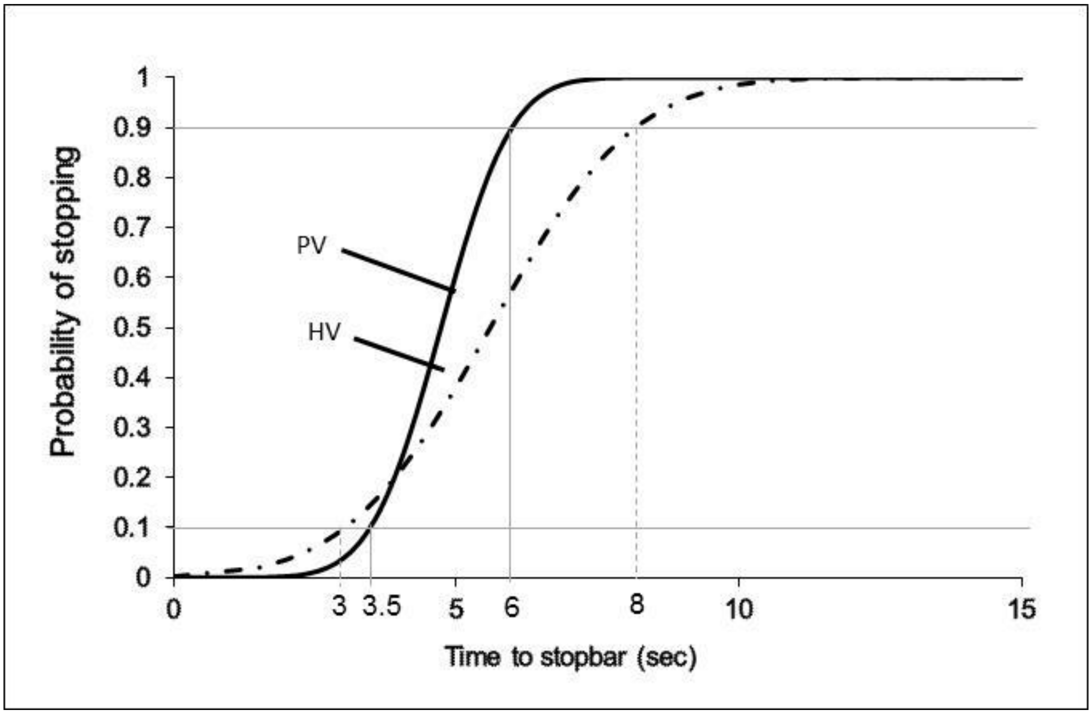


Figure 3.7 Probability of stopping curve for passenger vehicles and heavy vehicles for the test site

Table 3.2 Time to stop bar based probit model for stop and go decisions

Variable Name	Passenger Vehicle	Heavy Vehicle
DLZ start (s)	3.5	3
DLZ end (s)	6	8.2
Length of dilemma zone boundary (s)	2.5	5.2
Critical time threshold (s)	4.73	5.6
Standard deviation (s)	0.98	2.01
Yellow time (s)	5	5

3.4 Theory of Drivers' Perceived Conflict Resulting in Minor and Severe Traffic Conflicts

The driver decision process at the onset of yellow is a dynamic feedback system. The consequences of any decision made by the driver at a certain time step are fed back to that driver in the next time step. If a driver erroneously decides to go even though the required time is greater than the threshold, the driver will realize it after some duration of time. Similarly, an error would occur if a driver decided to stop even though the time required was less than the critical time threshold. The probability of a traffic conflict, therefore, would be the same as the probability of a detected error. The curve of probability of traffic conflict is termed the dilemma hazard function.

$$P_{CONFLICT} = \begin{cases} P_{STOP} & \forall T_{req} < T_t \\ P_{Go} = 1 - P_{STOP} & \forall T_{req} > T_t \end{cases} \quad (3.8)$$

Figure 3.8 shows the dilemma hazard function for passenger vehicles and heavy vehicles for the test site. It can be seen that, for heavy vehicles, the dilemma hazard function is spread over a larger region.

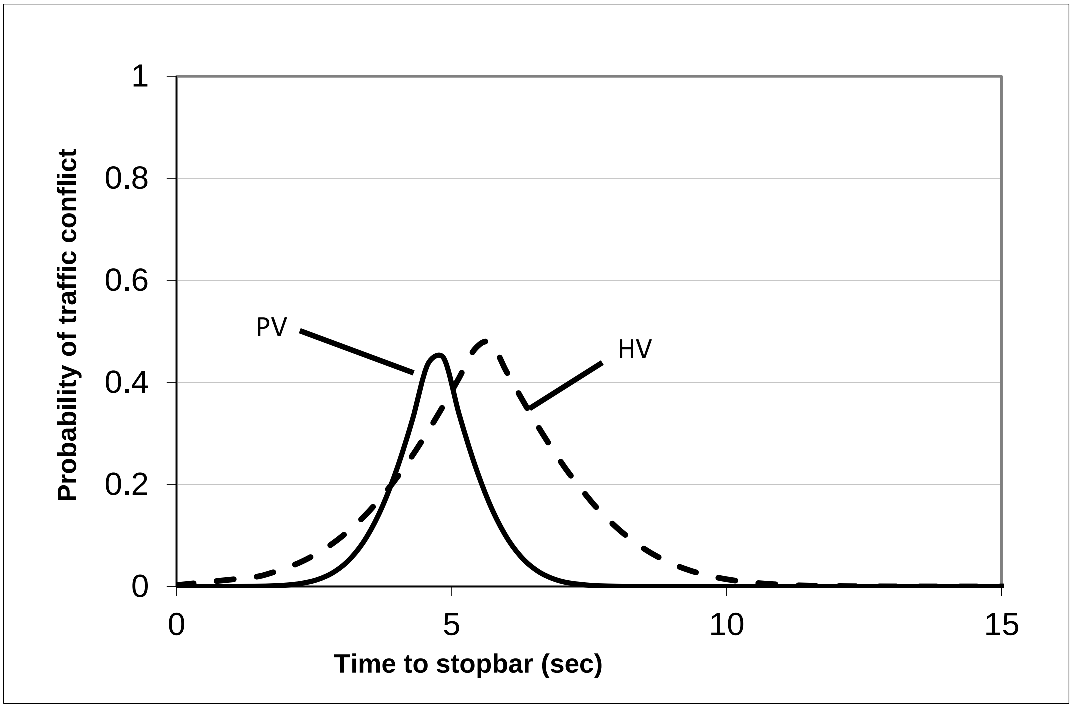


Figure 3.8 Dilemma hazard function for passenger vehicles and heavy vehicles

Sharma et al. (2011) derived a marginal cost-benefit approach that can be used to improve the safety and efficiency of operations at high speed intersections, using dilemma hazard functions. The optimal operation of intersections demands that the total cost levied on all drivers should be minimized. The total system cost can only be minimized if the marginal benefits of extending the main street green (beyond the minimum green time) to reduce the probability of traffic conflict are greater than the resulting marginal increase in the cost of delays on the accumulated queue of the opposing movement. Since the queue length on the side streets will increase with the passage of the main-street green, the protection provided to the main street driver has to be dynamically reduced.

This remainder of this section will present a methodology for implementing dynamic dilemma zone protection. Wide area detector technology can be used to identify vehicle class and speed. Note that the proposed algorithm is used only to reduce the protection provided for single vehicle conflict; full protection will be provided if there are more than two vehicles in their dilemma hazard zone in same lane. Also, the probability of traffic conflict might be further divided into severe and minor conflict using the typical acceleration and deceleration thresholds.

3.5 Cost of Delay Associated with Extension of Green Phase of the High Speed Approach

The cost of extending the green for clearing the vehicle from the high risk zone can be calculated by using the amount of delay incurred by the queue formed on the stopped phases. Figure 3.9 illustrates the concept of increase in delay for extending a through green by a single vehicle extension (t_{ext}). The un-shaded queue polygon in figure 3.9 is the delay experienced by the vehicles in opposing movement if the green were terminated without the green extension. The extra delay is shown as the shaded area, and this extra delay accrues to the side street if the through phase is extended by a time equal to t_{ext}. The extra delay associated with extending the main street green phase by t_{ext} after r seconds of green has elapsed is given by equation (3.9) (below).

$$\Delta Delay = \frac{q_{opp}}{\left(1-\frac{q_{opp}}{s_{opp}}\right)} \times r \times t_{ext} + \frac{q_{opp}}{2\times\left(1-\frac{q_{opp}}{s_{opp}}\right)} \times t_{ext}^2 \qquad (3.9)$$

where,

$\Delta Delay$ = Increase in the total delay for extending through green by a unit vehicle extension (veh-s);

q_{opp} = Total volume in the opposing direction (veh/s);

s_{opp} = Saturation flow rate for the opposing movements (veh/s);

r = red time elapsed for the opposing movements (s); and

t_{ext} = vehicle extension time (s).

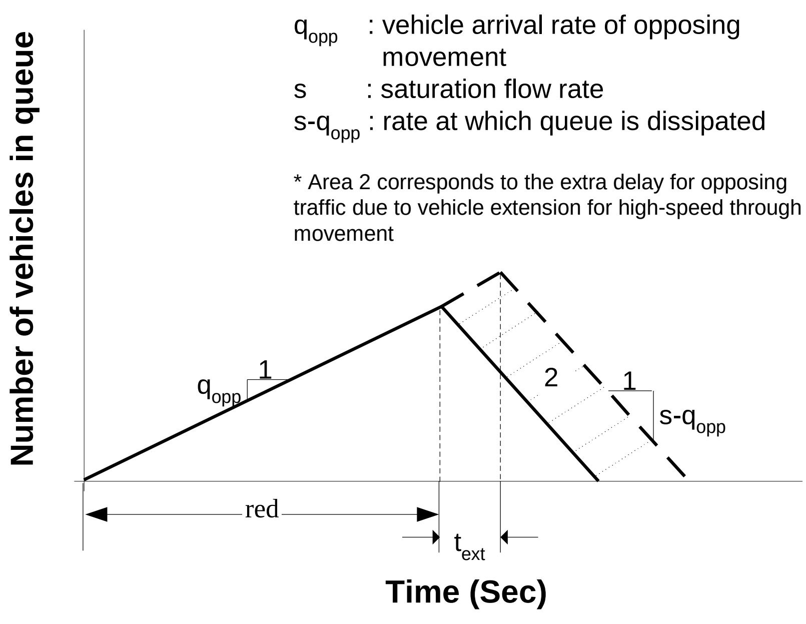


Figure 3.9 Increase in delay of the standing queue due to vehicle extension

The increase in the total system delay is multiplied by the cost of the delay ($/veh/s) to obtain the cost of extending the high speed through phase by a unit vehicle extension. For illustration purposes, in this report we use mean hourly rate income for the United States 20.32 $/hr.

3.6 Safety Benefits

The dollar value of safety benefits resulting from extending the green interval can be obtained by multiplying the expected probability of conflict by the cost of conflict. Table 3.3 illustrates an example of calculating the benefits of preventing a single vehicle traffic conflict. Columns 1 and 2 in table 3.3 list the type of crashes and their associated costs, respectively, as reported by the National Safety Council (2007b). The weighted average cost of the accident is calculated using the ratios of the type of accidents. The estimated benefits of preventing traffic conflict are obtained as the product of the average accident cost and the probability of occurrence of a crash given a traffic conflict has occurred (Gettman et. al. 2008). Based on this methodology, the estimated benefit of preventing a single traffic conflict for a passenger vehicle is $1.13. Alternatively, the number of crashes occurring at the intersection and corresponding conflicts can be observed for a period of time. The ratio of the number of crashes to the number of conflicts can be used as the probability of a crash given that the conflict occurred. It should be noted that similar techniques can be used to calculate the cost associated with heavy vehicle conflict.

Table 3.3 Estimation of cost associated with a traffic conflict of passenger vehicles

Type of Crash	Cost Estimate For Motor Vehicle Crashes (Ref: National Safety Council, 2007b)	Ratio of Each Type of Crash	Ratio * Cost
Death	$1,130,000	1	$1,130,000
Nonfatal Disabling Injury	$61,600	53	$3,264,800
Property Damage only	$7,500	209	$1,567,500
Weighted average cost per crash [*Cost($/Crash)*]			$22,670
Probability of being involved in a crash given a traffic conflict [*Pr(Crash*|*TC)*] *(Ref:Gettman et. al. 2008)*			0.00005
Estimated benefits of preventing a traffic conflict [Benefits($/TC)= Cost($/Crash) X Pr(Crash|TC)]			$1.13

<u>3.7 Calculation of Dynamic Dilemma Protection Boundaries</u>

We assume that a traffic signal controller has a resolution of 0.1 s. An initial dynamic protection region is defined, and with the passage of main-street green, this region was reduced with steps of 0.2 s. The step size of 0.2 s was chosen both because of the controller resolution and in order to maintain symmetry, such that probability of conflict at the start and end of the dilemma zone boundary is the same. Dynamic dilemma zone boundaries (DDZB) of protection at different durations of green can be calculated using the following steps:

1) The initial DDZB is the region where the probability of a traffic conflict is greater than 0.1. This can be calculated using the dilemma hazard function, as shown in figure 3.8. For passenger vehicle, the protection area is 3.5 to 6.0 s from the stop bar. It should be noted that the decision of starting dynamic dilemma zone boundary

depends on the site engineer; the value of 0.1 was chosen for the purposes of illustration.

2) The next step is to calculate the expected probability of traffic conflict for the dynamic protection region. The expected value of probability of traffic conflict can be calculated using equation 3.10. Expected probability of traffic conflict for passenger vehicles in the range 3.5-6 s can be calculated as 0.27.

$$E(pr(TrafficConflict)) = \frac{\int_{StartDDZB}^{EndDDZB} f_{pr(TC)}(x)dx}{EndDDZB - StartDDZB} \approx \frac{\sum_{StartDDZB}^{EndDDZB} f_{pr(TC)}(x) \times \Delta x}{EndDDZ - StartDDZB} \qquad (3.10)$$

where,

$E(pr(TrafficConflict))$ is the expected probability of having traffic conflicts over the given dynamic dilemma zone region;

$StartDDLB$ is the start dynamic dilemma zone boundary distance;

$EndDDLB$ End dynamic dilemma zone boundary distance;

$f_{pr(TC)}(x)$ is the dilemma hazard function.

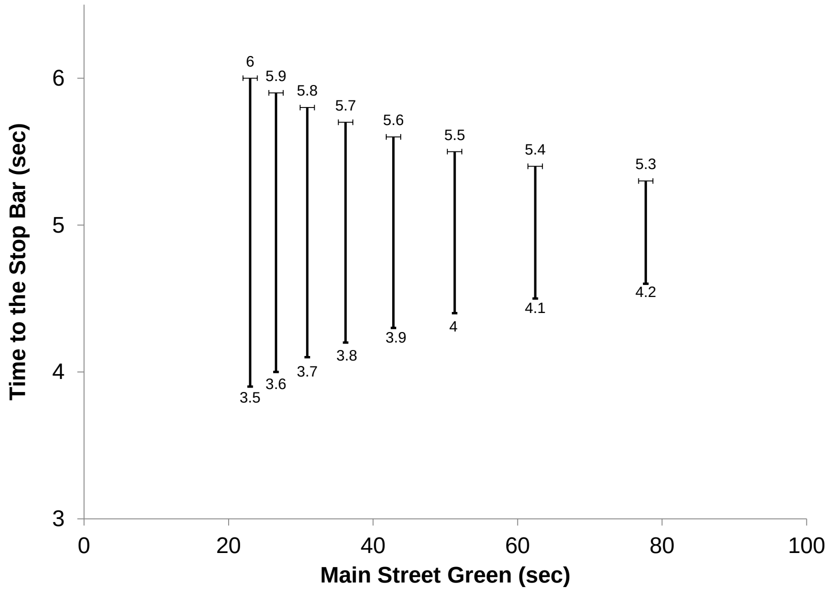
3) The safety benefits of the protection zone can be obtained by multiplying the expected probability of traffic conflict for a given set of DDZB by the monetary benefit associated with saving a single vehicle conflict, as shown in equation 3.11:

$$Safety\_Benefits = E(pr(TrafficConflict)) \times \text{Dollar Benifits(\$/Traffic conflict)} \quad (3.11)$$

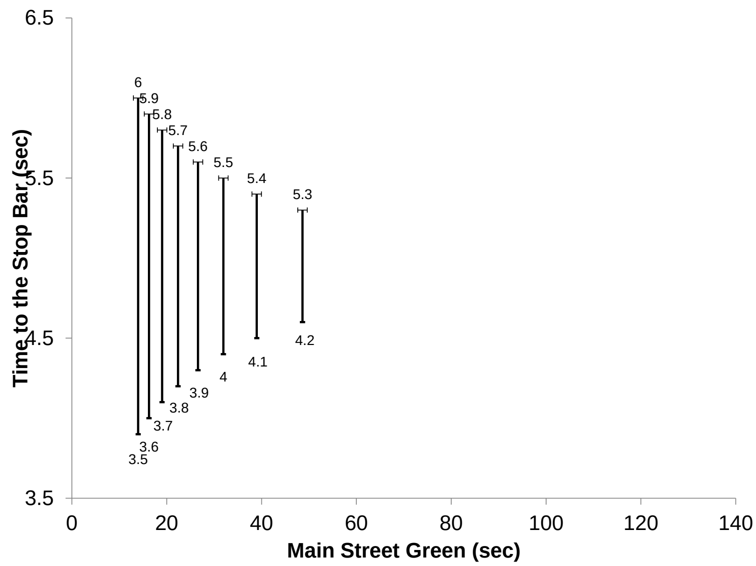
4) Break-even points are obtained for deciding the duration until which a specific set of DDZB is used. The break even points can be calculated using equation 3.12. Here, $t_{i,ext}$ is the extension time for the i^{th} set of DDZB. For the initial case in our example, $t_{1,ext}$ will be, 6-3.5 = 2.5 s. The term r_i represents the break even time until which the i^{th} set of DDZB are used.

$$\begin{aligned} &SafetyBenifits = DelayCosts \\ &E(pr(TrafficConflict)) \times \text{Dollar Benifits(\$/Traffic conflict)} \qquad (3.12) \\ &= \frac{q_{opp}}{\left(1 - \frac{q_{opp}}{s_{opp}}\right)} \times r_i \times t_{i,ext} + \frac{q_{opp}}{2 \times \left(1 - \frac{q_{opp}}{s_{opp}}\right)} \times t_{i,ext}^2 \end{aligned}$$

Figures 3.10a and b present the comparison of dynamically changing dilemma protection zone boundaries for hypothetical opposing volumes of 2500 vph and 3500 vph in six lanes. In the first case, the region between 6 s to 3.5 s to the stop bar will be protected for the first 23 s of green, after which the protection will be dropped to 5.9-3.6 s at 27 s. The protection region continues to gradually reduce with the passage of the main street green. It should be noted that the probability of gap-out increases as the extension interval is reduced; therefore, fewer and fewer cycles will max-out. From figure 3.10b, it can be seen that, for higher opposing volumes, the break event points for each set of DDZB are earlier than those of lower opposing volumes; this is because queue will be building at a higher rate in the case of higher opposing volumes; thus, the same extension time would lead to a higher delay cost for the side street.



a) Break-even points for opposing volume of 2500 vph



b) Break-even points for opposing volume of 3500 vph

Figure 3.10 Dynamic dilemma zone boundaries for a passenger vehicle

A technique similar to that utilized in the case of passenger vehicles can be used to develop site-specific dynamic dilemma zone boundaries for trucks or other heavy vehicles. A detailed discussion of the feasibility of implementation is provided in the next chapter.

3.8 Synthesis

The methodology presented in this chapter quantitatively assessed the risk of crash for passenger vehicles and heavy vehicles facing yellow phases at a high-speed intersection. The chapter extended the current literature on determining dilemma zone boundaries by providing a methodology to ascertain the probability of a traffic conflict for a single vehicle, thereby providing practitioners with a valuable tool for controlling signal operation, in order to quantitatively compare trade-offs between safety and efficiency at intersections. It also provided researchers with a potential tool for quantifying safety in other transportation applications.

A key conclusion drawn from this chapter is that the dilemma zone hazard function developed for single vehicle conflicts is not a binary function—as is typically assumed for the traditional dilemma zone definitions—but, rather, is a stochastic function which yields the probability of a perceived conflict given the ambient conditions. This function also classifies risk, based on the severity of the evasive action required, as severe or minor conflicts. Also, we found that heavy vehicles need to be protected over approximately twice the amount of time (3-8.2 s) in comparison to passenger vehicles (3.5-6 s) in order to maintain the same probability of traffic conflict.

This research proposed real-time estimation of the dilemma zone hazard function for different intersection and vehicle types using smart wide area sensors.

Chapter 4 Conclusions and Recommendations

It is estimated that there are 68 million instances per year at high speed intersections of signal change to the yellow phase, accompanied by the possibility of dilemma zone incursions. The four attributes of a dilemma zone hazard system that need to be carefully designed for dilemma zone protection are: the surrogate measure of safety and efficiency, signal control logic, the sensor system layout, and feasibility of implementation.

A brief discussion of the limitations of the current system in regards to these attributes was provided in chapter 2. Chapter 3 presented the dilemma hazard functions for passenger vehicles and heavy vehicles, and introduced an economic costs-benefit framework developed to inform the safe and efficient operation of high speed intersections through analysis of the ratio of marginal costs of delay over marginal enhanced safety benefits; the chapter also introduced a proposed methodology to develop a dilemma hazard function as an improved surrogate measure of safety.

The following section describes a methodology for implementing the proposed improvements as a dilemma zone protection system. A wide area detector can be designed to overcome the shortcomings of the current system.

4.1 Wide Area Detector

An adaptive wide area detector is envisioned to overcome the limitations in existing dilemma zone protection systems. The prototype sensor could leverage current smart sensor technologies, and would have following built-in features:

1. The sensor would house embedded logic to generate a site-specific and mode-specific dynamic dilemma hazard function using the methodology presented in chapter 3. This

sensor would be able exploit valuable historical data to generate curves sensitive to inclement weather conditions and special events.

2. The sensor would implement a cost-benefit analysis model using estimated safety and estimated delay costs to minimize the total system cost of operation.
3. The sensor would be able to track each vehicle through the dilemma zone, and also to sense the class of vehicle in order to implement an appropriate dilemma hazard function.

4.2 Feasibility of the Implementation of a Prototype Adaptive Sensor

4.2.1 Cost of Implementation

Currently available wide area sensors cost in the range of $5,000 per sensor and can detect one approach. This cost is comparable to the cost of an inductive loop at approximately $2,500 per loop. It is estimated that the cost differential could be quickly eliminated, as the number of lanes being monitored by WAD increases.

4.2.2 Special Controller

The prototype adaptive sensor would be a smart sensor, meaning that the adaptive logic of generating a dilemma hazard function would be embedded in the sensor. Also, it would have embedded marginal costs and benefits signal logic. The final output from the smart sensor therefore could be made to be compatible with the existing signal controller, thereby avoiding any need for an advanced controller.

4.2.3 Technical Expertise Needed to Program the Sensor

Most of the sensor parameters would be self-organizing and would adapt to the data collected from the site of implementation. There would be some start-up values for sensor parameters in order to operate the intersection prior to the point in time when enough history is generated to self-organize the sensor. All default values could be factory programmed, and thus made very easy to install on site.

4.2.4 Feasibility of the Development of Such a Sensor

Following the completion of this research, the sensor described herein is not considered to be a very difficult leap. The greatest foreseeable limitation is obtaining a wide area sensor with satisfactory performance. If such an operational sensor were developed, the prototype adaptive sensor could be developed with minimal effort.

4.3 Conclusion

The methodology presented in this report quantitatively assessed the risk of crash for a driver facing a yellow phase on a high-speed intersection, while also being specific to the mode of vehicle (passenger vehicle, heavy vehicle). This methodology extends the current literature on determining dilemma zone boundaries to enable researchers to ascertain the probability of traffic conflicts for single vehicles—thus providing practitioners with a useful tool for controlling signal operation while quantitatively comparing trade-offs between safety and efficiency at intersections. We found that, rather than being a binary function, the dilemma zone hazard function developed for mode-specific single vehicle conflicts was a stochastic function, yielding the probability of a conflict given the ambient conditions. It was found that heavy vehicles had a significantly wider dilemma zone boundary (5.2 s) than passenger vehicles (2.5 s). This implies that the mode-specific boundaries need to be calculated for each site, instead of protecting the heavy vehicles by using the same region as passenger vehicles.

This research also proposed a dynamic dilemma zone protection algorithm for implementing a marginal costs-benefit approach. The proposed algorithm gradually decreases the safety net as the queue on the side streets starts to build. This approach increases the economic efficiency of operations, in addition to reducing the probability of max-out, thus enhancing safety at the intersection.

The dilemma hazard function assigns a higher probability of traffic conflict to the central region, with risk deteriorating toward the boundaries. The dilemma hazard function is a case sensitive function, and depends on several other variables such as geometric conditions, mode of transportation, weather conditions, time of day, and driver aggressiveness. The range of the region to be protected will change depending on the dilemma hazard function; a steeper dilemma hazard function will reduce the region to be protected, thus the initial DDZB will have a lower value. Thus, a case sensitive design of the dilemma hazard function is needed to ensure safe and efficient operations. Wide area detectors could be used for real-time development of a dilemma zone hazard function for any intersection. A smart sensor could develop the probability of the stopping curves. Note that the process of manual calculation could be replaced by computational logic built into the smart sensor. The probability of stopping curves could then be used to develop a dilemma hazard function. The use of smart sensors would facilitate data collection to account for variables such as mode of transportation, weather conditions, time of day, driver aggressiveness, etc.

The methodology proposed in this study could be used to reduce delay and improve safety at high-speed intersections by using novel stochastic paradigms to overcome the limitations of the current generation of dilemma zone protection systems. Improved methodological constructs are proposed using only currently-utilized variables in signal hardware logic, thereby circumventing expensive infrastructure upgrade costs.

4.4 Future Research

It is recommended that future research pursues the development of a prototype adaptive sensor that could model a dilemma zone hazard function for different intersection and weather conditions using smart, wide area sensors. Future research is also needed to estimate the dilemma zone hazard function for multiple vehicle conflicts.

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