MD-04-SP308B4L

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STATE HIGHWAY ADMINISTRATION

RESEARCH REPORT

INTERRELATIONS BETWEEN CRASH RATES, SIGNAL YELLOW TIMES, AND VEHICLE PERFORMANCE CHARACTERISTICS

UNIVERSITY OF MARYLAND, COLLEGE PARK

FINAL REPORT

June 2004

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
MD-04-SP308B4L		

4. Title and Subtitle	5. Report Date / 6. Performing Organization Code
Interrelations between crash rates, signal yellow times, and vehicle performance characteristics	5. Report Date: **June 2004** 6. Performing Organization Code:
7. Author/s Dr. Gang-Len Chang, Professor, gang@eng.umd.edu Hua Xiang and Chi-Sheng Chou, Research Assistants	**8. Performing Organization Report No.**
9. Performing Organization Name and Address Department of Civil Engineering University of Maryland College Park, MD 20742	**10. Work Unit No. (TRAIS)** **11. Contract or Grant No.** SP308B4L
12. Sponsoring Organization Name and Address Maryland State Highway Administration Office of Policy & Research 707 North Calvert Street Baltimore MD 21202	**13. Type of Report and Period Covered** **Final Report** **14. Sponsoring Agency Code**

15. Supplementary Notes

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16. Abstract

This study has investigated the interrelations between crash rates, signal yellow times, driver characteristics and vehicle performance characteristics at signalized intersections, based on field observations of 732 drivers at nine intersections across five counties in Maryland. It has been found that driver responses during the yellow signal phase can be classified into four distinct types: "aggressive pass," "conservative stop," "normal stop," and "normal pass." Their response differences are due not only to discrepancies in individual characteristics, but also a variety of traffic environmental factors. The collective impacts of such factors have been evaluated with an ordered-probit model. In addition, based on the speed evolution data recorded from each observed driver, this study further analyzed the deceleration/ acceleration rates of drivers responding to yellow-light phases. Such information provides valuable data for computing the distribution of intersection dilemma zones under various types of driving populations and vehicle types.

17. Key Words	18. Distribution Statement: No restrictions
Dilemma zone, yellow phase, driver responses, vehicle performances, crash rates, ordered probit regression.	This document is available from the Research Division upon request.

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. Of Pages	22. Price
None	None	88	

Form DOT F 1700.7 (8-72) Reproduction of form and completed page is authorized.

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Introduction

1.1 Background

Improving traffic safety has long been one of the primary responsibilities of both federal and local transportation highway agencies across the nation. Over the past several decades, a tremendous amount of resources have been invested in projects and programs that improve the safety and efficiency of our transportation systems. Programs such as driver education, the enforcement of seat-belt use, and operational improvements to roadway geometric features have all contributed to making the public more aware of the dangers associated with driving. Despite the significant progress of these programs, traffic signal related crashes have not been reduced over the past years.

As highway agencies attempt to address this dilemma, one critical issue that has not yet been sufficiently addressed is an in-depth study of how technical factors such as the design of the yellow-light phase and improved technological advances of automobiles can ultimately have an adverse effect on a driver's decision making process within a critical part of the intersection called the dilemma zone.

For example, over the past decade, traffic signal related crashes constitute about 30 percent of the total crashes on Maryland state routes. The following factors can potentially increase or decrease the probability of having a traffic signal related crash: the duration of the yellow-light phase and the way a driver reacts to it while within the dilemma zone; and the operational capability of a vehicle's acceleration/deceleration performance.

This research paper will focus on the interrelationships of driver behavior, the design of traffic light phases, and the recent technological advances in vehicle acceleration/deceleration performance within a dilemma zone.

When researching driver behavior at signalized intersections, the following external factors must be considered: characteristics of other drivers, roadway geometric features, congestion levels, distribution of traffic flow speeds, and vehicle performance. The collective impacts of all these factors can potentially affect the decision a driver should make. This research will identify specific factors associated with driver behavior as it relates to his/her response to the yellow-light traffic phase.

Furthermore, the technological advances in vehicle deceleration/acceleration performance over the past decade may also have significant impacts on the behavior of a driver. As evident in the increasing number of aggressive driving related crashes in the Metropolitan Washington region, drivers frequently take advantage of these vehicle enhancement characteristics to accelerate through the yellow-light phase, despite its purpose to warn drivers to decelerate and come to a complete stop. However, as traffic congestion continues to worsen, drivers will continue to be aggressive. Thus, it is imperative for transportation agencies to recognize such evolving driving patterns and their complex interactions with traffic engineering and the technological enhancements of the automobile industry.

1.2 Research Objectives

In response to the above concerns, this study will focus on the following critical issues:

- Driver response to a yellow-light phase and potential contributing factors under various traffic conditions;
- Interrelations between driver responses to a yellow-light phase and the distribution of intersection dilemma zones.

The research results associated with the above issues will serve as a basis for developing effective tools to help traffic engineers predict behavioral differences of drivers within dilemma zones.

1.3 Related Literature Review

Despite an extensive amount of literature on intersection traffic safety, most studies focus on either the human-factor aspects of driver deceleration/acceleration process, or the relationship between dilemma zones and the yellow-light phase duration. One critical issue that has yet to be adequately addressed is the complex relationship between a driver's response during a yellow-light phase and the dynamic nature of dilemma zones under various traffic conditions. This section will highlight major findings in literature addressing this issue.

Intersection dilemma zones, yellow-light phase duration, and driver deceleration/

acceleration rates were developed by Gazis, Herman, and Maraduin (1960) in their land-marking paper, called *The GHM Model.* This model uses both mathematical and empirical observations to support the "amber light dilemma," wherein "*A motorist driving along a road within the legal speed limit finds himself, when the green signal turns to amber, in the predicament of being too close to the intersection to stop safely and comfortably, and yet too far from it to pass through, before the signal changes to red, without exceeding the speed limit*." (Gazis, Herman, and Maraduin, 1960) They also indicated that incompatibility frequently exists between a driver's desire to comply with the yellow-light-phase indication and his/her encountered constraints.

Inspired by the pioneering GHM model, Olson, and Rothery (1961) conducted field observations at five intersections and found that drivers tend to take advantage of the long yellow-light phase and view it as an extension of the green phase. Their research concluded that driver behavior does not seem to be affected by the yellow-light phase duration, especially since most motorists do not even know the typical phase duration.

Along the same lines of the GHM model, Liu, et al. (1996) recently extended the dilemma zone research to investigate the incompatibilities of the yellow-light phase duration and traffic ordinances, and a variety of vehicle characteristics such as deceleration/acceleration processes. Liu also provided an in-depth review of studies related to the design of the yellow-light phase interval, which ranges from the earliest transportation equations to current state-of-the-art practices offered in the ITE Handbook (1982).

Despite significant progress made by Liu in uncovering the complex interrelationships between dilemma zones, driver responses, and the yellow-light phase duration, the dynamic nature of dilemma zones had still not been fully recognized. Transportation researchers in the late 90s' began to realize that both the location and length of dilemma zones are not static in nature, but vary with the complex interactions between driving behavior, vehicle performance characteristics, and traffic conditions at intersections. One key study addressing this issue is the work of Moon and Coleman (2002), on highway-rail intersections. They proposed a strategy to minimize the gate delay by adjusting rail-gate closing actions based on the length and locations of dilemma zones. McCoy and Pesti (2003) also proposed detection/warning strategies for safety improvements at high-speed intersections in response to dilemma zones.

In researching literature regarding a driver's decision-making process in response to the yellow-light phase, one important study by Horst and Wilmink, indicated that such a process is governed by a multitude of factors, including driver attitude and emotional states, the crossing ability before the red phase, consequence of stopping and passing, interactions with other drivers, and the vehicle approaching speed. (Horst and Wilmink, 1986). Horst and Wilmink used extensive numerical analyses to illustrate the complex decision-making process and its relations with associated factors with extensive numerical analyses. Their employed parameters were also adopted in some later studies by Milazzo, et al. (2001), Koppa (1992), Shultz, et al. (1998), BMI (2002), and the Green Book (AASHO, 2001).

In classifying driver responses during the yellow-light phase, Shinar and Compton in one of their recent studies (Shinar and Compton, 2004)**,** observed more than 2000 drivers over a total of 72 hours at six intersections. Based on the relative risks, odd ratios, and comparisons with baseline data set, they concluded that (1) male drivers are more likely than female drivers in taking aggressive actions; (2) senior drivers, in comparison with young drivers, are less likely to manifest aggressive driving patterns during a yellow-light phase; and (3) the likelihood of taking aggressive actions increases with the driver's value of time. However, it has also been recognized that a driver's choice of responses in a yellow-light phase may vary with some other factors such as talking on the phone or not talking on the phone. For example, a very recent study by Patten investigated the impacts of mobile-phone usage on drivers from the perspective of cognitive workload and attention resource allocation. (Patten, et al., 2004). It reported that the reaction time of most drivers increases significantly during the use of cellular phones, regardless of the use of hand-free or handheld units.

1.4 Description of Research Plan

In order to accomplish the above research objectives, the entire project was implemented in three phases:

1. Theoretical analysis of dilemma properties,
2. Field observations of driver behavior, and,
3. A statistical analysis of observation results.

The focus of the first phase is to understand the spatial distribution of dilemma zones of drivers with differences in perception/reaction times and vehicle performance characteristics. Research was also conducted on state-of-the-art practices in design of the yellow-light phase.

Mathematical analyses supporting the complex nature of dilemma zones were also researched.

The second phase observed the responses of drivers to the yellow-light phase under different intersection geometric features and traffic conditions. Using a carefully designed field study, the following characteristics of drivers approaching signalized intersections were recorded: gender, age, vehicle type, talking-on-phone or other types of activities, and speed variance in the traffic flow. Researchers also noted the decisions drivers made in response to the yellow-light phase as well as each vehicles acceleration/deceleration rates. Phase Three is designed to statistically analyze the field data recorded in Phase Two. The goal of this stage is to identify the potential relationship between each contributing factor and the resulting responses of drivers approaching the yellow-light phase. The results of this analysis can provide insightful information for tackling the following issues:

- Identifying factors that correlate to a driver's reaction to the yellow-light phase;
- Assessing the need to conduct further field observations in order to reach definitive conclusions regarding driver responses to the yellow phase; and
- Identifying a model for use in classifying behavioral trends of different drivers at signalized intersections and estimating the location and length of dilemma zones.

1.5 Report Organization

Chapter 2 discusses existing theories and procedures used to compute intersection dilemma zones and the duration for a yellow-light phase. The relationships of these two factors are analyzed in detail. More specifically, a mathematical analyses of dilemma zone distributions used under different driving populations and vehicle performance characteristics. It is concluded that intersection dilemma zones are dynamic in nature, and specific locations and lengths actually vary with a driver's perception/reaction times and discrepancies in their acceleration/deceleration rates.

Chapter 3 illustrates the following design of field observation procedures: criteria for survey site selection, placement of survey instruments, data recorded by each camcorder and observer, and methods used to filter collected data and compute a set of target variables for drivers. The field study investigates the behavior of 732 drivers approaching yellow-light phases at nine intersections located across five counties. This chapter also presents a detailed description of geometric and control features associated with each selected intersection.

Additional information recorded during field observations, either directly or indirectly, includes the following primary groups of factors: (1) individual characteristics such as gender, age, and vehicle type; (2) behavioral responses to the signal phase such as the speed evolution from the commence of a yellow-light phase to either a complete stop or accelerated pass at intersections; (3) experienced traffic conditions during the yellow-light phase, including average flow speed, volume, and during the peak period or not; and (4) geometric and control features such as the yellow-light duration, intersection width, and the number of through lanes. This chapter concludes with a list of variables to be statistically analyzed in the next chapter.

Chapter 4 analyzes data observed during the field study. An emphasis on the discrepancies of driver responses to a yellow-light phase and the individual effect of each previously identified factor is analyzed. Driver responses are classified into four distinct types: "aggressive pass," "conservative-stop," "normal-stop," and "normal-pass." This discussion is then followed by a series of single-factor analyses of the impacts of each identified factor to the way a driver responds to the yellow-light phase. The complex interrelationships between a driver's approaching speed, the average traffic flow speed, vehicle types, traffic volume, and intersection geometric features constitute the core of this chapter. Based on the results of exploratory analyses, this chapter concludes with a set of hypotheses associated with driver responses during a yellow-light phase under various traffic conditions.

The primary focus of Chapter 5 is to test hypotheses proposed in Chapter 4, and evaluate the collective impacts of interrelated factors of driver responses to a yellow-light phase. The first group of factors undergoing statistical tests includes traffic volume, average flow speed, yellow-light phase duration, intersection width, number of through lanes, and if peak hours are in effect or not. Driver characteristics, such as age, gender, the approaching speed, and talking-on-phone or other types of activities, constitute the second group for statistical tests. The potential interrelationship of drivers with different types of vehicles and their responses at signalized intersections is the last group of factors tested in this chapter.

Chapter 5 also presents a set of exploratory models with data obtained from the field study and identifies key factors from a series of statistical tests. The applicability of the proposed model to compute the distribution of dilemma zones is also one of the main issues addressed in this chapter.

Chapter 6 summarizes the research results of this study. Recommendations for further research on driver/vehicle response discrepancies during a yellow-light phase and the distribution of intersection dilemma zones constitutes the core of this concluding chapter.

Chapter 2
The Impacts of Driver Responses to a Yellow Phase on the Distribution of Intersection Dilemma Zones

2.1 Introduction

This chapter focuses on exploring the interrelation between the dilemma zone and driver responses to a yellow phase at signalized intersections. All analysis results reported in the ensuing sections intend to address the response discrepancies of drivers during a yellow phase and the distribution of dilemma zones. Through numerical examples, this chapter has concluded that the dilemma zone at an intersection is not a "constant," but a distribution that dynamically varies with the acceleration/ deceleration rate of approaching drivers and their reaction times.

This chapter is organized as follows: the next section describes the conventional concept of intersection dilemma zones. Section 2.3 discusses key assumptions underlying the computation of the conventional dilemma zone. This is followed by an extensive numerical investigation of the dilemma zone distribution under different driving populations and vehicle characteristics in Section 2.4. Concluding comments on the dynamic nature of dilemma zones are summarized in the last section.

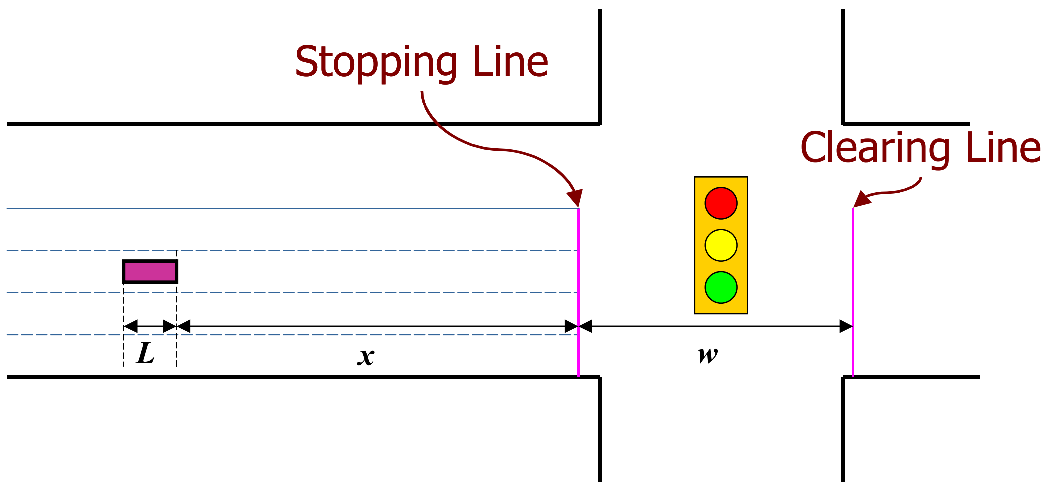
2.2 Conventional Definition of a Dilemma Zone

Consider an intersection shown in Figure 2-1, where key characteristics associated with approaching vehicles, drivers, and intersection features are defined below:

- τ duration of the yellow phase
- δ_1 reaction time-lag of the driver-vehicle complex
- δ_2 decision-making time of a driver
- v_0 approaching speed of vehicles
- x initial distance of a vehicle from the intersection when the yellow phase commences
- a_1 average vehicle acceleration rate
- a_1^* maximum acceleration rate of the approaching vehicles

- a_2 average vehicle deceleration rate
- a_2^* maximum deceleration rate of approaching vehicles
- w intersection width
- L average vehicle length

Figure 2-1 A graphical illustration of an intersection and its approaching vehicles



With basic kinematics equations, one can have the following relations:

- If approaching drivers choose to have a smooth stop, then

$$(x - v_0\delta_2) \geq v_0^2 / 2a_2 \tag{2-1}$$

- If approaching drivers decide to pass the intersection during the yellow duration, then

$$(x + w + L - v_0\delta_1) \leq v_0(\tau - \delta_1) + \tfrac{1}{2} a_1(\tau - \delta_1)^2 \tag{2-2}$$

Note that:

- To stop smoothly at the intersection, the approaching drivers need to exercise the following deceleration rate:

$$a_2 = \tfrac{1}{2} v_0^2 / (x - v_0\delta_2) \tag{2-3}$$

On the other hand, the critical distance required for a smooth "stop" with the given the maximum deceleration rate is :

$$x_c = v_0\delta_2 + v_0^2 / 2a_2^* \tag{2-4}$$

- To pass the intersection during the yellow phase, drivers need to exercise the following acceleration rate:

$$a_1 = 2x/(\tau - \delta_1)^2 + 2(w + L - v_0\tau)/(\tau - \delta_1)^2 \tag{2-5}$$

If without acceleration, the critical required distance for "pass" is:

$$x_0 = v_0\tau - (w + L) \tag{2-6}$$

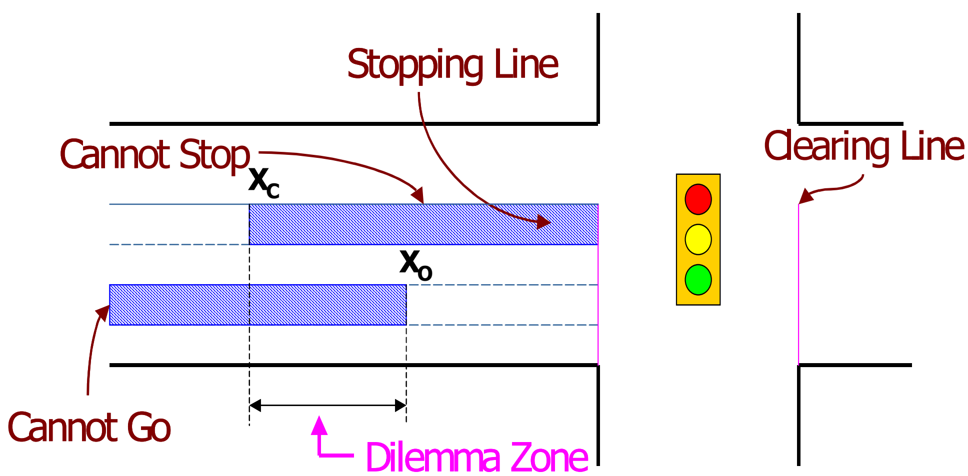
In contrast, the critical distance for "pass" under the maximum acceleration rate is:

$$x_0 = v_0\tau - (w + L) + \tfrac{1}{2}a_1^*(\tau - \delta_1)^2 \tag{2-7}$$

The length and location of the dilemma zone as shown in Figure 2-2 can be expressed as follows:

$$x_{dz} = x_c - x_0 = v_0\delta_2 + v_0^2/2a_2^* - v_0\tau + (w + L) - \tfrac{1}{2}a_1^*(\tau - \delta_1)^2 \tag{2-8}$$

Figure 2-2 A graphical illustration of the dilemma zone at signalized intersections



2.3 Assumptions underlying the Computation of Intersection Dilemma Zones

With the mathematical relations shown in the previous section, it is clear that both the length and location of a dilemma zone may vary with the speed of approaching vehicles if drivers are assumed to always exercise a comfortable maximum acceleration/ deceleration rate after making their decisions. A graphical illustration of the interrelation between a vehicle's approaching speed and the resulting distribution of dilemma zones, using the set of parameters in Table 2-1 is shown in Figures 2-3 and 2-4.

Table 2-1 Parameter values used in examples shown in Figures 2-3 to 2-6

Maximum deceleration rate	a_1^*	11.2	ft/s^2
Maximum acceleration rate at rest	a_{2r}^*	16.0	ft/s^2
Intersection width	w	72	ft
Length of car	L	12	ft
The reaction time-lag of a driver	δ_1	1.14	s
The decision making time of a driver	δ_2	1.14	s

Reference: Gazis et al., 1960

Figure 2-3 The relation between the approaching vehicle speed and the dilemma zone under the yellow phase of 4 seconds

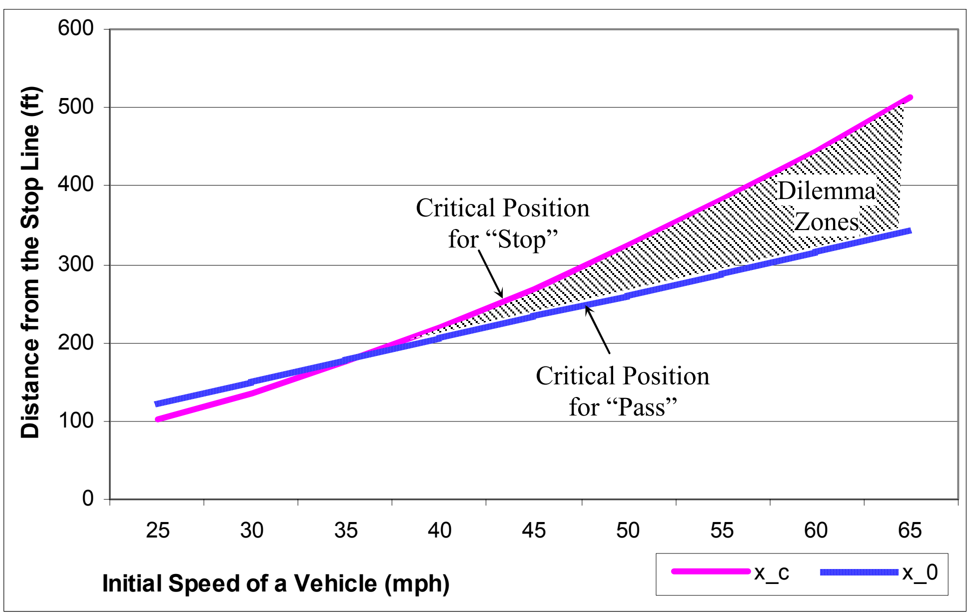
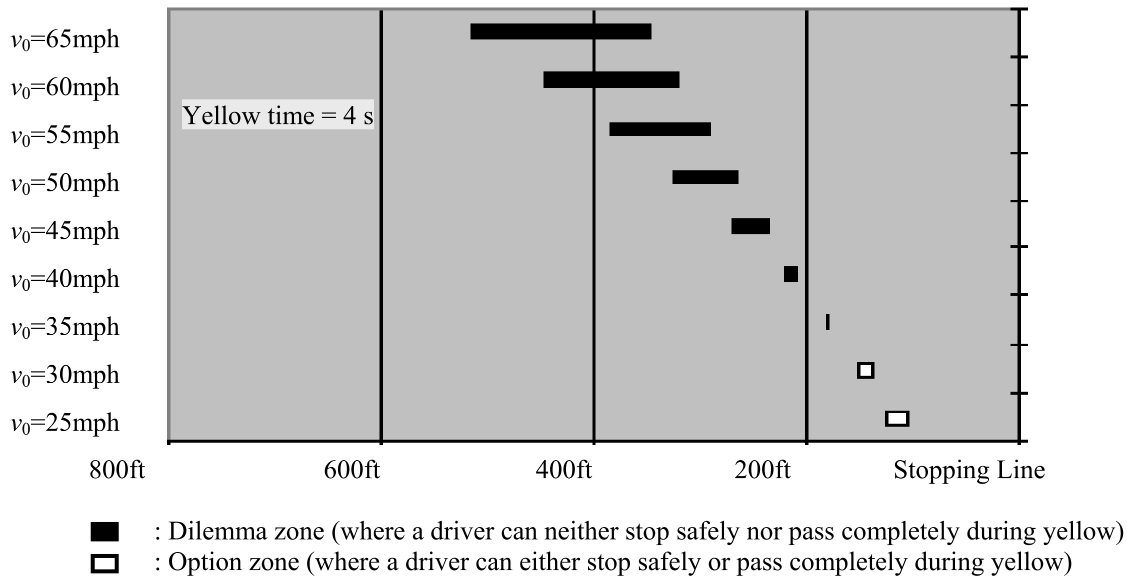


Figure 2-4 A graphical representation of the dilemma zone distribution for different approaching vehicle speeds when yellow phase duration is 4 seconds



Note that with the same set of parameters, one can use the yellow phase duration of 5 seconds to eliminate the dilemma zone for vehicles with an approaching speed equal to or lower than 55 mph, the approximate 85th percentile speed (see Figure 2-5 and Figure 2-6).

Figure 2-5 The relation between the approaching vehicle speed and the dilemma zone under the yellow phase of 5 seconds

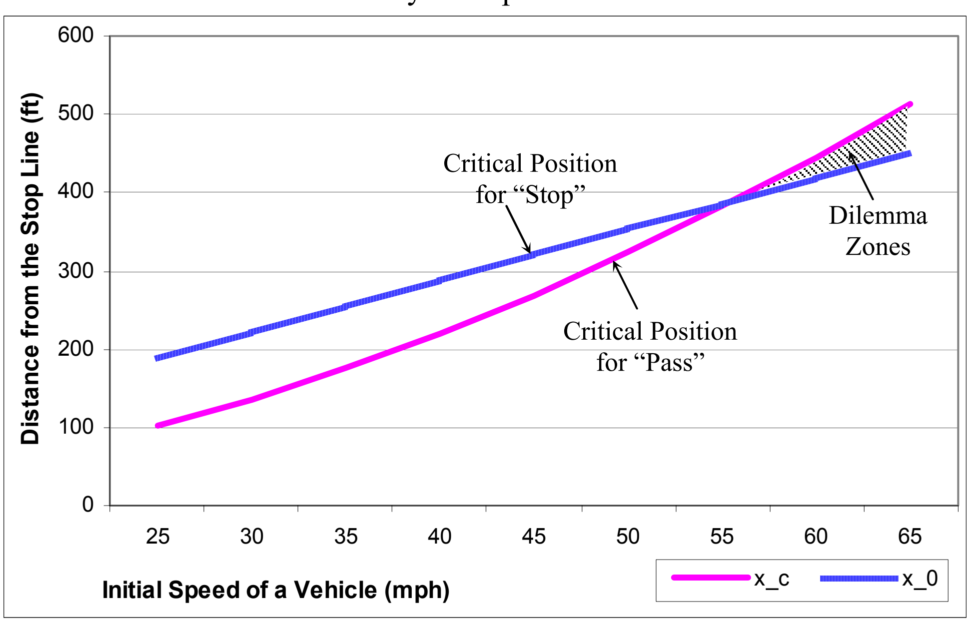
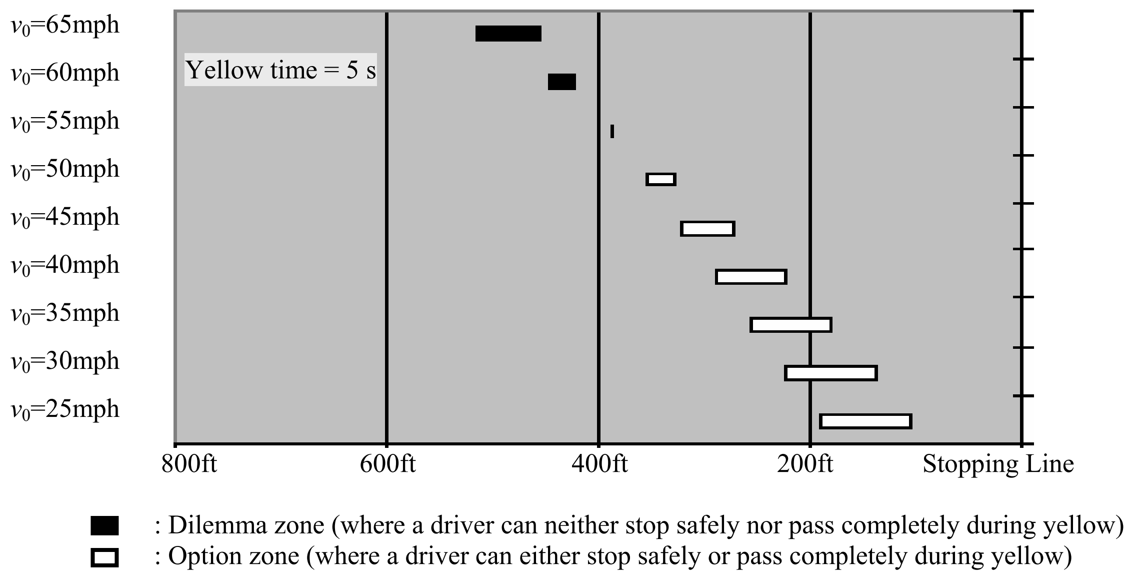


Figure 2-6 A graphical representation of the dilemma zone distribution for different approaching vehicle speeds when yellow phase duration is 5 seconds



It should be mentioned that increasing the yellow phase duration to 5 seconds appears to be able to eliminate the dilemma zone for most drivers if both the reaction times and vehicle acceleration/deceleration rates are identical among the driving populations. However, in reality the parameters, δ_1 and δ_2, δ_1 and δ_2, which represent the perception and reaction times may vary significantly among driving populations. The maximum acceleration/ deceleration rates that are denoted as a_1^* and a_2^* may also be distributed in a wide range among drivers and vehicle types. For example, the acceleration/ deceleration rates of sports utility vehicles are certainly different from those of sport cars. Thus, a variety of the dilemma zones may still exist, even with an increased yellow duration of 5 seconds.

2.4 The Impact of Driver Populations and Vehicle Types on Dilemma Zones

- *The impacts of driver responses (i.e., δ_1 and δ_2)*

McGee et al. (1983) reported that the total perception/ reaction time is the sum of eye movement time, fixation on the hazard time delay, recognition time delay and muscle response delay time (see Table 2-2). They reported that the 85th percentile of driver response times is about 3.19 seconds. By using the upper bound of 3.19 seconds for δ_1 and 1.64 seconds for δ_2 (the sum of the first four values in Table 3-2), Figures 2-7 to 2-14 present the distribution of dilemma zones under the selected range of δ_1 and δ_2 when the approaching speeds are 55mph, 50mph, 45mph, 40mph, respectively. From those graphical illustrations, it is clear that dilemma zones still exist for some driving populations even though the duration of the yellow phase is designed properly with the current practice.

Table 2-2 The components for the 85th percentile of driver response times

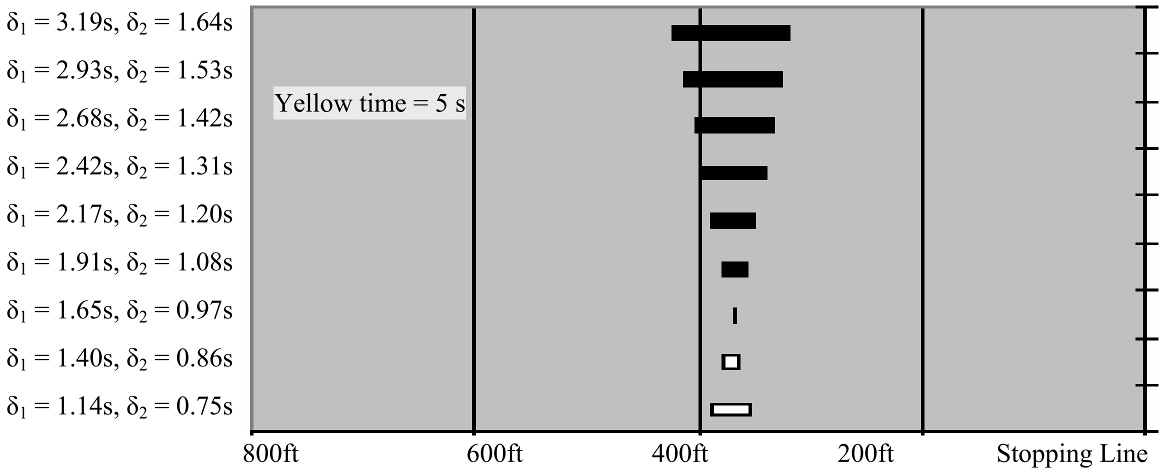
Eye movement delay	0.09 seconds
Fixation delay time	0.20 seconds
Recognition delay time	0.50 seconds
Decision time	0.85 seconds
Muscle response delay	0.31 seconds
Brake reaction time	1.24 seconds

(*Reference: McGee et al., 1983*)

Note that Gazis et al. (1960) assumed that drivers are comfortable with the constant maximum acceleration rate at rest is 16 ft/s^2 (4.86 m/s^2) and the constant deceleration rate of 11.2 ft/s^2 (3.4 m/s^2). They also stated that the acceleration rate also varies with the vehicle speed in the follow relation:

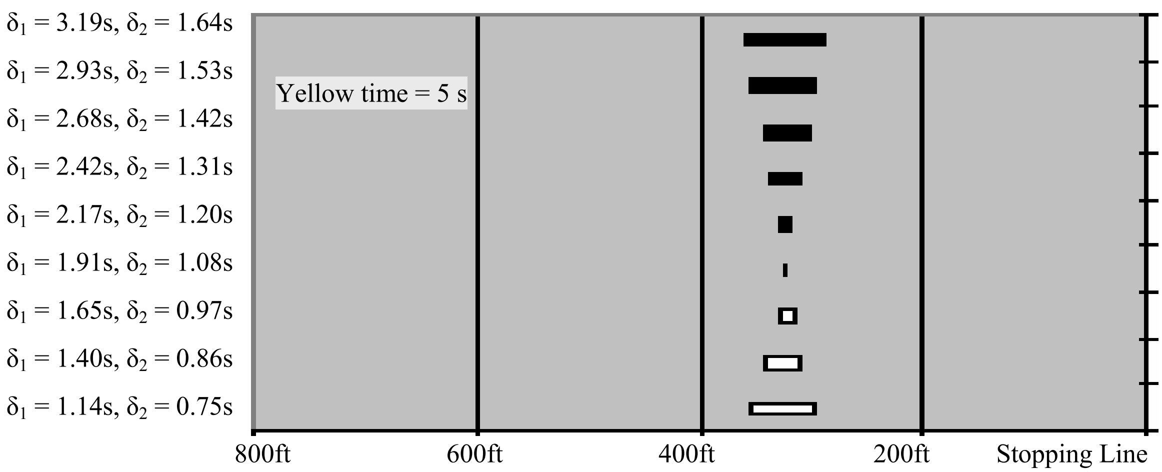
$$a_1(v_0)=(16-0.145*v_0)\,ft/sec^2 = (4.86 - 0.044*v_0)\,m/s^2.$$

Figure 2-7 A graphical representation of the dilemma zones when the yellow phase duration is 5 seconds and the approaching speed is 55mph



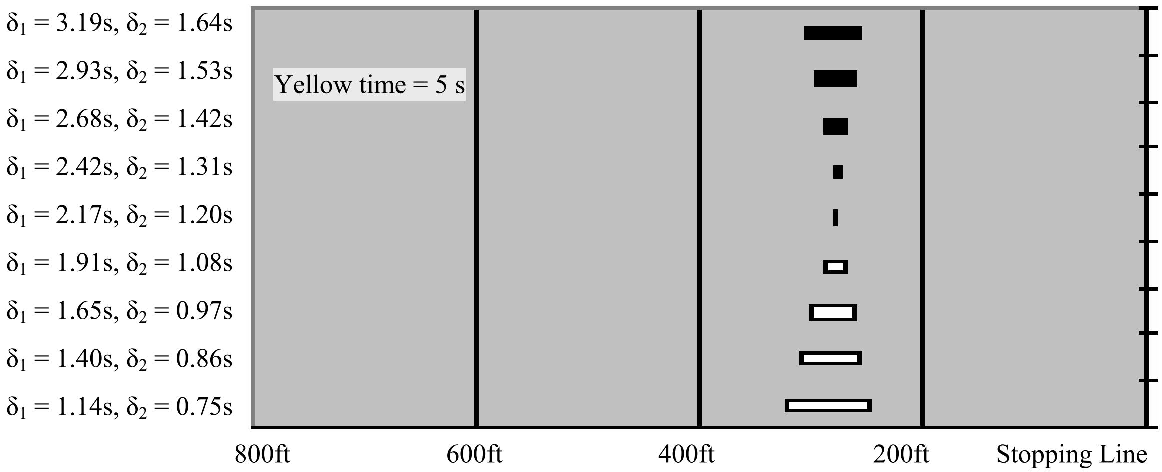
■ : Dilemma zone (where a driver can neither stop safely nor pass completely during yellow)
□ : Option zone (where a driver can either stop safely or pass completely during yellow)

Figure 2-8 A graphical representation of the dilemma zones when the yellow phase duration is 5 seconds and the approaching speed is 50mph



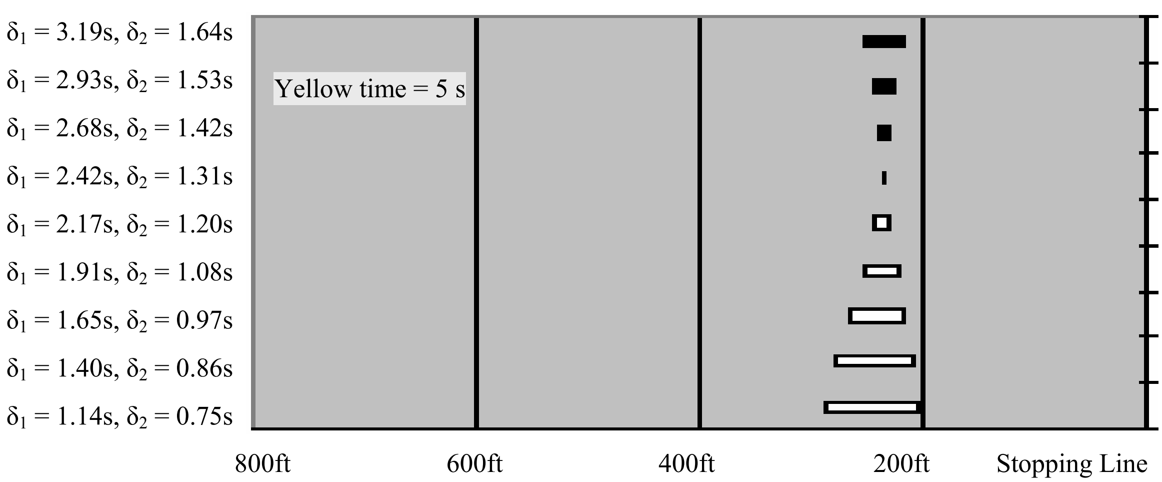
■ : Dilemma zone (where a driver can neither stop safely nor pass completely during yellow)
□ : Option zone (where a driver can either stop safely or pass completely during yellow)

Figure 2-9 A graphical representation of the dilemma zones when the yellow phase duration is 5 seconds and the approaching speed is 45mph



■ : Dilemma zone (where a driver can neither stop safely nor pass completely during yellow)
□ : Option zone (where a driver can either stop safely or pass completely during yellow)

Figure 2-10 A graphical representation of the dilemma zones when the yellow phase duration is 5 seconds and vehicle initial speed is 40mph



■ : Dilemma zone (where a driver can neither stop safely nor pass completely during yellow)
□ : Option zone (where a driver can either stop safely or pass completely during yellow)

- *The impacts of vehicle performance characteristics (maximum acceleration/ deceleration rate)*

As discussed previously, the distribution of dilemma zones also varies with their maximum acceleration/ deceleration rate. Table 2-3 presents the acceleration and deceleration rates used in the numerical analysis. Figures 2-15 through 2-18 presents the example of dilemma zone for each vehicle class with the constant response time. From these graphical illustrations, it is apparent that due to the discrepancy in vehicle performance characteristics some dilemma zones still exist for certain types of vehicles even though the yellow phase is designed properly under with state of the practice.

Table 2-3 Acceleration and deceleration rates for nine vehicle classes (ft/s^2)

Vehicle Class	Acceleration	Deceleration
Sports Utility <45K ($CAD)	9.5	9.9
Sports Utility >45K ($CAD)	9.9	10.4
Station Wagon / MPV	10.0	10.7
Sports / Performance Car	15.1	10.9
Sports Coupe / Sedan >35K ($CAD)	12.9	11.2
Sports Coupe / Sedan <35K ($CAD)	11.9	10.8
Luxury Car	11.9	11.0
Family Vehicle	9.1	10.1
Economy Car	8.9	9.4

(*Reference: the vehicle performance test summary of "Automobile Journalists Association" of Canada*)

Figure 2-14 A graphical representation of the dilemma zones when the yellow phase duration is 5 seconds and the vehicle approaching speed is 55mph

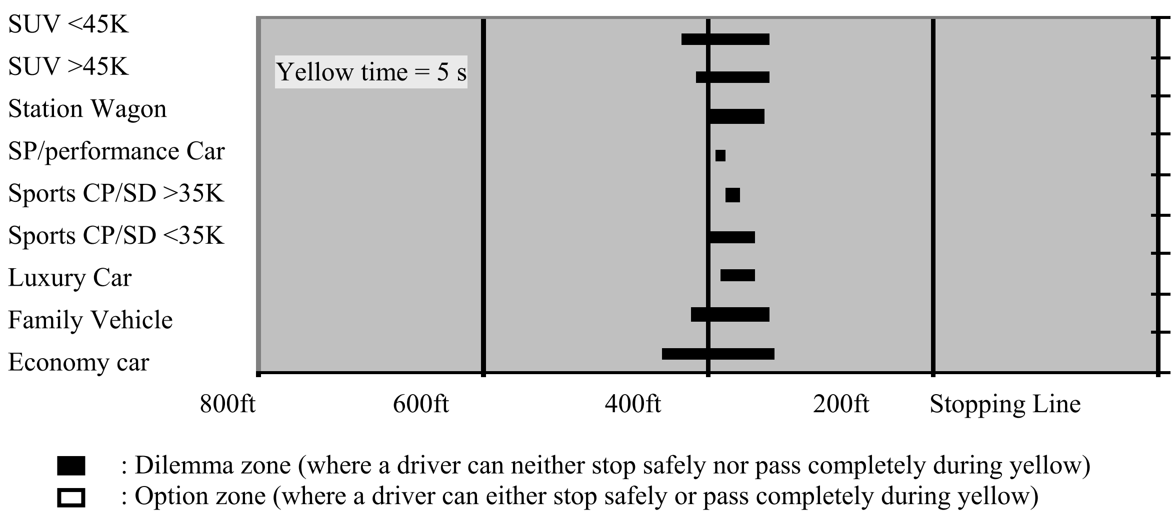


Figure 2-15 A graphical representation of the dilemma zones when the yellow phase duration is 5 seconds and the vehicle approaching speed is 50mph

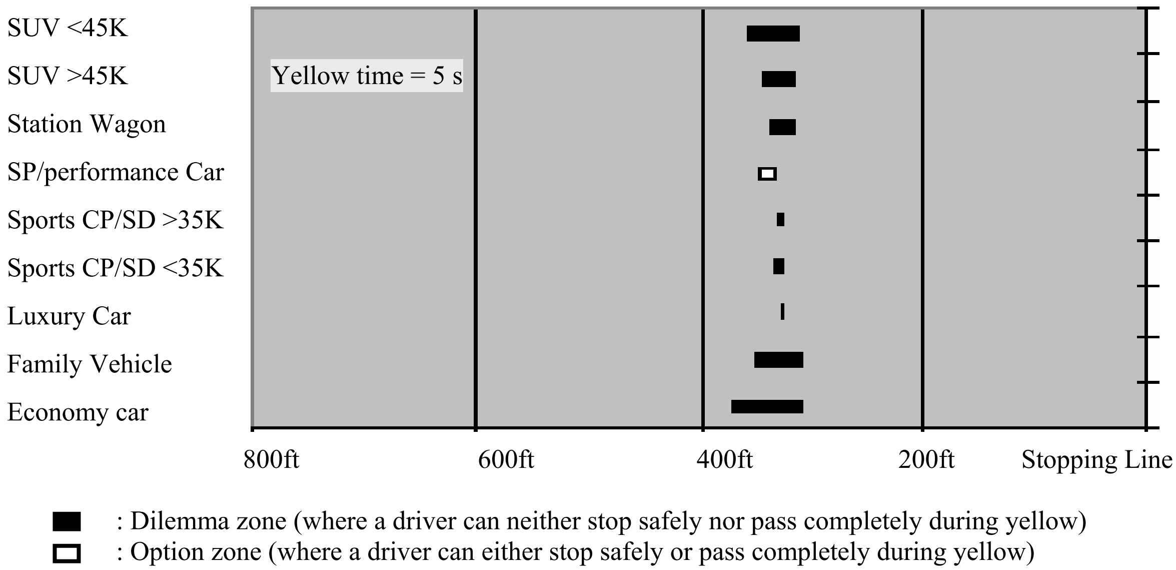


Figure 2-16 A graphical representation of the dilemma zones when the yellow phase duration is 5 seconds and the vehicle approaching speed is 45mph

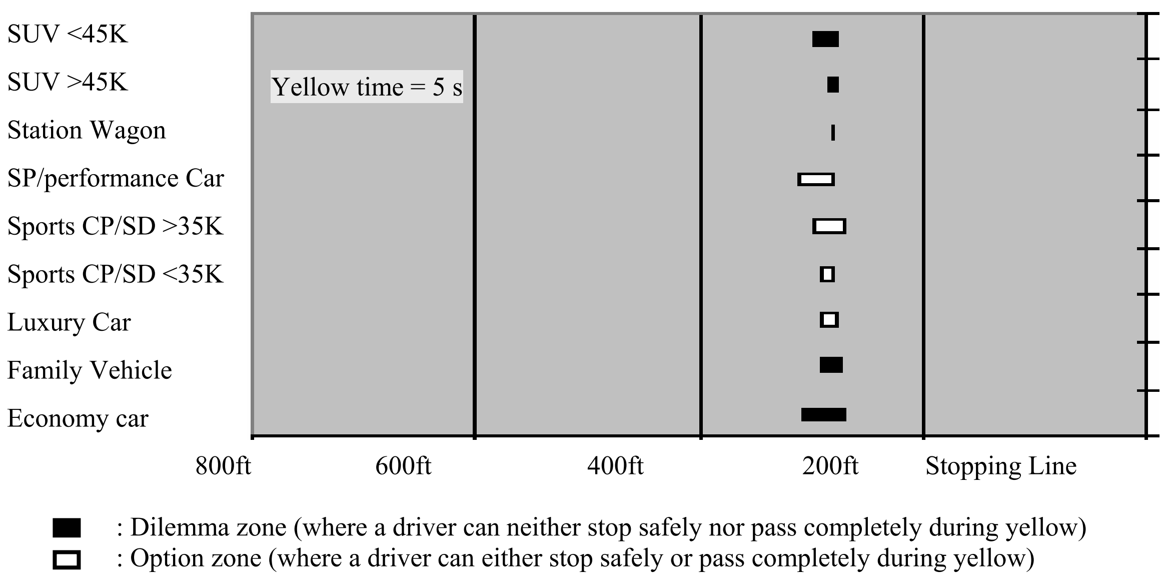
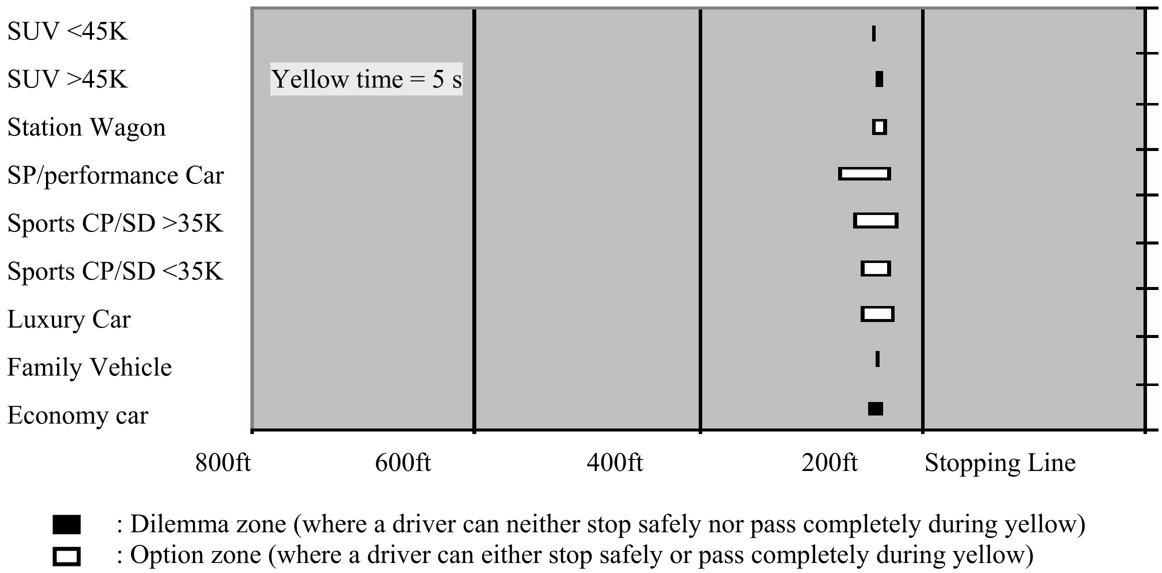


Figure 2-17 A graphical representation of the dilemma zones when the yellow phase duration is 5 seconds and the vehicle approaching speed is 40mph



2.5 Conclusions

The chapter has investigated the complex interrelations between driver response times, vehicle approaching speeds, and the resulting distribution of intersection dilemma zones. It has concluded that intersection dilemma zones are dynamic in nature, as their locations and ranges may vary with the behavior of driving populations and the deceleration/acceleration rate of their vehicles. The existing practice for computing dilemma zones is based on the assumption that most drivers have identical perception/ reaction times and most approaching vehicles have the approximately same level of performance characteristics such as acceleration/ deceleration rate. Hence, an increase in the yellow phase duration alone may not be sufficient for eliminating intersection dilemma zones unless driving populations and the vehicle types in the traffic flow are quite uniform.

Chapter 3
Methodology

3.1 Introduction

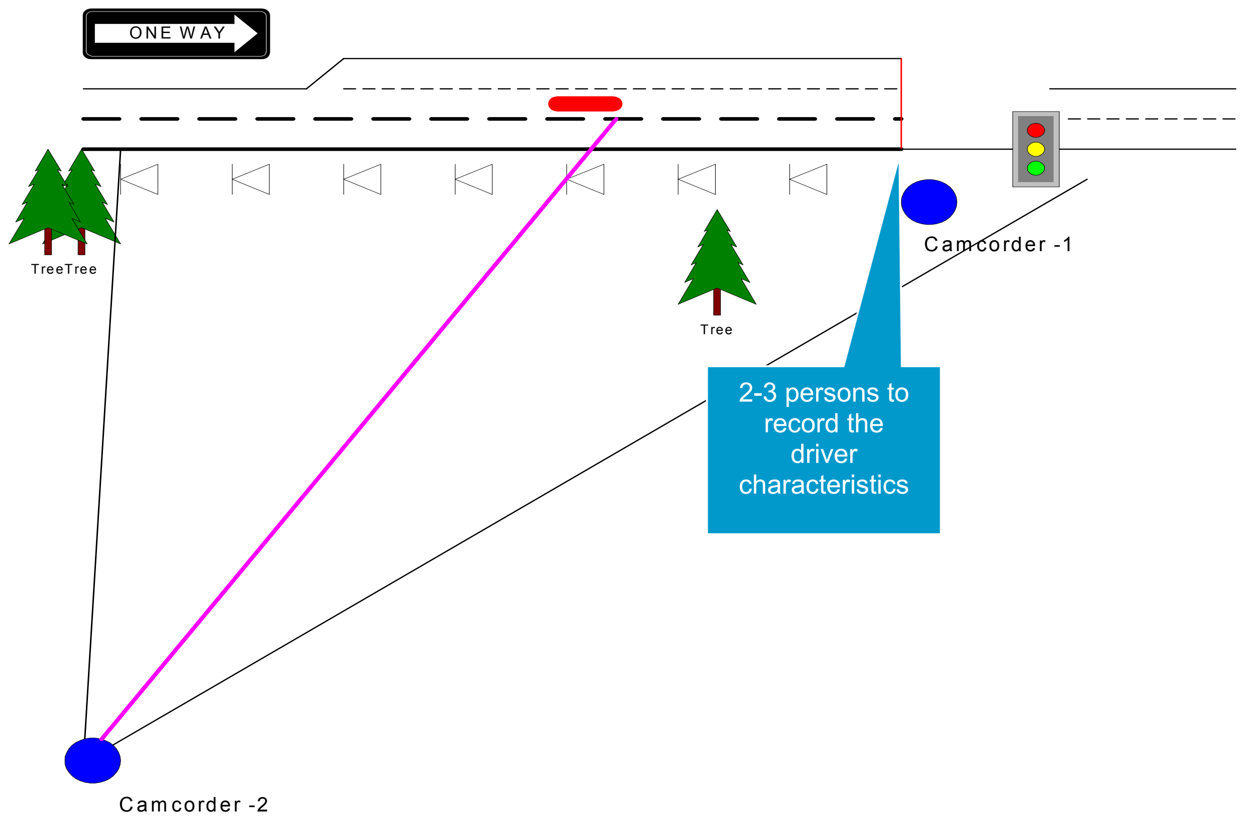
In order to investigate the response of drivers approaching a yellow-light phase, this study conducted field surveys at nine signalized intersections. The information collected from each field observation included: driver characteristics, vehicle types, intersection geometric features, and driver reactions to the yellow-light phase. A detailed description of the field surveys for 732 drivers will be presented in the next section. A summary of variables was recorded, that identified traffic flow characteristics and the individual actions of each driver. Data quality assessments and potential improvements for further surveys are reported in the last section.

3.2 Data Collection Method

Figure 3-1 illustrates an example of the way field observations of driver behaviors were collected. Two digital camcorders were located at specific distances from the intersection. Camcorder-1 was used to measure approaching vehicle speeds, and driver and vehicle related characteristics. Camcorder-2 was placed near to the stop line and used to collect information such as vehicle types (e.g., SUV, pick-up truck, minivan, sports vehicle) and colors. Six orange cones were placed on the outside shoulder of the intersection, and used to monitor the spatial evolution of each approaching vehicle toward the intersection. In order to minimize potential measurement errors, the location of each camcorder was vital in computing sufficient latent distance for speed. Two to three observers were stationed at the stop line and were responsible for recording driver characteristics such as gender, approximate age, and driver activities (such as talking on cell phone).

Because of certain logistics in design, the time lapse between two consecutive video frames is 1/29.97 seconds. Therefore, measurement errors associated with each vehicle's passing time over consecutive traffic cones are within ±1/29.97 seconds. The time duration of a vehicle to pass each cone is subjected to a potential measurement error of ±2/29.97 seconds. Considering all possible errors in the distance measurement, this study concludes that the resulting speed measurements will vary within about 2.5 percent of the actual speed.

Figure 3-1 An example design for field data collection



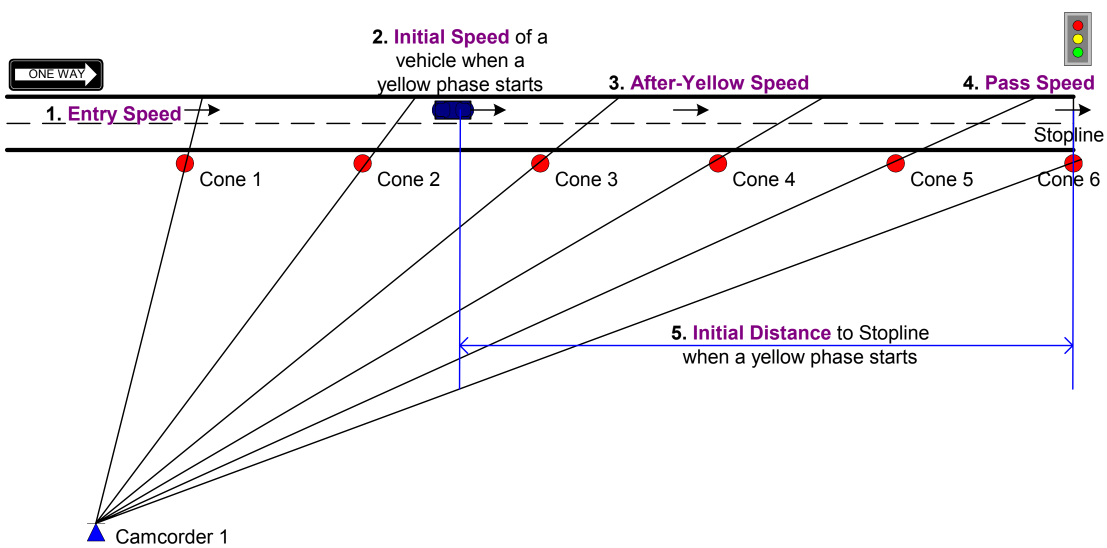
3.3 Field Observation Data

Field observations focused on drivers who approached an intersection during a yellow-light phase. Field observers were responsible for recording driver reactions regardless whether they have finally passed through or stopped at the intersection. The format in which field observers collected information is presented below:

- Intersection traffic characteristics and geometric features:
    - Yellow-light phase duration
    - Cycle length
    - Time of the day
    - Traffic volume during each cycle

    - Distances between consecutive traffic cones and between the far-side camcorder and cones
- Vehicle characteristics of responding driver-vehicle units
    - Vehicle type (SUV, pick-up truck, minivan, and passenger cars)
    - Vehicle model and vehicle colors
    - The time instants when a vehicle passes each cone
    - Vehicle entry speed (see Figure 3-2)
    - Vehicle initial speed (see Figure 3-2)
    - Vehicle after-yellow-light speed (see Figure 3-2)
    - Vehicle passing speed (see Figure 3-2)
    - Lane position (which lane the vehicle is on) (through lanes only)
    - Vehicle initial distance (initial position) to the stopline (see Figure 3-2)
- Driver characteristics
    - Driver's gender
    - Driver talking on cell phone or not
    - Driver is young (<21), senior (>65), or neither. (Judging by appearance)

Figure 3-2 Graphical illustrations of entry speed, initial position, and initial distance



As shown in Figure 3-2, five speed-related variables (initial distance, entry speed, initial speed, after-yellow-light speed and pass speed) were recorded and computed based on cone positions from the Camcorder**.** Traffic volumes during each cycle and yellow-light phase duration were also recorded. For convenience of synchronization between two camcorders, those field observers also record the signal phases with the nearside camcorder**.**

3.4 Selection of Sample Intersections

The main reference used in selecting sample intersections were based on the frequency of traffic signal related crashes over the past five years. Five intersections were selected based on the rank of traffic signal related crashes in 2001. The convenience for placing field survey equipments at the intersection was also considered.

Table 3-1 Crash frequency at five intersections

Prefix	#	mp_road_name	mp_int_rte_name	1997	1998	1999	2000	2001	Rank
US	29	COLUMBIA PIKE	STEWART LA	1	0	0	0	22	2
MD	355	FREDERICK RD	SHADY GROVE RD	21	16	9	18	17	4
US	40	BALTO NATIONAL PIKE	ROGERS AVE	15	16	17	16	16	5
MD	4	PENNSYLVANIA AVE	SILVER HILL RD	6	6	12	19	16	5
MD	193	GREENBELT RD	HANOVER PKWY	11	4	6	4	11	10

With the assistance from MSHA Safety Division, four additional intersections with high crash frequencies were also included in this study. All intersections included in this study are listed as follows:

- Kenilworth Ave. (MD201) at Crescent Rd, in Prince Georges County
- Pennsylvania Ave. (MD4) at Silver Hill Rd, in Prince Georges County
- Fredrick Rd. (MD355) at Shady Grove Rd., in Montgomery County
- Laurel Fort Meade Rd. (MD198) at Whiskey Bottom Rd., in Anne Arundel County
- Baltimore National Pike (US40) at Rogers Ave., in Howard County
- York Rd. (MD45) at Burke Rd., in Baltimore County
- Columbia Pike (US29) at Stewart Ln., in Montgomery County
- New Hampshire Ave. (MD650) at Sandy Spring Rd. (MD198), in Montgomery County
- Greenbelt Rd. (MD193) at Hanover Pkwy., in Princes Georges County

A summary of information associated with each intersection is shown in Tables 3-2 to 3-10 along with graphical illustrations in Figures 3-3 to 3-11.

Table 3-2 Kenilworth Ave. (MD201) at Crescent Rd.

Cycle length	From the observations on June 16th, 2003 100 seconds for the AM peak until 8:30am 120 seconds around 8:30am From the observations on May 14th, 2003 100 seconds before 5pm 120 seconds after 5pm
Yellow-light phase duration	5 seconds
Speed limit	40 MPH
Observed sample drivers	27

Figure 3-3 A graphical illustration of the intersection of MD201 at Crescent Rd.

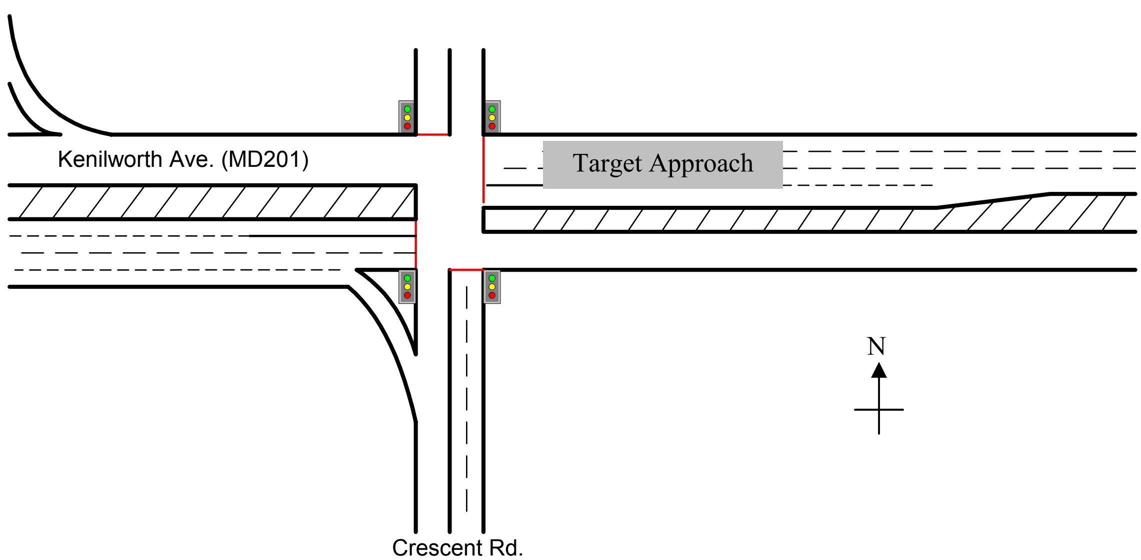


Table 3-3 Pennsylvania Ave (MD4) at Silver Hill Rd.

Cycle length	150 seconds regularly, and between 132 seconds and 198 seconds
Yellow-light phase duration	5 seconds
Speed limit	55MPH
Observed sample drivers	126

Figure 3-4 A graphical illustration of the intersection of MD4 at Silver Hill Rd.

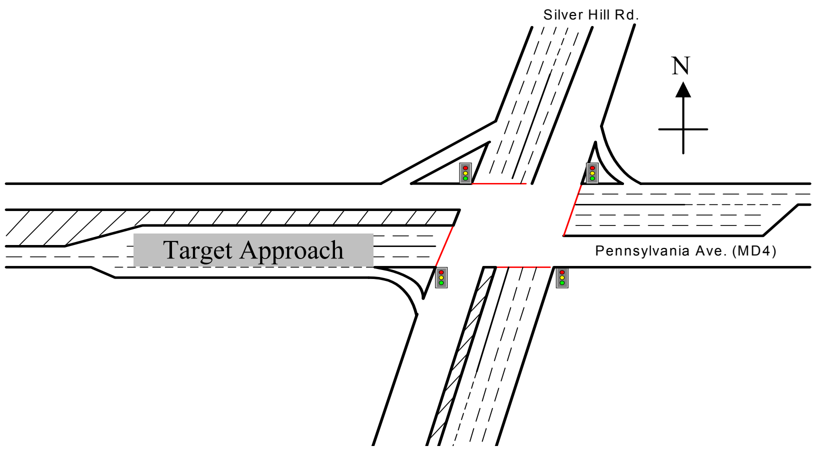


Table 3-4 Fredrick Rd. (MD355) at Shady Grove Rd.

Cycle length	150 seconds
Yellow-light phase duration	4 seconds
Speed limit	40 MPH
Observed sample drivers	94

Figure 3-5 A graphical illustration of the intersection of MD355 at Shady Grove Rd.

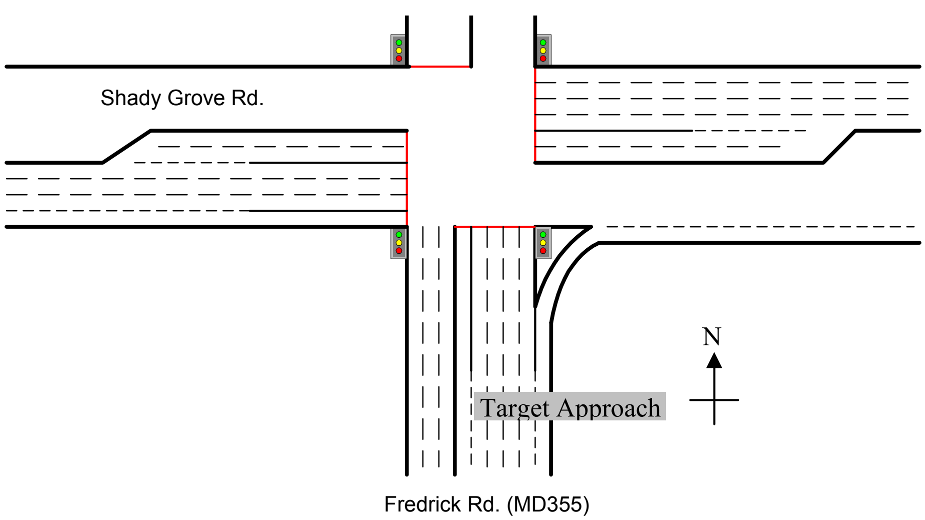


Table 3-5 Laurel Fort Meade Rd. (MD198) at Whiskey Bottom Rd.

Cycle length	150 seconds
Yellow-light phase duration	4 seconds
Speed limit	40 MPH
Observed sample drivers	15

Figure 3-6 A graphical illustration of the intersection of MD198 at Whiskey Bottom Rd.

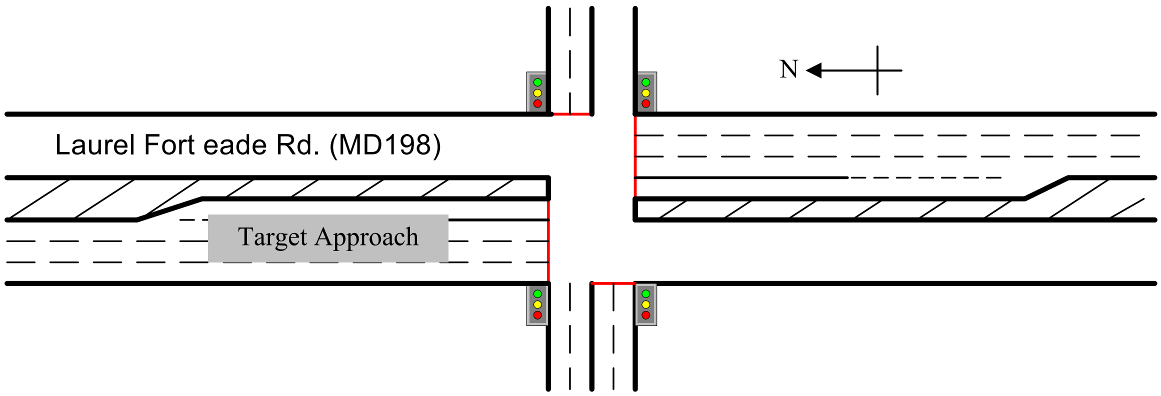


Table 3-6 Baltimore National Pike (US40) at Rogers Ave.

Cycle length	150 seconds
Yellow-light phase duration	5 seconds
Speed limit	45 MPH
Observed sample drivers	61

Figure 3-7 A graphical illustration of the intersection of US40 at Rogers Ave.

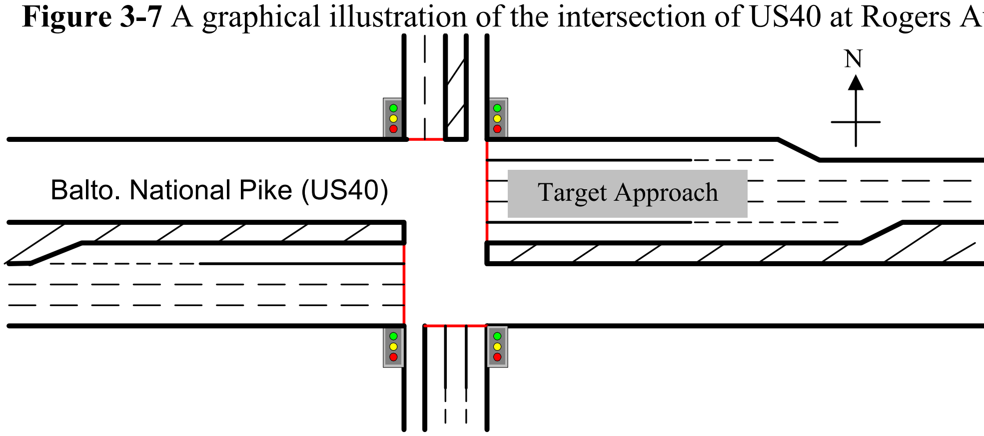


Table 3-7 York Rd. (MD45) at Burke Rd.

Cycle length	130 seconds
Yellow-light phase duration	4 seconds
Speed limit	35 MPH
Observed sample drivers	10

Figure 3-8 A graphical illustration of the intersection of MD45 at Burke Rd.

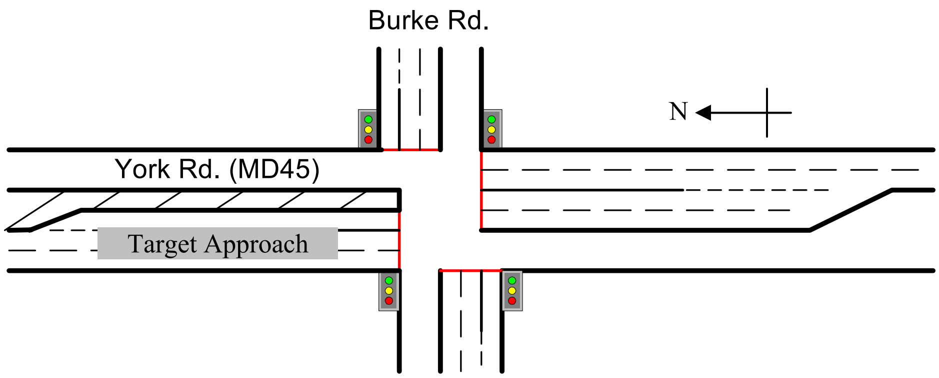


Table 3-8 Columbia Pike (US29) at Stewart Ln.

Cycle length	110 seconds
Yellow-light phase duration	5 seconds
Speed limit	45 MPH
Observed sample drivers	104

Figure 3-9 A graphical illustration of the intersection of US29 at Stewart Ln.

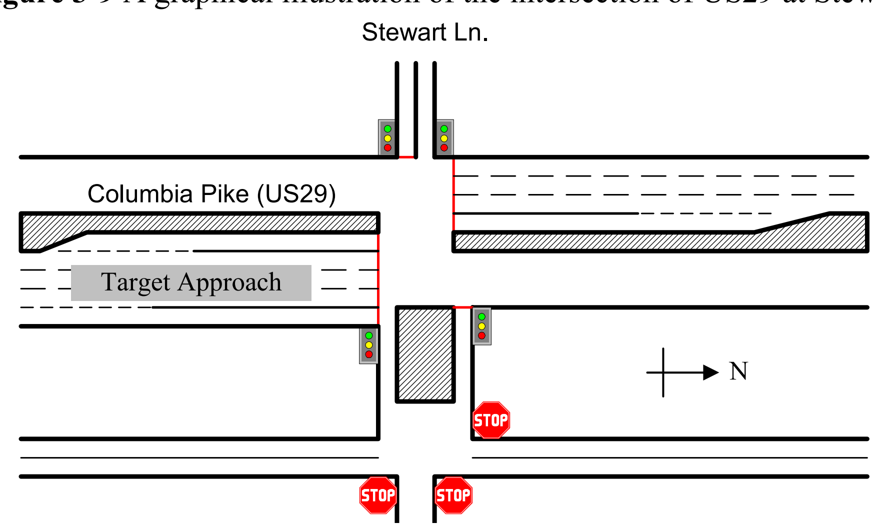


Table 3-9 New Hampshire Ave. (MD650) at Sandy Spring Rd. (MD198)

Cycle length	150 seconds and adaptive
Yellow-light phase duration	4 seconds
Speed limit	45 MPH
Observed sample drivers	59

Figure 3-10 A graphical illustration of the intersection of MD650 at Sandy Spring Rd.

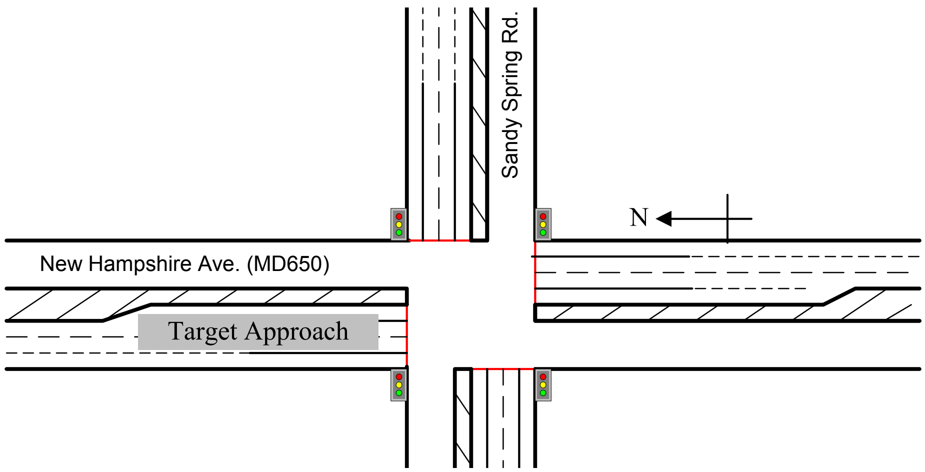


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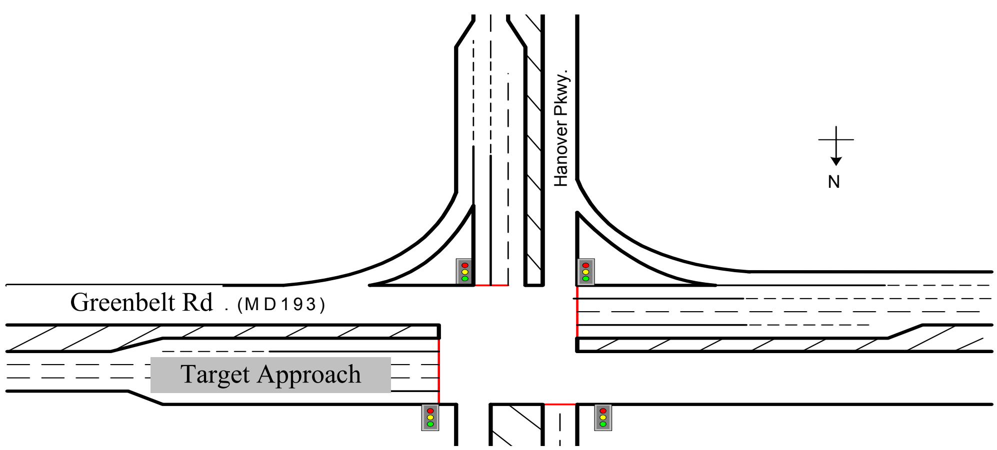
Table 3-10 Greenbelt Rd. (MD193) at Hanover Pkwy.

Cycle length	150 seconds
Yellow-light phase duration	5 seconds
Speed limit	45 MPH
Observed sample drivers	268

Figure 3-11 A graphical illustration of the intersection of MD193 at Hanover Pkwy.



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3.5 Conclusions

In conclusion, the design concept defined in this chapter was used to collect the responses of more than 700 drivers approaching yellow-light phases at nine intersections across the region. Despite the exploratory nature of the field observations, a significant amount of conclusive data regarding driver characteristics, roadway traffic conditions, and geometric features of an intersection were yielded. Such information can help researchers to further understand the interrelationships between vehicle performance characteristics, driver responses to a yellow-light phase, and the effects of surrounding traffic conditions.

Chapter 4
Classifying Driver Behavior at Signalized Intersections

4.1 Introduction

This chapter analyzes data obtained from field observations for 732 drivers at 9 intersections across the region. Due to technical difficulties in retrieving the volume data associated with 67 sample drivers, the results presented in this chapter are based on those remaining 665 observations.

This analysis will address the following critical issues regarding driver responses to a yellow-light phase:

- Classifying driver behavior based on pre-determined times to reach an intersection while approaching a yellow-light phase;
- Identifying the impacts of individual characteristics such as gender, age, to drivers' responses to the yellow-light phase;
- Identifying how a driver's response can be affected by the approaching speed of a vehicle and existing traffic conditions; and,
- Identifying potential influences a driver's vehicle has on the decision-making process while approaching a yellow-light phase.

Preliminary research findings for each of the above issues are presented in the following sections. Comparisons of drivers' responses to the yellow-light phase at sample intersections are also presented. Concluding comments, and proposed tests used to assess the impacts of interrelated critical factors are summarized in the last section.

4.2 The Classification of Driver Behavior at Signalized Intersections

Driver behavior at signalized intersections can be classified as "aggressive," "conservative" or " normal." The criteria used to classify driver behavior are mostly qualitative in nature. This study attempts to first, classify sample drivers into distinct groups based on their responses to a yellow-light phase, and second, identify key characteristics of each driver group and the associated traffic environment factors.

During field observations, drivers approaching a yellow-light phase either passed through or stopped at an intersection and were grouped into two groups, "*Pass*" or "*Stop*." Table 4-1 summarizes the relationships between the two groups.

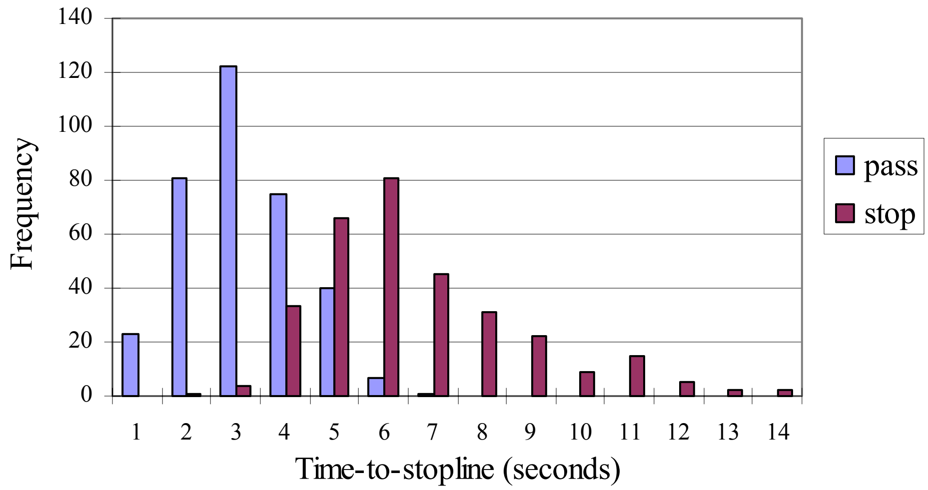
As shown in the group "*Pass,*" about 86% of drivers, decided to continue through the intersection when approaching the yellow-light phase. Drivers in this group reached the intersection in less than 4 seconds without acceleration. The remaining 14% of drivers in this group needed more than 4 seconds to go through the intersection. These drivers decided to aggressively accelerate and beat the yellow-light phase. Those drivers, as highlighted in the table, are classified as "*aggressive drivers*."

A similar pattern can also be observed from those drivers in the *"Stop*" group, where about 12% of drivers in this group could go through the intersection within 4 seconds but decided to stop. Those individuals making conservative decisions are classified as "*conservative drivers*" in the remaining analysis.

Table 4-1 Distribution of drivers by "time-to-stopline" in seconds

	"Pass" group			"Stop" group		
Time to the stop line (seconds)	Number of Samples	Percent	Cumulative %	Number of Samples	Percent	Cumulative %
0-1	23	6.59%	6.59%	0	0.00%	0.00%
1-2	81	23.21%	29.80%	1	0.32%	0.32%
2-3	122	34.96%	64.76%	4	1.27%	1.58%
3-4	75	21.49%	86.25%	33	10.44%	12.03%
4-5	40	11.46%	97.71%	66	20.89%	32.91%
5-6	7	2.01%	99.71%	81	25.63%	58.54%
6-7	1	0.29%	100.00%	45	14.24%	72.78%
7-8	0	0.00%	100.00%	31	9.81%	82.59%
8-9	0	0.00%	100.00%	22	6.96%	89.56%
9-10	0	0.00%	100.00%	9	2.85%	92.41%
10-11	0	0.00%	100.00%	15	4.75%	97.15%
11-12	0	0.00%	100.00%	5	1.58%	98.73%
12-13	0	0.00%	100.00%	2	0.63%	99.37%
>13	0	0.00%	100.00%	2	0.63%	100.00%
Total samples	349		100.00%	316		100.00%

Figure 4-1 A graphical comparisons of the number of drivers choosing to stop or pass (all samples)



The estimated time needed for a driver to the stop at the intersection stop line is based on a vehicle's initial approaching speed and location when the signal turns to yellow. The relationship between the estimated time to the stop line and a driver's decision to pass or stop is illustrated in Figure 4-1, where most drivers in the "*Stop*" group took 5 seconds or longer to reach their intersections. In contrast, the majority of vehicles in the *"Pass*" took 4 seconds or less to go through their intersections: that is generally shorter than the provided yellow-light duration.

To ensure that the above research findings do not vary with the length of the yellow-light phase, Figures 4-2 and 4-3 have further analyzed the same results for drivers at intersections having yellow-light phases of either 4 or 5 seconds. As evident in the following graphs, the time of 4 seconds remains the critical threshold for most drivers to make their decision to either pass or stop.

Figure 4-4 illustrates the relationship between the cumulative statistics of "pass" and "stop" groups under different time durations to the stop line. It again shows that the duration of 4 seconds seems to be a critical point for classifying driver responses during a yellow-light phase.

Figure 4-2 A graphical comparisons of the number of drivers choosing to stop or pass (yellow-light time = 4 seconds)

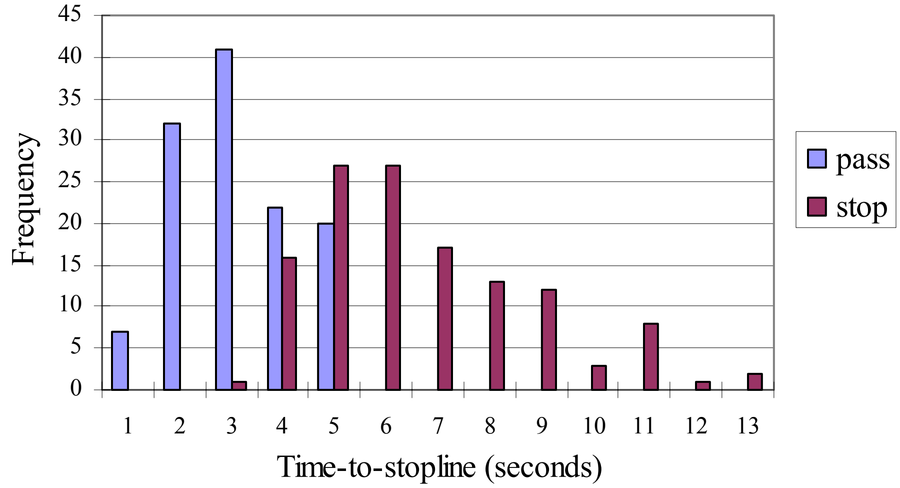


Figure 4-3 A graphical comparisons of the number of drivers choosing to stop or pass (yellow-light time = 5 seconds)

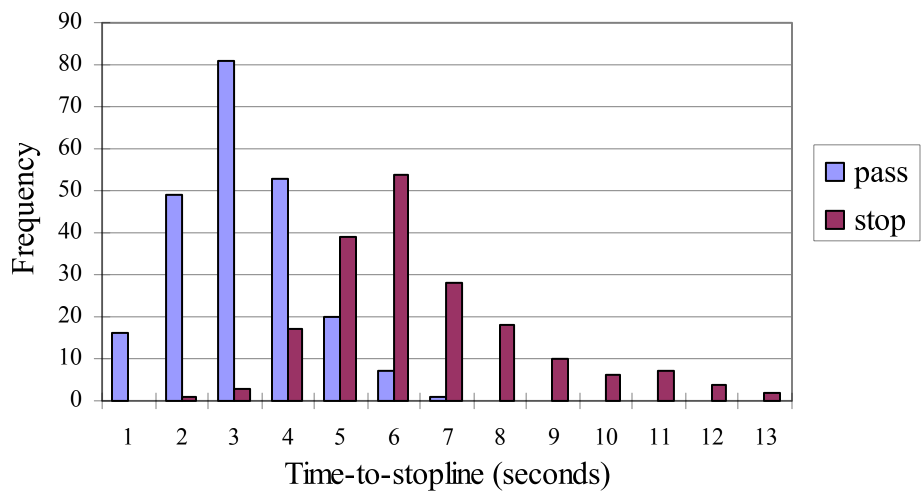
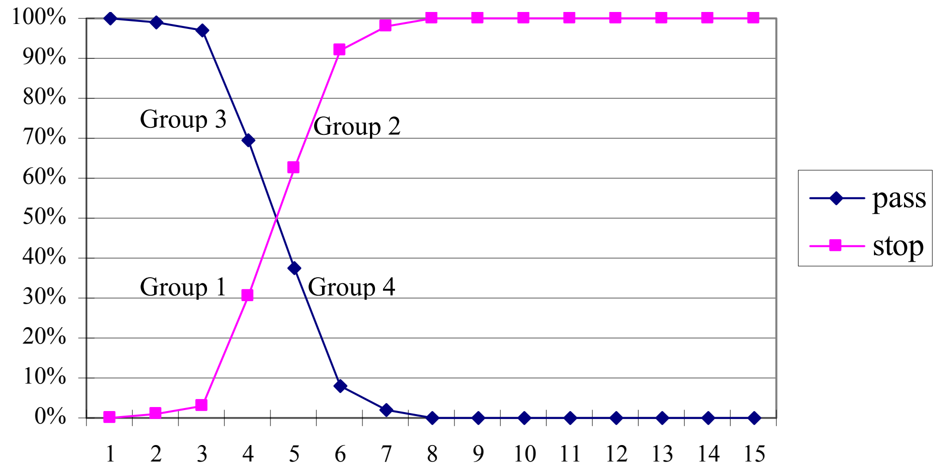


Figure 4-4 A graphical illustration of drivers in each classified group based on the cumulative statistics of "pass" and "stop" at different times to the stop line



Based on the relationships illustrated in Figure 4-4, drivers observed in this study are classified into the following 4 groups:

Group 1: *"Conservative-Stop"* -- Drivers that decided to stop even though they could have proceeded through the intersection during the yellow-light phase without changing their speed.

Group 2: *"Normal-Stop*"-- Drivers that decided to stop in a reasonable amount of time in view of the required time (time-to-stopline ≥ 4 seconds) to pass the intersection.

Group 3: "*Normal-Pass*"—Drivers that decided to pass through the intersection, despite the short amount of time needed to completely pass through the intersection. (time-to-stopline ≤ 4 seconds).

Group 4: "*Aggressive-Pass*"-- Drivers that decided to aggressively accelerate and pass the intersection during a yellow-light phase-- even though they were quite far away.

A graphical illustration of drivers in each of the above groups can be seen in Figures 4-5 to 4-7.

Figure 4-5 Field data vs. theoretically safe stop distances for all "stop" vehicles under different approaching speeds

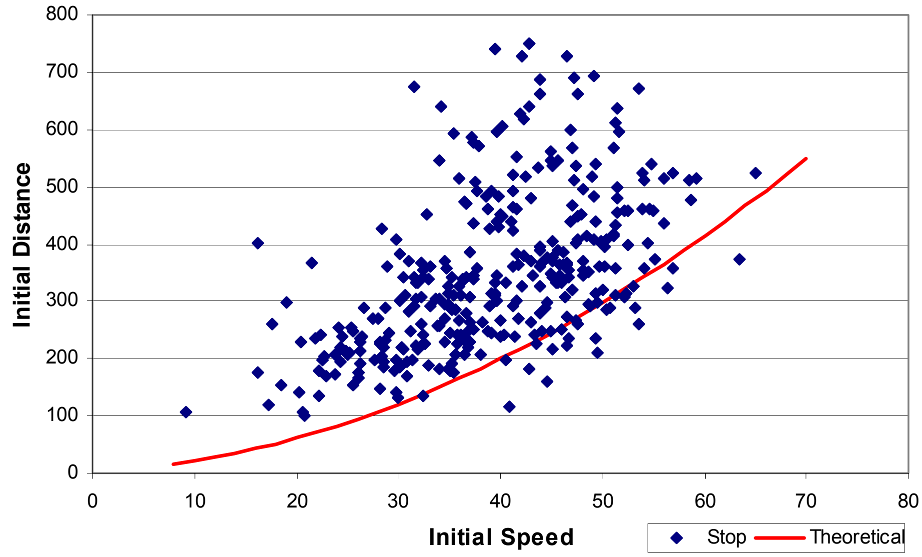


Figure 4-6 Field data vs. theoretical critical distances for "pass" vehicles under different approaching speeds (yellow-light duration = 4 seconds)

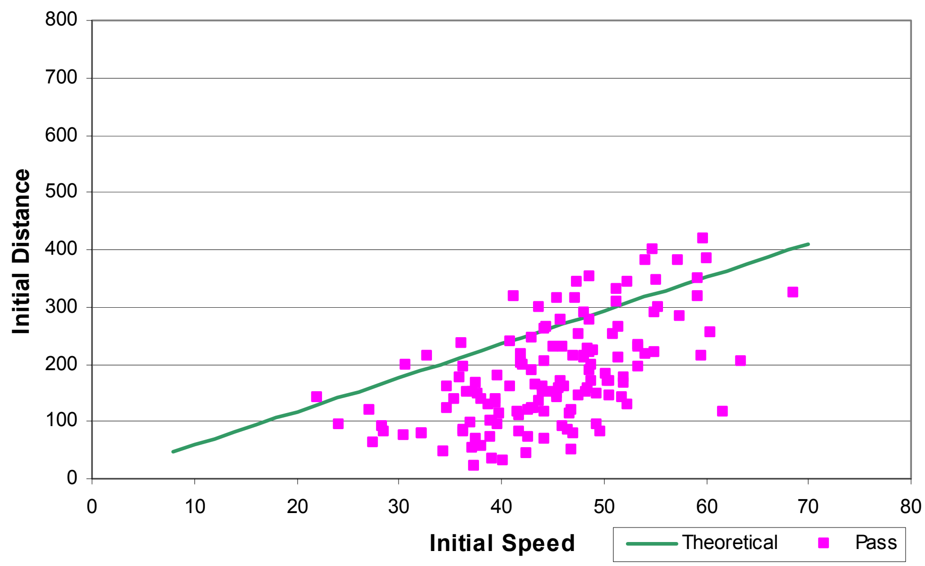
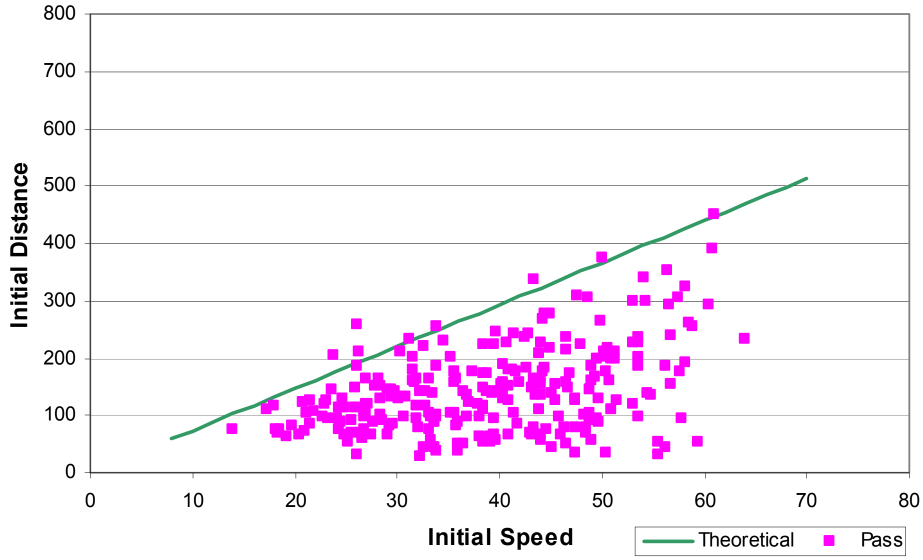


Figure 4-7 Field data vs. theoretical critical distances for "pass" vehicles under different approaching speeds (yellow-light duration = 5 seconds)



The above classifications are used as the basis in exploring the relationships between driver characteristics and their responses to a yellow-light phase under various traffic conditions and intersection geometric features.

The "normal-stop" and "normal-pass" groups are further divided into subgroups of drivers who made reasonable decisions based on their acceleration/deceleration rate (Benson, 2003; Bennett, 1994).

- Normal-stop Group:

- "*Sharp-stop*" subgroup: Drivers who exercised a deceleration rate of more than 11.2 ft/s^2.
- "*Smooth-stop*" subgroup: Drivers whose deceleration rate was less than 11.2 ft/s^2.

- Normal-pass Group:

- "*Deceleration-pass*" subgroup: Drivers whose deceleration rate was more than 5 ft/s^2 in passing the intersection.
- "*Acceleration-pass*" subgroup: Drivers whose acceleration rate was more than 5 ft/s^2 to pass through the intersection.
- "*Constant-pass*" subgroup: Drivers who kept a constant speed during the yellow-light phase to pass through the intersection.

4.3 Individual Driver Characteristics in Response to A Yellow-light Phase

Due to both the constraints of data availability and quality, the analysis of individual driver characteristics will explore only the impacts of the following factors: gender, age (young and senior drivers), talking on cellular phone or not talking on cellular phone.

Gender Factor

Table 4-2 classifies drivers based on gender. As noted in the sample size distribution, there are a total of 48 individuals being classified in Group 4 as aggressive drivers. It is about 7.22% out of a total of 665 sample drivers. Among those 48 individuals, 27 are male. The distribution of male drivers in the “aggressive-pass’ group, are less than 50 percent. The “conservative-stop” group (i.e., Group 1) suggests that male drivers are more likely to be aggressive in response to a yellow-light phase.

Group-1 had the highest distribution of female drivers, totaling 7.31%, which is statistically higher than the other groups. Of the total sample of 665 drivers, 5.71% were classified as female. Hence, by analyzing the gender factor alone, the following conclusions can be made:

- Male drivers are more likely to be aggressive when approaching a yellow-light phase.

Table 4-2 The distribution of gender among four driver groups

Group characteristic	Group 1(C-stop)	Group 2(N-stop)	Group 3(N-pass)	Group 4(A-pass)	Total
Sample size by group	38 (5.71%)	278 (41.80%)	301 (45.26%)	48 (7.22%)	665 (100.00%)
Male samples distribution	15 (4.46%)	137 (40.77%)	157 (46.73%)	27 (8.04%)	336 (100.00%)
Female samples distribution	19 (7.31%)	112 (43.08%)	111 (42.69%)	18 (6.92%)	260 (100.00%)

* The gender of some individual drivers cannot be determined due to some technical problems in the video image.

** C-stop: conservative stop; N-stop: normal stop; N-pass; normal pass; A-pass: aggressive pass.

Age factor

Table 4-3 compares drivers as the young and senior by the four predefined groups. Although it is obvious that the sample size for young drivers is fairly small for reaching any definitive conclusions, the number of young drivers (3 out of 18) in the aggressive group is fairly significant of the entire sample, 7.22% out of 665 drivers.

The sample of 36 senior drivers is an insufficient amount of information to reach any definitive conclusions. However, a further investigation of senior drivers in the "normal-stop" and "normal-pass" groups (see Table 4.4) reveals that most senior drivers prefer to either have a smooth stop (e.g., 78.57%), or to pass the intersection at a constant speed (i.e., 100% in Group-3). Hence, with the limited sample for young and senior drivers one may draw the following conclusions:

- The data is not sufficient to make any definitive conclusions regarding the responses of young and senior drivers during an intersection yellow-light phase; however,
  - For those senior drivers making a reasonable decision, they are more likely to smoothly stop or a pass through intersection without acceleration/deceleration; and
  - Young drivers appear to be more likely to take an "aggressive-pass" action during the yellow-light phase.

Table 4-3 The distribution of young and senior drivers in each driver group

Group characteristics	Group 1(C-stop)	Group 2(N-stop)	Group 3(N-pass)	Group 4(A-pass)	Total
Sample size by group	38 (5.71%)	278 (41.80%)	301 (45.26%)	48 (7.22%)	665 (100.00%)
Young samples distribution	1 (5.56%)	10 (55.56%)	4 (22.22%)	3 (16.67%)	18 (100.00%)
Senior samples distribution	3 (8.33%)	14 (38.89%)	15 (41.67%)	4 (11.11%)	36 (100.00%)

Table 4-4 The distribution of senior drivers in the "normal-stop" and "normal-pass" groups

Group characteristic	Group-2 (N-stop)			Group-3 (N-pass)			
	Sharp stop	Smooth stop	Total	Decelerate	Constant	Accelerate	Total
Sample size by group	111 (39.93%)	167 (60.07%)	278 (100.00%)	23 (7.64%)	265 (88.04%)	13 (4.32%)	301 (100.00%)
Senior samples distribution	3 (21.43%)	11 (78.57%)	14 (100.00%)	0 (0.00%)	15 (100.00%)	0 (0.00%)	15 (100.00%)

Cellular-phone factor

In response to an increasing concern of drivers talking on cellular phones while driving, this study observed a total of 25 drivers who were using cellular phones when the signal changed from Green to Yellow. Table 4-5 presents the distribution of those 25 cellular-phone drivers among the four classified groups.

Although the results of this sample are small, this information should be used for reference purposes only. Fifty-two percent of the “normal-stop” group drivers were observed as talking on the phone, which is comparatively higher than the amount of drivers in Group-2, 41.8%, (see Table 4-5). In addition, 3 out of 25 drivers (12%) were noted in the “conservative-stop” group; this total far exceeds their supposed share that should be around 5.71%. Thus, it appears that drivers are more likely to conservatively stop when approaching a yellow-light phase, while talking on a phone.

Table 4-6 further analyses drivers in the “normal-stop” and “normal-pass” groups. Nearly 70% of drivers in these groups smoothly stopped when approaching the yellow-light phase. Of this percentage, nearly all drivers maintained a constant speed.

The responses of talking-on-phone drivers in the “normal-stop” and “normal-pass” groups have following two hypotheses:

- While talking on the phone, drivers are more likely to take either a “conservative-stop” or “normal-stop” while approaching a yellow-light phase.
- Talking-on-phone drivers are more likely to smoothly stop or continue through an intersection without accelerating when approaching a yellow-light phase.

Table 4-5 The distribution of observed cellular-phone drivers among four groups

Group characteristic	Group 1(C-stop)	Group 2(N-stop)	Group 3(N-pass)	Group 4(A-pass)	Total
Sample size by group	38 5.71%	278 41.80%	301 45.26%	48 7.22%	665 100.00%
On-phone samples Distribution	3 12.00%	13 52.00%	7 28.00%	2 8.00%	25 100.00%

Table 4-6 The distribution of observed cellular-phone drivers in the "normal-stop" and "normal-pass" groups

Group characteristic	Group-2 (N-stop)			Group-3 (N-pass0			
	Sharp stop	Smooth stop	Total	Decelerate	Constant	Accelerate	Total
Sample size by group	111 (39.93%)	167 (60.07%)	278 (100.00%)	23 (7.64%)	265 (88.04%)	13 (4.32%)	301 (100.00%)
On-phone samples Distribution	4 (30.77%)	9 (69.23%)	13 (100.00%)	0 (0.00%)	7 (100.00%)	0 (0.00%)	7 (100.00%)

4.4 Traffic conditions and driver responses to yellow-light phases

This section explores the potential relationships between a driver's response during the yellow-light phase and the surrounding traffic conditions, including:

- Traffic flow speed and individual vehicle speed
- Traffic volume level
- During peak hours or not

The above factors are likely to be complex and interrelated, thus, will be investigated in the next chapter using statistical tests to support the findings of this research. The analysis reported in this section focuses on the relationship of a driver's response to the signal phase and traffic conditions the decisions were made in.

Traffic speed factors

Table 4-7 summarizes the distribution of entry speed, initial speed, and the average traffic flow speed among the four groups. It is notable that under approximately the same traffic flow speed of 42.58 mph, drivers who took "aggressive-pass' actions when approaching the yellow-light phases, on average, were moving at higher speeds than those drivers in the "conservative-stop" group at both the entry point (42.65 mph vs. 40.86 mph) and the location when they first noticed the yellow phases (41.51 mph vs. 40.47 mph).

Table 4-7 The distribution of average traffic flow and driver speeds among four groups

Group characteristic		Group 1(C-stop)	Group 2 (N-stop)	Group 3 (N-pass)	Group 4(A-pass)	Total
Entry speed	Avg.	40.86 mph	39.42 mph	41.83 mph	42.65 mph	40.83 mph
	(Stdev).	(9.73)	(9.84)	(10.89)	(12.80)	(10.60)
Initial speed	Avg.	40.47	39.08	40.67	41.51	40.05
	(Stdev)	(8.75)	(9.92)	(10.46)	(12.60)	(10.33)
Traffic flow Average speed	Avg.	42.58	41.68	41.82	42.48	41.85
	(Stdev)	(5.75)	(7.72)	(8.15)	(8.27)	(7.85)

* Entry speed: speed to enter the intersection approach
* Initial speed: speed at the time when the signal is changing to a yellow-light phase

Table 4-8 presents speed data associated with drivers in the "normal-stop" and "normal-pass" groups. As reflected in the statistics, drivers who took "sharp" stops in the "normal-stop" groups generally had quite high entry and initial speeds of 44.92 mph, and, 44.37 mph. In contrast, for those having low approaching speeds (35.77 mph, 35.56 mph), they generally experienced smooth stops at the intersection.

With respect to those in the " normal-pass" group, drivers decelerated to pass through the intersection, and were mostly in the vehicle groups with a high approaching speed, (i.e., 50.74 mph). This was above the average flow speed of 42 mph. For "normal-pass" drivers, who were moving at the speed of the average traffic flow, they maintained a constant speed or accelerated slightly during the yellow-light phase.

Table 4-9 presents the speed evolution of drivers in each subgroup, including their speeds approaching the intersection, then seeing and reacting to the yellow-light phase, and finally passing through the intersection. It is interesting to note that nearly all groups of drivers tended to reduce their speeds when they first noticed the yellow-light phase. For those taking a "stop" decision, they consistently began to decelerate after noticing the yellow-light phase.

The responses of those taking the "pass-through" decisions are quite different. For example, drivers in the "accelerate-pass" subgroup appeared to continue to accelerate even after passing the intersection. But those in the "aggressive-pass" subgroup seemed to maintain the same speed and continue through the intersection, after their initial speed when first noticing the yellow-light phase. Overall, most drivers reduced their speed after passing the intersection.

Table 4-8 The distribution of average traffic flow and driver speeds in the "normal-stop" and "normal-pass" groups

Group characteristic		Group-2 (N-stop)			Group-3 (N-pass)			Total
		Sharp stop	Smooth stop	Total	Decelerate	Constant	Accelerate	
Entry speed	Avg.	44.92	35.77	39.42	50.74	40.91	44.66	41.83
	(stdev)	(7.03)	(9.76)	(9.84)	(7.46)	(10.73)	(12.26)	(10.89)
Initial speed	Avg.	44.37	35.56	39.08	47.28	39.73	48.13	40.67
	(stdev)	(7.69)	(9.69)	(9.92)	(7.19)	(10.33)	(11.44)	(10.46)
Traffic flow	Avg.	42.09	41.41	41.68	42.00	41.75	43.04	41.82
Average speed	(stdev)	(6.86)	(8.25)	(7.72)	(8.50)	(8.20)	(6.98)	(8.15)

Table 4-9 Summary of the speed evolution for each group of drivers

		Entry speed	Initial speed	After yellow-light	Pass speed	85^{th} (%) speed
Conservative-stop	Mean	40.86	40.47	28.25	-	49.61
	(Stdev)	(9.73)	(8.75)	(17.55)	-	(5.95)
Sharp-stop	Mean	44.92	44.37	35.65	-	50.25
	(Stdev)	(7.03)	(7.69)	(13.29)	-	(5.91)
Smooth-stop	Mean	35.77	35.56	27.97	-	50.51
	(Stdev)	(9.76)	(9.69)	(12.84)	-	(5.95)
Constant-pass	Mean	40.91	39.73	37.22	36.98	49.54
	(Stdev)	(10.73)	(10.33)	(11.18)	(11.03)	(6.50)
Deceleration-pass	Mean	50.74	47.28	43.27	35.89	50.09
	(Stdev)	(7.46)	(7.19)	(9.95)	(10.22)	(6.26)
Acceleration-pass	Mean	44.66	48.13	47.31	51.70	48.65
	(Stdev)	(12.26)	(11.44)	(10.73)	(8.82)	(6.33)
Aggressive-pass	Mean	42.65	41.51	41.80	39.53	51.20
	(Stdev)	(12.80)	(12.60)	(12.89)	(13.29)	(5.95)

* Entry speed: the speed when vehicles just enter the intersection approach.

* Initial speed: the speed when drivers first notice the yellow-light phase.

* After-yellow-light speed: the speed of vehicles after the commence of the yellow-light phase.

* Passing-speed: the speed of vehicles after passing the intersection.

Overall, the above speed statistics associated with each driving group offers the following interesting hypotheses:

- Drivers at high speeds are more likely to take aggressive actions towards the yellow-light phase to pass through the intersection.

- Most drivers, taking overly cautious responses to the yellow-light phase, were those driving below the average flow speed.
- Drivers, reasonably responding to stop at the intersection during a yellow-light phase, are likely to experience a "sharp stop" if their speeds are higher than the average flow speed.
- Drivers in the normal-pass group are likely to decelerate if their speeds are significantly higher than the average flow speed. Otherwise, they may either move at a constant speed or accelerate slightly to pass the intersection

Volume factor

Traffic flow speed and roadway volumes are highly related (Figure 4-8). Thus, upon completing the analysis of speed impacts on the distribution of driving populations, it is essential to check the consistence of the revealed relations from the volume perspective.

Figure 4-8 The observed relation between traffic flow speed and volume

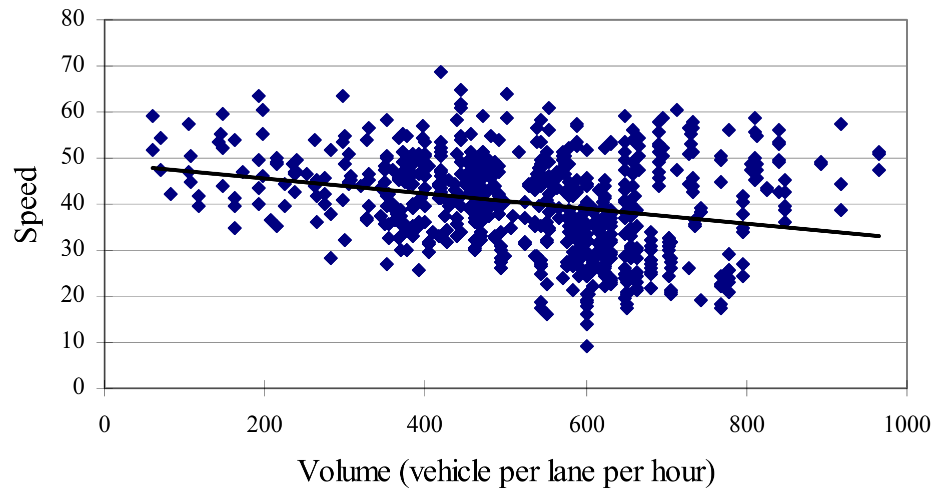


Table 4-10 The distribution of traffic volumes of drivers in each group

Group characteristic	Group 1(C-stop)	Group 2(N-stop)	Group 3(N-pass)	Group 4(A-pass)	Total
Avg. volume (vphpl) (StDev)	478.32 (126.09)	521.78 (174.56)	547.80 (162.65)	541.56 (166.30)	532.50 (166.84)

* Volume is the number of vehicles per lane per hour computed from each cycle

Table 4-10 summarizes the volume of drivers in each group. As expected, drivers in both the "aggressive-pass" and "normal–pass" groups, experienced the volume levels of 541 vph and

547 vph per lane. These rates were much higher than those in the “normal–stop” and “conservative-stop” groups, which were 521 vph and 478 vph per lane. A plausible explanation of these rates suggest that drivers in highly congested traffic conditions generally are more anxious to minimize their waiting times at intersections.

A further analysis of drivers in the *“normal-stop” and “normal-pass*” groups, however, reveals that drivers, who were in high volume traffic conditions and had a sufficient time to make non-aggressive decisions, are more likely to experience either a smooth stop or a pass at a constant speed. This is evident in the significantly higher volumes experienced by these two subgroups (550.99 and 557.39 vph per lane, see Table 4-11), and is more likely attributable to the constraints of traffic congestion. Overall, it appears that drivers in high-volume traffic conditions are more likely to take the “aggressive-pass” action, but the congestion associated with high traffic volumes may place some constraints on their desirable responses and force them to take “normal” smooth stops or “pass” at a constant speed.

Table 4-11 The distribution of traffic volume experienced by drivers in each group

Group characteristic		Group-2			Group-3			
		Sharp stop	Smooth stop	Total	Decelerate	Constant	Accelerate	Total
Volume	Avg.	477.84	550.99	521.78	478.00	557.39	475.78	547.80
	(StDev)	(174.78)	(168.68)	(174.56)	(176.46)	(161.32)	(121.50)	(162.650

Peak-hour indicator

As discussed previously, volume, speed and peak hours are three highly correlated factors, which may individually and collectively affect a driver’s decision to react to signal phases they have encountered. Table 4-12 illustrates the distribution of drivers observed during peak hours within the four classified groups. It is interesting to notice that although a total of 427 sample drivers were observed in peak periods (64%), about 81% percent of “aggressive-pass” drivers (39 out of 48) were detected during the same peak periods.

In contrast, only 50% of “conservative-stop” drivers were observed in the peak periods. However, for those in the “*normal-pass” and “normal-stop*” groups, their distributions in the peak periods are consistent with the total samples (64%) observed during the same period. This seems to support the hypothesis that drivers are more likely to take aggressive actions at signalized intersections during peak hours.

A further analysis of the relationship between peak hours and drivers in the "normal-stop" and "normal-pass" groups also reflect a similar pattern (Table 4-13). For example, a total of 72% (80 out of 111) of "normal-sharp-stop" drivers have been observed in the peak periods, much higher than the total "normal-stop" drivers (64%, 178 out of 278) observed during the same period. Furthermore, among those "*normal-pass*" drivers, a total of 63.4 % were observed in peak periods, but about 92% (12 out of 13) of drivers in this subgroup of taking acceleration during their pass movements were observed in the same period.

In brief, an insufficient amount of data from the samples were obtained for statistical tests at this stage, however, it seems fair to say that drivers in the peak hours tend to be more aggressive when responding to signal phase changes.

Table 4-12 The distribution of drivers during peak hours in each group

Group characteristic	Group 1(C-stop)	Group 2(N-stop)	Group 3(N-pass)	Group 4(A-pass)	Total
Sample size by group	38 (5.71%)	278 (41.80%)	301 (45.26%)	48 (7.22%)	665 (100.00%)
In peak period distribution	19 (4.45%)	178 (41.69%)	191 (44.73%)	39 (9.13%)	427 (100.00%)
Percent in the peak period	50%	64%	63.4%	81%	64%

Table 4-13 The distribution of drivers during peak hours in the "normal-stop" and "normal-pass" groups

Group characteristic	Group-2 (Normal-stop)			Group-3 (Normal-pass)			
	Sharp stop	Smooth stop	Total	Decelerate	Constant	Accelerate	Total
Sample size by group	111 39.93%	167 60.07%	278 100.00%	23 7.64%	265 88.04%	13 4.32%	301 100.00%
Samples in peak periods	80 (72%)	98 (58.7%)	178 (64%)	13 (56.5%)	166 (62.6%)	12 (92%)	191 (63.4%)

4-5 Geometric and control features and driver responses to a yellow-light phase

Geometric features of an intersection may vary with a variety of factors, such as traffic volume, turning flow distribution, and signal control strategies. Thus, the observed relationship between intersection geometric features and a driver's response to the yellow-light phase is likely to be impacted by those factors associated with intersection geometric features. For example, an intersection with more travel lanes is more likely to have a high daily traffic volume. These two factors, collectively can affect the behavior of a driver. However, due to the data limitations of this research, this section will only explore the correlation of drivers and the following two most critical factors: the number of through lanes and intersection width. The exploratory results, with respect to each individual factor, may provide some insightful information for the design of statistical tests in analyzing the collective impacts of all related factors.

Number of through lanes

Table 4-14 presents the average number of through lanes experienced by each group of drivers. The actual number of through lanes at each of the nine intersections varies between 2 to 5 lanes. It is interesting to note that drivers on a roadway segment with more lanes seem more likely to respond to the yellow-light signal phase in a conservative way. For example, those drivers in the "conservative-stop" group were observed to travel on arterial segments with a weighted average of nearly 3 through lanes, compared to about 2.63 lanes for those in the "aggressive-pass' group. This is likely due to the fact that traffic conditions and drivers in adjacent lanes may affect an individual's response and actions when approaching the yellow-light phase. For instance, a driver who prefers to take an "aggressive-pass" decision may be constrained by the high volume in a multi-lane segment, and/or be discouraged by surrounding drivers in the same approach.

Table 4-14 Distribution of through lanes experienced by drivers in each group

Group characteristic	Group 1(C-stop)	Group 2(N-stop)	Group 3(N-pass)	Group 4(A-pass)	Total
Average (StDev)	2.97 (0.68)	2.89 (0.62)	2.94 (0.58)	2.63 (0.53)	2.90 (0.6)

Intersection width factor

Based on the same weighted statistics, Table 4-15 summarizes intersection widths crossed by drivers in each group. As shown in the statistics, it appears that drivers are more likely to take "aggressive-pass" actions to the yellow-light phase if they need to cross a wider intersection. This is consistent with the general observations that drivers addressing minor approach intersections are less willing to wait for another green phase as they realize that the length of a red phase is correlated to the number of lanes in the major approach of an intersection. This observation is also consistent with the results shown in the previous table, where drivers in the major intersection approaches (i.e., more through lanes) are less likely to take an aggressive-pass action during a yellow-light phase.

A further analysis of driver responses in the "normal-stop" and "normal-pass" groups also reveal the same information (see Table 4-16). For example, drivers in the "normal-stop" group are more likely to experience sharp stops at the minor approach of intersections, than those in the "normal-pass" group, who tend to accelerate when facing a wide intersection of multiple crossing lanes.

The above statistics of the relationship between a driver's response to the signal phase and the number of through and crossing lanes encountered, are exploratory in nature. Those observations, however, are mutually consistent, and thus, may offer the following interesting hypothesis for further analysis:

- At intersections with major and minor approaches, drivers in minor intersection approaches (i.e., less through lanes and more crossing lanes) are more likely to react aggressively when encountering a yellow-light phase, as they are impatient and less likely to wait for another long, red phase.

Table 4-15 Distribution of intersection widths (represented with the number of crossing lanes) experienced by drivers in each group

Group characteristic	Group 1(stop)	Group 2(stop)	Group 3(pass)	Group 4(pass)	Total
Average (StDev)	6.37 (2.2)	6.47 (1.91)	6.39 (1.9)	6.67 (1.31)	6.44 (1.88)

Table 4-16 Distribution of intersection widths (represented with the number of crossing lanes) experienced by drivers in "normal-stop" and "normal-pass" group

Group characteristic	Sharp stop	Smooth stop	Stop total	Decelerate pass	Constant pass	Accelerate pass	Pass total
Average	7.01	6.11	6.47	6.04	6.31	8.46	6.39
(StDev)	(1.83)	(1.87)	(1.91)	(1.33)	(1.89)	(1.85)	(1.9)

Yellow-light duration factor

Theoretically, an increase in the yellow-light duration can reduce the length of an intersection dilemma zone and the number of aggressive responses when approaching the yellow-light phase. The empirical results shown in Table 4-17 seem to confirm this commonly assumed hypothesis, that suggests, the distribution of drivers in both the "conservative-stop" and "aggressive-pass' groups at intersections having a 4-second yellow-light phase are higher than the same distributions at intersections designed with the yellow-light duration of 5 seconds. Similarly, numerical results are also shown in Figures 4-9 and 4-10, where the space between x-axis and y-axis, based on the theoretical "stopping" and "passing" distance lines, has been divided into the following 4 zones: "can-stop zone," "can-pass" zone, " can-go-or-stop" zone, and "dilemma" zone. It is noticeable that the number of drivers trapped in the theoretical "dilemma" zone at intersections of 5-second yellow-light duration is less than those at intersections of 4-second yellow-light duration.

Table 4-17 The distribution of drivers in each group by yellow-light duration

Yellow-light duration	Group 1(C-stop)	Group 2(N-stop)	Group 3(N-pass)	Group 4(A-pass)	Total
4 seconds	17 (6.83%)	110 (44.18%)	102 (40.96%)	20 (8.03%)	249 (1005)
5 seconds	21 (5.05%)	168 (40.38%)	199 (47.84%)	28 (6.73%)	416 100%)

* Volume is the number of vehicles per lane per hour computed from each cycle

Figure 4-9 Distribution of driver responses to the yellow-light phase with respect to the theoretical stopping and passing lines (yellow-light duration: 4 seconds)

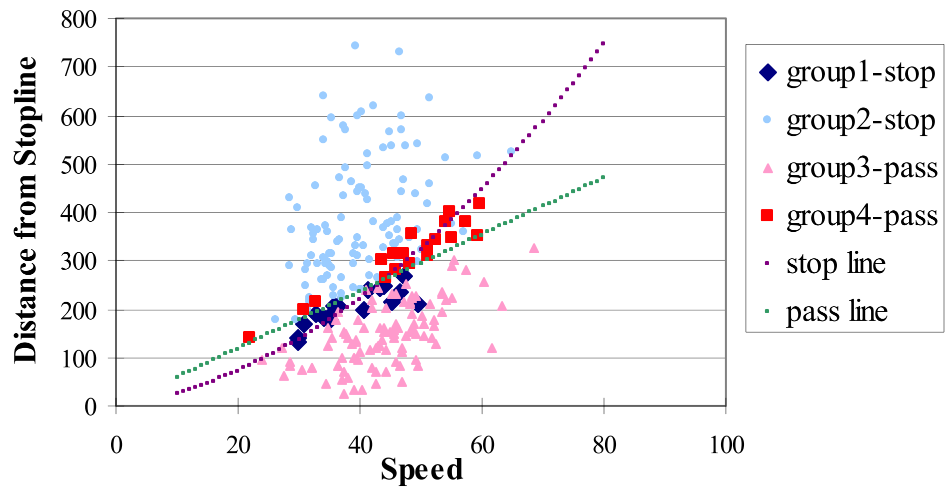
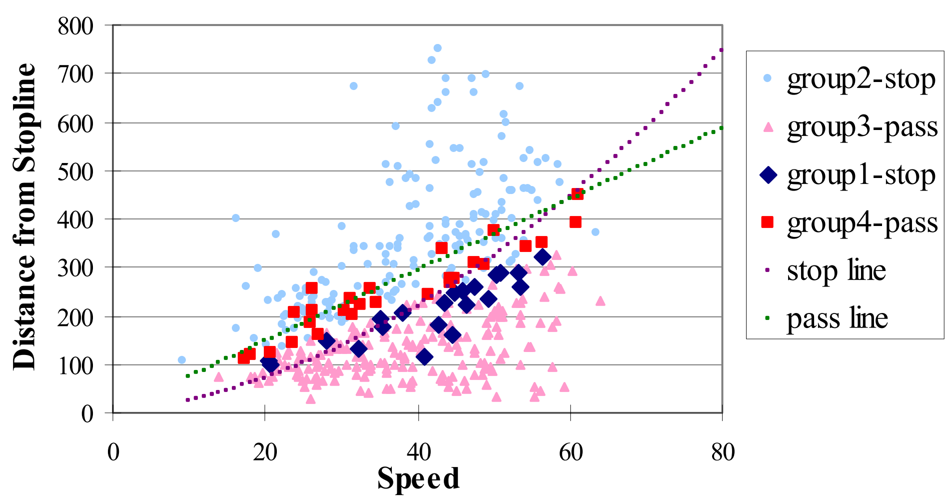


Figure 4-10 Distribution of driver responses to the yellow-light phase with respect to the theoretical stopping and passing lines (yellow-light duration: 5 seconds)



4.6 Vehicle types and driver responses to a yellow-light phase

Theoretically, it is likely that a driver's selection of vehicle type may correlate to his/her driving behavior. While the available data is insufficient to address this issue in a comprehensive way, the limited sample observations from this study have revealed some unique behavior patterns between the distribution of drivers and those having pickup vehicles and sport vehicles.

Table 4-18 identifies pick-up drivers within the four identified groups. It is notable that among those 60 pick-up drivers observed during the field study, about 13.3% took an "aggressive-pass" action when approaching the yellow-light phase; this is much higher than the 7.2% of the total "aggressive-pass" drivers in the entire sample observation. In contrast, the number of pick-up drivers in the "conservative-stop" group (3.33%) is less than it should be (5.71%) from the sample distribution perspective**.** The consistency between those two statistics seem to indicate that pick-up drivers, due to a variety of factors, appear to be more likely to take "aggressive-pass" actions at signalized intersections.

Table 4-18 Distribution of pick-up drivers among those four classified groups

Group characteristic	Group 1(C-stop)	Group 2(N-stop)	Group 3(N-pass)	Group 4(A-pass)	Total
Overall	38 (5.71%)	278 (41.80%)	301 45.26%	48 (7.22%)	665 100.00%
Pick-up	2 (3.33%)	23 (38.33%)	27 (45.00%)	8 (13.33%)	60 100.00%

Sport-car drivers

Table 4-19 illustrates the distribution of sport cars among the four driving groups. Most drivers in sport cars were classified in the "normal-stop" and "normal-pass" groups. The number of sport-car drivers in the "normal-stop" group (53.3%) actually exceeds the share of total drivers in Group-2, and the entire sample observations of 41.8%. A further analysis of sport-car drivers in the "normal-stop" and "normal-pass" groups (see Table 4-20) also revealed that most of drivers went through intersections at a constant speed (91.6%), and about 50% of them experienced smooth stops when they decided to stop. It appears that those sport-car drivers seemed to have better judgment and/or experience and were able to make a reasonable decision in response to the signal changing from a green to yellow. The performance characteristics of sport vehicles in terms of acceleration and deceleration rates may also be a key factor affecting the distribution of drivers among the four groups.

Table 4-19 Distribution of sport-cars among four driving groups

Group characteristic	Group 1(C-stop)	Group 2(N-stop)	Group 3(N-pass)	Group 4(A-pass)	Total
Overall	38 (5.71%)	278 (41.80%)	301 (45.26%)	48 (7.22%)	665 100.00%
Sports Car	1 (3.33%)	16 (53.33%)	12 (40.00%)	1 (3.33%)	30 100.00%

Table 4-20 Distribution of sport-cars in the "normal-stop" and "normal-pass" groups

Group characteristic	Sharp stop	Smooth stop	Stop total	Decelerate pass	Constant pass	Accelerate pass	Pass total
Overall	111 (39.93%)	167 (60.07%)	278 100.00%	23 (7.64%)	265 (88.04%)	13 (4.32%)	301 100.00%
Sports Car	8 (50.00%)	8 (50.00%)	16 100.00%	0 (0.00%)	11 (91.67%)	1 (8.33%)	12 100.00%

4.7 Comparison of the responses of drivers between sample intersections

Table 4-21 presents the distribution of driving populations at each intersection based on the proposed classification criteria. Also included, are key factors associated with each intersection, including speed limit, average flow speed, the 85^{th} percentile speed, yellow-light duration, and intersection geometric features. The statistics in this table suggest that the MD4 and Silver Hill intersection and the US29 and Stewart lane intersection have approximately the same average flow speed and in the 85^{th} percentile speed, but different speed limits and yellow-light durations. This offers an ideal case for exploring the response patterns of drivers under the impacts of design speed and yellow-light duration.

Table 4-22 summarizes observations related to the distance drivers first noticed the yellow-light phase and the percent of those choosing to stop at the intersection. As expected, the results indicate that drivers are likely to stop when they are further away from the intersection. A graphical comparison of the results (see Figure 4-11) indicate that drivers located at the US29 and Stewart Lane intersection are more likely stop than those located at the MD4 and Silver Hill Road intersection, if they were to respond to the yellow-light phase from the same distance. This is consistent with the previous findings that suggest that factors such as additional through lanes, wider intersection widths, and lower speeds are more likely to cause drivers to take conservative actions when approaching the yellow-light phase.

Another case, using US 29 at Stewart Lane intersection and the US 40 at Rogers Avenue intersection, both have nearly the identical 85th percentile approaching speed, the same yellow-light duration phase, and the same number of through as well as crossing lanes. However, their average traffic flow speeds differ significantly: the US 40 at Rogers Avenue intersection has an average speed of 44 mph, which is much lower than the average speeds at the US 29 at Stewart Lane intersection. Table 4-23 presents the same numerical analysis as in the previous comparison in Table 4-22. The graphical illustrations of analysis results are shown in Figure 4-12. It is notable that under similar conditions (except for a lower average flow speed), drivers at the US 40 at Rogers Avenue intersection were more likely to respond to the yellow-light phase by stopping than those drivers at the US 29 at Stewart Lane intersection. The observations that congestion and/or low traffic flow speed tend to prevent drivers from taking aggressive responses when approaching a yellow-light phase.

Further evidence of congestion impacts on a driver's response to the yellow-light phase can also be seen from the same comparison between the intersections of MD193 at Hanover Parkway and the US 40 at Rogers Avenue intersection. As reflected in the results of Table 4-24 and Figure 4-13, although both intersections are identical in their speed limits, 85th percentile speeds, and the number of through as well as crossing lanes, drivers at the MD193 at Hanover Parkway intersection (which is more congested than the other), were clearly more willing to stop when seeing a yellow-light phase.

Table 4-21 Summary of observed data at each sample intersection

	1	2	3	4	5	6	7	8	9
	MD201@ Crescent Rd.	MD4@ Silver Hill Rd.	MD355@ Shady Grove Rd.	MD198@ Whiskey Bottom Rd.	US40@ Rogers Rd.	MD45@ Burke Rd.	US29@ Stewart Ln.	MD193@ Hanover Pkwy	MD650@ Sandy Spring Rd. (MD198)
Aggressive Pass in Red	**0** (0%)	**5** (4.3%)	**1** (1.1%)	**0** (0%)	**0** (0%)	**0** (0%)	**0** (0%)	**3** (1.1%)	**1** (1.7%)
Aggressive Pass w/ Acceleration	**0** (0%)	**36** (31.0%)	**8** (8.8%)	**1** (7.1%)	**0** (0%)	**1** (10.0%)	**4** (4.2%)	**27** (10.3%)	**5** (8.5%)
Conservative	**0** (0%)	**4** (3.4%)	**2** (2.2%)	**0** (0%)	**10** (17.5%)	**2** (20.0%)	**5** (5.3%)	**9** (3.4%)	**6** (10.2%)
Normal Abrupt Stop	**5** (17.9%)	**25** (21.6%)	**26** (28.6%)	**2** (14.3%)	**6** (10.5%)	**4** (40.0%)	**3** (3.2%)	**37** (14.1%)	**14** (23.7%)
Normal Smooth Stop	**4** (14.2%)	**18** (15.5%)	**20** (22.0%)	**0** (0%)	**18** (31.6%)	**3** (30.0%)	**35** (36.8%)	**66** (25.2%)	**13** (22.0%)
Normal Pass w/ Acceleration	**1** (3.6%)	**3** (2.6%)	**5** (5.5%)	**1** (7.1%)	**1** (1.8%)	**0** (0%)	**0** (0%)	**1** (0.4%)	**0** (0%)
Normal Pass w/ Deceleration	**5** (17.9%)	**1** (0.9%)	**1** (1.1%)	**1** (7.1%)	**2** (3.5%)	**0** (0%)	**2** (2.1%)	**12** (4.6%)	**3** (5.1%)
Normal Pass w/ Const. Speed	**13** (46.4%)	**24** (20.7%)	**28** (30.7%)	**9** (64.3%)	**20** (35.1%)	**0** (0%)	**46** (48.4%)	**107** (40.8%)	**17** (28.8%)
	28	**116**	**91**	**14**	**57**	**10**	**95**	**262**	**59**
Speed Limit	40	55	40	40	45	35	45	45	45
Mean Speed	37.8	48.0	36.9	36.7	43.9	34.8	50.2	35.1	44.5
85^{th} Percentile Speed	44.6	55.2	42.8	41.3	53.2	39.8	56.0	47.6	49.6
Yellow-light Duration	5	5	4	5	5	4	5	5	4
Congestion observed?	N	N	N	N	N	N	N	Y	N
# of thru lanes	3	2	4	3	3	2	3	2	3
# of cross lanes	3	7	10	4	4	5	4	8	6

Table 4-22 Comparison of drivers stopping from different distances at two intersections with the same average flow speed and 85th percentile speed, but different geometric features

MD4 @ Silver Hill Rd.					US29 @ Stewart Ln.				
Distance	Number stop	Number not stop	P_s	Cumulative P_s	Distance	Number stop	Number not stop	P_s	Cumulative P_s
81′	0	4	0.00	0.00	88′	0	10	0.00	0.00
121′	0	6	0.00	0.00	128′	1	8	0.11	0.05
161′	0	8	0.00	0.00	168′	0	7	0.00	0.04
201′	1	10	0.09	0.03	208′	0	6	0.00	0.03
241′	0	12	0.00	0.02	248′	1	10	0.09	0.05
281′	1	7	0.13	0.04	288′	1	2	0.33	0.07
321′	2	10	0.17	0.07	328′	3	6	0.33	0.11
361′	3	7	0.30	0.10	**368′**	4	0	1.00	0.17
401′	7	4	0.64	0.17	408′	4	2	0.67	0.22
441′	4	1	0.80	0.21	448′	1	0	1.00	0.23
481′	7	0	1.00	0.27	488′	6	1	0.86	0.29
>481′	22	0	1.00	0.41	>488′	22	0	1.00	0.45
Total	**47**	**69**			**Total**	**43**	**52**		

* P_s denotes the percentage of drivers choosing to stop their vehicles when they notice the signal changing from a green to the yellow-light phase at the given distance.

Figure 4-11 Comparison of the cumulative percentage of stopping vehicles between two intersections

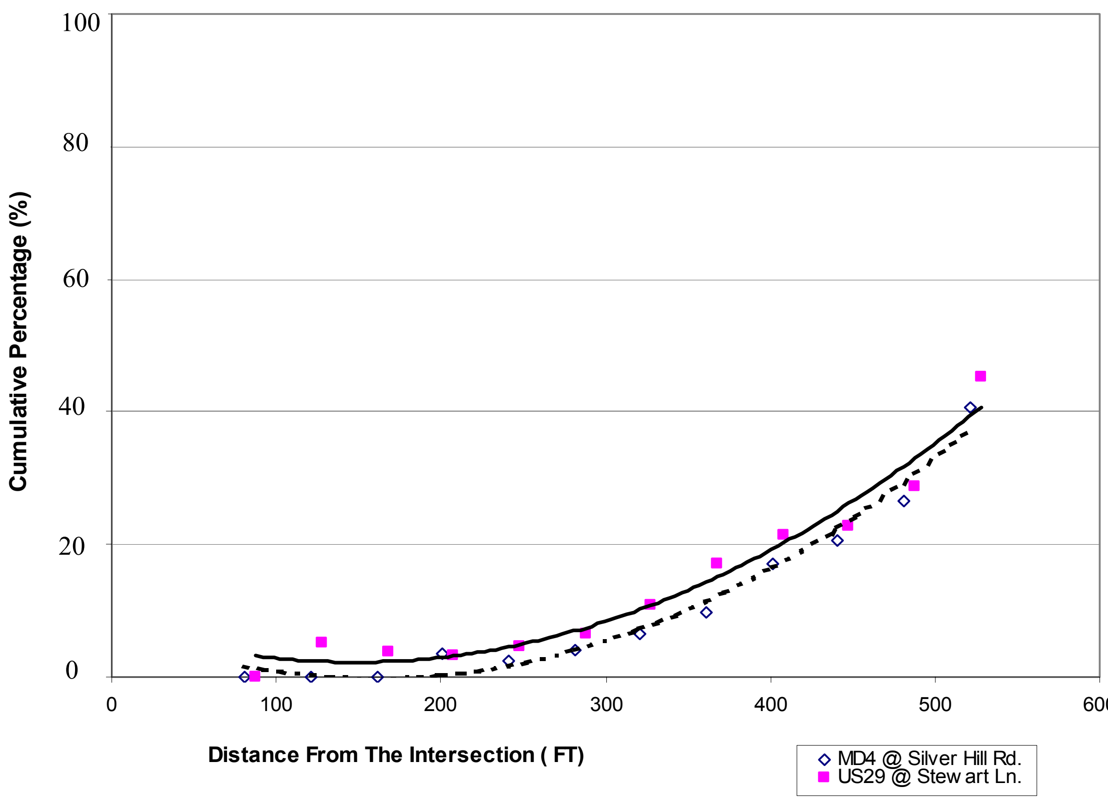


Table 4-23 Comparison of drivers stopping from different distances at two intersections with the same yellow-light duration and geometric features, but different flow speeds

US40 @ Rogers Ave.					**US29 @ Stewart Ln.**				
Distance	Number stop	Number not stop	P_s	Cumulative P_s	Distance	Number stop	Number not stop	P_s	Cumulative P_s
82′	0	7	0.00	0.00	88′	0	10	0.00	0.00
122′	1	5	0.17	0.08	128′	1	8	0.11	0.05
162′	2	4	0.33	0.16	168′	0	7	0.00	0.04
202′	1	4	0.20	0.17	208′	0	6	0.00	0.03
242′	4	1	0.80	0.28	248′	1	10	0.09	0.05
282′	5	1	0.83	0.37	288′	1	2	0.33	0.07
322′	4	0	1.00	0.44	328′	3	6	0.33	0.11
362′	4	1	0.80	0.48	**368′**	4	0	1.00	0.17
402′	6	0	1.00	0.54	408′	4	2	0.67	0.22
442′	1	0	1.00	0.55	448′	1	0	1.00	0.23
482′	2	0	1.00	0.57	488′	6	1	0.86	0.29
>482′	4	0	1.00	0.60	>488′	22	0	1.00	0.45
Total	**34**	**23**			**Total**	**43**	**52**		

Figure 4-12 Comparing the percent of vehicles stopping at the same distance at two different intersections

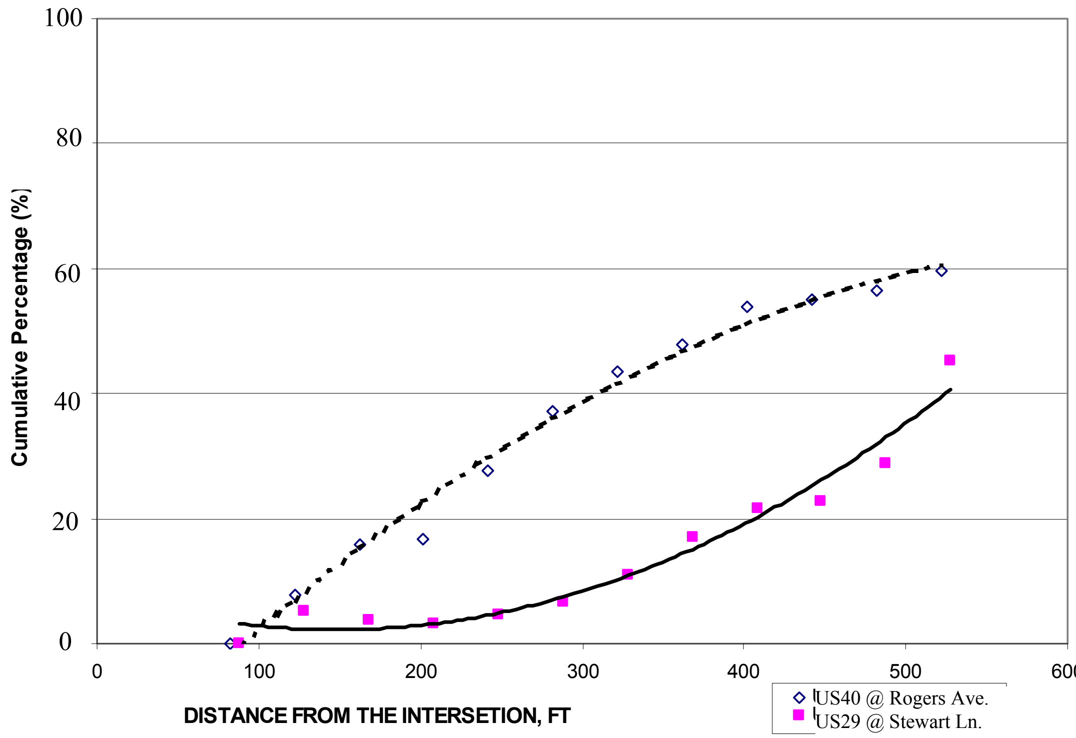
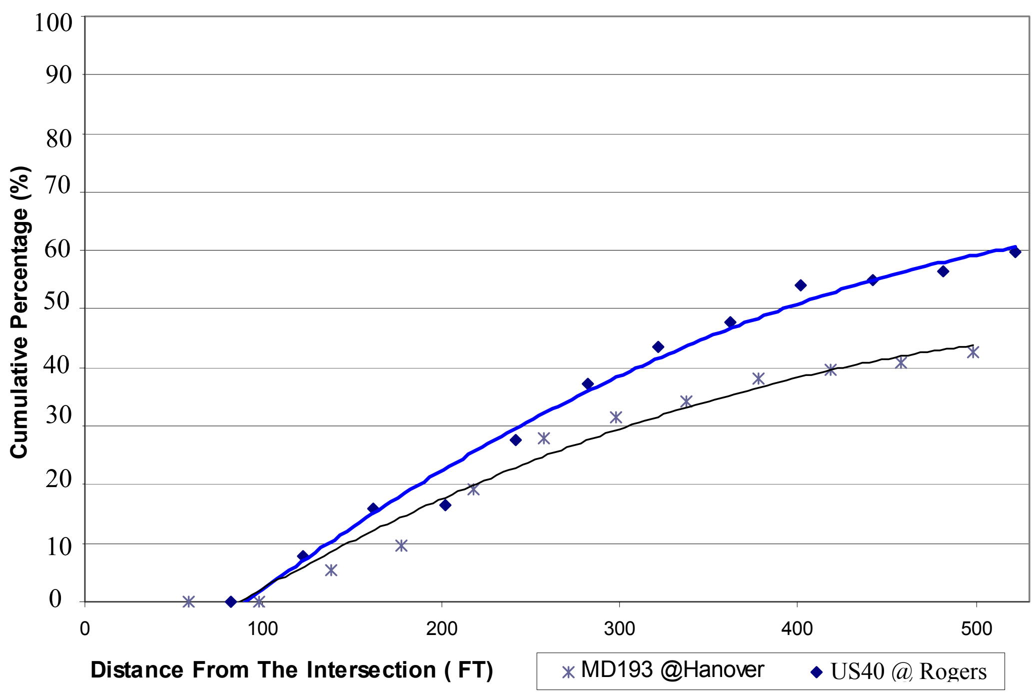


Table 4-24 Comparison of drivers stopping at different distances from two intersections

MD193 @ Hanover Pkwy.					**US40 @ Rogers Ave.**				
Distance	Number stop	Number not stop	P_s	Cumulative P_s	Distance	Number stop	Number not stop	P_s	Cumulative P_s
58′	0	7	0.00	0.00	82′	0	7	0.00	0.00
98′	0	40	0.00	0.00	122′	1	5	0.17	0.08
138′	5	39	0.11	0.05	162′	2	4	0.33	0.16
178′	7	28	0.20	0.10	202′	1	4	0.20	0.17
218′	19	17	0.53	0.19	242′	4	1	0.80	0.28
					282′	5	1	0.83	0.37
258′	24	11	0.69	0.28					
298′	12	4	0.75	0.31	**322′**	4	0	1.00	0.44
338′	10	1	0.91	0.34	362′	4	1	0.80	0.48
378′	16	3	0.84	0.38	402′	6	0	1.00	0.54
418′	6	0	1.00	0.40	442′	1	0	1.00	0.55
458′	4	0	1.00	0.41	482′	2	0	1.00	0.57
>458′	9	0	1.00	0.43	>482′	4	0	1.00	0.60
Total	**112**	**150**			**Total**	**34**	**23**		

Figure 4-13 Comparison of the cumulative percentage of stopping vehicles between two intersections



4.8 Concluding comments

This chapter presented exploratory results of 665 observed drivers' responses during a yellow-light phase under the following factors: volume, geometric, and surrounding traffic conditions. This analysis has divided all observed driver responses into "conservative-stop," "normal-stop," "normal-pass," and "aggressive-pass," based on their response (i.e., stop or pass) and initial distance to the intersection when the signal turns to the yellow-light phase. It is fully recognized that due to a large number of factors potentially related to a driver's response during the yellow-light phase and their complex interrelationships, the results from this analysis are preliminary in nature. Nevertheless, the findings concluded from these results offer a solid basis for further investigating the following hypotheses:

- Male drivers are more likely to take "aggressive-pass" decisions when approaching a yellow-light phase.
- Young drivers are more likely to be classified in the "aggressive-pass" group, compared with adult drivers.
- Senior drivers appear to be more likely to be classified in the "normal-stop" and "normal-pass' groups when approaching a yellow-light phases, compared with adult drivers.
- Drivers, talking on cellular phones generally respond to the yellow-light phase in a relatively conservative manner.
- Drivers at high speeds are more likely to be classified in the "aggressive-pass" groups when approaching a yellow-light phase.
- Most drivers, taking overcautious responses to the yellow-light phase, were those driving below the average speed flow.
- Drivers, who are in the "normal-response" group and choose to stop when approaching a yellow-light phase, are likely to experience a "sharp stop" if their speeds are higher than the average flow speed.
- Drivers, who experience a sufficient yellow-light duration to pass the intersection (i.e., normal-pass group), are likely to decelerate if their speeds are significantly higher than the average flow speed.
- Drivers under high-volume traffic conditions are more likely to be classified in the "aggressive-pass" group, but the congestion associated with high traffic volumes may

place some constraints on this response and force them to take “normal” smooth stops or “pass” at a constant speed.

- Drivers appear to behave more aggressively with respect to signal phase changes in the peak hours.
- At intersections with major and minor streets, drivers on those minor streets (i.e., less through lanes and more crossing lanes) are more likely to react aggressively when encountering yellow-light phases.
- Drivers at intersections with a longer yellow-light duration seem less likely to take the “aggressive-pass” decision.
- Drivers of pick-up vehicles tend to be classified in the “aggressive-pass” group when encountering a yellow-light phase.

Chapter 5
Model Testing and Applications

5.1 Introduction

Based on the results of the exploratory analysis reported in Chapter 4, this chapter focuses on hypothesis tests, model developments, and demonstrations of potential applications to identify the distribution of driver response patterns to a yellow-light phase. The speed evolution of drivers along with their acceleration/deceleration rates when approaching a yellow-light phase under various response patterns will also be discussed in this chapter. It is expected that the model developed to classify driver response patterns and their associated deceleration/ acceleration rates obtained from field observations, can potentially be used to improve the spatial distribution of dilemma zones at signalized intersections that have high crash frequency rates.

5.2 Statistical tests of critical factors and their impacts on driver responses

Based on the results of previous exploratory analyses, all factors potentially related to the response a driver makes when approaching a yellow-light phase can be classified into the following groups:

- *Traffic environment factors encountered by observed drivers*
  . Average traffic flow speed;
  . Yellow-light duration;
  . Traffic volume (per lane);
  . Number of through lanes;
  . Intersection width; and
  . Peak-hour period or not.
- *Individual driver related factors*
  . Gender;
  . Age (senior, or young drivers);
  . Entry speed to the intersection approach;
  . Distance to the intersection at the commence of the yellow-light phase;

. Talking on phone or not.

- *Vehicle related factors*

. Vehicle type (sport cars, minivans, sedans, sport-utility vehicles, or pick-ups);

. Vehicle make, (US, Europe, Japan, or Korea); and

. Vehicle year (old, new, or general).

Based on the above classifications, statistical tests used hereafter will evaluate the relationships between the response of drivers approaching the yellow-light phase and all aforementioned factors.

Note that the dependant variable in the ensuing statistical analysis represents the response of drivers that are discrete in nature and shall be in one of the following groups: "*aggressive-pass," "normal-pass," "normal-stop," and "conservative-stop*." Commonly used statistical methods for testing continuous dependent variables are not applicable for the purposes of this research. Instead, by assuming that the response variable is discrete and inherently ordered in nature (i.e., from conservative, normal, to aggressive patterns), one can employ the order-probit model, which is a popular behavioral analysis tool (Green, 2000). The methodology of the order-probity model for a generalized case of 5-class dependent variables is summarized below.

Core concepts of the Order-Probit model

An order-probit model for a generalized case of five classes can be presented with the following latent regression expression:

$$y^* = \beta' x + \varepsilon$$

Where, y* is unobservable, and those observed outcomes are:

$$\begin{aligned} y &= 1 \text{ if } y^* <= 0 \\ &= 2 \text{ if } 0 < y^* <= \mu 1 \\ &= 3 \text{ if } \mu 1 < y^* <= \mu 2 \\ &= 4 \text{ if } \mu 2 < y^* <= \mu 3 \\ &= 5 \text{ if } \mu 3 < y^* \end{aligned}$$

The unknown parameters, μ1, μ2, and μ3, representing the boundaries between those ordered responses, will be estimated with β (parameters for explanatory variables).

Prob(y = 1) = cnorm(0 – β'x) – 0

Prob(y = 2) = cnorm(μ1- β'x) - cnorm(0 – β'x)

Prob(y = 3) = cnorm(μ2- β'x) - cnorm(μ1- β'x)

Prob(y = 4) = cnorm(μ3- β'x) - cnorm(μ2- β'x)

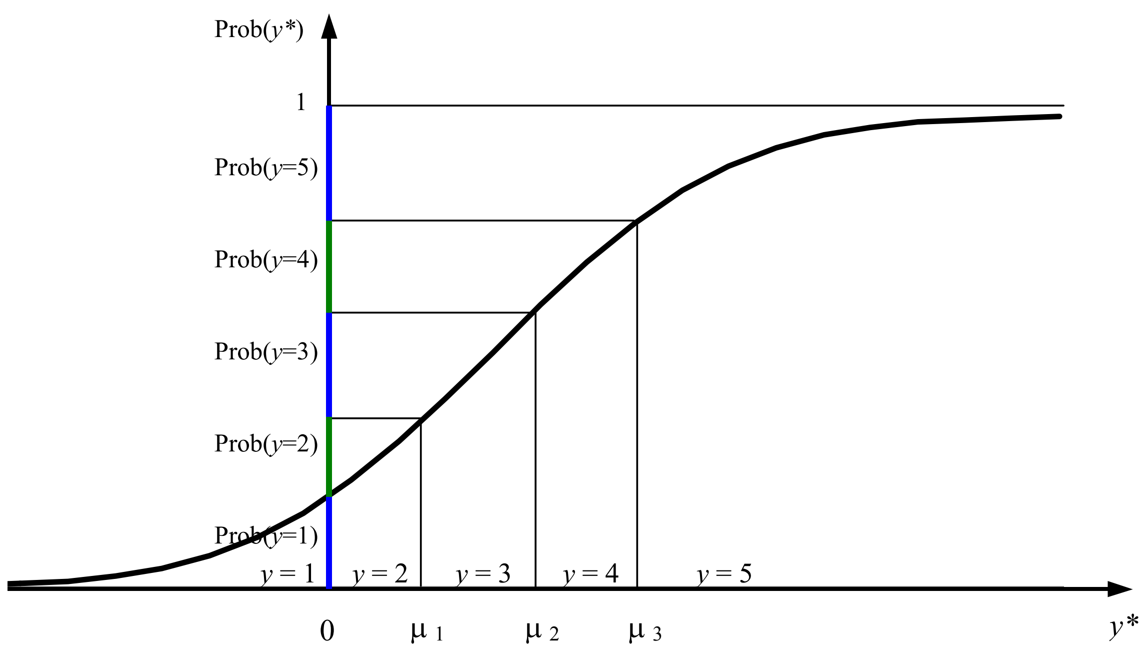
Prob(y = 5) = 1- cnorm(μ3- β'x)

For all the probabilities to be positive, it must have the follow relationships:

0 < μ1 < μ2 < μ3

A graphic depiction of the relationship between the probability and the observed outcomes is shown in Figure 5-1. One can construct a log-likelihood function based on the above assumptions to compute derivatives with a standard optimization method.

Figure 5-1 A graphical illustration of the probability distribution in an Ordered Probit Model



Estimation results

Parameter-significant tests, reported in the remaining section, are divided into two stages: the relationships between driver responses and traffic condition factors, and the compound impacts of additional factors under the same set of factors. The results of Stage-1 tests and associated variables are presented in Table 5-1 and discussed below:

Stage-1 test:

- *Dependent variable- one of the following responses:*" conservative-stop," "normal-stop or normal-pass," and "aggressive-pass
- *Test-1: traffic condition factors*
  - *volume per lane (VOLUME), average flow speed (AVG_SPEED);*
  - *average traffic flow speed (AVG_SPEED);*
  - *yellow-light duration (Y_DURATION);*
  - *number of through lanes (THRUL);*
  - *number of lanes to cross (CROSS); and*
  - *during the peak-hour or not (PH_HR).*

As shown in Table 5-1, all factors included in the group of traffic environmental groups are statistically significant at either the 95 percent or 90 percent confidence level, except the peak-hour factor, which may be limited because of insufficient samples taken during non-peak hours. Based on the sign of each estimated parameter, one may reach the following conclusions:

- A positive number for yellow-light duration, intersection width, average flow speed and traffic volume implies that the likelihood of a driver to take aggressive actions such as "aggressive-pass" during a yellow-light phase has a positive correlation with each of those factors. For example, the estimation results indicate that drivers are more likely to behave aggressively when encountering a yellow-light phase if they need to cross a wide intersection during the high volume traffic. The likelihood of doing so increases with the average traffic speed and the expected yellow-light phase duration. These statistical estimation results are consistent with the preliminary conclusions from exploratory data analyses reported in the previous chapter.

- A negative number of through lanes (i.e., -0.86) reconfirms the findings of Chapter 4, which state that drivers in a major intersection approach with multiple lanes are more likely to take non-aggressive responses towards a yellow-light phase. In contrast, those at minor intersection approaches tend to be more aggressive in passing through the intersection when encountering a yellow-light phase.
- The parameters for the peak hour factors are not statistically significant; this is likely due to an insufficient sample size and partly due to the use of traffic volume data that may have captured peak-hour impacts.

Table 5-1 Parameter estimation with an Order-probit model

Parameter Coefficient [P value]	Test-1	Test-2	Test-3
C	-8.04801 [.001]	-8.06354 [.001]	-8.06354 [.001]
INT_SPEED		9.29E-03 [.221]	
SPEED_D			9.29E-03 [.221]
THRUL	-0.86476 [.000]	-0.87962 [.000]	-0.87962 [.000]
CROSSL	0.475574 [.000]	0.479993 [.000]	0.479993 [.000]
Y_DURATION	1.70458 [.000]	1.70191 [.000]	1.70191 [.000]
AVG_SPEED	0.021813 [.041]	0.013167 [.303]	0.02246 [.036]
PK_HR	-0.08061 [.676]	-0.09302 [.631]	-0.09302 [.631]
VOLUME	8.15E-04 [.065]	8.96E-04 [.045]	8.96E-04 [.045]
MU3	3.25308 [.000]	3.25965 [.000]	3.25965 [.000]

* The number in each parenthesis denotes the statistical significance level
(e.g., 0.05 and 0.10 represent the significance level of 5% and 10%, respectively)

Stage-2 Tests:

Using the above traffic condition factors as the base set, the compounded impact of each additional factor of a driver's response pattern during the yellow-light phase can be tested. All additional tests performed in Stage-2 test are listed in Table 5-2:

Table 5-2 All tests performed in the Stage-2 probit model analysis

Test-2: traffic condition factors + the initial entry speed of each vehicle (INT-SPEED);

Test-3: traffic condition factors + the difference between the average traffic flow and each individual's speeds (INT_SPEED);

Test-4: traffic condition factors + the ratio between the average speed and each individual vehicle speed (SPEED_R);

Test-5: replacing the average flow speed in the traffic condition factors with the initial entry speed of each observed vehicle (INT-SPEED);

Test -6: traffic condition factors + the distance to the intersection when a driver first notice the signal changing to a yellow-light phase (INT_POSITION);

Test-7: traffic condition factors + male factor (MALE);

Test-8: traffic condition factors + female factor (FEMALE);

Test-9: traffic condition factors + young driver factor (YOUNG);

Test-10: traffic condition factors + senior driver factor (SENIOR);

Test-11: traffic condition factors + talking-on-phone factor (ONPHONE);

Test-12: traffic condition factors + talking-on-phone factor for male drivers (MALEPHONE);

Test-13: traffic condition factors + talking-on-phone factor for female drivers (FEMALEPHONE);

Tests 14-18: traffic condition factors + each of the following vehicle-type factors: pickup (PICKUP); sport car (SPORTCAR); sport utility vehicle (SUV); van (VAN); heavy vehicle (H_VEHICLE); and

Tests 19-22: traffic condition factors + each of the following vehicle-make factors: Japan (JAPAN), US (US); Europe (EURO); Korea (KOREA).

As shown in Table 5-2, Tests 2 and 3 propose to assess the additive impacts of each driver's initial entry speed and the differences in average speeds, when approaching a yellow-light phase. The estimated positive signs for both parameters shown in Table 5-1 indicate that the drivers with high speeds are more likely to respond to the yellow-light phase with an aggressive action; the likelihood of doing so increases with its difference with the average flow speed. However, due to the impact of the average speed and partly to the small sample size, both parameters cannot achieve more than the 90 percent confidence level (i.e., only about 78%). By the same token, using the speed ratio in place of speed difference in the model can reach the same conclusions.

Nevertheless, by removing the average speed factor from the model, the parameters of the initial vehicle speed does exhibit its significance at the 97% confidence level (see Test-4, Table 5-3). This seems to support the critical role of a vehicle's approaching speed and distance to the intersection (see Test-5, Table 5-3) when responding to a yellow-light phase.

Tests 6 and 7 are designed to evaluate the additive impact of the gender factor to a driver's behavior. Both test results shown in Table 5-5 consistently reveal the fact that female drivers tend to behave conservatively when responding to the change of signal phase from Green to Yellow.

Tests 8 and 9 intend to explore the behavior patterns of young and senior drivers, under the same traffic conditions. The estimated statistical results, as discussed in the previous chapter, are not conclusive, mainly due to the small size of such samples taken in the overall observations.

Tests 10 to 12 examine the impacts of cellular-phone usage on a driver's response when approaching the yellow-light phase. It is interesting to note that the parameter for overall impacts of talking on a cell phone exhibits a negative number and significant level of 0.238, which implies that drivers talking on the phone tend to make conservative actions when approaching a yellow-light phase. Some response discrepancies may exist among various driving populations. This is evident in the estimations shown in Tests 11 and 12, where the parameter for female drivers talking on the phone, shows a negative sign and a nearly 98% confidence level, which is quite different for male drivers talking on the phone. Thus, one can confidently conclude that drivers talking on the phone are more likely to make conservative decisions when approaching a yellow-light phase.

To assess how the differences of vehicle types play in a driver's response to a yellow-light phase, this study has identified a set of indicators to represent pickups, sport cars, vans, sport-utility vehicles, and heavy vehicles, which are included in Tests 13 to 17. Under identical traffic conditions, the results indicate that the parameter for pickups is positive and significant at the 90-percentile confidence level; implying that those drivers are inclined to be more aggressive, such as the drivers identified in the "aggressive-pass" group, when approaching a yellow-light phase. This may be attributed to the fact that most pick-up vehicles are for commercial use and drivers are more likely pressured by commitments to provide their services in a timely manner.

The final set of tests in exploring potential relationships between vehicle makes and driver behavior is divided into the following groups: Japan, U.S., Europe, and Korea. Tests 19-22 in Table 5-8 present results that suggest that US-made and Korean-made cars exhibit negative parameters and have statistically significant confidence levels of 88% and 93%, respectively. In contrast, drivers in Japan-made vehicles, overall, seem to behave more aggressively than others when responding to the yellow-light phase. This is evident in its positive and highly significant parameter (i.e., .246 at the 96% confidence level) shown in Test 19.

Table 5-9 presents the results with all factors that could potentially have impacts on a driver's response and action at signalized intersections. Some factors that are not statistically significant, however exhibit systematic patterns in preliminary analyses are also included in the list of potentially related factors. This is due to the belief that most of these factors should have a higher level of statistical confidence if more related observations are available in the overall data set.

Table 5-3 Parameter estimation with an Order-probit model

Parameter Coefficient [P value]	Test-1	Test-3	Test-4	Test-5
C	-8.04801 [.001]	-8.2939 [.001]	-6.77327 [.002]	-8.10875 [.001]
SPEED_R		0.248713 [.396]		
INT_SPEED			0.013601 [.032]	
INT_POSITION				1.01E-03 [.021]
THRUL	-0.86476 [.000]	-0.87372 [.000]	-0.89186 [.000]	-0.85786 [.000]
CROSSL	0.475574 [.000]	0.478199 [.000]	0.450573 [.000]	0.478261 [.000]
Y_DURATION	1.70458 [.000]	1.70154 [.000]	1.55251 [.000]	1.70543 [.000]
AVG_SPEED	0.021813 [.041]	0.022003 [.039]		0.015892 [.149]
PK_HR	-0.08061 [.676]	-0.08854 [.647]	-0.13572 [.473]	-0.08891 [.647]
VOLUME	8.15E-04 [.065]	8.70E-04 [.052]	9.52E-04 [.032]	8.91E-04 [.045]
MU3	3.25308 [.000]	3.25622 [.000	3.25615 [.000]	3.286 [.000]

* The number in each parenthesis denotes the statistical significance level
(e.g., 0.05 and 0.10 represent the significance level of 5% and 10%, respectively)

Table 5-4 Parameter estimation with an Order-probit model

Parameter Coefficient [P value]	Test-1	Test-6	Test-7
C	-8.04801 [.001]	-8.42202 [.001]	-8.39486 [.001]
MALE		0.218682 [.060]	
FEMALE			-0.23599 [.049]
THRUL	-0.86476 [.000]	-0.8661 [.000]	-0.91128 [.000]
CROSSL	0.475574 [.000]	0.48828 [.000]	0.493735 [.000]
Y_DURATION	1.70458 [.000]	1.74585 [.000]	1.81002 [.000]
AVG_SPEED	0.021813 [.041]	0.022013 [.039]	0.02172 [.042]
PK_HR	-0.08061 [.676]	-0.06424 [.740]	-0.08598 [.656]
VOLUME	8.15E-04 [.065]	7.86E-04 [.076]	7.91E-04 [.074]
MU3	3.25308 [.000]	3.26811 [.000]	3.27189 [.000]

* The number in each parenthesis denotes the statistical significance level
(e.g., 0.05 and 0.10 represent the significance level of 5% and 10%, respectively)

Table 5-5 Parameter estimation with an Order-probit model

Parameter Coefficient [P value]	Test-1	Test-8	Test-9
C	-8.04801 [.001]	-8.22863 [.001]	-8.08082 [.001]
YOUNG		0.347004 [.303]	
SENIOR			0.047739 [.847]
THRUL	-0.86476 [.000]	-0.85776 [.000]	-0.86285 [.000]
CROSSL	0.475574 [.000]	0.479504 [.000]	0.476383 [.000]
Y_DURATION	1.70458 [.000]	1.72736 [.000]	1.7081 [.000]
AVG_SPEED	0.021813 [.041]	0.022501 [.036]	0.021852 [.041]
PK_HR	-0.08061 [.676]	-0.07671 [.691]	-0.0797 [.679]
VOLUME	8.15E-04 [.065]	7.97E-04 [.072]	8.16E-04 [.065]
MU3	3.25308 [.000]	3.25723 [.000]	3.25322 [.000]

* The number in each parenthesis denotes the statistical significance level
(e.g., 0.05 and 0.10 represent the significance level of 5% and 10%, respectively)

Table 5-6 Parameter estimation with an Order-probit model

Parameter Coefficient [P value]	Test-1	Test-10	Test-11	Test-12
C	-8.04801 [.001]	-8.16552 [.001]	-8.08254 [.001]	-8.42388 [.001]
ONPHONE		-0.34632 [.238]		
MALEPHONE			0.289046 [.496]	
FEMALEPHONE				-0.86946 [.025]
THRUL	-0.86476 [.000]	-0.8825 [.000]	-0.8646 [.000]	-0.9075 [.000]
CROSSL	0.475574 [.000]	0.481986 [.000]	0.477392 [.000]	0.496279 [.000]
Y_DURATION	1.70458 [.000]	1.73197 [.000]	1.70689 [.000]	1.77661 [.000]
AVG_SPEED	0.021813 [.041]	0.022275 [.037]	0.021934 [.040]	0.023196 [.031]
PK_HR	-0.08061 [.676]	-0.08808 [.648]	-0.08225 [.670]	-0.10635 [.583]
VOLUME	8.15E-04 [.065]	8.25E-04 [.062]	8.22E-04 [.063]	8.64E-04 [.052]
MU3	3.25308 [.000]	3.26309 [.000]	3.25586 [.000]	3.28165 [.000]

* The number in each parenthesis denotes the statistical significance level
(e.g., 0.05 and 0.10 represent the significance level of 5% and 10%, respectively)

Table 5-7 Parameter estimation with an Order-probit model

Parameter Coefficient [P value]	Test-1	Test-13	Test-14	Test-15	Test-16	Test-17
C	-8.04801 [.001]	-7.93897 [.002]	-8.0195 [.001]	-8.06418 [.001]	-8.02805 [.001]	-8.03616 [.001]
PICKUP		0.324309 [.101]				
SPORTSCAR			-0.07501 [.792]			
SUV				-0.04741 [.761]		
VAN					-0.02469 [.896]	
H_VEHICLE						-0.36774 [.328]
THRUL	-0.86476 [.000]	-0.85944 [.000]	-0.8644 [.000]	-0.86434 [.000]	-0.86123 [.000]	-0.87108 [.000]
CROSSL	0.475574 [.000]	0.470651 [.000]	0.474157 [.000]	0.476105 [.000]	0.474648 [.000]	0.475477 [.000]
Y_DURATION	1.70458 [.000]	1.69033 [.000]	1.70032 [.000]	1.70817 [.000]	1.69999 [.000]	1.70867 [.000]
AVG_SPEED	0.021813 [.041]	0.020885 [.051]	0.021804 [.041]	0.021878 [.040]	0.021817 [.041]	0.021639 [.043]
PK_HR	-0.08061 [.676]	-0.07667 [.691]	-0.07863 [.684]	-0.07907 [.682]	-0.08 [.678]	-0.08678 [.653]
VOLUME	8.15E-04 [.065]	7.88E-04 [.075]	8.18E-04 [.064]	8.13E-04 [.066]	8.13E-04 [.066]	8.36E-04 [.059]
MU3	3.25308 [.000]	3.2654 [.000]	3.25351 [.000]	3.25322 [.000]	3.25305 [.000]	3.25839 [.000]

* The number in each parenthesis denotes the statistical significance level
(e.g., 0.05 and 0.10 represent the significance level of 5% and 10%, respectively)

Table 5-8 Parameter estimation with an Order-probit model

Parameter Coefficient [P value]	Test-1	Test-18	Test-19	Test-20	Test-21
C	-8.04801 [.001]	-7.99801 [.002]	-8.12718 [.001]	-8.14594 [.001]	-8.32198 [.001]
JAPAN		0.246796 [.045]			
US			-0.17947 [.126]		
EURO				-0.11714 [.648]	
KOREA					-0.78049 [.074]
THRUL	-0.86476 [.000]	-0.83243 [.000]	-0.8778 [.000]	-0.87232 [.000]	-0.89681 [.000]
CROSSL	0.475574 [.000]	0.468753 [.000]	0.480569 [.000]	0.480353 [.000]	0.49025 [.000]
Y_DURATION	1.70458 [.000]	1.65123 [.000]	1.72311 [.000]	1.72368 [.000]	1.75616 [.000]
AVG_SPEED	0.021813 [.041]	0.023585 [.028]	0.023255 [.030]	0.022038 [.039]	0.022811 [.033]
PK_HR	-0.08061 [.676]	-0.06721 [.729]	-0.06749 [.727]	-0.08238 [.669]	-0.07796 [.687]
VOLUME	8.15E-04 [.065]	7.89E-04 [.076]	8.39E-04 [.059]	8.13E-04 [.066]	8.41E-04 [.058]
MU3	3.25308 [.000]	3.27853 [.000]	3.26623 [.000]	3.25442 [.000]	3.27274 [.000]

* The number in each parenthesis denotes the statistical significance level
(e.g., 0.05 and 0.10 represent the significance level of 5% and 10%, respectively)

Table 5-9 Estimation results of all factors potentially related to the response of drivers during a yellow-light phase

Parameter	Estimate	Standard Error	t-statistic	P-value
C	-8.64638	2.58858	-3.34021	[.001]
FEMALE	-0.20793	0.127196	-1.63471	[.102]
FEMALEPHONE	-0.71906	0.420767	-1.70893	[.087]
INT_POSITION	9.83E-04	4.52E-04	2.17443	[.030]
SPEED_D	5.75E-03	7.86E-03	0.732461	[.464]
PICKUP	0.374987	0.206976	1.81174	[.070]
JAPAN	0.31718	0.130795	2.42502	[.015]
KOREA	-0.35428	0.475543	-0.74501	[.456]
THRUL	-0.91031	0.185907	-4.89659	[.000]
CROSSL	0.505842	0.121569	4.16096	[.000]
Y_DURATION	1.7909	0.451738	3.96447	[.000]
AVG_SPEED	0.019118	0.011319	1.68897	[.091]
PK_HR	-0.10105	0.197662	-0.51123	[.609]
VOLUME	9.07E-04	4.57E-04	1.98362	[.047]
MU3	3.38181	0.132841	25.4576	[.000]
Number of observations = 665		*LR (zero slopes) = 65.2914 [.000]*		
Mean of dep. var. = 2.01504		*Schwarz B.I.C. = 3310.221*		
Std. dev. of dep. var. = .359571		*Log likelihood = -282.473*		

* The number in each parenthesis denotes the statistical significance level (e.g., 0.05 and 0.10 represent the significance level of 5% and 10%, respectively)

5.3 Potential applications of the research results

Although the number of observations and intersections included in the field study are insufficient from the behavioral research perspective, this study intends to take advantage of available information and present procedures and results to potential applications. The procedures for computing the distribution of intersection dilemma zones can be divided into the following two stages:

Stage-1: Development of a set of models based on the estimation results in the previous section, where:

- Model-1 predicts the percent of "stopped" versus "passing through" drivers at a target intersection, based on associated and observable factors;
- Model-2 predicts the percent of "conservative-stop" versus "normal-stop" drivers among those "stopped" drivers; and
- Model-3 is predicts the percent of "aggressive-pass" versus "normal-pass" drivers among those "passing through" drivers.

Stage-2: Computing driver/vehicle performance results of the field observations:

- The spatial evolution of average acceleration and deceleration rates, as shown in Table 5-10; and
- The speed evolution in reference to their measured 85th percentile approaching speeds, as shown in Tables 5-11 to 5-14.

Stage-3: Estimation of the dilemma zone distributions for each group of drivers based on the results from the previous stages and the formulations shown in Chapter 2.

The set of models developed in Stage-1 along with a brief description of the estimation methodology are presented hereafter.

Table 5-10 Spatial evolution of the average acceleration/deceleration [ft/s^2] rates for each group

Group		Entry point	Initial point	After yellow-light	Passing point
conservative-stop	Mean	-4.53	-5.12	-6.83	-3.25
sharp-stop	Mean	-10.15	-9.47	-10.29	-1.65
smooth-stop	Mean	-4.89	-4.56	-5.43	-1.55
const-pass	Mean	-3.46	-1.44	0.09	0.08
deceleration-pass	Mean	-9.87	-0.65	-5.47	-4.17
acceleration-pass	Mean	-0.17	4.41	10.75	12.50
aggressive-pass	Mean	-3.98	1.02	-0.73	-1.07

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* “Entry point”: the location when vehicles were observed to enter the intersection approach;
* “Initial point”: the location of vehicle when the signal is changing to a yellow-light phase;
* “After yellow-light”: the approximate location between the initial point and the intersection stop line;
* “Passing point”: the location after passing the intersection.

Table 5-11 Spatial evolution of vehicle speeds for the “conservative-stop” group in reference to the 85th percentile speed

Group-1 (Conservative_Stop)					
Intersection Name	Speed-1 (mph)	Speed-2 (mph)	Speed-3 (mph)	Speed-4 (mph)	Total #
MD193@Hanover Pkwy.	-5.46 (10.98)	-5.32 (9.43)	-13.42 (8.91)	N/A	9
MD198@Whiskey Bottom Rd.	N/A	N/A	N/A	N/A	0
MD201@Crescent Rd.	N/A	N/A	N/A	N/A	0
MD355@Shady Grove Rd.	0.13 (6.88)	5.15 (1.85)	-0.02 (10.15)	N/A	2
MD4@Silver Hill Rd.	-6.16 (6.49)	-6.43 (6.97)	-11.51 (7.85)	N/A	4
MD45@Burke Rd.	-4.55 (9.21)	-3.71 (8.37)	-7.16 (5.21)	N/A	2
MD650@MD198	-3.58 (2.16)	-3.63 (2.32)	-8.58 (3.39)	N/A	6
US29@Stewart Ln.	-7.66 (5.29)	-8.43 (4.99)	-18.73 (4.53)	N/A	5
US40@Rogers Ave.	-2.24 (6.09)	-3.664 (6.79)	-11.95 (13.57)	N/A	10
Overall	**-4.21**	**-3.71**	**-10.19**		**38**

* Speed-1 = Entry Speed – 85th percentile speed;
Speed-2 = Initial Speed – 85th percentile speed;
Speed-3 = After-Yellow-light Speed – 85th percentile speed;
Speed-4 = Passing Speed – 85th percentile speed

Table 5-12 Spatial evolution of vehicle speeds for the "Normal-stop" group in reference to the 85th percentile speed

Group-2 (Normal_Stop)					
Intersection Name	Speed-1 (mph)	Speed-2 (mph)	Speed-3 (mph)	Speed-4 (mph)	Total #
MD193@Hanover Pkwy.	-14.37 (10.62)	-15.18 (10.01)	-20.21 (9.19)	N/A	104
MD198@Whiskey Bottom Rd.	-9.69 (0.74)	-9.69 (0.74)	-6.12 (4.77)	N/A	2
MD201@Crescent Rd.	-12.82 (4.21)	-12.82 (4.21)	-14.71 (3.13)	N/A	9
MD355@Shady Grove Rd.	-8.34 (4.67)	-7.93 (5.20)	-11.38 (4.59)	N/A	46
MD4@Silver Hill Rd.	-12.45 (7.15)	-12.41 (7.06)	-16.82 (6.65)	N/A	43
MD45@Burke Rd.	-8.99 (2.22)	-8.99 (2.22)	-12.13 (2.50)	N/A	7
MD650@MD198	-9.18 (5.06)	-9.19 (5.06)	-14.65 (5.88)	N/A	27
US29@Stewart Ln.	-8.48 (5.59)	-9.11 (7.46)	-15.37 (7.15)	N/A	38
US40@Rogers Ave.	-12.11 (6.40)	-12.75 (7.05)	-17.47 (6.48)	N/A	24
Overall	-10.71	-10.90	-14.32		300

Table 5-13 Spatial evolution of vehicle speeds for the "normal-pass" group in reference to the 85th percentile speed

Group-3 (Normal_Pass)					
Intersection Name	Speed-1 (mph)	Speed-2 (mph)	Speed-3 (mph)	Speed-4 (mph)	Total #
MD193@Hanover Pkwy.	-10.65 (10.78)	-12.52 (9.31)	-17.62 (7.85)	-17.08 (8.96)	120
MD198@Whiskey Bottom Rd.	-3.49 (3.65)	-0.89 (4.32)	-0.56 (2.65)	1.14 (4.71)	11
MD201@Crescent Rd.	-4.87 (6.64)	-2.41 (5.99)	-1.73 (8.22)	-3.38 (6.18)	19
MD355@Shady Grove Rd.	-5.80 (5.58)	-5.31 (6.56)	-5.19 (5.89)	-3.35 (5.87)	34
MD4@Silver Hill Rd.	-5.37 (5.45)	-7.69 (6.05)	-18.64 (21.71)	-7.48 (8.20)	28
MD45@Burke Rd.	N/A	N/A	N/A	N/A	0
MD650@MD198	-3.77 (4.16)	-5.51 (4.55)	-8.12 (5.61)	-6.97 (5.03)	20
US29@Stewart Ln.	-5.91 (6.15)	-6.28 (6.01)	-7.70 (7.36)	-10.31 (7.53)	48
US40@Rogers Ave.	-9.00 (9.16)	-9.62 (8.09)	-10.31 (8.30)	-11.23 (7.75)	23
Overall	-6.11	-6.28	-8.73	-7.33	303

* Speed-1 = Entry Speed – 85th percentile speed;
Speed-2 = Initial Speed – 85th percentile speed;
Speed-3 = After-Yellow-light Speed – 85th percentile speed;
Speed-4 = Passing Speed – 85th percentile speed

Table 5-14 Spatial evolution of vehicle speeds for the "aggressive-pass" group in reference to the 85th percentile speed

Group-4 (Progressive_Pass)					
Intersection Name	Speed-1 (mph)	Speed-2 (mph)	Speed-3 (mph)	Speed-4 (mph)	Total #
MD193@Hanover Pkwy.	-11.83 (10.99)	-13.23 (8.62)	-13.10 (9.15)	-15.96 (10.05)	29
MD198@Whiskey Bottom Rd.	-1.78 (N/A)	-1.78 (N/A)	2.77 (N/A)	9.74 (N/A)	1
MD201@Crescent Rd.	N/A	N/A	N/A	N/A	0
MD355@Shady Grove Rd.	-1.86 (5.61)	-4.53 (6.29)	-3.31 (7.04)	-5.63 (7.38)	9
MD4@Silver Hill Rd.	-6.29 (8.53)	-7.03 (8.48)	-6.71 (8.44)	-6.68 (8.34)	41
MD45@Burke Rd.	0.00 (N/A)	0.00 (N/A)	4.19 (N/A)	-4.08 (N/A)	1
MD650@MD198	-6.10 (3.66)	-5.82 (2.98)	-4.69 (4.19)	-5.82 (3.82)	6
US29@Stewart Ln.	-3.29 (4.53)	-3.63 (4.69)	-4.36 (3.92)	-5.12 (3.60)	4
US40@Rogers Ave.	N/A	N/A	N/A	N/A	0
Overall	-4.45	-5.15	-3.60	-4.79	91

* Speed-1 = Entry Speed – 85th percentile speed;
Speed-2 = Initial Speed – 85th percentile speed;
Speed-3 = After-Yellow-light Speed – 85th percentile speed;
Speed-4 = Passing Speed – 85th percentile speed

Estimation method

It should be mentioned that unlike the previous model estimation, the dependent variable in the set of prediction models is binary in nature. For example, the predicted outcome from Model–1 is either "stop" or "pass," and that from Model-2 is either "normal-stop" or "conservative-stop." Hence, one can employ the standard logistic regression method for the model development.

With the logistic regression method, the collective impacts of all explanatory variables of the dependent variable is that either "stop" or "pass" can be expressed as follows:

$$\mathbf{z} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots\ldots \beta_n x_n$$

By setting "stop" as the default outcome, the probability of a driver choosing the "pass" decision under the given set of factors is:

$$\text{Prob (pass)} = \frac{e^z}{1 + e^z}$$

The sum of each individual probability over the entire population is the total estimated number of drivers who are likely to decide to pass through the target intersection during a yellow-light phase.

Model development results

Table 5-15 presents the calibration results of Model-1, where Model-1A includes the following two sets of variables:

- Measurable traffic condition factors, including the number of through lanes, crossing lanes, yellow-light duration, average traffic flow speed, traffic volume, and peak-hour indicators; and
- The average distance for vehicles to reach the intersection when the signal turns to yellow.

Model-1B uses the first set of traffic condition variables. Based on the percentage of correct predictions (86% and 56%) shown in Table 5-15, one may conclude that developing a reliable model for such applications is practical and feasible as long as there is sufficient data for model calibration.

Using the same set of variables, Table 5-16 presents the calibration results for Model-2A and Model-2B. It is notable that Model-2A can achieve up to 92% of the prediction accuracy with only three significant variables: the initial distance to the intersection, number of through lanes, and the average traffic flow speed. In contrast, the performance of Model-2B, which relies mainly on factors such as the number of through lanes, crossing lanes, and the yellow-light duration, can provide about 87% of accurate predictions. Overall, the prediction accuracy provided by either model seems to be sufficient for field applications.

Model-3A and Model-3-B are two specifications proposed to distinguish the "aggressive-pass' drivers from those taking "normal-pass" movements. The calibration results are summarized in Table 5-17, where Model 3-A can reach about 93% of prediction accuracy, and all its explanatory variables are statistically significant, except for the peak-hour indicator. Without using the average initial distance factor, Model-3B has achieved up to an 86% accuracy rate, but both volume and peak-hour indicators do not play a significant role, as reflected in their statistically insignificant parameters

In summary, even with limited field observations and some inevitable measurement errors, the performance of those proposed prediction models is quite encouraging, and offers potential for implementing in real-world applications where more extensive filed data could be available for better model calibration.

Table 5-15 Estimation results for Model-1 (stop vs. pass)

Estimated Parameter	Model-1A	Model-1B
C1	-23.979	-11.4829
	[.000]	[.002]
INT_POSITION	-0.02456	
	[.000]	
THRUL	-1.56305	-0.51771
	[.000]	[.026]
CROSSL	1.05922	0.456376
	[.000]	[.005]
Y_DURATION	4.04288	1.78238
	[.000]	[.004]
AVG_SPEED	0.215298	0.03606
	[.000]	[.018]
PK_HR	-0.08775	-0.13306
	[.828]	[.616]
VOLUME	1.00E-05	8.96E-04
	[.992]	[.139]
Log likelihood	-217.018	-451.37
Percent of Correct Predictions	86.02%	55.94%

*The number in each parenthesis denotes the statistical significance level.

Table 5-16 Estimation results for Model 2 (normal-stop and conservative stop)

Estimated Parameter	Model-2A	Model-2B
C	-1.43639 [.881]	-13.5836 [.102]
INT_POSITION	0.040105 [.000]	
THRUL	-1.53121 [.070]	-1.32388 [.021]
CROSSL	0.542344 [.313]	0.775526 [.054]
Y_DURATION	1.62947 [.371]	2.83546 [.054]
AVG_SPEED	-0.34889 [.000]	0.022453 [.532]
PK_HR	-1.02509 [.246]	-0.27714 [.662]
VOLUME	3.48E-03 [.119]	1.42E-03 [.286]
Log likelihood	-53.3654	-110.596
Percent of Correct Predictions	92.41%	87.97%

*The number in each parenthesis denotes the statistical significance level.

Table 5-17 The estimation results for Model-3 (Normal Pass and Aggressive Pass)

Estimated Parameter	Model-3A	Model-3B
C	-19.3076 [.143]	-18.7102 [.015]
INT_POSITION	0.041677 [.000]	
THRUL	-2.235 [.011]	-2.28203 [.001]
CROSSL	1.11732 [.065]	0.907121 [.011]
Y_DURATION	2.83908 [.195]	3.38569 [.011]
AVG_SPEED	-0.19119 [.001]	0.023387 [.441]
PK_HR	-0.29762 [.720]	-0.04883 [.927]
VOLUME	4.94E-03 [.019]	1.22E-03 [.362]
Log likelihood	-56.2157	-126.799
Percent of Correct Predictions	93.410%	86.25%

*The number in each parenthesis denotes the statistical significance level.

5.4 Conclusions

This chapter uses discrete statistical methods to formally test the relationship between a driver's response during the yellow-light phase and collective as well as individual impacts of all factors. A list of statistically significant factors is presented in Table 5-9. The estimation results seem to support all hypotheses proposed in the previous chapter, except the age and peak-hour factors that appear to have insufficient sample observations to test with statistical methods. Through the statistical test of an order probit model, it is clear that if a driver decides to take aggressive actions in response to a yellow-light phase, factors such as traffic conditions and intersection geometric features have to be considered. A properly coordinated signal system and improved traffic conditions may encourage motorists to drive at proper speeds and to take non-aggressive actions at signalized intersections.

The second part of this chapter presented exploratory results regarding potential ways to apply the results of this research despite the limited the number of field observations. Based on critical factors identified from the statistical estimations, this chapter calibrated three sequential prediction models to use in estimating the distribution of driver responses to yellow-light phases at target intersections. With limited data for evaluation, the performance of these calibrated models seems quite promising, offering the potential use in future applications where additional field data from intersections of different locations can be obtained.

This chapter has also discussed the spatial evolution of vehicle speeds and acceleration/deceleration rates for each classified group of drivers, from entering an approach, responding to the yellow-light phase, and to passing through an intersection. Such valuable information can be used along with the predicted distribution of driver responses for computing the length and location of dynamic dilemma zones.

Chapter 6
Conclusions and Recommendations

6.1 Conclusions

This study investigated the responses of drivers when approaching a yellow-light phase under various traffic conditions. It also researched the impacts of a driver's decision within dilemma zones, as their lengths and locations can vary with the duration of the yellow-light phase and the behavioral patterns of the driver.

The first part of this research analyzes the relationship between the dilemma zone distributions and driver/vehicle performance characteristics. It concludes that dilemma zones are dynamic in nature and their locations and lengths are highly correlated with a driver's perception/reaction time, decision to pass or stop, and his/her vehicle's rate of deceleration/acceleration. Hence, most dilemma zones at intersections with high crash rates cannot totally be eliminated since the yellow-light duration is designed on the basis of the 85^{th} percentile of approaching vehicle speeds.

The theoretical analyses findings supported the necessity to observe driver behavior at signalized intersections. Thus, the field study conducted in the second part of this project included observations of more than 700 drivers approaching a yellow-light phase at nine intersections located across five different counties. Based on the amount of data associated with driver responses under various traffic conditions, all the recorded information in this study has been analyzed with rigorous statistical tests.

The extensive research results revealed that different driver responses during the yellow-light phase may be classified into the following types: "aggressive-pass," "conservative-stop," "normal-pass," and "normal-stop." The response difference in driving groups depends on not only their individual preferences, but also their encountered traffic conditions. Based on the speed evolution data recorded from each observed driver, this study further computed the average deceleration/acceleration rates of drivers responding to the yellow-light phase. Such information provides valuable data for computing the distribution of intersection dilemma zones under various types of driving populations and vehicles.

In summary, this project accomplished its research objectives and produced valuable information on the following issues that can be used directly or indirectly in computing the distribution of dilemma zones and thereby improving traffic safety at signalized intersections:

1. *The complex relationships between dilemma zones and the behavior of drivers approaching intersections:*
   - Provided numerical analyses to demonstrate the existence of dynamic intersection dilemma zones, which may vary with drivers' responses as they encounter yellow-light phases, their exercised accelerate/decelerate rates, and the yellow-light phase duration.
   - Proved a deficiency in existing practices that solely use the 85th percentile of the approaching vehicle speeds to design the yellow-light duration.
   - Developed convenient methods to classify the discrepancies of driver responses during the yellow-light phase into four distinct types.
   - Computed average deceleration/acceleration rates for each type of drivers based on vehicle speed when approaching a yellow-light phase, which was based directly on field data. The discrepancies of deceleration/ acceleration rates among driving populations are one of the main factors that cause dilemma zones to vary in location and length.
   - Proposed an effective methodology to compute "dynamic dilemma zones" at intersections of high crash frequency, based on the estimated distribution of driver responses during the yellow-light phase and their acceleration/deceleration rates.

2. *The response of drivers to a yellow-light phase under various traffic conditions*:
   - Female drivers, in general, are more likely to take conservative actions in response to a change in the signal phase.
   - Female drivers, talking on phone, tend to prefer to either conservatively or normally stop in response to the yellow-light phase.
   - Young drivers appear to more likely respond to yellow-light phases with an "aggressive-pass" decision, but definitive conclusions cannot be made due to the limited sample size in this category.

- Drivers approaching the intersection at a speed higher than the average traffic flow speed are more likely to take "aggressive-pass" actions when encountering the yellow-light phase.
- The difference between the average flow speed and an individual's driving speed is a key factor that can affect a driver's decision to pass through a yellow-light phase.
- Under congested traffic conditions, drivers are more willing to take "aggressive-pass" actions during a yellow-light phase unless they are prevented by vehicles ahead of them.
- Drivers at intersections with a longer yellow-light durations and higher average flow speeds are more likely to take an "aggressive-pass" decision.
- Among all observed drivers, those in pick-up vehicles revealed a more aggressive behavioral pattern than others.
- Peak-hour congestion seems to pressure most drivers to go through the yellow-light phase, but the opportunity to do so is often limited by the high traffic volume. The limited existing data from the field observations, however, do not show a significant relationship between the peak-hour factor and the response of drivers during a yellow-light phase.
- Aggressive drivers approaching a yellow-light phase, tend to accelerate their speeds initially, and then reduce to their normal speeds after passing the intersection.

6.2 Recommendations

It should be mentioned that all above reported findings are exploratory in nature and much remains to be studied, due to the complex interactions between drivers, their experienced traffic conditions, and the large number of potentially related factors. Further efforts for improving intersection traffic safety shall include:

- Performing more field observations at intersections located in different counties to evaluate the preliminary conclusions presented in this project.

- Refining the set of models proposed in this study for estimating the distribution of various driver responses to the yellow-light phase with more data from intersections of different geometric features and driving populations.
- Assessing the reliability of acceleration/deceleration rates associated with each group of drivers and their speed evolution patterns when approaching a yellow-light phase.
- Applying all developed models to intersections with high crash frequency rates on major state routes to test their effectiveness in identifying underlying factors that degrade the quality of traffic safety.
- Investigating potential technologies or devices in Intelligent Transportation Systems (ITS) for contending with dynamic dilemma zones at signalized intersections of non-uniform driving populations.

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