AN ABSTRACT OF THE DISSERTATION OF

Hameed Aswad Mohammed for the degree of Doctor of Philosophy in Civil Engineering presented on June 13, 2019.

Title: Evaluating Driver Response to the Onset of the Circular Yellow Indication in the Presence of a Following Vehicle at Isolated High-Speed Signalized Intersections.

Abstract approved:

David S. Hurwitz

Dilemma zones on the approach to high-speed signalized intersections have been identified as a safety problem that can contribute to rear–end and right–angle crashes. However, in situations when a pair of vehicles is caught in the dilemma zone, it is not well understood how the following vehicle's headway and classification influence the leading driver's decision in response to the Circular Yellow (CY) indication. This complex vehicle-vehicle-intersection interaction, and the consequences of faulty driver decision making warrant further evaluation.

This study analyzed driver behavior at the onset of the CY indication at isolated high-speed signalized intersections and evaluated three elements of the challenge: 1) yellow light laws and driver training manual instructions, 2) driver's visual attention, and 3) driver's stop-go decisions.

Findings indicated inconsistencies between the Driver Training Manual (DTM) guidance and yellow state laws. 74% of states followed a Class 1 (permissive law) yellow law while 72% of states followed Class 3 (restrictive law) guidance in DTMs. This inconsistency between state yellow laws and DTM guidance may contribute to inconsistencies in driver comprehension and decision making in response to CY indications, particularly when drivers travers state boundaries.

The highest percentage of Total Fixation Duration (TFD) was allocated to the traffic signal head (78.4%), followed by the rear view (20.3%) and then side view mirrors (1.3%). Repeated-measures ANOVA was performed to determine whether TFD differed between scenarios for each Area of Interest (AOI). When a significant effect was observed, pairwise comparisons were conducted to find the origin of the difference. For the traffic signal AOI, the following vehicle type and Time to Stop Line (TTSL) had significant effects on the TFD. For the rear-view mirror AOI, the following vehicle type and time headway had significant effects on TFD when the driver looked at the rear view mirror. No significant effect was observed for any independent variable or the two or three-way interactions on the TFD on the side view mirrors. Random-effect Tobit regression was used as the data involved repeated measures and numerous zeros. Two random-effect Tobit regression models were developed to deal with two AOIs (traffic signal and rear view mirror). TTSL, driver age of 45–55 years, and vehicle speed at the onset of CY indication (35–45) mph had positive and statistically significant effects on the TFD for the traffic signal with a 95% confidence interval (CI). For the rear view mirror, TTSL, driver age of 55–65 years, and drivers with some high school or less all had positively significant effects for TFD while time headway, driving once per week, and driving a van in one's personal life had negatively significant effects for the TFD for a 95% CI.

Finally, decision making results indicated that 51% of drivers decided to stop prior the stop line while 49 % chose to proceed through an intersection in response to CY indication. Nearly all drivers (97%) went through an intersection when they were 2.5 seconds from the stop line and red-light running violations start to increase when TTSL was 5.5 seconds. A random parameter binary logit model was used to deal with unobserved heterogeneity across observations. A total of 4 parameters were found to be statistically significant on driver's decision making at the onset of CY indication. The findings indicated that TTSL, time headway, and driver age of 20–36 years increased the probability of stopping while vehicle speed at the onset of the CY indication decreased the probability of stopping. The results showed that following vehicle type did not influence driver's decision to proceed or stop in response to the CY indication with statistical significance.

Evaluating Driver Response to the Onset of Circular Yellow Indication in the Presence of a Following Vehicle at Isolated High-Speed Signalized Intersections

by

Hameed Aswad Mohammed

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I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

Hameed Aswad Mohammed, Author

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Chapter 1 – Introduction

1.1 Motivation

Intersections represent a small percentage of the paved road surface. However, about 40% of vehicle crashes occur at intersections in the United States (Awadallah, 2009). Statistics show that crashes at signalized intersections have become a significant safety problem in the United States. According to the statistics given by National Highway traffic System Administration (NHTSA, 2017), 37,461 people were killed on the roads in 2016. Of these 3,145 were killed at signalized intersections. Responsibility for intersection safely depends on the actions of the driver as well as appropriate intersection planning, construction, operation, and maintenance.

Circular Yellow (CY) indications are intended to warn drivers that the green indication has ended and that a red indication will activate shortly. However, this phase transition elicits a wide variety of driver responses. Some drivers when presented a CY indication, accelerate to clear the intersection before a Circular Red (CR) indication is displayed. Dangerous driving behaviors like this one put drivers and other road users in potentially dangerous situations. Red-light running (RLR) is a serious safety issue that is associated with incorrect driver response to the display of a CY indication. It occurs when a vehicle enters an intersection any time after the onset of a CR indication at a signalized intersection. An estimated 165,000 crashes occur annually in intersections caused by RLR and the consequences of those crashes are significant. In 2016, 811 people were killed in crashes that involved RLR. Over half of those killed were pedestrians, bicyclists, and people in other vehicles who were hit by a RLR vehicle (NHTSA, 2017).

In most cases, rear-end and right-angle crashes are associated with incorrect driver decision making in response to the CY indication. Rear-end crashes can result when faulty driver decision making results in overly hard breaking which can increase the likelihood of rear-end collisions with following vehicles. Alternatively, if the first driver decides exposed to the CY decides to proceed through the intersection when there is not enough time to clear the intersection before conflicting movements are provided a green indication, a right-angle or head on crash could occur. Rear-end and right-angle crashes can lead to tragic consequences at high speed signalized intersections. Here we classify signalized intersections as high speed when the posted speed limit is 40 mph or higher (Zhang et al., 2014; Wei et al., 2011).

Significant previous work has been conducted to document, evaluate, and understand driver behavior in the dilemma zone of signalized intersection approaches. There is a clear absence of consideration of the influence that a following car has on driver behavior for the leading vehicle when presented a CY indication.

1.2 Existing Dilemma Zone Definitions

The dilemma zone concept was initially proposed by Gazis, Herman, and Maradudin (1960), commonly referred to as the GHM model (Wei, 2008). The dilemma zone is a space between two points on an approach to a signalized intersection, generally defined as beginning at a point where approaching drivers will likely stop at the stop line of the intersection when shown a CY indication and ending where drivers will likely proceed through the intersection before the CR indication is displayed.

Between these two points, drivers are in a dilemma as to whether to stop or proceed (ITE, 2010).

Previous literature has documented two forms of dilemma zone that drivers can experience as they approach an intersection and are presented with a CY indication. A Type I dilemma zone was first referenced by Gazis et al. in 1960. The Type I dilemma zone describes the possibility that a driver when presented a CY indication while approaching a signalized intersection will be unable to safely stop before the stop line or safely pass through the intersection due to the physical parameters of the intersection (Knodler and Hurwitz, 2009). Those physical parameters may include timing and phasing, detector layout and operation, and geometry. This can be the result of poor signal timing (excessively short yellow change intervals) and/or detector placement (detector setbacks too short), while site-specific characteristics such as approach grade, speed, and available sight distance can also contribute to these errors. Since the identification of this issue in 1960, signal timing practices have changed to account for this possible conflict and, when applied correctly, eliminate the potential for a Type I dilemma zone to occur.

The Type II dilemma zone has also been referred to as the “indecision zone” or “option zone,” reflecting their probabilistic nature. It was identified and formally documented in a technical committee report produced by the Southern Section of ITE (Parsonson, 1974). The Type II dilemma zone describes the region of pavement which begins at the position on the approach to a signalized intersection where most people choose to stop the vehicle when presented with the CY indication and ends at the position where most people choose to continue through the intersection (Knodler and

Hurwitz, 2009). The Type II dilemma zone is associated with driver behavior. As a group, drivers within a few seconds travel time of the intersection tend to be indecisive about their ability to choose either to clear the intersection before the end of the CY indication or stop at the stop line. This behavior yields a "zone of indecision" in advance of the stop line where some drivers may proceed and others may stop (Urbanik and Koonce, 2007). Figure 1.1 illustrates both types of dilemma zones.

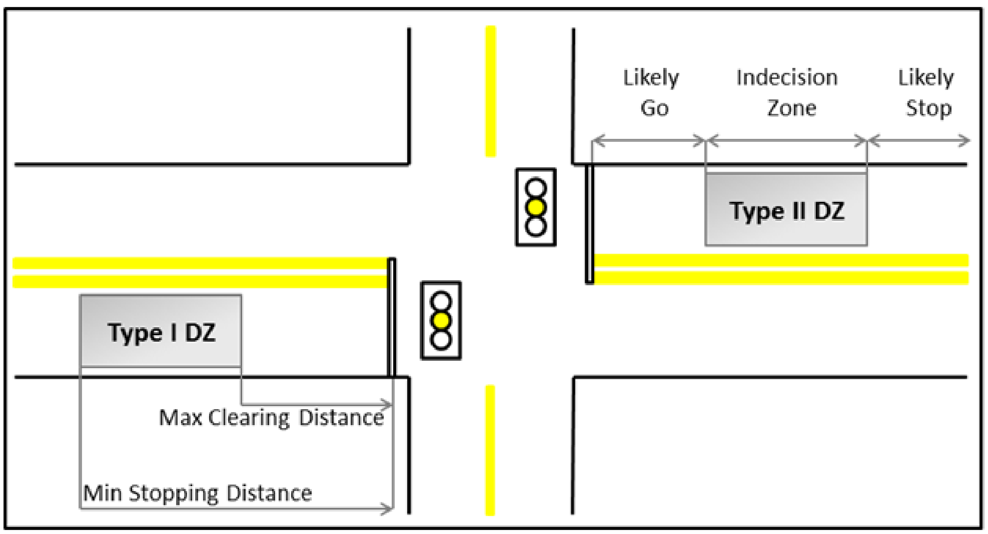

Figure 1.1 Type I and Type II dilemma zones (Hurwitz et al., 2011)

Dilemma zone issues become even more prevalent at high-speed intersections and many research efforts focus on the topic because there is greater potential for serious crashes and more variability in vehicle speeds. It is important to mitigate dilemma zone issues because they relate to two potential crash situations: sudden stops may cause rear-end crashes, and failure to stop may result in right-angle crashes (Knodler and Hurwitz, 2009).

1.3 Differing Yellow Laws

One important issue related to dilemma zones are the different laws associated with the CY indications that are enforced throughout the country. Each state has laws dictating what drivers should do at the onset of the CY indication. Laws that relate to the yellow change interval can be classified into two categories, either “permissive” or “restrictive”. Under a permissive yellow law, a vehicle can enter the intersection at any point during the yellow change interval and it is legal to be in the intersection during the red interval if the vehicle entered the intersection during the yellow. Both the Uniform Vehicle Code (UVC) and the MUTCD support a permissive yellow law, meaning that a vehicle can legally occupy an intersection on red as long as it entered the intersection while the CY indication was being presented (NCUTLO, 1992).

There are two variations of the restrictive yellow law. The first variation of the restrictive rule states that a vehicle cannot enter or be in intersection on red (i.e. vehicle must clear the intersection before light turns red). The second variation of the restrictive rule asserts that a vehicle must stop when presented with the CY indication but may proceed with caution through the intersection if it is not possible to do safely (Eccles and McGee, 2001). Generally, states following the second condition of restrictive yellow law are not considered to be in conflict with the permissive yellow law. At least half of the states follow the permissive yellow law, while the remaining states follow one of two versions of a restrictive rule. Another confounding factor is that each state also maintains a Driver Training Manual (DTM) that explains driving regulations and laws with text and figures. Each of the 50 DTMs has a section that describes the meaning and/or appropriate driver response to a CY indication. The variability in legal definitions across state boundaries can introduce confusion for drivers and transportation professionals. Traffic engineer should be aware of these subtle differences as they design and implement signal timing plans.

1.4 Purpose and Scope

The purpose of this dissertation was to analyze driver behavior at the onset of the CY indication at isolated high-speed signalized intersections, including three aspects: 1) yellow light laws and driver training manual instructions, 2) driver's visual attention, and 3) driver's stop-go decisions.

The language used in Driver Training Manual (DTM) guidance describes what drivers should do in response to a steady CY indication at a signalized intersection and at the same time, drivers should follow the applicable laws in the state in which they are operating their vehicle. Thus, this first study tries to determine if there an inconsistency between state yellow laws and DTM guidance. If the answer yes, these conflicting instructions may be another contributing source to the variability of driver comprehension and decision making in response to CY indications.

The second study seeks to evaluate the visual attention of drivers using an eye tracking system in the Oregon State University (OSU) driving simulator. The purpose of the second study is to better understand how participants distribute their visual attention between areas of interest while the traffic signal transitions to the CY indication at isolated high-speed signalized intersections and which factors influence the drivers' visual. Visual attention data were analyzed with repeated-measures analysis of variance (ANOVA) and a random effect Tobit model to identify how participants allocate their visual attention during the onset of the CY indication.

Finally, the third study focuses on driver behavior at the onset of the CY indication in the presence of a following vehicle. The experiment involved each participant driving a vehicle in the Oregon State University (OSU) driving simulator along highway that included several signalized intersections. A random parameter binary logistic regression model was developed to exam the probability of stopping at the stop line in response to the onset of the CY indication. This model is a function of the main contributing factors in driver’s decision including time to stop line (TTSL), time headway, and following vehicle type as well as approaching vehicle speed at the onset of CY indication, and demographic variables such as driver’s age and gender.

1.5 Dissertation Structure

This work is composed of three closely related manuscripts that address the scope of this dissertation. Figure 1.2 illustrates the structure of dissertation including: an introduction followed by three manuscripts and ends with a summary and conclusion.

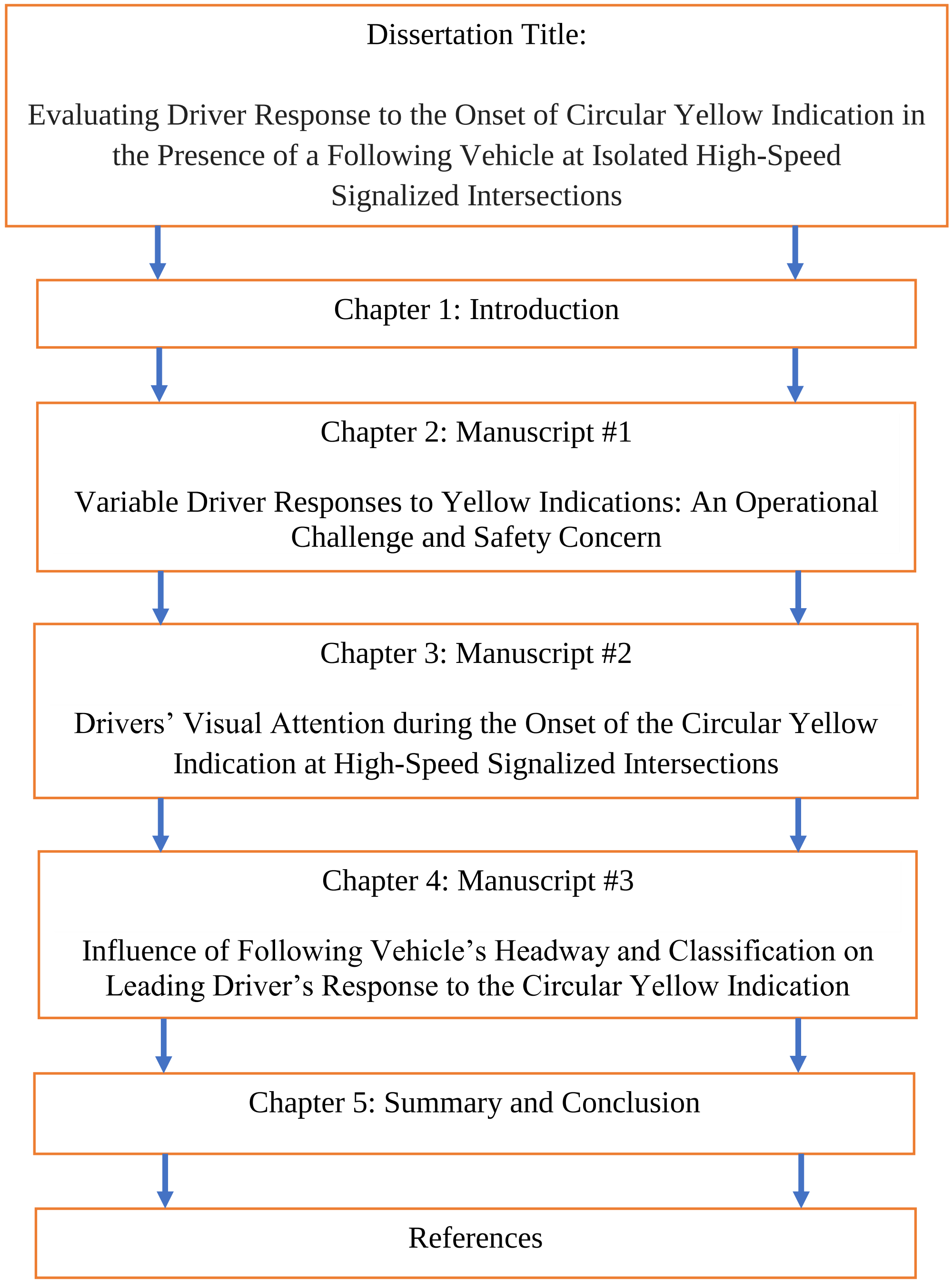

Figure 1.2 Dissertation structure

Chapter 2 – Manuscript #1

Variable Driver Responses to Yellow Indications: An Operational Challenge and Safety Concern

by

Hameed Aswad Mohammed, David S. Hurwitz, PhD, and Edward Smaglik, PhD

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ABSTRACT

This article provides a comprehensive review of the instructions provided to drivers in the 50 driver training manuals currently in use around the country. In doing so, the resultant driver behaviors in four situations at the onset of the circular yellow indication are presented and potential conflicts are emphasized.

Keywords: Driver Training Manual, Permissive, Restrictive, Yellow Light, Yellow Change Interval

2.1 Introduction

Intersections require a variety of crossing and turning maneuvers resulting in potential conflicts between vehicles, pedestrians, and bicycles that can contribute to crash outcomes. Although intersections represent a small portion of the roadway network, they are overrepresented in crash statistics (Antonucci et al., 2004). The National Highway Traffic Safety Administration reported in 2014 that 32,675 people died and 2,338,000 people were injured in motor vehicle crashes in the US (NHTSA, 2014). At signalized intersections, there were 4,825 fatal crashes and 855,000 injury crashes (NHTSA, 2014).

Section 4D.26 of the MUTCD explains that the Circular Yellow (CY) indication is used to warn drivers that the Circular Green (CG) indication has ended and that the Circular Red (CR) indication will be presented next. Additionally, it states that the yellow change interval should have a duration between 3-6 seconds with longer intervals used on higher speed approaches (FHWA, 2009). Yellow change intervals have been identified as potential challenges for both drivers and traffic engineers (Adwadallah, 2013) because at the CY onset, drivers must choose to slow down and stop at the stop line, or to proceed through the intersection. This decision can be difficult as the duration of yellow change intervals are not determined in a consistent manner, the laws governing driver response to CY indications vary across states, and because drivers' judgement of speed and distance are imperfect (McGee et al., 2012).

In 2013, the National Coalition for Safer Roads reported 697 people were killed and an estimated 127,000 people were injured in red-light running (RLR) crashes. Extensive research on signalized intersection safety in different countries has been performed and much of this work has considered driver's decisions to stop or proceed through an intersection during the yellow change or red clearance interval (Gazis et al., 1960; Chang et al., 1985; Gates and Noyce, 2010; Rakha et al., 2011; Hurwitz et al., 2012; Wu et al., 2013).

2.2 Background

Van der Horst and Wilmink (1986) suggested that the tendency of drivers to stop on yellow is based on driver behavior, the consequences of stopping, and the consequences of not stopping (Van der Horst, and Wilmink, 1986). Driver decision making at the onset of the CY is complicated and affected by several variables including travel time, speed, type of intersection control, headway, coordination, approach grade, and yellow change interval duration. The consequences of stopping abruptly at the onset of the CY are most commonly associated with the threat of a rear-end crash (especially at higher deceleration rates in closely spaced traffic) and delay, while the consequences of not stopping relate to the threat of right-angle crash (if the driver proceeds through the intersection when there is not adequate time to clear the intersection before conflicting movements are released) and of citation (Bonneson et al., 2002).

One of the fundamental problems at a signalized intersection is the dilemma zone. There are two general classes of dilemma zone conflicts, Type I and Type II. The Type I dilemma zone describes the possibility that a motorist presented with CY while approaching a signalized intersection may not able to safely go through intersection or stop before the stop line. Several factors can contribute to creating this scenario: intersection design, errors in signal timing, and detector placement (Hurwitz et al., 2012). The Type II dilemma zone is widely known as an area of intersection approach in which the driver has difficulty in correct decision making to stop or go. The driver may incorrectly decide to stop when the correct decision is to proceed and vice versa (Hurwitz et al., 2012). Either type may cause an increase in conflicts and crashes.

The primary purpose of the yellow change interval is to warn drivers that the green interval has terminated and that the red indication will be displayed next (Urbanik et al., 2015). A driver approaching a signalized intersection has two choices at the onset of the yellow change interval: (1) come to a stop at stop line of intersection or (2) clear the intersection before the onset of the CR indication (ITE, 2015). The Type I and II dilemma zones are commonly used to explain driver error in making this choice. The red clearance interval is considered a factor of safety for collision avoidance for vehicles that entered the signalized intersection at last moment of the yellow change interval (Urbanik et al., 2015). The aim of yellow change and red clearance intervals is to provide safe transition between all conflicting traffic movements at signalized intersections (McGee et al., 2012). Drivers are provided guidance on the appropriate response to the clearance interval in each state through yellow light laws that can be classified into three types:

Class 1 - vehicles can enter the intersection at any point during the yellow change interval and if entered during yellow, it is legal to be in the intersection during the red,

Class 2 - vehicles cannot enter or be in the intersection on red, and

Class 3 - vehicles should stop during the yellow indication, but they may proceed with caution through the intersection if it is not possible to do safely (Eccles and McGee, 2001).

Prior work has termed Class 1 to be a permissive yellow law and Class 2 and 3 to be restrictive yellow laws (McGee et al., 2012). The primary advantage of permissive yellow laws is to maximize the number of drivers who lawfully respond to the CY. The disadvantage of the permissive yellow law is that it can create a situation where the cross-street driver receives a CG but must yield the right-of-way (ROW) to a crossing vehicle on the alternate approach before entering the intersection, which can be of particular concern for a driver entering an intersection at the end of the yellow indication at a wide intersection without an all-red phase (Bonneson et al., 2002). Parsonson et al. (1993) indicate that about 60 percent of drivers do not understand that they should yield the ROW to crossing vehicles when they receive a CG. One solution recommended by Parsonson was to provide an all-red interval following the CY permitting vehicles to cross the intersection before conflicting traffic movements received a CG (Parsonson et al., 1993).

Currently there are four states that follow the Class 2 restrictive yellow law and nine states that follow the Class 3 restrictive yellow law. The remaining 37 states follow the permissive yellow law (Class 1). Figure 2.1 displays yellow law classifications for each state as defined by NCHRP Report 731. A self-published report by Järlström (2014) disagreed with the classification of four state laws (Connecticut, Louisiana, Tennessee, and West Virginia) in NCHRP Report 731 (Järlström, 2014). It was suggested that the yellow law classification for these states should be changed from Class 2 to Class 1 for three states and the Connecticut State law categorization should be changed from Class 3 to Class 1. The difference in classifications likely results from subtle differences in the language included in the brief legal definitions. If the word "warned" appeared in the definition Järlström argued the law should be classified as permissive. Two knowledgeable transportation professionals could review the same definitions and arrive at alternative conclusions as to the correct interpretation. Regardless, a challenge for drivers is introduced when they cross state boundaries and in doing so become bound by a yellow light law with distinctly different requirements.

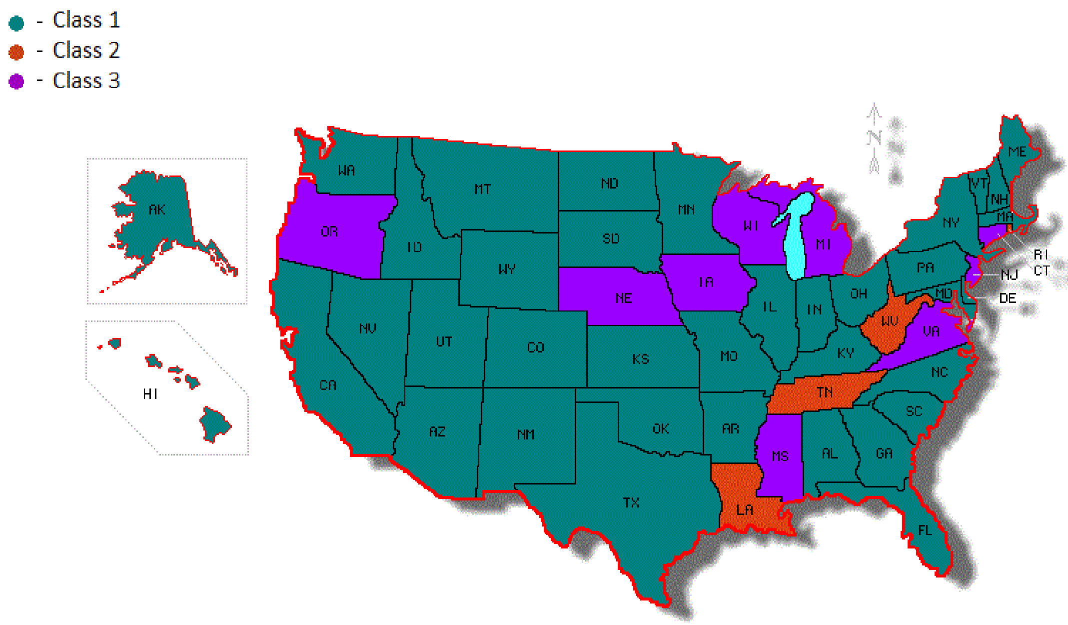

Figure 2.1 Classification of yellow light laws by state (NCHRP 731)

2.3 Driving Manual Language

State Departments of Motor Vehicles publish Driver Training Manuals (DTM) which include text and figures used to explain driving laws. There is a section in each of the 50 DTMs that describes the meaning and/or appropriate driver response to CY. This section of text was transcribed into table format, and each research team member independently reviewed the text to classify the possible scenarios described, and which state DTMs they were described in. Through discussions, the individual rankings were compared until a consensus was reach. Ultimately, the language used to describe what drivers should do in response to a steady CY includes one of four possible situations. These four situations are entirely derived from the DTM language in all 50 states, however 6 state DTMs do not provide direct instruction to drivers about how to respond to the CY, and therefore cannot be classified.

Situation 1**:** The vehicle should avoid entering the intersection during the CY. The vehicle is far enough away from stop line at the onset of the CY that the driver is able to decelerate and stop safely at the stop line. There are 40 states which include this language in their DTMs (Figure 2.2).

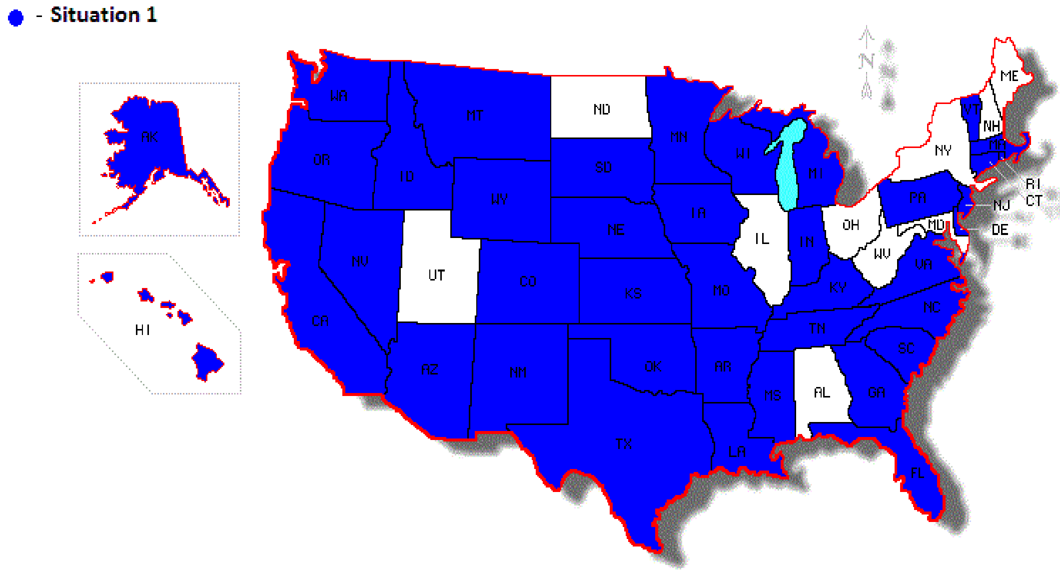

Figure 2.2 Forty states include situation 1 in their DTMs

Situation 2**:** If the vehicle is too close to stop safely, the vehicle should continue through the intersection with care. The vehicle is close enough to the stop line at the onset of the CY that drivers can clear the intersection. There are 19 states that include this language in their DTMs (Figure 2.3).

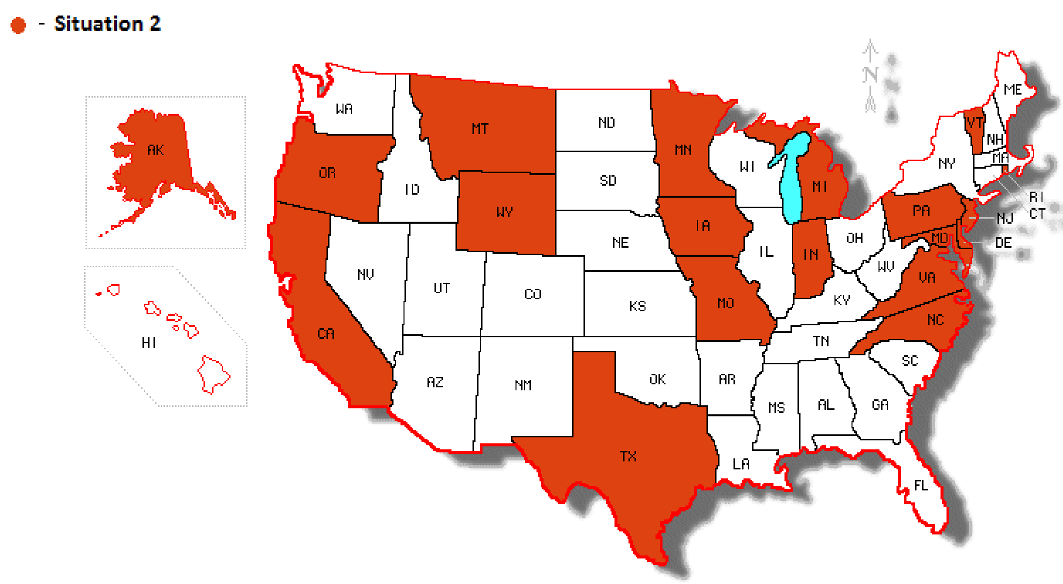

Figure 2.3 Nineteen states include situation 2 in their DTMs

***Situation 3*:** Accelerating to beat the light is illegal. The vehicle typically is not close enough to the stop line to clear the intersection at the current approach speed, so the driver accelerates. Nine states include this language in their DTMs (Figure 2.4).

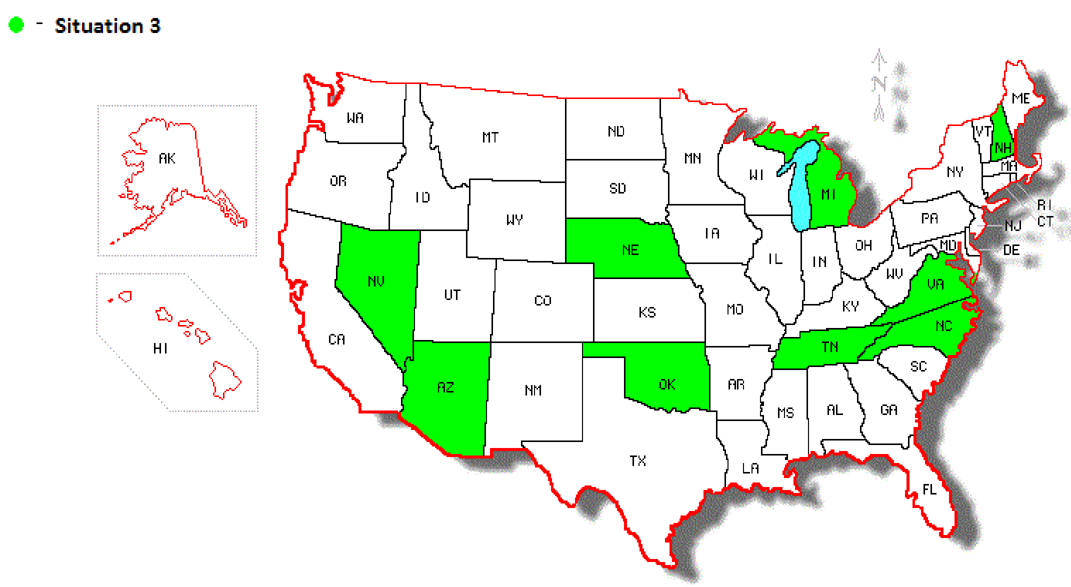

Figure 2.4 Nine states include situation 3 in their DTMs

***Situation 4*: The vehicle should continue through the intersection if the light turns yellow while in the intersection. If the vehicle is in the intersection at the onset of the CY, the driver should just continue through the intersection. There are 21 states that include this language in their DTMs (Figure 2.5).

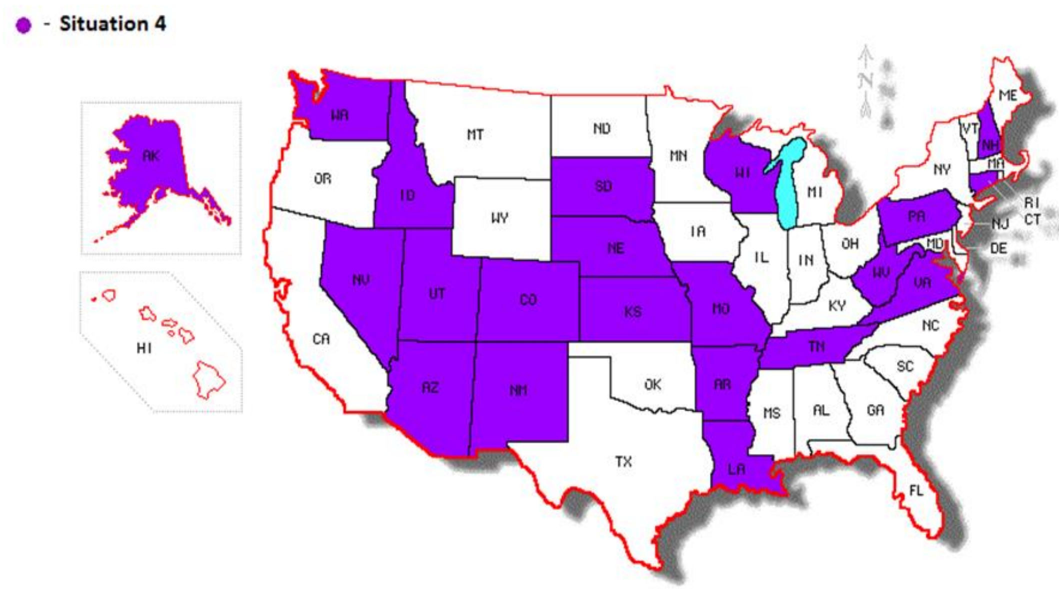

Figure 2.5 Twenty-one states include situation 4 in their DTMs

Much of the previous research on driver behavior at the CY onset has focused on the lead vehicle. One seemingly unanswered question is how do the characteristics of the following vehicle, specifically following headways and vehicle classification, influence the behavior of the lead vehicle? The phrase, “You must stop if it is safe to do so” appears in 11 DTMs (see Appendix A). This language is ambiguous in defining unsafe stopping conditions. One possible interpretation of an unsafe stopping choice is related to the likelihood of a rear-end collision. The likelihood of a rear-end collision is influenced by the headway and classification of the lead and following vehicles involved. These two issues are considered in the following cases.

Case 1: Both the lead and follow vehicles at the CY onset are passenger cars. Most drivers will proceed through the intersection when within 2.5 seconds of the stop line (Bonneson et al., 2002). Headway, speed, and perception reaction time (PRT) can play a vital role in the driver decision making of the following vehicle. Drivers may be hesitant to stop at the CY onset when closely followed due to increased rear-end crash risk. Allsop et al. (1991) indicated that drivers of following vehicles were more likely to be RLR at the CY onset when the headway of following vehicles was less than 2 seconds (Allsop et al., 1991).

Case 2: A heavy vehicle (HV) following a passenger car at the CY onset. Vehicle type has a significant effect on the rate of deceleration and RLR (Gates and Noyce, 2010). HVs behave differently at the CY onset due to characteristics of the vehicle and driver. The difference in driver behavior of passenger cars and HVs (i.e., single unit trucks, recreational vehicles, buses, and semi-trailers) has been previously investigated (Bryant, 2014). HVs were less likely to stop when the CY was displayed and they were more likely to perpetrate RLR. HVs cannot stop as rapidly as passenger cars and the operational cost of HVs is higher when delayed (Gates and Noyce, 2010). Also, the deceleration rate of HVs in dilemma zones has been shown to be lower than passenger cars when stopping (Gates and Noyce, 2010).

2.4 Results

The classification of guidance provided to drivers in DTMs indicate that 6 states provide Class 0 (do not fit any of three classes), 2 states provide Class 1 guidance, 6 states provide Class 2 guidance, and 36 states provide Class 3 guidance (Figure 2.6 A). However, the findings from NCHRP Report 731 analysis of yellow light laws classified

37 states as Class 1, 4 states as Class 2, and 9 states as Class 3 (Figure 2.6 B). Table 1 illustrates the comparison between NCHRP Report 731 and DTM Classifications. Based on this classification scheme, language that appears in state laws and DTMs may lack the needed degree of specificity.

Table 2.1 Comparison between NCHRP Report 731 and DTM Classifications

NCHRP Report 731			**Driver Manual Language**			
Class 1	*Class 2*	*Class 3*	*Class 0*	*Class 1*	*Class 2*	*Class 3*
37	4	9	6	2	6	36
74%	8%	18%	12%	4%	12%	72%

For example, the Montana DTM states that, “A steady yellow signal means “CAUTION.” Cautiously enter the intersection. The signal is about to turn red. Do not enter an intersection against a steady yellow light unless you are too close to stop safely” (Montana Driver Manual, 2015). This DTM guidance should be classified as a Class 3. The Montana yellow law indicates that, “Vehicular traffic facing a steady circular yellow or yellow arrow signal is warned that the traffic movement permitted by the related green signal is being terminated or that a red signal will be exhibited immediately thereafter. Vehicular traffic may not enter the intersection when the red signal is exhibited after the yellow signal” (McGee et al., 2012). The language from in the Montana yellow law should be classified as Class 1. The slight variations in language may cause confusion regarding what the correct action should be at the onset of the yellow indication.

Our classification shows that that only 4 % of states follow Class 1 guidance in DTMs, but the vast majority of state laws (74 %) are classified as Class 1 in NCHRP Report 731. The results also indicate that 12% of states follow Class 2 guidance in

DTMs and 8% of state laws classified as Class 2 in NCHRP Report 731. The large percentage of states (72%) follow Class 3 guidance in DTMs and 18% of state laws were classified as Class 3 in NCHRP Report 731. The results indicate an apparent inconsistency between the DTMs and yellow state laws (Figure 2.6).

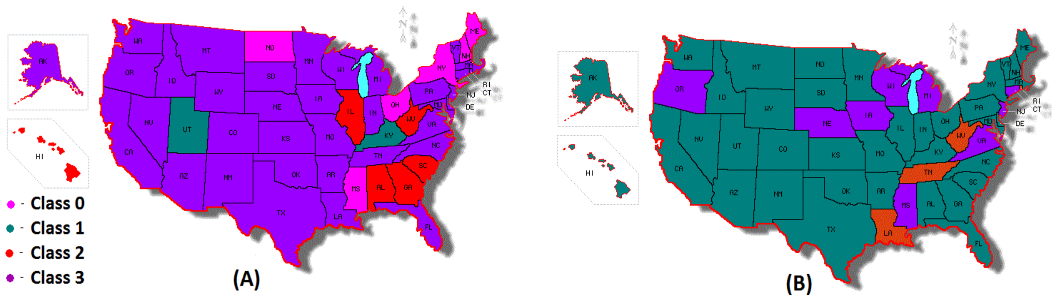

Figure 2.6 Classification of yellow light guidance in DTMs (A) and state laws (B)

2.5 Conclusions

Based on the consideration of yellow light laws and the DTM guidance from across the country, several conclusions can be reached.

Many DTMs provide yellow light guidance that may be confusing to drivers when considered in conjunction with the associated state law. A large percentage of states (72%) follow Class 3 guidance in DTMs while the vast majority of states laws (74%) were categorized as Class 1 in NCHRP Report 731. The inconsistency between state yellow laws and DTM guidance is another example of inconsistencies that may contribute to variability of driver comprehension and decision making in response to circular yellow indications.

The inconsistency between permissive and restrictive yellow laws poses a meaningful conflict. This conflict can create confusion for drivers when traversing state boundaries. The most concerning conflict is when a driver travels from a state with a permissive yellow law to a state with a restrictive yellow law as red clearance intervals may be less frequent contributing to angle crashes. Conversely, drivers accustomed to permissive yellow laws may anticipate lead vehicles continuing through intersections on CYs rather than stopping, contributing to rear-end crashes.

Finally, the guidance provided to drivers in DTMs is highly variable between states even between states with identical or nearly identical laws. The CY definition communicated to drivers in DTMs should be more consistent to mitigate misinterpretation and transferability across state lines.

2.6 Recommendations

There is a need to adopt a uniform legal interpretation of the circular yellow indication across state boundaries. This need has been recognized by transportation professionals for some time but has yet to result in meaningful change. A less commonly discussed aspect of yellow light comprehension and decision making is the guidance provided by DTMs. In conjunction with the institution of consistent legal interpretation across state boundaries, the translation of these laws into consistent DTM guidance cannot be ignored. Perhaps there is an opportunity to refine and improve DTM guidance as a half measure to the modification of state law.

Chapter 3 – Manuscript #2

Drivers' Visual Attention during the Onset of the Circular Yellow Indication at High-Speed Signalized Intersections

by

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ABSTRACT

Drivers have difficulty deciding whether to stop at the stop line or proceed through the intersection at the onset of the circular yellow (CY) indication. The purpose of this study was to understand how drivers distribute their visual attention between areas of interest (AOIs) when the traffic signal turns to the CY indication at high-speed signalized intersections, and which factors influence visual fixation behavior. Data included eye-tracking metrics obtained during a driving simulator experiment encompassing 24 driving scenarios. Independent variables were the time to the stop line (TTSL), time headway, and following vehicle type. The primary dependent variable was the total fixation duration (TFD). After discarding data from 9 participants due to eye-tracker calibration problems, data from 45 participants (28 men, 17 women) were analyzed. The driver's field of view was divided into three (AOIs): traffic signal, rearview mirror, and sideview mirrors. When the CY indication was presented, drivers spent most of their time with their eyes focused on the traffic signal; percentages of TFDs on the traffic signal, rearview mirror, and sideview mirrors were 78.4%, 20.3%, and 1.3%, respectively. Repeated-measures analysis of variance tests were performed with TTSL, time headway, and following vehicle type as within-subject factors for TFDs for each of the three AOIs. For traffic signal, the following vehicle type, TTSL, and combined effects of following vehicle type × time headway and time headway × TTSL had statistically significant effects on TFD. For rearview mirror, the following vehicle type and time headway had significant effects on TFD. For sideview mirrors, no significant effect on TFD was observed for any independent variable or any of the two- or three-way interactions. A random-effect Tobit model was

used to investigate the effect of controlled variables (TTSL, time headway, and following vehicle type) and uncontrolled variables (vehicle speed at onset of CY and demographic characteristics). The TTSL, time headway, speed at onset of CY, age, driving per week, personal vehicle type, and education level had statistically significant effects on TFD. This study highlights the importance of understanding the gazing behavior of drivers and the factors that influence driver visual behavior in an eye-tracking test.

***Key Words*:** Eye Tracking, Visual Attention, Area of Interest, Total Fixation Duration

3.1 Introduction

Driving behavior is a critical factor that contributes to safety at signalized intersections (Papaioannou, 2007). The circular yellow (CY) indication serves to caution drivers that the green interval has terminated and the red indication is imminent (Urbanik et al., 2015). However, language found in state laws describing the correct driver response to a CY indication sometimes differs from language in driver manuals, creating confusion on the right approach (Mohammed et al., 2018). When a CY indication is displayed, the driver has two choices: decelerate to a complete stop at the stop line or clear the intersection before onset of the circular red indication (ITE, 2015).

Two dilemma zone situations may occur when a driver faces a CY indication on the approach to a signalized intersection. In the Type I dilemma zone, the length of yellow change and red clearance intervals are insufficient, such that the driver cannot stop at the stop line without braking uncomfortably, but cannot clear the intersection without accelerating (Gates et al., 2007). In the Type II dilemma zone (indecision zone), the driver has difficulty making the correct decision at the onset of the CY.

Driver may incorrectly decide to go when the safer decision is to stop or vice versa, resulting in an increased frequency of rear-end collisions, severe right-angle crashes, and left-turn head-on collisions (Hurwitz et al., 2012). A meta-study of all available research at the time indicated that the indecision zone typically occurs between 2.5 and 5.5 s upstream of the stop line (Bonneson et al., 2002). The difficulty of driver decision making may increase with the presence of a following vehicle at the onset of CY indication. However, drivers' decision to proceed or not in response to the onset of the CY indication was associated with time to stop line (TTSL) (Xiong et al., 2016; El-Shawarby et al., 2011, Chang et al., 1985).

One of the most common means to determine how drivers acquire information is by using an eye-tracking device. Eye-movement recordings provide information about where users look at a point in time, how long they look at something, and the path that their eyes follow (Castro, 2008). Eye-tracking systems provide a constant stream of information about where a person is focusing their attention (Liu and Chuang 2011). Eye tracking has been applied to many fields, including human factors, cognitive psychology, marketing, road safety, hazard detection, energy consumption, and human-computer interactions (Bergstrom and Schall, 2014; Brazil et al., 2017). Drivers may drive normally while the eye-tracking device records their eye movements and are not required to perform any additional tasks related to the tracking software (Castro, 2008).

Researchers analyze eye-tracking data using heat maps and gaze plots, identifying areas of interest (AOIs) and determining how long (fixation duration) or how often (fixation frequency) the participant looks at different AOIs and where the participant looks next (order of fixations) (Bergstrom and Schall, 2014). An AOI refers to an individual component/area of the visual presentation (Brazil et al., 2017), which might be defined before or after an experiment (Borys and Plechawska, 2017). Eye-tracking systems differ in how they collect and analyze data (Rosch and Vogel, 2013). The analyst may compare several metrics to each AOI, including the fixation count, percentage fixated, time to first fixation, average fixation duration, and TFD (Brazil et al., 2017). The designer's experience and research question(s) should be considered when choosing metrics for analysis (Brazil et al., 2017). Researchers designed an experiment in the Oregon State University (OSU) Driving Simulator, using TFD as the primary dependent variable and TTSL, time headway, and following vehicle type as independent variables. Drivers divided their visual attention into three unique AOIs: traffic signal, rear view mirror, and side view mirrors.

From a safety perspective, rear-end crashes can occur when the driver is not attentive to a closely following vehicle and decides to stop suddenly during the onset of the CY indication. Right-angle crashes can also occur when the driver is unaware or does not focus on the traffic signal head at the onset of the CR indication. Thus, the main objective of this study was to understand how drivers distribute their visual attention between AOIs when the traffic signal turns to the CY indication at high-speed signalized intersections, and which factors influence visual fixation behavior.

3.2 Background

For use while driving, eye-movement recording devices can be either placed on the dashboard or in a driving simulator, or the driver can wear glasses with additional instrumentation. In both cases, adequate techniques must be available to record and analyze what the driver sees because the driving environment can suddenly change. Shinoda et al. (2001) examined the ability of drivers to detect stop signs when the signs were visible for short periods of time in a virtual environment. They found that the instructions and the local visual context can modulate detection performance during the task. This suggested that sign visibility requires active searching, and that the frequency of this search is affected by learned knowledge of the structure of the traffic environment. Geoffrey et al. (2001) analyzed the influences of aging, clutter, and luminance on the visual search of traffic signs embedded in digitized traffic scenes. They found that errors were more common among older people, and that search efficiency decreased as clutter and aging increased. However, older people did not suffer disproportionately compared to younger people when they faced increased clutter in the scene.

Eye-tracking measures are often used in scientific studies of a driver's visual attention to determine important sources of visual information in driving (Barakat et al., 2015). Underwood et al. (2002) observed novice and experienced drivers as they made lane changes under relatively unobstructed conditions and when they needed to shift into an occupied lane. Novice drivers were more dependent than experienced drivers on their rearview mirrors, even when a lane-changing maneuver required information about traffic in the adjacent lane (which would require the sideview mirror). Use of the sideview mirror by novices increased in response to driving needs, suggesting that they had an awareness of situations that required interweaving with traffic in their destination lane. This study indicated that experienced drivers quickly respond to dangerous situations appearing in the visual field, but they also have more frequent eye movements than novice drivers.

Knodler and Noyce (2005) used a driving simulator equipped with head- and eye-tracking equipment by created a virtual network of signalized intersections to identify sources of information used by left-turning drivers. Fourteen drivers participated in the experiment. Drivers looked at least once at the protected/permissive left-turn (PPLT) signal display and the opposing traffic stream. Drivers tended to scan the intersection from right to left, after first locating the PPLT signal display and opposing traffic and/or stop-line area. Pastor et al. (2006) studied the relation between the frequency of rearview mirror use and time variations in attention while subjects drove in a real environment on highway and local roads. The findings indicated a direct link between the attention level and mirror use in highway driving but a reverse connection while driving on local roads. Bohua et al. (2011) studied fixation duration and driver frequency in a virtual environment when drivers were reading traffic signs with different information quantities at various speeds. When the speed of driving and quantity of information were increased, the number and duration of fixations on the area of the traffic sign increased. An abrupt change occurred in the duration and frequency of drivers' fixations, and their visual cognition significantly decreased when the guide signs had more than five amounts of information.

Hurwitz et al. (2014) examined drivers' visual searches of three- and four-section flashing yellow arrow (FYA) signal configurations in a high-fidelity, motion-based driving simulator with mobile eye-tracking equipment. A 24-intersection simulated environment was created, and 27 subjects completed the course, producing

620 permissive left-turn maneuvers for further analysis. The primary difference between signal arrangements was in the vertical position of the FYA display. Little difference in the visual search tasks of drivers was observed, and there was no significant difference in the average driver fixation duration between any of the independent control variables studied, between the three- and four-section FYA displays. When the positions of pedestrians in the conflicting crosswalk were considered, when the driver initiated a left turn, a statistically significant difference between the four- and three-section arrangements was found only for the case in which a single pedestrian was walking away from the driver.

Based on data from driving simulator experiments, Zhang et al. (2016) examined the convenient visual search patterns during overtaking maneuvers on freeways. Participants' gaze and saccade durations had normal distributions. Saccade durations lengthened and saccade angles increased with increasing speed of the leading vehicle. Drivers tended to search for decisive traffic information by more frequently shifting their fixations between the initial lane and destination lane.

Despite extensive research on various aspects of eye movements and visual attention, there are still knowledge gaps related to driver behavior and safety at signalized intersections. Specifically, driver visual search patterns during the onset of the CY indication. This study is concerned with documenting and modeling drivers visual search task during interactions with the CY indication while a car is closing following the subject driver. In doing so, transportation professionals will be provided with guidance that could improve laws and driver training instructions that could improve signalized intersection safety.

3.3 Research Questions

No literature to date has specifically examined the visual attention of drivers while being closely followed in the dilemma zone of high-speed signalized intersections. Here, the driver's visual attention was documented with eye-movement data, which were collected by a mobile head-mounted eye-tracker device. In most cases, a motorist's visual attention provides direct evidence of whether they are able to recognize and anticipate hazards (Fisher et al., 2011). The potential influence of experimental factors on the motorist's eye movements formed the basis of the research questions on the visual attention of the driver.

- *Research Question 1 (RQ1):* Is the visual attention of the driver influenced by the TTSL, time headway, and following vehicle type at the onset of the CY indication?
- *Research Question 2 (RQ2)*: Do driver demographic variables affect the visual attention at the onset of the CY indication?

3.4 Method

3.4.1 Design

A partially randomized, counterbalanced, factorial experimental design was employed for this study. Three independent variables were used: following vehicle type (passenger car [PC] or heavy vehicle [HV]), time headway (0.5, 1, or 2 s), and TTSL (2.5, 3.5, 4.5, or 5.5 s). Participants were presented 24 scenarios across six experimental routes. Three AOIs were included: traffic signal, rearview mirror, and sideview mirrors. Fixations within each AOI during each experimental scenario were recorded. The primary dependent variable was the eye movement (i.e., TFD on each AOI) during dilemma zone situations. Frame-by-frame analysis was conducted on the AOIs to obtain accurate TFD results.

3.4.2 Participants

In total, 54 drivers were recruited to participate in the experiment. Data for 9 participants were excluded from further analysis due to technical issues in calibrating the eye-tracking apparatus. Data from the remaining 45 participants were used in the final analysis. Participants in the remaining sample included 17 women (M_{age} = 31 years, SD_{age} = 12.78 years) and 28 men (M_{age} = 31.29 years, SD_{age} = 14.01 years), aged 18 to 70 years. Participants had normal or corrected-to-normal vision.

3.4.3 Stimuli

Participants drove six predetermined routes in the OSU Driving Simulator. All six routes included a two-lane (one lane per direction) suburban road with moderate traffic that included four signalized intersections. Participants encountered different scenarios, such as different TTSLs, time headways, and following vehicle types. Duration of the yellow change interval was 4.5 s, and the speed limit was 45 miles per hour (mph). Researchers did not add any additional driving hazards to focus on the independent variables of interest.

3.4.4 Laboratory Equipment

The OSU driving simulator consists of a fully functional full-size 2009 Ford Fusion cab mounted on an electric pitch motion system. The cab is surrounded by screens where the simulated environment is projected. Researchers construct the virtual environment and monitor subjects using the operator workstation, which is out of view from participants within the vehicle. Three liquid crystals on silicon projectors with a resolution of 1,400 × 1,050 are used to project a front view of 180° × 40°. These front screens measure 11 ft. × 7.5 ft. A digital light-processing projector is used to display a rear image for the driver's rearview mirror. The two sideview mirrors have embedded LCD displays. The vehicle cab instruments are fully functional and include a steering control loading system to accurately represent steering torques based on vehicle speed and steering angle.

An Applied Science Laboratories (ASL) Mobile Eye-XG eye tracker was used to record eye movements. The tool allows the user unconstrained eye and head movements (Figure 3.1). A 30-Hz sampling rate was used, with an accuracy of 0.5–1.0°. Participant's gaze was calculated based on the correlation between the pupil position and the reflection of three infrared lights on the eyeball.

During vision, the eye is constantly moving, making fixations and saccades. A fixation is a pause in the eye movement on an area of the visual field. A saccade is a rapid eye jump between fixations, which helps the brain form a complete image (Bergstrom and Schall, 2014; Chen and Choi, 2008). The ASL Mobile Eye-XG system records a fixation when the subject's eyes pause in movement for >100 ms. Although saccades can be calculated from the dwell time between fixations, they were not analyzed in this paper.

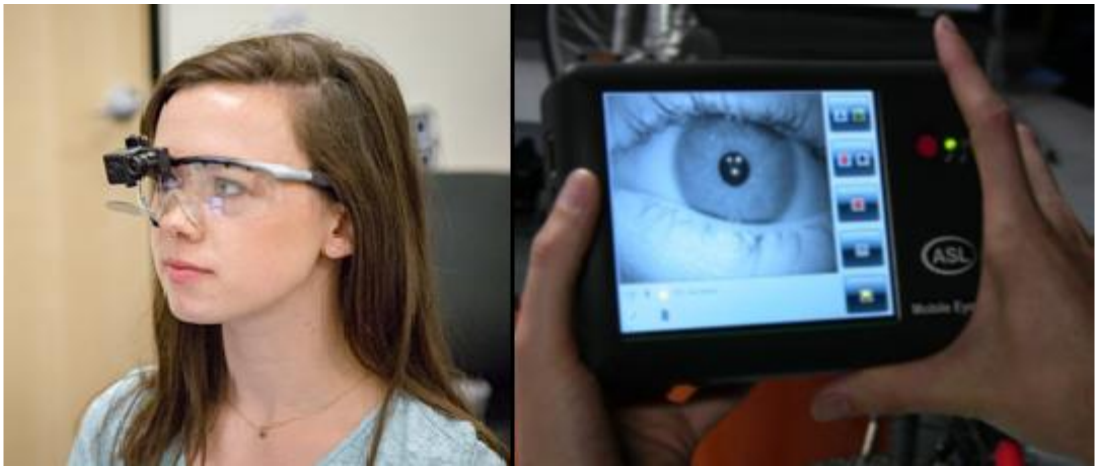

Figure 3.1 OSU researcher demonstrating the Mobile Eye XG Glasses (left) and Mobile Recording Unit (right)

3.4.5 Procedure

Before the experiment, all participants signed a consent form and completed a pre-study questionnaire asking demographic questions (i.e., age, gender, ethnicity, driving experience, highest level of education, and prior experience with driving simulators) (see Appendix B). They were seated at the simulator and told to adjust the driver's seat to a comfortable driving posture. All participants drove an approximately 5-min practice route. Their eye movements were calibrated with an 8-point calibration screen. After calibration, participants drove all six routes in a fully counterbalanced partially randomized order, to minimize any effects of route familiarity. They were instructed to drive as they would normally and to follow traffic regulations. Each route was ~5 min in duration. After the experimental drives, participants answered a post-drive survey that included questions on their experience and decisions about different situations at the onsets of the CY indications (see Appendix C). This study was approved by the OSU Institutional Review Board (Study #8080).

3.4.6 Eye-Tracking Data Reduction

After eye-movement data were collected, fixations were analyzed by coding AOI polygons in the ETAnalysis software suite. Researchers watched each video segment at the onset of the CY indication (24 per participant). Video segments were cropped to the length of time when the CY indication was displayed. Researchers drew AOI polygons on individual video frames in a sequence separated by 1-frame intervals. Once the researcher manually situated each AOI, an "anchor" was created in the software. Distance and size differences of AOIs between anchors were interpolated by the software, to ensure that all fixations on AOIs were captured. Researchers analyzed motorist's eye-tracking data from the moment the CY indication was displayed until the traffic signal turned to circular red or the participant completely crossed the intersection. Heatmaps were used to show the number or duration of fixations on different AOIs, with heatmaps transitioning from green to red from low to high duration or number of fixations, with varying levels in between.

Figure 3.2 presents an example video frame that has been coded with one AOI. At this moment in time, the participant was fixating on a traffic signal (red box). This figure includes heatmaps (green-red patterns, with red indicating higher gaze duration at that location) for the participant's fixations within the AOI.

Figure 3.2 Example of a participant fixation pattern for the traffic signal

Figure 3.3 provides a screenshot of the ETAnalysis software where the participant is fixating on the rearview mirror (red box).

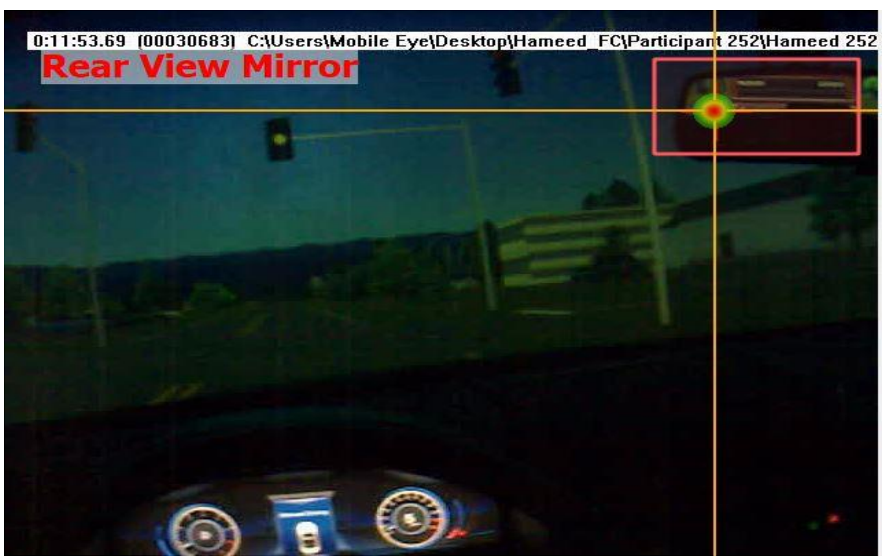

Figure 3.3 Example of a participant fixation pattern for the rearview mirror

After AOIs were coded for each individual video file, output spreadsheets of all fixations for each AOI were produced. Fixations outside the coded AOIs were defined as OUTSIDE and were not analyzed further. Researchers exported these files and imported them into different analysis packages (Microsoft Excel, RStudio, and SPSS) for further analysis.

3.4.7 Data Analysis

Data were analyzed in two parts. For the first part, data were analyzed with IBM SPSS Statistics software version 24. As each participant was exposed to all possible combinations of independent variables, repeated-measures analysis of variance (ANOVA) tests were performed with TTSL, time headway, and following vehicle type as within-subject factors. Mean (M) and standard deviation (SD) were calculated. Mauchly's sphericity test was used to confirm sphericity assumptions. An a-value of 0.05 was used as the criterion for statistical significance. Partial eta-squared was computed as an effect size statistic. Pairwise comparisons of estimated marginal means ($\alpha = 0.05$) were used to determine differences between TTSL, time headway, and following vehicle type levels. For the second part, the random-effect Tobit model was run using STATA software.

3.5 Results

3.5.1 Repeated-Measures ANOVA

Visual attention data were gathered and reduced from the ASL Mobile Eye XG for 45 participants with complete eye-tracking data. The TFD on AOIs was used as a measure of visual attention during the CY indication at high-speed signalized intersections. Three AOIs were used: traffic signal (N = 1069, M = 0.59 s, SD = 0.86 s), rearview mirror (N = 277, M = 0.18 s, SD = 0.35 s), and sideview (driver and passenger) mirrors (N = 17, M = 0.15 s, SD = 0.35 s). The highest percentage of TFD

(Figure 3.4) was located on the traffic signal head (78.4%), followed by the rearview mirror (20.3%) and sideview mirrors (1.3%).

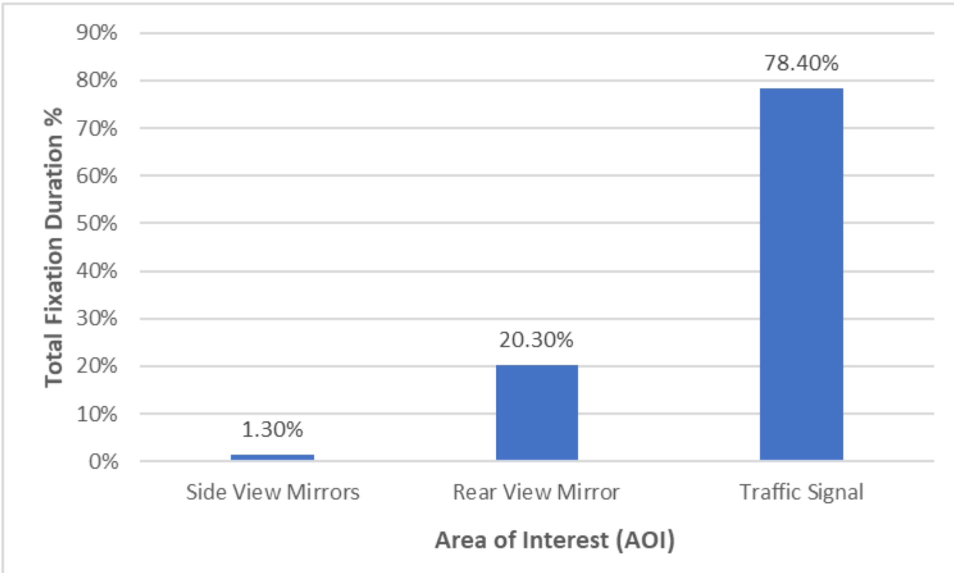

Figure 3.4 Percentage of AOIs

For each scenario when the CY indication was displayed, the number and length of participants' fixations on various AOIs were recorded. The TFD was generated by averaging all participants' fixations in each scenario for each AOI. A TFD of zero indicates that the participant did not fixate on that AOI during that scenario. A higher TFD indicates greater visual attention being allocated on a specific AOI. TFD measurements help determine whether a driver identified critical elements in the visual scene. As shown in Table 3.1, the highest mean TFD was on the traffic signal when the TTSL was 5.5 s (M = 0.81 s, SD = 1 s). Sideview mirrors had the lowest mean TFD (M = 0 s, SD = 0 s).

Table 3.1 Mean and standard deviation of TFD at independent variable levels

AOI	Descriptive Statistics	Following Vehicle Type		Time Headway (s)			TTSL (s)			
		PC	HV	0.5	1.0	2.0	2.5	3.5	4.5	5.5
Traffic Signal	M	0.62	0.55	0.54	0.61	0.61	0.27	0.46	0.80	0.81
	(SD)	(0.90)	(0.82)	(0.74)	(0.99)	(0.84)	(0.42)	(0.61)	(1.10)	(1.00)
Rear View Mirror	M	0.18	0.18	0.22	0.17	0.13	0.07	0.12	0.25	0.30
	(SD)	(0.32)	(0.37)	(0.41)	(0.31)	(0.28)	(0.15)	(0.24)	(0.46)	(0.42)
Side View Mirrors	M	0.09	0.20	0.07	0.31	0.02	0.10	0.09	0.00	0.49
	(SD)	(0.12)	(0.45)	(0.07)	(0.52)	(0.04)	(0.12)	(0.07)	(0.00)	(0.84)

Data were visualized as boxplots of TFD for three AOIs, disaggregated by different levels of time headway in Figures 3.5 and 3.6. For passenger car, higher median TFDs ranged from 0.09 to 0.37 s, with the traffic signal having the highest when the time headway was 2 s and the side view mirror having the lowest median when the time headway was 1 s. For heavy vehicle, median TFDs ranged from 0 to 0.30 s, with the traffic signal having the highest when the time headway was 1s and the rear-view mirror having the lowest median for all TTSLs.

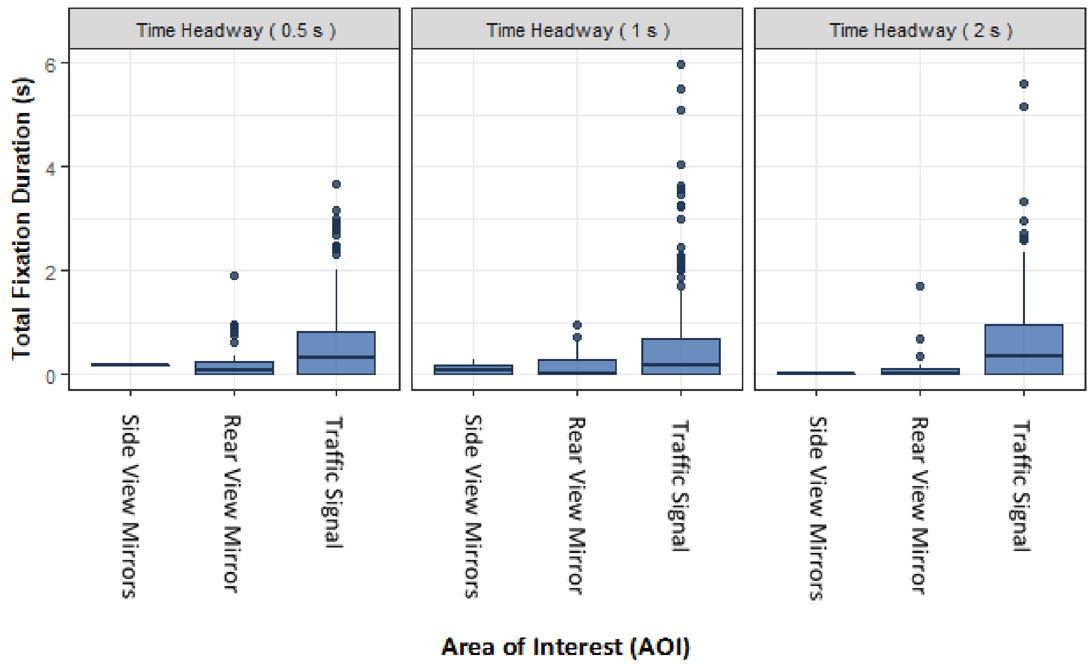

Figure 3.5 Boxplot of TFD for following passenger car

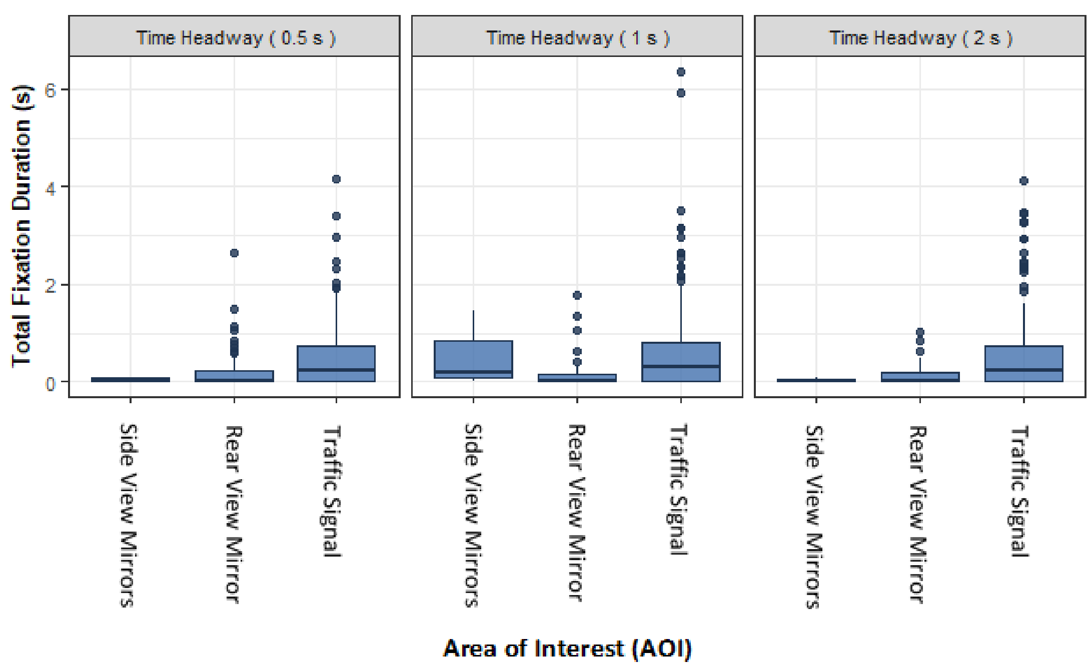

Figure 3.6 Boxplot of TFD for following heavy vehicle

Repeated-measures ANOVA was conducted to determine whether TFD differed between scenarios for each AOI. When a significant effect was observed, pairwise comparisons were conducted to find the origin of the difference. Only statistically significant comparisons are discussed. Mauchly's test of sphericity was also performed, with sphericity assumed for $P > 0.05$. For the traffic signal AOI, Mauchly's test for the time headway and the interaction between the following vehicle type and time headway was insignificant ($P > 0.05$); therefore, sphericity was assumed. Mauchly's test for all remaining variables was significant ($P < 0.001$); thus, sphericity was not assumed, and the Greenhouse-Geisser adjustment was used with repeated-measures ANOVA.

As shown in Table 3.2, the following vehicle type ($F(1, 44) = 6.348$, $P = 0.015$) and TTSL ($F(2.495, 109.764) = 4.916$, $P = 0.005$) had significant effects on the TFD when the driver fixated on the traffic signal at the onset of the CY indication. The Bonferroni-corrected post-hoc test for pairwise comparisons of the main effect of the following vehicle type revealed that regardless of the TTSL, the TFD was significantly different when the subject vehicle was followed by a PC or HV ($P = 0.015$). Regardless of the following vehicle type, pairwise comparisons showed that the TFD was significantly different for TTSL (4.5 s) and TTSL (3.5 s) when the CY indication was displayed ($P = 0.027$).

In repeated-measures ANOVA, effect size is measured by partial eta squared (η_p^2). Effect size reflects the magnitude of the influence of independent variables on the dependent variable. In this study, effect size measured "how much" TTSL, time headway, and the following vehicle type affected TFD. A change in the following vehicle type (PC or HV) had the greatest effect on the TFD on the traffic signal, accounting for about 12.6% of the within-subject variance.

Table 3.2 Repeated-measures ANOVA results for within-subject factors on the traffic signal AOI

Source	$F(v_1,v_2)$	P-value	η_p^2
Following Vehicle Type	6.348 (1, 44)*	0.015	0.126
Time Headway	0.649 (2, 88)	0.525	0.015
TTSL	4.916 (2.495, 109.764)*	0.005	0.100
Following Vehicle Type × Time Headway	3.314 (2, 88)*	0.041	0.070
Following Vehicle Type × TTSL	0.324 (2.3, 101.187)	0.754	0.007
Time Headway × TTSL	2.886 (4.357, 191.697)*	0.020	0.062
Following Vehicle Type × Time Headway × TTSL	1.023 (4.522, 198.951)	0.402	0.023

Note: F denotes F statistic; v_1 and v_2 denote degrees of freedom; η_p^2 denotes partial eta squared.
* Statistically significant at 95% confidence interval (CI).

The rearview mirror AOI was influenced by two independent variables: following vehicle type and time headway. Results of Mauchly's test for all variables were significant (P < 0.001), and sphericity could not be assumed. Therefore, a repeated-measures ANOVA with a Greenhouse-Geisser correction was applied. The following vehicle type (F(1, 44) = 4.392, P = 0.042) and time headway (F(1.538, 67.661) = 3.450, P = 0.049) had significant effects on TFD when the driver looked at the rearview mirror. Pairwise comparisons showed a significant difference in TFD when the subject vehicle was followed by a PC or HV (P = 0.042). There was no significant interaction between the combined effects of TTSL, time headway, and following vehicle type on TFD. Table 3.3 illustrates the repeated-measures ANOVA results on the rearview mirror, which showed that the following vehicle type and time headway had significant effects on TFD. One possible explanation could be that both following vehicle type and time headway can be most readily discerned from glancing at the rearview mirror. The effect size finding indicated that the change in following vehicle type had the highest effect on TFD, with about 9% of within-subject variance being accounted for by this interaction.

Table 3.3 Repeated-measures ANOVA results for within-subject factors on the rearview mirror AOI

Source	$F(v_1,v_2)$	P-value	η_p^2
Following Vehicle Type	4.392 (1, 44)*	0.042	0.091
Time Headway	3.450 (1.538, 67.661)*	0.049	0.073
TTSL	1.519 (2.423, 106.634)	0.220	0.033
Following Vehicle Type ×Time headway	0.733 (1.519, 66.85)	0.449	0.016
Following Vehicle Typed × TTSL	2.689 (1.854, 81.579)	0.078	0.058
Time Headway × TTSL	1.117 (3.914, 172.23)	0.350	0.025
Following Vehicle Typed × Time Headway × TTSL	0.558 (2.999, 131.977)	0.644	0.013

Note: F denotes F statistic; v_1 and v_2 denote degrees of freedom; η_p^2 denotes partial eta squared.
* Statistically significant at 95% confidence interval (CI).

No significant effect was observed for any independent variable or the two or three-way interactions on the TFD on the sideview mirrors. Results of ANOVA revealed two statistically meaningful two-way interactions, which were subsequently inspected by pairwise comparisons. Only the traffic signal AOI had significant two-way interactions. There was a statistically significant interaction between the combined effects of following vehicle type and time headway on TFD ($F(2, 88) = 3.314$, $P = 0.041$). There was also a significant interaction between the combined effects of time headway and TTSL on the TFD ($F(4.357, 191.697) = 2.886$, $P = 0.020$).

3.5.2 Model Selection: Random-Effect Tobit Model

Variables in the model were assumed to have "fixed effects", but it is also imperative to consider variations in response due to inherent differences among subjects, or "random effects". Each of the 45 subjects was exposed to 24 scenarios, resulting in panel data (repeated measures). Demographic variables that may influence TFD do not have within-group (subject) variance because subjects had the same quantifiable characteristics (e.g., age, sex, and driving experience). Only controlled variables (TTSL, time headway, following vehicle type) had within-subject variance. There was between-subject variance because participants, even when they shared identical demographics, were inherently different from each another. Thus, a random-effect model is more appropriate than a fixed-effect model for dealing with panel data. A linear regression model requires independent observations (i.e., single measurement per experimental unit). However, in this experimental design, multiple measures were collected from each participant. Each subject produced 24 TFD responses, which violated the independence assumption of a linear model. Multiple responses (i.e., repeated measures) from the same subject cannot be regarded as independent.

The Tobit model or censored regression model is applied when the dependent variable is continuous and has numerous zero-value observations (Calzolari et al., 2001; Washington et al., 2011; Anderson and Hernandez, 2017). Figures 3.7 and 3.8 illustrate the skewed distribution of the TFD data, showing the high frequency of zeros. These data require an analytical method that accounts for the cluster of observations while maintaining the linear assumption required for regression of the continuous dependent variable (TFD).

In summary, the data have repeated measures (panel data), no significant within-subject variance, and numerous zeros. To determine the effect of some variables on the TFD by AOI, a random-effect Tobit regression model was considered as the most appropriate mathematical model (Chen et al., 2014). Two random-effect Tobit regression models were used to deal with two AOIs (traffic signal and rearview mirror).

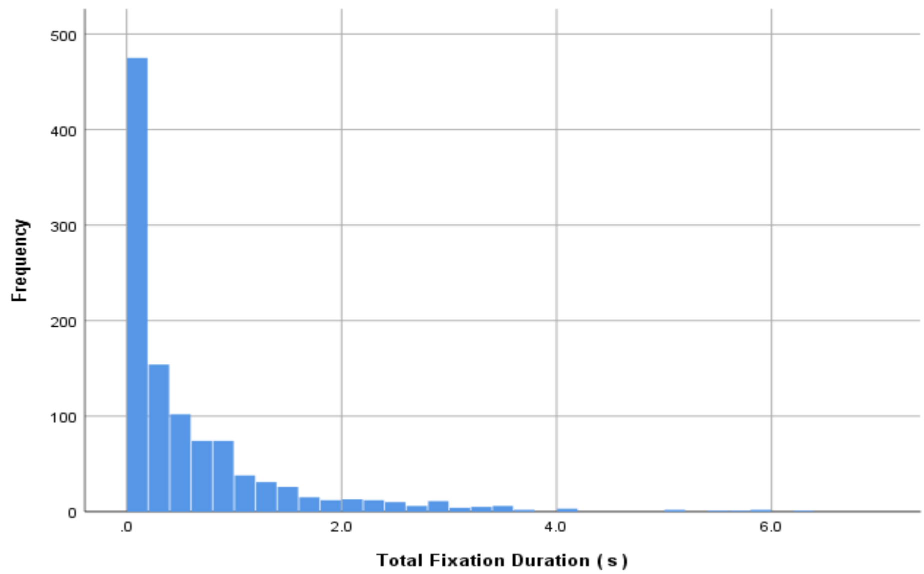

Figure 3.7 Distribution of TFD on the traffic signal

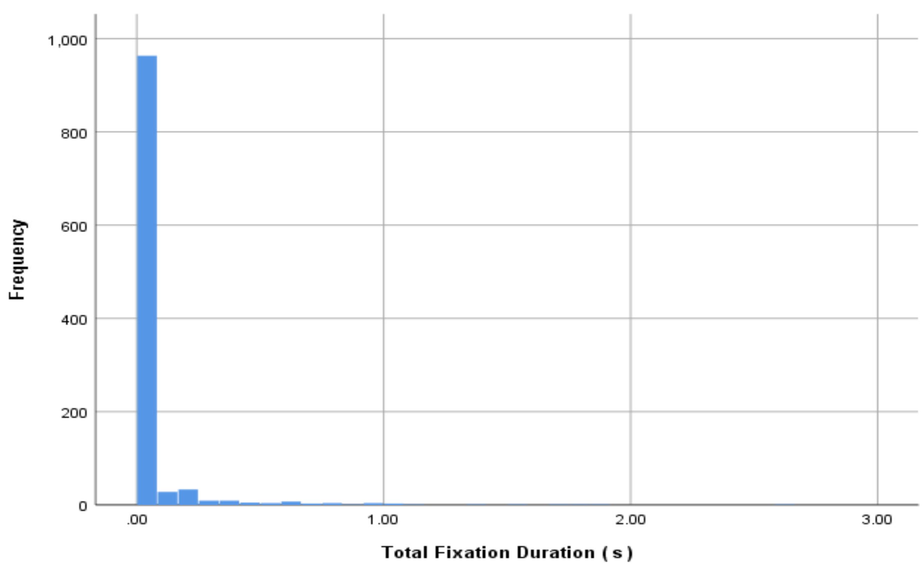

Figure 3.8 Distribution of TFD on the rearview mirror

Using STATA software, initial analysis began with all independent variables shown in Table 3.4 (with categories and levels), to determine which variables may influence TFD. The TTSL, time headway, and following vehicle classification were purely controlled variables. Vehicle speed at onset of the CY indication was included. Demographics were included to accommodate potential sources of variability from individual participants.

Table 3.4 Category and levels of independent variables

Variable	Category	Levels
	Controlled Variables	
Following Vehicle Type	Categorical	Two levels
Time Headway	Categorical	Three levels
TTSL	Categorical	Four levels
	Uncontrolled Variables	
Vehicle Speed at the Onset of CY (mph)	Continuous	Continuous
Age	Continuous	Continuous (18 to 70 years)
Gender	Binary	1 and 0 (Male or Female)
Driving Experience	Continuous	Continuous
Education Level	Categorical	Six levels
Personal Vehicle Type	Categorical	Four levels
Driving per Week	Categorical	Four levels
Driving Last Year	Categorical	Five levels

Model development required assessment of the correlation between explanatory variables. Driving experience was excluded due to high correlation (0.95) with age. A backwards elimination procedure was used to test each variable level to select the best model fit. Three explanatory variables (TTSL, driver age of 45–55 years, and vehicle speed of 35–45 mph) had statistically significant effects on the TFD on the traffic signal in the 95% confidence interval (CI). Estimation results of the random-effect Tobit model for TFD on the traffic signal are presented in Table 3.5.

Table 3.5 Random-effects Tobit model estimation results on the traffic signal

Variable	Coefficient	Standard Error	t-Stat	P-Value	Marginal Effect
Constant	-0.93	0.15	-6.01	0.000	
TTSL	0.28	0.03	10.15	0.000	0.16
Vehicle Speed (I if 35≤ speed <45, 0 otherwise)	0.23	0.08	2.96	0.003	0.13
Age (1 if 45≤ age <55, 0 otherwise)	1.49	0.68	2.20	0.028	0.89

Note: Number of observations = 1080; Number of groups = 45; Log likelihood at zero = -1244.53; Log likelihood at convergence = -1218.35; Maddala pseudo-R^2 =0.05

Six independent variables (TTSL, time headway, driver age of 55–65 years, driving per week, personal vehicle type, and education level) had statistically significant effects for the TFD on the rearview mirror in the 95% CI. Findings of the random-effect Tobit model for the TFD on the rearview mirror are shown in Table 3.6.

Table 3.6 Random-effect Tobit model estimation results on the rearview mirror

Variable	Coefficient	Standard Error	t-Stat	P-Value	Marginal Effect
Constant	-1.41	0.22	-6.42	0.000	
TTSL	0.16	0.04	4.16	0.000	0.03
Time Headway	-0.23	0.07	-3.30	0.001	-0.04
Age (1 if 55≤ age <65, 0 otherwise)	0.79	0.29	2.75	0.006	0.13
Driving Per Week (1 if 1 time per week, 0 otherwise)	-0.53	0.23	-2.33	0.020	-0.09
Personal Vehicle Type (1 if van, 0 otherwise)	-0.90	0.36	-2.48	0.013	-0.15
Education Level (1 if some high school or less, 0 otherwise)	0.96	0.39	2.45	0.014	0.16

Note: Number of observations = 1080; Number of groups = 45; Log likelihood at zero = -268.43; Log likelihood at convergence = -326.51; Maddala pseudo-R^2 =0.10

Development of a random–effect Tobit model reveals information about effects of different explanatory factors for the TFD on the AOI. All significant variables had positive effects for the TFD on the traffic signal, but the independent variables had positive and negative effects for the TFD on the rearview mirror.

Marginal effects (one-unit increases in an exposure variable with all others held constant) on the TFD are presented in Tables 3.5 and 3.6. For the traffic signal AOI (Table 3.5), TTSL positively affected TFD (P < 0.001). A one-unit increase in TTSL contributed a 0.16-s increase of TFD. Vehicle speeds within 35–45 mph at onset of the CY indication had a significant effect on TFD (P = 0.003). A one-unit increase in vehicle speed increased TFD by 0.13. Age of 45–55 years significantly affected TFD (P = 0.028). A one-year increase in age increased TFD by 0.89 s and had a greater influence on TFD than all other independent factors in the model. For the rearview mirror AOI (Table 3.6), TTSL was a statistically significant factor (P < 0.001). A one-unit increase in TTSL increased TFD by 0.03 s. Time headway had a negative effect on TFD (P = 0.001), and a one-unit increase in time headway decreased TFD by 0.04 s. Drivers aged 55–65 years were a statistically significant factor influencing TFD (P = 0.006). A one-unit increase in driver age increased TFD by 0.13 s. Driving once per week was a statistically significant factor for TFD (P = 0.020). A one-unit increase in driving trips per week was associated with a decrease in TFD by of 0.09 s. Some high school or less had a significant effect on TFD (P = 0.014). Lower levels of education were associated with increasing TFD by 0.16 s. Driving a van in one's personal life was associated with reduced TFD (P = 0.013) by 0.15 s.

3.6 Discussion

When the traffic signal turns to the CY indication, the driver may either stop before the stop line or proceed through the intersection. Factors that influence driver decision making at the CY indication include the vehicle's position relative to the stop line, the presence of a following vehicle and its classification (PC or HV), and the time headway to the following vehicle. A driver has limited time to make the correct decision because the yellow change interval is only 3 to 6 s (here, set at 4.5 s) (FHWA, 2009). The driver typically glances at the mirrors while driving to check for potential conflicts immediately behind them and to their right and left. It was hypothesized that the frequency and duration of rearview mirror-gazing would indicate driver attention on the following vehicle. In most cases, drivers look in the sideview mirror when they want to change lanes.

Initial results indicated that most of the TFD was allocated on the traffic signal 78.4%, with 20.3% and only 1.3% allocated to rearview and sideview mirrors, respectively. Thus, the driver gave only periodic glances to the rearview mirror and almost no attention to sideview mirrors. However, the road was a single lane in each direction on a suburban road, which reduces the need to use sideview mirrors for lane changing. Consistent with this, Underwood et al. (2003) found fewer mirror inspections on a suburban road and a rural, single-lane carriageway. Results of repeated-measures ANOVA revealed that some explanatory variables had significant effects on TFD while others did not. In general, two AOIs–the traffic signal and rearview mirror–were affected by independent variables. None of the explanatory variables or the two- or three-way interactions had significant effects for the TFD on the sideview mirrors. This result was not surprising because most participants did not use sideview mirrors to look at the following vehicle when the CY indication was displayed. The TTSL and the following vehicle type had significant effects on TFD on the traffic signal. Based on the results of this study, the TTSL plays a vital role in the driver's visual attention during the approach to a signalized intersection. Indeed, there was a direct correlation between the driver's fixation on the traffic signal and the magnitude of the TTSL.

Looking-ahead behavior is probably related to an increase in driver attention at the traffic signal because the driver's decision to proceed or stop is directly connected to the status of the CY indication. Therefore, it was not surprising to observe an increase in the frequency of traffic signal-gazing. As shown in Table 3.5, age of 45–55 years had a greater influence on TFD than all other independent factors in the model. Older or more experienced drivers are more likely to spend more time looking at specific AOIs as their visual search behaviors are more careful. Unsurprisingly, TTSL had a significant effect on TFD; 78.4% of TFD was allocated to the traffic signal, which has a strong correlation with the position of the vehicle from the stop line. Driving speed of 35–45 mph contributed to an increase in TFD. This independent variable had the highest effect on TFD in this model. The speed limit was 45 mph, and operating speeds mirrored the posted speed limit. Drivers spent more time looking ahead and allocating attention when driving at this speed.

In general, drivers look at their rearview mirrors to find visual information about possible changes in traffic situations. The reduced frequency of mirror-gazing during the CY indication was possibly due to the fact that drivers must look ahead for a long time at the CY indication; thus, there were less opportunities to look at their rearview mirrors. They had to focus on correct decision making (i.e., whether to go through the intersection or stop at the stop line). As in the previous model, TTSL had a significant association with TFD because it was related to the vehicle location from the stop line. One factor that could have contributed to the small but significant decrease in TFD is time headway. This finding is logical because the driver becomes more attentive and looks more frequently at the rearview mirror when the following vehicle is close.

There was a statistically significant positive correlation between driver age of 55–65 years and frequency of rearview mirror-gazing during driving. In general, drivers at this age are considered experienced drivers. This finding offers evidence that experienced drivers use rearview mirrors more selectively than novices, which is consistent with a previous study (Underwood et al., 2002). Statistically significant negative correlations were observed between the frequency of driving trips per week (once a week) and TFD. In general, when a driver drives their car many times per week, they will get a good driving experience and be able to deal with different traffic situations. When the driver drives less frequently, their driving ability may be reduced, and they may pay less attention to the vehicles behind them at the onset of the CY indication. Some high school or less had significant positive effects on frequency of fixation compared to other education levels of drivers. In fact, there is not specific justification for this result and the reason is unclear. One somewhat surprising result was that a driver who operated a van in their daily life had reduced TFD. This finding is difficult to interpret because only 5 participants reported driving vans in their daily lives compared to 28 participants who drove PCs.

3.7 Conclusions

Visual behavioral analysis is a robust way to understand and quantify attentional processes while driving. This is the first study to examine drivers' visual search behavior in the dilemma zone at the onset of the CY indication on the approach to a high-speed signalized intersection. Three AOIs were considered: traffic signal, rearview mirror, and sideview mirrors. When the CY indication was displayed, drivers spent most of their visual attention focused on the traffic signal (78.4% of TFD), followed by the rearview mirror (20.3%) and sideview mirrors (1.3%). Repeated-measures ANOVA was used to determine whether the TFD differed between scenarios for each AOI. The findings can be summarized as follows:

(1) Traffic Signal

- Following vehicle type, TTSL, the combined effects of following vehicle type and time headway, and the combined effects of time headway and TTSL had statistically significant effects on TFD.
- Results of effect size, measured by partial eta squared (η_p^2), indicated that the change in following vehicle type (PC or HV) had the highest effect on TFD, with about 12.6 % of within-subject variance being accounted for by this interaction.
- Pairwise comparison analysis showed that regardless of the TTSL, TFD was significantly different for PC and HV.
- Regardless of following vehicle type, pairwise comparison analysis showed that TFD was significantly different for TTSLs of 4.5 and 3.5 s.

(2) Rearview Mirror

- Following vehicle type and time headway had significant effects on TFD.
- No significant interaction was found between the combined effects of TTSL, time headway, and following vehicle type on TFD.

- Results of effect size indicated that the change in following vehicle type had the highest effect on TFD, with ~9% of within-subject variance being accounted for by this interaction.
- Pairwise comparison analysis showed that there was a significant difference in TFDs between PC and HV when the subject vehicle was followed by a PC or HV.

(3) Sideview Mirrors

- No significant effect was observed for any independent variable or for either of the two- or three-way interactions on TFD.

The TFD data were left-censored and included numerous zeros. The experiment produced panel data, where repeated measures (observations) were presented to each participant (e.g. TTSL, time headway, following vehicle type), such that correlations may be found among these measures. To account for the censoring effect and serial correlations between explanatory variables, a random-effect Tobit model was used. For the traffic signal AOI, three explanatory variables (TTSL, driver age of 45–55 years, and vehicle speed of 35–45 mph) were statistically significant at the 95% CI. For the rearview mirror AOI, six independent variables (TTSL, time headway, driver age of 55–65 years, driving per week, personal vehicle type, and education level) were statistically significant at the 95% CI.

Results and analytical methods presented in this paper highlight some of the ways that eye-tracking technology can be utilized to provide in-depth information regarding how the visual attention of participants is distributed across different scenarios in a laboratory experiment.

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Chapter 4 – Manuscript #3

Influence of Following Vehicle's Headway and Classification on Leading Driver's Response to the Circular Yellow Indication

by

Hameed Aswad Mohammed and David S. Hurwitz, PhD

ABSTRACT

Traffic crashes at signalized intersections are frequently linked to driver behavior at the onset of the circular yellow (CY) indication. To better understand behavioral factors that influence a driver's decision to stop or go at an intersection, this study analyzed the behavior of the driver of a leading vehicle at the onset of the CY indication. Driver performance data from 53 participants were collected in the Oregon State University Driving Simulator, simulating scenarios of driving through high-speed intersections under various conditions. Data included interactions where the driver stopped at the stop line (n = 644) or proceeded through the intersection (n = 628) in response to a CY indication. Data were analyzed as panel data while considering 12 indicator variables related to the driver's stop/go decision. Four indicator variables were significantly related to the driver's stop/go decision, but three factors varied across observations. Thus, a random-parameter binary logit model was used to handle unobserved heterogeneity across drivers. A driver's stop/go decision in response to a CY indication was associated with the time to the stop line, time headway to the following vehicle, vehicle speed at the onset of the CY indication, and driver's age (20–36 years), but was not significantly associated with the classification of the following vehicle. These findings provide insights into variables that affect driver decisions in a vehicle-following situation at the onset of the CY indication.

***Keywords**:* Dilemma Zone, Driver Behavior, Time Headway, Circular Yellow Indication

4.1 Introduction

Placement of traffic signals at intersections helps ensure the safety and efficiency of conflicting traffic movements. The Federal Highway Administration estimates that the U.S. is home to >3 million intersections, including at least 300,000 signalized intersections (FHWA, 2014). Approximately 40% of all crashes in the U.S. occur at intersections (Awadallah, 2009), particularly at signalized intersections where dilemma-zone conflicts may occur (Elhenawy et al., 2015). For example, in 2016, there were 3,145 fatalities resulting from crashes at signalized intersections in the U.S. (NHTSA, 2017).

According to the *Manual on Uniform Traffic Control Devices* (MUTCD), the circular yellow (CY) indication warns drivers that the circular green indication has ended and the circular red indication will be presented next (FHWA, 2009). The CY indication aims to provide a smooth transition during termination of the right-of-way for a particular movement (McGee et al., 2012). However, language in state laws on the correct driver response to a CY indication sometimes differs from language in driver training manuals, creating unnecessary driver confusion (Mohammed et al., 2018). At the onset of a CY indication, driver behavior can be considered a binary choice between coming to a safe stop before the stop line or proceeding through the intersection before termination of the yellow change interval (Elhenawy et al., 2015). Although these two options may seem straightforward, there are challenges associated with faulty driver decision making at the onset of the CY indication at isolated high-speed signalized intersections (Rakha et al., 2011). The inability of drivers to make correct decisions in the dilemma zone contributes to crashes at signalized intersections (Abbas et al., 2016).

This research focused on the Type II dilemma zone, also referred to as the indecision or option zone, which occurs as a result of complex driver behavior at the onset of the CY indication. Generally, the Type II dilemma zone describes the area where the driver has difficulty making the correct decision to stop or go (Hurwitz et al., 2011). This dilemma zone comprises the area upstream of the signalized intersection where 10% to 90% of drivers will stop in response to the CY indication (Gates et al., 2007). An incorrect decision may lead to various crash types. If the driver goes through the intersection when the correct decision is to stop, the driver may run the red light, leading to a right-angle or head-on crash with another vehicle. If the driver stops when the correct decision is to clear the intersection, a rear-end crash could occur (Hurwitz et al., 2012; Rakha et al., 2007).

At the onset of a CY indication, driver behavior and decision making are affected by: (1) driver characteristics (e.g., perception-reaction time, age, gender), (2) intersection characteristics (e.g., type of intersection control, time to the intersection at onset of the CY indication, signal coordination, approach grade, pavement conditions), (3) vehicle characteristics (e.g., classification, approach speed, safe acceleration/deceleration rates, (4) signal control settings (e.g., yellow change interval duration), and (5) traffic-flow characteristics (e.g., headway and travel time) (Abbas et al., 2016; Rakha et al., 2007; Bonneson et al., 2002). For example, driver behavior is generally affected by the vehicle classification, with heavy vehicles being less likely than passenger vehicles to stop when caught in a dilemma zone. Heavy vehicles cannot stop as quickly as passenger vehicles, and their operational cost is higher when delayed. Moreover, drivers of heavy vehicles try to use gentler deceleration rates during emergency situations to prevent the cargo from shifting (Gates et al., 2010).

Vehicle-following behavior is another important element of transportation safety. Drivers can avoid crashes by maintaining safe temporal and spatial separation with vehicles in their same lane (Qu et al., 2014). There are two distinct aspects of car-following behavior: (1) determining an acceptable headway when following a leading vehicle, and (2) controlling acceleration in response to shifts in trajectory of the leading vehicle. Rear-end crashes occur when the distance between the following and leading vehicles reduces to zero as a result of the deceleration or acceleration of the leading or following vehicle, respectively (Sato and Akamatsu, 2012). Differences exist in the following behaviors of drivers of passenger cars vs. heavy vehicles due to differences in physical and operational characteristics of the vehicles, which can significantly affect traffic stream characteristics. Acceleration, relative speed, and free space between the leading and following vehicles are all variables that significantly influence the following behavior of heavy-vehicle drivers (Aghabayk Eagely et al., 2012).

This research focuses on a driver's choice to stop or proceed when encountering a CY indication while being closely followed by another vehicle on the approach to a high-speed signalized intersection. A random-parameter binary logit model was developed to examine the probability that a driver will stop at the stop line or proceed through the intersection at the onset of the CY indication. The model was developed as a function of the main decision-making factors, including the time to the stop line (TTSL), time headway, classification of the following vehicle (see Figure 4.1), vehicle speed at the onset of the CY indication, and demographic variables, such as driver's age and gender.

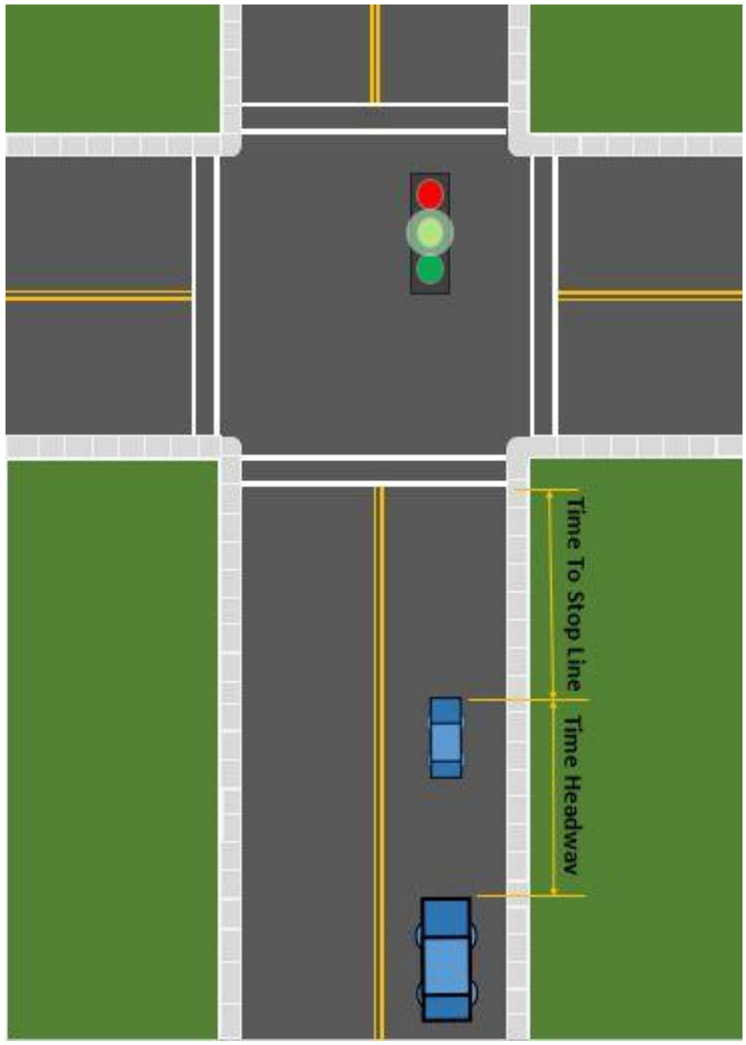

Figure 4.1 Vehicle-following behavior at onset of the CY indication

4.2 Review of Relevant Literature

Substantial previous research has addressed driver behavior in response to the CY indication. In 1978, Zegeer and Deen defined the boundaries of the indecision zone in terms of distance from the stop line, starting where 90% and ending where 10% of drivers stopped. Subsequently, Chang et al. (1985) attempted to define the boundaries in terms of travel time to the stop line, finding that 85% of drivers stopped if they were

≥3 s from the stop line. Almost all drivers continued through the intersection if they were ≤2 s from the stop line. Webster and Elison (1965) and Bonneson et al. (1994) similarly defined the indecision zone in relation to the stop line. Synthesizing results from several of the previously mentioned studies, Bonneson et al. (1994) developed the popular definition of the indecision zone as the area between 5.5 and 2.5 s from the stop line, as measured from the onset of CY indication.

Rakha et al. (2007) performed a field study of 60 participants to characterize driver behavior at the onset of the CY indication. Probability of stopping varied from 100% at a TTSL of 5.5 s to 9% at a TTSL of 1.6 s. Some previous driving simulator studies showed that TTSL (Caird et al., 2007) and driver age (Senserrick et al., 2007) had significant effects on the driver's stop/go decision at the CY indication. El-Shawarby et al. (2006) examined driver behavior at the onset of a CY indication on the approach to high-speed signalized intersections using field data from 60 participants. Driver stop/go decisions were analyzed at 5 distances when drivers approach the intersection at 72 km/h (45 mph). Probability of stopping varied from 9% at the shortest yellow distance of 32 m to ~100% at the longest 111-m distance.

Papaioannou (2007) examined driver behavior when presented with a CY indication at a signalized intersection in Thessaloniki, Greece. A binary choice model was used to calculate the probability that a driver would stop as a function of the speed of the approaching vehicle, distance from the intersection, driver gender, age, and existence of a dilemma zone. The author concluded that aggressive drivers represent a high percentage of all drivers and recommended that measures be enacted to improve driving behavior and/or to reduce vehicle speeds. Elmitiny et al. (2010) indicated that operating speed, vehicle distance from the stop line at the onset of the CY indication, and vehicle position (leading/following) in the traffic flow were important factors in the stop/go decision and red-light running (RLR) violations. Ohlhauser et al. (2011) used a driver simulator study to examine the effects of driver age differences, TTSL, and cellphone use on the likelihood that a driver would continue through a CY light. Age, driver distractions, and TTSL significantly affected the likelihood that a driver would proceed on a CY indication.

Hurwitz et al. (2012) developed a binary logistic regression model for the probability that a driver would stop or go at the onset of a CY indication based on empirical vehicle position data. Model input was generated from a fuzzy subset that required fewer data than similar models. Moore and Hurwitz (2013) used driving simulator data to build a fuzzy logic model based on the TTSL, which is a function of vehicle position and speed. Based on experiments performed in the National Advanced Driving Simulator Laboratory at the University of Iowa, Savolainen (2016) examined driver behavior at the onset of a CY indication when the driver was distracted by cellphone use while driving. Male drivers aged 18–45 years and drivers who were familiar with the simulator environment were more likely to stop.

Li at el. (2016) conducted a study to predict the stop/go decisions of drivers and RLR violations during a CY indication. Data were gathered by a vehicle data collection system and analyzed by a sequential logit model. TTSL at the onset of the CY indication was an important factor for stop/go decisions and RLR violations, and the speed of the approaching vehicle was a contributing variable for stop/go decisions. Vehicle acceleration after the onset of the CY indication was positively correlated with

RLR violations. Xiong at el. (2016) examined driver behaviors during CY indication maneuvers in a driving simulator. Driver stop/go decisions in response to a CY indication were associated with TTSL, age, and distractions.

In summary, previous research indicates that several factors, including TTSL, approach vehicle speed, and driver age, have important effects on the decision of drivers to stop or proceed in response to the CY indication. Our research adds to this body of knowledge by documenting how the following vehicle headway and vehicle classification influence the driver's response to the CY indication.

4.3 Research Question

The goal of the research was to understand the potential influence of experimental factors on a driver's decision to proceed through the intersection or stop at the stop line in response to a CY indication. The following research hypothesis was established to guide the assessment of driver behavior at the onset of the CY indication:

- *Research Question (RQ)*: Does TTSL, time headway, following vehicle type, participant demographics, or vehicle speed at the onset of the CY indication affect a driver's decision to proceed through the intersection or stop at the stop line in response to the onset of the CY indication?

4.4 Method

For the experiment, each participant traveled along a virtual highway with several signalized intersections in a driving simulator environment. Driver behavior was observed during the onset of the CY indication to investigate the effects of TTSL, time headway, and following vehicle type on the driver's decision to stop at the stop sign or proceed through the intersection. This section describes the driving simulator, scenario layout, intersection control, participants, data collection, and analysis.

4.4.1 Driving Simulator

The OSU Driving Simulator consists of a fully functional full-size 2009 Ford Fusion cab mounted on an electric pitch motion system that accurately reproduces acceleration and braking events. The cab is surrounded by screens projecting the simulated environment. Researchers typically build the environment and monitor subjects using the operator workstation, which is out of view from participants within the vehicle. Three liquid crystal on silicon (LCOS) projectors with a resolution of 1400 × 1050 are used to project a front view of 180º by 40º. These front screens measure 11 ft × 7.5 ft. A DLP projector is used to display a rear image for the driver's center mirror. The two side mirrors have embedded LCD displays. Sound is provided by surround sound speakers capable of 500 W.

The vehicle cab instruments are fully functional and include a steering control loading system to accurately represent steering torques based on vehicle speed and steering angle. The production instrument panel has been replaced with a configurable LCD instrument panel. The data update rate for graphics is 60 Hz. Figure 4.2 shows views of the simulated environment created for this experiment from inside (right) and outside (left) the vehicle.

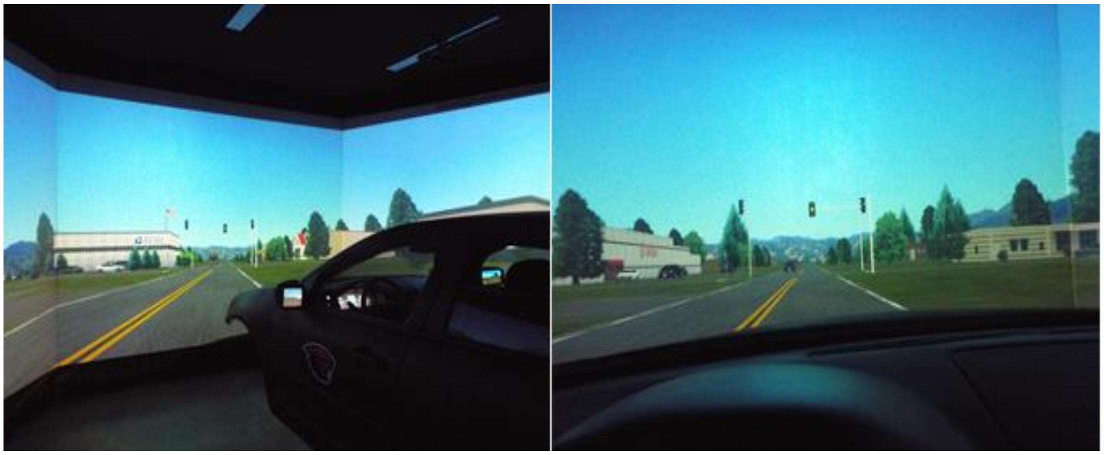

Figure 4.2 OSU Driving Simulator

The virtual environment was created by using Simulator software packages, including Internet Scene Assembler (ISA) and SimCreator (Realtime Technologies, Inc.), along with design Civil 3D and Blender. The simulated environment was developed in ISA by using Java Script-based sensors to change the signal indication and display dynamic objects, such as a following vehicle responding to the subject vehicle while approaching the intersection.

4.4.2 Scenario Layout and Intersection Control

Roadway cross-sections consisted of one lane in each direction of travel. The experiment required participants to drive a virtual roadway at a posted speed limit of 45 mph, except when stopping at intersections. The duration of the yellow change interval was 4.5 s, consistent with the duration suggested by the ITE kinematic equation. A within-group counterbalanced partially randomized factorial design was used. Participants were presented with combinations of 3 independent variables (Table 4.1): TTSL (2.5, 3.5, 4.5, or 5.5 s), time headway (0.5, 1, or 2 s), and following vehicle type (passenger car or heavy vehicle) (see Figure 4.3).

Table 4.1 Experimental factors and levels

Variable name	Acronym	Level	Description
Time to Stop Line	TTSL	0	2.5 s
		1	3.5 s
		2	4.5 s
		3	5.5 s
Time Headway	TH	0	0.5 s
		1	1 s
		2	2 s
Following Vehicle Type	FVT	0	PC
		1	HV

The 4 × 3 × 2 factorial design resulted in 24 scenarios being presented to participants across 6 grids (see Appendix D). A total of 53 participants were exposed to various conditions to measure their response to the onset of the CY indication. In each grid, 4 signalized intersections, each separated by roughly 2,000 ft of roadway, were modeled. Figure 4.4 shows an example grid layout as presented to the drivers.

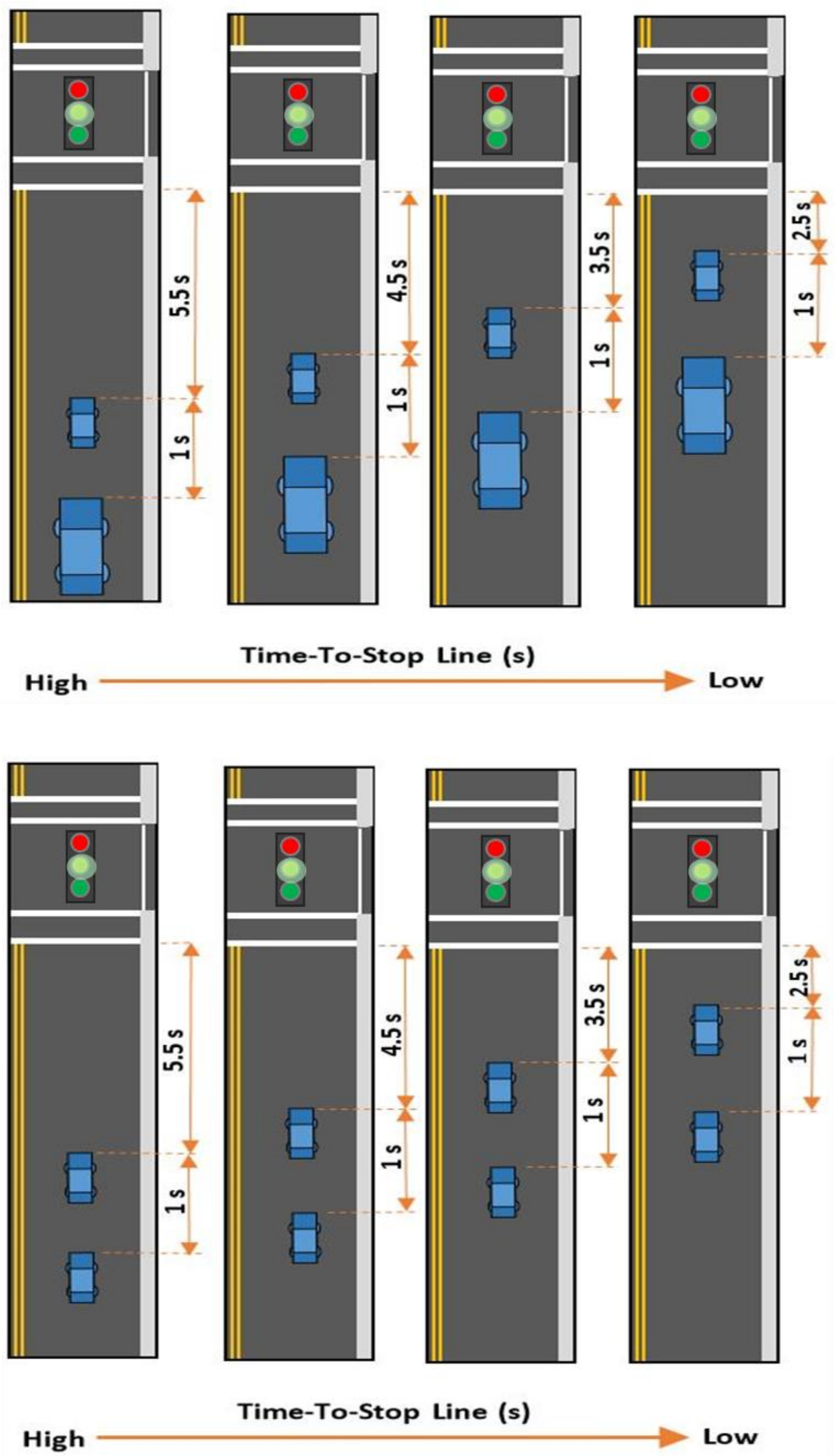

Figure 4.3 Examples of following vehicle scenarios

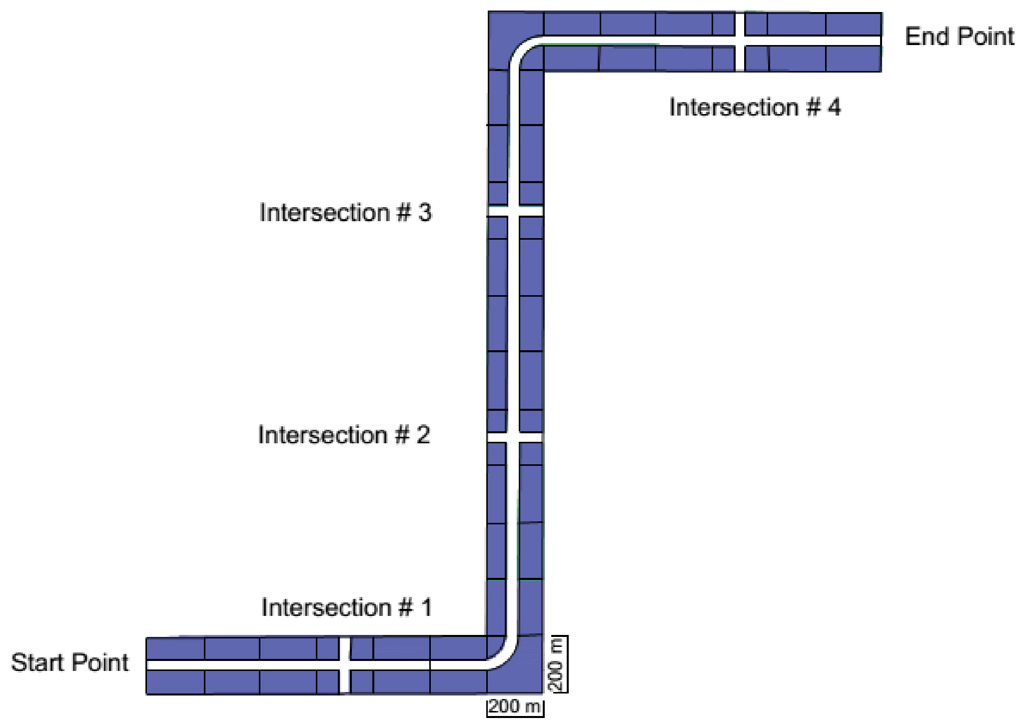

Figure 4.4 Grid layout

In this experiment, 24 scenarios were manipulated within-subject. This within-subject design provides advantages of greater statistical power and reduced error variance associated with individual differences (Cobb, 1998). However, this design can have practice and carryover effects, which can cause a participant's performance to degrade during an experiment as they become tired, bored, or familiar with the experimental design. To control for these effects, the factorial design was fully counterbalanced and partially randomized. Each scenario was randomly assigned to a position on a grid, and the grids were presented to each subject in a randomized order. Additionally, the duration of test drives was designed to be relatively brief.

4.4.3 Subject Recruitment and Sample Size

Participants between the ages of 18 and 75 years were recruited for the experiment from the area surrounding Corvallis, Oregon. Participants were required to possess a valid driver's license and to be able to be calibrated with the eye tracker. In total, 54 participants (30 men, 24 women) participated in the study. Only 1 woman experienced simulator sickness. Data from that participant were excluded from the analysis. Participant ages ranged from 18 to 70 years (M_{age} = 31.2 years, SD_{age} = 13.7 years). Efforts were made to recruit participants of all ages and varying backgrounds. Recruitment efforts included flyers posted and distributed around the OSU campus and the city of Corvallis. Unfortunately, due to the limitations of the eye-tracking system equipment and calibration procedures, individuals wearing glasses were unable to participate unless they also had contacts lenses that provided them with adequate driving vision. The research design and all study documentation were reviewed and approved by the OSU Institutional Review Board (IRB) (Study # 8080). The mission of the IRB is to ensure compliance with the Code of Federal Regulations issued by the U.S. Department of Health and Human Services for the conduct of research with human subjects.

4.4.4 Procedure

Upon a participant's arrival to the laboratory, the approved informed consent document was presented and explained to the participant. This document described the reasoning behind the study, the importance of the participant's contribution, and the test's risks and benefits to the participant. Each participant was given $10 compensation in cash for participating in an experimental trial after signing the informed consent document. Subjects were clearly informed that they could stop the experiment at any time for any reason and still receive full compensation. After providing informed consent, participants were asked to complete a prescreening and demographics survey, which asked questions about their prior experience with motion sickness, simulator sickness, and driver simulators, age, gender, driving experience, and highest level of education.

After the prescreening survey, each participant completed a test drive. The participant situated themselves comfortably in the driving simulator (e.g., adjusting mirrors, seat, fastening seat belt) and then performed a 3- to 5-min calibration drive, which was conducted on a track similar to those developed for the experiment. The purpose of this test drive was to acclimate the participant to the operational characteristics of the driving simulator, including the vehicle mechanics and virtual reality, and to determine whether they were susceptible to simulator sickness. If a subject reported simulation sickness during or after the calibration drive, they were excluded from the subsequent experimental drives and their ended their participation at that time.

After the participant's eyes were calibrated to the driving simulator screens, they were given brief instructions about the test environment and the tasks that they were required to perform. The experiment was divided into 6 grids. Participants were instructed to drive as they normally would. Participants performed the formal experiment with 24 scenarios, which were randomly ordered for each driver to eliminate the time order effect and potential bias from participants. The virtual driving course itself was designed to take the participant approximately 30 min to complete.

After the experimental drives, participants were escorted to a nearby office where they asked to respond to several questions in an online Qualtrics survey. The post-test questionnaire provided another source of data for the evaluation of various driving behaviors. The entire experiment, including prescreening survey, consent process, test drive and eye-tracker calibrations, experimental drive, and post-test questionnaire, lasted approximately 1 hour.

4.4.5 Data Analysis

The statistical software for data analysis was NLOGIT Version 5.0. There were 1,272 observations from the 53-participant dataset. A value of 0.05 was used as the criterion for statistical significance. A statistical model of drivers' stopping probability at a signalized intersection was developed, which considered both the response and explanatory variables.

4.4.5.1 Response Variable

An objective of this study was to examine whether drivers stopped or proceeded through the intersection on the CY indication under different conditions. Therefore, a binary dependent variable represented the drivers' response (1 = Stop or 0 = Go) to the onset of the CY signal indication.

4.4.5.2 Explanatory Variables

Predictors included TTSL, time headway, following vehicle type, and vehicle speed at the onset of the CY indication. TTSL represents the number of seconds it takes for a vehicle travelling at a certain speed to reach the stop line, starting from the onset of the CY indication. To accommodate potential sources of variability from individual subjects, demographics (age, gender, driving experience, level of education, personal vehicle type, number of times driving per week, number of miles driving last year, participation in previous simulation studies) were included in the analysis (see Appendix D).

4.5 Statistical Method

A driver's decision to stop or proceed through an intersection when the traffic signal turns from a circular green to a CY indication is a dichotomous variable. Discrete outcome models (e.g., binary logit and probit models) are well suited for such data (Savolainen, 2016) and can be used to examine driver decisions associated with factors such as driver demographic features and driving simulator events (e.g., TTSL, vehicle speed, time headway, etc.). Although several studies (Gates et al., 2007; Papaioannou, 2007; Rakha et al., 2008; Sharma et al., 2011; Liu et al., 2012) have adopted logit or probit models to study driver decision making at signalized intersections, authors typically assumed that estimated parameters were fixed across observations for participants. Fixing parameters that actually vary across observations will lead to biased and inefficient parameter estimates (Washington et al., 2011; Greene, 2012; Agbelie, 2016). Using models that allow all or some of the estimated parameters to vary across participants could provide more robust results, thereby improving understanding of the parameters that influence driver decision making at signalized intersections (Agbelie, 2016).

In the present study, data were classified as a panel dataset because multiple observations were collected from each participant. The final model accounted for potential correlations across observations. A random-parameter logit model approach was previously shown to be useful for accounting for unobserved heterogeneity across observations (Savolainen, 2016). When a panel dataset is modeled with this approach, parameter estimates are allowed to vary between participants, but each estimate is restricted to a fixed value for observations from the same participant (Lavrenz et al., 2014). Given the possibility of heterogeneity in observed and unobserved variables for driver behavior data, the random-parameter model can be an appropriate methodology for studying the driver's go/stop decision at the onset of the CY indication.

4.5.1 Modeling Framework

Binary logistic regression was applied due to the binary nature of the selected response variable. The response variable had two possible outcomes: 1, if the driver stopped at the stop line during the CY indication; and 0, if the driver went through the intersection. As such, the following binary logit formulation was used to determine the probability $\boldsymbol{Pij}$ of driver $\boldsymbol{i}$ stopping during event $\boldsymbol{j}$ as a function of covariates (Washington et al., 2011):

$$Pij = \frac{EXP\ (\acute{X}ij\beta)}{1 + EXP\ (\acute{X}ij\beta)} \quad (1)$$

where $\boldsymbol{\beta}$ is a vector of estimable parameters, and $\boldsymbol{Xij}$ is a vector of explanatory variables (e.g., characteristics of driver, vehicle, and simulation), used to determine the outcome probability of $\boldsymbol{Pij}$ being equal to 1 and associated with driver $\boldsymbol{i}$ and simulator event $\boldsymbol{j}$.

There are two important methodological concerns with a standard logit model. The first concern relates to the structure of data for the estimation of a standard logit model. The within-group experimental design resulted in the same 53 individuals being observed multiple (24) times, once during each scenario. As such, it is reasonable to expect there to be correlations in the decisions that are made by the same participants across simulator events. If these correlations are not taken into account, then the resulting parameter estimates will be inaccurate due to biased standard errors (Savolainen, 2016). To mitigate this concern, the 53 participants were treated as a panel, with parameter estimates assumed to be equal for each participant and allowed to vary across participants. The second concern related to the potential influence of unobserved heterogeneity. Specifically, each participant may show unique characteristics that make them more (or less) prone to stop at the stop line or proceed through the intersection at the onset of the CY indication. These concerns were addressed by using a flexible model, which is explained by relevant recent research in this area (Lavrenz et al., 2014; Savolainen, 2016).

One alternative model to account for heterogeneity across individuals is the random-parameter logit model. The model captures heterogeneity resulting from unobserved factors that are common to each study participant by allowing the constant term to vary across participants. This heterogeneity among participants is assumed to follow a parametric distribution (e.g., normal, lognormal, triangular, etc.) and can reflect those unobserved factors (e.g., tendency of risk, driving style, etc.) that may affect driver decision making. Another, yet-unsolved concern relates to the heterogeneity of covariate effects, as the model implicitly assumes that covariates have a compatible influence across participants. Heterogeneity is also caused by unobserved features of the participants or scenarios, which are not captured by the model. These concerns can be accommodated by allowing all parameters to vary across participants, while also holding parameters at the same value for each participant. Not accounting for this heterogeneity can lead to inaccurate or biased model estimates and corresponding inferences.

Therefore, to account for the heterogeneity, constants and covariates were allowed to vary across participants by applying a random parameters technique. Equation (2) is now written as (Washington et al., 2011):

$$Pij = \int_X \frac{EXP\ (\acute{X}ij\beta i)}{1 + EXP\ (\acute{X}ij\beta)} f(\beta/\phi)d\beta \quad (2)$$

where $(\boldsymbol{\beta i/\phi})$ is the density function of $\boldsymbol{\beta}$**,** with distributional parameter $\boldsymbol{\phi}$. All other terms are as previously defined. Density function $\boldsymbol{f(\beta i/\phi)}$ is defined as having a distribution, which depends on the analysis (e.g., normal, uniform, etc.) and which parameters are permitted to vary across observations. This approach permits $\boldsymbol{\beta}$ to account for observation-specific variations of the effect of $\boldsymbol{X}$ on $\boldsymbol{Pij}$ (Washington et al., 2011). A simulation-based maximum likelihood approach with 200 Halton draws was used to estimate the random-parameter logit model as recommended by previous research (Bhat, 2003).

Normal, uniform, and triangular distributions were tested, but only the normal distribution was found to have statistically significant standard deviations (SDs). To evaluate the effects of the variables, inferences from partial effects were applied. Partial effects measure the effect on the response variable when there is a one-unit increase in an explanatory variable while holding all other variables are constant (i.e., equal to their means) (Anderson et al., 2018).

4.6 Results and Discussion

4.6.1 Preliminary Investigation: Driver's Decision to Stop/Go

A driver's decision to stop before the stop line or proceed through the intersection is the foundation for developing models to describe the dilemma zone. The final dataset from this experiment contained a comprehensive set of variables for 1,272 vehicles approaching intersections during CY indications. Each vehicle had two choices: either to stop (n = 644) or go (n = 628), including cases of RLR (n = 46). Vehicle speed undoubtedly influences a driver's decision to stop or go; therefore, driver response was presented in relation to TTSL. As shown in Figure 4.5, nearly all drivers (97%) went through an intersection when they were 2.5 s from the stop line at the onset of the CY indication. This finding is consistent with the findings of Chang et al. (1985), Gates et al. (2007), and Moore and Hurwitz (2013), who likewise reported that nearly all vehicles proceeded through the intersection when they were ≤2.5 s from stop line at the CY onset. When TTSL was 5.5 s, most drivers decided to stop, and RLR violations started to increase.

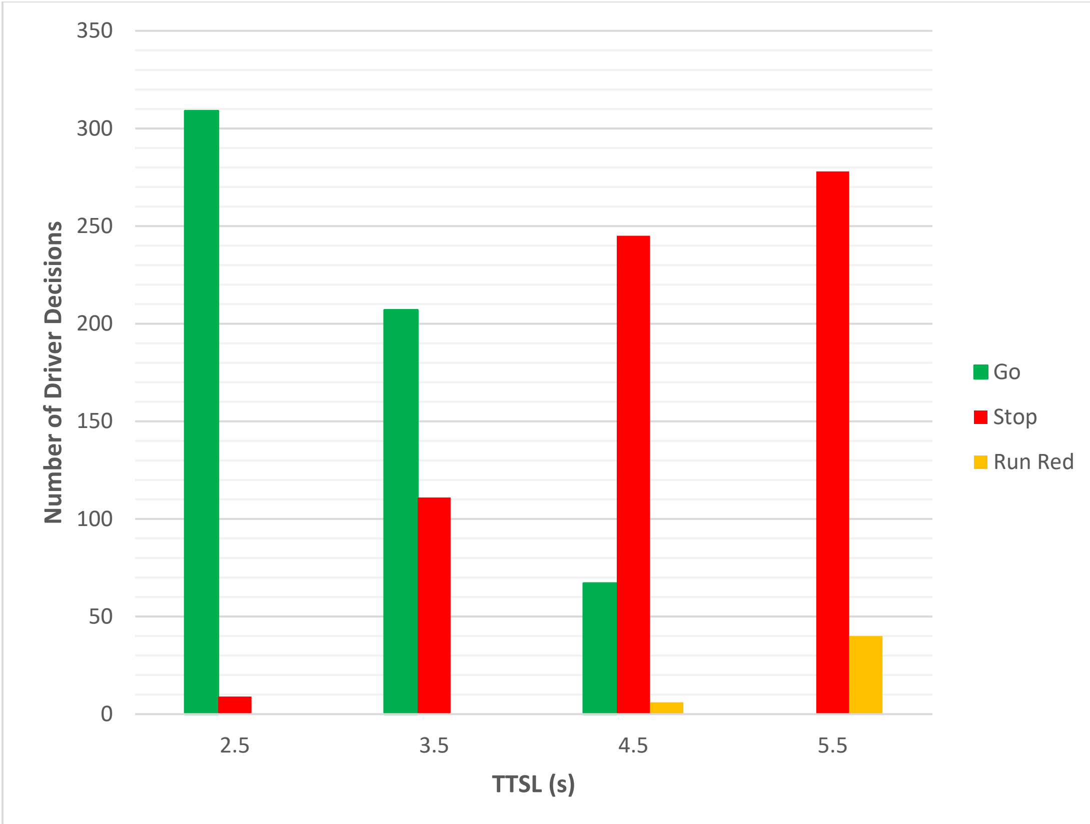

Figure 4.5 Probability of stopping based on TTSL

Next, this study considered how the driver's decision to stop or go varied depending on the position of the vehicle relative to the stop line (Figure 4.6). All vehicles proceeded through the intersection when they were ≤100 ft from the stop line at the onset of the CY indication. By contrast, when drivers were 340–400 ft from the intersection at the onset of the CY indication, only 7% of drivers went through the intersection, 8% were RLR, and 85% stopped at the stop line. No vehicles except RLR vehicles (16%) proceeded through the intersection where they were at 400–480 ft at the onset of the CY.

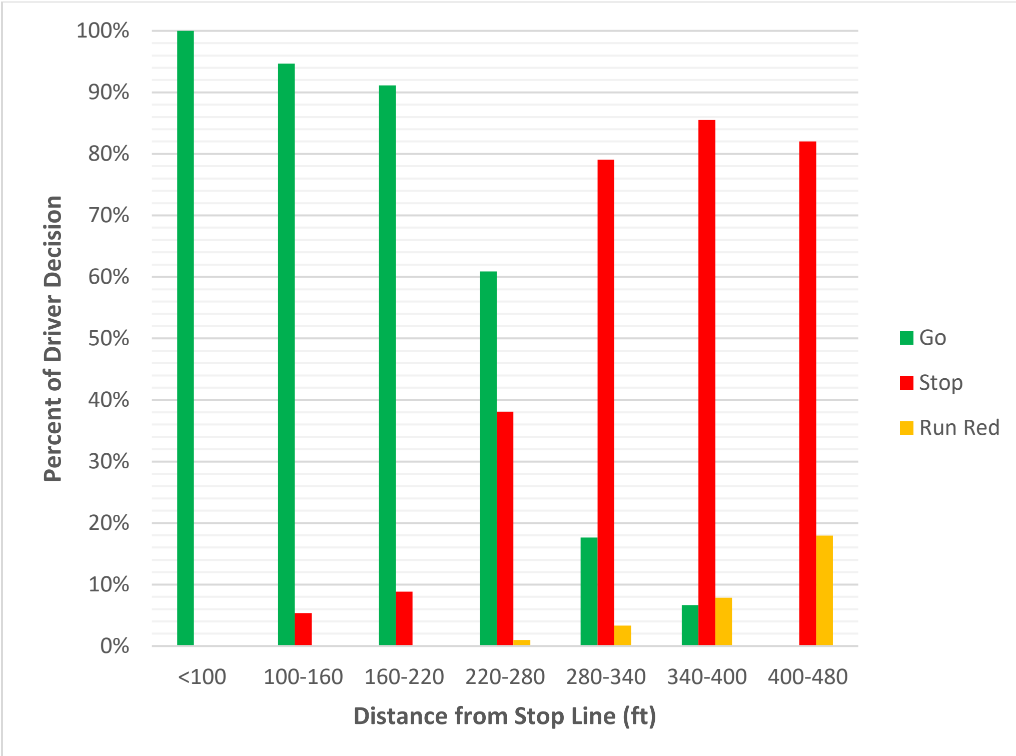

Figure 4.6 Probability of stopping based on distance from stop line

4.6.2 Model Results

To understand and evaluate the factors affecting driver decision, 12 indicator variables were generated from the factorial design and demographic characteristics. All possible combinations of the continuous and categorical factors that influence the driver's decision making at the onset of the CY indication were examined to construct the model. The final combination of model factors was based on the p-values at a 95% confidence interval. A stepwise procedure was used to test and determine the statistically significant factors. Four parameters were found to have statistically significant effects on the driver's decision to stop or go at the onset of the CY indication. Descriptive statistics for the significant parameters are shown in Table 4.2. Vehicle speeds at the onset of the CY indication varied from 19.2 to 64.7 mph. The mean speed was 46.5 mph, and the speed limit was 45 mph.

An estimated parameter is considered random across participants when the SD of the parameter density is statistically significant (Agbelie, 2014). If the estimated SD is not statistically significant (not statistically different from zero), then the estimated parameter can be considered fixed across participants. Three parameters were statistically significant and varied significantly across observations (Table 4.3). The estimated constants also varied across participants.

An important aspect in interpreting parameter estimates in a random-parameter logit model relates to the concept of driver stop/go decision making. The dependent variable of driver decision can take a positive or a negative value. In this model, for the possibility of stopping at the stop line, a positive (or negative) parameter estimate should be interpreted as an increased (or decreased) probability that the driver will stop.

Table 4.2 Descriptive statistics

Variable	Mean	SD	Min	Max	Cases
TTSL	3.99	1.11	2.5	5.5	1,145
Time headway	1.17	0.62	0.5	2	1,145
Speed at onset of CY indication	46.53	4.77	19.18	64.65	1,145
Driver age ($20 \leq$ years < 36)	26.55	4.68	20	36	38

Table 4.3 Random-parameter binary logit model estimates

Variable	Coef.	SE	t-Stat	P-Value	Partial Effects
Constant	-3.80 (0.49)	0.68 (0.11)	-5.60 (4.64)	0.000 (0.000)	- (-)
TTSL	1.89 (0.47)	0.10 (0.03)	19.34 (13.74)	0.000 (0.000)	0.46 (-)
Time headway	0.29 (0.02)	0.11 (0.08)	2.59 (0.21)	0.009 (0.833)	0.07 (-)
Speed at onset of CY indication	-0.10 (0.02)	0.01 (0.00)	-7.55 (6.40)	0.000 (0.000)	-0.03 (-)
Driver age (1 if 20 ≤ years < 36, 0 otherwise)	1.06 (0.40)	0.18 (0.12)	6.01 (3.29)	0.000 (0.001)	0.25 (-)
No. observations	1145				
Log likelihood at zero	-491.29				
Log likelihood at convergence	-384.08				
McFadden Pseudo R^2	0.22				

Note: Results for variables given as Mean (SD). SE, Standard error.

Partial effects of indicator variables were examined to understand their quantitative effects (Table 4.3). For continuous variables, such as TTSL, partial effects represent the percent increase in the probability that the driver will stop in response to the CY indication associated with a 1-s increase in the covariate. Partial effects indicated that the TTSL significantly increased the probability of stopping. Among the variables, TTSL had the largest effect on the probability of stopping, with the partial effect suggesting an increase of 0.46. Time headway increased the probability by 0.07, and driver age of 20–36 years increased the probability by 0.25. Conversely, faster vehicle speed at the onset of the CY indication reduced the probability of stopping by 0.03. Three estimated parameters were found to be random based on the statistical significance of SD as shown in Table 3. The model had a McFadden pseudo R^2 value of 0.22, which is considered a very good fit (Louviere et al., 2000) and sufficiently strong to predict driver behavior.

One of the main findings of this study was that the probability of stopping increased when TTSL increased. This finding is consistent with previous literature (Bonneson and Son, 2003; Caird et al., 2007; Elmitiny et al., 2010; Ohlhauser et al., 2011; Gates et al., 2012; Moore and Hurwitz, 2013; Savolainen, 2016; Li et al., 2016; Xiong et al., 2016; Pathivada and Perumal, 2017). Vehicles are more likely to stop in response to a CY indication when they have greater time (a product of distance and speed) from the stop line. Another finding of this study was that the probability of stopping decreased when vehicle speed was higher at the onset of the CY indication. Similarly, previous studies (Bonneson and Son, 2003; Papaioannou, 2007; Elmitiny et al. 2010; Gates et al., 2012; Li at el., 2016; Pathivada and Perumal, 2017) found that higher vehicle speed at the onset of the CY indication reduced the probability of stopping. The higher the vehicle speed is at the onset of the CY indication, the less time there is for the driver to react and brake, and the more likely it is that the driver will go through the intersection.

Time headway was hypothesized to play a role in the leading driver's decision to stop or go. In this study, the number of driver decisions to stop decreased when the leading vehicle was closely followed by another vehicle during the CY indication. For example, when the time headway between vehicles was 0.5 s, the likelihood of drivers deciding to stop was reduced for all TTSLs (2.5, 3.5, 4.5, or 5.5 s) (see Figure 4.7). In particular, many RLR violations were observed when the following vehicle was close to leading vehicle at the onset of CY indication. The total number of RLR violations was 46 (3.6% of total observations), with 50% of RLR violations occurring when the time headway was 0.5 s. This fact may relate to the short time gap between the following and leading vehicles. A shorter time headway may influence a driver's decision to run the red light, due to the pressure experienced by the leading vehicle. Of the RLR violations, 26% occurred when the time headway was 1 s, which provides additional evidence about the relationship between the driver's decision to run the red light and the time headway. Interestingly, the type of following vehicle did not significantly contribute to the driver's stop/go decision. Previous results related to visual attention during the CY indication indicated that only 20% of drivers use the rearview mirror to look at the following vehicle during the CY indication (Mohammed and Hurwitz, in review). Thus, most drivers are unaware of the types of vehicles behind them at the onset of the CY indication, which could explain this result.

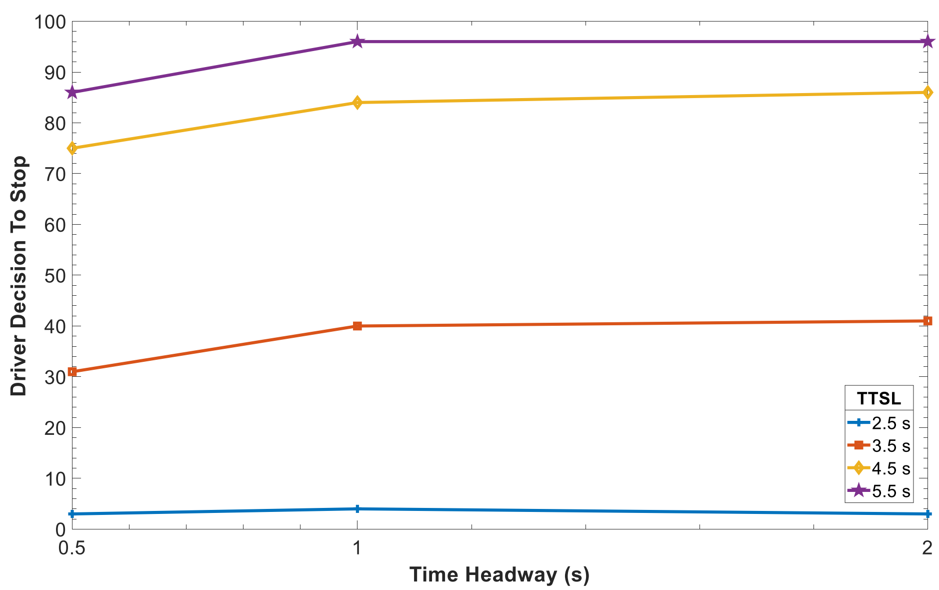

Figure 4.7 Relationship between driver decision to stop and time headway

The probability of stopping was highest among drivers aged 20–36 years. It was not clear whether these effects are due to differences in physiology, driving style, driving behavior, or familiarity and comfort in a simulated driving environment. This finding is consistent with a previous driving simulator study (Savolainen, 2016), which found that drivers aged 18–45 years were more likely to stop.

4.6.3 Model Validation

Model validation involved a two-step process. (1) The model was cross-validated with 90% of the data set. (2) Stopping probabilities were compared with other models based on distance from the stop line.

4.6.3.1 Model Cross-Validation

To validate the model produced by this research, 90% of the dataset was randomly selected to develop the model, which was used to predict driver decisions (go or stop) for the remaining 10% of the data. This approach has been used in previous research. For example, Pathivada and Perumal (2017) used 85% of the extracted data to develop the binary logit model, and the remaining 15% of the data were used to validate the developed model. In another example, Machiani and Abbas (2016) divided their dataset into two subgroups: a training set using 70% of the data and a validation set using 30% of the data.

Driver decisions from the experiment were taken as the “observed” responses, while computed decisions were taken as the “predicted” responses. The probability to stop was reported. If the model predicted a probability of ≥0.5, then the model predicted that the driver would stop at the stop line. If the probability was <0.5, then the model predicted that the driver would continue through the intersection. The model was validated by using the remaining 10% of the data. Results of the comparison between the actual observed behavior for 10% of the data and the predictive power of this model are presented in Table 4.4. The overall prediction accuracy for the developed model was 85%.

Table 4.4 Prediction accuracy of the model

		Predicted		%Correct
		Stop	Go	
Observed	Stop	60	9	87%
	Go	10	48	83%
			Predictive Power	85%

4.6.3.2 Probability of Stopping

Driver decision-making data were compared to empirical datasets from prior research, including experiments by Moore and Hurwitz (2013), Hurwitz et al. (2011), and Rakha et al. (2007). Figure 4.8 presents the probability of stopping from the present study to these previous experiments, one of which was conducted in the field, one on a test track, and two in a driving simulator.

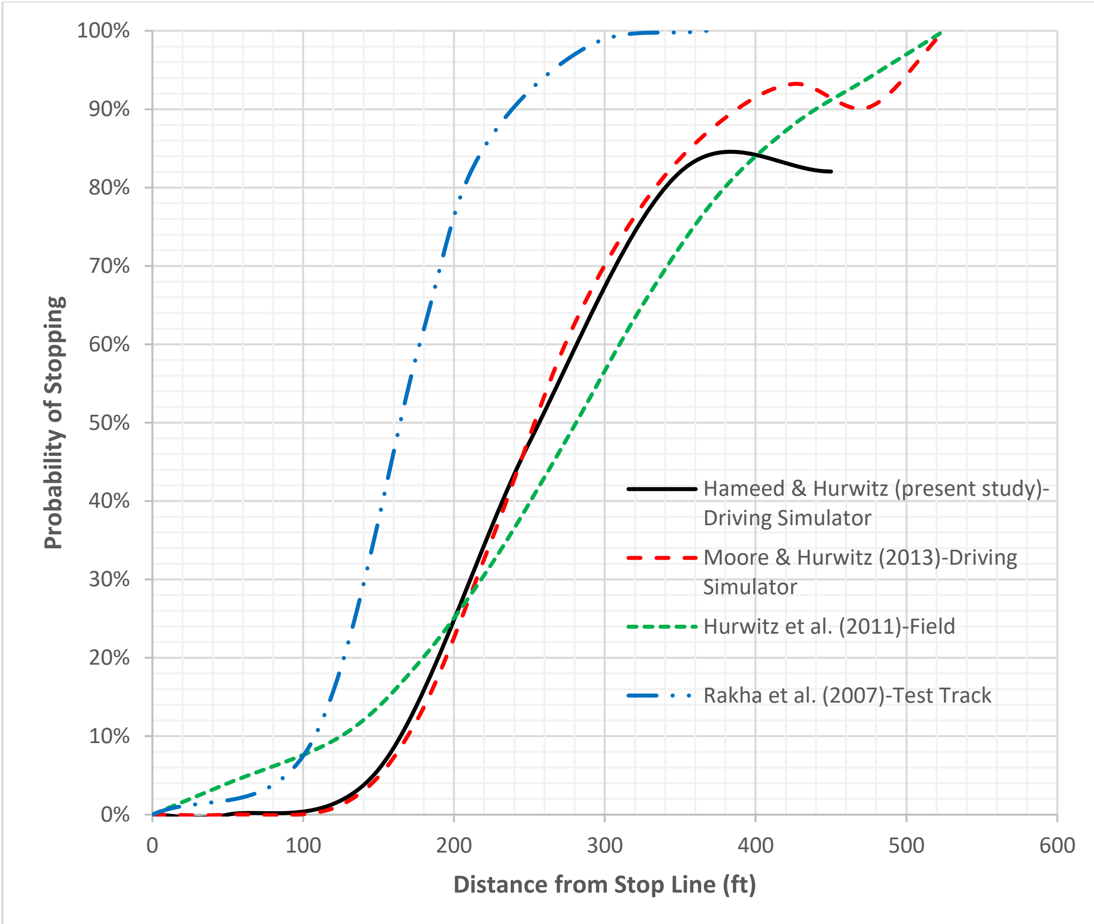

Figure 4.8 Probability of stopping

To test whether the probability distribution of the present study was similar to that of any of the previous studies, two-independent-samples Kolmogorov-Smirnov tests were applied between this study and Moore and Hurwitz (2013), Hurwitz et al. (2011), and Rakha et al. (2007). Results of the comparison showed that there were no statistically significant differences (failed to reject the null hypothesis, $p > 0.05$) among distributions at the 95% confidence level. The left-shift of the curve for the Rakha et al. (2007) study could be due to the lower operating speed and distance range used by the study during data collection.

4.7 Conclusions

Driver behavioral data were obtained from a study performed in the OSU Driving Simulator Laboratory. This dataset included data from 53 participants. Data were extracted from a series of events during which participants traversed virtual intersections as a traffic signal changed from the circular green to CY indication. A total of 1,272 observations were collected, wherein 51% of drivers stopped and 49% proceeded through the intersection in response to the onset of the CY indication. All drivers continued through the intersection at the onset of the CY indication if their distance to the stop line was ≤100 ft. If the distance was ≥400 ft, drivers were more likely to stop. The resulting dataset provides potential insights into how driver behavior was influenced by various factors. Analysis revealed four parameters that directly affect a driver’s decision to stop or proceed: TTSL, time headway, vehicle speed at onset of CY indication, and driver age (20–36 years).

This study provides important insights into how unobserved heterogeneity can be considered in simulator data. In general, a logistic regression (i.e., logit) model is the most widely used approach in many studies in this area. However, using this model in a study of panel data can introduce methodological concerns, due to the use of multiple driving events conducted by the same 53 participants, unobserved heterogeneity, and behavioral correlations among participants. To address these concerns and produce more accurate estimates, a random-parameter logit model was applied. Heterogeneity was found within three variables: TTSL, vehicle speed at onset of the CY indication, and driver age (20–36 years). The estimated constant was found to be random. The probability of stopping decreased with the increase in vehicle speeds at the onset of the CY indication. Findings showed that the probability of stopping when the car was followed increased with the increase in the time headway and TTSL. Driver age (20–36) had a statistically significant effect on the stopping probability. However, the type of following vehicle did not significantly affect a driver's decision to go or stop in response to the CY indication. The developed model was validated by using 10% of the extracted data, which showed the predictive accuracy of the model to be 85%.

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Chapter 5 – Summary and Conclusion

5.1 Summary

This research included three individual manuscripts that document a significant gap in the body of knowledge and contribute to that gap by presenting an understanding of driver's decision making and visual attention while approaching a signalized intersection during the onset of the CY indication at a high-speed signalized intersection. Legal definitions of the CY indication and how driver respond to the onset of CY indication was gathered from DTM guidance and yellow laws for all 50 states in the US. Next, a driving simulation experiment was developed using a high-fidelity full-scale driving simulator and eye-tracking system at OSU. Fifty-three participants (30 men, 23 women) successfully completed the simulation experiment.

First, the consistency of language used to describe what drivers should do in response to the CY indication as defined by state laws and in DTM guidance was documented and analyzed. Second, factors influencing the allocation of driver's visual attention at the onset of CY indication was evaluated experimentally. A factorial design was developed with time to stop line (5.5, 4.5, 3.5, and 2.5) second, time headway (0.5, 1, and 2) second and following vehicle type (passenger car, heavy vehicle). The dependent variable was total fixation duration (TFD). Data were extracted from 45 participants. Each participant conducted 24 scenarios in driving simulation experiment. Lastly, the influence of time headway and following vehicle typed on driver decision to proceed through the intersection or stop before the stop line in response to CY indication was analyzed with an identical factorial design. Data were gathered from 53 participants and the dependent variable was driver (stop/go) decision making. The effect of demographic variables (i.e., age, gender, driving experience, education level) on driver behavior at the onset of CY indication were considered in this study.

5.2 Findings

In the second chapter, the results indicate that only 4 % of states follow Class 1 guidance in DTMs, but most state laws (74 %) were classified as Class 1 in NCHRP Report 731. The results also indicate that 12% of states follow Class 2 guidance in DTMs and 8% of state laws classified as Class 2 in NCHRP Report 731. The large percentage of states (72%) follow Class 3 guidance in DTMs and 18% of state laws were classified as Class 3 in NCHRP Report 731. Moreover, the classification of guidance provided to drivers in DTMs indicate that 6 (12%) states provide Class 0, not fit any of three existing classes of guidance.

The results show that a large percentage of states (72%) follow Class 3 guidance in DTMs while the vast majority of states laws (74%) were categorized as Class 1 in NCHRP Report 731. The results indicate an apparent inconsistency between the DTM guidance and yellow state laws, and those laws as categorized in NCHRP Report 731. The inconsistency between state yellow laws and DTM guidance is another example of inconsistencies that may contribute to variability of driver comprehension and decision making in response to CY indications. The inconsistency between permissive and restrictive yellow laws poses a meaningful challenge that can create confusion for drivers when traversing state boundaries. The most concerning conflict is when a driver travels from a state with a permissive yellow law to a state with a restrictive yellow law as red clearance intervals may be less frequent, potentially contributing to angle crashes. Conversely, drivers accustomed to permissive yellow laws may anticipate lead vehicles continuing through intersections on CYs rather than stopping, contributing to rear-end crashes.

In the third chapter, the highest percentage of TFD was located on the traffic signal head (78.4%), followed by the rear view mirror (20.3%), and side view mirrors (1.3%). Repeated-measures ANOVA was performed to determine whether TFD differed between scenarios for each AOI. When a significant effect was observed, pairwise comparisons were conducted to find the origin of the difference.

For the traffic signal AOI, the following vehicle type and TTSL had significant effects on the distribution of TFD. Pairwise comparisons of the main effect of the following vehicle type revealed that regardless of the TTSL, the TFD was significantly different when the subject vehicle was followed by a PC or HV. Regardless of the following vehicle type, pairwise comparisons showed that the TFD was significantly different for the 4.5 s and 3.5 s TTSL when the CY indication was displayed. ANOVA results revealed two statistically meaningful two-way interactions, which were subsequently inspected by pairwise comparisons. Only the traffic signal AOI had significant two-way interactions. There was a statistically significant interaction between the combined effects of following vehicle type and time headway on TFD. In addition, there was a significant interaction between the combined effects of time headway and TTSL on the TFD. For the traffic signal AOI effect size, a change in the following vehicle type (PC or HV) had the greatest effect on the TFD on the traffic signal, accounting for about 12.6% of the within-subject variance.

For the rear view mirror AOI, the following vehicle type and time headway had significant effects on TFD when the driver looked at the rear view mirror. Pairwise comparisons showed a significant difference in TFD when the subject vehicle was followed by a PC or HV. There was no significant interaction between the combined effects of TTSL, time headway, and following vehicle type on TFD. The effect size finding indicated that the change in following vehicle type had the highest effect on TFD, with about 9% of within-subject variance being accounted for by this interaction. No significant effect was observed for any independent variable or the two or three-way interactions on the TFD on the side view mirrors.

The data included repeated measures (panel data) and numerous zeros. To determine the effect of the independent variables on TFD by AOI, a random-effect Tobit regression model was considered as the most appropriate mathematical model (Chen et al., 2014). Two random-effect Tobit regression models were used to deal with two AOIs (traffic signal and rear view mirror). Three explanatory variables (TTSL, driver age of 45–55 years, and vehicle speed at the onset of CY indication (35–45 mph)) had statistically significant positive effects on the traffic signal TFD with a 95% confidence interval (CI). For the rear view mirror, three independent variables (TTSL, driver age of 55–65 years, and drivers with some high school or less) had statistically significant positive effects for TFD while the other three independent variables (time headway, driving once per week and driving a van) had statistically significant negative effects for the TFD with a 95% CI.

In the fourth chapter, the findings showed that 51% of drivers decided to stop while 49 % chose to proceed through an intersection in response to CY indication. Nearly all drivers (97%) went through an intersection when they were 2.5 seconds from the stop line at the onset of the CY indication. When TTSL was 5.5 seconds, the majority of drivers decided to stop, and red-light running violations start to increase. A random parameter binary logit model was used to deal with unobserved heterogeneity across observations. All possible combinations of the continuous and categorical factors that influence the driver's decision making at the onset of CY indication were examined to construct the model and the final combination of model factors were based on p-values at 95% CIs. Using a step-wise procedure to test and determine statistical significance factors. A total of 4 parameters were found to be statistically significant on driver's decision making at the onset of CY indication. The findings indicated that TTSL had a significant impact on probability of stopping based on partial effects. Partial effects showed TTSL increases the probability of stopping. This variable had the largest effect on the probability of stopping, since the partial effect suggest an increase of 0.46. Similarly, time headway increases the probability of stopping by 0.07. For another continuous variable and based on partial effects, driver aged 20–36 years have a 0.25 increased probability of stopping. Conversely, it was found that vehicle speed at the onset of the CY indication reduces the probability of stopping by 0.03. Results showed that following vehicle type was not statically significant on driver's decision to proceed or stop in response to the CY indication. Three estimated parameters were found to be random (TTSL, vehicle speed at the onset of the CY indication, and driver age 20–36) based on the statistical significance of standard deviation. Only, time headway was fixed across observations.

5.3 Discussion of Findings Across Manuscripts

Driver behavior at the onset of CY indication cannot be documented and understood without considering other contextual factors. The laws and regulations established to communicate the desired driver response to the CY indication, are an important contextual factor for understanding observed driver behavior. Therefore, the authors examined yellow laws and DTM guidance around the country. After examining these laws and the consistency or inconsistency between them across US, **it became apparent that there was significant variability and little documented explanation regarding some of the presented guidance i.e. how to interpret "if and only if it is safe to do so"**. As, driver behavior is heavily influenced by visual attention, where the driver looks and how much particular areas of interest are focused on during CY indication could provide substantial information about potential failure mechanisms during dilemma zone interactions. Findings suggested that **driver's visual attention is connect with driver stop or go decision making**. Therefore, the authors to extend the study to model driver decision making during the CY indication. The findings indicated that time headway influenced leading driver decisions to stop or go at a CY indication. A shorter time headway increased a lead driver's red-light running frequency. Following vehicle type did not contribute to the driver's stop/go decision.

5.4 Practical Applications

The findings of this study could aid in the development of future policies regarding driver behavior in response to the CY indication in several ways. First, there is a need to adopt a uniform legal interpretation of the CY indication across state boundaries. In addition, the consistency in language used in DTM guidance and yellow state laws cannot be ignored. Moreover, perhaps there is an opportunity to refine and improve DTM guidance as a half measure to the modification of state law, as this would be an easier adjustment. This study opens provides evidence that highlights the need for transportation professionals to adopt a consistent yellow light law (permissive or restrictive) to avoid the confusion for drivers especially when they travel between states with varying legal and DTM definitions?

Second, this study documents driver visual attention during CY indication to better understand the frequency and duration of driver glances at a closely following vehicles of different types at different headways. In doing so, the work documents for the first time if drivers are properly attending to rear hazards during this difficult interaction, which can guide future education and training efforts. From a safety perspective, rear-end crashes can occur when the driver is not attentive to a closely following vehicle and decides to stop suddenly during the onset of the CY indication. There is an opportunity to involve drivers in education and training programs emphasizing the risks associated with ignoring rear view and side view mirrors during the response to CY indications. Moreover, advance vehicle technology could alert the driver of a leading vehicle if there is a closely following vehicle with a time headway of 1 s or less during CY indication.

Finally, the findings showed that drivers who were closely followed (0.5s, 1s) by vehicle during the CY indication were more likely to go through the intersection and in some cases, ran red lights. Drivers in this traffic condition have higher risk of being involved in right-angle crashes if they incorrectly choose to proceed through the intersection during CR indication. Thus, traffic safety efforts should include promoting longer headways between drivers on the approach to signalized intersection. Advanced in-vehicle technology could also play a vital role warning when a following vehicle is following a leading vehicle too closely.

5.5 Future Research

In the first manuscript, a comparison was made between the language used in yellow light laws and DTM guidance across the US. To better document the impact of this varying policies, a national survey focused on permissive and restrictive laws and how drivers respond if they travel between states that follow different yellow laws. Moreover, a pair of driving simulators could be used to study driver's behavior at the onset of CY indication with permissive and restrictive laws (capturing geographically diverse samples). In this study, authors studied the effect of two types of following vehicles (a passenger car and a class 5 truck), future research could add other vehicle types such as an SUV or larger heavy vehicle.

This research examined time to stop line, time headway, and following vehicle type as independent variables for driver's response to the CY indication. Many other variables could also be considered. For example, different classification of subject vehicles (i.e., heavy vehicle or pickup truck), different roadway configurations (i.e., two lanes or more in each direction), different weather conditions (i.e., rainy weather or foggy weather), and different posted speed limits (i.e., 35 or 55 mph) could all potentially influence driver decision making and visual attention. This study was conducted in a suburban area, for future research can study driver's behavior at onset of CY in rural and urban areas.

Finally, there is growing interest in the potential of connected vehicles which could play a significant role in mitigating signalized intersection safety challenges by facilitating information transfer between the traffic signal and the following and leading vehicles to promote safer headways.

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Appendix A: Circular Yellow Indication Language

Table 1 Comparison between steady yellow language and driver manual language

State	Steady Yellow Language	Driver Manual Language
Alabama	Steady yellow indication: a. Vehicular traffic facing a steady circular yellow or yellow arrow signal is thereby warned that the related green movement is being terminated or that a red indication will be exhibited immediately thereafter. *ALA COD § 32-5A-32*	YELLOW…A circular steady yellow means clear the intersection. It follows a green signal. You must not enter the intersection when the red signal comes on. *Alabama Law Enforcement Agency, Alabama Driver Manual,2015*
Alaska	"Steady yellow indication (A) vehicular traffic facing a steady yellow signal is warned that the movement allowed under [green indication] of this section is being terminated and that a red indication will be exhibited immediately following the yellow indication" 13 AAC *02.010*	"YELLOW BALL A red light is about to appear. Stop unless you are already within the intersection, or so close to the intersection that you cannot stop safely. If the light changes to yellow as you enter the intersection, you may proceed with extreme caution." *(Alaska Department of Administration Division of Motor Vehicles, 2013).*
Arizona	Steady yellow indication: Vehicular traffic facing a steady yellow signal is warned by the signal that the related green movement is being terminated or that a red indication will be exhibited immediately thereafter when vehicular traffic shall not enter the intersection. *28-645. Traffic control signal legend*	Yellow − Yellow Means Caution! This signal means CAUTION. A steady yellow light is a warning that the light is about to turn red. If you have not entered the intersection, you should come to a safe stop. If you are already in the intersection, you should continue moving and clear it safely. Speeding up to "beat the light" is illegal and could cause a crash. Arizona Department of Transportation. Arizona Driver License Manual,2013
Arkansas	Steady yellow alone means:(A) Vehicular traffic facing the signal is warned that the red or "STOP" signal will be exhibited immediately thereafter, and vehicular traffic shall not enter the intersection when the red or "STOP" signal is exhibited. *§ 27-52-107 - Signal legend*	A continuous yellow traffic light indicates the traffic signal is about to change. The driver of a vehicle must stop if such a stop can be executed safely without blocking the intersection. However, if the driver is within the intersection when the yellow light changes, the driver must not stop, but proceed through the intersection. (*Arkansas Driver License,2012)*

Table 1 Comparison between steady yellow language and driver manual language (continue)

State	Steady Yellow Language	Driver Manual Language
California	"A driver facing a steady circular yellow or yellow arrow signal is, by that signal, warned that the related green movement is ending or that a red indication will be shown immediately thereafter." California Vehicle Code *21452.*	"Solid Yellow – A yellow signal light means 'CAUTION'. The red signal is about to appear. When you see the yellow light, stop if you can do so safely. If you cannot stop safely, cross the intersection cautiously." *(California Department of Motor Vehicles, 2014).*
Colorado	Steady yellow indication: Vehicular traffic facing a steady circular yellow or yellow arrow signal is hereby warned that the related green movement is being terminated or that a red indication will be exhibited immediately thereafter. *604. Traffic control signal legend.*	Steady Yellow Light: A red light is about to appear. Stop unless you are already within the intersection. (Colorado Driver Handbook,2014).
Connecticut	Yellow: Vehicular traffic facing a steady yellow signal is thereby warned that the related green movement is being terminated or that a red indication will be exhibited immediately thereafter, when vehicular traffic shall stop before entering the intersection unless so close to the intersection that a stop cannot be made in safety. *Sec. 14-299. Traffic Control Signals.*	Yellow traffic lights mean the traffic light is about to change to red. You must stop if it is safe to do so. If you are in the intersection when the yellow light comes on, do not stop-continue through the intersection. *Department of Motor Vehicles, Driver's Manual,2014.*
Delaware	Circular yellow: Vehicular traffic facing the circular yellow signal is thereby warned that a red signal for the previously permitted movement will be exhibited immediately thereafter. *§ 4108 Traffic-control signal legend.*	Steady Yellow Light: This means that the signal is changing from green to red; prepare to stop. If you are too close to stop safely, continue through the intersection with care. Department of transportation, Delaware Driver Manual,2013
Florida	Steady yellow indication: Vehicular traffic facing a steady yellow signal is thereby warned that the related green movement is being terminated or that a red indication will be exhibited immediately thereafter when vehicular traffic shall not enter the intersection. *316.075*	**Yellow:** Stop if you can safely do so. The light will soon be red. *Florida Driver's Hanbook,2014.*

Table 1 Comparison between steady yellow language and driver manual language (continue)

State	Steady Yellow Language	Driver Manual Language
Georgia	Steady yellow alone*:* Vehicular traffic facing the signal is thereby warned that the red signal will be exhibited immediately thereafter. *Sec. 56-114. - Traffic control signal legend*.	A yellow light warns that the light is changing from green to red. Slow down and prepare to stop. *Georgia Department of Driver Services, Drivers manual,2014.*
Hawaii	Steady yellow indication: Vehicular traffic facing a steady yellow signal is thereby warned that the related green movement is being terminated or that a red indication will be exhibited immediately thereafter when vehicular traffic shall not enter the intersection. HI Rev Stat § 219C-32, (2013)	A Yellow Light means that the red light is going to be shown immediately thereafter. You should avoid entering the intersection when the yellow light is shown. You must not enter the intersection after the red light is shown. *Department of Transportation, Hawaii Driver's Manual, 2014*
Idaho	"Steady yellow indication: (a) A driver facing a steady circular yellow or yellow arrow signal is being warned that the related green movement is ending, or that a red indication will be shown immediately after it." I.C. § *49-802*	"Yellow Light: Means caution. An amber or yellow circular indication warns that the signal is about to change to red. If you have not entered the intersection and can come to a safe stop, you should do so. If you are already in the intersection, you should continue moving and clear it safely." *(Idaho Transportation Department, 2014).*
Illinois	Steady yellow*:* Vehicular traffic facing a steady yellow signal is thereby warned that the related green movement is being terminated or that a red indication will be exhibited immediately thereafter when vehicular traffic may not enter the intersection. *Sec 12-27*	Yellow light: The yellow light warns that the signal is changing from green to red. When the red light appears, you may not enter the intersection. *Illinois Rules of the Roads,2015.*
Indiana	Yellow alone or "CAUTION" when shown following the green or "GO" signal. Vehicular traffic facing the signal is thereby warned that the red or "STOP" signal will be exhibited immediately thereafter, and such vehicular traffic shall not enter or be crossing the intersection when the red or "STOP" signal is exhibited. Sec. 42.05. Traffic-control signal legend.	A yellow light means the green light has ended and the signal is about to turn red. If you are facing a yellow light, your right of way is ending. If you are approaching the intersection, or are too close to stop safely, you may complete your movement after yielding the right of way. *Indiana Driver's Manual, 2015.*

Table 1 Comparison between steady yellow language and driver manual language (continue)

State	Steady Yellow Language	Driver Manual Language
Iowa	Amber or "Caution." When shown with or following the green, traffic facing the signal shall stop before entering the intersection unless so close as to the intersection that a stop cannot be made in safety. *9.52.040 - Signal legend.*	Yellow: Do not enter the intersection if you can stop safely. If you cannot stop safely, proceed through the intersection with caution. (*Iowa Driver's Manual,2014).*
Kansas	Steady yellow indication*:* Vehicular traffic facing a steady circular yellow or yellow arrow signal is thereby warned that the related green movement is being terminated or that a red indication will be exhibited immediately thereafter when vehicular traffic shall not enter the intersection. *8-1508.Traffic-control signal legend.*	Steady YELLOW Traffic Light – This means the traffic light is about to change to red. You should slow down and come to a complete stop, if traffic flow to the rear allows. If you are already in the intersection when the yellow light comes on, you may continue safely through the intersection. (*Kansas Driving Handbook,2009).*
Kentucky	Steady yellow indication: Vehicular traffic facing a steady yellow signal is thereby warned that the related green movement is being terminated or that a red indication will be exhibited immediately thereafter when vehicular traffic shall not enter the intersection. *189.338bbb*	YELLOW: A yellow light means the traffic signal is about to turn red. Stop if you can do so safely. A vehicle may clear an intersection on a red light, if the vehicle entered the intersection while the signal was yellow; but it is against the law to enter an intersection after the light turns red. *Kentucky Driver Manual,2012*
Louisiana	Steady yellow indication*:* Vehicular traffic facing a steady yellow signal is thereby warned that the related green movement is being terminated or that a red indication will be exhibited immediately thereafter when vehicular traffic shall not enter the intersection.	Steady YELLOW Traffic Light – This means the traffic light is about to change to red. You should slow down and come to a complete stop, if traffic flow to the rear allows. If you are already in the intersection when the yellow light comes on, you may continue safely through the intersection. (*Louisiana Class D & E Driver's Guide, 2013).*
Maine	A yellow light: If steady and circular or an arrow, means the operator must take warning that a green light is being terminated or a red light will be exhibited immediately. *§2057. Traffic-Control Devices.*	Steady Yellow: Caution. Traffic signal is about to change to red. Begin to slow down. A yellow light clears the intersection before the red light. *Department of the Secretary of State, Motorist handbook and Study Guide, 2013*

Table 1 Comparison between steady yellow language and driver manual language (continue)

State	Steady Yellow Language	Driver Manual Language
Maryland	Vehicular traffic facing a steady yellow signal is warned that the related green movement is ending or that a red signal, which will prohibit vehicular traffic from entering the intersection, will be shown immediately after the yellow signal. *§21–202.*	Steady Yellow Signal: This means that the signal is changing from green to red. Its purpose is to provide time for approaching traffic to stop safely and to clear other vehicles from the intersection before the signal turns red. If you are too close to the intersection to stop safely, continue through the intersection with care. *Maryland Department of Transportation, Maryland Driver's Manual,2014*
Massachusetts	YELLOW**:** While the yellow lens is illuminated, waiting drivers shall not proceed and any driver approaching the intersection or a marked stop line, shall stop at such line unless too close to the intersection that a stop cannot be made in safety. *Sec. 25. - Traffic control signal legend*	Steady Yellow A steady yellow light means the traffic signal is changing from green to red. You must stop if it is safe. If you are already stopped at an intersection or a stop line, you may not proceed. *Massachusetts Driver's Manual,2014.*
Michigan	If the signal exhibits a steady yellow indication, vehicular traffic facing the signal shall stop before entering the nearest crosswalk at the intersection or at a limit line when marked, but if the stop cannot be made in safety, a vehicle may be driven cautiously through the intersection. *Section 257.612*	A yellow light means the green signal has ended and the signal is about to turn red. You are required to stop on a yellow light. If you cannot stop safely, do not speed up but drive cautiously through the intersection. *What Every Driver Must Know,2014.*
Minnesota	Steady yellow indication: Vehicular traffic facing a steady circular yellow or yellow arrow signal is thereby warned that the related green movement is being terminated or that a red indication will be exhibited immediately thereafter when vehicular traffic must not enter the intersection, except for the continued movement allowed by any green arrow indication simultaneously exhibited. *Section 169.06*	A steady yellow light means "caution." The signal is about to turn red. Do not enter the intersection if you can stop safely before doing so. If you cannot stop safely, proceed through the intersection with caution. (*Minnesota Department of Public Safety, Minnesota Driver's Manual, 2015).*

Table 1 Comparison between steady yellow language and driver manual language (continue)

State	Steady Yellow Language	Driver Manual Language
Mississippi	Yellow alone or "Caution" when shown following the green or "Go" signal*:* Vehicular traffic facing the signal shall stop before entering the nearest crosswalk at the intersection, but if such stop cannot be made in safety, a vehicle may be driven cautiously through the intersection. *§ 31-135. Traffic-control signal legend.*	A YELLOW LIGHT warns that the light is changing from green to red. Slow down and prepare to stop. Department of Public Safety, Mississippi Driver's Manual,2011
Missouri	Steady yellow indication: Vehicular traffic facing a steady yellow signal is thereby warned that the related green movement is being terminated or that a red indication will be exhibited immediately thereafter when vehicular traffic shall not enter the intersection. *Sec. 23-106. - Traffic-control signal legend.*	A STEADY YELLOW LIGHT tells you the traffic signal is changing from green to red. Stop for a steady yellow light unless you are within the intersection or are so close that you cannot safely stop before entering the intersection. (*Missouri Department of Revenue, Driver Guid,2014).*
Montana	(a) Vehicular traffic facing a steady circular yellow or yellow arrow signal is warned that the traffic movement permitted by the related green signal is being terminated or that a red signal will be exhibited immediately thereafter. Vehicular traffic may not enter the intersection when the red signal is exhibited after the yellow signal. 61-8-207. Traffic control signal legend.	A steady yellow signal means “CAUTION.” Cautiously enter the intersection. The signal is about to turn red. Do not enter an intersection against a steady yellow light unless you are too close to stop safely. *(Montana Driver Manual,2015).*
Nebraska	Yellow alone, when shown following the green signal. Vehicular traffic facing the signal shall stop before entering the nearest crosswalk at the intersection, but if such stop cannot be made in safety a vehicle may be driven cautiously through the intersection. *Sec. 36-85. - Traffic-Control Signal Legend.*	Yellow. Caution – a steady yellow light is a warning that the light is about to change. If the vehicle has not entered the intersection, it should be brought to a safe stop. If in the intersection, continue moving and clear it safely. Speeding up to "beat the light" is unlawful. (Nebraska Department of Motor Vehicles, Nebraska Driver’s Manual,2014)

Table 1 Comparison between steady yellow language and driver manual language (continue)

State	Steady Yellow Language	Driver Manual Language
Nevada	"Where the signal is a steady yellow signal alone: (a) Vehicular traffic facing the signal is thereby warned that the related green movement is being terminated or that a steady red indication will be exhibited immediately thereafter, and such vehicular traffic must not enter the intersection when the red signal is exhibited." NRS *484B.307*	"A yellow light means CAUTION. A steady yellow light is a warning that the light will be turning red. If you have not entered the intersection, you must stop. If you are already in the intersection, you should continue moving and clear it safely. DO NOT speed up to "beat the light." *(Nevada Department of Motor Vehicles, 2013).*
New Hampshire	Steady Yellow Indication. Vehicular traffic facing a steady circular yellow or yellow arrow signal is thereby warned that the related green movement is being terminated or that a red indication will be exhibited immediately thereafter when vehicular traffic shall not enter the intersection. 265:10 Traffic Control Signal Legend.	Yellow: Caution. The lights are about to change to red. The purpose of the yellow light is to allow vehicles already in the intersection to clear the intersection safely. Do not try to "beat the light" if you have not already entered the intersection. *Department of Safety, Driver's Manual,2013.*
New Jersey	Amber, or yellow, when shown alone following green means traffic to stop before entering the intersection or nearest crosswalk, unless when the amber appears the vehicle or street car is so close to the intersection that with suitable brakes it cannot be stopped in safety.	YELLOW LIGHT: A motorist should stop before entering the intersection or crosswalk, unless his/her vehicle is so close to the intersection that it cannot be stopped safely. A yellow arrow means the signal is changing from green to red and gives the motorist a chance to stop safely. New Jersey Motor Vehicle Commission, The New Jersey Driver Manual, 2014
New Mexico	Yellow alone when shown following the green signal: Vehicular traffic facing the signal is warned that the red signal will be exhibited immediately thereafter, and the vehicular traffic shall not enter the intersection when the red signal is exhibited except to turn as hereinafter provided. *66-7-105. Traffic-Control Signal Legend.*	A steady YELLOW traffic light means the traffic light is about to change to red. You must stop if it is safe to do so. If you are in the intersection when the yellow light comes on, do not stop but continue through the intersection. (New Mexico Driver Manual,2015).

Table 1 Comparison between steady yellow language and driver manual language (continue)

State	Steady Yellow Language	Driver Manual Language
New York	Yellow, when used, shall mean that colors in the signal are about to change and shall require that traffic shall stop and remain standing unless the yellow is lighted too late to allow a stop to be made with safety. *Sec. 15-95. - Traffic-control signal legend.*	STEADY YELLOW: The light will change from green to red. Be prepared to stop for the red light. *Department of Motor Vehicles, Driver's Manual, 2014*
North Carolina	Yellow or "caution." Vehicular traffic facing the signal is thereby warned that the red or "stop" signal will be exhibited immediately thereafter and such vehicular traffic shall not enter or be crossing the intersection when the red or "stop" signal is exhibited. Sec. 42-44. Traffic control signal legend.	A circular yellow signal means “caution” and indicates that the signal is about to turn red. Stop for a yellow signal unless you are too close to the intersection to stop safely — in that case, drive cautiously through the intersection. Never speed up for a yellow signal to “beat” the red signal. *Department of Transportation Division of Motor Vehicles, North Carolina Driver's handbook,2014*.
North Dakota	Steady yellow indication: Vehicular traffic facing a steady yellow signal is thereby warned that the related green movement is being terminated or that a red indication will be exhibited immediately thereafter when vehicular traffic may not enter the intersection. *8-0405. - Traffic-Control Signals Legend.*	A yellow indication means WARNING or CAUTION. The light is changing from green to red. (North Dakota Department of Transportation, Noncommercial Drivers License Manual,2015).
Ohio	Steady yellow indication: Vehicular traffic facing a steady circular yellow or yellow arrow signal is thereby warned that the related green movement is being terminated or that a red indication will be exhibited immediately thereafter. *11-202.Traffic-control signal legend.*	Clearance of vehicle within intersection. Digest of Ohio Department of Public Safety, Motor Vehicle of Laws,2012.

Table 1 Comparison between steady yellow language and driver manual language (continue)

State	Steady Yellow Language	Driver Manual Language
Oklahoma	Steady yellow alone*:* Vehicular traffic facing the signal is thereby warned that the red or "Stop" signal will be exhibited immediately thereafter, and such vehicular traffic shall not enter or be crossing the intersection when the red or "Stop" signal is exhibited. *Sec. 110-307. - Traffic-Control Signal Legend Generally*.	Yellow Light: Steady—Warning! The light is about to turn red! You must stop if you can stop safely before entering the crosswalk at the intersection. Adjust your speed as you approach so that you can come to a smooth stop if needed. Don't speed up to beat the light. Enter the intersection carefully. Collisions often happen here. *(Oklahoma Department of Public Safety, Oklahoma Driver's Manual,2014).*
Oregon	"Steady circular yellow signal. A driver facing a steady circular yellow signal light is thereby warned that the related right of way is being terminated and that a red or flashing red light will be shown immediately. A driver facing the light shall stop at a clearly marked stop line, but if none, shall stop before entering the marked crosswalk on the near side of the intersection, or if there is no marked crosswalk, then before entering the intersection. If a driver cannot stop in safety, the driver may drive cautiously through the intersection." ORS *811.260*	"Steady Yellow - A steady yellow signal warns you that the signal is about to turn red. Stop before entering the intersection. If you cannot stop safely, you may then drive cautiously through the intersection. Cautiously means slowly and carefully. Pedestrians facing a yellow light must not start across the street unless a pedestrian signal directs otherwise." *(ODOT, 2014).*
Pennsylvania	Steady yellow indication: Vehicular traffic facing a steady yellow signal is thereby warned that the related green indication is being terminated or that a red indication will be exhibited immediately thereafter. *75 Pa. Cons. Stat. § 3112*	A **STEADY YELLOW LIGHT** tells you a steady red light will soon appear. If you are driving toward an intersection and a yellow light appears, slow down and prepare to stop. If you are within the intersection or cannot stop safely before entering the intersection, continue through carefully. *Pennsylvania Department of Transportation, Pennsylvania Driver's manual,2015*.
Rhode Island	Yellow alone or "caution" when shown following the green or *"go" signal.* Vehicular traffic facing the signal is warned by it that the red or "stop" signal will be exhibited immediately afterwards, and the vehicular traffic shall not enter or be crossing the intersection when the red or "stop" signal is exhibited. *Sec. 36-77. - Traffic Control Signal Legend.*	Yellow Light: A yellow light tells a driver that a red light is next. Slow down and proceed with caution if a stop cannot be made safely. Clear the intersection. *Rhode Island Division of Motor Vehicles, Rhode Island Driver's Manual, 2014*.

Table 1 Comparison between steady yellow language and driver manual language (continue)

State	Steady Yellow Language	Driver Manual Language
South Carolina	Steady yellow indication: Vehicular traffic facing a steady circular yellow or yellow arrow signal is thereby warned that the related green movement is being terminated or that a red indication will be exhibited immediately thereafter. SC Code § 56-5-970	Yellow Caution Light**:** A yellow caution light follows the green signal. The yellow light is a warning that the signal is about to change, and that the red stop signal is about to be shown. Therefore, you should stop your car and wait for the next green light. *South Carolina Department of Motor vehicles, South Carolina Driver's Manual,2015*
South Dakota	A steady yellow light alone shall indicate that: Vehicular traffic facing the signal is thereby warned that the red or stop signal will be exhibited immediately thereafter and such vehicular traffic shall not enter the intersection when the red or stop signal is exhibited. *32-28-3*	A steady YELLOW traffic light means the traffic light is about to change to red. You must stop if it is safe to do so. If you are in the intersection when the yellow light comes on, do not stop but continue through the intersection. *(South Dakota Driver Manual,2013.)*
Tennessee	Yellow alone or “Caution,” when shown following the green or “Go” signal: Vehicular traffic facing the signal is warned that the red or “Stop” signal will be exhibited immediately thereafter and that vehicular traffic shall not enter or cross the intersection when the red or “Stop” signal is exhibited. *TCA 55-8-110*	YELLOW: Caution—prepare to stop. The red stop signal will be exhibited immediately after the yellow light appears. Adjust speed immediately to come to a smooth stop. You must stop if it is safe to do so. Do not speed up to beat the light. If you are already IN the intersection when the yellow light comes on, do not stop, but continue cautiously through the intersection. Tennessee law only requires the yellow light to be exhibited for a minimum of three seconds before the red light. *Tennessee Department of Safety, Tennessee Driver Study Guide, 2007.*
Texas	Steady yellow indication*:* Vehicular traffic facing a steady yellow signal is thereby warned that the related green movement is being terminated or that a red indication will be exhibited immediately thereafter when vehicular traffic shall not enter the intersection. *Sec. 17-63. Traffic-Control Signal Legend.*	Steady Yellow Light (Caution): A steady yellow light warns drivers to use caution and to alert them a red light is coming up. You must STOP before entering the nearest crosswalk at the intersection if you can do so safely. If a stop cannot be made safely, then you may proceed cautiously through the intersection before the light changes to red. (Department of Public Safety, Texas Driver's Handbook,2012).

Table 1 Comparison between steady yellow language and driver manual language (continue)

State	Steady Yellow Language	Driver Manual Language
Utah	Steady yellow alone: Vehicular traffic facing the signal is thereby warned that the red or "Stop" signal will be exhibited immediately thereafter and such vehicular traffic shall not enter or be crossing the intersection when the red or "stop" signal is exhibited. *16.05.050 Traffic-Control Signal Legend.*	Yellow **-** It is an indication that the light is about to turn red. Solid Yellow **-** If you are in the intersection making a left turn when the yellow light appears, proceed as soon as traffic allows, and it is safe. *(Department of Utah Safety, Utah Driver Handbook, 2014).*
Vermont	Steady yellow signal: Vehicular traffic facing a steady yellow signal is thereby warned that the related green signal is being terminated or that a red signal will be exhibited immediately thereafter, when vehicular traffic shall not enter the intersection. *1022. Traffic-Control Signals.*	Yellow Light: This light warns drivers that the light is about to turn red. If you are too close to the intersection to stop safely, proceed with caution through the intersection. *Vermont Driver's Manual,2015.*
Virginia	Steady yellow signal indication shall have the following meaning: Vehicular traffic facing a steady CIRCULAR YELLOW signal indication is thereby warned that the related green movement or the related flashing arrow movement is being terminated or that a steady red signal indication will be displayed immediately thereafter when vehicular traffic shall not enter the intersection. The rules set forth concerning vehicular operation under the movement(s) being terminated shall continue to apply while the steady CIRCULAR YELLOW signal indication is displayed. *Section 4D.04, Virginia Supplement to the 2009 MUTCD, (2011.)*	Yellow light or arrow: A yellow light or arrow are cautions warning that the light is about to change. If you have not entered the intersection, stop; or, if unsafe to stop, cautiously go through it. If you are already in the intersection, go through it cautiously. Do not speed up to beat the light. *Virginia Department of Motor Vehicles, Virginia Driver's Manual,2014.*
Washington	"Vehicle operators facing a steady circular yellow or yellow arrow signal are thereby warned that the related green movement is being terminated or that a red indication will be exhibited immediately thereafter when vehicular traffic shall not enter the intersection." RCW *46.61.055*	"A steady yellow traffic light means the traffic light is about to change to red. You must stop if it is safe to do so. If you are in the intersection when the yellow light comes on, do not stop but continue through the intersection." *(State of Washington Department of Licensing, 2014).*
West Virginia	Yellow alone or "caution" when shown following the green or "go" signal: Vehicular traffic facing the signal is thereby warned that the red or "stop" signal will be exhibited immediately thereafter and such vehicular traffic shall not enter or be crossing the intersection when the red or "stop" signal is exhibited. *WV Code § 17C-3-5, (2014)*	Steady Circular Yellow - This means that the green light is ending and will change to red. You should only drive through a yellow light if the vehicle clearance is within the intersection. *Department of Transportation, Driver's licensing Handbook, 2013*

Table 1 Comparison between steady yellow language and driver manual language (continue)

State	Steady Yellow Language	Driver Manual Language
Wisconsin	Yellow. When shown with or following the green, traffic facing a yellow signal shall stop before entering the intersection unless so close to it that a stop may not be made in safety. *346.37*	A steady YELLOW traffic light means the traffic light is about to change to red. You must stop if it is safe to do so. If you are in the intersection when the yellow light comes on, do not stop but continue through the intersection. *Wisconsin Department of Transportation, Motorist's Handbook,2014*.
Wyoming	Steady yellow indication: Vehicular traffic facing a steady circular yellow or yellow arrow signal is thereby warned that the related green movement is being terminated or that a red indication will be exhibited immediately thereafter. WY Sta 31-5-403	Amber light: If possible, you MUST stop before entering the intersection. If you cannot stop safely, you should carefully go through the intersection. (Wyoming Department of Transportation, Class C Driver License Manual,2014).

Appendix B: Pre-Simulation Survey

Q1: Participant Number?

____

Q2: Are you between the age of 18 and 75 years?

- ☐ Yes (1)
- ☐ No (2)

If No Is Selected, Then Skip to End of Survey

Q3: What is your age?

____

Q4: Are you a licensed driver?

- ☐ Yes (1)
- ☐ No (2)

If No Is Selected, Then Skip to End of Survey

Q5: What, if any, corrective eye-wear do you wear while driving?

- ☐ Glasses (1)
- ☐ Contacts (2)
- ☐ None (3)

If Glasses Is Selected, Then Skip to End of Survey

Q6: With which gender do you identify?

- ☐ Male (1)
- ☐ Female (2)
- ☐ Prefer not to answer (3)

Q7: How often do you drive per week?

- ☐ 1 time per week (1)
- ☐ 2-4 times per week (2)
- ☐ 5-10 times per week (3)
- ☐ More than 10 times per week (4)

Q8: In which state did you first obtain your driver's license?

____

Q9: How many miles did you drive last year?

- ☐ 0-5,000 miles (1)
- ☐ 5,000 – 10,000 miles (2)
- ☐ 10,000 – 15,000 miles (3)
- ☐ 15,000 – 20,000 miles (4)
- ☐ More than 20,000 miles (5)

Q10: What type of motor vehicle do you typically drive?
- □ passenger Car (1)
- □ SUV (2)
- □ Pickup Truck (3)
- □ Van (4)
- □ Heavy Vehicle) (5)

Q11: How many years have you been a licensed drive?

____

Q12: Are you color blind?
- ☐ Yes (1)
- ☐ No (2)
- ☐ Prefer not to answer (3)

Q13: Which race do you consider yourself?
- □ American Indian or Alaska Native (1)
- □ Asian (2)
- □ Black or African American (3)
- □ Hispanic or Latino/a (4)
- □ White or Caucasian (5)
- □ Other (please specify) (6) ____
- □ Prefer not to answer (7)

Q14: What is your annual household income?
- □ Less than $25,000 (1)
- □ $25,000 to less than $50,000 (2)
- □ $50,000 to less than $75,000 (3)
- □ $75,000 to less than $100,000 (4)
- □ $100,000 to less than $200,000 (5)
- □ $200,000 or more (6)
- □ Prefer not to answer (7)

Q15: What is the highest level of education you have completed?
- □ Some high school or less (1)
- □ High school diploma or GED (2)
- □ Some college (3)
- □ Four-year degree (4)
- □ Master's degree (5)
- □ PhD degree (6)
- □ Prefer not to answer (7)

Q16: Have you participated in other simulator experiments?
- □ Yes (1)
- □ No (2)

17: Did you experience simulator sickness?
- □ Yes (1)
- □ No (2

Q18: Do you experience motion sickness?
- □ Yes (1)
- □ No (2)

Q19: [If "Yes" is selected on Q18] Do you experience motion sickness as an automobile passenger?
- □ Never (1)
- □ Rarely (2)
- □ Often (3)
- □ Almost always (4)
- □ I do not ride in automobiles (5)

Q20: [If "Yes" is selected on Q18] Do you experience motion sickness as an airplane passenger?
- □ Never (1)
- □ Rarely (2)
- □ Often (3)
- □ Almost always (4)
- □ I do not ride in airplanes (5)

Q21: [If "Yes" is selected on Q18] Do you experience motion on boats?
- □ Never (1)
- □ Rarely (2)
- □ Often (3)
- □ Almost always (4)
- □ I do not ride on boats (5)

Q22: [If "Often" or "Always" is selected on Q19 or Q20 or Q21] We want to reiterate there is a chance that you will feel sick or nauseous if you choose to continue in the research.
- □ I understand and choose to continue (1)
- □ I understand and choose not to continue (2)

Q23: Track Layout (Researcher will select)
- ☐ 643152 (1)
- ☐ 153624 (2)
- ☐ 346521 (3)
- ☐ 451236 (4)
- ☐ 254361 (5)
- ☐ 513264 (6)

It is now time for the driving simulator portion. Please do not press next until instructed to do so.

Appendix C: Post Drive Survey

Q24: Could the eye tracker be calibrated?

☐ Yes (1)
☐ No (2)

Q25: In the test grid, did the subject experience simulator sickness at any time during the experiment?

☐ Yes (1)
☐ No (2)

Q26: In the first grid, did the subject experience simulator sickness at any time during the experiment?

☐ Yes (1)
☐ No (2)

Q27: In the second grid, did the subject experience simulator sickness at any time during the experiment?

☐ Yes (1)
☐ No (2)

Q28: In the third grid, did the subject experience simulator sickness at any time during the experiment?

☐ Yes (1)
☐ No (2)

Q29: In the fourth grid, did the subject experience simulator sickness at any time during the experiment?

☐ Yes (1)
☐ No (2)

Q30: In the fifth grid, did the subject experience simulator sickness at any time during the experiment?

☐ Yes (1)
☐ No (2)

Q31: In the sixth grid, did the subject experience simulator sickness at any time during the experiment?

☐ Yes (1)
☐ No (2)

Q32: Is easy or difficult to make your decision at onset of circular yellow indication when being followed by another car?

☐ Easy (1)
☐ Difficult (2)

Q33: Does the type of vehicle following you at the onset of the circular yellow indication influence your stop/go decision making in any way?

☐ Yes (1)
☐ No (2)

If No Is Selected, Then Skip the Next Question

Q34: which the type of vehicle following could influence on your stop/go decision making at the onset of the circular yellow indication?

☐ Passenger Car (1)
☐ Heavy Vehicle (2)

Q35: Does the time difference between your vehicle and the vehicle following you at the onset of the circular yellow indication influence your stop/go decision making?

☐ Yes (1)
☐ No (2)

If No Is Selected, Then Skip the Next Question

Q36: What is the headway threshold that causes your leading vehicle to proceed through the intersection at the onset of the circular yellow indication when being followed by another vehicle?

☐ 0.5 second (1)
☐ 1.0 second (2)
☐ 2.0 second (3)

Q37: Does an incorrect decision of vehicle following you at the onset of the circular yellow indication could enforce you to make wrong decision to stop/go in any way?

☐ Yes (1)
☐ No (2)
☐ Maybe (3)

Q38: Does the visual attention have any effect on your decision to go through intersection or stop before stop line when being followed during the onset of the circular yellow indication?

☐ Yes (1)

☐ No (2)

Thank you for participating in this experiment! Please wait for instruction before clicking next.

Appendix D: Driving Scenarios and Participant Demographics

Table 2 Driving Scenarios

Experimental Scenario #	Time Headway	Following Vehicle Type	Time To Stop Line
		Grid 1	
1	2	PC	2.5
2	2	PC	3.5
3	2	PC	4.5
4	2	PC	5.5
		Grid 2	
5	0.5	PC	5.5
6	0.5	PC	4.5
7	0.5	PC	3.5
8	0.5	PC	2.5
		Grid 3	
9	1	PC	3.5
10	1	PC	4.5
11	1	PC	2.5
12	1	PC	5.5
		Grid 4	
13	2	HV	2.5
14	2	HV	3.5
15	2	HV	4.5
16	2	HV	5.5
		Grid 5	
17	0.5	HV	5.5
18	0.5	HV	4.5
19	0.5	HV	3.5
20	0.5	HV	2.5
		Grid 6	
21	1	HV	3.5
22	1	HV	4.5
23	1	HV	2.5
24	1	HV	5.5

Table 3 Participant Demographics

How many years have you been a licensed driver?		
Possible Responses	Number of Participants	Percent of Participants
1-5	17	32%
6-10	16	30%
11-15	7	13%
16-20	5	10%
More than 20 years	8	15%
How many miles did you drive last year?		
Possible Responses	Number of Participants	Percent of Participants
0 - 5,000 miles	15	28%
5,000 - 10,000 miles	16	30%
10,000 - 15,000 miles	12	23%
15,000 - 20,000 miles	8	15%
More than 20,000 miles	2	4%
How often do you drive in a week?		
Possible Responses	Number of Participants	Percent of Participants
1 time per week	10	19%
2 - 4 times per week	8	15%
5 - 10 times per week	20	38%
More than 10 times per week	15	28%
What is the highest level of education you have completed?		
Possible Responses	Number of Participants	Percent of Participants
Some high school or less	1	2%
High school diploma or GED	3	6%
Some college	21	39%
Four-year degree	10	19%
Master's Degree	17	32%
PhD Degree	1	2%
What type of motor vehicle do you typically drive?		
Possible Responses	Number of Participants	Percent of Participants
Passenger Car	33	61%
Pickup Truck	5	10%
SUV	10	19%
Van	5	10%
Gender		
Possible Responses	Number of Participants	Percent of Participants
Male	30	57%
Female	23	43%
Age		
Minimum	Average	Maximum
18	31.21	70