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Title: Safety and Efficiency Benefits of Traffic Signal Countdown Timers: A Driving Simulator Study.

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Traffic signal countdown timers (TSCT) are innovative, practical and cost effective technologies with the potential to improve efficiency and safety at signalized intersections. The purpose of these devices is to assist motorists in decision making at signalized intersections with real time signal change information. While successful implementation of these devices is observed internationally, the Manual on Uniform Traffic Control Devices (MUTCD) prohibits the use of TSCT. This research explores the impacts of countdown timers on US drivers; a novel effort not yet conducted.

The research methodology includes two experimental media: an online survey, and the driving simulator study. The online survey focuses on driver comprehension of and preferences towards TSCT, whereas the simulator study records driver response to virtual TSCT. The online survey resulted in an overall comprehension rate of 82%, which is reasonably close to the ANSI Z535.3 standard threshold for traffic control devices. The driving simulator study identified benefits regarding

safety and efficiency. The presence of red signal countdown timers resulted in 0.72 seconds reduction in the first headway. In presence of green signal countdown timers, driver’s probability to stop at the onset of the circular yellow indication in dilemma zones increases by approximately 13%. These results are suggestive of an improvement in intersection performance, and with proper field validation, the application of TSCT may well be recommended at signalized intersections in Oregon.

Safety and Efficiency Benefits of Traffic Signal Countdown Timers: A Driving Simulator Study

by
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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.

Mohammad Rabiul Islam, Author

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ACRONYMS AND ABBREVIATIONS IN THIS DISSERTATION

AASHTO	American Association of State Highway & Transportation Officials
AIC	Akaike Information Criterion
ANSI	American National Standards Institute
CG	Circular Green
DZ	Dilemma Zone
FDW	Flashing Don't Walk
FHA	Federal Highway Administration
FL	Fuzzy Logic
FYA	Flashing Yellow Arrow
GSCT	Green Signal Countdown Timers
MUTCD	Manual on Uniform Traffic Control Devices
PCT	Pedestrian Countdown Timers
PRT	Perception Reaction Time
RLR	Red Light Running
RSCT	Red Signal Countdown Timers
SDW	Steady Don't Walk
SW	Steady Walk
TCD	Traffic Control Devices
TSCT	Traffic Signal Countdown Timers
VCT	Vehicle Countdown Timers
YSCT	Yellow Signal Countdown Timers

Chapter 1 Introduction

Signalized intersections are important elements of urban road networks, and their efficiency and safety significantly impact the performance of the entire roadway network. Thus, the application of innovative approaches to manage traffic at signalized intersections with a reasonable level of safety and efficiency is crucial. Traffic signal countdown timers (TSCT) are innovative, practical, and cost effective technology that has the potential to resolve certain operational issues at the signalized intersection. These devices can be used in conjunction with a variety of traffic signal indications. The purpose of using these devices is to provide the driving public with specific information regarding a pending change in traffic signal indication, i.e., change in right of way, at the intersection. Previous literature has suggested the operational and safety enhancement resulting from the use of TSCT at signalized intersections (Limanond et al., 2010; Sharma et al., 2009; Chen et al., 2009; Kidwai et al., 2005). However, these findings come almost entirely from international sources as such devices are not currently permissible by the Manual on Uniform Traffic Control Devices (MUTCD). This research focuses on improving our understanding of the benefits at signalized intersections for drivers in Oregon.

1.1. TSCT Background

TSCT are clocks that digitally display the time remaining for an active traffic signal indication. When implemented for a circular red indication, countdown timers (CT) alert the motorists to the forthcoming change from red to green. When used for a circular green indication, a CT serves as a warning of the imminent termination of the right of way. As shown in Figure 1.1, the countdown timer indicates that the green phase will be continued for the next 53 seconds before turning to yellow. It provides drivers with real time information to potentially improve driver decision making and vehicle control.

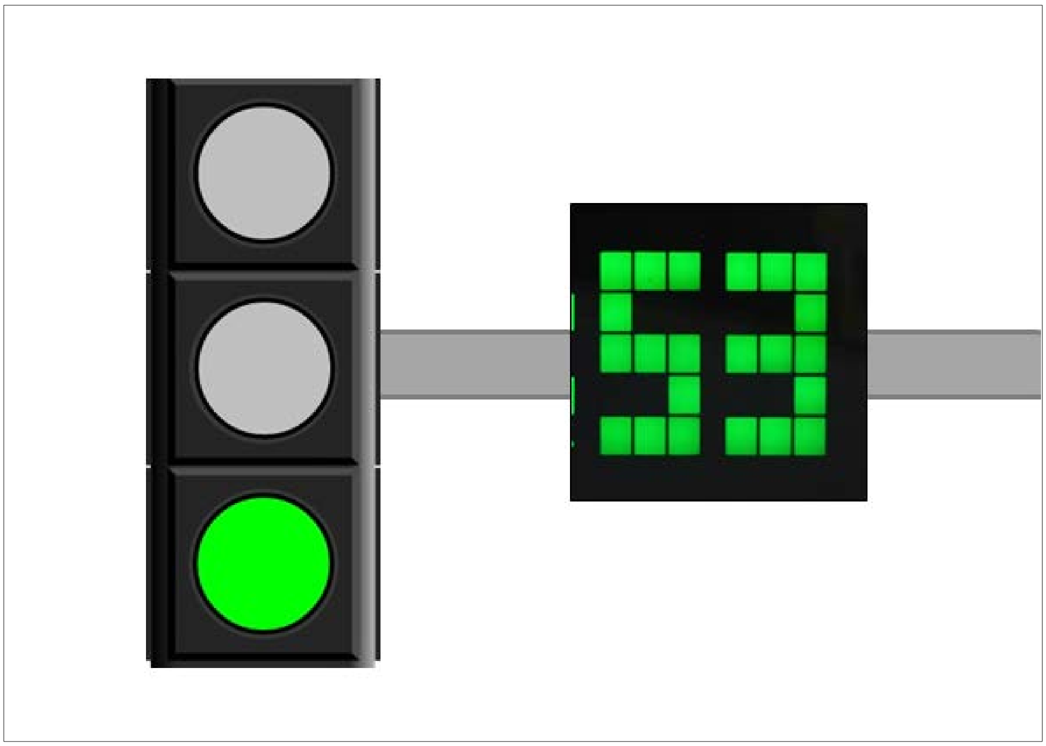


Figure 1.1: Example Green Signal Countdown Timer

Although, CT are yet to be deployed in the US for vehicular phases, they have been widely applied for pedestrian walk phases (Figure 1.2) for many years (Pulugurtha et al., 2010; Bundy and Schrock, 2007; Huey and Ragland 2007). The MUTCD approved the use of pedestrian countdown timers (PCT) in 2003. Due to the dramatically positive results reported on pedestrian safety and operations, PCT were mandated for all future installation of pedestrian signals (MUTCD, 2009).

Due to the operational similarities, TSCT are also expected to bring similar results for vehicular traffic, and the prime objective of this research is to evaluate the performance of TSCT. However, with currently available vehicle detection techniques, the application of traditional TSCT is limited to intersections operating under pre-timed control. Thus, the scope of the research is limited to pre-timed signals. This does not necessarily mean that the application of TSCT is seriously limited in context of the traffic control in the US. There is a significant amount of intersections that run under pre-timed control. Of the 311,000 signalized intersections in the US, approximately 58% are pre-timed signals (ITE, 2012).

The current state of the intersection operation in the US suggests urgent need for improvement. The overall score from National Traffic Signal Report Card (2011) was 69 (equivalent to a D+ letter grade), with Signal Operation and Timing Practices receiving 72 and 77, respectively. The need for improvement exists both in efficiency and safety, and TSCT is potentially an effective solution to many existing issues. For example, Limanond et al. (2009 and 2010) reported 1.00–1.92 seconds reduction in the start-up lost time per cycle, which is equivalent to a time savings of 17–32% and an increase in capacity of approximately 8–24 vehicles per hour. In addition, the use of green signal countdown timers (GSCT) will potentially reduce the dilemma zone (DZ) conflict at the onset of the yellow indication. DZ conflicts is responsible for many right-angle (from red light running, RLR) and rear-end (from sudden brake) crashes at the signalized intersections. In

2005, the National Highway Traffic Safety Administration (NHTSA) reported 805 fatalities resulting from RLR (FHWA, 2010).

Yellow signal countdown timers (YSCT) were not included in the research scope as the potential benefit (reductions in red-light-running) have only has been shown to be negligible in previous research (Long et at., 2011).

Figure 1.2: Example Pedestrian Countdown Timer

1.2. Anticipated Benefits

CT are a promising signal control application with potential to yield operational benefits at pre-timed signalized intersections. The hypothetical benefits of TSCT can be classified into two groups: efficiency benefits, and safety benefits.

1.2.1. Efficiency Enhancements

The anticipated efficiency benefit of RSCT is the potential reduction in startup lost time. Startup lost time is the incremental increase in time taken by the first four to five drivers waiting at the red indication to react to the signal change (from red to green) and accelerated up to the saturation flow rate. It is the resultant sum of the reaction time, vehicle acceleration, and any delay caused by distraction. One negative of conventional signal systems is that the lost time can lead to capacity reduction. By displaying the remaining red time, CT alert the driver for prompt reaction, resulting in the reduction of start-up lost time.

1.2.2. Safety Enhancements

The expected safety benefits of GSCT include reduced dilemma zone conflicts and reduced red light running (RLR). In many conventional signal locations, the transition time from green to yellow indication is difficult for drivers to predict. It can cause drivers to get caught in the dilemma zone where the likelihood of making judgment errors is significantly higher. Therefore, by providing the warning about the onset of the transition point, CT can improve intersection safety and reduce the number of rear-end and right-angle crashes.

1.3. Organization of this Dissertation

Chapter 1 of this dissertation presents a general introduction to TSCT and a discussion on the background of this work. Chapter 2 presents a discussion on the available literature relevant to this research, which forms the basis for the research questions of interest. This work includes an online survey to gain insight on drivers' comprehension and preferences toward TSCT. A detailed analysis of the survey responses are presented in Chapter 3.

The main research questions of this dissertation work were addressed by two driving simulator experiments; one for RSCT and another for GSCT. The design of experiments, subject recruitment for the simulator tests, data collection and analysis procedures, and the results were presented in Chapter 4. Finally, in Chapter 5, the findings of this work were summarized.

Chapter 2 Literature Review

The literature review encompasses topics central to the consideration of safety and efficiency benefits achieved by the application of Traffic Signal Countdown Timers (TSCT) to vehicular movements at signalized intersections. The state-of-the-practice regarding TSCT in the US and internationally is examined to provide context. It is important to understand driver comprehension for various TSCT if they are to be implemented successfully. It is also critical to understand the potential safety concerns that can also arise from TSCT. A comprehensive review of the benefits and costs experienced predominantly by other countries who have widely implemented TSCT, was also performed.

The logical progression of the discussions presented in this chapter begins with a definition of the related terminologies in Section 2.1. A brief overview of the state of the practice regarding the Countdown Timers (CT) is given in Section 2.2, which is followed by a number of case studies of the application of PCT and TSCT in the US and internationally in Section 2.3 through 2.6. The available literature on potential benefits and risks of implementing TSCT in terms of intersection safety and efficiency are explained in the following two sections, Section 2.7 and 2.8. The next section of the chapter, Section 2.9, synthesizes the studies that attempted to understand driver comprehension of TSCT. The chapter concludes with a summary that identifies the gap in the knowledge and a list of suggested research works that need to be done in Section 2.10.

2.1. Related Traffic Engineering Terminologies

It is important to discuss several traffic engineering terms and concepts pertaining to the concept of CT. Although this section may not be comprehensive, it should serve to provide a working knowledge of the terms being used through the rest of this document.

2.1.1. Headway

Headways can be defined in two different ways, one based on time and the other based on distance. The term headway refers to the time headway, in the context of this document. It can be defined as the time elapsed between two successive vehicles to pass a given point on the roadway. A special case of headway, called the "first headway", exists at signalized intersections. Because there is no vehicle in directly front of the first vehicle in a standing queue on a red indication, the headway of the first vehicle (i.e., first headway) is defined as the time lapse between the onset of the green indication and the time when the front axle of the vehicle passes the stop line (Roess et al., 2011). A detailed definition of the first headway is given in Chapter 4.

2.1.2. Perception Reaction Time

Driver are given a set of tasks when presented with new information. These tasks include detection of the event, processing the information, making a decision to respond, and initiating the chosen reaction, and in combined these tasks are called perception-reaction process (Roess et al., 2011). The time it process takes to complete this process is known as the perception-reaction time (PRT). Driver's PRT at the onset of green indication is of particular interest in this study.

2.1.3. Start-Up Lost Time

It is defined as the sum of the extra time required over the minimum headway (at saturation flow) at the beginning of green indication and signalized intersection. The Traffic Signal Timing Manual defines start-up lost time as:

"The additional time, in seconds, consumed by the first few vehicles in a queue at a signalized intersection above and beyond the saturation headway due to the need to react to the initiation of the green phase and to accelerate to a steady flow condition (Koonce et al. 2008)."

2.1.3. Dilemma Zones

Dilemma zones (DZ) are the areas upstream of a signalized intersection where drivers have difficulty deciding whether to stop or go through when presented with yellow indication. Depending on how they are produced at signalized intersections, DZ are classified into two categories: Type I and Type II. Type I DZ results from the inadequate design parameters (Gazis, et al., 1960), whereas Type II DZ results purely from driver's indecision to stop or go through the intersection (Zeeger and Deen, 1978). For the context of this research, dilemma zone refer to the Type II DZ.

2.2. State of the Current Practice Regarding CT

Currently, the application of CT in the US is limited to pedestrian signals, where they have been widely embraced. Pedestrian Countdown Timers (PCT) are used to notify a pedestrian, who is crossing or about to cross the road, how much time is remaining duration of the Flashing Don't Walk (FWD) phase. The Federal Highway Administration (FHWA) approved the use of PCT in the 2003 version of

Manual on Uniform Traffic Control Devices (MUTCD): "*A pedestrian interval countdown display may be added to a pedestrian signal head in order to inform pedestrians of the number of seconds remaining in the pedestrian change interval* (MUTCD, 2003)." Many state and local agencies throughout the US have adopted PCT for the pedestrian signals since then. The widespread implementation of PCT across the nation was guaranteed in 2009 when MUTCD enforced the use of PCT in all new pedestrian signals with a Pedestrian Clearance Interval (i.e., the FDW phase) longer than 7 seconds due to the dramatically positive effects on pedestrian safety observed at signalized intersections (MUTCD, 2009). According to the 2009 version of MUTCD: *"All pedestrian signal heads used at crosswalks where the pedestrian change interval is more than 7 seconds shall include a pedestrian change interval countdown display in order to inform pedestrians of the number of seconds remaining in the pedestrian change interval."*

For vehicular traffic at signalized intersection, traditional signal displays of a standard color (e.g., red, green, and yellow) have been used in the US since their first implementation in the early twentieth century. In November 1935, the first edition of the MUTCD was accepted as the standard for Traffic Control Devices (TCD) (FHWA, 2008). Since then, vehicular traffic signals have undergone numerous modifications such as the inclusion of turn arrows, flashing yellow indications, and flashing red for four way stop control. However, TSCT have not yet been approved for implementation in the US (Chen et al., 2009). Therefore, the potential benefits and costs of TSCT are still unknown to transportation professionals.

2.3. What is TSCT?

TSCT are clocks that digitally display the time remaining for a particular signal indication, i.e., red, yellow, or green. They provide drivers with real time information to potentially improve driver decision making and vehicle control. Frame 1 of Figure 2.1 shows CT for red signal which inform the drivers at a signalized intersection waiting for the right-of-way, i.e., green signal, that the signal will turn green from red in 10 seconds. This information makes the driver alert of an oncoming green signal and reduces the time lost at the beginning of the green due to driver reaction time. Frame 2 of Figure 2.1 shows CT for green signal which inform drivers approaching an intersection and going through, have 35 seconds of green time to cross the intersection before the signal turns yellow. Similar, display can be shown for a yellow signal as well. In both examples, TSCT were used with a five-cluster horizontal signal head. However, there are numerous combinations of signal head and CT configurations, and selection of a certain type varies geographically.

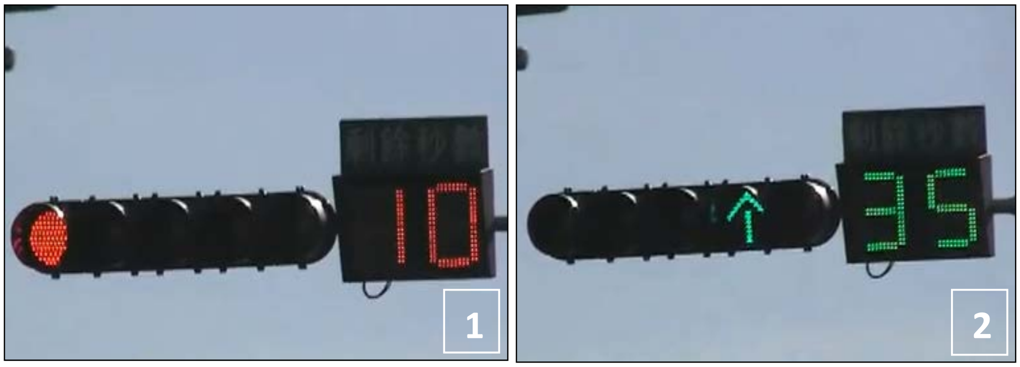
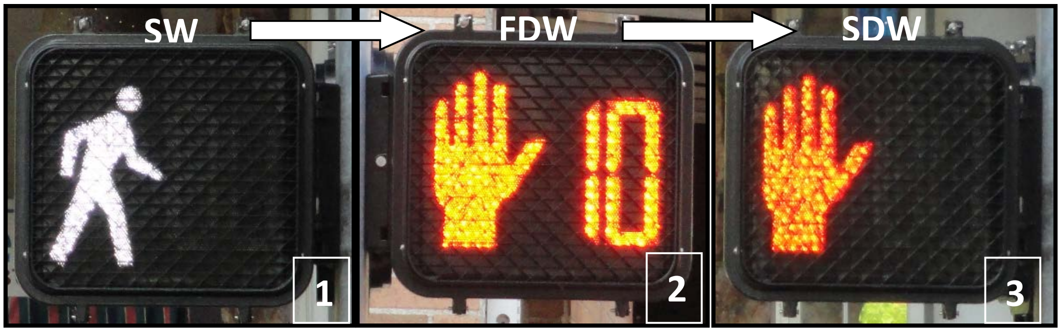


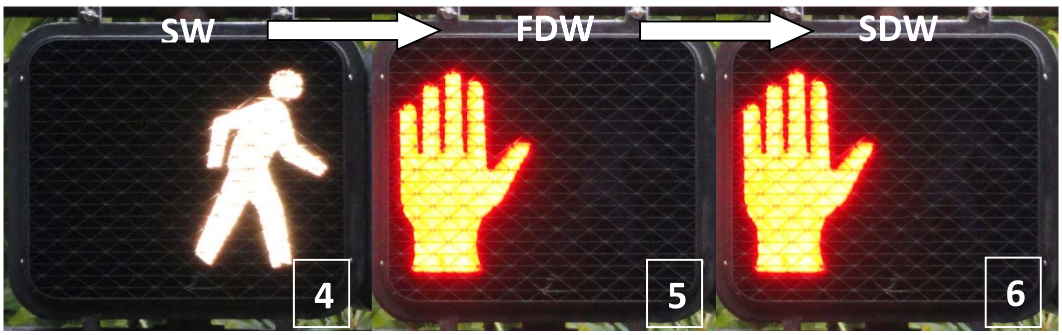
Figure 2.1: Countdown Timer for Red and Green Signal

2.4. Application of PCT in the US

Due to the change in pedestrian signal standard, PCT are overwhelmingly replacing traditional pedestrian signals with no timers at many urban signalized intersections in the US. PCT provide additional information about the pedestrian signals to both pedestrians and drivers. The intent of installing PCT is to enhance pedestrian understanding of the FDW interval by displaying the number of seconds remaining for the pedestrian change interval. The three different displays on the PCTs are illustrated in Figure 2.2(a), where frame-1 is the Steady Walk (SW) phase, frame-2 is the Flashing Don’t Walk (FDW) phase with the remaining time on it, and frame-3 is the Steady Don’t Walk (SDW) phase (MUTCD, 2009; Hawkins et al., 2007). The classic pedestrian signal indication sequence without a countdown timer is displayed in Figure 2.2(b). The most important distinction between the two types of pedestrian signals is the absence of a time display on the FDW phase for the classic pedestrian signals.



(a) Pedestrian Signal with Countdown Timer



(b) Traditional Pedestrian Signal

Figure 2.2: Displays on the Pedestrian Signals w/ and w/o CT

PCT monitor the time allocated to the pedestrian phases, i.e., SW and FDW indications, during the first cycle after installation and records the duration of the SW and FDW durations. The timer is not displayed during the first cycle, and the PCT operate normally from the subsequent cycles by counting down the SW and the FDW intervals. However, the timer is only displayed during the FDW and not during the SW indication. Most state supplements to the MUTCD, suggest that there should be no countdown displays during the walk interval of pedestrian signals (Hawkins et al., 2007). However, a survey conducted by Arhin, et al. (2011) at twenty-five intersections in District of Columbia suggests that the majority of the pedestrians and drivers prefer the countdown to begin at the onset of the SW instead of the FDW.

2.4.1. Implementation Experience: In Favor of the PCT

A myriad of studies with conflicting results regarding the effectiveness of PCT are offered in the literature. Some studies argue that these timers are actually costly or even counterproductive as they are likely to reduce pedestrian compliance and induce erratic crossing behaviors (Petraglia, 2004; Botha et al., 2002; Huang and Zeeger, et al., 2000). Conversely, the vast majority of studies suggest positive outcomes regarding pedestrian compliance and safety (Chester and Hamond, 1998; Schmitz, 2011; Schattler et al., 2007; Arhin and Noel, 2007; Eccles et al., 2003; Markowitz et al., 2006; Pulugartha and Nambisan, 2004; Mahach et al., 2002; and DKS Associates, 2001). These studies provided enough evidence that the benefits of PCT outweigh their costs, as such, the most recent version of the MUTCD (FHWA, 2009) dictates that in all new installation of pedestrian signals the PCT shall be used (MUTCD, 2009).

Available literature on PCT indicates that pedestrian signals with CTs can improve pedestrian behavior as compared to traditional pedestrian signals. Chester (1998) evaluated pedestrian understanding of countdown timers through field interviews among 50 randomly selected local citizens and visitors at one intersection in Orlando, Florida. The crosswalk selected for the study measured about 140 feet in length, traversed eight lanes of vehicular traffic, and the CT was applied for the entire SW and FDW indication. The result indicated that 88% of the pedestrians surveyed understood the functions of PCT. The observed comprehension level was high among local citizens and visitors, 91% and 81%, respectively.

A case study in Lincoln, Nebraska (Schmitz, 2011) on the effects of PCT on safety and efficiency detected little effect on safety at signalized intersection. However, a significant effect on pedestrian crossing efficiency was observed due to an increase in pedestrian walking speed. Contrary to the initial hypothesis, the vehicular efficiency decreased due to 1 mile/hour reduction in mean speed during the yellow change interval.

The performance of PCT was assessed by Schattler, et al. (2007) in terms of their effectiveness on both pedestrian and motorist behaviors at thirteen intersections in Peoria, Illinois. A before-and-after study at three intersections where PCT were installed and a comparative study between five test intersections with PCT and five control intersections with traditional pedestrian signals showed an improvement in pedestrian safety with the use of PCT based on the frequency of motorists' risk-taking behavior. The study also found that the countdown displays increased pedestrian compliance for both the FDW and the SDW phase of pedestrian signals.

Pedestrians' perception of safety and their crossing behavior at intersections with PCT was examined in the District of Columbia with a before-and-after study (Arhin, et al., 2007). The study showed that pedestrians overwhelmingly attribute their increased perception of safety to the existence of the countdown timers. PCT were recognized and understood effectively by the pedestrians, and no adverse effect on pedestrians' crossing behavior was observed. In addition, 80% of all the pedestrians surveyed at the seven intersections, were in favor of using countdown timers for pedestrian signals due to the additional information provided by PCT. Some participants found it confusing to have a countdown for only one of the three indications (i.e., the FDW). Eccles, et al. (2004) performed a similar study at five intersections in Montgomery County, Maryland. The effect of PCT on pedestrian and motorist behavior was observed and no evidence of a negative effect on pedestrian behavior was found based on the observation. The approach speed of the vehicles during the pedestrian clearance interval (FDW) was observed to have no change due to the presence of PCT. There was also a significant decrease in pedestrian-vehicle conflicts at all four intersections where the conflicts were observed. The study also included a pedestrian survey, which indicated a general understanding of the CT.

Markowitz et al. (2006) evaluated the potential impact of PCT to reduce pedestrian injuries as well as dangerous crossing behaviors. The study reported a positive influence of PCT on both driver and pedestrian behavior. The range of positive influence includes a reduction in pedestrian injuries, better understanding of pedestrian signals, and a reduction in the number of pedestrians finishing crossing on SDW. The authors reported that hypothetical concern for public complaints regarding insufficient crossing times and the use of the CT for the FDW did not materialize.

In 2004, Pulugurtha evaluated the effectiveness of PCT at fourteen intersections in the downtown area of Las Vegas, Nevada. PCT were implemented for the FDW phase at ten intersections, while the other four intersections were equipped with traditional pedestrian signals. Video data was collected to determine pedestrian compliance with the signals, pedestrian–vehicle conflicts, and pedestrians trapped in the crosswalk at the end of the FDW. Even though the PCT were applied only to the FDW phase, the results of the study showed improved pedestrian compliance for all phases of pedestrian signals; 29% (SW), 75% (FDW), and 11% (SDW). The study also reported about 7% reduction in pedestrian-vehicle conflicts at the intersections with PCT compared to the intersections with traditional signal displays. The researchers also conducted a field survey which indicated that over 90% of the pedestrians understood the functions of PCT and the FDW indications.

Pedestrian signal preference between traditional pedestrian signals and PCT was compared by Mahach, et al., (2002) and it was observed that about 60% of the pedestrians favored PCT. DKS Associates' (2001) study on pedestrian satisfaction in San Francisco with traffic control devices revealed overwhelming approval of PCT among the pedestrians over the traditional pedestrian signals. When asked whether the pedestrian signals were "very helpful" or not, 34% pedestrians answered in favor with conventional signals, but the number increased to 78% when the intersection had PCT. About 92% of post-installation interviewees expressed their preference for PCT over traditional pedestrian signals in the same study.

2.4.2. Implementation Experience: Against the PCT

Although, most research on the effectiveness of PCT suggested increased pedestrian compliance and improvement in pedestrian safety over traditional pedestrian signals, several studies tend to overshadow the benefits of PCT with conflicting and consistent results.

In 2004, Petraglia conducted a study on PCT at three intersections in Boston, Massachusetts. Similar to the practice in the District in Columbia, the CT were displayed for both the SW and the FDW intervals. A before-and-after study was conducted by comparing the number of pedestrians starting to cross the street during the SW and FDW intervals, the number of pedestrians completing their crossing during the DW interval, and the number of pedestrians running or in conflict with vehicular traffic. No significant improvement in pedestrian safety due to the use of PCT was found, rather there were statistically significant increase in the number of pedestrians finishing crossing on SDW phase in two out of three sites.

Botha (2002), conducted a before-and-after study at 5 intersections in San Jose, California to evaluate the performance of PCT with the countdown starting at the beginning of the FDW. The effectiveness of PCT were measured by the proportions of pedestrians arriving during the FDW and waiting for the SW interval before starting to cross the street, the proportion of pedestrians entering the cross walk during the SW, FDW and DW intervals, and those running or hesitating while crossing the road. A frequency analysis of the data collected from all five intersections suggested that differences in performance before and after the implementation of PCT were not significant. The researchers also conducted a survey which revealed that approximately 59% of pedestrians incorrectly interpreted the FDW phase. Although a decrease in the frequency of pedestrian-vehicle conflicts was observed, no discernible effect was reported due to the application of PCT.

In an observational study of the effectiveness of PCT at five intersections in Lake Buena Vista, Florida, Huang and Zegeer (2000) found results contrary to their expectations. In the study, two treatment intersections were observed where countdown began at the onset of SW phase. After analyzing the data observed from a single crosswalk at each intersection, researchers found that the pedestrians were more likely to begin crossing during the FDW phase rather than wait for the SW phase in the next cycle. 47% of pedestrians were observed to begin crossing during the SW phase at the PCT locations, compared to 59% of the traditional signal locations. Additionally, about 3% more pedestrians were found at the PCT locations to be unable to complete their crossing before the SDW phase than those with traditional signals.

2.4.3. Driver Response to PCT

PCT display the remaining time available for different pedestrian signal indications, which are intended to assist pedestrians in making better decisions about when to begin crossing, and at what speed. The overarching expectation is that this additional information will improve pedestrians' crossing behavior, and thus, the safety at signalized intersections. However, this information is also available to motorists, and will likely influence their behavior as well (MTC, Oakland, CA, 2007). The concern is that as the approaching drivers see the PCT, they may drive more aggressively, increasing speeds to clear the intersection before the onset of the red indication, adversely effecting safety. As a result, studies considering driver behavior, attempted to address the potential negative impacts and overlooked the possibility that PCT may have positive effects on motorists as well. For instance, Markowitz, et al., (2006) concluded that PCT have negligible effect on driver behavior. Even though the results showed a 1% to 2% reduction in Red Light Running (RLR), the authors attributed the reduction to increased speeds motivated by avoiding the red phase.

One of the most recent studies on driver response to PCT (Nambisan and Karkee, 2010) indicated that the drivers tend to increase their speed during the FDW interval of pedestrian signals in presence of CT. Researchers observed speeds of the vehicle in spatial and temporal proximity to intersections with PCT, and found that the mean speed was higher on the segment closer to the stop line (within 100 feet of stop line) compared to the segment farther upstream of the intersection (between 100 and 200 feet from the stop line). In addition, the results of the study clearly showed that the speeds during the SW phase of the pedestrian signal were significantly lower than those during the FDW phase, as CT were applied only with the FDW display. The findings of the research support the hypothesis that PCT displays affect driver behavior, at least in terms of their speed choices in close proximity to the intersection.

Huey and Ragland (2007) conducted similar study on driver behavior, and concluded that the type of the pedestrian signals used (e.g., traditional or PCT), influence driver behavior at the intersection. Drivers were found to increase their speed by using the information on the countdown displays to cross the intersection during the FDW. The results also found a significantly higher number of drivers in traditional intersections, as the yellow expires. Depending on the yellow law of the jurisdiction, this behavior may have potential adverse effects on safety. However, this benefit of CT was undermined by the fact that vehicles at intersections with PCT generally entered the intersections with higher speeds. Therefore, the implication of the results on overall intersection safety was unclear. Furthermore, drivers exhibited different stopping behavior, i.e., braking habits, at the two intersections based on the information available to them.

A similar study, conducted by Bundy and Shrock (2007), dispelled the notion that PCT induce aggressiveness among drivers. Compared to conventional intersections, drivers were found to drive less aggressively at intersections with PCT on the same corridor, and a significantly smaller proportion of drivers were found to increase their speeds while approaching an intersection with a PCT than at a traditional intersection. The results suggested two important findings: first, drivers use the information from the PCT in their decision making process near the intersection even though the information is not intended to be used by them; second, drivers use the information from the PCT to make better decisions in terms of proceeding through or stopping at the intersection, rather than being aggressive.

2.5. Application of TSCT in the US

For many drivers, the yellow change interval is perceived as challenge rather than a warning, therefore, they tend to try to beat the signal rather than slowing down, which is a risky behavior and often the cause for serious injury crashes at intersections. One of the many innovative solutions to address RLR at signalized intersections is to implement a CT for the yellow change interval (Kidwai et al., 2005).

The technique was tested for implementation in Abilene, Texas in 1965, which is known to be the first study conducted on countdown devices for vehicular traffic signals in the US (Times Magazine, 1966). The VCTs were applied at a busy intersection where traffic crashes were reported to decrease about 44% during the eight month test period. The CT, displayed in 10-in.-high numerals, was visible for 200 ft. It was set to start nine seconds before the beginning of the yellow change interval and lasted three more seconds for the entire duration of the yellow change interval. As explained by the Abilene City Traffic Engineer Russell Taylor, after noticing the timer, motorists slowed down instead of accelerating through the intersection, which was contrary to his expectations. As a result of the positive outcome, Abilene planned to installed three more TSCT, Houston planned to install 73, and 19 foreign countries also expressed their interest regarding TSCT.

However, the research on TSCT did not continue to progress like PCT, and US drivers have not been tested with the technology since. As such, the benefits of TSCT are yet to be uncovered and have not been included in the MUTCD as of today, whereas PCT are the default standard for pedestrian signals in the US (FHWA, MUTCD 2009).

One possible explanation for the limited application of TSCT in the US is the prevalence of actuated traffic control. Unlike fixed-time traffic control, actuated traffic control responds to traffic demand at the intersection and distributes the green time accordingly. Because of the uncertainty in vehicular movements the duration of indications, specifically the red and green cannot be predetermined. Therefore, in a given cycle, the traffic controller does not have the information on how long the red or the green signal would be for a certain traffic movement, because the state of the timing parameters is depended on calls from the detectors on the active and conflicting phases. Nonetheless, a sizeable portion of all signalized intersections in the US, 272,000 in 2008 (FHWA, 2013), have fixed-time signal, as such, application of TSCT has great potential for those fixed-time signals and for the predictable yellow change intervals of actuated signals.

Figure 2.3 illustrates the concept of operations for a TSCT. “The countdown time display panel is under the control of a countdown controller that runs in step with the signal controller. When a signal is counting down for a specific phase, the countdown control system shows the remaining time for that phase (Chen et al., 2009)".

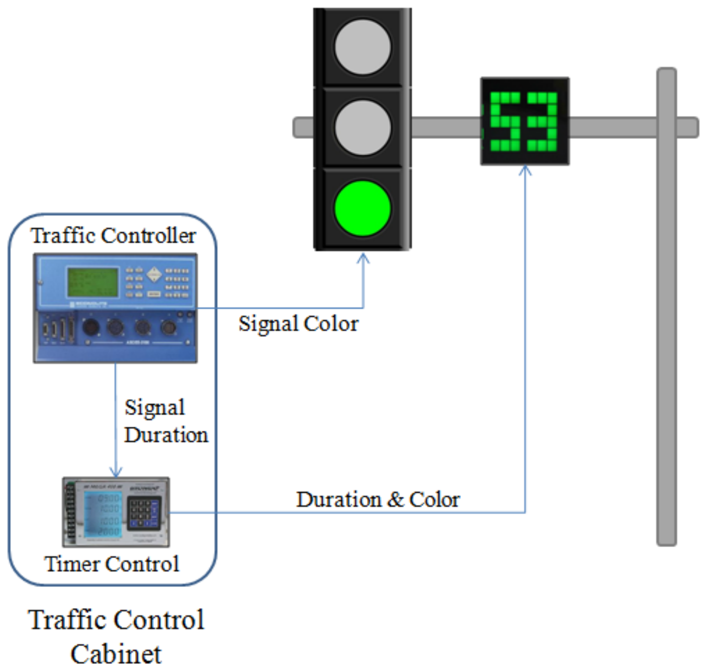


Figure 2.3: Connections between Signal and Countdown Controller

As illustrated in Figure 2.3, signal controller feeds the countdown device control with signal duration information, which then displays the information in the form of a countdown timer. Since its first application in Baltimore, Maryland in 1928, the actuated signal has received much attention among the traffic engineering community because of the gain in operational efficiency, and thus, they are more widely used than the fixed-time signals, especially in North America (Signalfan, 2013). The countdown device controller can only be installed with a fixed-time signal as the currently available technology cannot predict the duration of green and red signals in an actuated signal. This condition greatly restricts the installation of TSCT with an actuated signal. Although, real time countdown in actuated signal may become possible with wide area detection, with the use of predominantly in-pavement detectors it is nearly impossible.

In addition to the limitations posed by the technology, the absence of TSCT in the US can also be attributed to the lack of research on the performance and drivers' perception of TSCT. Even though many foreign countries have been using this technique to boost the safety and efficiency of signalized intersections (Chen et al., 2009; Kidwai, 2005), conflicting results on the performance of TSCT have appeared in the literature. Some studies found that the use of TSCT have potential detrimental effect on driver behavior in terms of speed choice and visual search pattern, and thus, are likely to deteriorate the safety at signalized intersections (Chiou and Chang, 2010; Ma et al., 2010; Kejun et al., 2011), whereas other studies found very encouraging results both in terms of safety and efficiency (Chen et al., 2009; Köll et al., 2004; Lum and Halim, 2006; Chen et al., 2007; Limanond et al., 2010). Due to a lack of understanding regarding how TSCT affect the behavior of US drivers, the 2009 MUTCD prohibits any display that gives warning of an upcoming signal change.

2.6. Application of TSCT: Internationally

Although countdown timers for traffic signals are yet to begin their journey in North America, many East Asian countries have successfully applied the technique. China, Malaysia, Singapore, Thailand, and India have deployed TSCT and have experienced both operational and safety benefits in terms of energy conservation, reduction in travel time and environmental pollution, improving efficiency, and reducing the likelihood of crashes (Kidwai, 2005; Köll et al., 2004). In addition to the observed benefits in safety and efficiency, drivers of these countries highly favored the installation of TSCT at signalized intersection (Limanond et al., 2009). TSCT have also been used in Russia, Turkey, and some other European countries. Many different forms and configurations for the countdown have been observed. CT can be applied for all three signal indications (red, yellow, and green). However, CT for the red and the green signals are the most commonplace. The reason why a CT for yellow signal is not frequently used is that unlike the red and the green signal, the duration of the yellow signal is predictable to the drivers. A flashing green light of varying duration at the end of the green phase is used in Cambodia, Israel, Mexico, Austria, Estonia, Latvia, Lithuania, Turkey, Russia, and in some other parts of Europe, to indicate that the yellow signal is imminent, especially on high speed roads (Köll et al., 2004). Austria introduced the flashing green at the end of the green phase in 1969 and finalized that in 1983:

"*The green light will end with four dark/green light sequences, where each of the dark and illuminated phases last half a second. Flashing green indicates the approaching end of the green light (Köll et al., 2004).*"

In many countries, such as Austria, Denmark, Germany, Iceland, Sweden, Poland, Switzerland, United Kingdom, Argentina, Columbia, Paraguay, Israel, Pakistan, and Hong Kong, the red and yellow signals are displayed together for a few seconds at the end of the red signal to inform the motorists that the signal indication is about to change from red to green. It helps to reduce what is called the start-up lost time at the beginning of the green phase by alerting the drivers about the oncoming green signal.

Urban signalized intersections in Asia are predominantly fixed-timed, which is why TSCT are so common place there. Therefore, the majority of field studies that constitute the available literature on the performance of the TSCT in terms of safety and efficiency were predominantly conducted in Asia. The results of the studies have varying outcomes, and can be categorized into two major areas of intersection performance: safety and efficiency.

2.7. Influence of TSCT on Intersection Safety

CT for the green indication, Green Signal Countdown Timers (GSCT), inform approaching drivers about the number of seconds of green remaining before the signal changes to yellow. This additional information improves approaching drivers' decision to stop or proceed through the intersection, which is expected to minimize dilemma zone issues at signalized intersection. Whereas, Yellow Signal Countdown Timers (YSCT) are expected to reduce RLR by providing drivers with the exact number of seconds left before the signal turns red. At best, the research examining the safety benefits of GSCT and YSCT is inconsistent.

2.7.1. TSCT Improve Intersection Safety

RLR is one of the predominant safety concerns at signalized intersections, which is expected to be reduced by the use of CT. In order to investigate this claim, Kidwai et al. (2005) observed drivers at two signalized intersections in Kuala Lumpur, Malaysia, one with and one without TSCT. Average RLR was found to be 37.1% with the CT and 66.2% at the traditional intersection. Although the number of RLR for both cases is alarming, using TSCT appeared to have merit in terms of reducing the red light running at signalized intersection.

Köll et al. (2004) investigated driver behavior while approaching a flashing green at 10 intersections in Switzerland, Austria, and Germany. Data were collected for nearly five thousand cycles. The frequency of drivers stopping at the intersection while 2–3 seconds away from the stop lines at the onset of flashing green were observed 70-80% in Austria, 35% in Switzerland, and 28% in Germany. This phenomenon is likely to minimize the safety impact of the dilemma zone by reducing the right-angle crashes. The tendency of drivers to underestimate the time at the end of the green indication was attributed to the early stops. However, the study showed that the speed and the distance from the stop line highly influence drivers' decision to stop at the intersection.

In a before-and-after study, Lum and Halim (2006) acknowledged that CT reduce the RLR at signalized intersections, however, they found that the effect lasted only for limited duration of time. The study was conducted in Singapore, where a 65% decrease in RLR was observed after one and half months of the installation of TSCT. Although, a continuous data collection effort revealed that after six months the frequency of RLR reached pre-installation levels. Chen et al. (2007) showed that if only Red Signal Countdown Timers (RSCT) are used, both the frequency of crashes and the number of injuries are likely to decrease by 50%.

A public opinion survey conducted by Limanond et al. (2010) on more than 300 local drivers in Bangkok familiar with TSCT found that the presence of CT would help reduce the number of RLR violations by about 50%. More than half of the survey participants also reported that CT would also help relieve the frustration while waiting on a red signal.

2.7.2. TSCT Deteriorate Intersection Safety

Contrary to expectations, many studies found that TSCT induce aggressive behavior among drivers, and as such, deteriorate intersection safety. A detailed study conducted by Chen et al. (2007) showed that TSCT had negative effects on intersection safety. CT were installed at 187 intersections in Taiwan and crash data was collected from 2003 to 2006. One of three CT configurations (GSCT, RSCT, or both GSCT and RSCT) were applied to each intersection. The intersections with green indication CT had twice the number of reported crashes, and a 33% increase in the number of injuries. Locations where CT were applied exclusively to red indications, a 50% reduction in both the total crashes and the number of injuries were reported. On the other hand, intersections with CT applied to both the red and the green indications, showed a 19% and 23% increase in reported crashes and injuries, respectively. In a similar study, Chiou et al. (2010) found that TSCTs made drivers' more aggressive, extended the dilemma zone by 28 meters, and increased the frequency of rear-end crashes at the termination of the green phase.

Ma et al. (2010) examined the performance of green indication CT in Shanghai, China. Compared to a traditional intersection, drivers crossed the stop line at an intersection with CT at higher speeds. Due to this unexpected phenomenon, green signal CT increased the likelihood of crashes at the onset of the yellow change interval with undetected vehicles or pedestrians.

Kejun, et al. (2011) examined the effects of CT on driver behavior during the yellow change interval at four urban signalized intersections in China. A strong correlation was found between the presence of TSCT and an increase in RLR violations. TSCT were found to influence the drivers to enter into the intersection during the later portions of the yellow and even the red. Further investigation was called for before the field deployment of TSCT at urban signalized intersections.

2.8. Improved Intersection Efficiency with TSCT

The effectiveness of TSCT to improve operational efficiency at signalized intersections is more clearly supported in the literature than the safety benefits. Most studies attempt to quantify the operational benefits of TSCT with the performance measures of delay and throughput. TSCT are generally expected to reduce vehicular delay at signalized intersections (Chiou and Chang, 2010; Limanond et al., 2010; Limanond et al., 2009; Sharma et al., 2009), and increase the capacity by more efficiently discharging the queue (Chiou and Chang, 2010; Limanond et al., 2010; Sharma et al., 2009; Ibrahim et al., 2008; Liu et al., 2012).

2.8.1. Reduction in Delay due to TSCT

RSCT alert drivers waiting for the red indication to turn green, and thus, are expected to reduce the start-up lost time of the standing queue. On the other hand, a combination of green and a yellow indication CT have the potential to reduce "clearance lost time" (i.e., unused portion of the change or clearance interval) by displaying the amount of time remaining before the signal changes to red, which could reduce the overall delay at the intersection.

Limanond et al. (2009) found that the RSCT in Bangkok slightly increased the capacity of the intersection by reducing the start-up lost time. Forty eight hours of data were collected at an intersection; 24 hours while the CT were active and 24 hours while the CT were inactive. The results of the study found that CT reduced the start-up lost by 1.00–1.92 seconds per cycle, equivalent to a time savings of 17–32%. This time savings represents an increase in capacity of approximately 8–24 vehicles per hour.

Further investigation by Limanond et al. (2010) found a 22% reduction in the start-up lost time at the beginning of the green phase. Chiou et al. (2010) also reported a similar reduction in the start-up lost time and saturated headway in presence of RSCT.

Sharma et al. (2009) investigated the effect of countdown timers on headway distribution in Chennai, India and found that TSCT effectively reduced both the start-up lost time and clearance lost time.

2.8.2. Increase in Throughput Attributed to TSCT

The discharge or departure headways of a traffic stream are usually highest at the beginning of green for the first few vehicles due to the perception reaction time (PRT) of the first few drivers. It is also assumed that the saturation headway will be reached by the fourth (HCM 2010) (HCM, 2010) or fifth (Roess et al., 2011) vehicle in the queue, and vehicles will continue to process at the saturation flow rate until the last vehicle of the queue is processed, as shown in Figure 2.4.

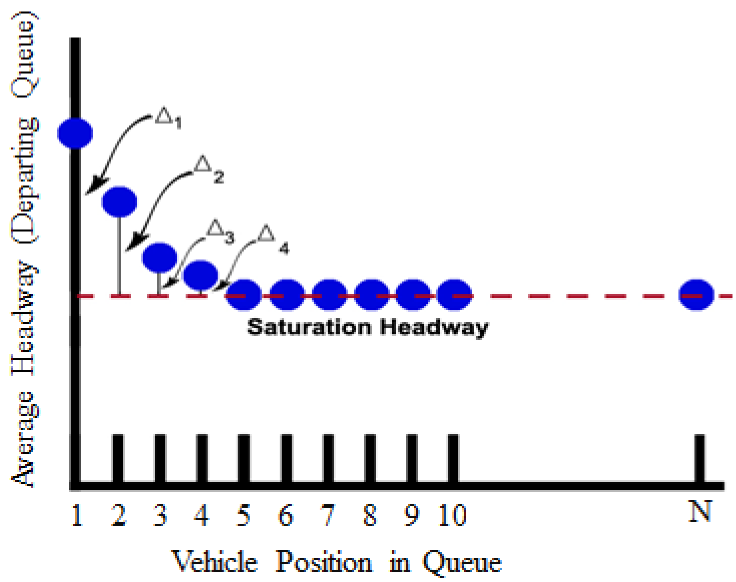


Figure 2.4: Departure or Discharge Headway and Start-up Lost Time (Roess et al., 2011)

RSCT are clearly visible to the first four or five vehicles in a standing queue waiting to respond to the green indication. Thus, headways between the vehicles responding to RSCT, as the queue starts moving at the end of the red indication, are expected to be lower than that of a traditional signal. This reduction in headways has the potential to increase capacity at signalized intersections. Chiou et al. (2010)

observed a reduced saturation headway in the presence of a red light CT compared to a traditional signal.

Ibrahim et al. (2008) performed a comparative study of the discharge patterns between signals with and without CT. The headway data collected from three intersections equipped with CT suggested that TSCT tend to reduce the discharge headways of the first six vehicles in the standing queue.

The queue discharge characteristics and headway distribution at signalized intersections with CT under heterogeneous traffic conditions in India were studied by Sharma et al. (2009). The analysis was carried out with data collected from two intersections, one with and one without CT. The headway distributions for locations with no CT were found to follow the accepted distribution as shown in Figure 2.3. In presence of TSCT, the gaps remained constant for green durations shorter than 21 seconds and started to decrease at a rate 0.02 gap-s/s for longer green duration exceeds 21 seconds.

A similar study was conducted by Liu et al. (2012) to evaluate the effects of TSCT on queue discharge characteristics at signalized intersections in China for protected left-turn and through movements. Data were collected from 13 approaches at seven signalized intersections. It was found that TSCT significantly affected the start-up lost time for both protected left-turn and through movements. The start-up lost times were reduced an average of 0.6 seconds per cycle for the protected left-turn and 2.25 seconds per cycle for the through movements. The reduction in start-up lost time for the left-turn movement was smaller than the through movement, because the drivers were already alert about the shorter green duration for left-turn movements at the selected sites. TSCT had little effect on the saturation headways for both movements. The study also reported an interesting phenomenon termed "headway compression" at the end of the green signal resulted from CT. Headways were observed to take a reduced value during the last 5 seconds of the green signal for protected left-turns. For the through movements, the phenomenon was observed to begin as early as 14 seconds before the end of the green indication.

Limanond et al. (2010) also found a similar reduction in headways resulting from TSCT for red signals. As shown in Figure 2.5, there is a significant reduction in the mean headway of the lead vehicle in the presence of CT. However, the saturation headway was reached at about the eighth vehicle in the queue for both situations, suggesting that the vehicle throughput was not affected by the use of TSCT.

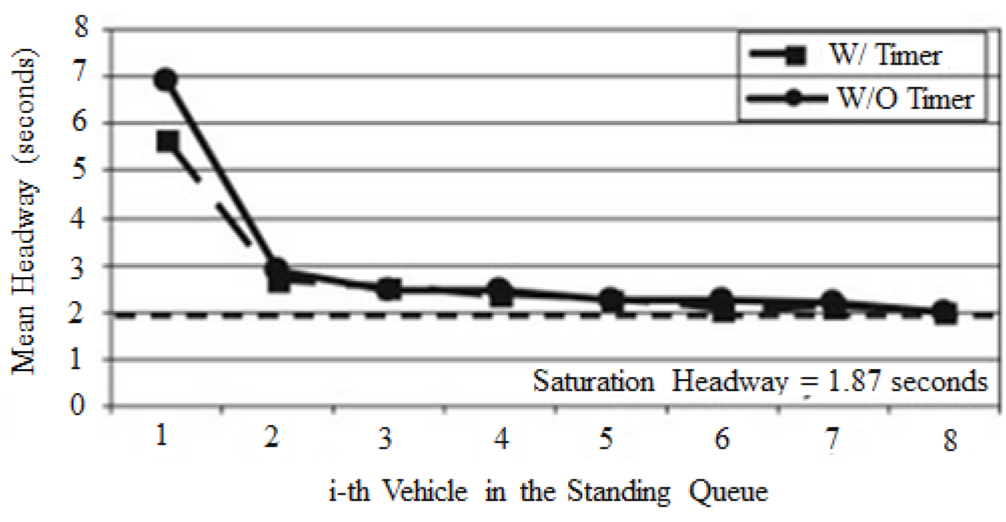


Figure 2.5: Headway Comparison of the First Few Vehicles (Limanond, 2010)

2.9. Driver Comprehension of TSCT

Users' understanding is the key to the successful deployment of any traffic control device. The introduction of a novel device therefore requires research to validate user behavior and comprehension. As indicated by the available literature on PCT, pedestrians and drivers, in general, have a very good understating of how the CT operates. The comprehension level of PCT in the US have been found to be very high (Arhin and noel, 2007; Pulugartha and Nambisan, 2004; Mahach et al., 2002). The fact that TSCT do not exist in North America, limits researchers ability to conduct field studies and understand driver comprehension and compliance to such devices. However, numerous studies suggest that the presence of PCT at signalized intersections in US are already influencing driver behavior (Nambisan and Karkee, 2010; Huey and Ragland, 2007; Bundy and Shrock, 2007).

2.9.1. Driving Simulator: Driver Behavior with TSCT

A driving simulator study has the merits of examining driver comprehension of TSCT in the absence of field deployment. Simulator based studies also provide the benefit of a safe and efficient data collection system, and offer more control over the test environment and associated variables. Driving simulator validation efforts for TSCT experiment will be discussed by considering the Dilemma Zone (DZ) and the Flashing Yellow Arrow (FYA) experiments as their evaluations depend on similar performance matrices, such as, driver Perception Reaction Time (PRT), speed, acceleration/deceleration profile, and visual search pattern.

Speed related research efforts concerned with the validation of simulators are of particular interest to TSCT modeling. Drivers were found to travel at slightly higher speeds in the simulator than the real world environment (Godley et al., 2002; Bella, 2008) due to the lower perceived risk. In an effort to determine the accuracy of driver perception of speed in both simulated and real world environment, Hurwitz and Knodler (2007) found that compared to the real world drivers consistently travelled about 5 miles/hour faster in the simulated environment. This result was consistent to other similar research performed by Godley et al. (2002) and Bella (2008), as such, the researchers concluded that driving simulator can be effectively utilized for speed-related research. Therefore, a driving simulator based study of drivers' speed choice at the intersection on different TSCT displays is expected to produce reliable results.

By using a driving simulator, Knodler et al. (2006) evaluated driver comprehension of pedestrian requirements at signalized intersections with FYA indication. The authors evaluated drivers understating of the Protected Permitted Left Turn (PPLT) maneuver on a FYA indication with 180 driving simulator responses, and suggested that drivers do not understand that they must yield to pedestrians. The outcome of this study suggests that driver comprehension of different TSCT displays can be studied as well through a simulator if the simulated environment is properly designed.

In 2003, Knodler et al. conducted another driving simulator based experiment to evaluate 12 experimental PPLT signal displays. The experiment followed by a questionnaire of the subjects. Two simulator labs located at the UMass Amherst and the Texas Transportation Institute (TTI) were used in the study. With a total of 432 participants split between the two simulators, it was found that the number of correct responses in the scenarios with FYA or Circular Green (CG)/FYA combination indications were greater than scenarios operating only on CG. The findings of the simulator experiments were later supported by the survey results. The outcome of this research not only supports the application of simulator to study driver perception of TSCT, rather it provides with a framework to validate the results from simulator experiments.

2.10. Summary

The existing literature reviewed in this chapter can be summarized into the following key findings that indicate the gaps in the body of knowledge related to TSCT:

- Extensive research on PCT has taken place in the US, which supported their nationwide implementation. Comparatively, TSCT have received significantly less attention, as such; their potential benefits remain obfuscated to the traffic engineering community. Studies on PCT showed that most road users in the US have high level of comprehension, and thus, the application of TSCT are expected to cause minimal driver confusion.
- Despite the fact that PCT are intended for the pedestrians' use only, it is apparent that the information displayed on PCT are frequently used by the

motorists at the signalized intersections. Therefore, to some extent, TSCT are not entirely non-existent in the US. In other words, drivers are using PCT as a form of TSCT. In addition, some studies found that the effect of PCT on the motorists positively impact safety and efficiency at signalized intersections. Therefore, the notion that the additional information from TSCT can overload driver's cognitive ability needs to be justified with evidence.

- Different studies performed around the world showed varied outcomes in terms of safety, efficiency, and the level of driver comprehension. This suggests that the outcomes resulting from the use of TSCT are sensitive to geographic location of the system users. In fact, the rate of traffic violations, RLR, and other aggressive driving behaviors are different in the US than in other parts of the world. Therefore, studying drivers in the US has the merit of uncovering the benefits of using TSCT at the signalized intersections.

Chapter 3 Static Survey

Traffic control devices are only considered successful if they illicit consistently correct responses from transportation system users. Therefore, a common approach before installing a novel sign, signal, or pavement marking is to conduct studies of user comprehension. One commonly applied technique is to perform a survey of the transportation user population of interest. This chapter presents the online survey study of driver comprehension of TSCT.

3.1. Research Scope

Most research on TSCT and PCT has examined the effectiveness of the systems through direct field observation and by conducting user surveys. As documented in Chapter 2, pedestrian comprehension and preference for the PCT was primarily investigated post field installation. When a critical mass of consistent research evidence was produced from around the US that the pedestrians have a high level of comprehension, and significant unanticipated consequences were not observed, PCT were endorsed by the MUTCD for national application (2009). The absence of TSCT in the US eliminates the possibility of conducting field surveys or direct observations of driver responses to these devices. As such, an online survey was undertaken as a first step towards understand driver comprehension and perceptions of TSCT. This chapter includes the rationale for, analyses of, and findings from the survey.

3.2. Research Questions and Objectives

The objective of the online survey was to establish a concrete base on Oregon drivers' comprehension and preference towards TSCT. The following TSCT research questions were developed to fill gaps in knowledge identified in the literature review and to guide the design of the follow-up driving simulator experiments:

- Is the information displayed on TSCT correctly comprehended by drivers?
- Do drivers think that TSCT will assist their decision making at signalized intersections?
- Which application of CT (GSCT, YSCT, or RSCT) do drivers think will be the most useful for their decision making at signalized intersection?
- Which countdown timer display is most easily understood by drivers?

These research questions were foundational to the design of the online survey.

3.3. Survey Design

A "cross-sectional study" (Shaughnessy, 2011) design was implemented for the survey. In a cross-sectional study, a sample is drawn from the relevant population and studied once. It describes the characteristics of a given population at one time and does not provide any insight as to the causes of the population characteristics.

The survey was coded in *Qualtrics* (Qualtrics Research Suite, Version [56395]), a web-based tool for building online surveys. The online survey was disseminated (through flyers with direct web link to the survey, and email list serves) to general public. A minimum sample of 100 responses with demographics representing those of Oregon Drivers was desired. Information on various TSCT and corresponding signal displays was presented in the form of static images.

The steps to construct the survey were chosen carefully to produce reliable and valid responses. Initially a list of the information desired from the survey was documented. Then, a first draft of the survey was developed. The survey was revised three times and was alpha and beta-tested before final dissemination.

3.3.1. Exclusion Criteria

The responses from the survey participants included in the final analysis were selected after applying the following exclusion criteria:

- Driver's License: Excluded if not licensed in Oregon
- Age: Excluded if below 18 years or above 78 years
- Color Blindness: Excluded if experienced color blindness

If the respondents self-reported as having met the exclusion criteria (e.g., not licensed in Oregon) they were thanked for their participation and the survey was terminated.

3.3.2. Question Type

The two most common survey question types are "free" and "closed" questions. Typically, free response questions are open-ended in nature and closed questions involve some form of multiple choice response. In this study, both question types were used.

Open-ended questions were chosen to examine driver comprehension of TSCT. Although, open-ended responses are often more difficult and time consuming to analyze, potentially requiring extensive coding and interpretation, they provide a greater flexibility to the responders by letting them explain their thinking more completely (Shaughnessy et al., 2012). Alternatively, closed questions can prohibit the expressivity and spontaneity of the responders. Further, alternatives presented in the questions may not accurately reflect respondents' views, resulting in the choice of a "less-than-preferred" response in many cases.

In their research on traffic sign comprehension, Wolff and Wogalter (1998) suggested that there are several concerns with multiple-choice questions:

- Even the participants who have no idea about the questions, have at least a 20% to 25% (for five or four choices) probability of guessing the correct answers.
- Open-ended questions provide opportunity to detect critical confusions, whereas, it is difficult to assess critical confusions with multiple-choice questions.
- Multiple-choice questions fail to realistically reflect actual cognitive tasks that people perform in the real world with pictorial symbols. In other words, open-ended questions are ecologically valid, multiple-choices are not.

Despite having the advantage of more realistic responses, open-ended questions may be disadvantageous for participants as they have to invest comparably more time to answer them. To resolve this issue, the number of questions in the survey was reduced. Additionally, only the questions regarding TSCT comprehension (i.e., GSCT, YSCT, and RSCT), were open-ended.

3.3.3. Survey Distribution, Collection, and Analysis

The survey was created and distributed with Qualtrics software, a web-based application, widely used for online surveys (Qualtrics Research Suite, Version [56395]). Since the internet has become increasingly accessible, and it offers the easiest and the most cost effective means of reaching out to many respondents in a relatively short time, it was used to distribute the survey and collect responses. The online nature of the survey allows for a wider variety of demographics to be captured more easily. Unfortunately, there is still the potential issue of sample bias, as not everyone has access to the internet or the skill to use it properly.

Another problem with an internet based survey is that because researchers have no control over the survey environment, it is not possible to verify whether participants are taking the survey carelessly, taking it by themselves, or taking the survey more than once. However, in a comparative study on paper-based and web-based surveys, Dilman et al. (2006) discovered that people provide better open-ended responses in web-based surveys than in traditional pen-and-paper surveys. In a non-experimental comparison of responses to some question, the researchers first administered a paper survey and then several years later in a web survey. The test was conducted on two different samples, but from the same population. They found that the web respondents provided 10 to 15 word longer answers that contained more themes and elaboration than the paper respondents (R Studio, Version 0.98.490). The survey responses were analyzed using the open-source statistical analysis package R Studio (R Studio, Version 0.98.490).

3.4. Survey Structure

The survey included three categories of questions. The first category included demographic questions, concerning characteristics such as age, education, driving experience, etc. The second category focused on drivers' comprehension of the countdown devices when presented with traditional traffic signal displays, and the third component of the survey addressed drivers' preference regarding alternative countdown timer display configurations.

3.4.1. Participant Demographics

The population of interest for the static survey was licensed drivers in Oregon. The following participant demographics were collected during the survey: age, gender, education, language, state of licensure, driving experience, and color blindness.

3.4.2. Comprehension of TSCT

Different TSCT applications were presented to the participants through static images. Figure 3.1 is an example of an image used in one of the comprehension survey questions. A GSCT is displayed along with a three section vertical signal head. Participants were asked to explain separately what message each component, i.e., traffic signal and the CT, was trying to convey to them. Although, testing the effectiveness of YSCT was left out of the scope of driving simulator study, it was included in the online survey while testing driver comprehension.

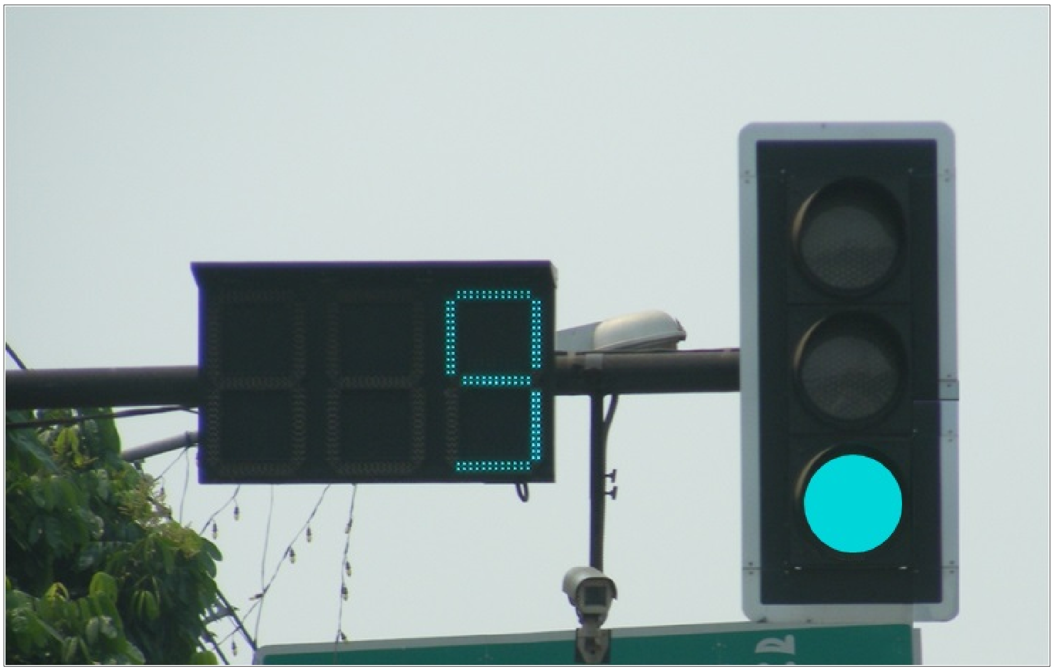


Figure 3.1: Example Presentation of GSCT Adjacent to a Signal Head

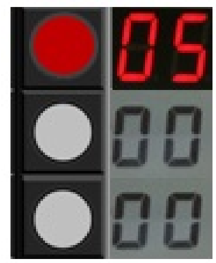
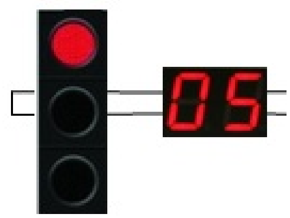
3.4.3. Preference towards TSCT

To understand drivers' preference regarding TSCT, the following questions were included in the survey:

- Which application of TSCT (red, green, or yellow) would provide the most useful information for driver decision making at signalized intersection?
- Which presentation of TSCT will be most easily understood by drivers?

To discover the most readily understood TSCT displays, four of the most common TSCI displays (Table 3.1), identified through research on international applications, were presented to the survey participants.

Table 3.1: Alternative TSCT Displays

Alternative:	**Description:**	**Picture:**
A	• Separate countdown timers for each signal indication; placed next to the signals. • Information about the signals are presented through numbers, colors, and the positions of the CT.	
B	• Single countdown timer for all signal indications; placed next to the signal head. • Information is presented through numbers and the colors of the CT displays.	
C	• A series of colored lights radially surrounding the signal indication. • Information is presented through the number of lights turned on at a given time, rate at which the lights turn off, color of the lights, and their positions.	
D	• Single countdown timer for all signal indications; placed at the bottom of the signal head. • Information is presented through numbers and the colors of the CT displays.	

3.5. Participant Demographics

The generalizability of survey results depends on the representativeness of the sample in question. There are frequent difficulties encountered while selecting a representative sample. From the collected data it can be seen that the participants of the survey compose a representative sample of the population of licensed Oregon drivers. A total of 196 participants started the online survey, and with a dropout rate of approximately 5%, 177 surveys were completed (85 males and 92 females). The minimum and maximum age of the participants were 18 and 78 respectively, which conforms to the exclusion criteria stated in sub-section 3.3.1. The mean and median ages were 38 and 35 respectively with a standard deviation of 14.9.

3.5.1. Age Distribution

A comparison of age distributions for Oregon drivers from 2000-2009 and that of the survey participants who completed the survey is given in Figure 3.2.

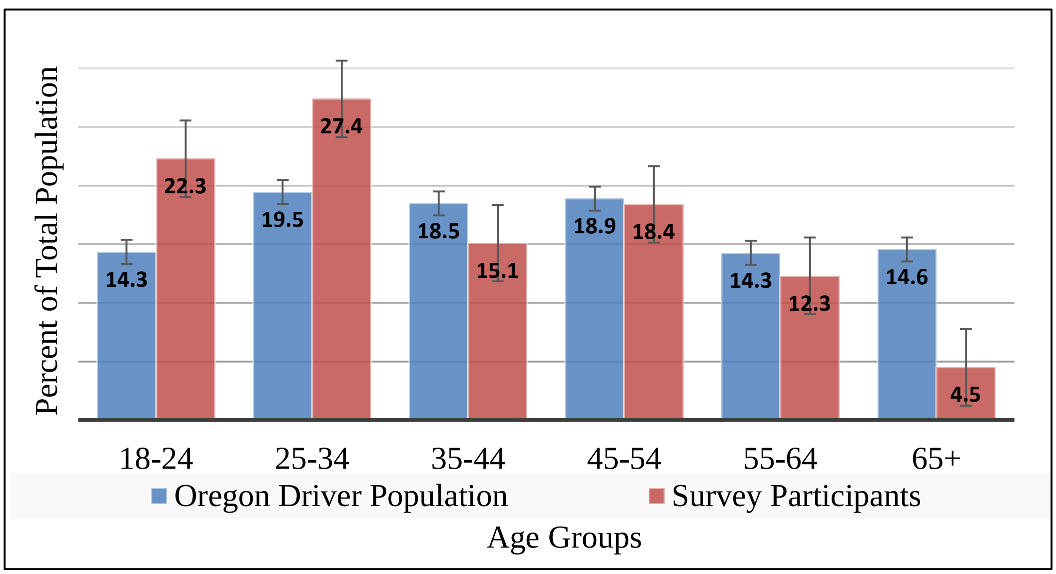


Figure 3.2: Age Distribution of Oregon Driver Population and Survey Participants

The age groups 35-44, 45-54, and 55-64 (Figure 3.2), have a similar distribution compared to the Oregon DMV data for licensed drivers. However, there is an under representation in the age group 65+, and an over representation of the age groups 18-24 and 25-34. This is likely a result from the over representation of Oregon State University students who are mostly between 20-30 years of age, participating in the survey.

To test whether the survey participants constitute a representative sample of the Oregon driver population, a Chi-Squared Goodness-of-fit test for given probabilities was conducted. The result of the test (χ-squared = 0.289, df = 5, *p*-value = 0.998) indicated that the null-hypothesis (i.,e., the survey participants group has identical age distribution with the Oregon driver population) cannot be rejected.

3.5.2. Highest Level of Education

A large number of participants (65%) who completed the survey were found to have at least a four-year college degree or higher (Table 3.2). There is a slight overrepresentation of participants with a 4 year degree or higher for both male and female participants. The distribution of education level is similar for both male and female.

Table 3.2: Participants' Highest Level of Education

Education Level:	**Male:**	**Female:**
Less than High School	0%	0%
Some High School / GED	2%	1%
Some College	26%	23%
2-year College Degree	7%	2%
4-year College Degree	39%	41%
Master's Degree	15%	24%
Doctoral Degree	6%	3%
Professional Degree (JD, MD)	5%	4%

The slight over representation of subjects with higher levels of education was influenced by the community the survey was distributed in, a small college town. Some bias in the drivers' average comprehension may have occurred due to this. However, due to the simplicity of the information presented through the TSCT, it is expected that the bias was minimal. In the worst case, the results will be overly conservative. In order to better understand the influence of education on participants' comprehension of TSCT, education was included in the regression model as a predictor variable. The analysis is presented in the Survey Analysis section of this Chapter.

3.5.3. Language & Color Blindness

The majority of participants were Oregon residents whose first language was English. Only 4% of women and 12% of men reported English as their second language. Although, participants' language was expected to have no direct correlation with their ability to comprehend the TSCT displays, it was included in the survey to see if the sample captured participants from different demographic background. None of the participants reported color blindness.

3.5.4. Driving Experience

Most of the participants were found to have significant driving experience (Table 3.3). Both male and female participants had similar distributions of driving experiences (χ-squared = 0.075, df = 5, *p*-value = 0.999).

Table 3.3: Participants' Driving Experience

Years of Driving Experience:	**Male:**	**Female:**
0 - 1	1%	1%
1 - 5	18%	13%
6 – 10	21%	15%
11 - 15	12%	15%
16 - 20	11%	9%
More than 20	38%	48%

3.6. Analysis of Comprehension

Survey data is dependent in part upon how truthful participants are in their responses to the survey questions (McNemar, 1947). In general, researchers accepted the data as honest responses as there was no reasonable cause for suspicion. Significant effort was expended to ensure the consistency of coding the open ended responses from the survey. The final data analysis was done after establishing inter-rater reliability. Two individual researchers coded the text responses separately and then compared the interpretations. In the case where an item was scored inconsistently, both researchers discussed the item until a consensus was reached.

Next, the coding methods of participants' verbal responses; an elaborate picture of participants comprehension of TSCT; influence of age, gender, driving experience, and education on the comprehension of TSCT; and participants' preference of TSCT will be detailed.

3.6.1 Coding Responses

The typed participant responses to the open ended TSCT questions were exported from the Qualtrics software. Each response was categorized as correct, incorrect, confused, or no clue. Responses that demonstrated participants understood that the devices were CT for the adjacent traffic light were included in the correct category, and in the incorrect category if not. The third category (confused) included responses where the participants had given mostly correct answers with some degree of confusion. In cases where the participants failed to even guess the meaning of the devices, responses were categorized as do not know. Example quotes for each response category for the question on GSCT are given in Table 3.4.

Table 3.4: Example Quotes from Survey Responses

Response Category:	**Score:**	**Example Quote:**
Correct	1	*"The light will remain green for 9 more seconds, then change to yellow."*
Confused	0.5	*"Countdown timer - assume it's associated with the vehicle head - color arbitrary"*
Incorrect	-1	*"9 sec pedestrian countdown signal - ped in crosswalk can continue, but ped not already in crosswalk should not start"*
Do not know	0	*"I've never seen this in this placement before."*

3.6.2 Comprehension of TSCT – Overall Picture

The first step of the analysis includes an overall picture regarding participants' comprehension of the TSCT (Table 3.5). For traffic sign comprehension research, ANSI Z535.3 standards from 1998 and 2002 state that a symbol must receive comprehension rates greater than 85% with not more than 5% critical confusions (i.e., comprehension of the sign is opposite to that intended).

It can be seen from the result that the overall comprehension of TSCT is 82%. This is just shy of the desired standard for traffic signal device comprehension (ANSI Z535.3). This can be considered as a satisfactory comprehension rate considering the majority of participants had never encountered these devices. Additionally, the presentations were static in nature, and correct answers that expressed any degree of uncertainty were excluded from the "correct response" category. As documented in the literature review chapter, most of the surveys conducted on road users' comprehension of PCT were based of field demonstration. This strategy cannot be pursued at this time due to the lack of TSCT implementation in the US.

Table 3.5: Survey Participants Comprehension of TSCT

TSCT Type:	**Number of Responses (%)**			
	Correct:	**Confused:**	**Incorrect:**	**Do not know:**
RSCT	133 (77%)	13 (8%)	12(7%)	13 (8%)
GSCT	141 (81%)	10 (6%)	8(5%)	14 (8%)
YSCT	149 (85%)	9 (5%)	5(3%)	12 (7%)
Total	423 (82%)	32 (6%)	25(5%)	39 (8%)

Further investigation of the incorrect responses revealed that for a significant number of incorrect responses (19 out of 25), participants misinterpreted the TSCT as PCT. An example incorrect response follows:

> ***Question:*** *What does the left component of the following signal (Figure 3.1: GSCT displaying 9 seconds on the timer) mean to you?*
>
> ***Response:*** *"9 sec pedestrian countdown signal - ped in crosswalk can continue, but ped not already in crosswalk should not start"*.

A reasonable explanation of such phenomenon could be the widespread use of the PCT and the nonexistence of TSCT in the US. One of the potential sources of confusion detected in the incorrect responses was the static nature of the survey images. One participant misunderstood the display on the timer as the speed limit of the road. This likely would not have happed if the participant could see the timer counting down. Similarly, one participant confused the number on the timer as the lane number, and again, if the numbers were dynamic in the survey this confusion may not have occurred. Some of the participants mentioned that the numbers represent the number of vehicles passing through the intersection. If there were dynamic countdown displays, the participants could have been able to perceive that instead of counting up, the device was actually counting down.

The influences of gender, experience and education level on comprehension rates were also examined.

3.6.3. Comparison of RSCT, GSCT, and YSCT

Before developing a statistical model for the comprehension of TSCT, participants' comprehension between the three applications, i.e., RSCT, GSCT, and YSCT, was compared. McNemar's test (1947) was used to examine whether participant's comprehension of any of the TSCT application was different from that of the other application. For each application, the responses were grouped into two categories – correct (if the score was 1 or 0.5), and incorrect (if the score was 0 or -1). The responses were then grouped into the four possibilities for each subject: both correct; both wrong; RSCT correct, but GSCT wrong; and RSCT wrong, but GSCT correct. The resulting data for the RSCT and GSCT comprehension, as shown in Table 3.6, were used for the McNemar's test. The test result (p-value = 0.803) indicated no evidence of the difference in participants' comprehension of RSCT and GSCT. Other comparisons, e.g., GSCT vs. YSCT, and RSCT vs. YSCT, showed similar results (p-values 0.58 and 0.301, respectively).

Table 3.6: McNemar's Test Data: Comparison between RSCT and GSCT

	GSCT Correct:	**GSCT Incorrect:**	**Marginal Total:**
RSCT Correct:	137	7	144
RSCT Incorrect:	9	17	26
Marginal Total:	146	24	170

3.7. Predictive Model

As the participants demonstrated no difference in their ability to comprehend different applications of TSCT, a logical next step was the development of a mathematical model that reflected the driver's comprehension of TSCT. The selection of an appropriate mathematical model to describe the dataset was strongly influenced by the types of response and predictor variables considered. The response variable of interest was the level of correctness as explained in sub-section 3.5.1, which was a categorical variable with four possible outcomes. The responses for all three applications (RSCT, GSCT, and YSCT) were combined into one data set as the comprehension responses were identical. The data set was coded for the comprehensive mathematical model as shown in Equation 3.1:

$$\boldsymbol{Score_i} = \begin{cases} \boldsymbol{1, if\ the\ average\ of\ the\ scores\ > 0.5} \\ \boldsymbol{0, otherwise} \end{cases} \tag{3.1}$$

Where:

$Score_i$ is the combined score for i-th participant.

The above recoding transforms the dependent variable into a dichotomous variable of two possible outcomes: 1 or 0. If a participant answered the question on RSCT and YSCT correctly, and GSCT incorrectly, his combined score would be 1, because the average of 1, 1, and -1 is less than 0.5. As such, a participant is required to have at least two correct answers and no incorrect answer to receive a combined score of 1.

The most appropriate model to analyze a dichotomous outcome variable is a Linear Logistic Regression, also termed a logit model (Aldrich and Nelson, 1984; Schwab, 2002; Hosmer and Lemeshoow, 2000; Long, 1997). In this model, the log odds (i.e., the logit) of the outcome is modeled as a linear combination of the predictor variables.

3.7.1. Predictor Variables

To select appropriate predictor variables for the model, survey results were applied and the following four predictors: age, gender, education level, and driving experience were selected for the initial model:

Age:

The age of the participant was taken as a continuous variable. However, to conduct a preliminary analysis, ages were grouped in 7 categories, (Figure 3.2). A comparison of the comprehension of TSCT between two age groups, 18-24 and 65+, shows evidence of the influence of age on participants' comprehension level. The 65+ age group experienced greater difficulty in comprehending the TSCT. Only 41% of responses made by this group were correct, and 45% of responses were incorrect. Comparatively, the comprehension rate for the 18-24 age group was significantly higher than the 65+ age group. Ninety one percent of the responses made by the 18-24 age group were correct, with only 3% incorrect responses.

Gender:

Gender was included as a categorical (binary) variable. Table 3.7 compares the comprehension rates of male and female participants. For all three TSCT configurations, male participants generally had a better comprehension of the TSCT than female participants. It was found that 88% of all male responses were correct, whereas only 76% of the female responses were correct (Appendix A). Therefore, gender was also included in the logit model.

Table 3.7: TSCT Comprehension Rates by Gender

Configurations:	Gender:	Correct:	Incorrect:	Confused:	No Clue:
RSCT	Male	84%	6%	4%	6%
	Female	72%	8%	11%	9%
GSCT	Male	87%	1%	6%	6%
	Female	78%	7%	6%	10%
YSCT	Male	92%	1%	2%	5%
	Female	79%	4%	8%	9%

Education:

The influence of education on the comprehension of TSCT was also examined. Different levels of education were classified into seven categories. Thus, education was considered as a categorical variable of seven levels. Two groups with substantial difference in education were chosen for comparison (participants with some college or a Master's degree). There is almost no difference in the comprehension level between the two groups for GSCT and YSCT (Table 3.8). Rather counterintuitively, participants with some college education had better comprehension of RSCT than those with a Master's degree. To understand whether education influences the outcome, it was also included in the list of predictors in the initial regression equation.

Table 3.8: Comparison of Comprehension Rate Based on Education

Display:	Level of Education:	Correct:	Incorrect:	Confused:	Do Not Know:
RSCT	Some College	87%	10%	5%	7%
	Master's Degree	77%	9%	9%	6%
GSCT	Some College	90%	2%	2%	5%
	Master's Degree	88%	6%	3%	3%
YSCT	Some College	89%	3%	3%	6%
	Master's Degree	89%	3%	3%	6%

Driving Experience:

In the online survey, driving experience had a categorical response, that is, instead of inputting an exact number of years, participants selected a one of six experience categories. In order to investigate possible difference in TSCT comprehension due to driving experience, two groups of participants with substantial difference in driving experience (1-5 years and 16-20 years), were selected for comparison. The overall quantity of correct responses for the 1-5 year group was 89%, whereas it was 92% for the 16-20 year group. Although the difference in the comprehension rate appeared to be minor, driving experience was included in the mathematical model due to the initial assumption that it might have some influence.

3.7.2. Model Development

The initial linear logistic regression model included the log-odds (the logit) of the probability of one of the two outcomes (1 and 0) as the dependent variable. Age was considered as a continuous predictor variable (as input by the participants in the survey), and gender, education level, and driving experience were included as categorical predictor variables with 2, 7, and 6 levels respectively. The mathematical model (Equation 3.2) was as follows:

$$\boldsymbol{logit\ (\pi_i) = log\ \left(\frac{\pi_i}{1-\pi_i}\right) \sim Age + Gender + Education + Driving\ Exp.} \qquad (3.2)$$

Where:

π_i = the predicted probability for *i*-th participant to have a combined score of 1

Equation 3.1 was considered the full model. The summary information produced from R is given in Appendix B, which indicates that none of the predictor variables were statistically significant.

In search of a better mathematical model, driving experience was excluded from the full model. The general perception, which was also observed in the survey data, was that the driving experience increased with age. Therefore, incorporating both predictors in the model was not justified. To decide whether the age or the driving experience should be excluded, the models resulting from the exclusion of each variable, were compared. From the statistical significance of the variables resulting from the two models, age appeared to be a better predictor, and thus, was included in the first iteration. In the first reduced model (with driving experience excluded) only the age became statistically significant (p-value = 0.005). Thus, another model with only age as the predictor was developed. In this final model, both the intercept and the age were statistically significant; p-value <0.001 and 0.005, respectively. The final model (Equation 3.3) was determined to be:

$$\boldsymbol{logit\ (\pi_i) = log\ \left(\frac{\pi_i}{1-\pi_i}\right) \sim Age}$$

Or, $$\boldsymbol{logit\ (\pi_i) = log\ \left(\frac{\pi_i}{1-\pi_i}\right) = 2.66 - 0.034 * Age} \qquad (3.3)$$

Unlike a simple linear regression, multinomial logistic regression it does not assume normality, linearity, or homoscedasticity (Starkweather and Moske, 2011), as such, it is often considered an attractive analysis. However, as a necessary diagnosis effort, multicollinearity was evaluated with simple correlations among the independent predictors. In addition, sample size guidelines for logistic regression, a minimum of 10 cases per independent variable (Schwab, 2002), was satisfied.

3.7.3. Interpretation of the Final Model

It is important to note that Equation 3.2 is only valid for Oregon drivers between 18 and 78 years old. Figure 3.3 shows a graphical representation of the final model. Instead of the log odds, the probability that a participant will comprehend the information displayed by TSCT was shown on the y-axis. For example, the odds that the outcome will have a value 1 for a participant of age 25 is calculated as (2.660 – 0.034*25) = 6.055, while the odds for a participant of age 65 is 1.53. In other words, the predicted probabilities that two participants of age 25 and 65 will comprehend the information on TSCT, are 85.82% and 60.48%.

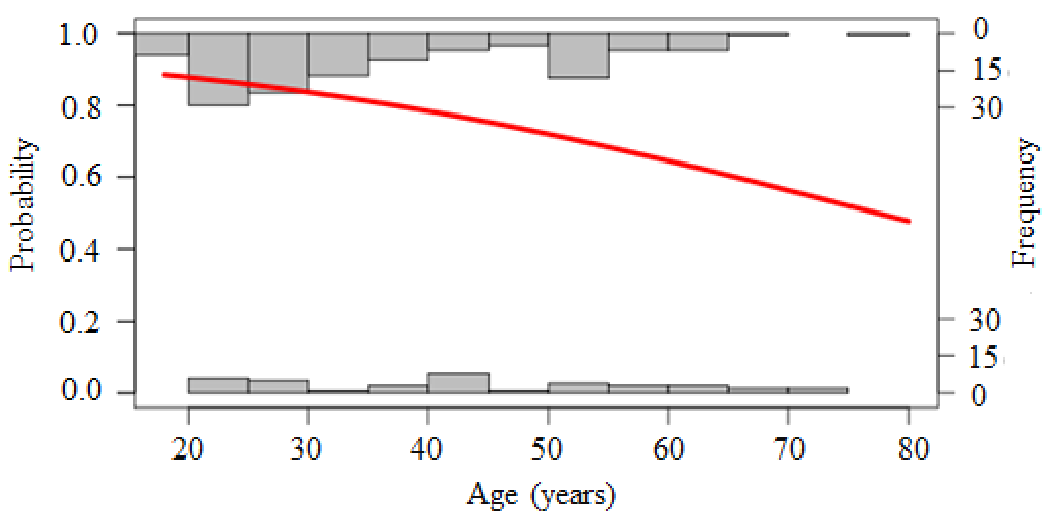


Figure 3.3: Probability of Correct Responses with Age as Predictor

3.8. Preference of TSCT

Participants were given two questions regarding their preferences towards the TSCT. The first question addressed their preference among the three applications of TSCT, while the second question addressed their preference on the display of the TSCT with respect to the signal head.

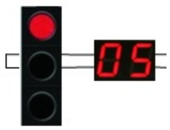
3.8.1. TSCT Application Preference

One key question investigated drivers' preference as to which application of TSCT (RSCT, GSCT, or YSCT) they considered most useful. When asked about their preference, 50% of participants chose GSCT, 35% chose YSCT, and 15% chose RSCT as the most useful TSCT application to improve their decision making at signalized intersections.

3.8.2. TSCT Display Preference

A total of 170 responses were recorded for the question regarding participants' preference of TSCT display. Participants were asked to rank the four display alternatives according to their preference, one represented the most preferred, and four represented the least preferred. Table 3.9 shows the number of responses for each alternative for a given rank. To test if an alternative was consistently preferred over others the weighted average of the ranking was calculated. From Table 3.9 it can be see that the weighted average of the rankings for alternative A and B are very close. Alternative C and D have larger weighted averages, indicating that they are less preferred than the other two alternatives.

Table 3.9: Participants’ Display Preference for TSCT

Display Alternatives:		**Number of Responses**				**Weighted Average of Ranks:**
		Rank 1:	**Rank 2:**	**Rank 3:**	**Rank 4:**	
A		76	37	35	22	2.02
B		56	64	39	11	2.03
C		22	26	19	103	3.19
D		16	43	77	34	2.76

Participants’ preference for a particular display alternative was further investigated with a Friedman Rank Test (Friedman, 1937; Galili, 2010). The test result suggests that there is a significant difference between the four display alternative rankings (*p*-value < 0.001). The Friedman test was followed by a post-hoc analysis to determine which pairs of alternatives are significantly different then each other. The post-hoc analysis showed that the difference between alternatives A and B was not significant (*p*-value = 0.997). Differences between all other alternatives (e.g., A vs C, or B vs D) were significant (*p*-value < 0.001). The boxplot display of the data supports this result (Figure 3.4).

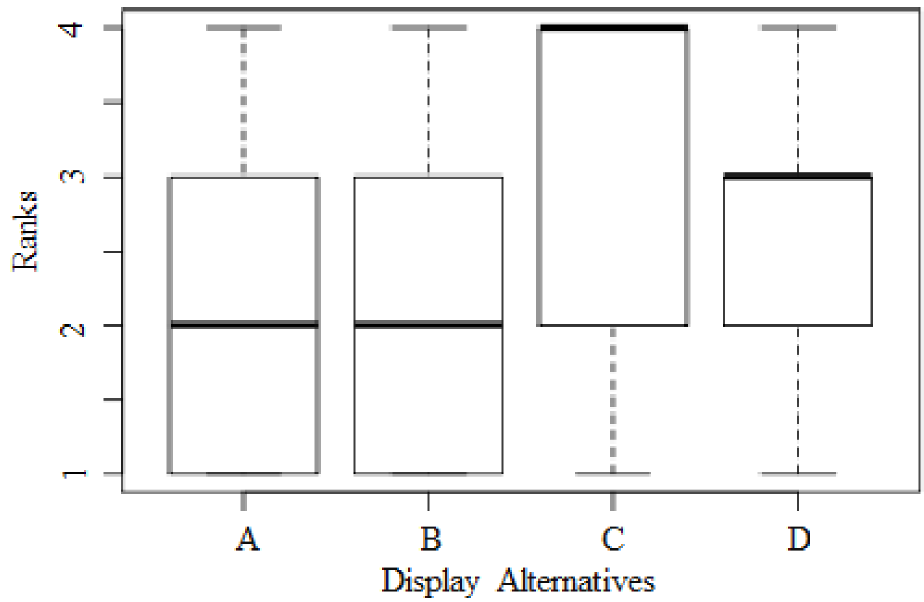


Figure 3.4: Display Alternative Rankings for TSCT

3.9. Summary

From the analysis of survey results, the key findings are categorized into two groups, TSCT comprehension and TSCT preference. In addition, the implication of the survey findings for the driving simulator study were also summarized.

3.9.1. TSCT Comprehension

This sub-section summarizes the findings from the statistical analysis of survey participant TSCT comprehension. The findings relevant to the driving simulator study, are also detailed:

- The overall comprehension rate for the TSCT was 82%. Approximately, 5% of responses were incorrect, 6% expressed some confusion (although they were mostly correct), and 8% of responses suggested no knowledge of TSCT.

- The Majority of incorrect responses, 19 out of 25, were misinterpreted as PCT. The likelihood of this confusion was minimized in the simulator experiment by introducing a written instruction describing the meaning of the displays before subjects were exposed to the displays.
- Participants' comprehension of the three applications of TSCT were found to be similar (p-value ≈ 1.0 from Chi-squared test for given probabilities for all three applications).
- Age appeared to influence participants' comprehension of TSCT; only 41% of all responses from the 65+ age group were correct regarding various applications of TSCT, while 18-24 year age group had 91% correct responses for the same questions. It was also evident from the logistic regression model developed to predict participant's comprehension of TSCT that age was a significant predictor (p-value = 0.005) to model the outcome of participant responses. One possible reason for this difference might be the presentation of the questions in an online survey; participants of age group 18-24 were mostly current college students who frequently encounter questions like these, and use internet in their daily activities. Alternatively, older participants may encounter survey questions of this type less frequently.
- There was no evidence of significant differences in participants' ability to comprehend the TSCT due to gender differences (p-value = 0.83 in the full model with age, gender, education, and driving experience as possible predictors).

- The comprehension of the information displayed by the TSCT was not greatly influenced by participants' highest level of education and driving experience.

3.9.2. TSCT Preference

The findings regarding survey participants' preference of different applications and configurations of TSCT are summarized as following:

- The GSCT was considered to be the most useful application of TSCT. Fifty percent of the participants favored GSCT over YSCT or RSCT. This may be due to participants' realization of the safety implications of GSCT, especially to eliminate confusion when approaching a signalized intersection.
- The weighted average of the ranks (i.e., preferences; 1 being the most preferred and 2 least preferred) given by the participants for each of the four configurations of TSCT, showed that alternative A (one timer next to each signal indication) and alternative B (one timer placed next to the signal head) were most preferred, and alternative C (LED lights radially placed around each signal indication) was least preferred.

  Differences among the four alternatives were found to be statistically significant (p-value < 0.001), except between alternative A and B (p-value = 0.997).

3.9.3. Implications for Driving Simulator Study

In addition to the findings regarding participants' comprehension of and preference towards TSCT, the online survey provided valuable insight in the design of driving simulator study. For example, participants' preference of display alternative B over other alternatives led to its application in the simulated environment designed for the driving simulator study.

It was found from the online survey that age influences the comprehension of the TSCT. As such, it was insured that the test subjects of all age groups were included the simulator study. Although, the gender appeared to be irrelevant to the comprehension of TSCT, it was ensured that the participation of male and female were even in the driving simulator experiment. Because, even though the level of comprehension of traffic signals are similar for both male and female, their response and driving behavior might have significant differences.

During the driving simulator study, a different survey was administered that included questions from the online survey to gain better understanding of drivers' preference and comprehension of TSCT as they encountered them in the simulator lab.

Chapter 4 Driving Simulator Study

Each type of TSCT has potential safety and efficiency benefits, which have yet to be evaluated with respect to the driving population of Oregon. In an effort to assess the potential benefits of TSCT, the two most common applications of TSCT (e.g., the RSCT, and GSCT) were evaluated. As detailed in the literature review chapter, most previous research concerned with TSCT or PCT examined the effectiveness of these devices through user survey and direct field observation. As such, the comprehension and preferences of TSCT displays by Oregon drivers were initially studied through the online survey, presented in Chapter 3. However, the absence of TSCT in the US eliminates the possibility of conducting field observation. Therefore, as an alternative to field observation, a driving simulator study was performed to further address the research questions.

This chapter provides a detailed description of the experimental methodology, data collection and analysis procedures, and results of the driving simulator study. The content of this chapter was organized into four primary sections. The background section provides the scope of the driving simulator study, and the specific research questions. Development of test beds for the two experiments (i.e., one for RSCT, and another for GSCT) constituted the second section. The third and fourth sections provide detailed analysis of the two experiments, test of effectiveness of RSCT and GSCT, respectively.

Background

The experimental design is strongly influenced by the research questions of interest. Therefore, the scope of the research, questions of interest, and their rationales are elaborated in Section 4.1 and 4.2.

4.1. Research Scope

As discussed in the literature review chapter, TSCT have predominantly been used internationally for pre-timed signals. The reason why TSCT are typically used for actuated signals is that the current vehicle detection mechanisms and signal control algorithms for actuated systems permit the precise estimation of time remaining for a signal indication only a few seconds before phase termination. Typically, the final determination is made 1 to 4 seconds (Tarnoff and Parsonson, 1981) before the indication changes (e.g., green to yellow, or red to green), providing a limited interval for the countdown to be displayed. This characteristic has widely been described as the most significant limitation to applying TSCT in actuated traffic signal systems (Chen et al., 2009). Therefore, this research studied driver behavior in presence of TSCT exclusively at pre-timed traffic signals.

The research also focused on the investigation of TSCT effectiveness by only considering the RSCT and the GSCT. The YSCT was not considered as previous research (Long et al., 2011) has shown minimal positive impact.

To simplify the experimental design and reduce the potential occurrence of simulator sickness, left-turns were excluded from the study design. Although, TSCT have been used for left-turn movements as well, limiting the scope to through movements enabled the researchers to focus on the effectiveness of CT while minimizing the risk of simulator sickness for participating drivers.

4.2. Research Questions and Rationale

The objective of the research was to investigate whether TSCT had the potential to improve traffic safety and efficiency at signalized intersections in Oregon. As suggested by previous literature, RSCT and GSCT can help improve the signalized intersection efficiency by reducing delays. GSCT inform approaching drivers about the number of seconds of green remaining before the signal indication changes to yellow. This additional information could improve approaching drivers' decision to stop or proceed through the intersection, minimizing Type II DZ issues. The Type-II DZ is the segment of a roadway upstream of a signalized intersection where drivers have difficulty deciding whether to stop or proceed through at the onset of the circular yellow indication.

GSCT have been found to increase drivers' probability of stopping before the end of green signal (Köll et al., 2004), potentially reducing the frequency of RLR. However, there are conflicting results regarding TSCT as well (Long et al., 2011), particularly for the GSCT. The potential influence of GSCT on intersection safety formed the basis of the fundamental research question.

- Does the presence of GSCT eliminate or reduce Type II DZ conflicts by increasing driver's correct decision to stop or proceed at the end of the green phase?

Reduction in the start-up lost time at a signalized intersection is of significant importance. It is not only the first vehicle that experiences the benefit, but the entire queue, as the delay incurred by the start-up lost time is a cumulative function. Therefore, it is of great interest to traffic engineers to apply innovative techniques to reduce start-up delays, i.e., improving efficiency, and using RSCT has the potential to contribute to this outcome. This potential outcome formed the basis of the research questions regarding the RSCT.

- Does the presence of the RSCT reduce the start-up lost time by reducing the headway of the first vehicle in a discharging queue?
- Does the duration of wait time during the red indication influence the performance of the RSCT to reduce the headway of the first vehicle in a discharging queue?

Virtual Driving Environment

Development of the virtual driving environment was guided by the previously identified research questions. Thus, a primary consideration while developing the test-tracks for the simulator study was to ensure that the variables associated with the research questions were accurately measured and recorded. The variables of interest for each experiment will be explained in detail in the following sections of this chapter. However, in order to accurately detail the development process of the test environments, the variables that were measured during the experiment, are briefly described in section 4.3. An illustration of all test track configurations, a brief description of Oregon State University (OSU) driving simulator, test subject demographics, and a step-by-step subject testing procedure are presented in the following sections, Section 4.4 through 4.7 respectively.

4.3. Design of Experiments

The research hypotheses were tested in a virtual driving environment rather than in the real world. This section explains the variables measured, and the test tracks used to execute the experiment. The variables measured in the driving simulator study were classified into two groups; one for the RSCT experiment and the other for the GSCT experiment. Since the objective of the research was to compare drivers' response in the presence and absence of CT, two types of test tracks were designed; one with no CT (control scenario), and another with CT (treatment scenario).

4.3.1 Responses Measured for RSCT Experiment

The objective of the RSCT experiment was to determine whether the presence of RSCT reduced the headway of the first vehicle departing a queue in response to the onset of the green indication. As defined in Section 2.2 of Literature Review Chapter, start-up lost time is the sum of the extra time that drivers waiting in a queue on red signal require over the saturation headway. In the driving simulator, only one subject can be tested in a built environment, which limits the headway measurement for only the first vehicle, i.e., subject's vehicle. From the previously mentioned studies on start-up lost time we know that the first headway in a standing queue is a major component of the start-up lost time. Therefore, if the presence of RSCT helps reducing the first headway of a standing queue, it can be said that it contributes to reducing the start-up lost time.

Assuming that the subject vehicle in the simulator study is the first vehicle of a standing queue developed in response to a red indication, the headway was measured as the time lapse between the onset of the green indication and the time when the front axle of the vehicle crossed the stop line (Roess et al., 2011). The headway calculation process is further illustrated in Figure 4.1. The centroid position of the vehicle was collected from the simulator every tenth of a second, which was used to calculate the headway.

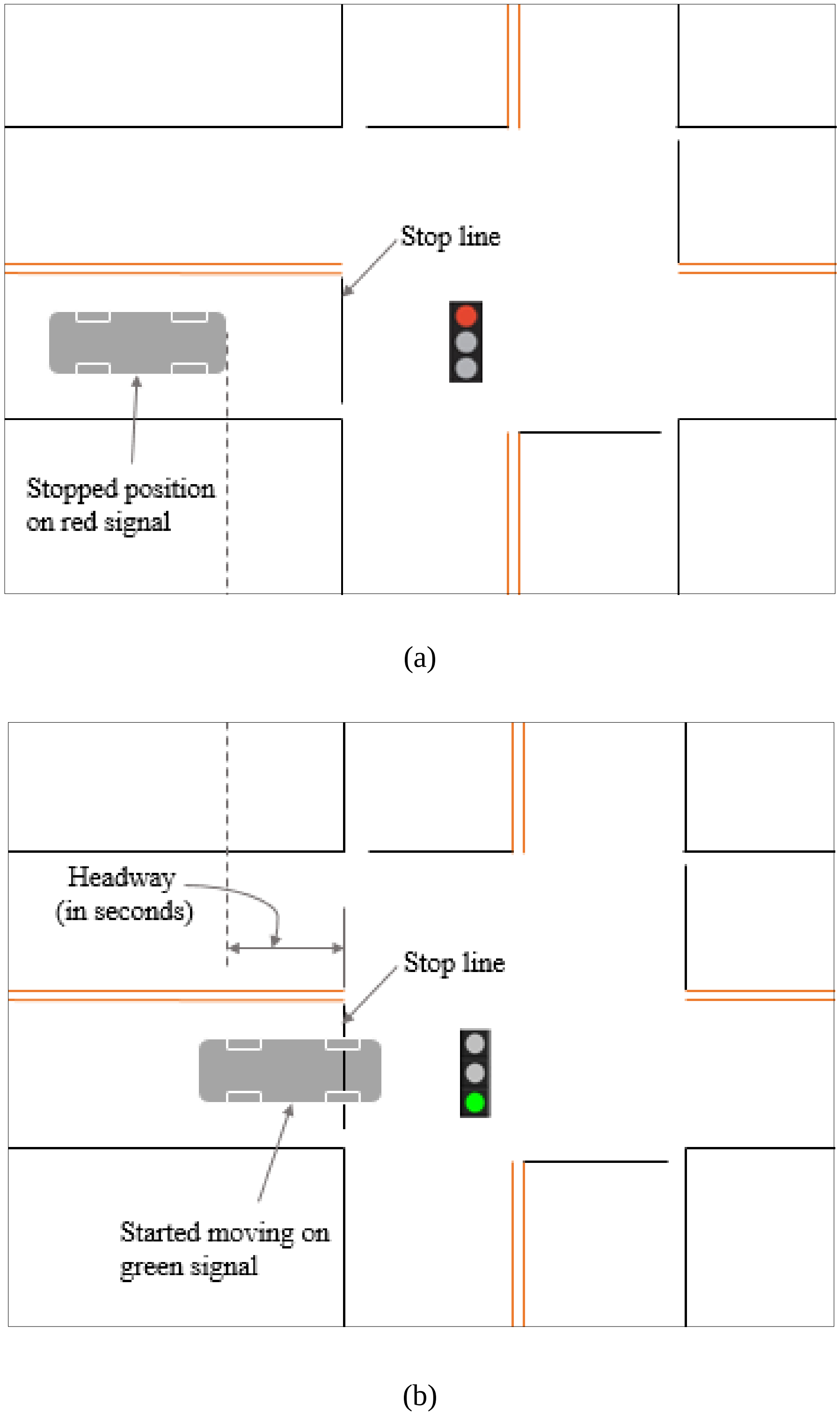


Figure 4.1: Headway of the First Vehicle in a Standing Queue

Driver behavior at signalized intersections is influenced by a variety of environmental factors, including excessive wait times during red intervals (Abou-Zeid et al., 2011). It has been documented that drivers waiting at an intersection during longer red signals are more likely to be distracted and respond more slowly at the onset of the green signal, resulting in longer headways (Hurwitz et al., 2013). The experimental design sought to determine if the first headway was influenced by the presence of RSCT. Additionally, three different red signal durations (20, 40, and 60 seconds) were used to test first driver headways during different lengths of wait time.

4.3.2 Driver Responses Measured during GSCT Experiment

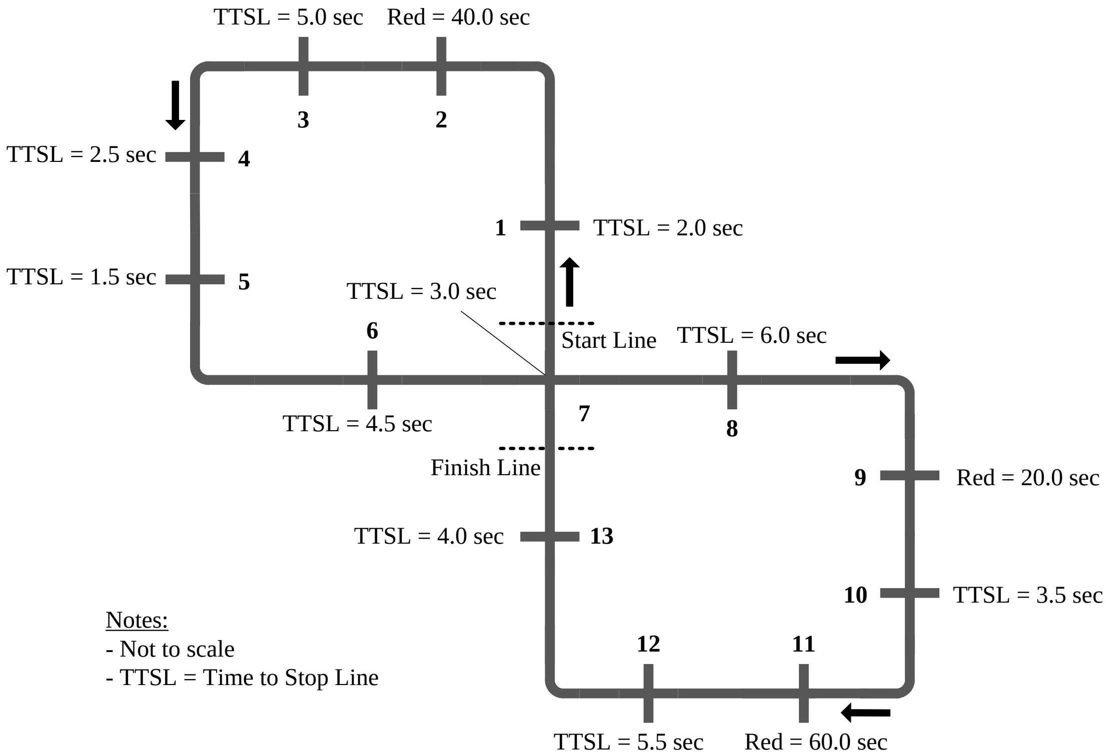
As mentioned earlier in this chapter, the use of GSCT could prove effective if it increased the probability of stopping during the red signal in a given scenario (speed, and distance from the stop line) as compared to traditional intersection with no CT. Experimental scenarios were developed based on the instantaneous speed and position (i.e., distance from stop bar) of the vehicle at the onset of the yellow. The speed and position information was used to calculate different Time to Stop Line (TTSL) characteristics for each experimental scenario of interest. TTSL is the number of seconds it takes for a vehicle travelling at a certain speed to reach the stop line, starting from the time of the yellow onset. TTSL was chosen as a predictor of driver's probability to stop, as it accounts for both vehicle's speed and position, and has been previously documented as a strong predictor of driver behavior (Hurwitz et al., 2013). For example, a driver approaching a signalized intersection at 45 mph is more likely to stop on yellow if the TTSL = 5 seconds compared to the scenario when TTSL = 2 seconds (Moore & Hurwitz, 2013). Thus, the experiment was designed to build a mathematical model to quantify the probability to stop function in different TTSL scenarios for a given driving environment (e.g., posted speed limit = 35 mph).

4.4. Test Track Configurations

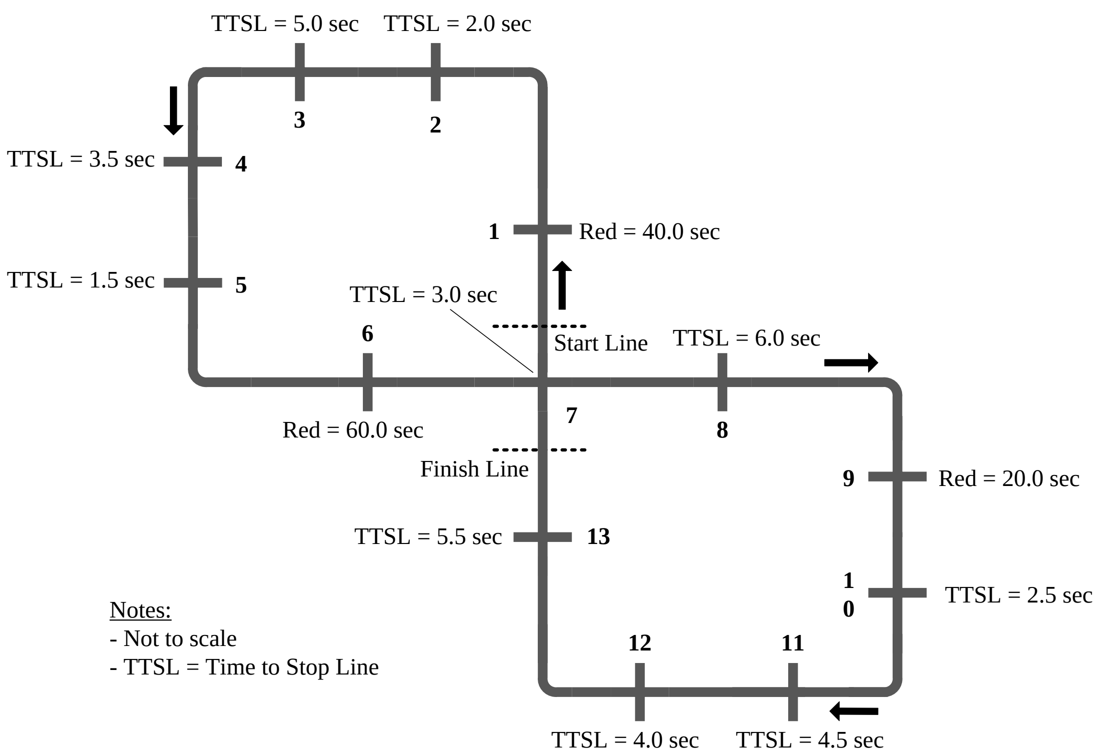
When designing a simulator test track it is important to minimize the total amount of time that a test subject is required to drive in the simulator thereby minimizing the risks of simulator sickness. This constraint can restrict the number of scenarios that a test subject can be exposed to. As such, the scenarios required for both RSCT and GSCT experiments were included in a single test track. That is, both type of test tracks, e.g., without CT and with CT, included the scenarios for RSCT and GSCT experiments, rather than having separate test tracks for each experiment.

As explained in Section 4.3, the RSCT experiment included three test scenarios, 20, 40, and 60 second long red signals. Meanwhile, the GSCT experiment was comprised of ten different test scenarios; TTSL = 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, and 6.0 seconds. Thus, a total of 13 test scenarios, presented at thirteen different intersections, were included in both types of test tracks, those with and without CT. The total length of each test track was close to 6.25 km. Thus, each test subject was required to drive approximately 12.50 km in total combining the total lengths of both test tracks.

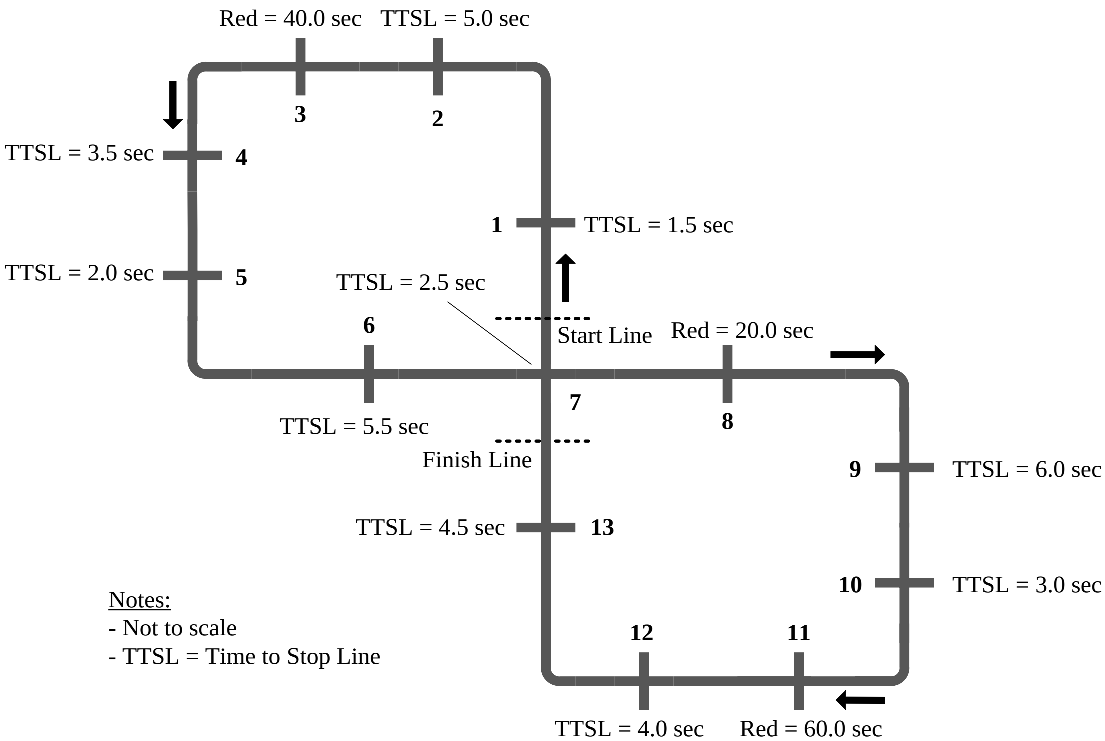
The RSCT test scenario intersections were each separated by at least two additional intersections, to prevent the requirement for stopping at successive intersections. Each scenario was assigned a number, and a random number generator was used to arrive at a final scenario sequence. After placing the intersections for RSCT experiment, GSCT test scenarios were randomly placed in the remaining ten intersections. This process of signal arrangement was used to create four test track configurations - A, B, C, and D. The random assignment of intersections with each level of independent variables, and the multiple track configurations contributed to minimizing the confounding effects of the order of exposures or an upcoming event. The speed limit was kept the same (35 mph) for the entire roadway to reduce variability due to speed. In all four test tracks, the roadway was divided with one lane going each direction. The four test track configurations are shown in Figure 4.2.



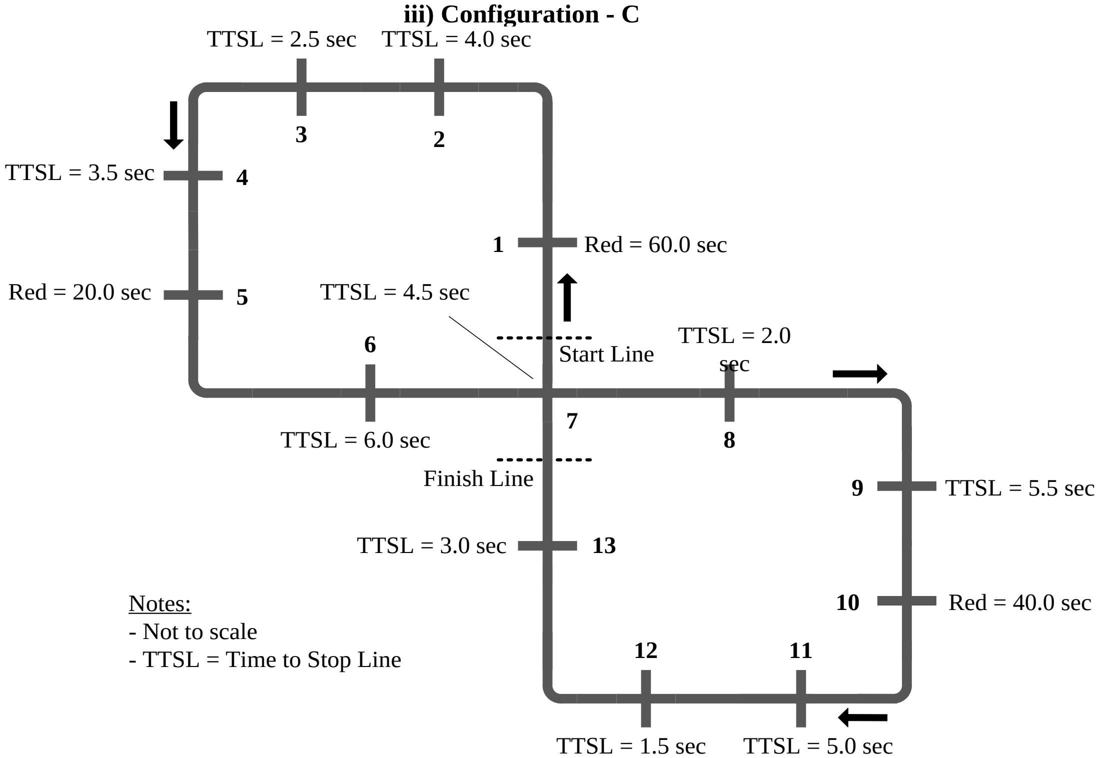
i) Configuration - A



ii) Configuration - B



iii) Configuration - C



iv) Configuration - D

Figure 4.2: Test Track Configurations

All four configurations had two prototypes; with CT and without CT. Thus, there were eight different test tracks (Table 4.1).

Table 4.1: Test Track Configurations for the two Test Scenarios

Test Track #:	Configuration:	Intersection Type:
1	A	Without CT
2	B	Without CT
3	C	Without CT
4	D	Without CT
5	A	With CT
6	B	With CT
7	C	With CT
8	D	With CT

4.5. Driving Simulator

Drivers were asked to traverse the virtual roadways that included both intersections with and without TSCT. The design of the virtual environment and data collection were performed in the OSU Driving Simulator, described in this section.

4.5.1 OSU 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 allows for onset cues for acceleration and braking events. The cab is surrounded by screens where the simulated environment is projected. As shown in Figure 4.3, three projectors project a 180 degree front view. A fourth projector displays the rear image for the driver’s center mirror. Two side mirrors have embedded LCD displays that permit the driver to see both rear sides. The cab instrument includes a steering control loading system that accurately represents steering torques based on speed and steering angle. The computer system consists of a quad core host that runs the “SimCreator” Software (Realtime Technologies, Inc.). The data update rate for the graphics is 60 Hz. It is a high-fidelity simulator to capture and output highly accurate performance data such as speed, position, brake, and acceleration.

Figure 4.3: Oregon State Driving Simulator

The virtual test tracks were developed using Internet Scene Assembler (ISA) software, which permitted using Java Script based sensors on the test tracks to change the signal indication and displaying dynamic objects, such as a countdown timer, based on the subject vehicle’s presence. The TSCT triggering sensors were placed at a distance upstream from the intersection. The signal change took place when the vehicle was at a desired distance, measured in terms of TTSL. The following parameters were recorded at roughly 10 Hz (10 times a second) throughout the entire duration of the experiment:

- Time – To map the change in speed and acceleration with the change in signal indication or CT display.
- Signal Indication – To correlate driver response with respect to the change in signal indication or CT display.
- Instantaneous Speed – To identify changes in speed in response to the GSCT display.
- Instantaneous Position – To estimate the headways and distance upstream from the stop line.
- Instantaneous Acceleration/Deceleration – To identify any acceleration or deceleration in response to the GSCT display.

4.6. Test Experience for Individual Subject

To minimize the occurrence of simulation sickness, the time subjects spend driving in the simulated environment was minimized. The entire data collection process was carefully designed to insure that all necessary information were recorded efficiently. This section describes the step-by-step procedure of the driving simulator study, as conducted, for an individual subject.

4.6.1. Step 1: Informed Consent

Upon the test subject's arrival to the laboratory, the informed consent document that was approved by the Institutional Review Board (IRB) of OSU was presented explained. It provided the subjects with the opportunity to have an overall idea of the entire experiment and ask any questions regarding the test. The informed consent document included the reasoning behind the study and the importance of subject's participation. In addition, the document explained the risks and benefits to the subject associated with the test. Subjects were also clearly informed that they could stop the experiment at any time for any reason and still receive full compensation.

4.6.2. Step 2: Prescreening Survey

The second step of the simulator test was a prescreening survey targeting subjects' demographics, such as age, gender, driving experience, and highest level of education, as well as their prior experience with driving simulators and motion sickness. In addition to the demographic information, the survey included questions in the following areas:

- Visual acuity – Subject's visual acuity was crucial for the test. Subjects' were asked if they use corrective glasses or contact lenses while driving. It was insured during the test drive that the subjects were able to read the information displayed on CT and distinguish the color from a distance relevant to the test requirements, such as TTSL = 6 seconds (close to 350 feet if travelling at 40 mph speed).
- Color blindness – All test subjects were required to be able to accurately read the signal indication color.
- Prior driving simulator experience – Subjects with experience driving in a simulator in the recent past were excluded from the test.
- Simulation sickness – Subjects with previous driving simulation experience (not in the recent past) were asked about any simulation sickness they

experienced. If they had previously experience simulator sickness, they were encouraged not to participate.

- Motion sickness – Test subjects were surveyed about any kind of motion sickness they experienced in the past. If an individual had a strong tendency towards any kind of motion sickness, they were encouraged not to participate in the experiment.

4.6.3. Step 3: Calibration Drive

A test drive followed once the prescreening survey was completed. At this stage, drivers were required to perform a 3-5 minutes calibration drive to acclimate to the operational characteristics of the driving simulator, and to confirm if simulator sickness was a likely outcome for them. The test drive was conducted on a track similar to that developed for the experiments. However, it included only 3 signalized intersections and no CT. In the case that a subject reported simulation sickness during or after the calibration drive, they were excluded from the experimental drives.

4.6.4. Step 4: Experimental Drive-1

Test subjects who met the inclusion criteria and acclimated to the operational characteristics of the driving simulator during the calibration drive, were given a brief instruction about the test environment and the tasks they were required to perform. The entire experiment was divided into two portions. In the first portion, subjects were required to drive on a track with typical intersections (without CT), and in the second portion, they were asked to drive on a similar track including intersections with CT. The author did not perform a "crossover" design where the order of exposure to different treatments varies between subjects. In a cross-over design, a significant time gap should exist between exposures to different treatments to “washout” the carryover effect and remove statistical bias (Stufken, 2003). Testing each subject at two different times with considerable time gap was not a viable option for this study, as such, a crossover design was not performed. However, the instantaneous speeds (measured at a distance upstream of the intersections where no effect of CT should exist) from the control and the treatment scenarios were examined to confirm that subjects’ usual driving behavior was not different. As expected, the mean of the differences was found to be 0.79 mph.

The test track configuration (A, B, C or D) that the subject drove was selected by random assignment. The parameters required to measure subject’s responses to the signal indications (explained in detail in experiment one and two of this chapter) were recorded directly from the simulator.

4.6.5. Step 5: Experimental Drive-2

In this portion of the experiment, subjects drove on the test track that included intersections with CT. Before starting this experimental drive, the subjects were given a brief instruction on how TSCT operate. The instruction included a one page instruction with pictures and simple texts, shown in Figure 4.4, was an attempt to provide an explanation of the exact meaning of the information they were going to be presented on the TSCT. They were asked explicitly if they understood the information conveyed on the instruction, and were permitted to ask any questions required for their comprehension. This procedure of instructing drivers on the new traffic signal devices was consistent with previous driving simulator based research (Knodler et al., 2005). The same test track configuration, as was presented in Experimental drive-1, was used for this portion. For example, if the random assignment of test track in Experimental drive-1 for a subject was configuration B (test track number 2), then he/she was tested with same track configuration (test track number 6) for this portion of the experimental drive.

Traffic Signal Countdown Timer

What is a traffic signal countdown timer?

A traffic signal countdown timer is a clock that digitally displays the time remaining for a particular signal indication (red, green, or yellow) to alert the driver. In the following driving session, you will encounter countdown timers for red and the green signal indications.

How does a red signal countdown timer work?

A red signal countdown timer informs the driver that the red signal will turn green in a certain number of seconds. In the following picture, for example, the countdown timer indicates that the red signal will change to green in 10 seconds.

How does a green signal countdown timer work?

A green signal countdown timer informs the driver that the green signal will turn yellow in a certain number of seconds. In the following picture, for example, the countdown timer indicates that the green signal will change to yellow in 9 seconds.

Figure 4.4: Instruction on CT before Experimental Drive - 2

4.6.6. Step 6: Post Drive Survey

As the final step of the experiment, drivers were asked to respond to several questions on a post drive survey. This post drive survey focuses on answering the following categories of questions:

- Driver understanding – Did drivers understand the TSCT display? Was there anything about the display that led to confusion?
- Preference **–** What was driver preference towards TSCT? Specifically, did drivers feel that TSCT were helpful in their decision making, would like to have TSCT installed at signalized intersections, and did they thing the RSCT or GSCT was the most useful and why?

4.7. Test Subjects

A total of 67 individuals, mostly from Corvallis and its surrounding areas, participated as test subjects in the driving simulator study. The population of interest was Oregon residents; therefore, only licensed Oregon drivers with at least one year driving experience were recruited for the experiment.

In addition to Oregon residency, subjects were required not to exhibit any significant visual impairment, or to have participated in a driving simulator study in the prior two years.

Sixty seven subjects participated in the simulator study. Approximately 18 percent (7 female and 5 male) of subjects reported simulation sickness at various stages of the experiment. Simulation sickness is a special phenomenon where a person exhibits symptoms similar to motion sickness caused by a simulator (Fisher, 2011; Owen, 1999). The symptoms are often described as very similar to that of motion sickness, and can include headache, nausea, dizziness, sweating, and in extreme situation, vomiting. While there is no definitive explanation for simulation sickness, one widely accepted theory, cue conflict theory, suggests that it arises from the mismatch of visual motion cues and physical motion cues, as perceived by the vestibular system (Owen, 1999). All responses recorded from the subjects who exhibited simulator sickness, were excluded from the original data set before starting the analysis. Thus, the final data set was composed of 55 test subjects; 32 male (58 % of total) and 23 female (42 % of total). Subjects' demographics are summarized in Table 4.2.

Table 4.2: Diving Simulator Subject Demographics

Demographic:	Possible Responses:	Number of Participants:	Percentage of Participants:
What is your highest completed level of education?	High School Diploma	4	6 %
	Some College	19	28 %
	Associates Degree	5	7 %
	4-year Degree	18	27 %
	Master's Degree	20	30 %
	PhD Degree	1	1 %
	Other	0	0 %
How many years have you been licensed?	1 - 5 years	1	22 %
	6 - 10 years	15	25 %
	11 - 15 years	17	12 %
	16 - 20 years	18	6 %
	More than 20 years	23	34 %
What corrective lenses do you wear while driving?	Glasses	21	31 %
	Contacts	15	22 %
	None	31	46 %
Do you experience motion sickness?	Yes	8	12 %
	No	59	88 %
Gender	Male	37	55 %
	Female	30	45 %
Age	**Minimum**	**Average**	**Maximum**
	19	35.89	73

4.8. Test Track Configurations vs Subjects' Response

Subjects of different age groups and genders were tested in all test track configurations to minimize age or gender bias on speed choice. Subjects' instantaneous speed at the onset of the circular yellow indication was taken from the control scenario (without CT) for the four control configurations. The box plot of the instantaneous speeds for the four control configurations is shown in Figure 4.5, which shows little variation between mean speeds.

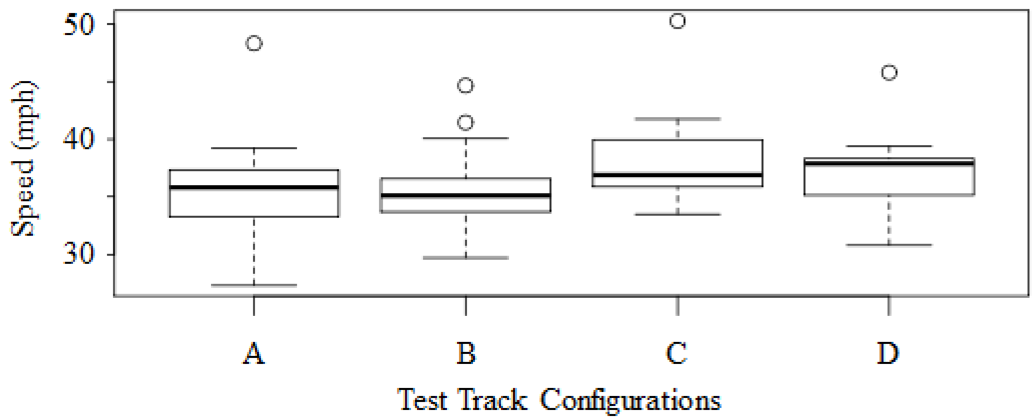


Figure 4.5: Control Test Track Configurations vs Instantaneous Speed

To provide additional evidence, a one-way ANOVA (Ramsey and Schafer 2013) was conducted to test the null hypothesis that the test track configuration had no effect on subjects' speed choice. The null hypothesis was failed to be rejected based on the test result (*p*-value = 0.369). Therefore, no evidence of variation in subjects' behavior due to different test track configurations was found.

Experiment 1 - Test of RSCT Effectiveness

The first driving simulator study was concerned with the effectiveness of RSCT. Experimental design, as explained in Section 4.4, was developed to respond to the research questions identified from the literature review and the results of the online survey. This section contains the objective and research hypotheses for RSCT experiment, variables of interest, data analysis, development of a statistical model to quantify the benefits of RSCT, and validation of the statistical model.

4.9. Research Objective and Hypotheses

The experimental design, as explained in Section 4.4, was developed to respond to the gaps in existing knowledge identified in the Chapter 2: Literature Review. These gaps in knowledge are expressed in terms of an overarching research objective and associated hypothesis.

4.9.1. Research Objective

RSCT are intended to alert drivers waiting at a signalized intersection of an imminent green signal. Drivers should anticipate the onset of the green due to the information on RSCT, thereby reducing reaction time and decreasing the headways of the first four to five vehicles in the standing queue. Therefore, a gain in traffic signal efficiency is expected by implementing RSCT due to a reduction in start-up lost time. Due to the constraints associated with in the number of scenarios that can be explored in a driving simulator study (Fisher, 2011), and to isolate the maximum possible effect, only the first headway (i.e., headway of the first vehicle waiting in a queue during a red signal) was measured. Therefore, the principal objective of conducting this experiment was to observe whether the presence of RSCT affected the first headway of a standing queue.

4.9.2. Research Hypotheses

The duration of time a driver waits at an intersection can affect their compliance to the signal. Longer signal delays (e.g., due to longer red lights) can reduce the attentiveness of drivers to the impending light change (Abou-Zeid et al., 2011; Hurwitz et al., 2013). This can potentially affect their perception reaction time at the onset of green. Therefore, the effect of the duration of the red signal on the first vehicle headway was also examined, as reflected in the following research hypotheses:

H_0 - There is no difference between the mean headways of the first vehicle in a discharging queue measured at the onset of the green indication at signalized intersections with and without RSCT.

H_0 - The mean headways of the first vehicle in a discharging queue measured at the onset of the green indication at signalized intersections are independent of the red signal durations.

4.10. Variables of Interest

In order to quantify the effectiveness of RSCT presented with different red signal durations, a statistical model was developed to estimate the first headway at a signalized intersection with CT. This section explains both the response and the explanatory variables considered to develop the model.

4.10.1. Independent Variables

The research hypotheses of the RSCT experiment suggested that the mean headway of the first vehicle is a function of two independent variables: presence of RSCT, and the duration of the red signal. Although, other factors, such as distraction or situational awareness, may influence driver behavior, the scope of the research was limited to investigate the performance of drivers operating without distraction as the most conservative assumption. To accommodate potential sources of variability from individual subjects, demographics such as age, gender, driving experience, and level of education, were also included in the analysis.

The first independent variable, presence of RSCT, had only two levels (present or not present) which enabled it to be included as a factor in the model. Although the duration of the red signal can have many different levels, only three commonly observed durations (20, 40, and 60 seconds) were tested in the experiment due to the limitation of the number of scenarios a subject can reasonably be exposed to. To clearly differentiate the effects of each level on the driver behavior, large enough gaps are considered between the levels.

Subjects' age was included as a continuous variable, while gender, education, and driving experience were included as factors of multiple levels. The levels of each independent variable were listed in Table 4.3.

Table 4.3: Levels of Independent Variables for Experiment 1

Name of the Variable:	**Category:**	**Levels:**
Presence of the RSCT	Binary	1, and 0 (present or absent)
Duration of Red Indication	Categorical	20, 40, and 60 seconds
Age	Continuous	Continuous (18 to 78 years)
Gender	Binary	M (Male), and F (Female)
Diving Experience	Categorical	Five levels as indicated in Table 4.2 (1 through 5)
Education	Categorical	Seven levels as indicated in Table 4.2 (1 through 7)

The first two variables, presence of RSCT and duration of red signal, were purely controlled, while subjects' driving experience and education were purely observed. Subjects' age and gender were not purely observed in the sense that the subject pool was selected to be representative of the Oregon driving population. That is, male female proportion and the age distribution of the sample were kept as reasonably close to the Oregon driving population as possible.

4.10.2. Dependent Variable

As RSCT can be seen by the drivers waiting at the intersection, their reaction time at the onset of green is likely to be reduced. It is not only the first driver in the queue whose reaction time will be impacted by RSCT, however, the first driver has the greatest potential for improved reaction time (Hurwitz et al., 2013). The first headway is larger than each of the subsequent headways and it controls the delay experienced by the rest of the queued vehicles (Figure 2.4). Therefore, the first headway was taken as a dependent variable for this experiment. Figure 4.2 explains how the first headway was measured in the simulator. The centroid position of the subject vehicle, its speed, and the signal display information were reported by the simulator every tenth of a second. This data and the position of the stop line were used to compute the first headway. The algorithm (Equation 4.1) of calculating the first headway adopted in this experiment (Roess et al., 2011) was as following:

$$\boldsymbol{Headway = T_2 - T_1} \tag{4.1}$$

Where,

T_2 = Time recorded when the signal state changed from Red to Green

T_1 = Time when the front axle cleared the stop line

The headways were measured at three intersections designed with three red signal durations (20, 40, and 60 seconds) from each test tracks (no CT and with CT). Thus, there were six data points generated for each test subject.

4.10.3. Data Exploration

As stated in the previous subsection, for each test subjects, the headways were measured with and without a RSCT and for three red signal durations, in six different headway measurements for each subject (Table 4.4).

Table 4.4: Six Measurements from Individual Test Subject

		RSCT Present? (N/Y):	
		No	**Yes**
Duration of Circular Red Indication (seconds)	20	H_{N20}	H_{Y20}
	40	H_{N40}	H_{Y40}
	60	H_{N60}	H_{Y60}

Each of the six measurements from Table 4.4 (HN20, HN40, etc.) had 55 observations from 55 test subjects. It is critical to understand that observations for H_{N20} and H_{Y20} were from the same experimental unit (i.e., a test subject), and thus, were not independent. Same logic applied to the other measurements listed in the Table 4.4. A visual representation of the variation in the data based on the two major controlled independent variables (presence of RSCT, and duration of red signal) was constructed (Figure 4.6). Although, variations due to different red signal durations and other sources, such as subjects' demographics, are unclear in the presentation, it is reasonable to say that headways appear to have been affected by the presence of CT. The presence of CT seemed to have a negative effect on the first headway. In other words, the first headway appeared to be decreased in presence of CT, as anticipated.

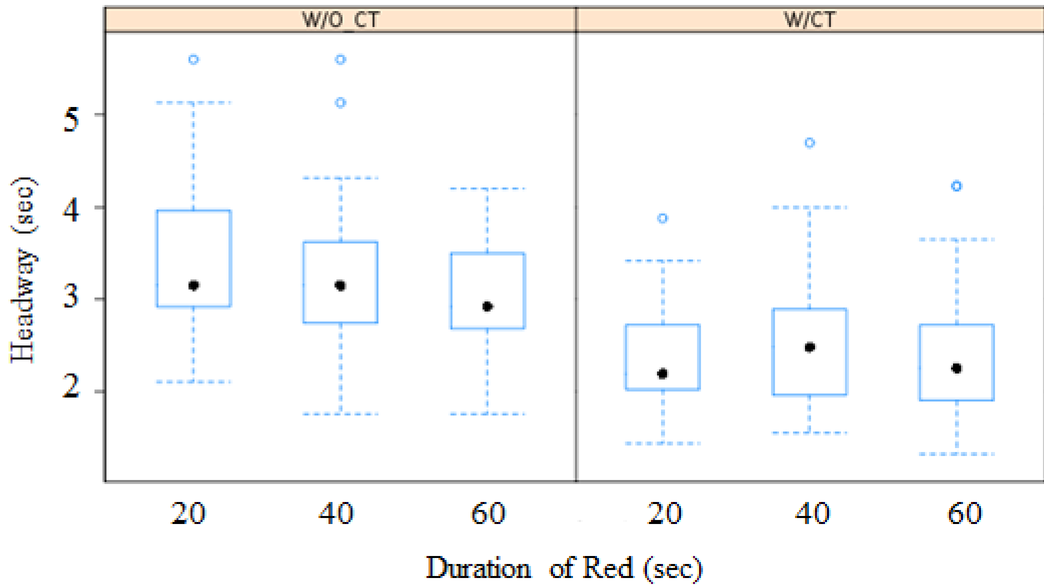


Figure 4.6: Box-plot of First Vehicle Headway Data

A logical step before developing a mathematical model was to statistically test whether the presence of CT truly affected the headways. As the data were collected from the same sample, paired t-tests were conducted to report the variations in the sample means for different scenarios. Although, the two values that made up each paired difference were not independent from each other, the paired differences were independent. Thus, the assumption of the independence of the paired differences, required for the tests, was not violated.

Three independent tests were conducted to compare the means of observations H_{N20} with H_{Y20}, H_{N40} with H_{Y40}, and H_{N60} with H_{Y60}. It can be seen from the test results (Table 4.5) that regardless of the red signal duration, the mean differences in first vehicle headways were statistically significant ($p < 0.001$). In addition, the mean headways for the scenarios where CT were present, were smaller in all three cases of red durations. This indicated that the presence of CT effectively reduced drivers' reaction time at the onset of green (0.44, 0.91, and 0.61 seconds for red duration equals to 20, 40, and 60 seconds, respectively).

Table 4.5: Results of Paired t-test (No CT and With CT)

Test Results:	**Duration of Circular Red Interval (seconds):**		
	20	**40**	**60**
Significant *p*-values	**< 0.001**	**< 0.001**	**< 0.001**
Mean of Differences (sec)	0.44	0.91	0.60
Relationship between Means	$H_{No\ CT} > H_{CT}$	$H_{No\ CT} > H_{CT}$	$H_{No\ CT} > H_{CT}$
95% Confidence Interval (sec)	0.25 – 0.62	1.26 – 1.56	0.39 - 0.80

4.11. Development of Mathematical Model

The experiment was designed with a plan to develop a mathematical model for the first headway with reasonable predictive power. This section includes a justification for the type of statistical model used, and an explanation of the model finalizing process.

4.11.1. Model Selection: Linear Mixed Effect (LME) Model

The variables included in the model were explained in Subsection 4.10.1 described all potential sources of variations, which were assumed to have a "fixed effect". It was also imperative to consider the variation in response due to the inherent differences among subjects; a "random effect".

In addition, a simple linear regression model requires independent observations, i.e., single measurement per experimental unit. However, in this experimental design multiple measures were taken per subject. Each subject gave six headway responses, which violated the independence assumption of a linear model. Multiple responses (in statistical terminology, "repeated measures") from the same subject cannot be regarded as independent (Winter, 2013). Every subject was different from one another, even when two subjects have identical demographics. Thus, a "mixed effect" model (Fox, 2002) was considered as the most appropriate mathematical model for the data from experiment 1.

In order to further explain the subjective variations, headways for five randomly selected males and females were plotted (Figure 4.7). As can be seen in the figure, the responses were visually different for different test subjects. Also noticeable, the between subjects variation was higher for females than for males. Because all test subjects were exposed to the same experimental treatments, this graphical presentation supports the argument that every test subject was indeed different from one another, which also supports the inclusion of subject in the model as a random effect.

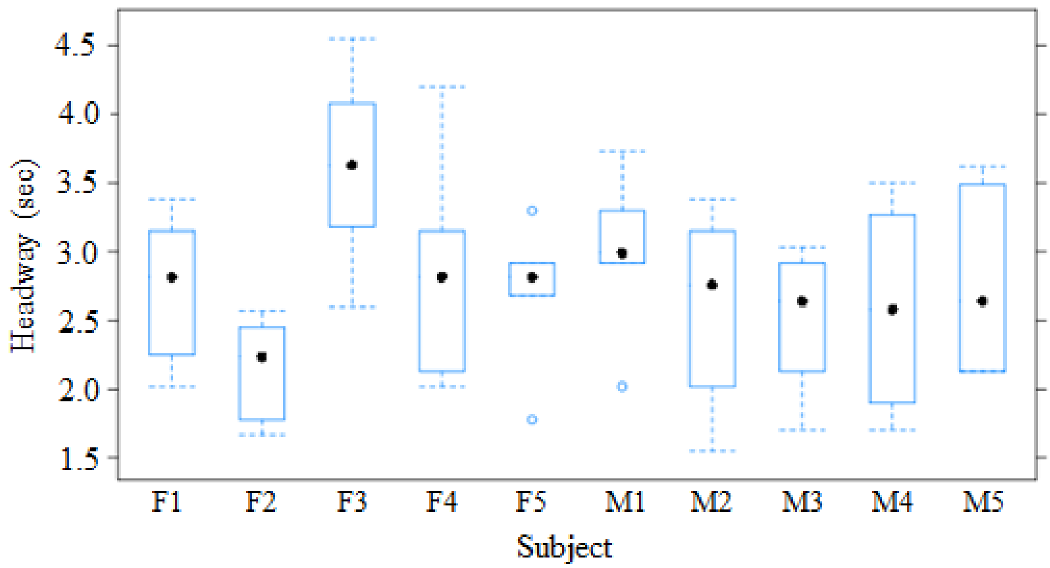


Figure 4.7: Box Plot of Headway Responses from 10 Subjects

4.11.2. Finalizing the Model

The entire data set was randomly split in half, for the purpose of developing the model with one half, and cross-validate the model with the second half. To divide the data, the responses from males and females of different age groups were placed into separate bins, and then the first half was picked randomly from each bin. Table 4.6 further explains the data splitting process.

Table 4.6: Splitting Data for Model Development and Cross-Validation

	Column1 AgeGroup1	**Column2** AgeGroup2	**Column3** AgeGroup3	**Sample**
# of Males (total data set)	M1	M2	M3	…so on
# of Females (total data set)	F1	F2	F3	
Data for Model (Randomly picked)	(M1/2) + (F1/2)	(M2/2) + (F2/2)	(M3/2) + (F3/2)	∑(Column N) (N = 1,2,…Number of age groups)
			Total	55/2 ≈ 28 subjects

As previously described, a Linear Mixed Effect (LME) model was considered best suited. For the LME, only a random intercept model was considered rather than selecting a model with both random intercept and random slope. In this model, a baseline difference in headway was accounted for, but whatever effect of the presence of RSCT might have on subjects, was assumed to be the same. This assumption might have compromised the precision of the model to some degree, but provided a simpler model, less complex than a random slope model. In order to justify this assumption, a validation attempt will be taken later, and the prediction accuracy will be estimated.

The full model (Equation 4.2) that included all explanatory variables was as following:

$$\boldsymbol{Headway_1} \sim (\mathbf{1}|\boldsymbol{Subject}) + \boldsymbol{RSCT} + \boldsymbol{Red} + \boldsymbol{Age} + \boldsymbol{Gender} + \boldsymbol{Edu} + \boldsymbol{DExp} \quad (4.2)$$

Where,

$Headway_1$ = First headway, or the headway measured in different test scenarios

$(1|Subject)$ = Random effect of subjects

$RSCT$ = Presence of RSCT; 1 if present, and 0 otherwise

Red = Duration of red signals; 20, 40, and 60 seconds

Age = Subject's age in years

$Gender$ = Subject's gender; factor with two levels

Edu = Subject's education; factor with seven levels

$DExp$ = Subject's driving experience; factor with five levels

The full model was taken as the starting point of selecting the final model. As shown in Table 4.7, the next iteration of the LME model was taken based on the AIC and significant fixed effect predictors. At each iteration, one non-significant fixed effect predictor was removed and the resulting model was compared with the previous model(s). For example, in iteration 2, the driving experience was excluded from the model as it was found non-significant.

In the fourth iteration, the coefficients of red-duration 60 seconds (0.24) and 40 seconds (0.023) were found statistically significant (*p*-value = 0.015) and non-significant (*p*-value = 0.76), respectively. Both of these coefficients represent the difference in coefficients with red-duration equals to 20 seconds. In other words, the first headway for red-duration 60 seconds is expected to be 0.24 seconds longer that the red duration 20 seconds, if all other predictors remain unchanged. Similarly, the difference between 20 seconds and 40 seconds is expected to be only 0.023 seconds. Due to this inconsistent results, it was of interest whether the whole variable improved the model fit. To check that, red-duration was excluded to fit the model in iteration 5 and a likelihood ratio test was conducted between the two linear models; one with, and one without the red-duration as a predictor. The likelihood ratio test was non-significant (*p*-value = 0.12), suggesting that excluding the red-duration from the model should not result in a significant reduction of its prediction power. As such, the final model (Equation 4.3) included subject as random effect, and presence of RSCT, and age as fixed effects.

Final Linear Mixed Model:

$$\boldsymbol{Headway_1} \sim (\mathbf{1}|\boldsymbol{Subject}) + \boldsymbol{RSCT} + \boldsymbol{Age} \qquad (4.3)$$

Table 4.7: Model Selection of RSCT Experiment

Iteration:	Model:	AIC:	Significant Fixed Effects:	Comments:
1	$\boldsymbol{Headway_1} \sim (\mathbf{1}\vert\boldsymbol{Subject}) + \boldsymbol{RSCT} + \boldsymbol{Red} + \boldsymbol{Age} + \boldsymbol{Gender} + \boldsymbol{Edu} + \boldsymbol{DExp}$	343.9	RSCT, and Red	-
2	$\boldsymbol{Headway_1} \sim (\mathbf{1}\vert\boldsymbol{Subject}) + \boldsymbol{RSCT} + \boldsymbol{Red} + \boldsymbol{Age} + \boldsymbol{Gender} + \boldsymbol{Edu}$	342.9	RSCT, and Red	Similar to Model 1
3	$\boldsymbol{Headway_1} \sim (\mathbf{1}\vert\boldsymbol{Subject}) + \boldsymbol{RSCT} + \boldsymbol{Red} + \boldsymbol{Age} + \boldsymbol{Gender}$	333.8	RSCT, Red, and Age	Improved model than 1 and 2
4	$\boldsymbol{Headway_1} \sim (\mathbf{1}\vert\boldsymbol{Subject}) + \boldsymbol{RSCT} + \boldsymbol{Red} + \boldsymbol{Age}$	331.4	RSCT, Red, and Age	Improved model than 1, 2, and 3
5	$\boldsymbol{Headway_1} \sim (\mathbf{1}\vert\boldsymbol{Subject}) + \boldsymbol{RSCT} + \boldsymbol{Age}$	328.5	RSCT and Age	**Final Model**

The numerical representation of equation is a bit complex than simple multiple linear regression due to the presence of random effect in the equation. The random effect is presented in matrix form including one intercept for each test subject. The equation can be written in the following general form (Fox, 2002):

$$\boldsymbol{Y_i} = \boldsymbol{X_i\beta} + \boldsymbol{Z_i b_i} + \boldsymbol{\varepsilon_i} \tag{4.4}$$

Where,

$\boldsymbol{Y_i}$ = $n_i \times 1$ response vector for observations in i-th group

$\boldsymbol{X_i}$ = $n_i \times p$ model matrix for the fixed effects for observations in group i

$\boldsymbol{\beta}$ = $p \times 1$ vector of fixed-effect coefficients

$\boldsymbol{Z_i}$ = $n_i \times q$ model matrix for the random effects for observations in group i

$\boldsymbol{b_i} =$ q × 1 vector of random-effect coefficients for group i

$\boldsymbol{\varepsilon_i} =$ n_i × 1 vector of errors for observations in group i

Numerically, the final model is as following (Equation 4.5):

$$\underbrace{\begin{pmatrix} \boldsymbol{Headway_{11}} \\ \boldsymbol{Headway_{12}} \\ \vdots \\ \boldsymbol{Headway_{128}} \end{pmatrix} = \begin{pmatrix} 3.54 \\ 3.53 \\ \vdots \\ 3.79 \end{pmatrix} \begin{pmatrix} X_1 \\ X_2 \\ \vdots \\ X_{28} \end{pmatrix}}_{\text{Random Effect}} + \underbrace{\begin{pmatrix} -0.72 \\ -0.72 \\ \vdots \\ -0.72 \end{pmatrix} \boldsymbol{CT} + \begin{pmatrix} -0.013 \\ -0.013 \\ \vdots \\ -0.013 \end{pmatrix} \boldsymbol{Age}}_{\text{Fixed Effects}} \qquad (4.5)$$

Where,

$Headway_{1i}$ = The first headway for i-th subject

$X_i =$ 1 for i-th subject, and 0 otherwise.

The coefficients of intercept in Equation 4.5 are different, representing the random effect of subject. The coefficients for the fixed effect variables are the same because the random slopes for the by-subject effect were not considered.

In general, the model assumptions, such as linearity, normality, and homoscedasticity hold. The fitted values of headways were computed from the model and a paired t-test was performed to test the difference between the headways of with and without RSCT. The t-test result indicated the difference in headways (0.73 seconds) was statistically significant (*p*-value < 0.001).

The residuals were plotted in the form of a histogram (Figure 4.8), and as expected, they were approximately normally distributed around a mean zero. The residual vs. fitted values plot, and the normal quantile-quantile plot (Appendix B) prove the assumptions of homoscedasticity and normality, respectively.

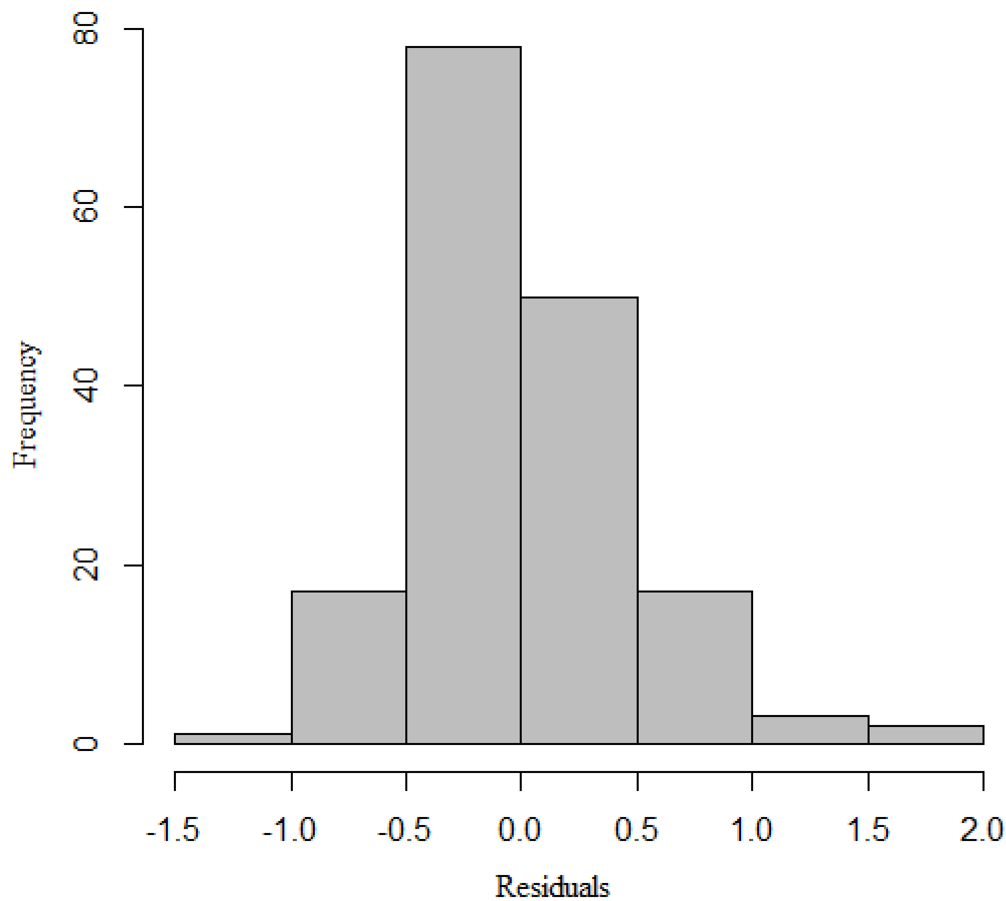


Figure 4.8: Histogram of the Residuals

4.11.3. Validation of the Model

In an attempt to validate the model, the second half of the data (27 subjects) was used, and the headways were considered as the "observed" responses, while headways computed from the model were taken as the "predicted" responses. The results of the comparison between the predicted and the observed responses are presented in Table 4.8.

Table 4.8: Validation of the Model

	Mean First Headway	
	Without RSCT	With RSCT
Predicted (Model)	3.19	2.46
Observed	3.26	2.35
Two sample t-test result	No evidence of difference (*p*-value = 0.46)	No evidence of difference (*p*-value = 0.26)
Prediction accuracy	97.8 %	95.5%

The comparison of the mean headways showed no significant difference for both scenarios - presence and absence of RSCT. Thus, it can be concluded that the mathematical model developed using the first half of the data was capable of predicting the variation in headways explained by the second half of the data.

Experiment 2 - Test of Effectiveness of GSCT

The second driving simulator study was concerned with the effectiveness of GSCT. This section describes the hypotheses variables of interest, and data analysis for the GSCT.

4.12. Research Objective and Hypotheses

The gaps in the knowledge regarding the application of GSCT in the US are expressed in terms of an overarching research objective and associated hypotheses.

4.12.1. Research Objective

GSCT alert drivers approaching a signalized intersection of an imminent change in right-of-way. By displaying the number of seconds left before the signal turns yellow, GSCT are expected to minimize the Type-II DZ conflict and minimize the number of drivers who incorrectly choose to proceed through the intersection. However, the existing literature evaluating the performance of GSCT, as explained in Chapter 2, revealed conflicting findings regarding the efficacy of GSCT. Instead of slowing down and stopping at intersection due to upcoming yellow and red signals, some drivers actually exhibited a tendency to accelerate during the end of green phase in the presence of GSCT. Inconsistency in the results of published literature and the generally accepted differences in driver behavior across geographic and cultural characteristics motivated the author to examine how US drivers' (specifically those in Oregon) respond to GSCT at signalized intersections.

4.12.2. Research Hypotheses

The research hypotheses of the GSCT driving simulator study, derived from the research objective explained in subsection 4.12.1, included:

H_0 - There is no significant difference in the probability to stop functions at the onset of the yellow indication at signalized intersections with and without GSCT.

H_0 – There is no difference in deceleration of the drivers who decide to stop at the onset of the yellow indication at signalized intersections with and without GSCT.

Installing GSCT will result in the greatest safety benefit if the null hypotheses are determined to be false. Confirmation of the first null hypothesis would mean that GSCT fail to increase drivers' probability of stopping before the onset of the red signal, resulting in no change in the probability of RLR. If the second null hypothesis is true, installation of GSCT would not improve the unsafe condition of drivers' dilemma in close proximity to the intersection.

4.13. Variables of Interest

A statistical model of drivers' stopping probability at a signalized intersection was developed as a means of quantifying the safety benefits of GSCT. This section explains both the response and the explanatory variables considered to develop the stopping probability model.

4.13.1. Independent Variables

Hurwitz et al. (2012) applied Fuzzy Logic (FL) to develop a model for the probability to stop function based on empirical vehicle position data, while Moore and Hurwitz (2013) used driving simulator data to build a FL model based on the Time-To-Stop-Line (TTSL), which is a function of vehicle position and speed. The model, shown in Figure 4.9, was developed using trapezoidal functions in MATLAB. Rakha et al. (2007) performed a field study on 60 drivers and evaluated their behavior at the onset of yellow indication. FL was used to model drivers' uncertainty in the decision-making process at the DZ. Based on the successful application of FL in a variety of previous literature; it is a strong choice as an analytical technique to differentiate the impact of the GSCT on the probability to stop function. Therefore, the presence of GSCT and the TTSL were included in the model as binary and continuous variables, respectively. The TTSL could also be used as a categorical variable of ten levels. The justification of using the TTSL as a categorical variable was that in reality the nature of this variable is continuous rather than discrete.

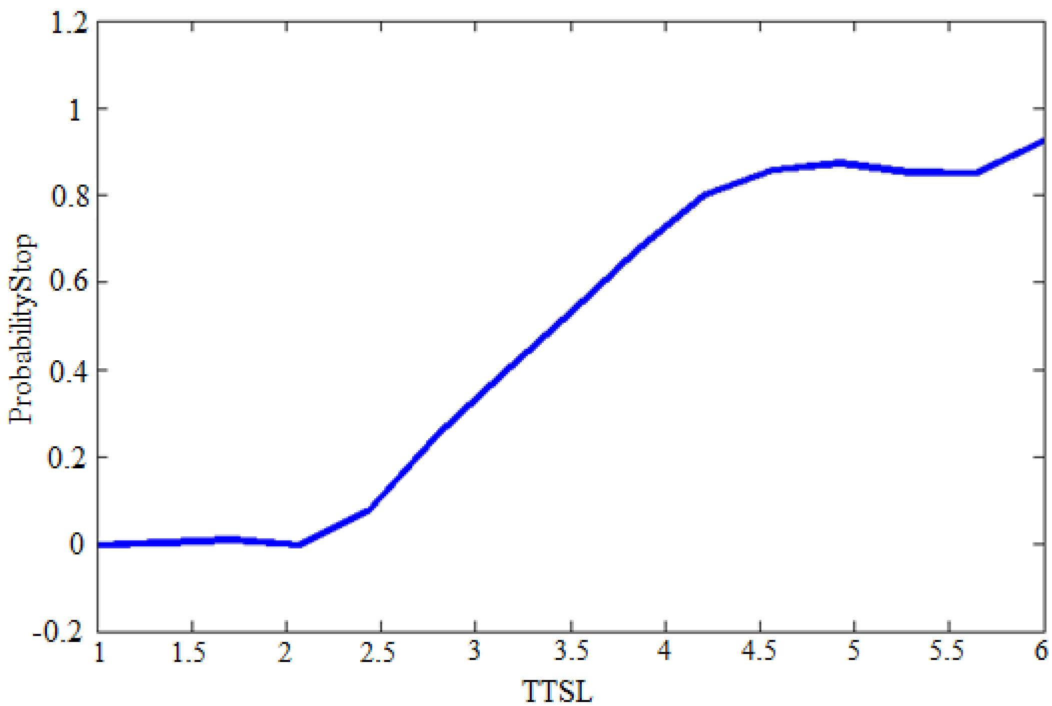


Figure 4.9: TTSL-Based FL Model (Moore & Hurwitz, 2013)

Moore and Hurwitz used 11 TTSL values to develop the model ranging from 1.0 to 6.0 seconds in 0.5 seconds intervals to ensure that driver behavior was captured across the entire Type-II DZ region. They found that nearly 100% of the drivers proceeded through the intersection when presented the yellow signal at a distance 2 seconds or less and stopped as a distance of 6 seconds or more. Based in part on the result from previous research, and a desire to reduce the complexity of the experimental design, TTSLs from 1.5 to 6 seconds at 0.5 second increments were considered in experiment 2. Table 4.9 lists the independent variables and their levels.

Table 4.9: Independent Variable and Levels for Experiment 2

Name of the Variable:	**Category:**	**Levels:**
Presence of the GSCT	Binary	1, and 0 (present or absent)
TTSL (seconds)	Continuous	1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, and 6.0 seconds
Age	Continuous	Continuous (18 to 78 years)
Gender	Binary	M (Male), and F (Female)
Diving Experience	Categorical	Five levels as indicated in Table 4.2 (1 through 5)
Education	Categorical	Seven levels as indicated in Table 4.2 (1 through 7)

4.13.2. Dependent Variable

Drivers' difficulty in determining the correct response at the onset of the yellow indication while approaching a signalized intersection could be mitigated by GSCT. That is, because Oregon uses a restrictive yellow law, drivers' probability to stop on a yellow signal is likely to increase in presence of GSCT.I If true, it would prove the effectiveness of GSCT mitigating Type-II dilemma zone conflicts. Therefore, the probability to stop function was established as the variable of interest to determine in this experiment. Additionally, drivers' stop-or-go decision was coded as a binary variable (i.e., categorical variable of two levels) in the mathematical model to estimate the probability to stop for a given combination of explanatory variables.

In the driving simulator, vehicle speed, acceleration, and signal state data were collected from ten intersection scenarios which were included in the GSCT experiments. Java script based sensors were used to continuously monitor the driver's position and speed to calculate the TTSL and change the signal state from green to yellow when the vehicle was at a desired distance (e.g., TTSL = 3.0 seconds) from the stop line. The final driver decision to stop or go was extracted from the simulator data output files.

4.14. Model Development

The experiment was designed to produce data relevant to the development of a mathematical model for the driver's decision in response to the onset of the yellow indication. The model development required an assessment of the correlation between variables, a justification for the type of statistical model used an explanation of the model finalizing process, and finally the model validation.

4.14.1. Data Exploration

For each test subject in the experiment, the driver's decision to stop or go through the intersection on the yellow interval was recorded 10 times in both with and without GSCT scenarios. That is, each test subject was observed interacting with 20 intersections that were included in the model. Thus, the final data set consisted of 1100 intersection interactions from 55 test subjects. Like the previously developed mathematical models (e.g., headway model in RSCT experiment), driver demographics were also considered.

A graphical display of the correlation of model variables was prepared using R's data visualization package "*pair()*" (Figure 4.10). While most of the plots failed to convey meaningful information due to the categorical nature of the variables and data overlapping, two noticeable correlations (marked by the red box) were Age vs. Diving Experience and Age vs. Education.

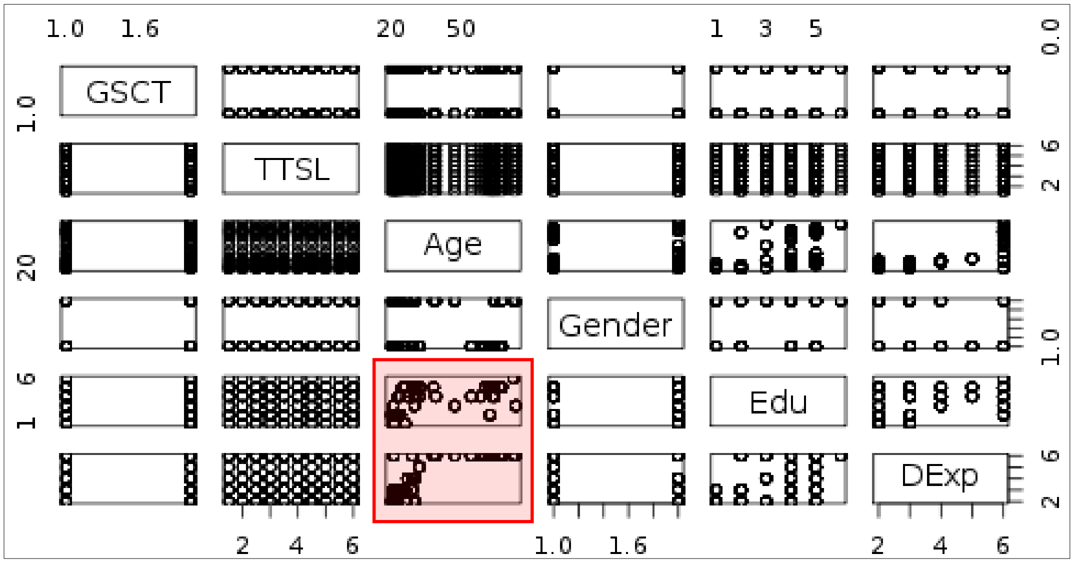
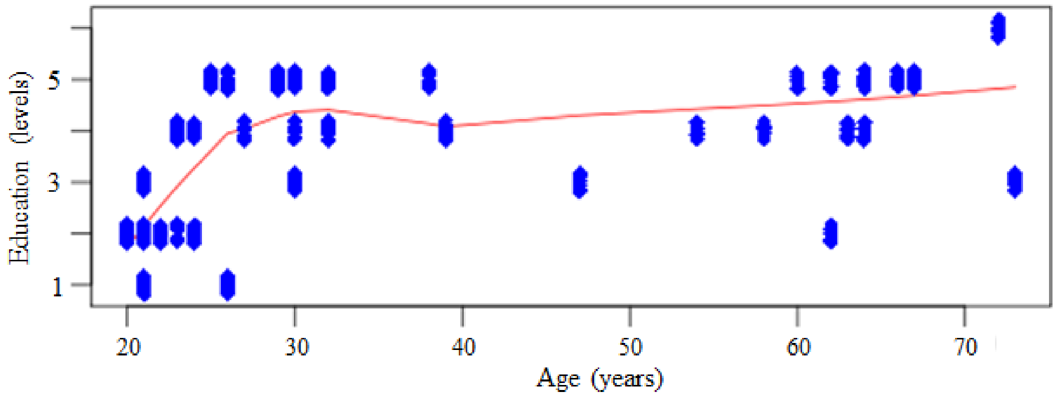
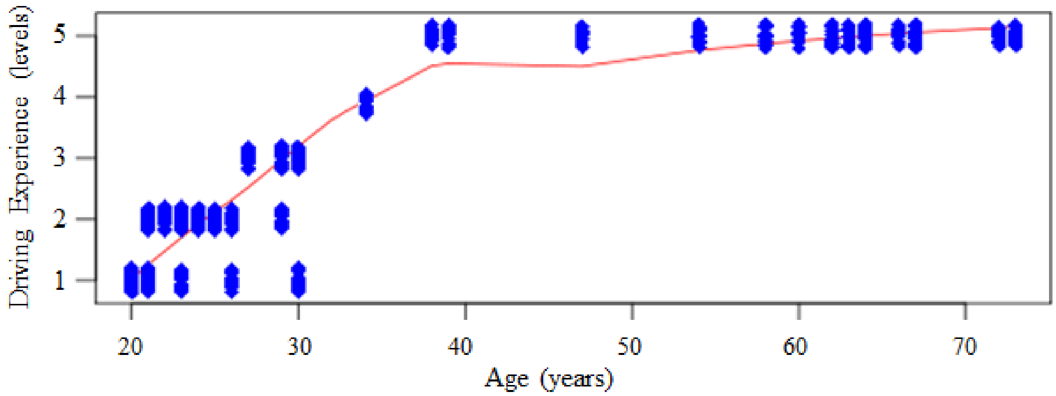


Figure 4.10: Correlation between Predictor Variables

For a better representation, the two correlations were separately plotted in Figure 4.11(a) and (b). Trends of increasing levels of both education and driving experience related to age were observed. However, driving experience and educations were still included in the full mathematical model to test for statistical significance.



(a)



(b)

Figure 4.11: Correlations between Variables: (a) Age vs. Driving Experience (b) Age vs. Education

For additional data visualization a boxplot (Figure 4.12) was constructed to display the association of the two principal predictors of interest with the response variable. Visual inspection of Figure 4.12 provides preliminary evidence that the presence of GSCT influenced driver's decision of stop/go at the onset of the yellow indication. For example, the median TTSL for the drivers who decided to go through the intersection was 2.5 seconds in absence of the GSCT, whereas it was 2.0 seconds when GSCT were present. Similarly, the median TTSL for drivers who chose to stop was 5 seconds and 4.5 seconds in absence and in presence of GSCT respectively. This leftward shift in presence of GSCT suggested an improvement in driver's stopping behavior. They were more prone to stop at a distance closer to the intersection when a GSCT was present than in absence of GSCT.

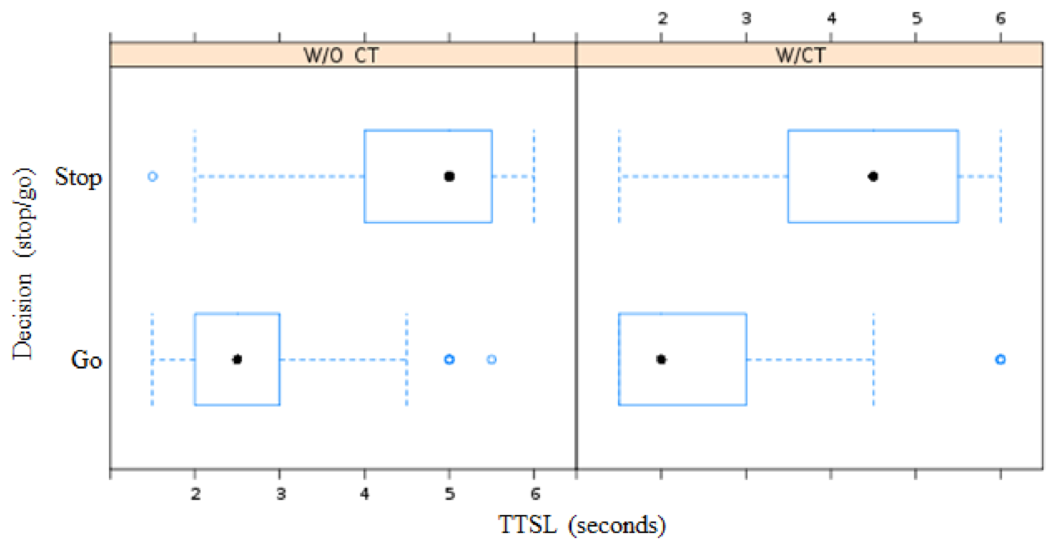


Figure 4.12: Boxplot of Driver's Stopping Decision Data

For this experiment, a high resolution (i.e., subject level) display of the raw data, shown in Figure 4.13, constructed a better representation of drivers' decision with respect to the TTSL and the presence of GSCT. In presence of GSCT, the number of instances when drivers chose to stop increased compared to the absence of GSCT (Figure 4.13).

The TTSL description of the boundary conditions of a DZ suggests that it is located between 2.5 to 5.5 seconds upstream from the intersection (Chang et al., 1985). From the visual inspection of Figure 4.13, it can be seen that in presence of GSCT (TTSL = 3.5 seconds), the number of stoping instances increased when the drivers were in the DZ, i.e., a TTSL equal to 2.5 to 5.5 seconds upstream of the traffic signal. Similar diagrams for TTSL equals to 1.5, 2.0, 2.5, 3.0, 4.0, 4.5, 5.0, 5.5, and 6.0 seconds were shown in Apendix C.

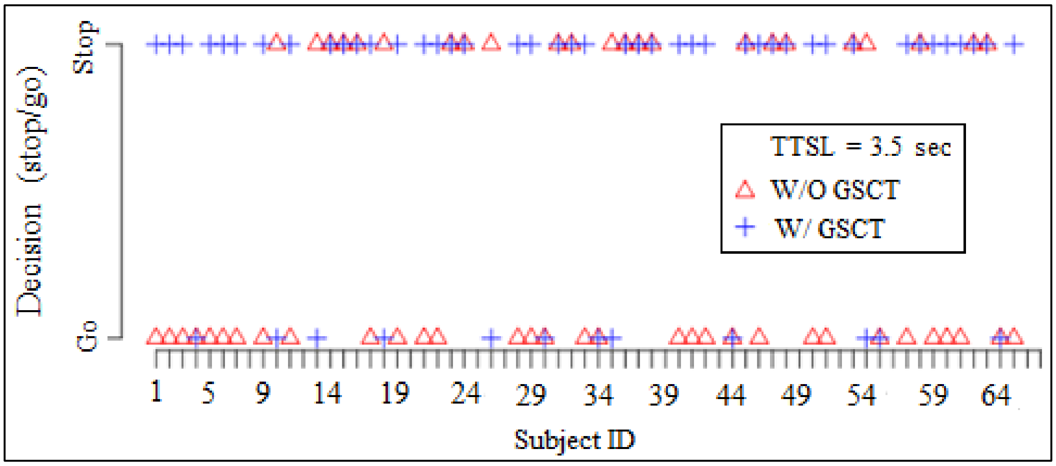


Figure 4.13: Driver's Decision with Respect to TTSL and Presence of GSCT

4.14.2. Model Selection: Generalized Linear Mixed Model (GLMM)

The dependent variable to be modeled from the data was a binary response (stop/go on yellow) from the drivers. For a continuous response variable, a linear regression model is generally sufficient (Ramsey and Schafer, 2002). However, classical statistical procedures often fail to deal with non-normal data such as counts or proportions, like the driver response in this experiment. In addition, as explained in Section 4.11, the data included a random effect from the subjects. A means of capturing within subject variations observed in repeated measures needed to be present in the model. One effective and flexible approach to analyze non-normal data when random effects are present is called a Generalized Linear Mixed Model (GLMM), which accounts for both the fixed effects and the random effects in the response. The variables included in the model listed in Table 4.9, described all potential sources of variations, which were assumed to have fixed effects. A random effect was also included to account for the inherent differences among subjects.

Following the same procedure described in Table 4.6, the entire data set was split in half. The model was developed using one half, and cross-validation of the model was attempted with the second half.

A GLMM with a random intercept was considered best suited model for this experiment. The full model (Equation 4.6) that included all explanatory variables was as following:

$$\boldsymbol{Logit(p)} \sim (\mathbf{1}|\boldsymbol{Subject}) + \boldsymbol{GSCT} + \boldsymbol{TTSL} + \boldsymbol{Age} + \boldsymbol{Gender} + \boldsymbol{Edu} + \boldsymbol{DExp} \quad (4.6)$$

Where,

p = Probability that a driver will stop at the onset of yellow

$(1|Subject)$ = Random effect of subjects

$GSCT$ = Presence of GSCT; 1 if present, and 0 otherwise

$TTSL$ = Time to stop line in seconds (1.5 through 6.0 with 0.5 seconds increment)

Age = Subject’s age in years

$Gender$ = Subject’s gender; factor with two levels

Edu = Subject's education; factor with seven levels

$DExp$ = Subject's driving experience; factor with five levels

The full model was taken as the starting point for arriving at the final model. As shown in Table 4.10, the next iteration of the model included the random effect, but excluded the non-significant fixed predictors (based on p-values). The AIC value for this first version of the reduced model (405.4) was compared to that of the full model (413.3), and was found to be very similar. This suggested that the removal of statistically non-significant predictors did not result in significant loss of the prediction power.

Table 4.10: Model Selection of GSCT Experiment

Iteration #:	**Model:**	**Significant Predictors:**	**Comments:**
1	$\boldsymbol{Logit(p) \sim (1\|Subject) + GSCT + TTSL + Age + Gender + Edu + DExp}$	GSCT, and TTSL	GLMM (Full model with random effect)
2	$\boldsymbol{Logit(p) \sim (1\|Subject) + GSCT + TTSL}$	GSCT, and TTSL	GLMM (Reduced model with random effect)
3	$\boldsymbol{Logit(p) \sim GSCT + TTSL}$	GSCT, and TTSL	GLM (Reduced Model without random effect) **Final Model**

In the first iteration it was observed whether the random effect included in the model was indeed meaningful. One way of explaining this was to observe the summary statistics for the random effect from the GLMM (Appendix B), which showed that the variance in the response due to the random effect was very close to zero ($1.029e^{-05}$), suggesting that the variation in the response was not sourced from the random effect of predictor. As such, the random effect of subjects was removed in the third iteration. Exclusion of the random effect from the model resulted in a Generalized Linear Model (GLM), or logistic regression model (LRM). Thus, the final model (Equation 4.5) was a GLM with two predictors; one binary (GSCT) and one continuous (TTSL).

Final Generalized Linear Model:

$$\boldsymbol{Logit}(\boldsymbol{p}) \sim \boldsymbol{GSCT} + \boldsymbol{TTSL} \tag{4.5}$$

It can be noticed in Equation 4.5 that in contrast to the mathematical models developed for the online survey and experiment 1, drivers' age was found statistically non-significant. This suggests that drivers' stopping behavior on the circular yellow indication cannot be explained by their age.

In order to be able to numerically calculate the probability to drivers' stop function, the final model was transformed from a logit to a probability (Equation 4.7). The transformation is as following:

$$\boldsymbol{Logit(p) = log\left(\frac{p}{1-p}\right) = a + bx + cy}$$

Or, $$\boldsymbol{p = \frac{1}{1+e^{-(a+bx+cy)}}} \quad (4.7)$$

Where,

p = Probability that a driver will stop at the onset of yellow

a, b, c = Coefficients of the predictors in the final model

x, y = The two predictors, GSCT and TTSL

The final model (Equation 4.8) was derived by plugging in the values of the coefficients a, b, and c in Equation 4.8, which is as following:

$$\boldsymbol{p} = \frac{1}{1+e^{-(-5.90+1.05*GSCT+1.71*TTSL)}} \quad (4.8)$$

4.15. Model Validation

Model validation involved a three-step process; 1) the observed deceleration rates in the study were compared to previous studies, 2) the model was cross-validated with half of the data set, and 3) The stopping probabilities were compared with other TTSL based FL models.

4.15.1. Deceleration Rates

The first step of model validation was to justify the use of the driving simulator by validating the observed deceleration rates. The ITE recommended value of the deceleration rate to compute the change interval is 10 ft/sec^2 (ITE, 1999). The observed decelerations were compared to this threshold as well as to the results of other previous studies. The average deceleration rates were computed by dividing the instantaneous speed (at the moment the brake was first applied) with the time taken to come to a complete stop. Figure 4.14 shows the cumulative distribution of the observed decelerations for the two scenarios, with and without GSCT. It can be noticed that the observed deceleration rates were higher in absence of the GSCT. The mean deceleration rate with GSCT was 10.69 ft/sec^2 (95% confidence interval: 11.35 and 10.03 ft/sec^2) and 9.19 ft/sec^2 (95% confidence interval: 8.51 and 9.95 ft/sec^2) without. A statistically significant difference (p-value = 0.016) was found between the deceleration rates observed in the two conditions.

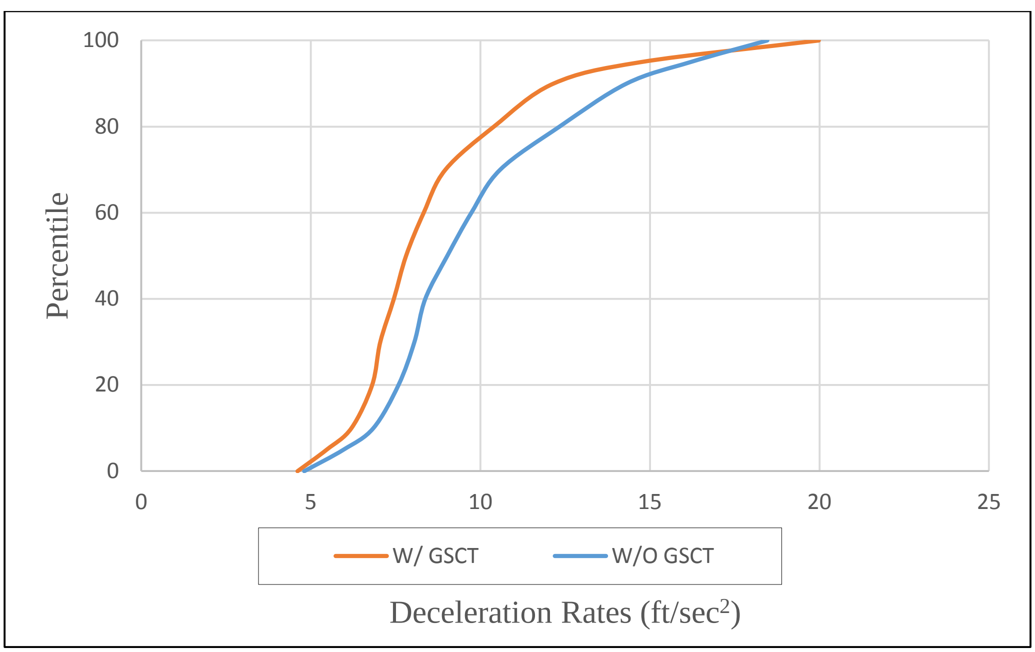


Figure 4.14: Cumulative Deceleration Rates - with and without GSCT

The cumulative distribution of deceleration rates observed in scenario with no GSCT was also compared with that found in several previous studies (Figure 4.15). As shown, the deceleration rates observed from the simulator study (without GSCT) are consistent with previous field research.

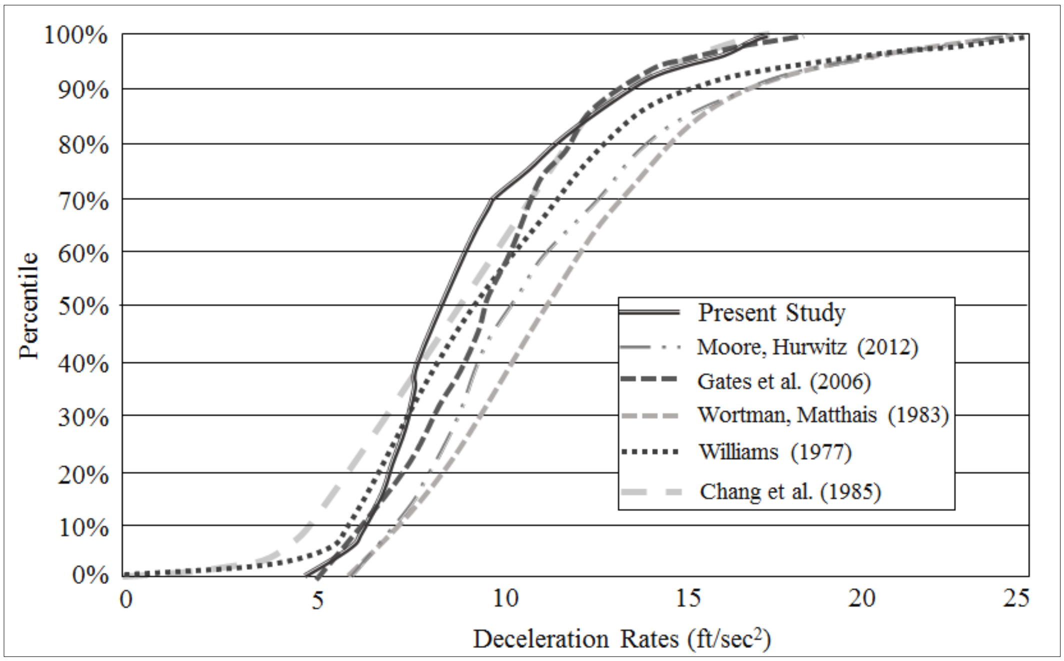


Figure 4.15: Comparison of Cumulative Deceleration Rates

4.15.2. Cross-validation of the Model

Data regarding the presence of GSCT and TTSL from the second half of the database (27 drivers) were input into the model, and a probability to stop on yellow was calculated for each subject interaction with the signal. The following algorithm (Equation 4.8) was applied to identify the conditions of stopping before the intersection, and continuing through the intersection:

$$\boldsymbol{Stopped_{predict}} = \begin{cases} \boldsymbol{yes}, & \boldsymbol{p \geq 0.5} \\ \boldsymbol{no}, & \boldsymbol{p < 0.5} \end{cases} \tag{4.8}$$

Where,

$Stopped_{predict}$ = Predicted behavior of the driver at the intersection (stop/go through the intersection on yellow indication)

p = Calculated probability to stop before intersection using Equation 4.7

The calculated values of drivers' stopping probability were compared to the actual observed behavior of the 27 drivers, and the predictive power of this model was estimated (Table 4.11).

Table 4.11: Prediction Accuracy of the LRM Model for GSCT

		Predicted:		% **Correct**:
		Stop:	**Go:**	
Observed:	Stop	295	32	90.2%
	Go	29	184	86.4%
			Total	88.7%

As shown in Table 4.11, the mathematical model developed in this study correctly predicted the behavior for the remaining 27 test subjects with an accuracy of 88.7%. In a similar study, Moore and Hurwitz (2012) was able to correctly predict driver's stopping behavior with an accuracy of 90% with their TTSL based FL model.

4.15.3. Probability to Stop

It was anticipated that the LRMs developed from the two scenarios (i.e., with and without GSCT) should yield different probability distributions. A comparison between the current model (LRM) for with GSCT and Moore and Hurwitz's FL model should be significantly different. However, the probability distribution of the current model for without GSCT should be very similar to the FL model.

At the onset of the yellow indication, drivers are presented with the difficult task of assessing their speed and position with respect to a downstream intersection, and deciding whether to go or stop. FL is capable to predicting the outcome of drivers' decision making in the type II dilemma zone (Moore & Huwitz, 2013; Rakha et. al., 2007). In order to validate the model developed in this study, it was compared with both Moore and Hurwitz (2013) and Rakha's (2007) TTSL based FL model. At first the probability to stop function was calculated for the 10 TTSLs by using both the LRM model and the FL model. The calculated values of the probability were shown graphically (Figure 4.16). The blue and red lines represent the probability to stop functions in the presence and absence of GSCT respectively, calculated from the model developed in this study. The green line represents the probability to stop function derived from the FL model (Moore & Huwitz, 2013). From visual inspection it can be said that the probability to stop at a certain value of TTSL in presence of GSCT were higher than that calculated from the FL model. A similar comparison of the probabilities calculated from the W/O GSCT_LRM and Moore and Hurwitz's FL model (which are essentially the same cases) would result in smaller differences.

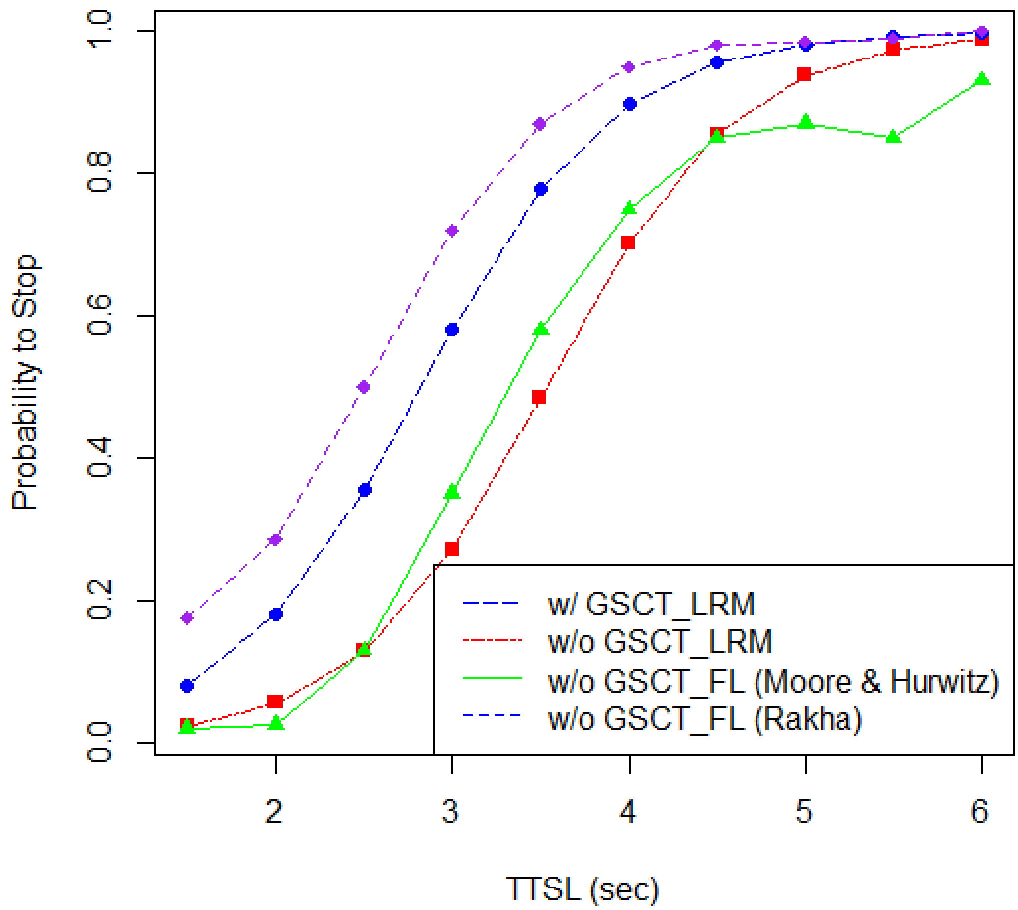


Figure 4.16: Comarison between the LRM and the Moore & Hurwitz's FL Model

In order to test if the w/o GSCT_LRM and w/o GSCT_FL (Moore and Hurwitz) model yields similar probability distribution, a non-parametric goodness-of-fit test, specifically a two-sample Kolmogorov-Smirnov test, was performed to compare the distributions. The null hypothesis that the distributions were the same, was failed to be rejected from the test result (p-value = 0.759).

One of the research objectives was to quantify the benefit of using the GSCT in terms of the improvement in driver's probability to stop at the intersection, i.e., the vertical separations between the blue and the red lines in Figure 4.16. The difference in probabilities (Δp) was calculated from the derived model and shown in Figure 4.17. It can be observed that for cases of TTSLs, the values of Δp are positive, which suggests that the presence of GSCT always increases drivers probability to stop on yellow indication.

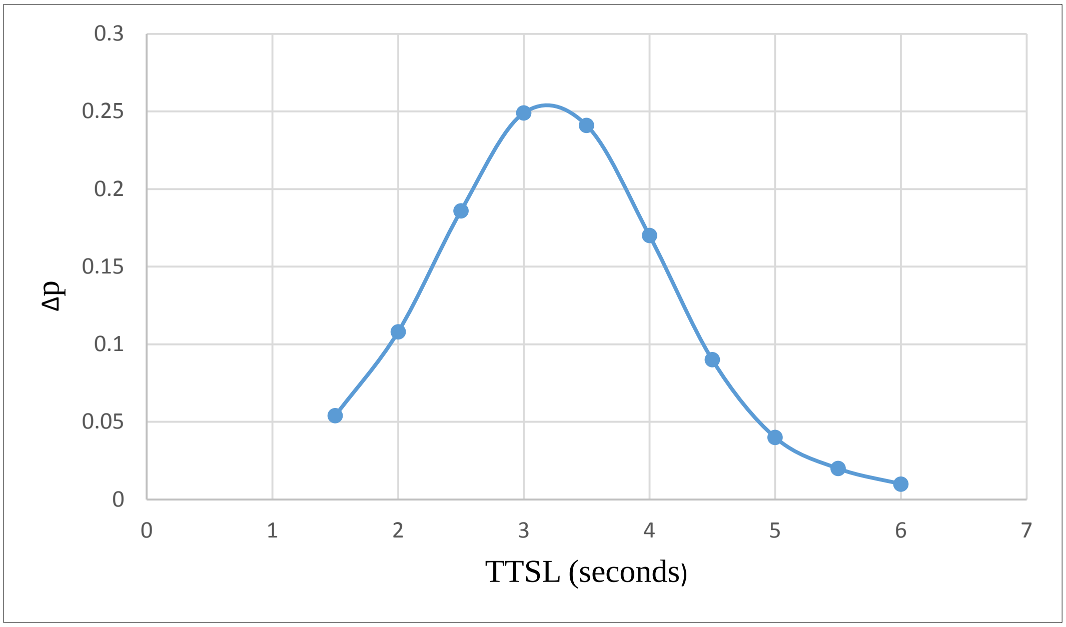


Figure 4.17: Difference in Driver's Stopping Probabilities (Δp) with TTSL

In the DZ study, Moore and Hurwitz (2012) found that most of the drivers go through the intersection if the TTSL is equal or less than 2 seconds, and stop at the intersection if the TTSL is equal or greater than 4.5 seconds. Thus, it can be said that the DZ is generally located between these two TTSL cases, for the particular intersection condition examined by Moore and Hurwitz. Therefore, the area under the curve between a TTSL equal to 2 and 4.5 seconds was divided by the difference in TTSL (4.5-2.0 = 2.5 seconds) to estimate the overall increase in the probability to stop resulting from the presence of GSCT. The overall increase in the probability was found to be 13.10%. That is, the presence of GSCT is expected to increase driver's probability to stop in the DZ by 13.10%.

Chapter 5 Conclusions

The Conclusions Chapter consists of three sections: a summary of the key findings, brief descriptions of how the research questions stated in Chapter 3 and Chapter 4 were addressed by this work, and a list of recommendations for future study.

5.1. Key Findings

The key findings were categorized based on the experimental mediums (online survey or driving simulator) applied in this research. The online survey findings were principally focused on the comprehension of and preferences towards TSCT, whereas the driving simulator study was concerned with drivers' response to TSCT recorded in the OSU simulator.

5.1.1 Preliminary Examination of TSCT

An online survey was used as a robust experimental medium to evaluate the comprehension of and preference towards TSCT by Oregon drivers. While it provided the advantage of accessing a relatively larger and more geographically diverse sample to represent the target population, it introduced the risk of untrue/misleading input from the participants. The survey analysis and resulting inferences, assumed that all recorded responses were authentic.

TSCT demonstrated an overall comprehension rate of 82%, with approximately 5% of incorrect responses, 6% expressing some degrees of confusion (although mostly correct), and 8% suggesting no knowledge of TSCT. The author's use of inter-rater reliability to code open-ended responses adds confidence that the responses were correctly interpreted.

The comprehension standard set forth in this study originated from the ANSI Z535.3 standard in 1998 and 2002, which recommends a minimum comprehension rate of 85% as an acceptable threshold for signage. The overall observed comprehension was very close to this limit considering that the TSCT were introduced for the first time to most participants without supplemental instruction. Furthermore, the static nature of the TSCT presented in the online survey imposed an additional challenge for participants as the CT were not animated. . Therefore, the author concluded that TSCT comprehension reported in the static online survey meets an acceptable threshold for driver comprehension and could be considered for field implementation.

While investigating the causes of errors in participant responses, it was discovered that the majority of incorrect responses were related to misinterpreting TSCT as PCT. The use of PCT at signalized intersections was mandated by the MUTCD in 2003, and their application has become widespread in the US. Currently, PCT are the only countdown device in use at signalized intersections. This is likely the proximate cause for participants having misinterpreted TSCT as PCT.

The possibility that one of the TSCT applications might have higher comprehension rates than another was examined. The pair-wise comparison of the comprehension scores of different TSCT applications (e.g., RSCT vs GSCT) suggested no statistically significant difference (e.g., the p-value for RSCT and GSCT comparison was 0.803). As such, it was concluded that all three applications of TSCT received similar comprehension scores.

A linear logistic regression model was developed based on participant demographics. The initial model considered age, gender, education, and driving experience as potential predictors of participants' TSCT comprehension, but only the age was found to be a significant predictor to explain the variation in observed comprehension scores. However, the author suspects that the influence of age in the model may have resulted from the under-representation of age group 65+ in the data (Figure 3.2), where only 41% of responses were correct.

The reduced model was capable of predicting the probability of whether a given driver will correctly comprehend the TSCT display at a signalized intersection. The prediction accuracy of the model was found to be approximately 75%. Considering the minimum input requirements (i.e., age) and the challenge of modeling human behavior and decision making, the author concludes that it is a reasonable level of predictive accuracy, and thus, can be effectively applied to predict the comprehension of TSCT by Oregon drivers. One potential application is to define the driver population that lacks comprehension of TSCT, and to target public education and information campaigns to that driver group, in advance of TSCT installation. However, one should understand the limitation of the inferences while using the model. From example, the model only included Oregon drivers between

18 and 78 years old. Therefore, any inference made on driver comprehension of TSCT is limited to Oregon drivers of a comparable age.

Survey participants' preferences of different applications and configurations of TSCT were also examined. It was found that GSCT were the most useful application of TSCT; fifty percent of the participants favored GSCT over YSCT or RSCT. This result suggests that participants recognized the safety benefits of GSCT.

A statistically significant difference was found between participants' preferences for four TSCT configurations (*p*-value < 0.001). There was convincing evidence that display alternative B (one common timer for all signal indications, placed next to the signal head) was the most preferred among the four tested configurations tested. Alternative C (LED lights radially placed around each signal indication) was found to be the least preferred configuration. From this result, the author selected alternative B for inclusion in the driving simulator study.

The above discussion on the findings can be summarized as following, which explains how this study answers the research questions associated with the online survey:

- <u>Research Question:</u> Is the information displayed on TSCT correctly understood by drivers?

Answer: Driver comprehension level of TSCT is what considered as acceptable threshold for traffic control devices. Of all open-ended responses regarding the three applications of TSCT, 82% were reported as correct.

- Research Question: Do drivers think that TSCT will assist their decision making at signalized intersections?

  Answer: Ninety eight percent drivers favor the use of TSCT to ease their decision making process at signalized intersection.

- Research Question: Which application of countdown timers (GSCT, YSCT, or RSCT) do drivers think will be the most useful for their decision making at signalized intersection?

  Answer: GSCT is the most favored of all three applications of TSCT. Fifty percent drivers favored GSCT over RSCT and YSCT.

- Research Question: Which countdown timer display method is most easily understood by drivers?

  Answer: One common timer for all signal indications, placed next to the signal head, is considered the most easily understood display method of TSCT.

5.1.2 Efficiency Implications of RSCT

As detailed in Chapter 4, the effectiveness of RSCT was quantified in terms of the time a driver takes to cross the stop line (after the onset of the green indication) from the stopped condition (on red indication). The influence of the presence of RSCT and the duration of the red indication on the first vehicle headway were examined. The t-test result confirms that the presence of RSCT influence drivers reaction to the change in signal (from red to green), resulting in the reduction of the first vehicle headway by 0.73 seconds (p-value < 0.001). On the other hand, the influence of red-duration on the headways was not as clear. No significant difference in the headways was reported between red duration 20 and 40 seconds. Whereas, a difference was found significant between a red duration of 20 seconds and 60 seconds. Drivers frequently encounter red durations of 20 to 40 seconds at the low volume intersections. Thus they were more alert when the wait time at intersection was below 40 seconds. This result provides some evidence that drivers may become more distracted as intersection delay increases.

This study produced a statistical model to calculate the first vehicle headway at a signalized intersection in presence of TSCT. A linear mixed effect model was used to examine within subject variations, and there was convincing evidence that the random effect of subjects explains the variation (52.54%) in the headway. This result suggests that the response time at the onset of green, and distraction while waiting on red, vary widely between subjects. The negative coefficient of age in the final model proves that the older subjects were more responsive (or more attentive) to the information displayed by RSCT. The model suggests a 0.72 second reduction for the first vehicle headway in the presence of RSCT. The first headway of a discharging queue ranges from 2.65 seconds to 4.5 seconds (Bonnensen, 1992), and both predicted and observed headways from the study fell in this range. The study concludes that the presence of RSCT will reduce the first headway by approximately 22.5%. As such, in the best possible scenario (the driver is not distracted), the model estimates that the reduction in delay per cycle per intersection approach will occur in the magnitude of 0.72N vehicle-second, where N is the number of phases per hour. This is the most conservative estimate of the reduction in delay as it only considers the time saved from the first vehicle. If a similar reduction in delay results from the subsequent vehicles (which was outside the scope of this research), that will also be added to the total time saved.

The likelihood ratio test between two models (with and without red-duration as a predictor) suggested that the exclusion of the red-duration from the final model did not result in a significant reduction in the prediction power. In general the model assumptions hold, however, the model was validated within the boundaries stated in the design of experiment. A comparison of the predicted and observed headways performed with half the data (not used in model development) showed convincing prediction accuracy (>95%). The comparison of the mean headways showed no significant difference for both scenarios - presence and absence of RSCT.

This study reports a mean reduction of 0.91 seconds in the first headway resulted from the presence of RSCT. Limanond et al. (2010) found that CT reduced the start-up lost by 1.00–1.92 seconds (2009), and 1.24 seconds reduction in the start-up lost time at the beginning of the green phase. Chiou et al. (2010) reported 0.6 seconds and 2.25 seconds reduction in the start-up lost time for left-turns and through movements respectively in presence of RSCT. As defined in Chapter 2, the first headway is the major contributor in the start-up lost time. It is suggestive that the reduction in start-up lost time reported by the previous research is consistent with the findings of this work.

From the above discussion, the author concludes that the implementation of RSCT at signalized intersections in Oregon will likely result in a significant reduction in the first vehicle headway, which in turn will reduce the start-up lost time and improve intersection efficiency.

Given the evidence, this study answers the research questions regarding the RSCT as following:

- Research Question: Does the presence of RSCT reduce the start-up lost time by reducing the headway of the first vehicle in a discharging queue?

  Answer: The presence of RSCT significantly reduces the first headway. It reduces the delay to the order of 0.72 seconds per vehicle (at a minimum) in a discharging queue at the onset of green indication.

- Research Question: Does the duration of wait time during the red indication influence the performance of RSCT to reduce the headway of the first vehicle in a discharging queue?

  Answer: The effect of the duration of red, i.e., the duration of wait time, on the first headway, was minimal.

5.1.3 Safety Implications of GSCT

A probabilistic model was developed to quantify the safety benefits of GSCT in terms of the change in drivers' stopping probability in response to a yellow indication while they are at DZ. The model development procedure was similar to that used for RSCT. Due to the binary nature of the outcome (stop/go through the intersection at the onset of yellow), and repeated measurement from single test subjects, a Generalized Linear Mixed Model was fitted initially. Although, driver demographics were considered in the initial model, none appeared to be as significant predictors. In addition, the random effect of the subject was found to be incapable of explaining the variability in stopping probability. Thus, the final model was reduced to fit a Generalized Linear Model (GLM). This work delivers a final model that is capable of predicting drivers' stopping probability with a prediction accuracy of 88.7%.

An effort was made to quantify the safety improvement due to the presence of GSCT by using the model. An overall increase in driver's probability to stop in the DZ was predicted. The improvement was found most prominent for TTSL measurements equal to 3.0 and 3.5 seconds, representing an approximately 25% improvement in the probability to stop.

The average deceleration rates recorded in absence of the GSCT, were found to be consistent with previous research, which contributes to the validity of driving simulation for this study. A potential improvement of safety due to the use of GSCT was observed in the reduction of deceleration rates. Statistically significant (*p*-value = 0.016) reduction in the mean deceleration rate (1.5 ft/sec^2) was found due to the presence of GSCT.

A special case of the model developed in this work can be created by setting the value of GSCT to zero in Equation 4.7. The resulting model can be applied to predict drivers stopping probability for different TTSL cases. This is essentially the same model developed Moore and Hurwitz's TTSL based FL model, and should yield similar results. Therefore, as a validation effort, the predicted probabilities calculated from the two models were compared by a two-sample Kolmogorov-Smirnov test. No evidence of a significant difference (*p*-value = 0.759) was detected.

The discussion presented in this section forms the basis of author's conclusion that a reasonable validation effort was made to consolidate the findings of this work. As such, the author further concludes that this research contributes to the body of knowledge on the safety implications of GSCT at signalized intersection.

This work addresses the research questions regarding GSCT as following:

- <u>Research Question</u>: Does the presence of GSCT eliminate or reduce Type II DZ conflicts by increasing driver's correct decision to stop or proceed at the end of the green phase?

Answer: The presence of GSCT increases driver’s stopping probability at the onset of yellow indication, thus, reduces Type II dilemma zone conflicts. In presence of GSCT, drivers were found to be 13.10% more likely to stop compared to the absence of GSCT.

5.2. Potential Future Work

This research established preliminary evidence supporting the benefit of applying TSCT at signalized intersections. It developed and validated several predictive models, with high levels of accuracy. However, the scopes of inference for the developed models were limited due to the scope of the experiments, and subject recruitment. These limitations form the basis of recommendations for future work including:

- A larger and more diverse sample for both the online survey and the driving simulator study. In the online survey, older age groups were slightly under-represented in the sample. A larger sample size has the potential of eliminating unexpected bias on the response variable.
- Expanding the driving simulation studies to include YSCT, other TSCT display configurations, and other intersection types. Additional evidence will strengthen the case for the use of these signals.
- Field testing of TSCT. The correspondence between real-world and simulated environment needs to be good enough to insure that driver behavior is reasonably similar in both situations. Although reasonable validation efforts were made in this work, studying driver response to TSCT

in the field is critical if they are to be considered for adoption at any scale in the US.

Chapter 6 References

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Appendix A: Online Survey

Default Question Block

Survey on Traffic Signal Comprehension

The aim of this survey is to gain insight on your understanding of new traffic signal installations. It is important to ensure that roadway users properly understand the messages conveyed by the signals before they are installed.

Your participation in this survey is completely voluntary. Your responses will be strictly confidential and data from this survey will be reported only in the aggregate. Your information will be coded and will remain confidential. The security and confidentiality of information collected from you online cannot be guaranteed. Confidentiality will be kept to the extent permitted by the technology being used. Information collected online can be intercepted, corrupted, lost, destroyed, arrive late or incomplete, or contain viruses.

There are no risks concerning your participation in this online survey. There are no direct benefits, but the information collected in this survey will give insight into the understanding of traffic signals.

This online survey is expected to take approximately 10 minutes and you will not be allowed to skip any of the questions. If you wish to end the survey before you finish, simply close the window.

If you have any questions about the research, contact David Hurwitz at David.Hurwitz@Oregonstate.edu or (541) 737–9242.

If you have any questions about your rights or welfare as research participants, feel free to contact the Oregon State University Institutional Research Board by phone at (541) 737-8008 or by email at IRB@oregonstate.edu.

Thank you for your participation.

○ **I have read and understood the above information.**

Please answer the following questions.

What is your gender?

Male ○ Female ○

What is your age in years?

[ ]

What is the highest level of education you have completed?

- ○ Less than High School
- ○ Some High School / GED
- ○ Some College
- ○ 2-year College Degree
- ○ 4-year College Degree
- ○ Masters Degree
- ○ Doctoral Degree
- ○ Professional Degree (JD, MD)

Is English your first language?

- ○ Yes
- ○ No? Please Specify [ ]

Are you an Oregon licensed driver?

- ○ Yes
- ○ No

How many years have you been a licensed driver?

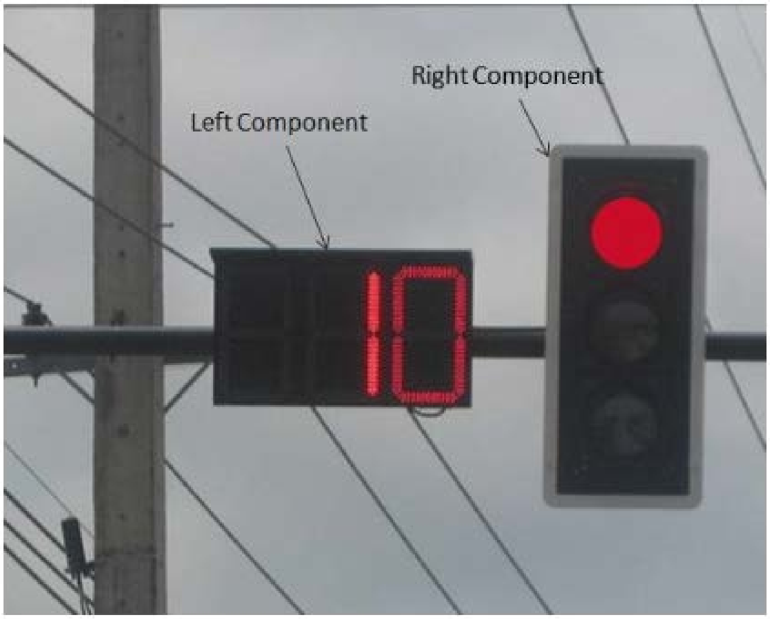
- ○ 0 - 1
- ○ 1 - 5
- ○ 6 - 10
- ○ 11 - 15
- ○ 16 - 20
- ○ More than 20

Do you experience color blindness?

- ○ Yes
- ○ No

Please carefully read the following questions about traffic signals and write down your response in the text box.

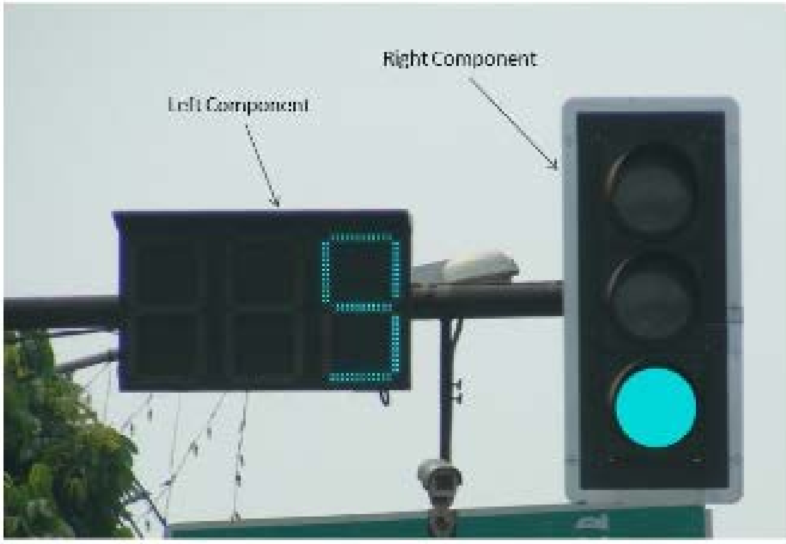
What does the following traffic signal mean to you?



Please explain separately for left and right components in the image.

Left Component	
Right Component	

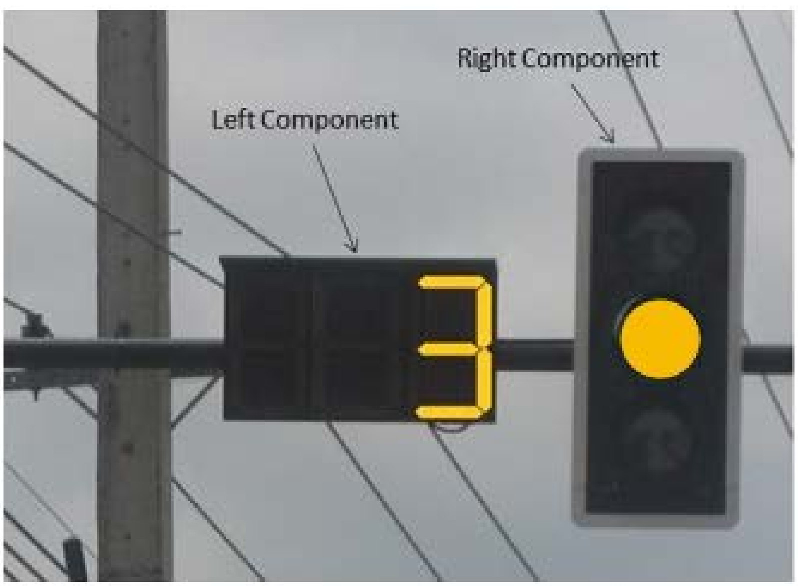
What does the following traffic signal mean to you?



Please explain separately for left and right components in the image.

Left Component	
Right Component	

What does the following traffic signal mean to you?



Please explain separately for left and right components in the image.

Left Component	
Right Component	

Of the three applications of traffic signal countdown timers which one do you think would be most useful for the drivers?

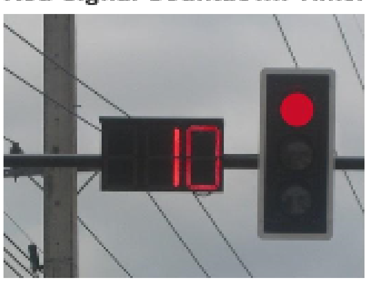
○ **Green Signal Countdown Timer**

Note: A green signal countdown timer, as shown in the above picture, informs the driver that the green signal will change to yellow in 9 seconds.

○ **Yellow Signal Countdown Timer**

Note: A yellow signal countdown timer, as shown in the above picture, informs the driver that the yellow signal will change to red in 3 seconds.

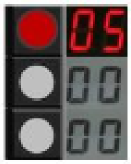
○ **Red Signal Countdown Timer**

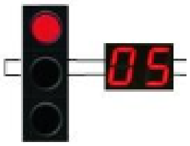


Note: A red signal countdown timer, as shown in the above picture, informs the driver that the red signal will change to green in 10 seconds.

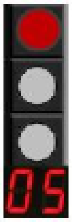
A traffic signal countdown timer displays the time remaining for a particular signal indication to alert the driver. As such, a red signal countdown timer, shown in the following pictures, informs the driver that the red signal will turn green in a certain number of seconds.

Rank the following signal displays based on how easily you think they can be understood by the drivers as a countdown timer for a red signal; 1 being the easiest and 4 being the most difficult to understand.

☐ 

☐ 

☐ 

☐ 

Appendix B: Data Analysis Plots

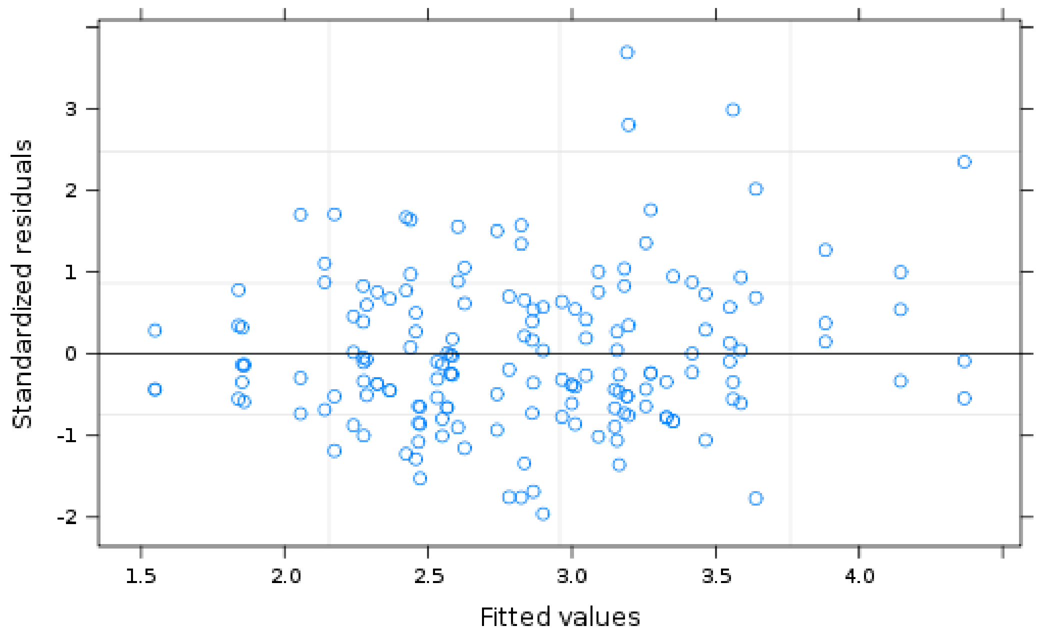


Figure B.1: Residual vs Fitted Values Plot (LME Model for RSCT)

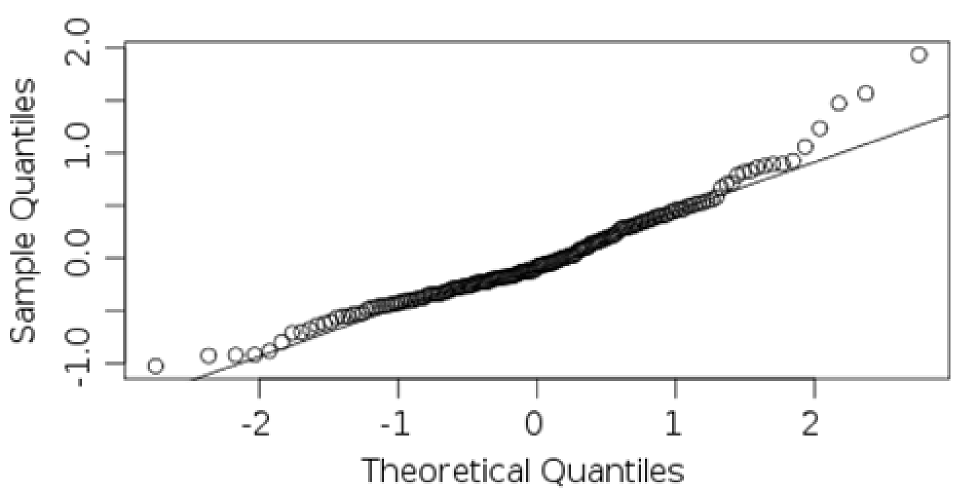


Figure B.2: Normal Q-Q Plot (LME Model for RSCT)

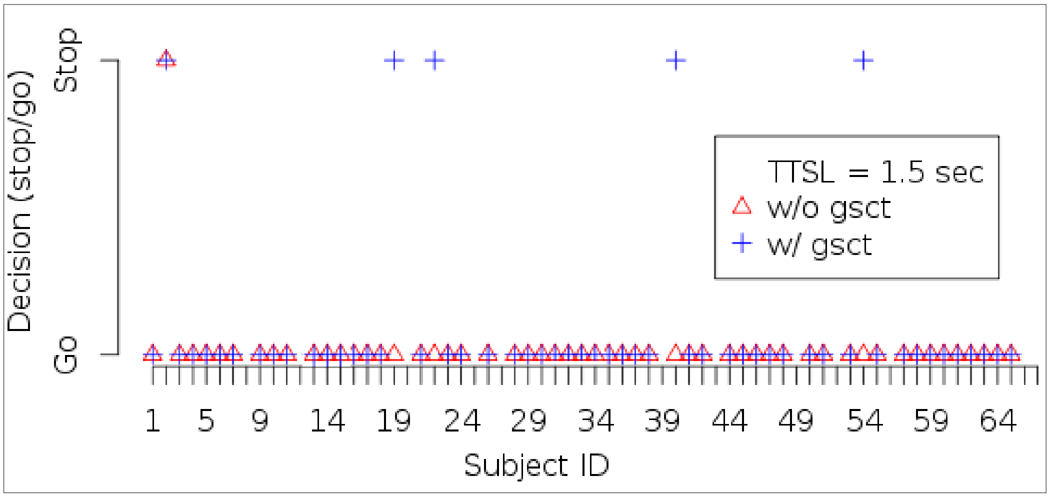


Figure B.3: Driver's Decision with Respect to TTSL = 1.5 seconds and Presence of GSCT

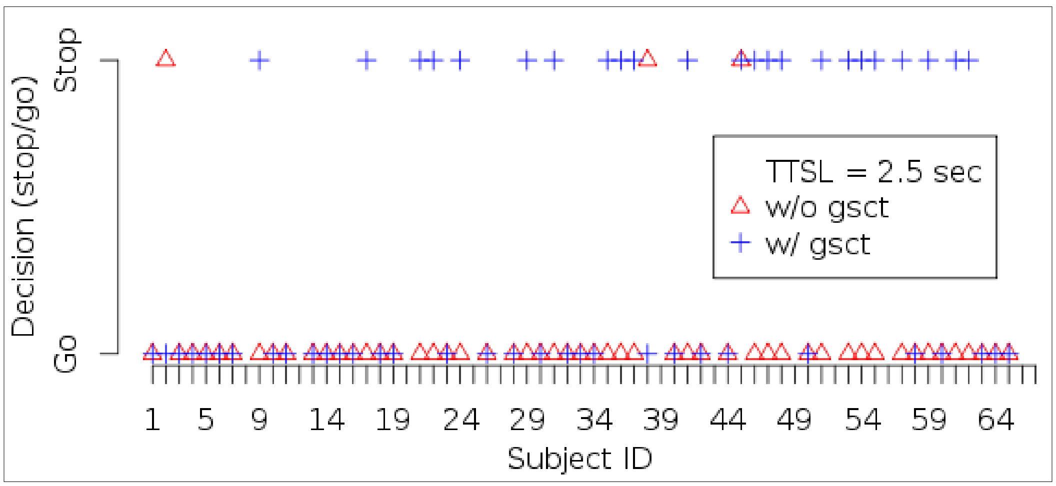


Figure B.4: Driver's Decision with Respect to TTSL = 2.5 seconds and Presence of GSCT

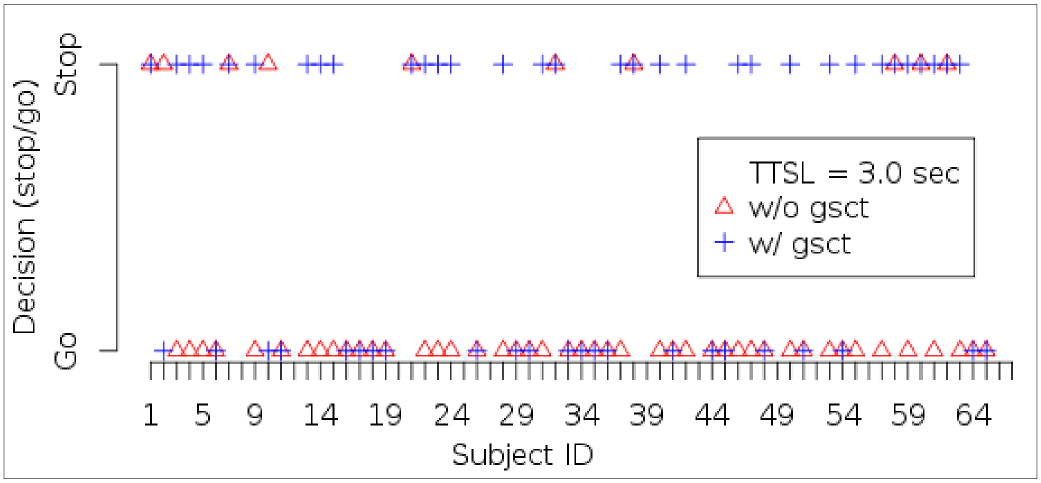


Figure B.5: Driver's Decision with Respect to TTSL = 3.0 seconds and Presence of GSCT

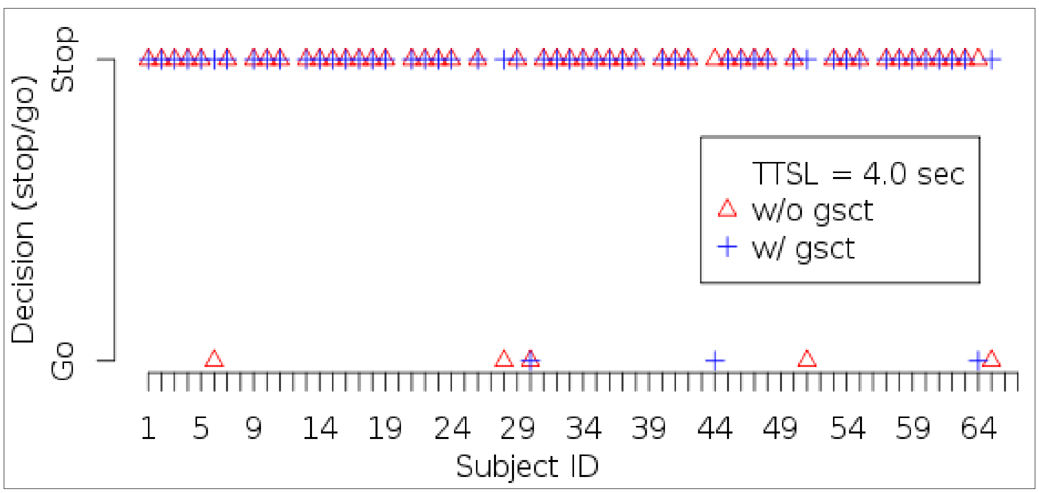


Figure B.6: Driver's Decision with Respect to TTSL = 4.0 seconds and Presence of GSCT

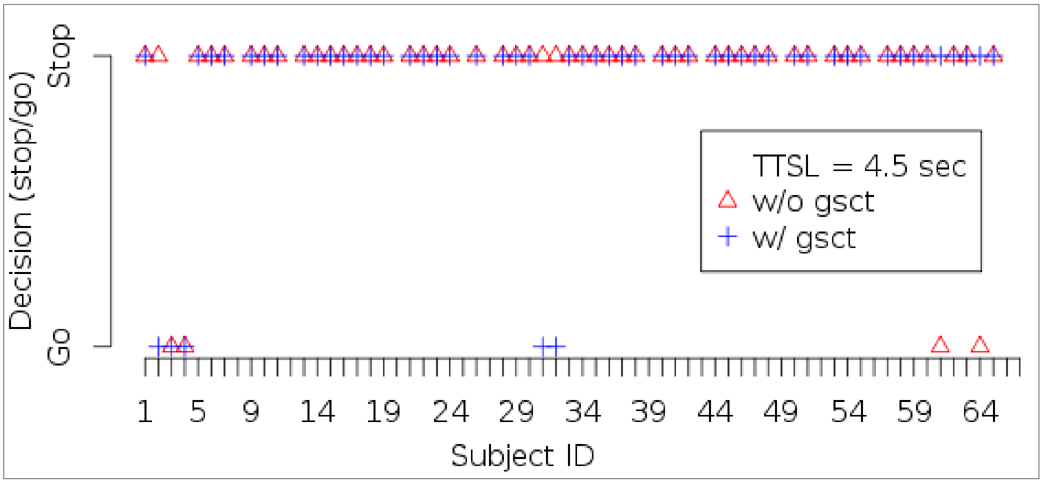


Figure B.7: Driver's Decision with Respect to TTSL = 4.5 seconds and Presence of GSCT

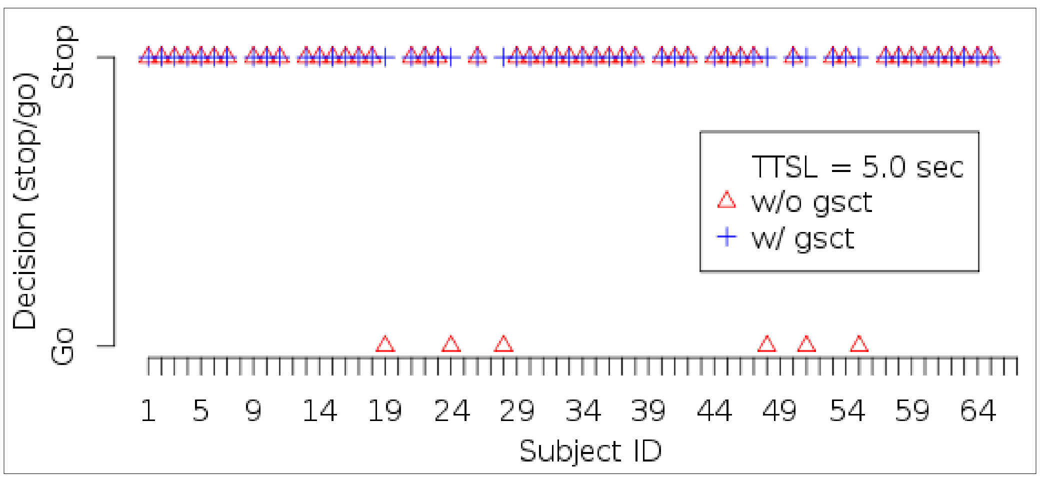


Figure B.8: Driver's Decision with Respect to TTSL = 5.0 seconds and Presence of GSCT

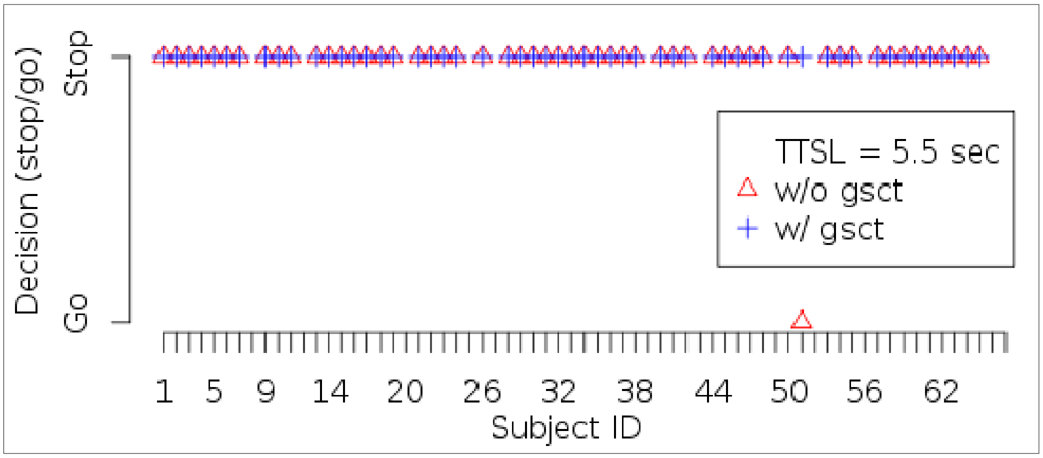


Figure B.9: Driver's Decision with Respect to TTSL = 5.5 seconds and Presence of GSCT

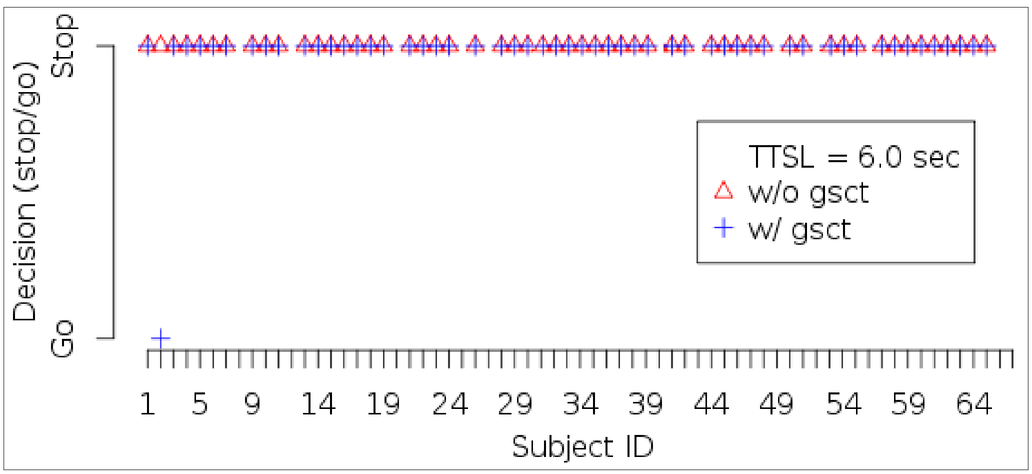


Figure B.10: Driver's Decision with Respect to TTSL = 6.0 seconds and Presence of GSCT