In-Vehicle Dynamic Curve-Speed Warnings at High-Risk Rural Curves

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Lane-departure crashes at horizontal curves represent a significant portion of fatal crashes on rural Minnesota roads. Because of this, solutions are needed to aid drivers in identifying upcoming curves and inform them of a safe speed at which they should navigate the curve. One method for achieving this that avoids costly infrastructure-based methods is to use in-vehicle technology to display dynamic curve-speed warnings to the driver. Such a system would consist of a device located in the vehicle capable of providing a visual and auditory warning to the driver when approaching a potentially hazardous curve at an unsafe speed.

This project seeks to determine the feasibility of in-vehicle dynamic curve-speed warnings as deployed on a smartphone app. The system was designed to maximize safety and efficacy to ensure that system warnings are appropriate, timely, and non-distracting to the driver. The developed system was designed and implemented based on the results of a literature survey and a usability study. The developed system was evaluated by 24 Minnesota drivers in a controlled pilot study at the Minnesota Highway Safety and Research Center in St. Cloud, Minnesota.

The results of the pilot study showed that, overall, the pilot study participants liked the system and found it useful. Analysis of quantitative driver behavior metrics showed that when receiving appropriately placed warnings, drivers navigated horizontal curves 8-10% slower than when not using the system. These findings show that such a curve-speed warning system would be useful, effective, and safe for Minnesota drivers.

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FINAL REPORT

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LIST OF ABBREVIATIONS

ADT: Average Daily Traffic

ISA: Intelligent Speed Adaptation

MHSRC: Minnesota Highway Safety and Research Center

MUTCD: Manual for Uniform Traffic Control Devices

ROR: Run Off Road

SUS: System Usability Scale

EXECUTIVE SUMMARY

Lane-departure crashes at horizontal curves represent a significant portion of fatal crashes on rural Minnesota roads. Because of this, solutions are needed to aid drivers in identifying upcoming curves and informing them of a safe speed at which they should navigate the curve. One solution that seeks to avoid costly infrastructure-based methods is to use in-vehicle technology to display dynamic curve-speed warnings to the driver. Furthermore, information could be delivered based on the driver's real-time behavior. Such a system would consist of a device located in the vehicle that is capable of providing a visual and auditory warning when approaching a hazardous curve at an unsafe speed. This would serve to notify drivers of both the curve's presence and that they are exceeding the advisory curve speed.

This project seeks to determine the feasibility of in-vehicle dynamic curve-speed warnings as deployed on a smartphone app. To maximize efficacy and minimize distraction, the system designed in this study incorporated human factors principles to result in high usability and trust in the delivery and content of the warnings. Design considerations included a visual display placed near the driver's forward field of view, an infrequent auditory message free of annoyance, and a visual display using prescribed contrast, luminance, size, and color elements. The system was incorporated into a smartphone app capable of displaying warnings to drivers based on their speed and distance to the curve and was evaluated using real drivers in a pilot study. Special consideration of drivers' behaviors around curves and in response to traditional curve-speed signing was taken to maximize the efficacy among high-risk (e.g., speeding or distracted) drivers.

The human machine interface of the curve warning system was iteratively designed through a usability test with 10 Minnesota drivers. The audio component tested contained three main components (i.e., context, command, and distance) to best communicate curve information and result in driver comprehension. The visual component tested was derived from a set of curve warning signs selected from the Manual on Uniform Traffic Control Devices (MUTCD) and combined with differing color coding and backgrounds to indicate varying degrees of severity. The most favorable design included a curve warning sign placed above an advisory speed limit sign with a "mph" label all on a black background. The prescribed sign color (e.g., white, yellow, flashing red) would change to indicate the severity of the warning. Further, the most favorable audio message would state the context first, followed by the distance to the curve and the command last.

The system functionality was designed so that drivers would receive information as they drove through virtual checkpoints. At checkpoint 1, drivers would receive a simple yellow curve sign with corresponding curve speed placard and no auditory warning. At checkpoint 2, the image and lack of audio message would persist if the diver were traveling at a speed lower than the approach speed limit; however, if speed exceeds the approach speed limit (i.e., speeding), the sign would change to red and the audio message "curve speed ahead, reduce speed" would be presented. Finally, checkpoint 3 removed the visual display and presented no audio for drivers approaching at less than the curve speed, but for those traveling greater than the curve speed, the "Reduce speed" audio message would be presented. The position of checkpoint 2 was shifted to different locations for the four experimental treatments tested in the study. Positions for Curve A (a curve with a 45 mph advisory speed and a 55

mph approach speed) were at 213 m, 167 m, 125 m, and 33 m for Treatments 1 through 4, respectively. Positions for Curve E (a curve with a 35 mph advisory speed and a 55 mph approach speed) were at 240 m, 180 m, 150 m, and 60 m for Treatments 1 through 4, respectively.

The location for the pilot study was the Minnesota Highway Safety and Research Center (MHSRC) in St. Cloud, Minnesota. A total of 24 drivers aged 20 to 40, with no cognitive, visual, or hearing deficits and with a valid driver's license were recruited from the St. Cloud area and were paid $50 for their 2 hour participation. A within-subjects experimental design was used so that participants were tested on all four of the treatment levels, which varied based on how far the second checkpoint was placed relative to the curve's entry.

The driving task was made up of 6 runs, each run consisting of a forward and reverse lap around the track both with a single treatment condition. The first and last runs were always a baseline run where the system provided no feedback and only collected data. These runs were used to establish the participants' natural behavior (with no system intervention). For each of the 4 experimental runs, participants were asked to interact with the system in the same way, each treatment only varying the distance from the curve at which the warning would be displayed. Participants were instructed to drive at 60 mph until they heard the system's warning or until they felt they needed to brake (even if the warning hadn't sounded yet). A single run consisted of this procedure twice, once in each direction to approach both curves. Baseline drives were similar in that participants were asked to drive at 60 mph but were allowed to brake whenever they chose to. After each of the treatment runs, participants completed 4 subjective measures questionnaires, which included a rating of their mental effort for the driving task, a system usability scale, a system trust questionnaire, and a quick usability inventory. After the baseline drives, participants only completed the mental effort rating questionnaire. After all drives were completed, participants were asked about their overall thoughts and perceptions of the system.

Subjective data analyses revealed that mental workload was significantly higher in Treatment 4 compared to other treatments. Mental workload was not significantly different for Treatments 1-3 compared to baseline drives. Usability scores in the System Usability Scale (SUS) and quick usability survey revealed significantly lower usability for Treatment 4 compared to all other treatments. Treatment 2 received significantly higher usability scores in the SUS compared to all other treatments. Treatment 4 received significantly poorer trust scores in overall trust, performance and process trust compared to all other treatments. Finally, Treatment 2 received the greatest number of preference rankings for having the most appropriate timing of the four treatment types.

Quantitative driver behavior data was collected using the smartphone. It logged vehicle position and speeds as the driver navigated the course. The analysis focused on the speed of the vehicle as it passed the curve's midpoint (i.e., the apex of the curve, halfway between the curve's entry and exit). The vehicle speeds at this position during the treatments were compared against the baseline conditions. Treatments 1 – 3 did not significantly differ from each other. However, when comparing Treatment 2 (the preferred warning distance) to the baseline condition, speeds were 8 – 10% lower.

These findings show that the curve-speed warning system developed and tested as a part of this work was effective, well received, and safe. Driver behavior data collected by the phone showed a reduction in speeds when the system displayed appropriately placed and timed warnings for upcoming curves as opposed to when the system was not active. Participant feedback data showed that the system was felt to be trustworthy, usable and understandable and did not increase drivers' perceived mental workload. Additionally, based on driver feedback and limited data collected using an eye tracker, it was determined that the system did not increase driver workload or require an unsafe amount of visual attention to interpret the displayed warnings.

CHAPTER 1: INTRODUCTION

Lane-departure crashes at horizontal curves represent a significant portion of fatal crashes on rural Minnesota roads. Because of this, solutions are needed to aid drivers in identifying upcoming curves and informing them of a safe speed at which they should navigate the curve. The most common method for warning drivers about hazardous horizontal curves is with infrastructure-based systems ranging from standard curve warning signs to sensor-triggered dynamic warning displays. Signing is a common warning method for curves and commonly includes curve warning, advisory speed, and chevron signs. While signing curves can help, static signage is frequently disregarded by drivers and can only offer support to drivers who are alert and looking for curve information. Furthermore, signing curves is not required for roads with low average daily traffic (ADT). Dynamic speed displays offer a more active interface to better catch drivers' attention and inform them of both their speed and the recommended speed. However, these systems are very costly, which can be difficult to justify, especially for rural roads with low traffic volumes where hazardous curves are most common.

One solution that seeks to avoid costly infrastructure-based methods is to use in-vehicle technology to display dynamic curve-speed warnings to the driver. Furthermore, information could be delivered based on the driver's real-time behavior. Such a system would consist of a device located in the vehicle that is capable of providing a visual and auditory warning when approaching a hazardous curve at an unsafe speed. This would serve to notify drivers of both the curve's presence and that they are exceeding the advisory curve speed.

This project seeks to determine the feasibility of in-vehicle dynamic curve-speed warnings as deployed on a smartphone app. It is noted that although a smartphone is the delivery method used for this project, warnings could be integrated into a number of different systems such as navigation systems or the vehicle's own infotainment stack. The selected driver warning methods must demonstrate effectiveness without distracting the driver from safely navigating through the curve. To maximize efficacy, the system designed in this study incorporated human factors principles to result in high usability and trust in the delivery and content of the warnings. The system was incorporated into a smartphone app capable of displaying warnings to drivers based on their speed and distance to the curve and was evaluated using real drivers in a pilot study.

This report documents the work performed as a part of this project. Chapter 1 provides an overview of the project. Chapter 2 provides a summary of the literature survey conducted to inform the design of the system. Chapter 3 describes the curve-speed warning system as implemented on the smartphone app. Chapter 4 is an overview of the experimental methods designed to evaluate and provide feedback to improve the system. Chapter 5 discusses the results of the experiment performed as a part of the pilot study. Chapter 6 is a discussion of major project findings and recommendations for future work, system refinements, and implementation.

CHAPTER 2: LITERATURE SURVEY

2.1 DRIVER BEHAVIOR AND SAFETY RISK

Lane departure, or run-off-road (ROR), crashes are particularly prevalent at curves and account for approximately 90% of all crashes located on curves, a significantly higher proportion compared to straight road segments where ROR events account for 62% of crashes (Liu & Subramanian, 2009). Curves account for a small proportion (~3%) of Minnesota's total roadway system, but are drastically overrepresented in fatal crashes (Leuer, 2015). The loss of control of a vehicle on a curve can result in a lane departure crash to the right or left, often resulting in a collision with a fixed object (e.g., tree or light pole), or a head on collision. These types of collisions represent approximately half of the fatal crashes within Minnesota in 2015 (MnDPS, 2016). Moreover, a significant number of these types of crashes tend to occur on rural roadways. From 2009 to 2013, 30.1% of all fatal crashes on two-lane rural roadways in Minnesota were caused by ROR collisions (Leuer, 2015).

2.1.1 Driver Characteristics

Males are typically at greater crash risk compared to females and over twice as many males (i.e., 295) were killed in Minnesota crashes in 2015 compared to females (i.e., 116) (DPS, 2016). Injury severity at curves differs, however, for males and females. Schneider, Savolainen, and Zimmerman (2009) found that females were 23% to 31% more likely to be injured in a curve related crash compared to males. This discrepancy may stem from physiological differences between the sexes and the role that the relationship between body type and vehicle characteristics may have on female physical fragility in such crashes.

While a problem for young drivers on all road segments (Quimet, Pradhan, Brooks-Russell, Ehsani, Berbiche, & Simons-Morton, 2015), the presence of passengers is associated with greater crash severity risk at curves (Schneider et al., 2009). Like males, young drivers are also typically at greatest crash risk and have been shown to make less anticipatory glances into curves and begin slowing later for curves compared to experienced drivers (Muttart, Fisher, Pollatsek, & Marquard, 2013). As drivers age, however, they are more likely to be injured in a curve-related crash. This is perhaps again attributed to the role that fragility has in the survivability of crashes. Cognitive decline may also be a factor in the increase. Older drivers who have a restricted useful field of view have been found to be six times more likely to have been in a crash in the past five years compared to those who do not (Ball, Owsley, Sloane, Roenker, & Bruni, 2009). Moreover, similar types of visual and cognitive declines have been associated with poorer visual scanning patterns (Romoser & Fisher, 2009) and are more likely to leave the road in a driving simulator (Rinalducci, Mouloua, & Smither, 2002).

2.1.2 Risk Taking Behaviors

Risk taking is associated with greater crash severity risk at curves. Drivers who are under the influence of drugs, alcohol, or are fatigued are at greater risk of serious injury or fatal crash at curves (Schneider et

al., 2009). Other forms of risk taking are often the result of distraction or inattention. Drivers may have inattentional blindness (i.e., failing to notice a curve ahead) if they are distracted by some non-driving task like interacting with a cell phone (Strayer, Drews, & Johnston, 2003). In a simulation study, drivers were observed to approach curves at a higher speed when distracted with a cell phone-type task compared to a baseline state (Charlton, 2004).

Other curve-specific risk taking can include a behavior known as "cutting the curve" where the driver deviates outside of their lane towards the inside of the curve. Males are more than four times more likely to engage in this behavior, most often engaging in this behavior when they are on the outside lane of the curve (Hallmark, Tyner, Oneyear, Carney, & McGehee, 2015).

Excessive speed is a common factor in ROR collisions, because the driver has reduced time to perform corrective action to control the vehicle. As speed increases, reaction time and the capacity for driver cognitive performance decreases, creating a dangerous circumstance for the safety of the driver, other motorists, and property. Although traffic safety engineers survey and dictate the entrance speed for curves, ROR events prove to be a consistent problem for transportation safety. Schneider and colleagues (2009) found that speeding was a significant predictor of injury risk at curves where the likelihood of fatalities increased by 72% if it was included as a contributing factor to the crash. Further, drivers who travel at higher speeds upstream from the curve are more likely to enter the curve at 5 mph over the advisory speed (Schneider et al., 2009).

2.2 IN-VEHICLE MESSAGING USAGE AND INTERFACE DESIGN GUIDANCE

One method for delivering messages and safety warnings to drivers is through in-vehicle messaging. intelligent speed adaptation (ISA) is one form of in-vehicle messaging which uses sensors to monitor drivers' speed and subsequently alerts them when they are traveling at an unsafe speed. ISA has been demonstrated to be effective in reducing overall speeds of drivers by providing speed limit information and alerting drivers when they are engaged in speeding (Regan, Young, & Hayworth, 2003; Regan, et al., 2006; Agerholm, Juhl, Sonne, & Lahrmann, 2007). Similarly, advisory ISA has high user acceptance and is effective at reducing maximum and average speeds of drivers by notifying drivers with a visual or auditory warning when they are speeding (Spyropoulou, Karlaftis, & Reed, 2014). Moreover, advisory ISA has demonstrated its effectiveness through prolonged use (i.e., 12 weeks) by recidivist speeders who reduced the amount of time spent traveling over the speed limit, time to decrease speed for new speed limits, and overall mean speeds (Stephan et al., 2014).

Given the importance of reducing speeds at curves to reduce crashes, in-vehicle curve warning devices have been examined by previous research teams with varied success. A team in Virginia examined how haptic pedal feedback may improve speed reductions to an unexpected curve compared to auditory-visual prompts (McElheny, Blanco, & Hankey, 2006). Drivers were quicker to reduce their speeds and had speeds at entry that more closely matched the posted speed for both the auditory-visual feedback and the auditory-visual-haptic feedback compared to no feedback in the study. Interestingly, drivers continued to better reduce and match speeds when prompted with feedback even after they were aware of the presence of the curve, perhaps a result of being reminded the appropriate target speed on

each pass through. The haptic feedback did not improve performance; however, many participants reported not noticing the haptic feedback suggesting the 12 pounds of pressure was insufficient to elicit a proper response.

A research team in Spain adapted an ISA system to provide drivers with curve speed feedback (Jimenez, Liang, & Aparicio, 2012). A significant portion of this work focused on the timing of a warning prior to curve entry and used a graded warning approach depending on the deceleration rate which would be required to reach the target speed as the driver approached the curve (i.e., 1-5 m/s^2 required braking given a 1.5 second initial driver reaction time). The system calculated a "safe limit" for the curve at hand and displayed a visual warning with graded vertical bars to communicate the increased urgency of the required braking. Their iterative testing found that drivers braked much later in normal driving conditions compared to their system and had a later reaction time. This indicates that the "safe limit" and required braking parameters were set too conservatively. This is a notable problem since any safety system design tends to error on the side of caution, however, drivers may be unsatisfied to use such a system if it is significantly more conservative than they wish for their driving behavior.

While previous work on in-vehicle warning systems for curves provides some useful guidance in the design of this study, it is important to consider all aspect of human-computer interaction and cognitive limitations in our design. This study will consider standards and guidance on cognitive workload, display positions, auditory message design, and visual design for safe operation of a motor vehicle and high user satisfaction.

2.2.1 Visual Attention, Cognitive Workload, and In-Vehicle Displays

Research has been conducted to evaluate the impact of using different in-vehicle interface designs while driving. This guidance was included in consideration of the design of the curve speed warning human machine interface. Green (2004) summarized the literature on in-vehicle interface design, driver distraction, and workload managers. A workload manager is a system that constantly measures the complexity of driving and moderates the flow of information to the driver. For example, if a driver is traveling through an intersection or changing lanes, the workload manager may delay a text message or phone call. The author posits that a workload manager could monitor when the driver is not paying attention to the road, and only show warnings for which the driver was unaware (Green, 2004). While integrating all of the workload manager functions into our curve speed warning system may not be feasible, it is important to consider which features are possible to make the messages safer and more useful to the driver.

Recarte and Nunes (2003) conducted a study examining how mental workload affected visual search and decision making tasks while driving in a simulation. Results indicate that higher mental workload diminishes a driver's ability to visually detect stimuli and lowers spatial gaze variability. However, the findings did not suggest that mental workload causes tunnel vision.

Early literature assessing visual attention during driving has shown drivers attend to the forward roadway and apex locations throughout their duration driving through curves (Land & Lee, 1994).

Previous work has also discovered that novel, complex, and demanding driving environments significantly impact drivers' visual attention by reducing fixation duration (i.e., the time spent looking at a specific area of interest) (Chapman & Underwood, 1998). More recent work has explored in-vehicle technology use, specifically smartphone devices, and its impacts on drivers' visual attention while performing driving tasks (Horrey, Wickens, & Consalus, 2006; Sodhi, Reimer, & Llamazares, 2002).

Instead, drivers seemed slow to detect stimuli and performed poorly at identification of stimuli (Recarte & Nunes, 2003). These findings are similar to some findings by Green (2004) that indicate drivers are at greater crash risk when they are overly preoccupied with a secondary, non-driving task. Such distractions may even stem from interacting with an in-vehicle interface through manual operation or prolonged fixations. It is important to consider these factors in order to ensure that the interface design requires minimal to no interaction and only merits brief fixations to the display when communicating curve and speed information.

Angell and colleagues (2006) assessed the visual, manual, and cognitive workload of drivers while performing tasks with an in-vehicle system. Tasks were designed to be high or low workload, and either auditory-vocal tasks or visual-manual tasks. This research found that visual-manual tasks mostly increased the rate and number of glances away from the road as well as the percentage of times that the driver missed a lead-vehicle's center high-mounted brake light activation, follow-vehicle turn signal activation, and lead-vehicle deceleration events (Angell et al., 2006). Conversely, auditory-vocal tasks did not affect the same dimensions as the visual-manual tasks because they do not require the driver to look inside the vehicle to accomplish a task. Auditory-vocal tasks increased the duration of road glances, the number of mirror glances, and the range of speeds driven during the tasks (Angell et al., 2006). Further, visual-manual tasks adversely impacted driving more than auditory-vocal tasks. Again, this may help to guide how information is presented and in which ways, if necessary, drivers will be prompted to interact with the system (i.e., through vocal, not manual, interactions).

2.2.2 Interface Display Position

Wittmann and colleagues (2006) studied the effect of changing the position of an in-vehicle display on driving performance in a simulated driving setting. The authors tested seven different display positions in a car and measured driving behavior, eye movements, and subjective ratings. Their work showed that drivers had longer braking reaction times when using a display that was further from their primary task line of sight (i.e. looking straight forward to navigate the vehicle). The positions tested are shown in Figure 2.1.
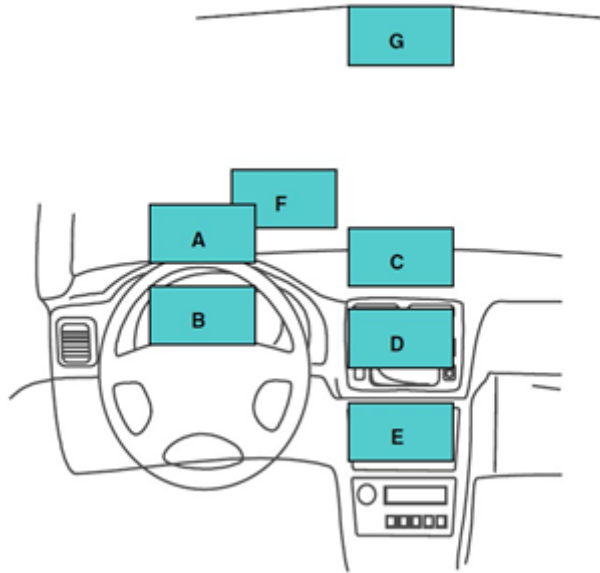
Figure 2.1 Display positions tested (adapted from Wittmann et al., 2006).

Among the positions tested, F, C, and A had the best performance (e.g., less lane departure time, faster reaction times, improved subjective ratings, etc.) This is an important consideration when providing guidance to drivers regarding where they should place the display if the system is presented through a secondary device, such as a GPS or smartphone.

Drivers' visual attention towards the dashboard center console, radio, and gear selector regions have been found to account for a significant proportion (60%) of crashes and near-crash incidents (Klauer, Dingus, Neale, Sudweeks, & Ramsey, 2006).

2.2.3 Auditory Message Design

The efficacy of auditory messages can be affected by several factors, such as annoyance, message appropriateness, urgency in sound, and word choice.

Annoyance can be a barrier to the effectiveness of auditory messages if the user perceives an audio message as too noisy, unwanted, or unacceptable. If a message is annoying, users tend to turn off the auditory warnings or ignore them (Marshall, Lee, & Austria, 2007). Annoyance can manifest after repeated exposure to auditory warnings (Lee, Gore, & Campbell, 1999).

Message appropriateness is vital to establish the effectiveness of an auditory message. For example, an appropriate message must optimize the timing of a curve warning that allows for a reasonable time to react to the warning, but not too early that the driver forgets the information. Further, the message should be succinct to facilitate message recognition. Repetition of warnings may lead to annoyance (Kryter, 2013), and may encourage drivers to ignore similar messages in the future (Wiese & Lee, 2004).

Urgency in auditory messages can be expressed by manipulating the loudness, frequency, pulse, and time between tones (Haas & Edworthy, 1996; Edworthy, Heiller, & Rivers, 2003; Marshall et al., 2007). Messages with too much urgency can be a distraction. Long tone durations and short delay between tones are perceived as more urgent and annoying (Marshall et al., 2007). Further, female voices have been perceived as more urgent than male voices (Edworthy et al., 2003). This effect may be attributable to the higher pitch of female voices.

Word choice is an important factor for auditory messages. Messages should contain three or less sets of information to minimize workload demands imposed on the driver (Barshi, 1997). Additionally, messages should be in succinct, list format (e.g., sharp curve ahead, 500 feet, reduce speed) instead of full sentences (e.g., There is a sharp curve ahead in 500 feet, reduce your speed). Moreover, the context of the message should precede the prompt to guide the driver's behavior (e.g., reduce speed, curve ahead 500 ft; Dingus et al., 1997). Words with specific definitions (e.g., danger) communicate urgency better than words with flexible definitions (e.g., beware, attention) (Hellier, Edworthy, Weedon, Walters, & Adams, 2002). Further, intonation and inflection affect the perceived meaning of the message (Hass et al., 1996; Edworthy et al., 2003).

2.2.4 Visual Message Design

The efficacy of visual messages can be affected by several factors, such as position in field of view, visual angle, contrast, display luminance, and color coding. Displays should be located in line of sight, within 15° from the driver's viewing position (Green, Levison, Paelke, & Serafin, 1994; UNECE, 2010). Contrast ratio of symbols in a display should be at least 3:1 (Campbell, Richard, Brown, & McCallum, 2007). Further, luminance of visual messages on a display should be approximately double the background luminance (UNECE, 2010). Color coding can be used to indicate important information on a visual display (UNECE, 2010).

2.3 DETERMINING CURVE ADVISORY SPEEDS

Horizontal curves are the familiar feature in a roadway where the horizontal alignment of the road deviates from a straight line in order to join two tangential sections of paved road (AASHTO, 2011). The Federal Highway Administration's (FHWA) Safety Program established guidelines for determining advisory speeds on curves (Milstead, et al., 2011). The authors note a number of important factors which include curve radius, super-elevation, tangent speed, and vehicle type.

2.3.1 Ball-Bank Indicator Method

There are many methods for setting curve advisory speeds which include naturalistic observation-based techniques and calculation-based methods determined by the roadway design, but the most frequently used method is the ball-bank indication method.

The ball-bank indicator method is based on measuring the lateral forces a vehicle encounters as it navigates a horizontal curve. These lateral forces are primarily affected by the speed at which the vehicle travels, the curve's radius, and its super-elevation (i.e., how much the road surface is banked).

Conventional ball-bank indicators operate by the movement of a metal ball inside a curved tube which is filled with a fluid that acts as a damper for the ball (AASHTO, 2011). As the vehicle encounters a curve, the lateral forces case the ball to move away from the center (i.e., zero) position. The engineer can then observe the deflection of the ball. Figure 2.2 shows an example of a ball bank indicator.

Figure 2.2 Conventional ball bank indicator (Cornell University, 2014).

Digital ball-bank indicators utilize electronic accelerometers to determine the lateral acceleration of the vehicle as it travels through a curve. This acceleration is then converted to the equivalent ball deflection angle and reported in this way to maintain compatibility with conventional ball bank indicators and advisory speed determination protocols. Figure 2.3 shows an example of the Reiker Inc. electronic ball bank indicator used in this study.

Figure 2.3 Electronic ball bank indicator (Rieker Inc.).

Both styles of ball bank indicator display the measurement as degrees offset from 0 where a measurement of 0 degrees corresponds to no lateral force, and 20 degrees corresponds to a relatively high lateral force. To determine an advisory curve speed, the curve is driven at different speeds until the measured offset exceeds the threshold for the given speed. These threshold values were historically

based on tests conducted in the 1930s representing the 85th to 90th percentile speeds of vehicles passing through curves at that time (Chowdhury, Warren, Bissel, & Taori, 1998). The outdated values were eventually adapted to account for modern cars. The 2009 edition of the MUTCD uses the following threshold values:

- 16 degrees for 20 mph or less
- 14 degrees for 25 to 30 mph
- 12 degrees for 35 mph and higher

While the modernized values are more representative of motorists' speeds, there may still be a disconnect between the validity of the method and the drivers' trust in the method. This may stem from multiple issues. First, the prescribed values of the ball bank method have feasibly been overly conservative for the 50 years prior to the MUTCD update by failing to account for the vehicle capabilities of the time. Second, the modern values may still be too conservative since they are set with the vehicle dynamics of a commercial truck in mind and not a passenger vehicle. Finally, there may be little consistency in application of the ball bank method. Chowdhury and colleagues (1998) examined 28 curves in Virginia, West Virginia, and Maryland and found that approximately half of them had a posted speed lower than as would be indicated by a ball bank indicator.

2.3.2 Driver Acceptance and Trust in Advisory Speeds

Given the increase in crash likelihood for drivers traveling above the posted advisory speed at curves, it is important to clearly alert drivers to the presence of the curves as well as their associated advisory speeds. Drivers' trust and compliance with static signs at curves, however, appears to be low. Chowdhury and colleagues (1998) measured motorist behavior at 28 curves and found that 9 out of 10 drivers exceeded the posted speed. Curves with overly conservative advisory speeds had worse driver compliance than curves with more appropriate advisory speeds, set with modern guidelines. The danger of inconsistent advisory speed selection is that motorists who routinely exceed advisory speeds based on their experience with conservatively signed curves will be at great risk when encountering unfamiliar curves with a less conservative and more appropriately signed advisory speed.

All drivers traveled at least 5 mph over the posted speed if they were set lower than 20 mph. While drivers did decrease their speed on approach, the degree to which the reduction is attributable to the sign is debatable. One factor in poor compliance may be, in part, due to poor adherence to curve speed methodologies. About half of the curves had lower posted advisory speeds than would be indicated by the ball bank method. Since the methods are typically overly conservative, setting further conservative speeds with little consistency is likely to result in poor trust in the validity of posted advisory speeds.

Another consideration is that to safely set an advisory curve speed, generally the speed must be set such that it is safe for the most severe portion of the curve. While this takes into account the vehicle's dynamics at the apex of the curve, it does not take into consideration the human behavior in sections of the curve before and after this critical point. For example, in some cases the curve's entry design may appear to be predictable to the motorist, who at that point may not see the critical point of the curve,

for which the curve speed is set. In this example, the motorist may feel the signage does not accurately represent the reasonable speed for the curve at this point of entry. When the motorist arrives at the critical point, presumably exceeding the advisory speed, they may find themselves in a safety-critical situation requiring excessive braking and steering events—all of which can lead to a ROR collision resulting in injury or fatality. These disconnects between motorist confidence and trust in signage and perceptual awareness of the road geometry along with persistent ROR collision rates on rural curves motivate the need for a trustworthy in-vehicle safety technology to assist drivers navigating hazardous horizontal curves.

2.3.3 Signing Methods

The method of displaying a static curve advisory speed can vary and as such has varying results. Charlton (2004) tested an in-road marking warning (i.e., transverse line warning, see Figure 2.4a), the standard diamond sign (see Figure 2.3b), and a chevron warning "sight board" (see Figure 2.4c) in a simulation and found that the diamond sign was the least effective at lowering speed when drivers were experiencing high workload. This is troubling since the diamond sign is the most commonly used sign for signing curves; however, it may be the novelty of the alternative signs that better captured drivers' attention, an effect which would diminish over continued exposure. This finding is consistent with naturalistic study results by Schneider and colleagues (2009) who found drivers were more likely to deviate out of the lane to the right at curves marked with the standard diamond curve sign. They did note that curves with this sign may overrepresent curves problematic due to other factors (therefore motivating the sign's installation). However, they concluded that even if the sign does not lead to more lane departures, it is still not successful in reducing lane departures.

Figure 2.4 Examples of curve signage tested in the Charlton (2004) study.

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An alternative to the static speed advisory signs are dynamic speed display signs. These signs are typically used in urban areas to reduce driver speeds and slow traffic by displaying the speed limit along with a digital display that shows the speed of the approaching vehicle. They have been shown to be most successful in select use cases, such as school zones. Although they have less pronounced effects on driver speed on other general roadways, their use still tends to encourage drivers with excessive speed to slow down (Ullman & Rose, 2005).

Utilizing such a system could be a beneficial tool in encouraging speed reduction prior to curve entry, especially for drivers who are approaching at already excessive speeds. Dynamic speed display signs have been employed on rural curves to give approaching drivers feedback about their speed. A study of 22 signs in seven states found that dynamic speed display signs reduced crashes by 5-7% (Hallmark, Qui, Hawkins, & Smadi, 2015). While this is a notable improvement, it may not be a cost-effective solution on rural, low ADT curves.

CHAPTER 3: WARNING SYSTEM DESIGN

The goal of the warning system design was to develop a curve speed warning user interface that is safe and useful for drivers navigating hazardous horizontal curves. This process was informed by the literature survey which provided guidance for the development of the audio and visual warning message components. Additionally, a usability study was conducted to collect feedback about a number of different prototype warnings in order to maximize system user satisfaction and ease of use.

3.1 WARNING INTERFACE DESIGN CONSIDERATIONS

3.1.1 Visual Component Design

The design of an in-vehicle messaging system requires careful consideration of how the visual components are presented to the driver. In the context of a curve warning system, the delivery of visual information needs to be as concise as possible due to the potential safety risk during the time of the warning (i.e., when approaching a curve). If the visual message causes the driver to take their focus off the roadway while approaching or navigating a curve, the system could decrease driver safety and increases the probability for a crash or ROR event. The following display guidelines referenced from human factors, visual in-vehicle technology literature assisted the research team in the design of a curve warning system that optimizes the delivery of critical information to the driver while mitigating and minimizing the exposure to risk when using the system. The designs in the current work are based on the user mounting their mobile device in the recommended forward dashboard location, or for use in common OEM-equipped infotainment systems (i.e. centrally located on the dashboard center-stack).

Visual component guidelines:

- Interface displays positioned in the central dashboard top and immediate forward dashboard (slightly offset to the left or right) regions of the interior cabin have been shown to improve safe driving behaviors (e.g. reduce lane departure time, quicker reaction times to roadway events) (Wittmann et al, 2006). Furthermore, drivers report higher willingness to use and user satisfaction of interface display devices when they are placed in the forward dashboard position (Wittmann et al, 2006). The optimal location for the placement of an interface is closest to the driver's line of sight, without interfering with the central field of vision. In other words, the best compromise of safety and information delivery of an interface's location should be in the forward and slightly off-centered position from the driver's immediate forward line of sight (Green, Levinson, Paelke, & Serafin, 1994).
- The contrast ratio of an image (e.g., picture, icon) or symbol (e.g., text item, number) in a visual interface display requires at least a three to one ratio, however, prior studies have found that a ratio of seven to one is optimal for ease of viewing (Campbell, Richard, Brown, & McCallum, 2007).
- Drivers that engage with in-vehicle devices are much more likely, some 900%, to be involved in a collision (Klauer et al., 2006). This risk is increased when the interaction with the device is

required, especially in the form of manipulating the interface, such as selecting options or changing parameters within an application embedded in the device (e.g. smartphone navigation app) (Green, 2004).

- The presentation of text can have a profound impact on driver workload and their time to process the displayed information in a meaningful way. Icon symbols in a display are most effective at the 1.43° visual angle, with a floor of 0.69° for implementation. At arm's length (25 in.), the icon is optimal at 0.65 in. or larger (Campbell et al., 2007).

- Federal mandate requires text size to be 0.26°. The suggested text size is 0.40° or greater (Campbell et al., 2007). Text or letter symbols in a display must be at least a visual angle of 0.50° for key elements (6.5mm at arm's length), 0.33° visual angle for critical elements, and 0.266° visual angle for noncritical elements (Campbell, Lyle, Carney, & Kantowitz, 1998).

3.1.2 Auditory Component Design

Auditory message used with in-vehicle technologies has been demonstrated as a less distracting and less resource-demanding of drivers compared to visual messages (Angell et al., 2006). The design parameters of an audio message must be carefully specified, however, in order to usefully and safely convey information to drivers. For example, an auditory message that is irregular in pitch or tone can be considered a nuisance by users. Additionally, if the auditory message is presented too frequently, contains irrelevant or unimportant information, or is delivered at an inappropriate time, the user may lose satisfaction with the system and consequently abandon use. Notes on the special considerations for the design of a concise and effective audio message for use within an in-vehicle messaging technology are described below.

3.1.2.1 Auditory Component Guidelines

- The selection of words in an in-vehicle messaging system impacts the driver's understanding of what the system is attempting to convey. Word choice with higher definition specificity (e.g. caution, hazard, danger) are more effective at conveying urgency than other less-defined terms (e.g., beware, look out, attention) (Hellier, Edworthy, Weedon, Walters, & Adams 2002). The auditory message should be calculated and succinct (Cao, Castronovo, Mahr, & Muller, 2009) to ensure that only relevant information is delivered at the fastest, yet coherent, pace possible.

- The timing of the auditory message is crucial for efficacy and user satisfaction. Systems that alert the driver too frequently can cause a lack of trust in the system (Marshall, 2007), result in annoyance to the driver (Kryter, 2013), and potentially lead to an ultimate system discontinuation.

- Differences in the pitch of male and female speakers have proven to have an impact on the annoyance and urgency of an auditory message. Edworthy, Hellier, and Rivers (2003) found that female voices communicate more urgency than male voices, however, Campbell and colleagues (2007) found evidence of male voices possessing a higher degree of authority in their delivery.

- Machine-generated messages have been found to improve the delivery of message urgency and importance compared to naturally spoken messages in the context of driving research (Campbell et al., 2007).

3.1.2.2 Message Syntax

The presentation of an audio message is similar to the language structure found in reading, however, presenting full sentences in auditory messages can be problematic in terms of driver workload due to the demanding conditions while driving (Harbluck, Noy, Trbovich, & Eizenman, 2007; Lui 2001). Because the demands of operating a motor vehicle are mentally taxing, the warning message should be designed in a concise and easily understood manner.

Modifying a sentence's length, in this example a notification of an approaching curve, to fit within a short time window can provide the driver with a concise message that is easily processed. Three main components must be communicated for the best driver comprehension: context, command, and distance. Consider a message notifying a driver that they need to slow down because they are approaching a curve that is a half mile ahead. One possible message following this structure may be:

"Curve ahead, reduce speed, half mile."

- Context – The "why" of the situation. Here, the context is "curve ahead."
- Command – The response to the situation, or the "what to do." Here, the command is "reduce speed".
- Distance – The "when or where" in the situation. Here, the distance is "half mile".

3.1.3 Attenuating Distraction

While the independent use of auditory or visual message modalities have their shortcomings and inherent risks to driver safety, various studies have shown that coupling the two message types has the ability to safely reach the driver at substantially reduced safety risk (Lee 1999; Lui, 2001; Marshall, 2007). The mitigation of driver mental workload can lead to improvements in attention on the roadway. For example, drivers with lower levels of cognitive load tend to be quicker to react to events (Lui 2001; Makishita, 2008), and show improved visual attention (e.g. scanning the roadway) while driving (Harbluck, Noy, Trbovich, & Eizenman, 2007).

Intuitively, engaging in additional tasks while driving reduces the focus on the primary task by the driver. In fact, prior research has shown that secondary task engagement (e.g. texting, manipulation of a smartphone app, passenger conversation) increases the probability for collision (Green, 2004). While the use of an in-vehicle device can be detrimental to roadway safety, these devices can be made to operate when workload conditions are low. Using workload managers, or logic within the in-vehicle device that measures the demands of the driving situation, can help a system deliver pertinent information while maintaining safety (Green, 2004). The current system follows the workload manager system by presenting salient information at differing levels (e.g. staged warnings relative to conditions) when approaching curves at various speeds.

3.2 USABILITY TEST

While the interface can be designed by following the human factors literature guidelines discussed to the closest extent possible, the success of the warning system ultimately hinges on the degree to which the user is satisfied and willing to use it.

Ten Minnesota drivers were recruited for a 30-minute interview to assess the visual component and auditory message design and structure. The purpose of this interview was to assess the degree to which the designs are readable, understandable, and attention grabbing and determine which warnings are most preferred by users. Participants were encouraged to think aloud while assessing the designs and rank-order all signs on a scale of preference. All participants verbally confirmed to having a state-issued driver's license, were regular drivers, and had used a navigation system in the past while driving.

3.2.1 Interview Components

3.2.1.1 First Impressions

Participants were first shown a set of curve warning signs selected from the MUTCD and asked to interpret their meaning. Participants were informed that the purpose of the usability study was related to curve speed warnings, but were given no additional information before being shown the signs. The goal of this was to avoid priming the participants before receiving their interpretations of the signs. The curve warning signs used are shown in Figure 3.1.
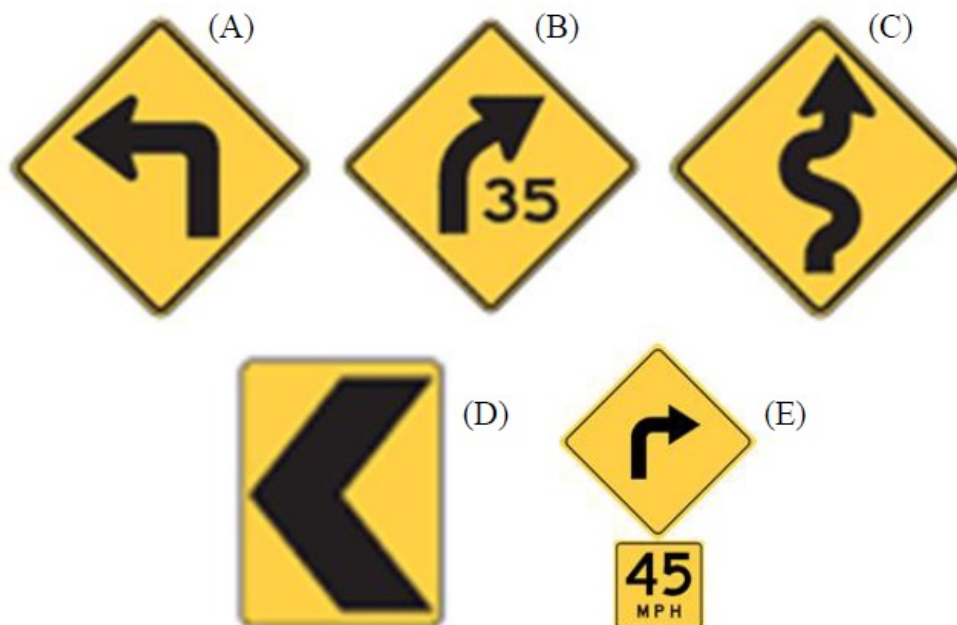
Figure 3.1 Curve warning signs selected from the MUTCD.

3.2.1.2 Visual Message

The research team created a total of six curve warning indication visual stimuli that consisted of design qualities that fit the literature guidelines and recommendations. These designs were made to ensure that the final iteration of the visual component was one that would provide the best usability to users, in turn, bolstering use and the willingness to routinely use the curve warning system.

To increase comprehension, the visual warnings incorporated existing curve warning signs. Colors (white, yellow, red) were used to indicate the severity of the warning progressing from the least severe (white) to the most severe (red). Figure 3.2 shows the warnings along with their labels. Note that for blackback_flash and combo_flash, the layered white and red signs indicate that in the interface, the sign would flash, alternating between red and white.
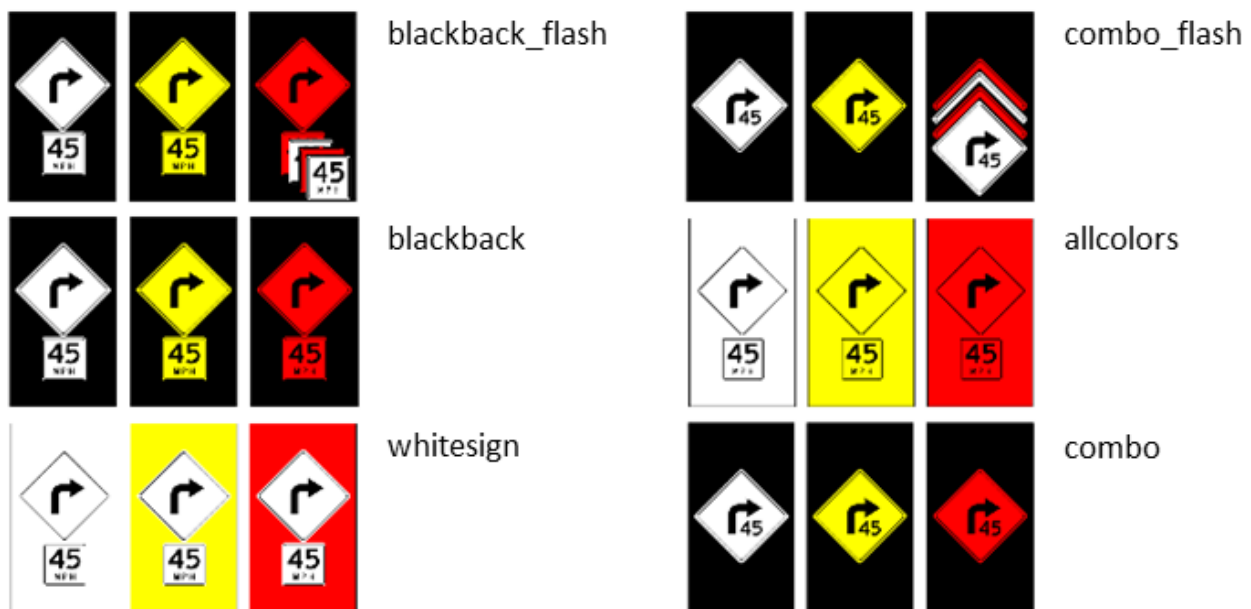
Figure 3.2 Experimental curve warning visual components and sign design labels.

Participants were shown these warning system designs and asked to share their initial impressions for each of the six options. Then, the researcher described the intent and function of the system and asked the participant to walk through each sign design while thinking aloud. Participants were encouraged to imagine that they were using the system while driving and to share any comments or thoughts about the designs that came to mind. Participants were prompted to expand on comments that they stated, when appropriate. Further, participants were asked to comment on the degree to which each sign design was readable, understandable, and attention grabbing.

Participants ranked the options using a 0 to 50 scale to indicate preference. A 0 on the scale represented the lowest preference score possible, while a 50 represented the highest preference score possible. Scores on this scale were converted to rank data to assess which sign was preferred overall.

3.2.1.3 Auditory Message

The development of the accompanying auditory message also had six different options. Here, instead of varying the message content, the syntax (the order of the information) was varied. The participant had the opportunity to choose which message format best fit their needs. Because the auditory messages contain the bulk of the information delivered to the driver, it was critically important to validate the communicative proficiency of each message. Participants were presented with the following message structures:

- Context, Command, Distance
- Command, Context, Distance
- Command, Distance, Context
- Context, Distance, Command
- Distance, Command, Context
- Distance, Context, Command

Each participant was asked to comment on the degree to which each message was understandable and rank all messages on a scale of preference.

3.2.2 Results

3.2.2.1 First Impressions

All participants correctly interpreted signs B and E (shown in Figure 3.1) as curve warnings with a posted advisory speed limit. These two signs were also integrated into the visual warning message (shown in Figure 3.2). Participants commented that sign B (combined speed and arrow) was cluttered while sign E (separate signs for speed and arrow) more clearly conveyed the information and was more authoritative.

3.2.2.2 General Visual Message Design Impressions

The majority of the participants (9 out of 10) stated that signs that were flashing were more attention grabbing. However, one participant thought that the flashing sign might be distracting. Although participants did not misunderstand the "combo" sign, most (9 out of 10) stated that the combination of the curved arrow and speed limit numbers without the "mph" label could be confusing to other drivers. Conversely, participants stated that the designs with the advisory speed limit sign separate from the curve warning sign seemed more official (2 out of 10) and that the "mph" label is important (4 out of 10). Participants frequently stated (7 out of 10) that the sign information was difficult to read when the entire screen color changed in the "allcolors" sign. Further, participants correctly expected that the white color coding indicated that the driver was within the appropriate speed for a curve, the yellow color coding indicated that the driver should use caution with their speed, and the red color coding indicated that the driver should immediately slow down.

3.2.2.3 Visual Message Preference

Participants ranked the sign with the black background and a flashing advisory curve speed limit sign (i.e., blackback_flash) as the most preferred sign design (Mean Rank = 1.9). See Figure 3.3 below for mean preference rankings for each sign. Lower mean rankings indicate a higher preference.
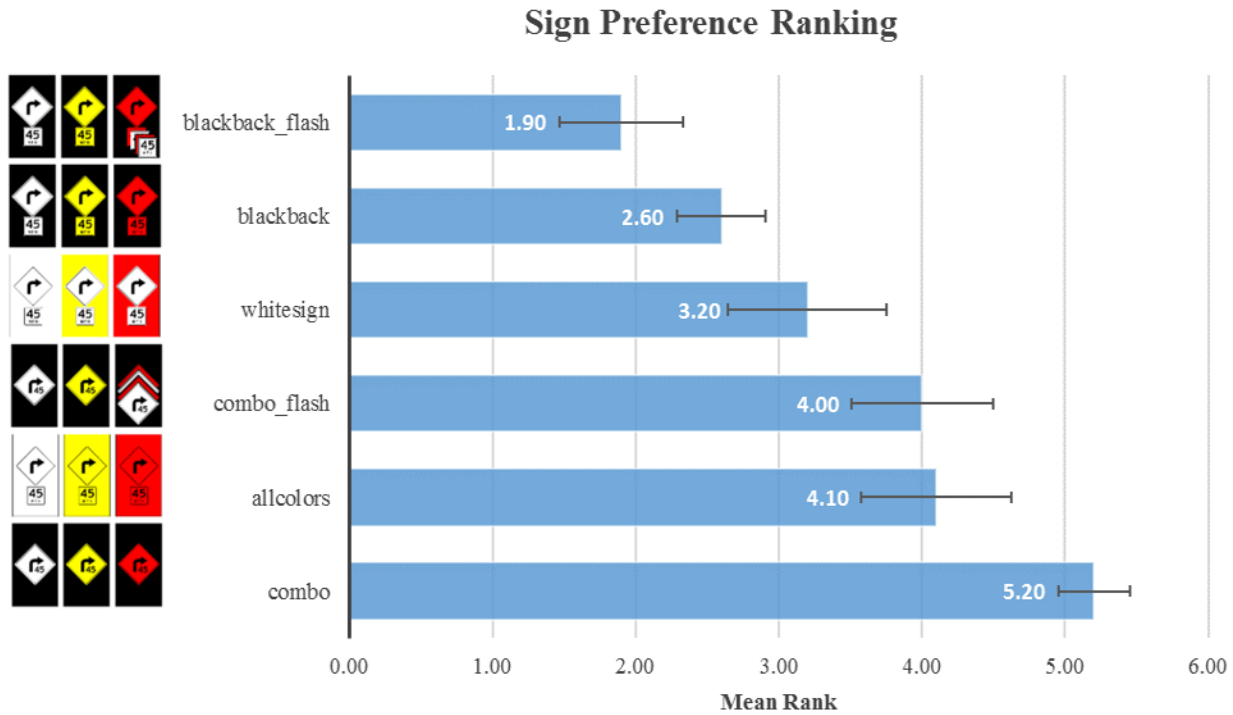
Figure 3.3: Mean rankings for sign preference.

3.2.2.4 Auditory Message Preference

In general, participants wanted to hear the context of a message (e.g., "curve ahead") before the distance information (e.g., "half-mile") or a command (e.g., "reduce speed"). Participants ranked the audio message with the context stated first, distance stated second, and command stated last as the most preferred audio message structure (Mean Rank = 2.20). Differences between this message structure and the next highest preferred message structure (context/command/distance) were not statistically significant. The structure with the lowest mean (i.e. most preferred) was selected for the purposes of this study; however, further testing would be needed to determine whether the two different message structures would result in different response behaviors. See Figure 3.4 for mean preference rankings for each audio message structure. Lower mean rankings indicate a higher preference.

Audio Preference Ranking
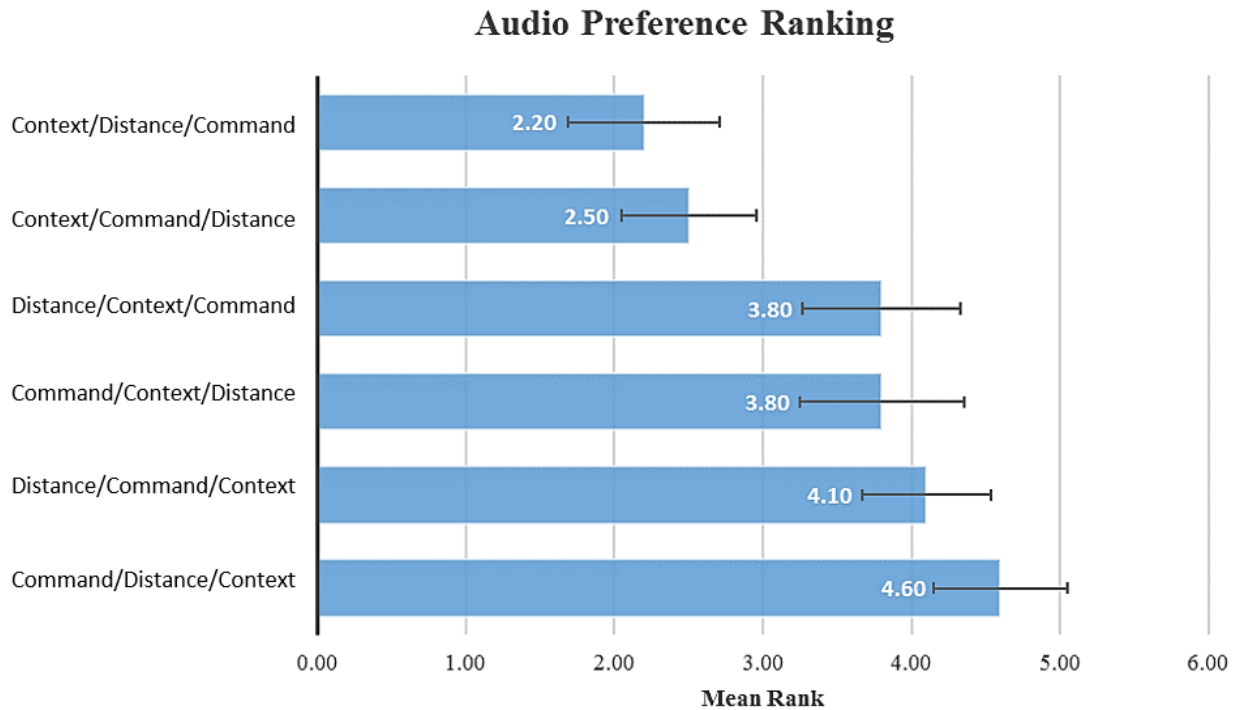
Figure 3.4 Mean rankings for audio message preference.

3.2.3 Conclusions

Participant comments and preference rankings suggest that the most favorable design would include a curve warning sign placed above an advisory speed limit sign with a "mph" label all on a black background. Then the sign color (e.g. white, yellow, flashing red) would change to indicate the severity of the warning. Further, the most favorable audio message would state the context first, followed by the distance to the curve, and the command last.

3.3 APP FUNCTIONALITY

The curve speed warning system was implemented as an app to run on an Android smartphone. The system was designed to deliver visual and audio warnings based on the vehicle's speed as it approaches a curve. The design of the system was informed by the information gathered in the literature survey as well as the preference feedback collected in the usability study.

The visual message component of the warning is based on a standard sign configuration for curves described in the MUTCD. Color is also used to give additional information about the severity of the warning or the urgency with which the driver must take action. The warning shows two signs: a "curve ahead" sign (i.e. a diamond with an arrow pointing up and to the right or left depending on the direction of the curve) which is accompanied by an "advisory speed" sign (i.e. a square sign with the advisory speed limit numerals and "MPH". The visual warning has three levels: white, yellow, and red. These

levels correspond to the severity of the warning (red being the most serious). Additionally, for a red warning, the "advisory speed" sign flashes red and white. Figure 3.5 shows the three levels of the visual warning. Note that here, the flashing "advisory speed" sign is represented by overlapping red and white signs.
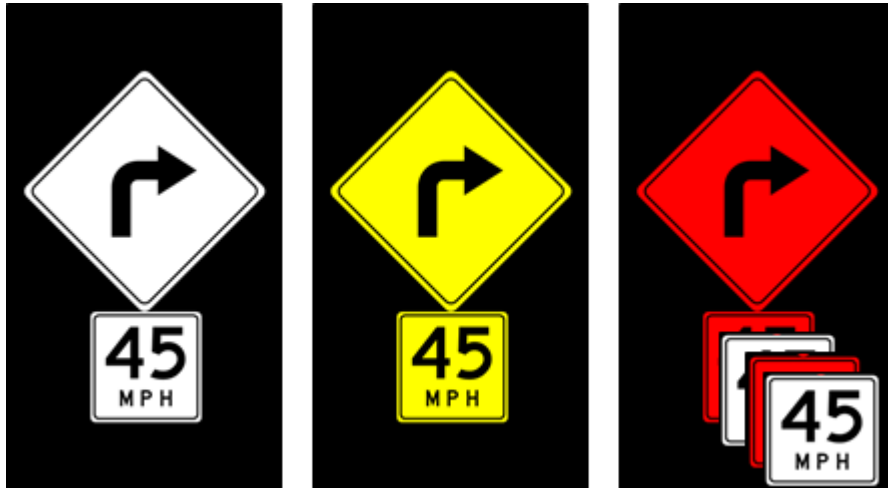
Figure 3.5 Dynamic curve speed warning visual messages.

The auditory component of the warnings is based on the driver's position relative to the curve, as opposed to the severity of the warning. This method was selected to limit the amount of information the driver must listen to as they approach and navigate the curve. There are two auditory warnings the driver may hear. Warnings delivered ahead of the curve say, "Curve ahead, reduce speed." Although per the usability study, the context/distance/command format was the most preferred, here information about the curve's distance from the vehicle is omitted in order to reduce the warning length to give the driver more time to understand the message and take action. Warnings delivered as the driver enters the curve say only, "Reduce speed." Again, this is a succinct message containing only the necessary information about what the driver must do. This way, drivers aren't listening to and parsing an auditory information as they navigate the curve.

As drivers approach the curve, they travel through three virtual checkpoints. The first is located 300 meters away from the curve's entry point. At this checkpoint, the system displays a yellow warning containing the curve's direction and advisory curve speed. This is shown regardless of the vehicle's speed to provide information to the driver about the presence of the upcoming curve. No audio message is played at this checkpoint.

As the driver continues to near the curve, they travel through the second virtual checkpoint which is located a set distance from the curve. For this checkpoint, the actual distance from the curve's entry point is an experimental variable and is set depending on which treatment level the driver is experiencing. Here, if the vehicle's speed exceeds the approach speed limit (i.e. the speed limit of the road before the curve), the visual component of the warning will change to red (with flashing red-white advisory speed sign) and the "Reduce speed, curve ahead" auditory warning will sound. If the vehicle

speed is less than the approach speed limit, then the visual component will stay yellow and no auditory warning will sound.

The third and final checkpoint is located at the curve's entry point (i.e. where the vehicle's path would first deviate from a straight line). Here, if the vehicle's speed exceeds the advisory curve speed, the "Reduce speed" auditory message will sound. If the driver's speed is less than the advisory curve speed, no auditory warning will sound. Regardless of the audio warning triggered at this checkpoint, there is no visual component (i.e. the screen shows all black). The intent is that as the driver enters the curve, their attention should be focused on navigating the curve and not the warning display. A diagram illustrating the system's checkpoints warning criteria and levels is shown in Figure 3.6.
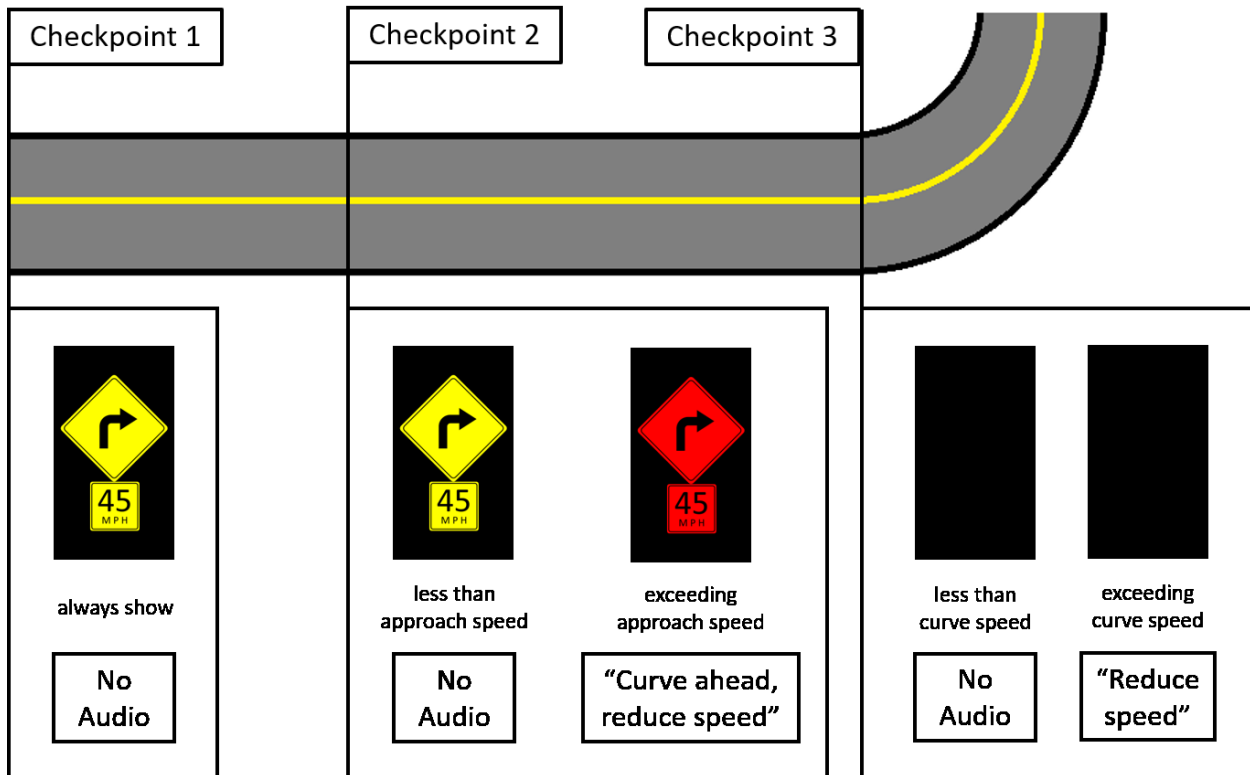
Figure 3.6 Warning deployment criteria.

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CHAPTER 4: EXPERIMENTAL METHODS

4.1 PILOT STUDY SITE

The location for the pilot study was the Minnesota Highway Safety and Research Center (MHSRC) in St. Cloud, Minnesota. This facility is a 160-acre driving range containing multiple configurable driving courses (see Figure 4.1). The purpose of the facility is to provide programs that, relative to driving and transportation, prevent financial loss and human injuries while advancing safe and efficient operation of the highway transportation system.

Figure 4.1 Minnesota Highway Safety and Research Center aerial view.

The MHSRC's closed driving range allowed for the pilot study to be conducted in a controlled way, limiting safety risks and providing greater validity and generalizability as compared to a simulation. Moreover, the wide variety of curve radii present on the track allowed for the examination of driver behavior for multiple situations over a shorter period of time and distance than would be necessary on a real roadway. Finally, the location of the test site allowed for recruitment in an area where more drivers frequently drive on rural roads as compared to participants recruited from the Twin Cities metro area.

The curve advisory speeds for the course were determined prior to the pilot study using an electronic ball bank indicator. This method was selected after consulting with county and state traffic engineers. The procedure to collect this data was done in accordance to the guidelines in the MUTCD. These collected advisory speeds were incorporated into the app in order to show realistic advisory curve speeds in the visual component of the system.

The course that participants were asked to travel was the outermost track on the driving range. This would allow for highway speeds when participants encountered the curves at the end of the straightaway along the south edge of the track. The curves were labeled A through E. This established a forward direction in which the course could be traveled (i.e. curves encountered in alphabetical order) and a reverse direction (i.e. curves encountered in reverse alphabetical order). It is noted that this selection was made arbitrarily. Using this convention, forward corresponds to counter clockwise and reverse corresponds to clockwise. Figure 4.2 shows the route used in the pilot study identified with red along with the curve labels.
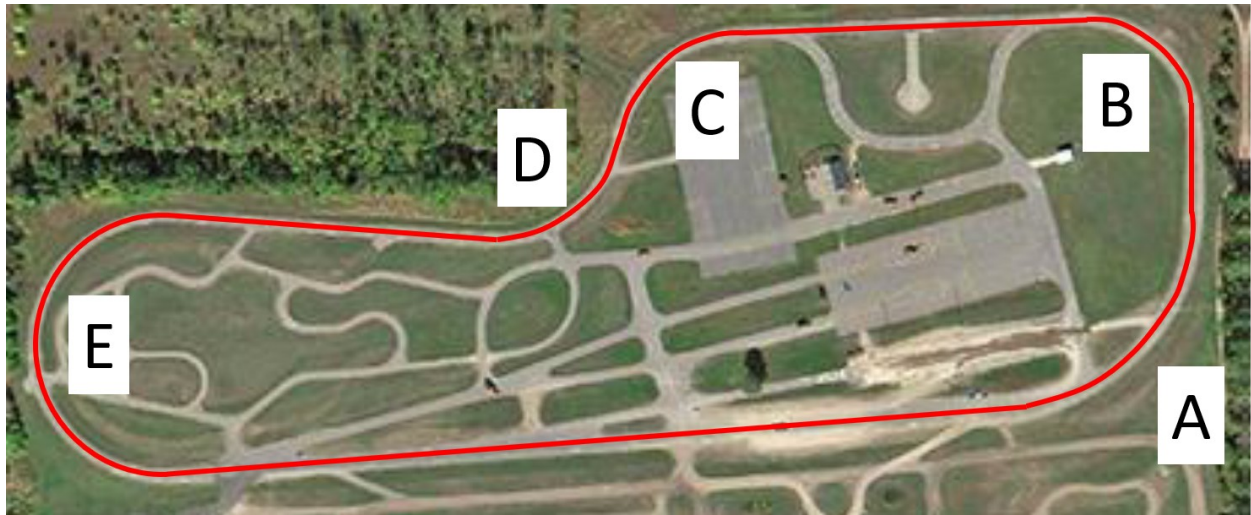
Figure 4.2 Experimental route with curve labels.

4.2 PARTICIPANT RECRUITMENT

A total of 24 drivers between the ages of 20 and 40 were recruited to participate in the pilot study. The goal was to achieve a target mean age of 30 and a balanced number of males and females. These recruitment goals are summarized in

Table 4.1. The target population of research participants focused on experienced drivers, with no cognitive deficits, who would be most likely to benefit from and use an in-vehicle warning system. Focusing on this driver population helped to increase the statistical power of the research study and limit other confounding variables that may be included with a wider age distribution.

Table 4.1 Recruitment goals.

Gender	Age Range	N	Mean Age
Males	20-40	12	30
Females	20-40	12	30
Total	20-40	24	30

Potential participants were screened to exclude anyone with cognitive or physical constraints that might limit their performance. Other requirements included having at least two years of licensed driving experience, a valid state-issued driver's license, a minimum of 4,000 miles driven each year, normal or corrected-to-normal vision (20/40 or better, normal color vision), normal hearing function, and normal cognitive function. Participants were excluded from the study if they have a history of hearing loss that inhibits everyday conversation, health problems that affect driving, inner ear or balance problems, lingering effects of stroke, tumor, head trauma, or infection, and history of migraines or epileptic seizures.

Recruitment efforts focused on the St. Cloud metro area which included posting flyers on university campuses, local business, and community gathering places and by using advertisements on community websites, social media (Facebook, Twitter, Craigslist, and newsletters or magazines). It was required that participants were capable and willing to travel to the Minnesota Highway Safety & Research Center in St. Cloud, MN. Participants were asked to plan on spending 2 hours in the study and upon its completion, they were paid $50.

Prior to initiation of active recruitment, approval was sought and obtained from the Institutional Review Boards (IRB) of both the University of Minnesota and St. Cloud State University. This approval helped to ensure that the safety and confidentiality of research participants was sufficiently protected under the proposed research activities and procedures.

4.3 EXPERIMENTAL DESIGN

This study used a within-subjects design approach where the treatment being tested was the placement of the middle (2nd) checkpoint. Each participant was exposed to a baseline configuration where the system displayed no information as well as the four treatment levels. The order of the treatments was fully counterbalanced (i.e. determined by Latin square) and participants were randomly assigned to one of the counterbalanced sets such that each participant experienced a unique order of treatments. For both the baseline and treatment configurations, the participant was asked to drive the course in both the forward and reverse directions.

The four treatment levels varied how far the second checkpoint was placed relative to the curve's entry. Because the straightaway between curves E and A was the only segment where participants could safely achieve highway speeds (>55 mph) only the curves at the end of the straightaway were used for data collection. This means that for the forward direction, participants only received warnings when encountering curve A and similarly for the reverse direction, they would only receive warnings for curve E. Only data from these two situations was considered.

Because the two curves had different radii and therefore different advisory curve speeds, the treatment levels were set differently for each direction (i.e. forward to curve A, reverse to curve E). Curve A was determined to have an advisory curve speed limit of 45 mph and curve E, a 35 mph advisory curve speed limit. Treatments were set and manually tuned to account for these differences such that a given treatment level would feel similar regardless of the direction/curve. This means that the perceived

braking severity and timeliness of the warning would feel the same. Table 4.2 summarizes the positions of the second checkpoint under each of the 4 treatments.

Table 4.2 Checkpoint 2 distance from curve by treatment.

	Checkpoint 2 Distance to Curve A [m]	Checkpoint 2 Distance to Curve E [m]
Treatment 1	213 m	240 m
Treatment 2	167 m	180 m
Treatment 3	125 m	150 m
Treatment 4	33 m	60 m

4.4 EXPERIMENTAL METHODS

Participants first completed an informed consent process with a researcher. This process briefed the participant about the study, its goals, as well as potential risks of participating. Participants were then screened to make sure they had a valid driver's license, normal color vision using an Ishihara's Color Deficiency Test, and 20/40 or greater visual acuity using a Snellen chart.

Once researchers obtained participants' consent and determined their eligibility, participants completed a questionnaire about their demographics and driving history collecting information such as how long they had been driving, if they had been in a crash or near crash, as well as where and how frequently they drove. Participants also completed a sensation seeking assessment to determine the extent to which they pursue sensory pleasure and excitement. Participants were fitted with the eye tracker and the system was calibrated and tested. In some cases, the system was not able to be calibrated in which case, the eye tracking system was not used.

Participants first completed a practice drive to become accustomed to the research vehicle, its dynamics, and the test course. This consisted of four laps around the course (two laps in each direction). The practice drive also served a secondary purpose which was to normalize or level the participants' driving performance. By providing sufficient practice in advance, the potential for a continued learning effect during the experiment was minimized. Once the practice drive was complete, participants were given additional information about the driving task they would be asked to complete.

The driving task was made up of 6 runs, each run consisting of a forward and reverse lap around the track both with a single treatment condition. The first and last runs were always a baseline run where the system provided no feedback and only collected data. These runs were used to establish the participants' natural behavior (with no system intervention). Performing a baseline run before and after the experimental runs also allowed for the detection of any learning effects throughout the driving task.

The experimental runs were the middle 4 runs in which participants were asked to drive while receiving feedback from the system. The order in which the participants experienced the treatments were determined according to the random Latin square ensuring each participant received the treatments a unique order.

For each of the 4 experimental runs, participants were asked to interact with the system in the same way, each treatment only varying the distance from the curve at which the warning would be displayed. Participants were instructed to drive at 60 mph until they heard the system's warning or until they felt they needed to brake (even if the warning hadn't sounded yet). A single run consisted of this procedure twice, once in each direction. Baseline drives were similar in that participants were asked to drive at 60 mph but were allowed to brake whenever they chose to.

Participants experienced complete system warnings for the first curve of each lap. This corresponded to the first curve after a long straight-away. For subsequent curves, a yellow curve speed warning was shown regardless of speed, and without any audio component. This methodology was used because drivers were only able to reach highway speeds (i.e. 55 – 60 mph) when on the long straight-away. For subsequent curves, there generally was not enough space to safely accelerate to highway speeds. The curves at either end of the long straight-away were a left curve with an advisory speed limit of 45 mph and a right curve with an advisory speed limit of 35 mph.

After each of the treatment runs, participants completed 4 subjective measures questionnaires which included a rating of their mental effort for the driving task, a system usability scale, a system trust questionnaire, and a quick usability inventory. After the baseline drives, participants only completed the mental effort rating questionnaire.

After completing the driving tasks, participants were asked about their overall thoughts about the system as they experienced it. They were also asked usage questions about a hypothetical system that functioned perfectly as they would want it to. Participants also completed a brief wellness evaluation to ensure they were feeling no ill effects due to participating in the study. Lastly, participants were paid $50 for their participation in the study.

4.5 STATISTICAL APPROACH

4.5.1 Dependent Variables

The dependent variables used in the experiments are grouped into the constructs of Driver Performance and Subjective Measures to better understand the extent to which warning system types will facilitate road users to safely navigate through curves. A summary of the dependent variables is presented in Table 4.3.

Table 4.3 Dependent variables.

Measure	Description
Curve Speeds	Measure of vehicle speeds sampled at curve's entry, midpoint, and exit
Usability Survey	A survey to rate driver's experience with the warning sign options along nine dimensions (Van Der Laan, Heino, & De Waard, 1997)
Perceived Trust	Perceived trust in the sign is evaluated using the system trust questionnaire
Perceived System Usability and Fit	Subjective self-report on usability dimensions of the curve speed warning system using the System Usability Survey
Perceived Mental Workload	Rating Scale Mental Effort is a standardized Likert scale method to quickly assess mental workload

4.5.2 Analysis

The analyses of the driver performance and user acceptance were carried out using multiple ANOVA models to examine how the safety performance of each warning system design compared to baseline performance and how the effectiveness of different warning criteria compared with each other. Subjective measures were analyzed using descriptive statistics to determine participant opinions about the system's fitness, usefulness, trustworthiness, and their overall opinion of the curve speed warning system. The data analysis also examined participants' self-reported mental workload both with and without the curve speed warning system active as well as the impact that any increased mental workload had on their driving performance. Additionally, vehicle speeds at key points through the curve were analyzed to quantify the system's impact on driver behavior and performance.

CHAPTER 5: EXPERIMENTAL RESULTS

The goal of the pilot study was to gather driver behavior data and user feedback about the curve speed warning app from a small sample of road users who volunteered to use the app while navigating curves on a closed test track. This feedback includes participant driving behaviors both with and without the app active and subjective feedback about their experience using the app.

The pilot study took place at the Minnesota Highway Safety and Research Center (MHSRC) in St. Cloud, MN over 5 days from June 23, 2017 through June 27, 2017. In this time, 25 participants used the app and provided their feedback.

Data from this experiment was analyzed and used to better understand driver preferences with respect to comfortable speeds through curves, approach speeds, braking rates, and how best to inform the driver in a meaningful but non-distracting way.

5.1 PARTICIPANT DEMOGRAPHICS

A total of 25 drivers participated in the pilot study. The mean age of participants was 28 years old with a standard deviation of 6.14 years. Participant gender distribution was nearly equal, with 12 males and 13 females (see Table 5.1). Drivers had an average of 11.5 years driving experience (SD = 6.9 years). Drivers reported they drove everyday (97.3%), on highways (100%), main roads other than highways (95%), urban roads (91%), and country roads (82%). Only two participants reported at fault minor traffic incidences within the past three years, and not involving major traffic collisions. All participants reported they frequently use smartphones for in-vehicle navigation app services, such as Google and Apple Maps.

Table 5.1 Participant demographics.

Gender	N	Mean Age (SD)
Male	12	30.2 (6.83)
Female	13	25.9 (6.2)
Total	25	28 (6.14)

5.2 SYSTEM USABILITY AND USER FEEDBACK ANALYSIS

5.2.1 Rating Scale Mental Effort (RSME)

Drivers' mental workload was assessed through self-report measures after each drive. Participants rated their mental workload through the Rating Scale Mental Effort (RMSE) by indicating their perceived mental effort on a vertical scale ranging from 0 to 150. A score of 0 would indicate "absolutely no effort", a score of 57 would indicate "rather much effort", while a score of 100 would indicate "very great effort".

Mental effort was examined across the first baseline drive and the final baseline drive to determine if any fatigue or practice effects could be observed. The differences between the first baseline drive (M = 40.04, SD = 26.53) and the second baseline drive (M = 39.21, SD = 29.50) for mental effort was not significant (p > .05). To reduce the data, accounting for the similar mental effort across baseline drives, the responses were averaged for comparison to treatment drives.

A one-way within subjects ANOVA was conducted with the factor being type of warning system and the dependent variable being the RSME scores. The means and standard deviations for RSME scores are presented in Table 5.2. The results or the ANOVA indicated a significant effect for system type, Greenhouse-Geisser corrected, $F(4,92) = 2.88$, $p < .05$, $\eta2 = .11$.

Table 5.2 RSME scores by treatment type.

	Mean	Std. Deviation
Baseline Average	39.6	25.6
Treatment 1	37.0	25.8
Treatment 2	37.4	24.3
Treatment 3	39.4	27.8
Treatment 4	50.2	27.4

Follow up comparisons revealed significantly higher perceived mental workload for Treatment 4 compared to all other treatment types ($p < .05$). This indicates that the late onset of Treatment 4 increased mental workload for drivers and should be initiated further from the curve. Despite being slightly higher on average, mental workload did not differ significantly between the baseline scores and Treatments 1-3 ($p > .05$). This is a positive indication that the use of the curve warning systems (excluding the late warning onset of Treatment 4) does not increase mental workload compared to normal driving with no technology assistance.

5.2.2 System Usability Scale

One of the two usability metrics administered was the System Usability Scale (SUS) which assesses user satisfaction and willingness to use a system in the future through 10 Likert scale questions (see Appendix B). The scale was administered at the end of each of the four treatment drives (i.e., no system was present to assess during baseline drives). The highest rating possible was 100 points, which expressed they would like to use the in-vehicle messaging system, they found it easy to use, well integrated, etc. The lowest SUS score possible was 0, indicating that the participant felt the system was hard to use, unnecessarily complex, obtrusive, or annoying. An average SUS score is 68, which regards the system as useable and relatively efficient for the user.

A one-way within subjects ANOVA was conducted with the factor being type of warning system and the dependent variable being the SUS scores. The means and standard error for SUS scores are presented in,

Figure 5.1 with all treatments receiving above average SUS scores. The results or the ANOVA indicated a significant effect for system type, Wilk's Λ = .55, $F(3,21)$ = 5.8, $p < .01$, $\eta2$ = .45. Follow up comparisons revealed that the usability of Treatment 2 was significantly higher (M = 88.85, SD = 2.27) than all other treatment measures ($p < .05$) and Treatment 4 received significantly lower usability scores (M = 76.98, SD = 3.3) compared to all other treatments ($p < .05$).

SUS Scores by Treatment
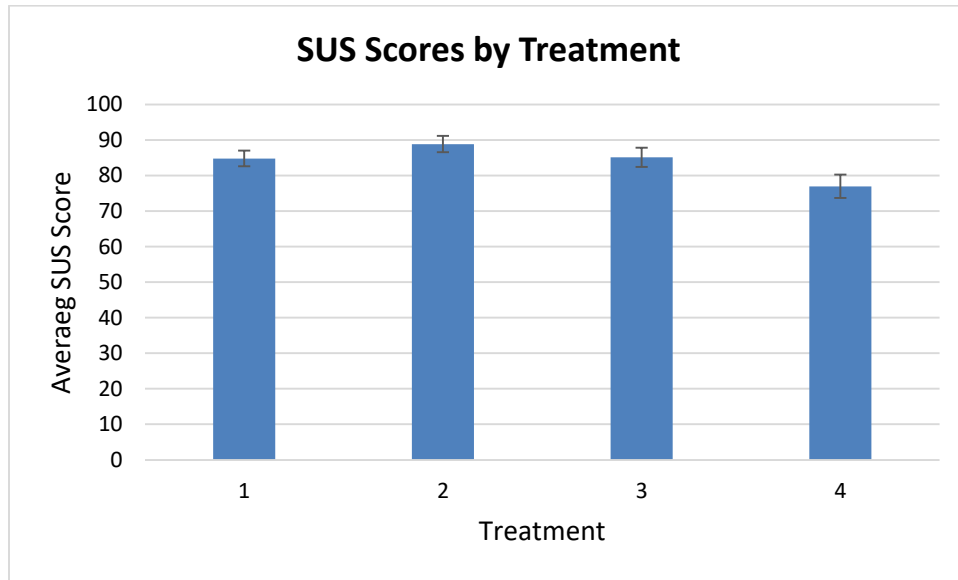
Figure 5.1 Average system usability score by treatment type.

5.2.3 Nine Dimensions of a Quick Usability Test

The second usability metrics administered was the Nine Dimensions of a Quick Usability Test that assesses user judgements of the system based on a spectrum of attributes (e.g., useful to useless, bad to good, etc.). The total rating possible was 18 points, which expressed they perceived the system to be nice, likable, assisting, etc. The lowest score possible was -18, indicating that the participant felt the system unpleasant, annoying, worthless, etc.

A one-way within subjects ANOVA was conducted with the factor being type of warning system and the dependent variable being the SUS scores. The means and standard error for SUS scores are presented in Figure 5.2, with all treatments receiving above average SUS scores. The results or the ANOVA indicated a significant effect for system type, Wilk's Λ = .58, $F(3,20)$ = 4.78, $p < .05$, $\eta2$ = .42. Follow up comparisons revealed that the usability of Treatment 4 received significantly lower usability scores compared to all other treatments ($p < .05$). Difference in system trust among other treatment types was not significant ($p > .05$).
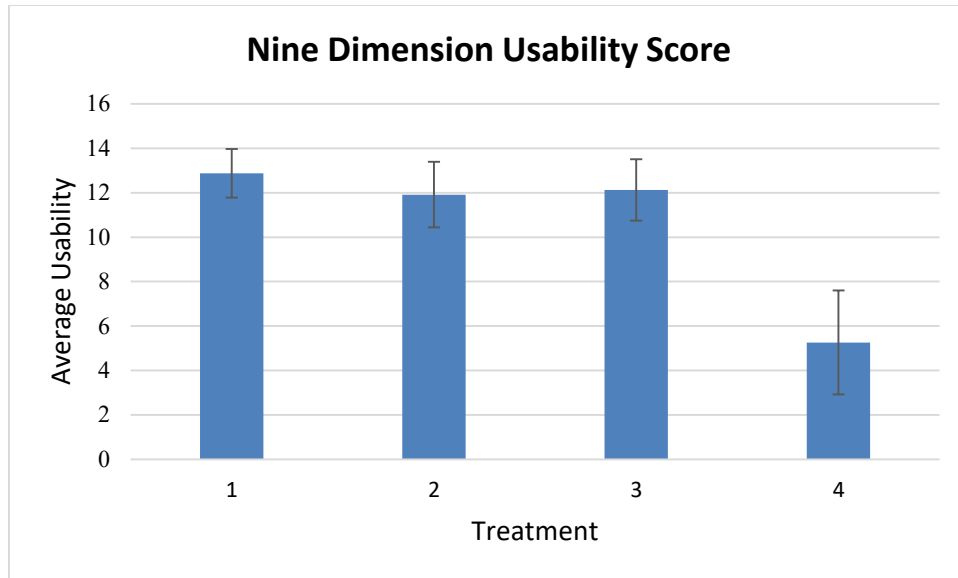
Figure 5.2 Average system Quick Usability Score by treatment.

5.2.4 System Trust

Drivers were surveyed about system trust and usability using the System Trust Questionnaire (see Appendix C). The questions can be divided by content related to safety and driver performance, trust and reliability, and comprehension. Overall trust was examined for this purpose with the maximum trust score possible as 100.

A one-way within subjects ANOVA was conducted with the factor being type of warning system and the dependent variable being the System Trust scores. The means and standard error for SUS scores are presented in Figure 5.3. The results or the ANOVA indicated a significant effect for system type, Wilk's Λ = .55, $F(3,21)$ = 5.82, $p < .01$, $\eta2$ = .45. Follow up comparisons revealed that driver trust in Treatment 4 was significantly lower (M = 88.85, SD = 2.27) than all other treatment measures ($p < .05$) indicating that the warning onset was too late for acceptable system trust. Difference in system trust among other treatment types was not significant ($p > .05$).

Overall System Trust by Treatment
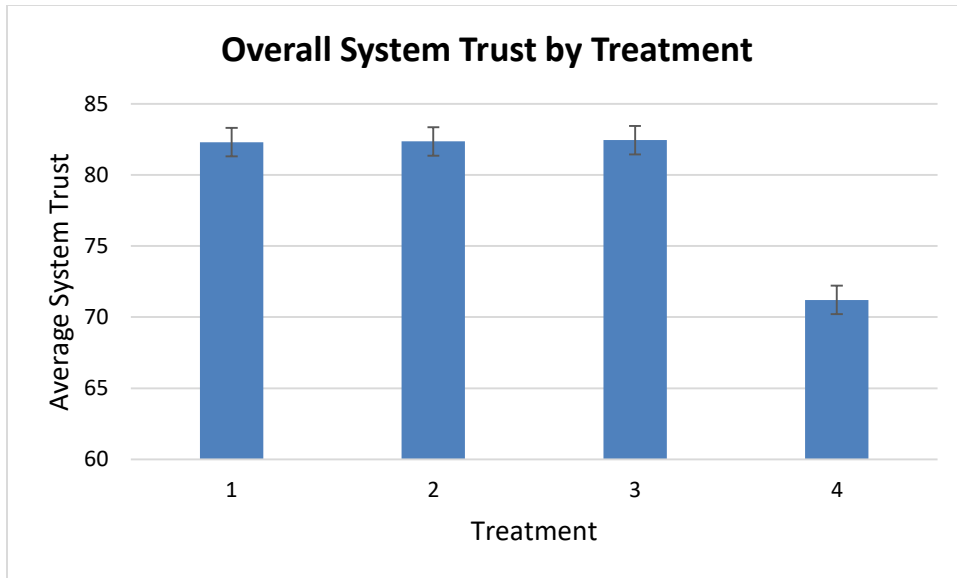
Figure 5.3 Average system trust score by treatment.

Performance Trust: A one-way within subjects ANOVA was conducted with the factor being type of warning system and the dependent variable being the Performance Trust scores. The means and standard error for SUS scores are presented in Figure 5.4. The results or the ANOVA indicated a significant effect for system type, Wilk's Λ = .69, $F(3,21)$ = 3.22, $p < .05$, $\eta 2$ = .32. Follow up comparisons revealed that driver trust in the performance of Treatment 4 was significantly lower than all other treatment measures ($p < .05$). Difference in system trust among other treatment types was not significant ($p > .05$).
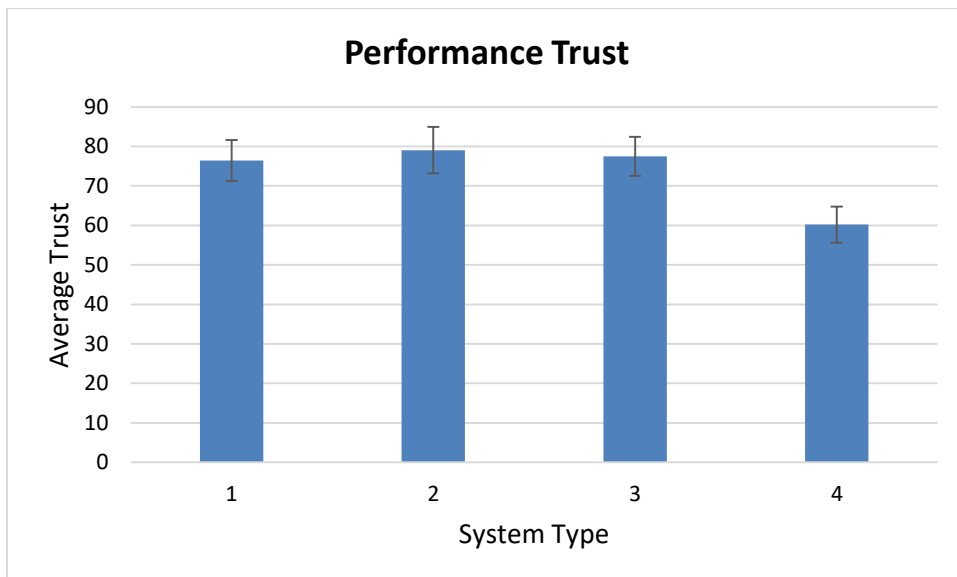
Figure 5.4 Average system performance trust score by treatment.

Process Trust: A one-way within subjects ANOVA was conducted with the factor being type of warning system and the dependent variable being the Process Trust scores. The results or the ANOVA indicated no significant effect for system type ($p > .05$), demonstrating that generally users found the familiarity and reliability of the treatment types to be similar to one another.

Purpose Trust: A one-way within subjects ANOVA was conducted with the factor being type of warning system and the dependent variable being the Purpose Trust scores. The means and standard error for SUS scores are presented in Figure 5.5. The results or the ANOVA indicated a marginal effect for system type, Wilk's $\Lambda = .71$, $F(3,21) = 2.9$, $p = .058$, $\eta2 = .29$. Follow up comparisons revealed that driver trust in the purpose of Treatment 4 was significantly lower than all other treatment measures ($p < .05$). Difference in purpose trust among other treatment types was not significant ($p > .05$).
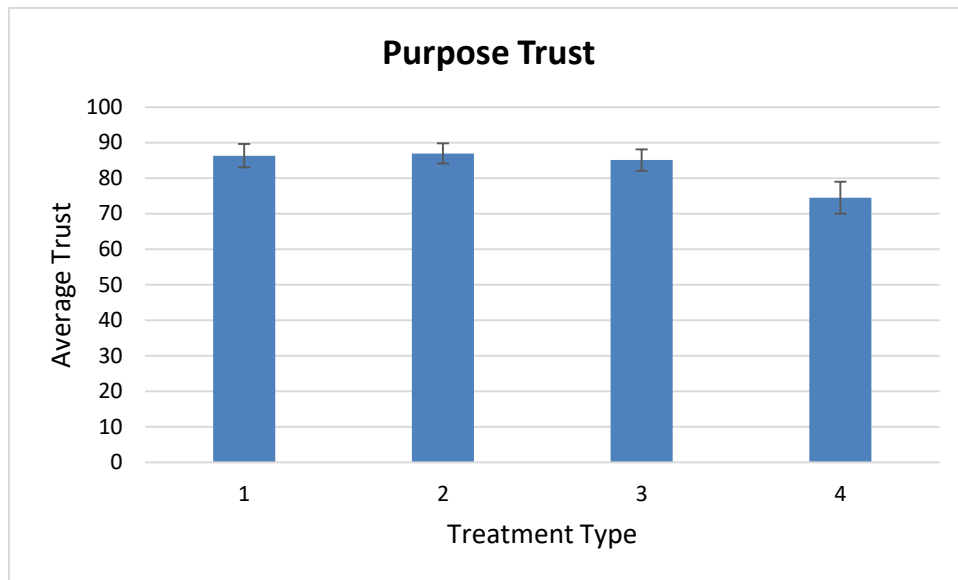
Figure 5.5 Average system purpose trust score by treatment type.

Foundation Trust: A one-way within subjects ANOVA was conducted with the factor being type of warning system and the dependent variable being the Foundation Trust scores. The results or the ANOVA indicated no significant effect for system type ($p > .05$), demonstrating that generally users reported similar confidence in their ability to drive safely without the system.

5.2.5 System Timing Appropriateness

After each drive, users were asked to express how appropriate was the timing of the alert they received prior to approaching the curve. Once more than one treatment alert type was experienced, they were asked to reflect if the most recent was the same, better or worse in terms of timing appropriateness (see Table 5.4). Overall, Treatment 2 received the greatest percentage (i.e., 79%) of participants who felt it was appropriate in timing, while a small proportion felt it was too early (i.e., 21%) and no participants felt it was too late. Similarly, 75% of participants felt Treatment 3 also had timing which was appropriate and received no judgements of being too early; however, 25% of participants felt it was too late. The

remaining treatment types either received a high percentage of "too early" ratings (i.e., 79% for Treatment 1) or an overwhelming proportion of "too late" ratings (i.e., 100% for Treatment 4).

Table 5.3 Participant agreement for treatment timing appropriateness.

	Too Early	Appropriate	Too Late
Treatment 1	79%	21%	0%
Treatment 2	21%	79%	0%
Treatment 3	0%	75%	25%
Treatment 4	0%	0%	100%

5.3 DEBRIEFING INTERVIEWS

5.3.1 System Evaluation

Participants were interviewed at the end of the study after completing all the drives. Researchers prompted each participant to respond to four questions that assessed their outlook on using the system after experiencing each of the curve entry speed treatment levels. These questions allowed participants to reflect on their experiences with the curve speed warning system, which provided researchers with an understanding of how the participants viewed the system, theoretical usage of the system if available, and greater perceived implications of the system's safety benefits when used by other drivers on the road. Each question was rated on a 5-point Likert scale, with 0 representing the lowest score (e.g. "Strongly Disagree") and 5 representing the highest score (e.g." Strongly Agree"). These results are summarized in Table 5.4.

Table 5.4 Likert-scale qualitative system use questions and participant scores.

System Question	Mean Feedback Score	Feedback Score Standard Deviation
I would use this system myself	4.24/5	1.03
I would recommend this system for a family member, friend, or other person.	4.5/5	0.76
This system would make me feel safer when driving in rural curvy areas.	4.52/5	0.80
I would feel safer if other drivers used this system.	4.68/5	0.73

Results from system use questions indicate participants would use the system, would feel safer if others used the system (either people they know or strangers), and anticipated that the system would increase their safety when driving through rural areas featuring series of curves.

Following the system use questions, researchers prompted participants to give their feedback on seven additional questions that about their experience with the curve speed warning system. These questions were in an open-ended format, meaning participants verbally responded to the best of their abilities to each item. The following open-ended participant debriefing questions were given to each participant:

1. Which type of situations, environments, or circumstances would you use the system?
2. Would you use this system as a standalone app, or integrated with a navigation system?
3. Which do you prefer, and why?
4. What did you like about the system? Why?
5. What did you dislike about the system? Why?
6. Do you have any suggestions on how we can improve the system?
7. Would you be willing to purchase a system similar to ours, if perfected? If so, how much would you be willing to play?

Researchers recorded participant responses to each question and analyzed each response accordingly.

5.3.2 System Use Cases

Participants provided a variety of responses for when they would opt to use the curve speed warning system while driving. The most frequently reported circumstance in which participants would use the system was in the case of drivers travelling on unfamiliar roads, specifically when drivers anticipated successive curves on those roads. All participants described unfamiliar roads as their primary use case for driving with the curve speed warning system. Roads which lack sufficient signage on speed limits, advisory curve speeds, or any signage at all were also cited as circumstances in which the system would be best used while driving, according to participants. Weather factors (e.g., rain, fog, snow, or icy conditions) were cited as circumstances which may spur their use of the system. Finally, poor lighting conditions were frequently mentioned as reasons to use the system, with many drivers reporting insecurities when driving under dusk and nighttime lighting conditions.

5.3.3 User Preference of Curve Speed Warning System Platform

The majority of participants, 14 of 25, stated they would like to see the curve speed warning system in a standalone format, such as the smartphone application they experienced during their drives throughout the study (see Figure 5.6). Some participants cited ease of access and equitability of use as making the standalone format their choice, while others stated the disproportionate variation in average vehicle age on the roadway as their reasoning for standalone formatting. Eight participants preferred to see the system presented integrated with navigation apps (i.e. Google, Apple Maps) or center-stack in-vehicle infotainment systems (i.e. Ford Sync, in-dash navigation suites). Three participants did not have a preference to system format, and stated either option would suffice as long as the system was easily obtainable. While system format preferences varied across participants, all participants emphasized

their desire to see the curve speed warning system developed into a platform they could easily download and use while driving in rural and curvy areas.

Participants' Preferred System Format
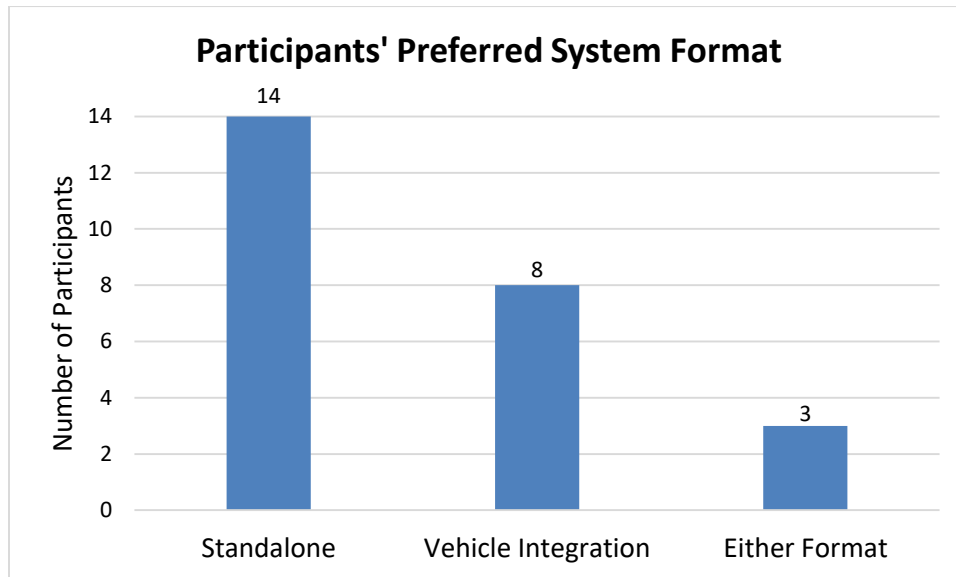
Figure 5.6 Participants' preferred curve speed warning system format.

5.3.4 Participants' Likes and Dislikes of the System

Researchers asked participants to provide their thoughts on which characteristics or functions they liked during their experience with the curve speed warning system. Feedback results varied from the general function of the system and its purpose to the details of the visual components (i.e. color, flashing icons) within the staged alerts. Overall, participants were receptive of the system as an emergent technology and felt it could improve their safety or the safety of other drivers on the road, which reflects their original high ratings on the Qualitative System Use Questions (see Table 5.4). Various usability dimensions of the system were unpacked in the majority of responses, including positive feedback on the staging and flashing of visual alerts, the auditory messaging component to the visual alerts, color coding of yellow and red to indicate urgency, and the simplicity and ease of use of the system. Additional comments included further qualitative items related to system trust and perceived safety benefits, such as increased awareness about their speed and the curve speed, advance warning notifications, increased comfort, and reduced uncertainty.

When prompted to provide the cons, or characteristics of the system that were missing or unsatisfactory, participants reported a limited number of concerns that negatively impacted their experience using the system. Of the 25 participants, 10 replied "none" which meant they had no dislikes with the system during the experiment, while the remaining 15 provided one dislike item. Of those 15, eight responses were based on the timing characteristics of the curve speed warning system as the driver approached the curve, namely the latest warning onset treatment. These participants reported they did not want to see Treatment 4 in a developed system, because they felt the warning was too late relative to the curve entry point and therefore a potential safety risk. The remaining criticisms of the

system included the lack of speed context, the volume of the computerized voice in the auditory alerts, and concern that the system might decrease drivers' ability to drive without the system.

Overall, feedback gained from the like / dislike exercise provided researchers with additional qualitative data on participants' perceptions of the curve speed warning system and its usability traits. Data acquired from this exercise will help researchers understand which functions or usability dimensions need revision, therefore guiding new design iterations of the system.

5.3.5 Participants' Suggestions for Improving the Curve Speed Warning System

Researchers were interested in collecting feedback on how the curve speed warning system could be improved or redesigned to promote the highest safety benefits and usability qualities for potential users of the system in the future. In addition to studying the dislike responses provided by participants in the like / dislike exercise, researchers offered a solicitation for suggestions on how to improve the system. Overall, participants reported their primary concerns with alert timing onset relative to the curve (i.e. treatment option and consistency), adding a real-time speed value on the visual display, and ensuring the system does not interfere or overlap with navigation commands or stereo use. Additionally, participants desire the ability to customize basic interface parameters, such as the lighting brightness of the system and volume of the auditory alerts. Other suggestions were based on integration of the system into an infotainment system or navigation app, such as including the ability to show a navigation map while driving.

Interestingly, nearly 25% of participants did not offer any suggestions for improving the system despite being encouraged to do so, indicating that the beta iteration of the system was sufficient as-is for use and met their expectations.

5.3.6 Purchase Price Inquiry

In order to estimate the general value and desirability of an in-vehicle technology such as the curve speed warning system, researchers added an open-ended question on how much the system was worth to the participant and the amount of money they would spend on acquiring the system. Results varied in their pricing points and system formats. Nine participants (36%) stated the system should be free as an integrated function within an infotainment system or navigation app. Price points changed depending on if the system was an add on in a new car (e.g. $200-300), was a one-time app purchase (e.g. $1-$20 app), or was added into a standalone navigation unit (e.g. Garmin, add $1-$50). It should be noted that researchers did not provide a pricing floor or ceiling, meaning that the potential purchase prices for the system were purely subjective from the participants' viewpoint. While this is likely responsible for the variety of answers and diversity of prices per system format, allowing participants to give their first impression on pricing points ensured their answers were not influenced or skewed by researchers.

5.4 EYE TRACKING ANALYSIS

Researchers assessed the visual attention and visual scanning behaviors of participants while driving using the curve speed warning system. In order to examine participants' gaze behavior while driving and make inferences on the extent to which the system was visually taxing, researchers employed the use of Tobii Pro Glasses (Tobii, AB) which feature binocular eye tracking abilities that record both eye movements, as well as video of the participant's field of view via a forward-facing scene camera (see Figure 5.8). The Tobii system is a non-intrusive, wearable glasses tool which is similar to common sports sunglasses. All participants were presented with the Tobii (see Figure 5.7) glasses during their experiment, however, many participants (N = 13) were ineligible to use the eye tracker due to prescription lens requirements, driver comfortability, or system calibration quality factors.
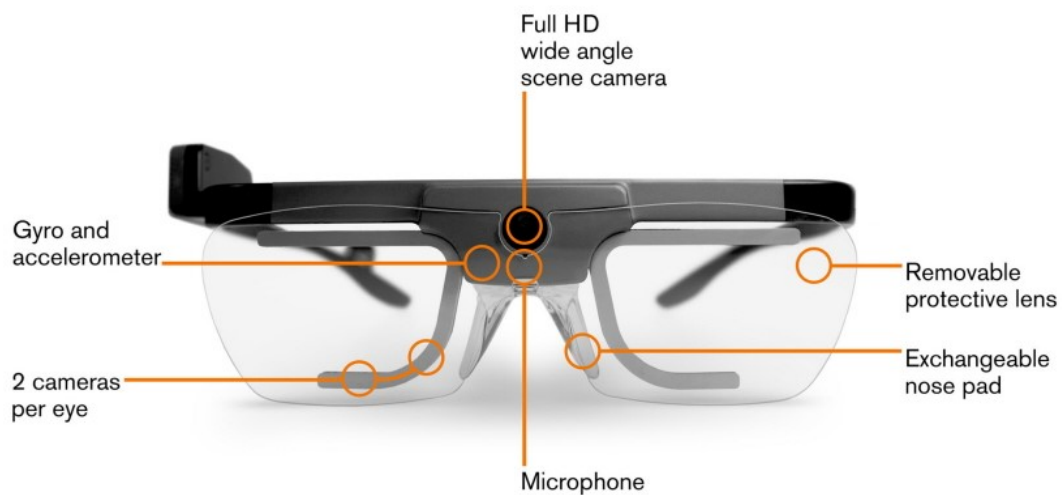
Figure 5.7 Tobii Pro Glasses Technical Overview (Tobii, AB).

Figure 5.8 Participants' driving perspective through the Tobii Pro Glasses (Tobii, AB).

5.4.1 Eye Tracking Visualization- Heat Map Analysis

In order to approximate the qualitative data analysis from the participant trials, researchers employed the heat map analysis technique to visualize fixation point distribution and concentration across specific points over each curve's total duration. Heat map analyses are used to illustrate the overall concentration, or clustering, of participants' visual attention, in addition to showing the distribution of where they looked. The Tobii Pro Glasses System's heat map generation relies on fitting distributions of adjacent fixations relative to a primary fixation point to the cubic Hermite spline polynomial, a Gaussian curve approximate, see Figure 5.9 (Tobii, AB).
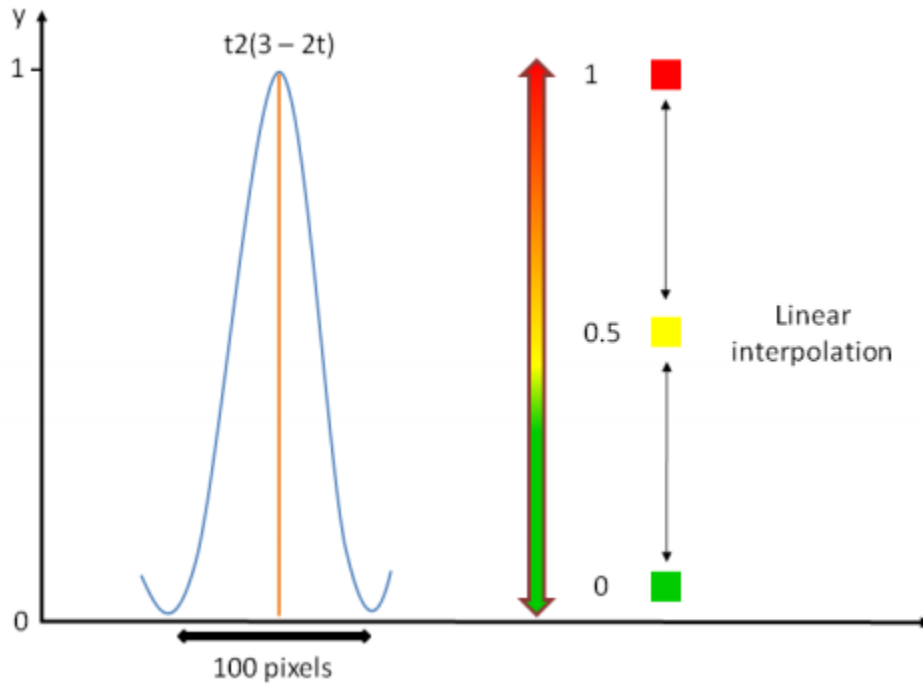
Figure 5.9 Graphical depiction of Tobii eye tracking heat map calculation (Tobii, AB).

In simpler terms, the distribution of fixations around a central fixation location point using a polynomial coefficient provides researchers the ability to visualize multiple clustered independent fixation events near areas of interest (Figure 5.9 and Figure 5.10). This analysis provides researchers with meaningful fixation data point distributions to assess how the presence of the device influences drivers' visual attention.
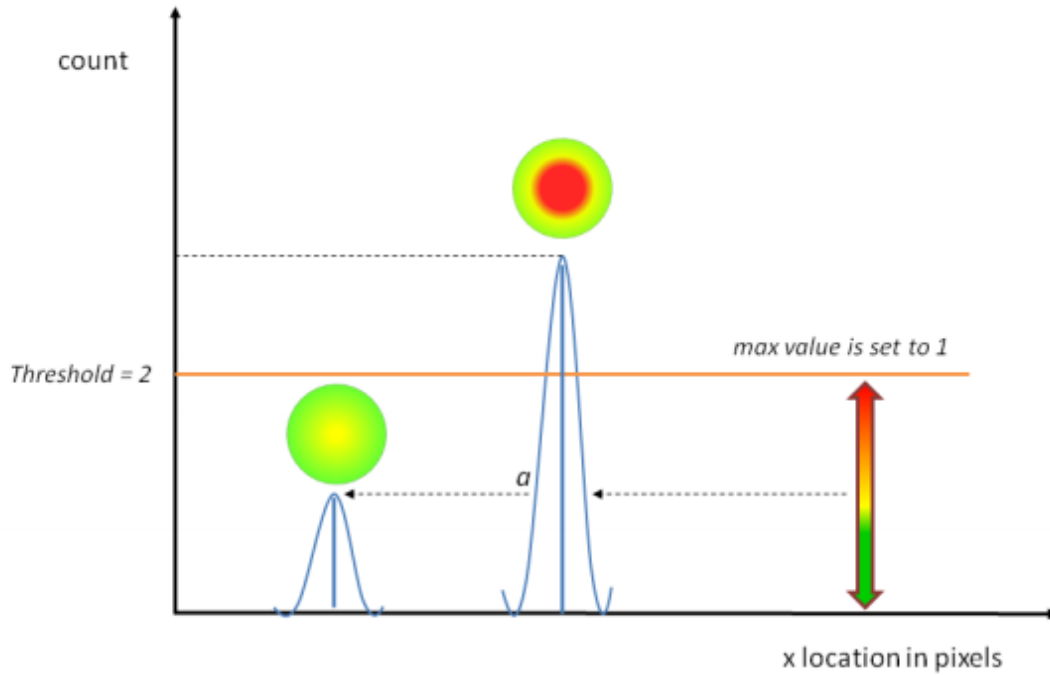
Figure 5.10 Visualization of aggregate fixation duration and frequency calculation criteria (Tobii, AB).

In Figure 5.11, the heat map analysis results show a participant's visual attention aggregated across a single curve trial (i.e., Treatment 2, Forward direction) by color coding fixation durations on a linear color gradient from shortest (i.e., green) to longest (i.e., red). The clusters of fixations that appear as red and orange, or near the instrument cluster and immediate forward roadway relative to the driver in Figure 5.12, illustrate where the driver was most focused while navigating through the curve.
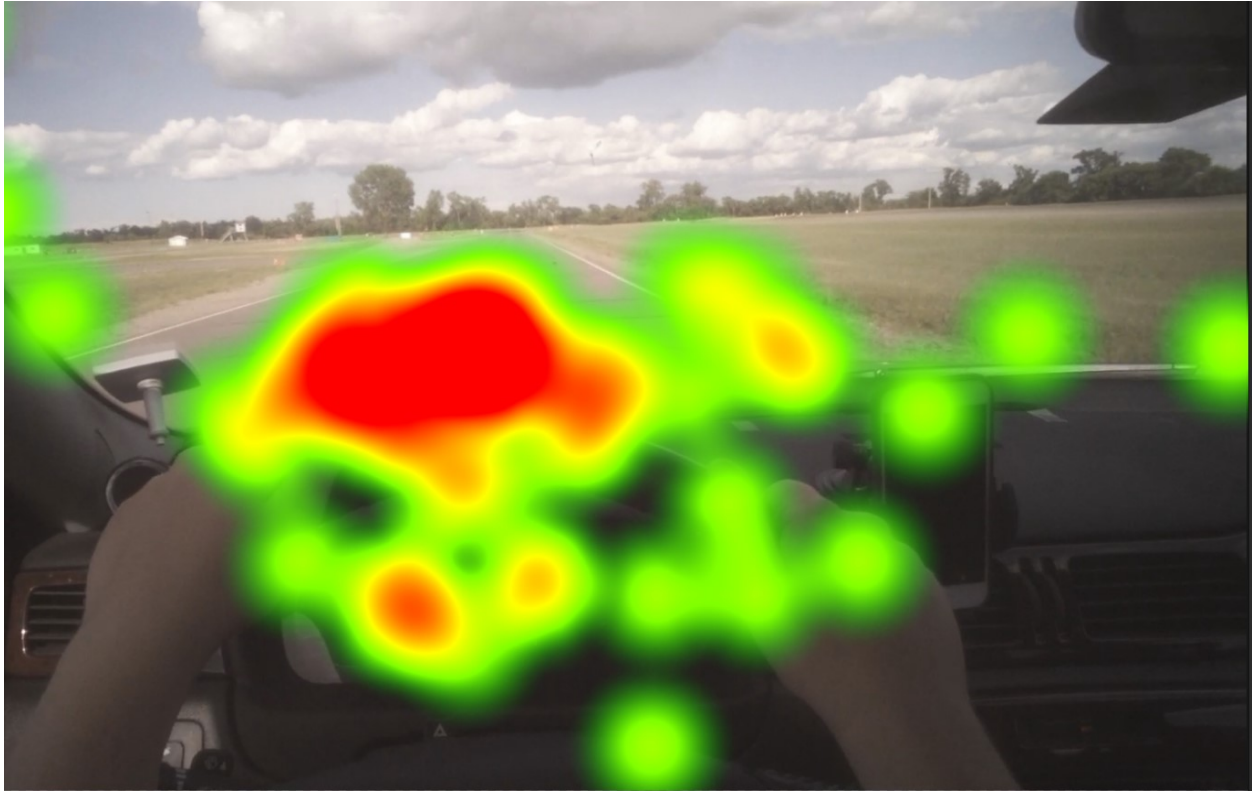
Figure 5.11 Heat map analysis for entire curve under Treatment 1.

Figure 5.12 Heat map analysis for entire curve under Treatment 4.

5.4.2 Fixation Gaze Plot and Gaze Trail Analysis

In order to examine the visual searching strategies participants employed during their drives with the curve speed warning system, researchers performed gaze plot analyses with a subset of the collected eye tracking data. The gaze plot analysis visualizes where participants fixated in the scene by providing a set of numbered markers for each fixation event and subsequent fixations over a time period. Gaze plot analyses provide researchers with meaningful observations of how participants used their visual attention, or where, when, and how long they looked at any specific area in the scene.
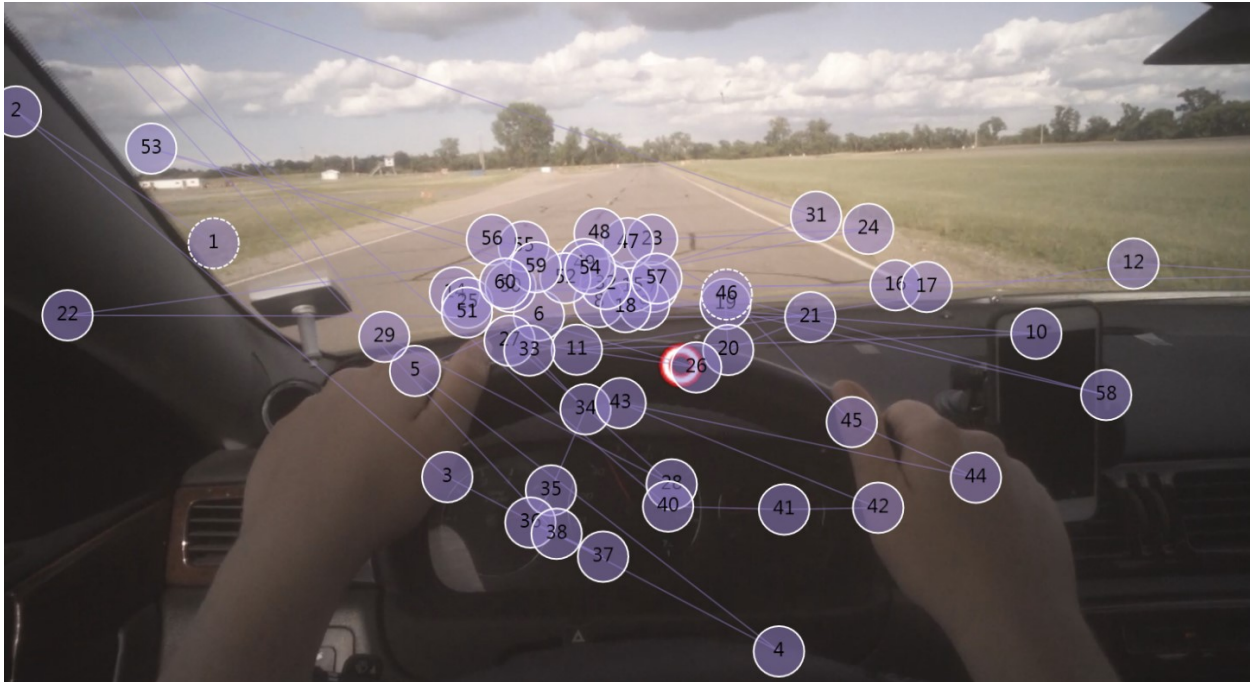
Figure 5.13 Aggregate gaze plot trail analysis for entire curve under Treatment 2.

Figure 5.13 depicts a sample curve trial under the second-earliest curve speed entry alert (i.e., Treatment 2). The purple circles represent a location of fixation at the 100ms level or greater and the attached purple lines indicate the trailing pattern of where the previous and subsequent fixations occurred relative to the specific fixation point. These fixation locations and path trails provide data points that describe participants' visual attention or visual searching patterns throughout each curve trial. The visual behavior demonstrated in Figure 5.13 suggests that the phone displaying the curve speed warning alert did not significantly impact the overall gaze distribution during the drive, and did not demand a disproportionate amount of visual attention in order to complete the curve trial using the system. Figure 5.14 illustrates the change in visual attention, or gaze behavior, when participants were exposed to the latest of the curve speed entry alerts (i.e., Treatment 4). Restricted visual search has been found to indicate high mental workload in the driving context, which reduces the overall variability in participants' distribution of glances on the forward roadway and interior regions (Sodhi, Reimer, & Llamazares, 2002).

Figure 5.14 Gaze plot for Treatment 4.

5.4.3 Exploratory Eye Tracking Results Summary

Results from the heat map and gaze plot analyses suggest the curve speed warning system did not negatively influence participants' visual attention while performing the curve navigation tasks. The corresponding quantitative eye data tracking data analysis of fixations on the phone region on the dashboard did not reveal any fixations lasting two seconds or more, a commonly used benchmark in in-vehicle technology design standards (Martinelli & Medelin, 2012). Additionally, very few fixations at the 100ms level were recorded, providing evidence alongside the heatmap and gaze visualization data that our drivers did not rely on the phone's visual display to process the curve speed warning alert's information. The gaze plot analyses were consistent with the heat map analyses which showed participants' gaze behavior became more restricted to the immediate forward roadway and inner lane or apex region of the curve during the later (i.e., Treatment 4) warning alerts.

Most notably, our participants demonstrated visual attention patterns that fit well with the literature's consensus; during the earlier alerts which required the driver to respond with less immediacy, the drivers were able to distribute their gaze more liberally (see Figure 5.11 and Figure 5.13), whereas the analyses under the latest curve speed warning alerts, the fixation data indicate high mental workload and salient task priority (Horrey, Wickens, & Consalus, 2006) (i.e., Treatment 4), see Figure 5.12 and Figure 5.14. As hypothesized, drivers in the field study made infrequent glances to the phone on the dashboard during each drive, a similar finding in other driving studies examining visual attention to in-vehicle devices (Broström, Bengtsson, & Aust, 2016; Craig, Achtemeier, Morris, Tian, & Patzer, 2017; Sodhi, Reimer, & Llamazares, 2002).

In summation, the curve speed warning system demonstrated the ability to communicate curve speed information to drivers in the field study without the expense of driver visual distraction, based on the sample eye tracking data. While only a subset of eye tracking data were suitable for analyses, the researchers are confident that the general pattern of eye tracking results were consistent with drivers' overall visual behavior based on their subjective feedback using the system and with the debriefing interviews conducted post-study.

5.4.4 Eye Tracking Data Acquisition and Analysis Caveats

Out of the 12 total drivers that were eligible and willing to use the eye tracking glasses, a total of 8 participant data sets became unusable due to gaze calibration drift, or the deviation of the eye tracking cameras' ability to accurately estimate the fovea locations. Researchers attribute the excessive gaze calibration drift incidences to the extended period of time wearing the glasses throughout the study (i.e., 1-2 hours), in addition to the frequent up-and-down head movements to clipboards participants were required to make to complete each subjective measures item during the study. In the event the glasses slipped down the participant's nose, moved from lateral acceleration forces at high curve entry speed, or as simply as a participant readjusting the glasses, the calibration of the eye tracker may have become offset and therefore inaccurate. Figure 5.15 illustrates the most common occurrence of inaccurate calibration, showing fixation events in the clouds and headliner or visor interior region. Other data sets (N = 6) featured eye gaze plots that did not represent realistic visual behavior, including fixations to only one location of the image).
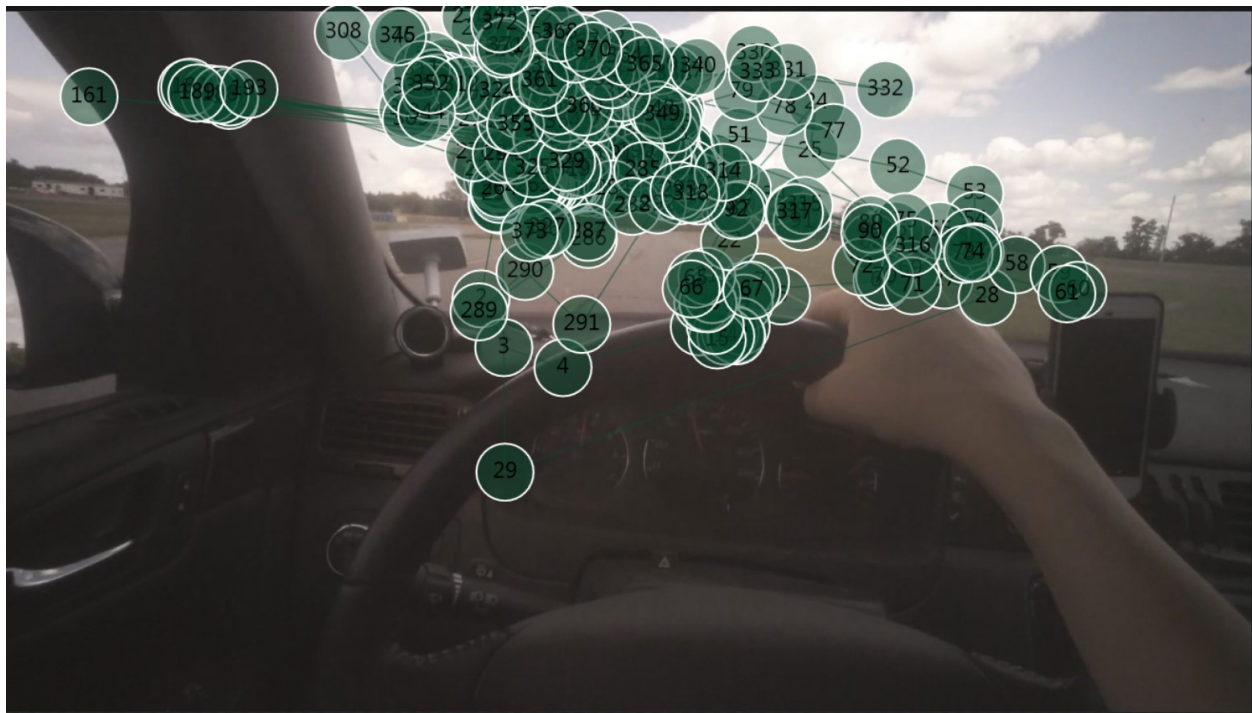
Figure 5.15 Inaccurate eye tracking data due to gaze calibration drift.

5.5 ANALYSIS OF PHONE-COLLECTED DATA

5.5.1 Driver Behavior Under Baseline Conditions

The advisory curve speeds displayed to the driver were determined through the use of a digital ball bank indicator. The methods used to determine these speeds were consistent with the procedures described in the Manual on Uniform Traffic Control Devices (MUTCD). For ease of data collection and analysis the curves were labeled A through E as shown in Figure 5. It is noted that complex curves (i.e. "S" curves or curves of varying radii) were treated as a combination of multiple simple curves. For example, the "S" curve in the top middle of Figure 5.16 could be considered to be a single complex curve, but here is considered two simple curves.
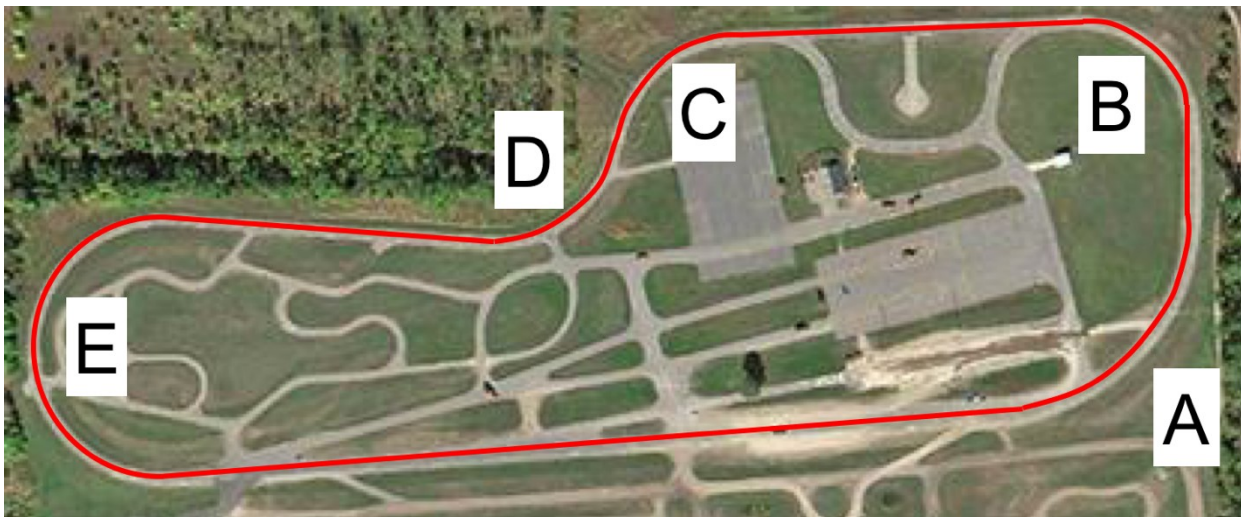
Figure 5.16 MHSRC driving range with curve labels.

As a part of the driving task, drivers were asked to navigate the course without the assistance of the system in order to collect their baseline behavior. The system collected drivers' speeds as they entered the curves.

Table 5.5 Baseline driver behavior shows the advisory curve speed for each curve along with the mean and 85 percentile baseline speeds.

Table 5.5 Baseline driver behavior by curve.

Curve	Advisory Curve Speed [mph]	Baseline Curve Entry Speeds Counter-Clockwise		Baseline Curve Entry Speeds Clockwise	
		Mean [mph]	85 pctl. [mph]	Mean [mph]	85 pctl. [mph]
A	45	45.4	49.2	40.7	44.0
B	30	39.3	43.1	37.6	41.5
C	30	38.1	42.8	33.7	37.3

D	30	35.0	38.6	38.3	42.5
E	30	39.6	43.0	42.2	46.1

The data is separated by course direction (i.e. clockwise or counter-clockwise) because of the effect that prior curves may play on driver's behavior for upcoming curves. For example, drivers approaching curve A from the long straightaway (counter-clockwise) will slow down to a speed they feel is appropriate for the curve, but when approaching from the other direction, they may already be driving slower than they would due to curve B. Overall, these results confirm that in general, drivers are willing to exceed the advisory curve speeds by around 5 to 10 mph depending on the characteristics of the curve.

The baseline conditions before and after the treatment conditions were also analyzed separately in order to determine whether participants experienced a learning effect while repeatedly driving the course. For this analysis, like all other treatment analyses, only the behaviors encountering the first curve after the straightaway was considered. Vehicle speeds at a number of points along the approach and the curve were compared in pairwise comparisons. Based on this analysis, it was determined that differences between the two baseline runs were insignificant. This indicates there was no significant learning effect.

5.5.2 Driver Behavior During Preferred System Operation

Based on the preference and other qualitative data collected, it was determined that treatment 2 represented warning deployment criteria that were the most preferred by drivers. To investigate behavior under these treatments, driver speeds were taken at curve midpoints (i.e. halfway between the curve's entry and exit) to characterize their speed as they navigate the curve. Warnings were only displayed for the curves at the end of the straightaway. This corresponds to curve A when traveling through the course counter-clockwise and curve E when traveling through the course clockwise. Table 5.6 summarizes drivers' mid-curve speeds.

Table 5.6 Comparison between baseline and treatment mid-curve speed for preferred treatments.

Curve	Advisory Curve Speed [mph]	Baseline Mean Mid-Curve Speed [mph]	Treatment 2 Mean Mid-Curve Speed [mph]
A (CCW)	45	43.8	38.8
E (CW)	30	36.4	33.6

These results show that when receiving the warnings, drivers will travel through the curves roughly 9% slower than without the system. Additionally, a pairwise comparison was performed to compare the baseline and Treatment 2 behavior and it was found to be statistically significant (p-value $p<0.005$ forward, $p<0.001$ reverse). This indicates that drivers receiving appropriately placed warnings will have lower speeds through curves than without warnings. Further analysis showed that there was no significant difference between any of the preferred treatments (Treatments 1, 2, and 3). This shows that the system is insensitive to the precise placement of the warnings as long as they are not unreasonably close to the curve (i.e. Treatment 4).

5.6 SYSTEM FAILURE RATES

Out of 200 drive trials in which the system was expected to provide curve speed entry warnings, researchers observed a total of 22 failures in system notifications to drivers. In the majority (N = 13) instances, participants failed to drive the test vehicle at the 60MPH straight road advisory speed as they entered the curve. Participants that prematurely braked before entering the curve would not trigger the curve speed warning app, therefore limiting their exposure to the system treatments. These events were coded as "too early" events based on participant feedback (i.e., "I felt uncomfortable, I was going too fast") and researchers' observations. The remaining 9 instances when the system did not operate as expected occurred due to errors with the curve speed warning system app on the test phone. In these events, the alert did not appear on the phone screen and sound on curve speed entry did not alert to the driver. The failure events were removed from data analyses.

CHAPTER 6: CONCLUSIONS

6.1 FUTURE WORK

6.1.1 Determining Warning Placement Criteria

The focus of this work was to determine the feasibility of a curve-speed warning system as implemented on a smartphone. The pilot study used to evaluate the warning system was designed to collect user driving behavior and feedback about the system as a whole and specifically for different warning placements relative to the entry of the curve. Although the results show relatively low sensitivity to a reasonably placed warning, designing an experiment with more granularity warning placements and different experimental procedures could provide additional information about driver preference in warning timings and placements. The warning distances used in this experiment were tuned by the research team, but future work could be used to develop a model for determining the warning distances and timings for a given curve advisory speed and approach speed limit. This would allow for a more automated method for assigning warning deployment criteria for curves.

6.1.2 Field Operational Testing

In the experiment, participants' use of the system was highly controlled in that the experimenter operated the smartphone and the participants' route was planned out *a priori*. A field operational test would involve recruiting a number of drivers in a given geographic area to aid in testing and assessing the performance of the system. This would give researchers a great deal of information on measures such as system robustness (i.e., how prone the system was to failure), how system-use metrics change over time, and feedback data to further refine the app to make it more user friendly or effective. Additionally, deploying the warning system in this way would enable participant-use metrics in a diverse set of environments and circumstances. For example, participants may have differing opinions of the system when traveling through curves with traditional static signing or infrastructure-based dynamic speed feedback signs.

6.2 SUMMARY

This study showed that an in-vehicle curve-speed warning system deployed as a smartphone app is a feasible method for delivering critical curve-related information to drivers as they approach hazardous horizontal curves. Overall, participants in the pilot study had a positive impression of the system, noting that they would be interested in using it if it were available to the public. The usability information they provided during the experiment showed that they found the system to be useful and non-distracting. The experiment also examined differences between warning deployments at different distances from the curve. The data showed that there was a slight preference for the warnings delivered 167 m from the curve with the 45 mph advisory speed (curve A) and the warnings delivered at 180 m from the curve with the 35 mph advisory curve speed (curve E). However, there was low sensitivity to the exact

placement of the warnings except for the warnings that were excessively close to the entry of the curve, which were extremely unpopular.

The data collected on the phone monitored the vehicle's speed as the driver navigated the course. By comparing the mid-curve speeds across the different warning configurations, differences in speed behavior were calculated between the baseline conditions and the preferred warning distance as described above. On average, there was an 8-10% decrease in speed at the midpoint of the curve when drivers were using the system as compared to the baseline condition when no warnings were given. This shows that drivers following the warning prompts successfully lowered their speeds as compared to when no warnings were present.

These findings show that the curve-speed warning system developed and tested as a part of this work was effective, well received, and safe. Driver behavior data collected by the phone showed a reduction in speeds when the system displayed appropriately placed and timed warnings for upcoming curves as opposed to when the system was not active. Participant feedback data showed that the system was felt to be trustworthy, usable and understandable and did not increase drivers' perceived mental workload. Additionally, based on driver feedback and limited data collected using an eye tracker, it was determined that the system did not increase driver workload or require an unsafe amount of visual attention to interpret the displayed warnings.

REFERENCES

Agerholm, N., Juhl, J., Sonne, I., & Lahrmann, H. (2007). *Speed map maintenance: Experiences from the ISA project "Spar På Farten".* Proceedings from the 6th European Congress on Intelligent Transport Systems and Services. Aalborg, Denmark: ERTICO – ITS Europe.

American Association of State Highway Transportation Officials (AASHTO). (2011). *A policy on geometric design of highways and streets.* (6th ed.). Washington D.C.: American Association of State Highway and Transportation Officials.

Angell, L., Auflick, J., Austria, P. A., Kochhar, D., Tijerina, L., Biever, W., … Kiger, S. (2006). *Driver workload metrics project task 2 final report* (No. DOT-HS-810-635). Washington D.C.: National Highway Traffic Safety Administration, U.S. Department of Transportation.

Barshi, I. (1997). *Effects of linguistic properties and message length on misunderstandings in aviation communication* (Unpublished doctoral dissertation). University of Colorado, Boulder, Colorado.

Broström, R., Bengtsson, P., & Aust, M. L. (2016). Individual glance strategies and their effect on the NHTSA visual manual distraction test. *Transportation Research Part F: Traffic Psychology and Behaviour*, *36*, 83–91. https://doi.org/10.1016/j.trf.2015.10.017

Cao, Y., Castronovo, S., Mahr, A., & Müller, C. (2009). On timing and modality choice with local danger warnings for drivers. *Proceedings of the 1st International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (pp. 75-78). New York, New York: Association for Computing Machinery. https://doi.org/10.1145/1620509.1620524

Campbell, J. L., Carney, C., & Kantowitz, B. H. (1998). *Human factors design guidelines for advanced traveler information systems (ATIS) and commercial vehicle operations (CVO)* (No. FHWA-RD-98-057). Washington D.C.: Federal Highway Administration, U.S. Department of Transportation.

Campbell, J. L., Richard, C. M., Brown, J. L., & McCallum, M. (2007). *Crash warning system interfaces: Human factors insights and lessons learned* (No. DOT-HS-810-697). Washington D.C.: National Highway Traffic Safety Administration, U.S. Department of Transportation.

Chapman, P. R., & Underwood, G. (1998). Visual search of dynamic scenes: Event types and the role of experience in viewing driving situations. In G. Underwood (Ed.), *Eye guidance in reading, driving, and scene perception* (pp. 369-393). Oxford, England: Elsevier. https://doi.org/10.1016/B978-008043361-5/50018-3

Charlton, S. G. (2004). Perceptual and attentional effects on drivers' speed selection at curves. *Accident Analysis and Prevention, 36*(5), 877-884. https://doi.org/10.1016/j.aap.2003.09.003

Craig, C. M., Achtemeier, J., Morris, N. L., Tian, D., Patzer, B. (2017). *In-vehicle work zone messages* (No. MN/RC 2017-19). St. Paul, MN: Minnesota Department of Transportation. http://hdl.handle.net/11299/189538

Dingus, T. A., Hulse, M. C., Mollenhauer, M. A., Fleischman, R. N., McGehee, D. V., & Manakkal, N. (1997). Effects of age, system experience, and navigation technique on driving with an advanced traveler information system. *Human Factors, 39*(2)*,* 177-199. https://doi.org/10.1518/001872097778543804

Edworthy J., Hellier E., Rivers J. (2003). The use of male or female voices in warnings systems: A question of acoustics. *Noise Health, 6*(21), 39-50. http://www.noiseandhealth.org/text.asp?2003/6/21/39/31683

Federal Highway Administration, U.S. Department of Transportation. (2009). *Manual on Uniform Traffic Control Devices* (2009 ed.). Washington D.C.: Federal Highway Administration, U.S. Department of Transportation.

Fitzpatrick, K., Elefteriadou, L., Harwood, D. W., Collins, J. M., McFadden, J., Anderson, I. B., … Passetti, K. (2000). *Speed prediction for two-lane rural highways* (No. FHWA-RD-99-171). Washington, D.C.: Federal Highway Administration, U.S. Department of Transportation.

Green, P. (2004). *Driver distractions, telematics design, and workload managers: Safety issues and solutions* (No. 2004-21-0022). Warrendale, PA: Society of Automotive Engineers.

Green, P., Levison, W., Paelke, G., & Serafin, C. (1994). *Suggested human factors design guidelines for driver information systems* (No. FHWA-RD-94-087). Washington D.C.: Federal Highway Administration, U.S. Department of Transportation.

Hallmark, S. L., Tyner, S., Oneyear, N., Carney, C., & McGehee, D. (2015). Evaluation of driving behavior on rural 2-lane curves using the SHRP 2 naturalistic driving study data. *Journal of Safety Research, 54*, 27.e1-27. https://doi.org/10.1016/j.jsr.2015.06.017

Hallmark, S. L., Qui, Y., Hawkins, N., & Smadi, O. (2015). Crash modification factors for dynamic speed feedback signs on rural curves. *Journal of Transportation Technologies, 5*(1), 9-23. https://doi.org/10.4236/jtts.2015.51002

Harbluk, J. L., Noy, Y. I., Trbovich, P. L., & Eizenman, M. (2007). An on-road assessment of cognitive distraction: Impacts on drivers' visual behavior and braking performance. *Accident Analysis & Prevention, 39*(2), 372-379. https://doi.org/10.1016/j.aap.2006.08.013

Hellier, E., Edworthy, J., Weedon, B., Walters, K., & Adams, A. (2002) The perceived urgency of speech warnings: Semantics versus acoustics. *Human Factors, 44*(1), 1-17. https://doi.org/10.1518/0018720024494810

Horrey, W. J., Wickens, C. D., & Consalus, K. P. (2006). Modeling drivers' visual attention allocation while interacting with in-vehicle technologies. *Journal of Experimental Psychology: Applied*, *12*(2), 67–78. https://doi.org/10.1037/1076-898X.12.2.67

Klauer, S. G., Dingus, T. A., Neale, V. L., Sudweeks, J. D., & Ramsey, D. J. (2006). *The impact of driver inattention on near-crash/crash risk: An analysis using the 100-car naturalistic driving study data* (No. DOT-HS-810-594). Washington D.C.: National Highway Traffic Safety Administration, U.S. Department of Transportation. http://hdl.handle.net/10919/55090

Kryter, K. D. *The effects of noise on man* (2nd ed.). Orlando, FL: Academic Press.

Lee, J. D., Gore, B. F., & Campbell, J. L. (1999). Display alternatives for in-vehicle warning and sign information: Message style, location, and modality. *Transportation Human Factors, 1*(4), 347-375. https://doi.org/10.1207/sthf0104_6

Leuer, D. (2015). *Fatal run off the road crashes on rural two-lane two-way highways in Minnesota*. St. Paul, MN: Office of Traffic, Safety, and Technology, Minnesota Department of Transportation.

Liu, Y. C. (2001). Comparative study of the effects of auditory, visual and multimodality displays on drivers' performance in advanced traveler information systems. *Ergonomics, 44*(4), 425-442. https://doi.org/10.1080/00140130010011369

Liu, C., & Subramanium, R. (2009). *Factors related to fatal single-vehicle run-off-road crashes* (No. DOT-HS-811-232). Washington D.C.: National Highway Traffic Safety Administration, U.S. Department of Transportation.

Liu, C., & Ye, T. J. (2011). *Run-off-road crashes: An on-scene perspective* (No. DOT-HS-811-500). Washington, D.C.: National Highway Traffic Safety Administration, U.S. Department of Transportation.

Makishita, H., & Matsunaga, K. (2008). Differences of drivers' reaction times according to age and mental workload. *Accident Analysis & Prevention, 40*(2), 567-575. https://doi.org/10.1016/j.aap.2007.08.012

Marshall, D. C., Lee, J. D., & Austria, P. A. (2007). Alerts for in-vehicle information systems: Annoyance, urgency, and appropriateness. *Human Factors, 49*(1), 145-157. https://doi.org/10.1518/001872007779598145

Martinelli, D., & Medelin, L. (2012). *Assessing distraction using an in-vehicle tracking system* (No. WVU-2007-02). University Park, PA: Thomas D. Larson Pennsylvania Transportation Institute, Pennsylvania State University.

Milstead, R., Qin, X., Katz, B., Bonneson, J., Pratt, M., Miles, J., & Carlson, P. (2011). *Procedures for setting advisory speeds on curves* (No. FHWA-SA-11-22). Washington, D.C., Federal Highway Administration, U.S. Department of Transportation.

Muttart, J. W., Fisher, D. L., Pollatsek, A. P., & Marquard, J. (2013). Comparison of anticipatory glancing and risk mitigation of novice drivers and exemplary drivers when approaching curves. *Proceedings of the Seventh International Driving Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design* (pp. 212-218). Iowa City, IA: Public Policy Center, University of Iowa. https://doi.org/10.17077/drivingassessment.1490

Ouimet, M. C., Pradhan, A. K., Brooks-Russell, A., Ehsani, J. P., Berbiche, D., & Simons-Morton, B. G. (2015). Young drivers and their passengers: A systematic review of epidemiological studies on crash risk. *Journal of Adolescent Health, 57*(1)*,* S24-S35.e6. https://doi.org/10.1016/j.jadohealth.2015.03.010

Regan, M. A., Triggs, T. J., Young, K. L., Tomasevic, N., Mitsopoulos, E., Stephan, K., & Tingvall, C. (2006). *On-road evaluation of intelligent speed adaptation, following distance warning and seatbelt reminder systems: Final results of the TAG SafeCar project* (No. 253). Clayton, Australia: Monash University Accident Research Centre.

Regan, M. A., Young, K., & Haworth, N. (2003). *A review of literature and trials of intelligent speed adaptation devices for light and heavy vehicles* (No. AP-R237/03). Sydney, Australia: Austroads.

Recarte, M. A., & Nunes, L. M. (2003). Mental workload while driving: Effects on visual search, discrimination, and decision making. *Journal of Experimental Psychology: Applied, 9*(2), 119-137. https://doi.org/10.1037/1076-898X.9.2.119

Rinalducci, E. J., Mouloua, M, & Smither, J. (2002). *Cognitive and perceptual factors in aging and driving performance* (No. VPL-03-01). Tallahassee, FL: Florida Department of Transportation.

Romoser, M. & Fisher, D. L. (2009). Effects of cognitive and physical decline on older drivers' side- to-side scanning for hazards while executing turns. *Proceedings of the Fifth International Driving Symposium on Human Factors in Driving Assessment, Training, and Vehicle Design* (pp. 61-68). Iowa City, IA: Public Policy Center, University of Iowa. https://doi.org/10.17077/drivingassessment.1303

Schneider, W. H., Savalainen, P. T., & Zimmerman, K. (2009). Driver injury severity resulting from single-vehicle crashes along horizontal curves on rural two-lane highways. *Transportation Research Record: Journal of the Transportation Research Board, 2102*, 85-92. https://doi.org/10.3141/2102-11

Spyropoulou, I. K., Karlaftis, M. G., & Reed, N. (2014). Intelligent speed adaptation and driving speed: Effects of different system HMI functionalities. *Transportation Research Part F: Traffic Psychology and Behaviour, 24*, 39-49. https://doi.org/10.1016/j.trf.2014.02.008

Stephan, K. L., Young, K. L., Newstead, S. V., Lenné, M. G., Cavallo, A., Duck, N., … Healy, D. (2014, November). *The effectiveness of an advisory intelligent speed adaptation (ISA) system for Victorian repeat speeders*. Paper presented at 2014 Australasian Road Safety Research, Policing & Education Conference, Melbourne, Australia.

Sodhi, M., Reimer, B., & Llamazares, I. (2002). Glance analysis of driver eye movements to evaluate distraction. *Behavior Research Methods, Instruments, & Computers*, *34*(4), 529–538. https://doi.org/10.3758/BF03195482

Strayer, D. L., Drews, F. A., & Johnston, W. A. (2003). Cell phone-induced failures of visual attention during simulated driving. *Journal of Experimental Psychology: Applied, 9*(1), 23-32. https://doi.org/10.1037/1076-898X.9.1.23

Ullman, G. L., & Rose, E. R. (2005). Evaluation of dynamic speed display signs. *Transportation Research Record: Journal of the Transportation Research Board, 1918*, 92-97. https://doi.org/10.3141/1918-12

United Nations Economic Commission for Europe (UNECE). (2011). *Guidelines on establishing requirements for high-priority warning signals* (No. ECE/TRANS/WP.29/2011/90). Working document from the 154th Session of the World Forum for Harmonization of Vehicle Regulations. Retrieved from https://www.unece.org/fileadmin/DAM/trans/doc/2011/wp29/ECE-TRANS-WP29-2011-90e.pdf

Wiese, E. E., & Lee, J. D. (2004). Auditory alerts for in-vehicle information systems: The effects of temporal conflict and sound parameters on driver attitudes and performance. *Ergonomics, 47*(9), 965-986. https://doi.org/10.1080/00140130410001686294

Wittmann, M., Kiss, M., Gugg, P., Steffen, A., Fink, M., Pöppel, E., & Kamiya, H. (2006). Effects of display position of a visual in-vehicle task on simulated driving. *Applied Ergonomics, 37*(2), 187-199. https://doi.org/10.1016/j.apergo.2005.06.002

APPENDIX A: SCREENING AND DEMOGRAPHICS QUESTIONAIRES

Participant Pre-Screening Questionnaire

This questionnaire will be administered during the recruitment process to determine eligibility for participation.

1. What is your age?
   - EXCLUDE IF NOT 20-40

2. Have you had a U.S. driver's license for at least two years?
   - EXCLUDE IF NO

3. Do you drive a minimum of 4,000 miles each year?
   - EXCLUDE IF NO

4. Do you have at least 20/40 visual acuity, either corrected (contact lens only) or uncorrected? (i.e. persons that use corrective contact lenses which improve their vision to 20/40 may participate)
   - EXCLUDE IF NO

5. Do you have normal color vision?
   - EXCLUDE IF NO

6. Do you have any history of hearing loss which inhibits every day conversation?
   - EXCLUDE IF YES

7. Do you have any health problems that affect your driving?
   - EXCLUDE IF YES

8. Do you experience inner ear problems, dizziness, vertigo, or balance problems?
   - EXCLUDE IF YES

9. Are you suffering from any lingering effects of stroke, tumor, head trauma, or infection?
   - EXCLUDE IF YES

10. Do you or have you ever suffered from epileptic seizures?
    - EXCLUDE IF YES

Driving History Questionnaire

This questionnaire asks you to indicate some details about your driving history and related information. Please tick <u>one</u> box for each question.

1. Your age: _____ years

2. Your sex: ☐ Male
☐ Female

3. What is your <u>highest</u> educational level completed?
☐ High School / Vocational School
☐ Associates Degree
☐ Bachelor of Arts / Bachelor of Science
☐ Masters
☐ PhD

4. Are you currently taking any college level classes?
☐ Yes
☐ No

5. Please state your occupation: _____

6. Please state the **year** when you obtained your full driving license: _____

7. About how often do you drive nowadays?

☐ ======= ☐ ======= ☐ ======= ☐ ======= ☐
Never **Hardly** **Sometimes** **Most** **Every**
Ever **Days** **Day**

8. Estimate roughly how many miles you personally have driven in the past year:
☐ Less than 5000 miles
☐ 5000-10,000 miles
☐ 10,000-15,000 miles
☐ 15,000-20,000 miles
☐ Over 20,000 miles

9. About how often do you drive to and from your place of work or school?

☐ ======= ☐ ======= ☐ ======= ☐ ======= ☐
Never **Hardly** **Sometimes** **Most** **Every**
Ever **Days** **Day**

10. Do you drive frequently on…   Yes   No

    a. Highways?   ☐   ☐

    b. Main Roads other than Highways?   ☐   ☐

    c. Urban Roads?   ☐   ☐

    d. Country Roads?   ☐   ☐

11. During the last three years, how many <u>minor</u> traffic crashes have you been involved in where you were at fault? A minor crash is one in which no-one required medical treatment, AND costs of damage to vehicles and property were less than $1500.

        Number of minor accidents ____ (if none, write 0)

12. During the last three years, how many <u>major</u> traffic crashes have you been involved in where you were at fault? A major crash is one in which EITHER someone required medical treatment, OR costs of damage to vehicles and property were greater than $1500, or both.

        Number of major accidents ____ (if none, write 0)

13. During the last three years, have you ever been convicted for:

                                        Yes   No

    a. Speeding   ☐   ☐

    b. Distracted, careless or dangerous driving   ☐   ☐

    c. Driving under the influence of alcohol/drugs   ☐   ☐

14. What type of vehicle do you drive most often?
    ☐ Motorcycle
    ☐ Passenger Car
    ☐ Pick-Up Truck
    ☐ Sport utility vehicle
    ☐ Van or Minivan
    ☐ Other, briefly describe: _____

  16. If yes: Describe the most recent cell phone (select all that apply)
    ☐ Basic phone (camera equipped or not)
    ☐ Android Smartphone
    ☐ iPhone Smartphone
    ☐ Windows Smartphone
    ☐ Blackberry Smartphone
    ☐ I do not have a cell phone

17. Please select the type of navigation system you have used. (select all that apply)
- ☐ Built-in vehicle navigation systems
- ☐ Portable navigation systems (e.g. Garmin, TomTom)
- ☐ Smart phone based navigation systems (Apple, Google maps)
- ☐ Other:_____

18. How frequently do you use a GPS or navigation system? (select one)
- ☐ Never
- ☐ Rarely (e.g. When alone on roadway)
- ☐ Sometimes (e.g. When stopped at a stoplight)
- ☐ Often (e.g. Cruising down the highway, stopped traffic)
- ☐ All of the time (e.g. At any time while driving)

19. What are the primary uses for the navigation system? (choose all that apply)
- ☐ Driving in unfamiliar cities/neighborhoods
- ☐ Determining the best route to my destination
- ☐ Determining alternate route (i.e. in case of road construction or traffic)
- ☐ Determining my arrival time or trip time to my destination
- ☐ Getting directions to recent destinations
- ☐ Driving in familiar cities/neighborhoods
- ☐ Finding direction to return home
- ☐ Finding gas stations/restaurants/shopping locations etc.
- ☐ Fitness or exercise tracking
- ☐ Biking or walking directions
- ☐ Other

Sensation Seeking Questionnaire

1. I can see how it would be interesting to marry someone from a foreign country.

1	2	3	4
Describes me very well	Describes me somewhat	Does not describe me very well	Does not describe me at all

2. When the water is very cold, I prefer not to swim even if it is a hot day.

1	2	3	4
Describes me very well	Describes me somewhat	Does not describe me very well	Does not describe me at all

3. If I have to wait in a long line, I'm usually patient about it.

1	2	3	4
Describes me very well	Describes me somewhat	Does not describe me very well	Does not describe me at all

4. When I listen to music, I like it to be loud.

1	2	3	4
Describes me very well	Describes me somewhat	Does not describe me very well	Does not describe me at all

5. When taking a trip, I think it is best to make as few plans as possible and just take it as it comes.

1	2	3	4
Describes me very well	Describes me somewhat	Does not describe me very well	Does not describe me at all

6. I stay away from movies that are said to be frightening or highly suspenseful.

1	2	3	4
Describes me very well	Describes me somewhat	Does not describe me very well	Does not describe me at all

7. I think it's fun and exciting to perform or speak before a group.

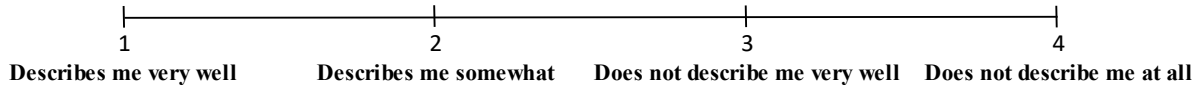| 1	2	3	4
Describes me very well	Describes me somewhat	Does not describe me very well	Does not describe me at all

8. If I were to go to an amusement park, I would prefer to ride the rollercoaster or other fast rides.

1	2	3	4
Describes me very well	Describes me somewhat	Does not describe me very well	Does not describe me at all

9. I would like to travel to places that are strange and far away.

1	2	3	4
Describes me very well	Describes me somewhat	Does not describe me very well	Does not describe me at all

10. I would never like to gamble with money, even if I could afford it.

1	2	3	4
Describes me very well	Describes me somewhat	Does not describe me very well	Does not describe me at all

11. I would have enjoyed being one of the first explorers of an unknown land.

1	2	3	4
Describes me very well	Describes me somewhat	Does not describe me very well	Does not describe me at all

12. I like a movie where there are a lot of explosions and car chases.

1	2	3	4
Describes me very well	Describes me somewhat	Does not describe me very well	Does not describe me at all

13. I don't like extremely hot and spicy foods.

1	2	3	4
Describes me very well	Describes me somewhat	Does not describe me very well	Does not describe me at all

14. In general, I work better when I'm under pressure.

1	2	3	4
Describes me very well	Describes me somewhat	Does not describe me very well	Does not describe me at all

15. I often like to have the radio or TV on while I'm doing something else, such as reading or cleaning up.

1	2	3	4
Describes me very well	Describes me somewhat	Does not describe me very well	Does not describe me at all

16. It would be interesting to see a car accident happen.

1	2	3	4
Describes me very well	Describes me somewhat	Does not describe me very well	Does not describe me at all

17. I think it's best to order something familiar when eating in a restaurant.

1	2	3	4
Describes me very well	Describes me somewhat	Does not describe me very well	Does not describe me at all

18. I like the feeling of standing next to the edge on a high place and looking down.

1	2	3	4
Describes me very well	Describes me somewhat	Does not describe me very well	Does not describe me at all
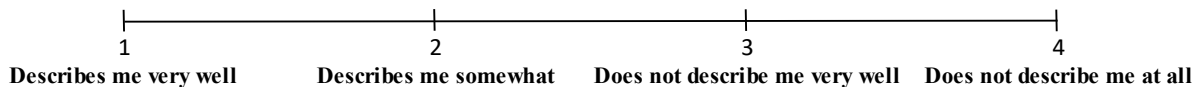
19. If it were possible to visit another planet or the moon for free, I would be among the first in line to sign up.

1	2	3	4
Describes me very well	Describes me somewhat	Does not describe me very well	Does not describe me at all
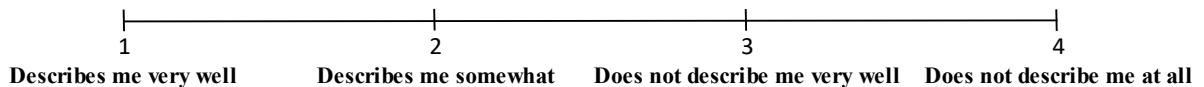
20. I can see how it must be exciting to be in a battle during a war.

1	2	3	4
Describes me very well	Describes me somewhat	Does not describe me very well	Does not describe me at all
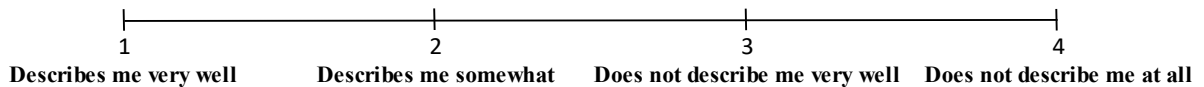
APPENDIX B: SUBJECTIVE MEASURES QUESTIONAIRES

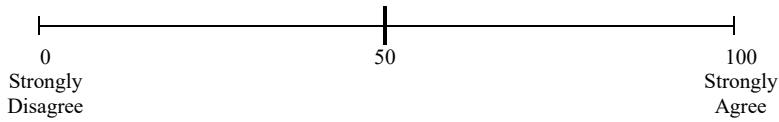# The Nine Dimensions of Quick Usibility Test

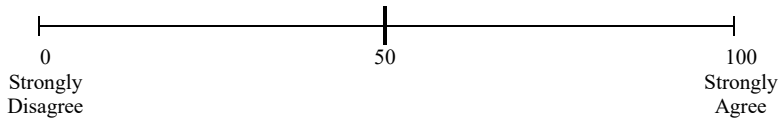My judgements of the (...) system are... (please tick a box on every line)

1	useful|_|_|_|_|useless
2	pleasant|_|_|_|_|unpleasant
3	bad|_|_|_|_|good
4	nice|_|_|_|_|annoying
5	effective|_|_|_|_|superfluous
6	irritating|_|_|_|_|likeable
7	assisting|_|_|_|_|worthless
8	undesirable|_|_|_|_|desirable
9	raising alertness|_|_|_|_|sleep-inducing

System Trust Questionnaire

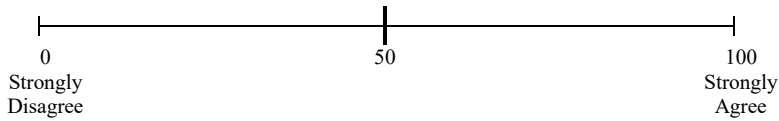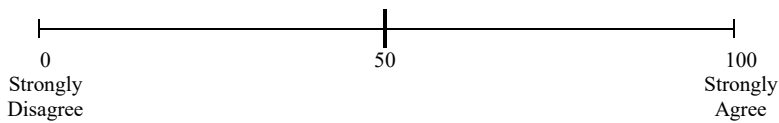**The performance of the system enhanced my driving safety.**

```
├──────────────────────┼──────────────────────┤
0                      50                    100
Strongly                                  Strongly
Disagree                                    Agree
```

I am familiar with the operation of the system.

```
├──────────────────────┼──────────────────────┤
0                      50                    100
Strongly                                  Strongly
Disagree                                    Agree
```

I trust the system.

```
├──────────────────────┼──────────────────────┤
0                      50                    100
Strongly                                  Strongly
Disagree                                    Agree
```

The system is reliable.

```
├──────────────────────┼──────────────────────┤
0                      50                    100
Strongly                                  Strongly
Disagree                                    Agree
```

The system is dependable.

```
├──────────────────────┼──────────────────────┤
0                      50                    100
Strongly                                  Strongly
Disagree                                    Agree
```
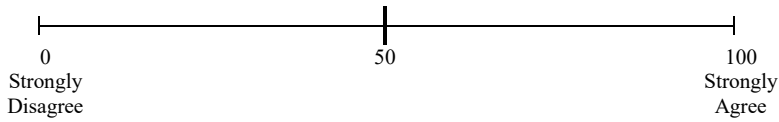
The system has integrity.

```
├──────────────────────┼──────────────────────┤
0                      50                    100
Strongly                                  Strongly
Disagree                                    Agree
```
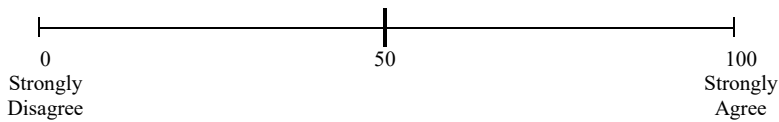
I am comfortable with the intent of the system.

```
├──────────────────────┼──────────────────────┤
0                      50                    100
Strongly                                  Strongly
Disagree                                    Agree
```
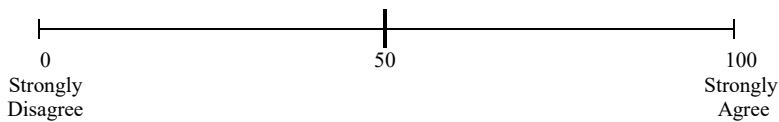
I am confident in my ability to drive the car safely without the system.

```
├──────────────────────┼──────────────────────┤
0                      50                    100
Strongly                                  Strongly
Disagree                                    Agree
```
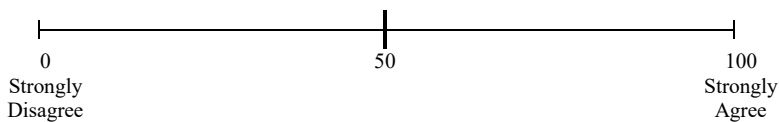
Rating Scale Mental Effort

Please indicate, by marking the vertical axis below, how
much effort it took for you to complete the task you've just finished

```
150

140

130

120

110 ──────── EXTREME EFFORT

100 ──────── VERY GREAT EFFORT

90

80 ──────── GREAT EFFORT

70 ──────── CONSIDERABLE EFFORT

60

50 ──────── RATHER MUCH EFFORT

40 ──────── SOME EFFORT

30

20 ──────── A LITTLE EFFORT

10 ──────── ALMOST NO EFFORT

0 ──────── ABSOLUTELY NO EFFORT
```
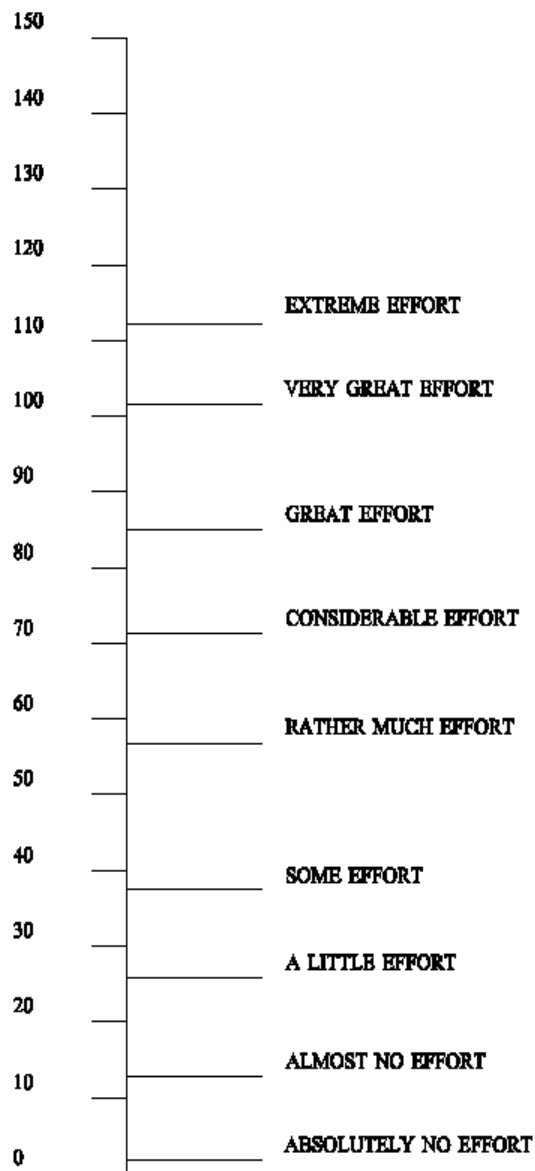
System Usability Survey SUS

For each of the following questions, place an "X" through the one number to indicate your response. "1" for strongly disagree, "3" for neutral- neither agree nor disagree, "5" for strongly agree.

1. I think that I would like to use this system frequently.

Strongly Disagree		Neutral		Strongly Agree
①	②	③	④	⑤

2. I found the system unnecessarily complex.

①	②	③	④	⑤

3. I thought the system was easy to use.

①	②	③	④	⑤

4. I think that I would need the support of a technical person to be able to use this system.

①	②	③	④	⑤

5. I found the various functions in this system were well integrated.

①	②	③	④	⑤

6. I thought there was too much inconsistency in this system.

①	②	③	④	⑤

7. I would imagine that most people would learn to use this system very quickly.

①	②	③	④	⑤

8. I found the system very cumbersome to use.

①	②	③	④	⑤

9. I felt very confident using the system.

①	②	③	④	⑤

10. I needed to learn a lot of things before I could get going with this system.

①	②	③	④	⑤