Examining the Effects of a Signless Roadway: Holographic Traffic Control Devices and their Potential for Replacing Traditional Post-Mounted Traffic Control Devices

SAFETY RESEARCH USING SIMULATION

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Executive Summary

In recent years, there has been an ever-increasing demand for the integration of technology into vehicles. As the expansion of in-vehicle technology continues, obvious concerns exist with the number of potential distractors added into the driving environment. In particular, technology-based distractors have the potential to attract drivers' attention away from the roadway and increase the probability of driver error. Nevertheless, advances in technology provide an opportunity for improving safety if used to augment and improve guidance, control, and navigation tasks.

Traffic control devices (TCD) provide the primary form of communication between the roadway environment and drivers. However, many confounding factors such as clutter and traffic volume can lead to drivers missing important TCD often displayed via post-mounted signs. Advanced in-vehicle technologies may allow for a more focused presentation of TCD information, especially by displaying the information in the line of sight of drivers. Placing important TCD in the line of sight of the drivers is not a new idea. In fact, in a study sponsored by the Federal Highway Administration (FHWA), elongated pavement markings (EPM) were considered as a supplement to enhance post-mounted regulatory and warning signage [40]. EPM signs were placed in the center of the travel lane directly in front of the driver, creating a head-up reinforcement of the critical TCD information.

Results from the study suggest that regulatory and warning sign information placed directly in front of the driver to enhance the traditional signing methods increases awareness and decreases operating speeds, thus improving regulation compliance and safety. A natural evolution of the aforementioned research is to study if in-vehicle technologies in the form of holographic-style displays can be used to effectively augment the reality of the road and lead to safer driver behavior. Furthermore, can holographic-style displays replace traditional post-mounted signs?

Holographic-style displays are a natural evolution of head-up displays (HUD), which are already an option in some vehicles to display navigation information along with collision and lane-departure warnings. Head-up display systems augment the reality of the road and have been found to be an effective form of communicating information to drivers [7, 32, 33, 35, 37]. The objective of the research presented was to explore the use of holographic technology to place TCD information in the drivers' line of sight in order to determine if this technology and type of presentation could be used as a replacement for traditional post-mounted TCD. A full-scale driving simulator experiment that included 20 subjects was conducted.

In the experiment, subjects were asked to drive on three different scenarios. Scenario A was a completely signless roadway allowing unrestricted free-flow driving without reliance on TCD information. Scenario B was a traditionally signed roadway that included post-mounted regulatory and warning signs. Scenario C was a "virtually signed" roadway (no post-mounted signs) in which virtual traffic control devices were displayed on the screen as if the signs were produced by holographic technology. Speed compliance monitoring across key points on the scenarios suggest that holographic displays could be a viable option to safely and optimally replace or reduce the need for traditional post-mounted TCD signs.

1 Introduction

The 21st century is witnessing unprecedented technological innovations in consumer electronics and the automotive industry that are revolutionizing driving. Arguably, the most recent groundbreaking development is the emergence of self-driving vehicles, expected to become commonplace in the near future. While current infrastructure is designed to support traditional vehicles by communicating with drivers via traditional traffic control devices (TCD), autonomous vehicles do not depend on roadside regulatory devices, suggesting a potential future without post-mounted traffic signs. However, the high costs of autonomous vehicles will delay mass adoption of the new technology, resulting in a timeframe in which both traditional and self-driving vehicles will share the same roads. During this transitional period, the safety of drivers without autonomous vehicles is of paramount concern, necessitating the development of technology to provide a smooth transition to universal adoption of self-driving vehicles. Holographic displays, which augment the reality of the road by synthesizing computer text and real-world images, represent a potential intermediary step between traditional and autonomous vehicles.

In 2009, federal spending on operation and maintenance of United States highway infrastructure totaled $2 billion USD [1]. A major part of that infrastructure consists of TCD that include post-mounted signs, pavement markings, traffic signals, and various geometric features of the roadway. Traffic control devices convey regulatory, guidance, and warning information to roadway users and act as an important tool for traffic engineers to communicate with drivers [2]. While a standard practice, the means by which guidance and warning information are presented have long been a topic of discussion for researchers across the world. Some of the newer research marries the new age of technology in vehicles with the presentation of guidance and warning information. Specifically, companies like Navdy, Continental, Garmin, and some vehicle manufacturers are selling products that convey information and warnings (lane departure and collision) to drivers using HUD technology [4, 5, 6]. All of these applications of in-vehicle technology aim to improve safety while driving. One of the safety improvement arguments is that the aforementioned technology allows drivers to keep their attention and focus on the road ahead without having to manipulate handheld devices and in-dash controls to obtain supplemental information.

Previous research has shed light on the fact that HUD can be an effective communication tool for drivers, especially when navigating a complex roadway environment [7]. Holographic technology, a natural evolution of HUD, could eventually assist drivers by augmenting the reality of the road. Augmenting the reality of roadways can help highlight components of the roadway that are key to supporting navigation and guidance tasks, especially in a roadway environment that continuously grows in complexity. As the roadway and surrounding environment becomes more complex, there tends to be a disparity when it comes to seeing post-mounted signs [8]. Known as visual clutter, the disparity leads to an increased potential for drivers to miss important regulatory, warning, or guidance information that is often displayed using post-mounted signs.

Previous research has shown that depending on the sign type, post-mounted signs have a low registration rate among drivers [8]. Additionally, in a study sponsored by the Federal Highway Administration (FHWA), elongated pavement markings (EPM) were explored as a supplement to critical post-mounted TCD information [40]. Elongated pavement markings were placed in the center of the travel lane directly in front of the driver, creating a heads-up reinforcement of critical TCD information displayed using post-mounted signs. Results from the aforementioned research showed that regulatory and warning sign information can be placed directly in front of the driver to enhance traditional signing methods, increase awareness, and decrease operating speeds, thus improving regulation compliance and safety. Results also suggest that providing regulatory and warning sign information in a head-up presentation may be effective in reinforcing regulatory and warning messages to drivers and improving safety. With the advances in technology and the continuous exploration of holographic-style displays by companies and vehicle manufacturers, it can be argued that the roadway of the future could be a signless one, or at least one with limited use of signs.

1.1 Objectives

In this research, the behavior of subjects as they drive on a road containing only traffic control devices of holographic nature is evaluated. Subjects participating in the experiment were asked to drive three different scenarios in a full-scale driving simulator. The three different scenarios (A, B, and C) had the same rural two-lane highway geometry. The only difference across scenarios was the TCD included. Scenario A included no regulatory or warning signs. Scenario B included traditional post-mounted regulatory and warning signs. Finally, Scenario C did not include physical signs but relied on holographic-style traffic control devices. To understand the driver behavior, the speed profiles of drivers across all three scenarios were evaluated in order to assess if the use of holographic-style traffic control devices has the potential for replacing post-mounted signs.

1.2 Organization

This report consists of five chapters, references, and an appendix. Chapter 1 comprises an introduction to the study and the objectives of the research. Chapter 2 is a detailed literature review consisting of elements from previous research on areas relevant to the objectives of this research. Chapter 3 describes the research methodologies that were used in completing this analysis as well as defining and explaining various characteristics of the apparatus and research test scenarios. Chapter 4 provides the results of the research and the data obtained, along with the statistical analysis completed. Chapter 5 presents conclusions and recommendations for future research. Chapter 6 includes references used in this research. Finally, appendices containing figures and tables relevant to the data and data collection, as well as additional information regarding the research, are included. Figures and tables in the appendices will be referenced in the main body of this report where relevant.

2 Literature Review

2.1 Traffic Control Devices

Traffic control devices are the media through which traffic engineers communicate with drivers. Essentially every traffic law, guidance, regulation, or operational instruction is communicated with TCD. There are three main categories of TCD: traffic markings, traffic signs, and traffic signals. Each of these TCD categories represents the communication of guidance, regulatory, or warning information [2]. In order for a TCD to be effective, it must fulfill a need, command attention, convey a clear and simple message, command the respect of road users, and give adequate time for proper response. These requirements also carry underlying assumptions that redundant or non-critical signage/markings should not be added to the roadway. In order to command the respect of drivers, each TCD must contribute to the drivers' expectancy that the information presented is critical and important at the time/place that it is seen.

Traffic control devices are regulated by the *Manual on Uniform Traffic Control Devices* (MUTCD) and are essential for the safe and efficient transportation of people and goods. Every state in the nation uses some form of the MUTCD, whether it is the comprehensive use of the MUTCD (e.g., Montana, Florida, New Jersey), a combination of the MUTCD and their own individual regulations (e.g., Wisconsin, Colorado, New York), or their own specific adaptation of the MUTCD for use in that particular state (e.g., Utah, Minnesota, California) [12]. The MUTCD itself is a dynamic document that changes with time to address contemporary safety and operational issues [13].

2.2 Human Error in Driving

The driving task is based on human ability and includes cognitive work load, visual strain, and muscle memory to complete tasks and properly operate a vehicle. The U.S. Department of Transportation reported that over 75% of vehicle crashes can be attributed to some type of human error [14]. Some believe the number is actually more than 90%. In the 100-car naturalistic driving study that was performed by USDOT, human error was a main contributing factor in the analysis of light vehicle-heavy vehicle interactions (LV-HV). In both heavy and light vehicles, the largest contributing factor towards error was driving technique (68.4% for HV and 70.3% for LV). Further, 66.9% of all crashes observed in this study were related to some form of human error [15].

Stanton and Salmon applied three different human error taxonomies to the driving task, specifically on the impact that human error had while interacting with various intelligent transportation systems (ITS) applications (automated cruise control, navigation systems, collision warning systems, etc.) [15]. The three error taxonomies are Norman's error categorization; Reason's slips, lapses, mistakes, and violations classification; and Rasmussen's skill, rule, and knowledge error classification [16]. These three theories for human error relate to the prediction of making some type of error or violation while completing a task, either intentionally or unintentionally. More specifically, errors in recognition, errors in decision, and errors in performance were large metrics for determining the proposed taxonomy. Stanton and Salmon identified 24 potential driver errors and assigned various ITS applications that would help remediate or eliminate errors [16].

Human error in driving can be broken down into four categories: slips, lapses, mistakes, and violations. Slips occur when a driver misreads a sign or turns on the headlights when trying to activate the wiper blades. Lapses happen when the driver has no clear recollection of the road just traveled. Mistakes might be underestimating the speed of an oncoming vehicle when overtaking or using the wrong lane in a roundabout. Violations are further separated into two sub-categories: unintended and deliberate. Unintended violations might include unknowingly speeding or forgetting to change the sticker on a license plate. Deliberate violations occur when driver emotions are involved, as in a race or impatience with slower drivers, for example [17].

Reason et al. defined violations as deliberate (not necessarily reprehensible) deviations from the practices believed necessary to maintain safe operation of a potentially hazardous system [17]. Reason also argues that people may err without violation and, reciprocally, may perform a violation that is not an error. Drivers will have their own interpretation of what is safe or unsafe, comfortable or uncomfortable, etc. for any given set of roadway conditions. These errors and violations are of high interest due to their likely cause of or influence on roadway crashes and/or safety issues. Based on a 50-item driver behavior questionnaire (DBQ) given to 500 subjects, the most significant violation, in terms of frequency, was unknowingly speeding. This is classified as an unintentional violation that poses a possible risk to others. This high frequency supports the argument that roadside signage may not be commanding the attention of drivers, calling for actions to improve the communication of that information.

Human error in driving not only occurs from slips, lapses, and violations, but also from the various characteristics of the roadway: geometry, TCD, and roadside variables. Fitzpatrick et al. considered these roadway characteristics with the goal of identifying cause-and-effect relationships in order to develop designs that result in desired driver behavior and minimal errors [18]. Four categories were considered when performing the analyses: alignment, cross-section, roadside, and TCD. The study found that drivers were more likely to slow down, not only because of the radius of horizontal curves, but because of the deflection angle. This was due, in part, to the driver's perception of the way the curve looked upon approach. When examining the cross-section of the roadway, the presence of a median was significant, not specific to type. Among roadside characteristics, access density and roadside development caused drivers to slow most significantly. Posted speed limit proved to be the most significant TCD. It is important to note that there are many factors that affect driver speed, meaning that there are also many ways in which a driver can err. The crucial part of this error is understanding what can be done so that the risk of repeating errors is minimized.

2.3 Situation Awareness

Situation awareness can be defined many ways, and although it has primarily been a subject for flight and airplane pilots, the concepts fit nicely within the driving task and the type of behavior a driver exhibits when making decisions and executing basic driving maneuvers and functions. Endsley states that the concept of situation awareness is best seen as encompassing perceptual and comprehension processes but not decision-making and response execution processes [19]. Further, Endsley points out that the operator of a vehicle, for example, must do more than perceive the state of their environment; they must also understand the meaning of what they are perceiving as it relates to their goal or objective (making a lane change, coming to a stop, yielding for a pedestrian).

Knowledge of situation awareness can be utilized in design processes for engineers to understand the impacts that certain designs might have on the driver/operator given a specific roadway environment. Situation awareness is also closely linked to the decision-making process. The perception one has of a situation can dramatically affect the decision being made. This becomes crucial in tasks like driving at night when there is less visual evidence of the true nature of a roadway or condition to make safe and effective decisions.

Adams et al. describe situation awareness as a dynamic mental model of the situation that has two elements: one, explicit focus or active knowledge in working memory, and two, implicit focus or less active knowledge that is relevant to the current situation but more accessible than irrelevant knowledge in long-term memory [20]. This definition relates to the nature of situation awareness during complex systems/tasks. Driving can easily be defined as a complex system that includes controlling the vehicle, navigating, interpreting and addressing gauge readings, and dealing with the addition of passengers, radio, and technology.

Situation awareness in driving can be affected by many factors. Distraction usually takes the blame for most errors occurring during the driving task that require extra mental effort. This lack of attention is identified as one of the main factors in traffic accidents and crashes [21]. As Gugerty suggests, keeping track of dynamic and changing situations is a key element of real-time tasks like driving [22]. The research of situation awareness during driving can have useful applications because of the adverse effects that poor situation awareness has on driving, namely, with crashes and accidents.

2.4 Visual Clutter

Performing the driving task safely and effectively requires a heavy strain on information in the driver's field of view. As commercial development and traffic volumes increase, the roadside signage used to convey important information to drivers is easily lost in what is called "visual clutter." The driving task is not only dependent on what drivers see, but the manner in which they see it. As regulatory, warning, and guidance information is presented to drivers on the side of the road using various post-mounted signs, the task of finding those signs and the information they convey becomes increasingly difficult due to the factors mentioned above.

Akagi, Seo, and Motoda studied these very effects in Japan, where regulations for road-side signing are poor, and therefore regulatory, warning, and guidance signs are easily lost within all the other types of signs (advertising, billboards, etc.) present on the roadside. This unnecessary amount of signing may adversely affect the acquisition of necessary driving information [8]. This visual clutter or "visual noise" can be defined as objects that hinder drivers' field of view, such as billboards, buildings, and other vehicles along the roadside.

In their study, Akagi et al. observed 54 cases between nine subjects in which they had the subjects detect the national highway number sign on each test section. Using eye-tracking equipment, they were then able to examine the fixation characteristics of each driver at the time the sign was detected. A detection distance was defined as the distance between where the subject detected the sign and the place where the sign was installed. After a regression analysis was conducted for the correlation between detection distance and visual noise, it was found to be statistically significant that as visual noise increased, detection distance decreased

[8]. It is apparent that excess information and roadside clutter can deteriorate the effectiveness of a driver's search for necessary information.

2.5 Driver Attention and Distraction

Driver attention is a key component of driving. Specifically, for the purpose of this research, there is a relationship between driver attention and the use of in-vehicle systems [23]. In-vehicle systems have become increasingly popular as technology advances. Eysenck defines attention as the human's ability to focus on certain objects and allocate processing resources accordingly [24]. So, distraction can then be defined as anything that takes away from attention to some primary task.

Distraction and, therefore, lack/loss of attention can occur in many ways. A common form of distraction is the selective withdrawal of attention. This can be caused by daydreaming, talking on the phone, or other passengers in the vehicle. Kahneman states that there are two factors that contribute to the allocation of attention: (a) intention and experience and (b) evaluation of demands [25]. Intention and experience relates to giving higher priority to objects that are more familiar or interesting to a person. Evaluation of demands is the concept that a person would determine which processes or objects need the most attention based on available capacity.

Attention, or lack thereof, and distraction can be seen by the way drivers process primary and secondary tasks while driving. Primary tasks such as steering or acceleration/deceleration garner the highest amount of attention. However, as secondary tasks are introduced, studies show that the allocation of attention to these secondary tasks (e.g., talking on the phone, using a navigation device) can lead to compensatory behaviors that affect the driver and those in the same environment. Most research shows that operating speeds decrease and following distances and headways increase when performing secondary tasks [26]. It is clear that distraction and lack of attention lead to less-than-ideal driving behaviors. Further, as the road environment changes and becomes more complex perceptually (additional traffic, intersections), distraction effects from secondary tasks like talking on the phone intensify [27].

2.6 Eye-Tracking

Eye-tracking is a common practice in most driving simulator studies, and reasonably so. As different driving tasks or driver assistance applications are tested, it becomes imperative to understand where the driver is looking so that these tasks and devices can be optimized. As vision is a major key to a person's ability to drive and operate a vehicle, it is important to study where drivers are looking as they navigate a complex roadway.

Therefore, eye-tracking equipment allows researchers to study the glance and gaze of subjects while driving and performing primary (steering, speed compliance) and secondary (navigation, reading signage, operating a radio) tasks. Eye-tracking has a place in multiple fields, including neuroscience, psychology, industrial engineering and human factors, marketing/advertising, and computer science [28].

Within industrial engineering and human factors lie activities like aviation and driving, both of which are crucial to understanding where the pilot/driver is looking while operating their respective vehicles. There is consistent research evidence that deficiencies in visual attention are responsible for a large proportion of road traffic accidents [29]. Chapman and Underwood further state that eye movement and tracking allows for understanding the nature of the driving task and the development of driver training and accident countermeasures.

Research from Sodhi et al. shows that eye movements can be assumed to be indicators/predictors of attention [30]. Therefore, when studying driving behavior, it is important to look at the eye of the driver to obtain information about driver responses to different situations. Sodhi et al. investigated the effect of distraction to drivers by analyzing their eyes with a head-mounted eye-tracking device (HED). Seven distractions were presented to the drivers over the course of a 20-mile real-world drive in predetermined locations. Results from this study comply with previously published literature, including the effect of time sharing between the primary (driving) and secondary (distraction) tasks. Additionally, when faced with a more cognitively intense distraction (a phone call with a computational task), visual tunneling became a factor.

Based on the literature, it is apparent that understanding the eye movements of the driver is crucial to driving behavior. It can be assumed that, as drivers are required to search for signage or other objects around them, whether on-road or off-road, a certain level of distraction from the roadway and driving task will be present. This poses a potentially dangerous situation as traffic scenarios become more and more complex.

2.7 Application of In-Vehicle Display

Several applications of in-vehicle displays have been tested in both commercial and research applications. The most common types of displays are the head-down display (HDD), head-up display (HUD), and holographic augmented reality displays (AR). While many vehicles today are equipped with each of these technologies, there has been much research pertaining to their various applications. A deeper investigation of their uses and applications can be helpful when determining the correct use in the current study.

Head-down displays are stock options in most production vehicles today. These HDD are often referred to as infotainment systems because they are capable of bringing internet connectivity into the vehicle for use of music, news, navigation, and phone functions (phone calls and text messages). While HDD are helpful in many aspects, they also pose a potentially serious problem when it comes to driver distraction. When operating a HDD, as can be inferred by the name, drivers must look down, away from the roadway, to manipulate the system (looking at navigation directions, adjusting the radio/music source, and even monitoring the climate inside the vehicle).

Head-up displays are also available in production vehicles, most often as an extra option. Some vehicle manufacturers are beginning to include this as a stock option. Continental is one of the leaders in HUD production, offering HUD for BMW, Mercedes Benz, and Audi models [31]. The concept of the HUD is the same as the HDD; however, information is presented to the driver on the windshield, i.e., in the line of sight. HUD can mirror dashboard data such as speed and navigation aids. Other capabilities of existing HUD systems include displaying speed limits on a specific section of road, thus improving awareness about speed limit compliance. These safety features, as well as the convenience they provide drivers, are a major reason for many vehicle manufacturers to include this technology in their vehicles.

Further advancements to the traditional HUD lean towards AR displays that facilitate features like lane-departure warnings, automated cruise control, blind-spot monitoring, and even night vision. For a system like the Continental lane-departure warning, the driver is warned by both auditory and haptic means as well as the visual aid from the AR that denotes the lane boundaries [32]. Vehicle manufacturers like Chevrolet have included these systems in their vehicles [33], but AR displays are mostly seen in the luxury brands like those described above.

The ever-growing presence of this technology and its different useful applications have led to research being done using most, if not all, of the aforementioned applications. As this boom in technology continues to develop, it will become important to study the effects that these displays have on drivers and the optimal uses to increase safety and efficiency while driving.

2.8 Use of Driving Simulators for Testing In-Vehicle Displays

When evaluating driver performance in driving simulators, there have been many studies that involve using in-vehicle signage (IVS) or in-vehicle displays. One such study conducted by the Minnesota Department of Transportation was geared toward evaluating driver performance and distraction during use of in-vehicle signing information [34]. The research team used 60 participants in their 2 (drive: display system off and display system on) X 3 (condition: IVS + navigation, IVS only, navigation only) mixed-model design, where drive was a within-subjects situation (counterbalanced) and condition was between subjects. The 60 participants were assigned to one of the three different conditions (3 groups of 20, 19, and 21 drivers, respectively). There was no mixing of drivers between conditions (IVS + navigation, IVS only, navigation only). The test zones/signs included three speed, three curve, two school, and two construction scenarios. The signs appeared in the IVS as they would on the road according to MUTCD standards, using posted speed limits and distances as the measure for when and where to display the information.

The goal of the study was to identify if drivers were better able to comply with speed limits when IVS information was present. It was found that drivers were prepared to react to new speed limits before entering a zone, and in most cases complied with the zone speed limits, regardless of whether or not the IVS information was there. A paired comparisons t-test was used to compare the baselines for each within-groups condition (system on or off). A one-way ANOVA was used for the between-groups treatment analysis. Both tests resulted in p-values less than 0.05. Bonferroni corrections were used for significant ANOVAs with a p-value less than 0.017.

A comparison of HUD and HDD done by Liu and Wen [7] investigated the effects of these two different in-vehicle displays for commercial delivery truck drivers in Taiwan. Drivers were asked to perform four tasks during the 2 (high/low driving load roadway) x 2 (head-up/head-down display) x 2 (different arrangements of display sequences used) mixed-factor simulated drive. The four tasks included goods delivery, navigation, speed detection and maintenance, and response to an emergency event (police, ambulance).

The 12 drivers in the study were all equal in terms of experience and qualifications, as reported by their company's performance reviews and standards. As they drove the simulated route using both HDD and HUD, it became apparent that the HUD showed statistical significance as reaction times for speed limit detection and response to emergency events were considerably faster than with the HDD. However, there were instances of challenge when drivers were presented with HUD first, indicating that there might need to be some sort of training associated with the device before use, where the same was not true of drivers using the HDD first [7].

In a study performed by Boyle and Mannering, the effects of driving behavior using in-vehicle and out-of-vehicle traffic advisory systems were examined using a driving simulator [35]. In this study, there were 51 participants to be placed in 4 different signing condition groups (no signing, in-vehicle only, out-of-vehicle only, in- and out-of-vehicle). This made it possible to have at least 12 drivers in each of the four conditions. One of the four advisory systems was randomly assigned to each driver. There were also two different types of weather conditions, fog and no fog, as well as two types of incidents, snowplows and no snowplows.

Results from the study show that over long segments, there was no significant difference in mean speed and standard deviation speed. It was also found that once the warning sign had either passed or become out of range, drivers would speed up to make up for the lost time incurred from being warned to slow down.

A study by Schall et al. examined the use of AR cues in order to assist elderly drivers with various levels of cognitive impairments [36]. Using challenging driving environments and their difficulties for elderly drivers, the researchers were able to use AR cues to aid the 20 elderly drivers in the study in detecting various roadside hazards. Research has shown that elderly drivers have trouble driving and navigating with in-vehicle systems at the same time [37]. The AR system used in this study was comprised of broken yellow lines that slowly converged on the roadside object in question in the form of a complete rhombus. Motion was used in order to help attract driver attention to the various roadside objects used. Cued and un-cued scenarios were used in this test for identifying roadside hazards. Cued scenarios included the use of the AR to help detect the various roadside objects, while the un-cued scenarios offered no aid to drivers.

Based on the results of this research, it is clear that AR cueing aided the subjects in detecting low-visibility roadside objects like pedestrians and warning signs. Drivers were able to respond quicker to cued scenarios when identifying roadside objects than they were to un-cued scenarios. However, this study environment was relatively low-load, cognitively. A rural scene offers less distraction and less workload on drivers than would an urban scene. Thus, it is important that the benefits of AR cueing be noted while using a scene that offers a more difficult cognitive environment (urban with heavy/constant on-coming traffic) [36].

In a similar study, Rusch et al. examined their AR cueing device and methods on middle-aged drivers. Drivers participated in cued and un-cued scenarios and were asked to flash the high beams when they had identified the roadside object/hazard. Immediately after the driver had flashed the high beams, they were asked about the presence of the roadside object. There were no significant effects associated with cueing for question accuracy, suggesting that cueing did not cause interference. Dynamic cues proved more favorable in attracting drivers' attention. Drivers became more attentive, responding to 1-2 more targets in all scenarios after the first un-cued scenario. Time to target (TTT), a measure of reaction time, provided evidence that AR cues were reducing response time for identifying targets. Augmented reality cues may lead to improving driver safety, reducing response time, and increasing detection of roadway hazards [38].

A study by Cheng et al. instrumented a live vehicle with a HUD device in order to study the effects of warning displays for drivers who were speeding [39]. In this test, drivers faced four possible scenarios: (1) no HUD was used, (2) a warning sign was displayed when the driver's speed exceeded the speed limit, (3) a numeric warning was displayed at all times showing the driver's speed and the speed limit (e.g., 43/45 in mph), and (4) a graphical representation clearly showing the driver's speed and the speed limit.

The main test measure was the amount of time it took drivers to slow back down to the speed limit or below when presented with the HUD information. In this study, the most effective presentation of HUD information was a simple warning sign that consisted of a triangular exclamation point sign. This warning was presented only when the driver exceeded the speed limit. To garner the attention of drivers, as the warning sign was displayed, it bounced, similar to a rubber ball on cement, until the driver reached the speed limit. It took drivers 1.93 seconds to slow back down to the speed limit when presented with the warning sign, on average. The next closest time was over 2.5 seconds on average. It is clear from the experimental results that drivers spent less time in total over the speed limit when presented with a warning sign.

A study sponsored by the FHWA used the driving simulator at the UW – Madison Traffic Operations and Safety Laboratory as well as field trials in Kansas, Missouri, and Wisconsin to explore the use of EPM as a supplement to existing post-mounted TCD signage [40]. Elongated pavement markings have been shown to significantly improve recognition distance when compared to non-elongated markings. Furthermore, pavement marking signs are more likely to be detected by drivers than post-mounted signs due to their targeted location within the drivers' path. Drivers spend most of the time looking at the road directly ahead, resulting in objects on the side of the road having a lower chance of being recognized.

Elongated pavement marking signs were placed in the center of the travel lane directly in front of the driver, creating a head-up reinforcement of the critical TCD information. The results of this research showed that regulatory and warning sign information placed directly in front of the driver to enhance the traditional signing methods increased awareness and decreased operating speeds, improving compliance and safety behavior. Results further demonstrated that providing regulatory and warning sign information in a head-up presentation may be effective in reinforcing regulatory and warning messages to drivers and improving safety [40].

2.9 Literature Review Summary

Through an extensive literature review, it was seen that advanced in-vehicle technologies offer an undoubtedly effective means of presenting information to drivers in the form of navigation, logistics, and safety measures. However, there remains a hole in the research when it comes to examining the use of holographic-style displays and other in-vehicle technologies for presenting critical regulatory and warning TCD information. Combining all the many distractors and theories for human error and situation awareness provide an avenue to keep exploring the idea of using holographic technology to display important information while minimizing the risks associated with roadside objects, such as post-mounted signage and other useful driving information.

3 Research Methodologies

Over the past 25 years, research in academia and industry has laid a path to follow when using a driving simulator to perform research. One of the most important factors in any driving simulation is the fidelity of the roadway models being used in the virtual world [41]. The process of bringing out a high degree of fidelity is a somewhat arduous one, using a variety of software from CAD tools to 3D modeling software. However, with these tools and a high-fidelity driving simulator to use, scenarios and virtual environments can imitate the real world.

3.1 Apparatus

For this research, the full-scale, state-of-the-art, RealTime Technologies, Inc. (RTI) driving simulator housed in the University of Wisconsin – Madison Transportation Operations and Safety (TOPS) lab was used. The simulator, as seen below in Figures 3.1- 3.3, consists of a full-size Ford Focus body mounted on a one-degree-of-freedom motion platform. This one degree of freedom refers to the ability of the vehicle to move in a one-directional plane, forward and backward in this case, providing the driver with the feeling of acceleration and deceleration.

Figure 3.1 – UW – Madison TOPS lab driving simulator [42].

To display the virtual environments, five front-facing projectors, one rear-facing projector, and two LCD monitors are used. The five front-facing projectors display the virtual environment on a 240-degree, seven-foot-tall, curved screen. The rear-facing projector displays the virtual environment that a driver would see in the rear-view mirror. The projectors used to produce the visual driving environment can be seen in Figure 3.2. The two LCD screens are mounted inside each side-view mirror and also display the virtual environment that would be seen in the side-view mirrors.

Figure 3.2 – Projectors responsible for producing the driving environment [42].

Processing power and capabilities are made possible by an array of eight custom-built, rack-mounted servers. These eight channels generate the 3D world and control the interaction between the environment and the vehicle at a refresh rate of 60Hz. Similarly, driver actions such as steering, braking, and accelerating can also be monitored at 60Hz.

Figure 3.3 – Ford Fusion mounted on one-degree-of-freedom motion platform [42].

3.2 Assumptions

Due to the nature of this research and the various applications of design contained within, some assumptions were made to keep the research study focused and refrain from attaining too broad a scope. Below are the assumptions that were used in designing the geometric characteristics of the roadway and the surrounding environment.

In designing the roadway centerline and cross-section, it was assumed that the test scenario would be similar to a roadway typically found in Wisconsin. The test roadway was designed such that the design speed was equivalent to the posted speed. Design speeds for this study were 35 mph and 55 mph, respectively. Design speed directly affects the geometric features of the roadway, so using the two design speeds, horizontal curves were designed using limiting values of superelevation and side friction (*e* and *f*).

Values for minimum curve radii that corresponded to the respective design speeds were found using the American Association of State Highway and Transportation Officials (AASHTO) Green Book [10]. The minimum horizontal curve radius for a 35 mph design speed, *e* of 4%, and *f* of 0.18, was 371 feet, while the minimum horizontal curve radius for a 55 mph design speed, *e* of 6%, and *f* of 0.13, was 1,060 feet [10], where *e* is the rate of superelevation (percent) and *f* is the side friction factor. An extensive list of values and variables from AASHTO can be seen in Table 3.1, including the values described above.

Table 3.1 – Minimum curve radius using limiting values of e and f [10].

Metric						U.S. Customary					
Design Speed (km/h)	Maximum *e* (%)	Maximum *f*	Total (*e*/100 + *f*)	Calculated Radius (m)	Rounded Radius (m)	Design Speed (mph)	Maximum *e* (%)	Maximum *f*	Total (*e*/100 + *f*)	Calculated Radius (ft)	Rounded Radius (ft)
15	4.0	0.40	0.44	4.0	4	10	4.0	0.38	0.42	15.9	16
20	4.0	0.35	0.39	8.1	8	15	4.0	0.32	0.36	41.7	42
30	4.0	0.28	0.32	22.1	22	20	4.0	0.27	0.31	86.0	86
40	4.0	0.23	0.27	46.7	47	25	4.0	0.23	0.27	154.3	154
50	4.0	0.19	0.23	85.6	86	30	4.0	0.20	0.24	250.0	250
60	4.0	0.17	0.21	135.0	135	35	4.0	0.18	0.22	371.2	371
70	4.0	0.15	0.19	203.1	203	40	4.0	0.16	0.20	533.3	533
80	4.0	0.14	0.18	280.0	280	45	4.0	0.15	0.19	710.5	711
90	4.0	0.13	0.17	375.2	375	50	4.0	0.14	0.18	925.9	926
100	4.0	0.12	0.16	492.1	492	55	4.0	0.13	0.17	1186.3	1190
						60	4.0	0.12	0.16	1500.0	1500
15	6.0	0.40	0.46	3.9	4	10	6.0	0.38	0.44	15.2	15
20	6.0	0.35	0.41	7.7	8	15	6.0	0.32	0.38	39.5	39
30	6.0	0.28	0.34	20.8	21	20	6.0	0.27	0.33	80.8	81
40	6.0	0.23	0.29	43.4	43	25	6.0	0.23	0.29	143.7	144
50	6.0	0.19	0.25	78.7	79	30	6.0	0.20	0.26	230.8	231
60	6.0	0.17	0.23	123.2	123	35	6.0	0.18	0.24	340.3	340
70	6.0	0.15	0.21	183.7	184	40	6.0	0.16	0.22	484.8	485
80	6.0	0.14	0.20	252.0	252	45	6.0	0.15	0.21	642.9	643
90	6.0	0.13	0.19	335.7	336	50	6.0	0.14	0.20	833.3	833
100	6.0	0.12	0.18	437.4	437	55	6.0	0.13	0.19	1061.4	1060
110	6.0	0.11	0.17	560.4	560	60	6.0	0.12	0.18	1333.3	1330
120	6.0	0.09	0.15	755.9	756	65	6.0	0.11	0.17	1656.9	1660
130	6.0	0.08	0.14	950.5	951	70	6.0	0.10	0.16	2041.7	2040
						75	6.0	0.09	0.15	2500.0	2500
						80	6.0	0.08	0.14	3047.6	3050

Sign placement for warning signs in the traditional post-mounted scenario followed MUTCD standards as laid out below in Table 3.2 [11]. With posted speeds of 35 and 55 mph, the minimum distance was taken from Condition B in Table 3.2, where the vehicle was slowing to the listed advisory speed. From this condition, the warning signs were placed at 100 feet and 325 feet for 35 and 55 mph advisory speeds, respectively. Where distance could not be exactly determined, curve warning signs were placed at or near the point of curvature (PC) of the specific horizontal curve.

Table 3.2 – Guidelines for advance placement of warning signs [11].

Posted or 85th-Percentile Speed	Advance Placement Distance[1]								
	Condition A: Speed reduction and lane changing in heavy traffic[2]	Condition B: Deceleration to the listed advisory speed (mph) for the condition							
		0[3]	10[4]	20[4]	30[4]	40[4]	50[4]	60[4]	70[4]
20 mph	225 ft	100 ft[6]	N/A[5]	—	—	—	—	—	—
25 mph	325 ft	100 ft[6]	N/A[5]	N/A[5]	—	—	—	—	—
30 mph	460 ft	100 ft[6]	N/A[5]	N/A[5]	—	—	—	—	—
35 mph	565 ft	100 ft[6]	N/A[5]	N/A[5]	N/A[5]	—	—	—	—
40 mph	670 ft	125 ft	100 ft[6]	100 ft[6]	N/A[5]	—	—	—	—
45 mph	775 ft	175 ft	125 ft	100 ft[6]	100 ft[6]	N/A[5]	—	—	—
50 mph	885 ft	250 ft	200 ft	175 ft	125 ft	100 ft[6]	—	—	—
55 mph	990 ft	325 ft	275 ft	225 ft	200 ft	125 ft	N/A[5]	—	—
60 mph	1,100 ft	400 ft	350 ft	325 ft	275 ft	200 ft	100 ft[6]	—	—
65 mph	1,200 ft	475 ft	450 ft	400 ft	350 ft	275 ft	200 ft	100 ft[6]	—
70 mph	1,250 ft	550 ft	525 ft	500 ft	450 ft	375 ft	275 ft	150 ft	—
75 mph	1,350 ft	650 ft	625 ft	600 ft	550 ft	475 ft	375 ft	250 ft	100 ft[6]

In a similar way, spacing for post-mounted chevron signs was determined based on MUTCD guidelines. For curves with a design (posted) speed of 35 mph, a spacing of roughly 120 feet was used. For curves with a design (posted) speed of 55 mph, a spacing of 160 feet was used. Guidelines from the MUTCD on chevron spacing can be seen below in Table 3.3.

Table 3.3 – Typical spacing of chevron signs on horizontal curves [11].

Advisory Speed	Curve Radius	Sign Spacing
15 mph or less	Less than 200 feet	40 feet
20 to 30 mph	200 to 400 feet	80 feet
35 to 45 mph	401 to 700 feet	120 feet
50 to 60 mph	701 to 1,250 feet	160 feet
More than 60 mph	More than 1,250 feet	200 feet

3.3 Scenario Creation

Pre-built scenarios on the system software have limited use in most studies, specifically in site-specific studies. Although this study is not site-specific, the scenario-creation process was a crucial task due to the custom nature of this research. Essentially, there are two tiers to scenario design; first, bringing 2D CAD drawings into 3D modeling software, and second, directly importing proposed road and terrain surfaces into the modeling software.

AutoCAD 2015 was used to create the scenario roadway and cross-section. The test scenario consists of two sets of four horizontal curves. All curves were designed using tabulated values from the AASHTO Green Book with a design speed of 35 mph and 55 mph, respectively, a normal cross-section, and a maximum superelevation, as previously seen in Table 3.1. Using values from the same table for curve radius, the centerline and cross-section of the roadway were drawn in AutoCAD 2015, as seen in Figure 3.4.

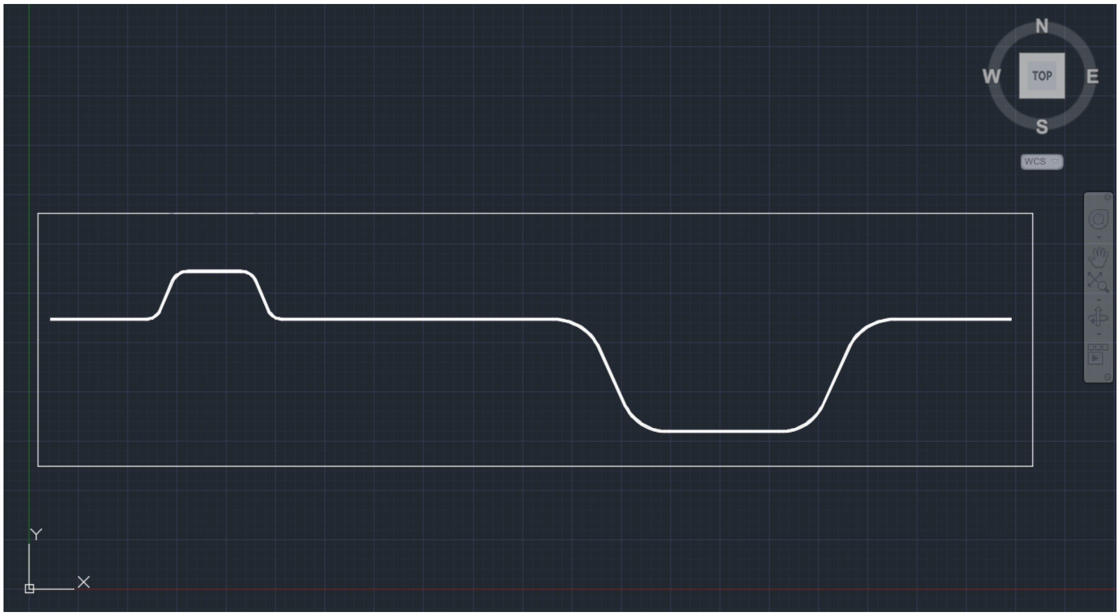


Figure 3.4 – AutoCAD centerline used for scenario creation.

From AutoCAD, the open source 3D modeling software Blender was used to transform the 2D drawings into a workable 3D model. Roadway surfaces and environmental textures were created using GIMP 2, an open source photo editing software, and imported to the scenario in Blender. Below, Figure 3.5 exhibits the 3D editing done in Blender.

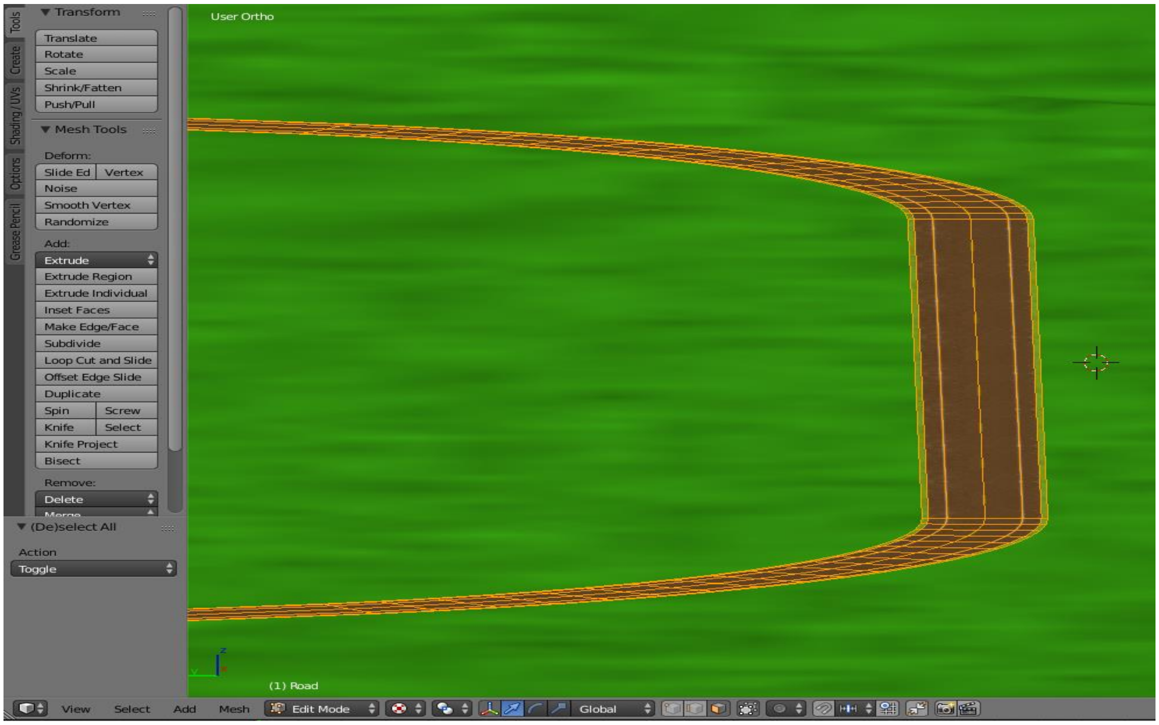


Figure 3.5 – 3D modeling in Blender for a pair of curves.

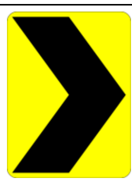
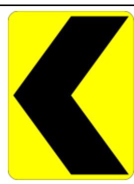
To comply with the RTI simulator software, the 3D modeling program Internet Scene Assembler (ISA) was used to install a variety of terrain features such as trees and landscaping, as well as the classic post-mounted signs that one would expect to see on the roadway. Figure 3.6 shows an example of the landscaping and sign placement using ISA.

Figure 3.6 – Scenario creation in ISA for a curve segment.

3.4 Experimental Design

This experiment consists of three geometrically identical scenarios. Within the first scenario (Scenario A), there were no TCD or any additional signage, only the roadway geometry and proper lane line markings. Scenario A was intended to serve as a baseline for determining how a driver would behave on a signless roadway. The second scenario (Scenario B) contained geometry identical to that of Scenario A; however, it had been fitted with the appropriate TCD. The TCD signage included can be seen in Table 3.4. This signage offered a variety of regulatory and warning information and was selected because it was easy to test in the simulator and tease out a variety of driving behaviors. In the third scenario (Scenario C), these same signs were displayed using the simulator projectors as holographic displays.

Table 3.4 – Standard MUTCD signage contained within Scenarios B and C [43, 44].

Sign	Sign Code	Description
	R2 – 1	Regulatory sign denoting the maximum speed of 35 mph.
	R2 - 1	Regulatory sign denoting the maximum speed of 55 mph.
	W1 – 2	Warning sign denoting an upcoming left-hand curve. No advisory speed is given.
	W1 – 2a	Warning sign denoting an upcoming right-hand curve. Advisory speed of 35 mph is shown as a suggestion for the speed at which to navigate the curve.
	W1 – 8R	Chevron alignment denoting that the horizontal alignment of the roadway is moving towards the right. Installed at right-hand curves.
	W1 – 8L	Chevron alignment denoting that the horizontal alignment of the roadway is moving towards the left. Installed at left-hand curves.
	W11 – 2	Pedestrian Crossing. Warning sign denoting the possible presence of pedestrians ahead.

Sign placement along the roadway geometry can be seen in Figure 3.7. Standard post-mounted signs were installed to MUTCD specifications for sign face size and mounting height. The roadway was assumed to be classified as an expressway for MUTCD sizing purposes. Thus, warning sign plaque sizes followed the guidelines in Table 2C - 2 in the MUTCD. Regulatory signs followed the same expressway designation in the MUTCD and were sized accordingly from the information in Table 2B - 1 in the MUTCD. It is important to note that the stop sign seen in Figure 3.7 only represents the end of the scenario where the subjects were prompted to stop the vehicle.

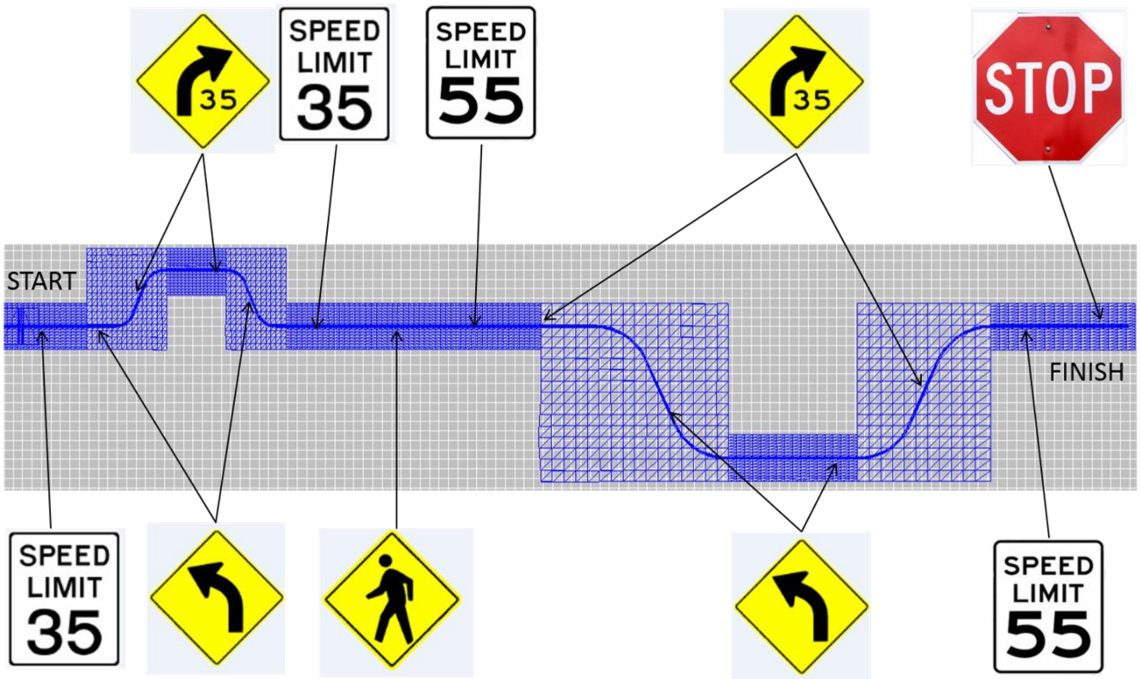


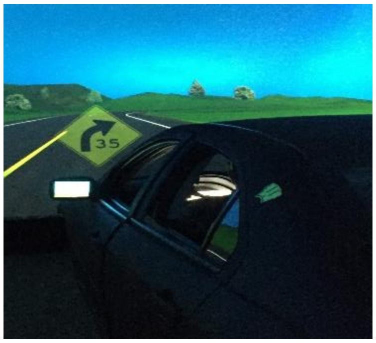
Figure 3.7 – Sign placement for Scenarios B and C

Post location for warning signs in the traditional post-mounted scenario followed MUTCD standards as laid out in Table 3.2. With posted speeds of 35 and 55 mph, the minimum distance was taken from Condition B in Table 3.2 where the vehicle is slowing to the listed advisory speed. From this condition, the warning signs were placed at 100 feet and 325 feet for 35 and 55 mph advisory speeds, respectively. Where distance could not be exactly determined, curve warning signs were placed at or near the PC of the specific horizontal curve.

The manner in which signs are displayed in Scenario C is quite different than in Scenario B. In Scenario C, signs are displayed as a holographic image roughly 5 inches above the hood of the car (heights will vary depending on the driver due to the differing physiological traits of each subject). The image appears as it is seen in Table 3.4 but with a slight transparency and directly in the driver's line of sight; examples can be seen in Table 3.5. This was done in lieu of using external hardware devices and to create an ideal holographic display.

Signs in Scenario C are displayed dynamically with a flash rate of 0.25 seconds and a duration of 4 seconds. No previous research was found during the literature review to support a specific flash rate, so settling on 0.25 seconds was an iterative process, taking into account perception reaction time and simply what looked the best upon driving through the simulation. Prior research has shown that dynamic displays utilizing some type of flashing or bouncing (motion onset) draw the attention of those looking at them, making them more noticeable than stationary or constant displays [34, 36, 37, 45].

Table 3.5 – Examples of Scenario C signage.

Virtual Display and Description	**Virtual Display and Description**
	
35 mph Speed Limit sign following MUTCD R2-1 formatting.	55 mph Speed Limit sign following MUTCD R2-1 formatting.
	
Left Curve Warning sign following MUTCD W1-2 formatting.	Right Curve Warning with Advisory Speed following MUTCD W1-2a formatting.
	

Pedestrian Crossing Sign following MUTCD W11-2 formatting.	Dynamic, in-road, chevron alignment warnings. Created using scaled dimensions of the W1-8r/l chevron portion. Elongated 5:1.

Another difference that occurs in Scenario C is the manner in which changes in horizontal alignment (curves) are denoted. The traditional display technique for chevron alignment signs installs them on the outside of the curve such that the sign face is at approximately a right angle to oncoming traffic and spaced between 120 feet and 160 feet (spacing will differ based on the advisory/design speed of the curve). The chevrons are mounted at a minimum height of 4 feet above the elevation of the near surface of the pavement. This methodology was used in Scenario B. Chevron alignment signs in Scenario C were displayed in the same manner as the other signs in the scenario, as a dynamic holographic projection. Chevrons were installed along the pavement surface and spaced at the same distances as their post-mounted counterparts. As can be seen in Figure 3.8, the chevrons do not follow the typical W1 – 8 layout from Table 3.3.

Figure 3.8 – Example of the holographic projection chevron alignment warnings.

These chevrons were designed so that they would follow the centerline of the lane, showing the actual curvature of the lane to the driver. They flashed at a rate of 4 times per second, 0.25 s intervals. At faster flash rates (< 0.25 s), the chevrons became too unrecognizable, while slower flash rates failed to saturate the driver with information and behaved more similarly to the post-mounted approach. The MUTCD uses a flash rate for displaying items like the flashing yellow arrow for left-turn movements. This rate of one display every second was not used due to a subjective approach that deemed this rate too slow for the purposes of this study and the information that was to be conveyed. The chevrons activated when the driver passed over a set point before the start of the curve and remained flashing at a rate of 0.25 seconds throughout the duration of the curve. The dynamic manner of displaying the chevrons was aimed at catching the attention of the driver in such a way that navigating the curve would be an easier task than in a situation with post-mounted chevron alignment signs.

3.5 Testing Procedure

Twenty test subjects were initially selected to participate in this research and provided a sufficient sample size under the repeated measure study design. Eleven males and nine females participated. The average age of all participants was 32 years old (standard deviation = 14 years, max = 68 years old, min = 20 years old), and the average driving experience in years was 16.1 years (standard deviation = 13.7, max experience = 52 years, min experience = 4 years).

Before each subject could partake in the driving simulation, they were given an institutional review board (IRB) compliance form detailing the purpose of the research, the uses for the data collected, an explanation of any possible health risks (simulator sickness), and the manner by which they would be compensated for participating. The participants were required to sign the compliance form before testing could begin. Each participant received $20.00 USD upon completion of the three scenarios.

Before actual testing commenced, each subject was given a five-minute beta test in the driving simulator to get adjusted to the simulator controls and for researchers to observe the driver's behavior and physical condition. Each subject drove the same route. After a successful beta test, subjects were fitted with an ASL eye-tracking device and were prepared to begin the experimental segments. There was a rest period of five minutes between each test segment, during which data was extracted and the eye-tracker was re-calibrated. Each scenario was selected at random by assigning a random number to Scenario A, Scenario B, and Scenario C. Once the random numbers had been assigned, the order in which the subject would drive the scenarios was determined by ascending order of the random number.

3.6 Data Analysis

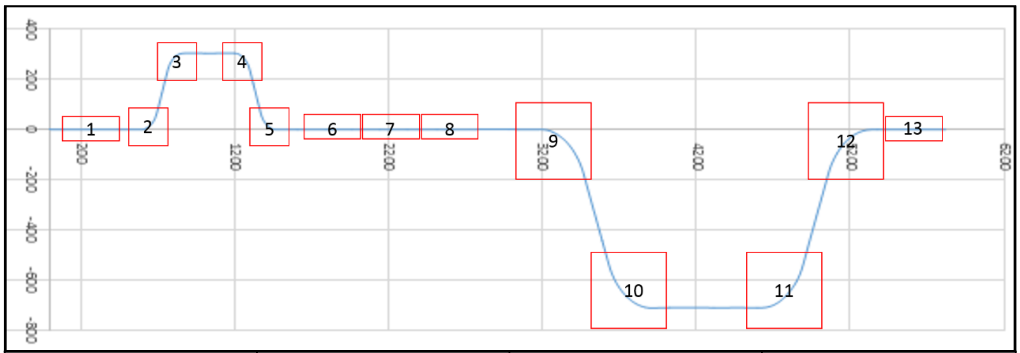
As mentioned in the previous section, 13 analysis zones were created to sort the data. Each zone corresponds to a specific feature of the scenario and is defined by X, Y position in the roadway environment. Table 3.6 defines the 13 zones. Within each zone, data were extracted from each simulator run and included speed readings, simulation run time, cumulative distance traveled, and vehicle trajectory.

Table 3.6 – Analysis zones.

Analysis Zone	Roadway Feature
Speed Zone 1	35 mph Speed Limit
Curve Zone 1	Curve Warning and Chevron Alignment
Curve Zone 2	Curve Warning and Chevron Alignment
Curve Zone 3	Curve Warning and Chevron Alignment
Curve Zone 4	Curve Warning and Chevron Alignment
Speed Zone 2	35 mph Speed Limit
Pedestrian (Ped) Zone	Pedestrian Traffic

Speed Zone 3	55 mph Speed Limit
Curve Zone 5	Curve Warning and Chevron Alignment
Curve Zone 6	Curve Warning and Chevron Alignment
Curve Zone 7	Curve Warning and Chevron Alignment
Curve Zone 8	Curve Warning and Chevron Alignment
Speed Zone 4	55 mph Speed Limit

Each of the zones from Table 3.6 can be seen in Figure 3.9. These zones are uniform across all three test scenarios, meaning that they do not change position in any of the three scenarios, and capture sufficient portions of data for analysis of speed in both tangent segments and curve segments. The dimensions of each analysis zone were determined subjectively, but with consideration of perception reaction time, the assumed speed the driver would be traveling at the specific point (speed limit), and the critical points of each analysis feature, such as the PC, midpoint, and PT of horizontal curves. Initially, the speed profiles of each subject through each zone were collected and plotted. Speed profiles were compared across the three test runs by subject in order to observe how each subject changed his or her driving behavior when presented with different roadway environments.



1) Speed Zone 1	2) Curve Zone 1	3) Curve Zone 2	4) Curve Zone 3
5) Curve Zone 4	6) Speed Zone2	7) Pedestrian Zone	8) Speed Zone 3
9) Curve Zone 5	10) Curve Zone 6	11) Curve Zone 7	12) Curve Zone 8
13) Speed Zone 4			

Figure 3.9 – Data analysis zones.

3.7 Statistical Analysis

In order to determine if the average speeds would be significantly different across each scenario comparison, the Wilcoxon signed-rank hypothesis test was used. This test is good for non-parametric data (non-normal distributions) and for comparing two related samples. To set up the hypothesis test, average speeds from each critical point of each curve were taken for all subjects in all scenarios. Next, the null hypothesis and alternative hypothesis were developed.

H_0: Average speeds are equivalent at critical points

H_a: Average speeds are not equivalent at critical points

Using these hypotheses, the statistical program R was used to compute the p-values for comparing the critical points at each curve for the following scenario comparisons: Scenario A vs. Scenario B, Scenario A vs. Scenario C, and Scenario B vs. Scenario C. The p-value is the probability of the test statistic realizing to a value as or more extreme than what was observed if H_0 is true. The test statistic for the Wilcoxon signed-rank test is computed using the equation below. From this test statistic, R generates a p-value under an alpha level of $\alpha = 0.05$; the maximum value at which H_0 is rejected. When the p-value is less than alpha, then the average speeds are significantly different. When the p-value is greater than alpha, then there is no statistically significant difference in average speeds

$$W = \sum_{i=1}^{N_r} (x_{2,i} - x_{1,i}) \cdot R_i \qquad (3.1)$$

where

N_r = the reduced sample size,

x = the average speed form both comparisons, and

R_i = the rank, starting with the smallest difference as 1, with ties receiving a rank of 0.

4 Results Analysis

4.1 Descriptive Data

These speed profiles can be seen in Figures A.1 through A.13 in Appendix A. From these speed profiles, smaller zones were created to define specific instances where speed changed between test runs. By slicing the analysis zones into smaller segments, more accurate data regarding speeds and changes in speeds could be examined at critical points in the analysis zone.

A summary of each subject's average speed at these critical points can be seen in depth below. Speed profiles portrayed behaviors that were expected from the experimental design. As drivers were traversing Scenario A, speeds were appreciably higher than in Scenario B or C. This can easily be explained by the fact that there were no regulations placed on the driver in Scenario A. This behavior is consistent with the expected case because nothing is limiting the driver other than the geometry of the roadway.

Average speeds and changes in speeds in Scenario A were visibly greater than in either of the other scenarios. Figures 4.1 and 4.2 below show an example of the unregulated Scenario A behaviors as compared to the regulated Scenario B and C behaviors in speed compared with the average deviations from the entry speed of Curve Zone 1. The average speeds are taken across the small slices of each zone that contain the critical points. Here, for Curve Zone 1, the critical points included: two upstream readings, sign readings at post location and virtual display location, point of curvature (PC), midpoint of curve (MP), point of tangency (PT), and intermediate points along Curve 1. Further descriptive data can be found in the standard deviations from the average speeds at these critical points. As expected, standard deviations are substantially higher in Scenario A than in either Scenario B or C. Standard deviations from average speed can be found in Appendix C.

Figure 4.2 shows the deviation in speed from the average speed at which drivers entered the analysis zone to the location of the sign, PC, etc. As can be seen by the average deviations from the zone entry speed, the behavior of the drivers shows that, when unrestricted, as in Scenario A, as drivers' speed is measured at points before the sign locations, there was already a 6 mph drop in speed from the time they entered the analysis zone (thus the -6 mph start point for Scenario A). There are large reductions in speed when coming upon geometric features of the roadway, such as curves. Now, the figures shown above are only displaying evidence from Curve Zone 1, but as the same approach was taken while looking at the other curves, the behavioral patterns are very similar to those of drivers operating at higher speeds in Scenario A.

Table 4.1 – Average speed summary for all subjects.

		Average Speeds in mph at Critical Points for Subjects 1-20																																
		Scenario A											Scenario B											Scenario C										
		35 mph Curves				55 mph Curves				Pedestrian Zone			35 mph Curves				55 mph Curves				Pedestrian Zone			35 mph Curves				55 mph Curves				Pedestrian Zone		
Subject	Run Order*	Sign	PC	MP	PT	Sign	PC	MP	PT	US	Sign	DS	Sign	PC	MP	PT	Sign	PC	MP	PT	US	Sign	DS	Sign	PC	MP	PT	Sign	PC	MP	PT	US	Sign	DS
1	A	50.87	30.67	35.37	39.41	63.70	46.68	52.49	54.40	61.35	63.67	66.41	38.00	34.51	31.97	32.52	49.11	44.04	46.20	49.29	35.57	32.87	37.37	39.35	36.27	35.88	36.94	56.25	49.17	49.05	51.75	40.20	39.31	38.25
2	B	48.41	46.80	44.65	44.74	57.84	55.64	54.41	54.72	55.32	56.43	58.02	43.77	42.44	41.03	41.15	54.45	52.61	50.12	50.94	44.03	42.61	44.16	43.18	41.74	40.90	41.09	58.94	55.50	53.57	54.22	42.29	42.07	40.98
3	A	45.49	42.47	40.73	39.79	62.21	53.11	51.13	55.06	56.27	59.03	62.90	32.63	31.21	29.38	28.47	51.05	49.38	45.81	46.04	34.47	33.97	33.86	36.66	34.83	33.71	33.38	52.47	49.62	47.92	47.76	35.32	34.31	34.33
4	C	36.16	34.28	31.21	30.60	47.01	42.86	40.63	43.00	40.18	41.56	43.45	35.95	33.86	31.78	31.70	45.53	41.70	41.25	42.86	40.64	39.29	39.23	32.80	31.20	28.73	28.92	49.16	44.46	43.00	45.27	34.63	34.92	33.58
5	B	42.56	42.61	41.70	41.26	55.83	55.51	54.26	53.75	47.17	47.98	49.18	37.98	37.22	35.93	35.90	54.44	53.73	51.49	50.87	43.27	43.17	43.88	37.86	36.20	35.18	35.34	53.85	51.75	50.17	49.83	38.69	39.31	38.84
6	D	33.67	29.81	27.88	28.15	42.10	39.40	36.04	36.26	39.54	38.10	36.68	36.71	35.12	32.84	31.81	45.99	44.34	40.20	39.03	39.47	31.19	38.37	35.62	33.92	31.99	31.25	45.99	40.46	37.42	37.69	35.99	37.06	29.24
7	E	49.19	41.01	39.37	41.70	59.62	48.80	52.30	54.94	56.45	55.78	57.62	35.32	33.54	32.66	33.32	48.75	38.98	40.73	42.31	36.69	33.74	32.06	36.72	36.31	36.92	36.11	51.89	42.78	47.15	48.71	34.36	33.02	14.54
8	D	54.90	50.07	47.05	47.70	71.62	63.31	64.82	66.25	66.88	68.82	71.64	44.43	42.46	42.13	42.54	53.06	49.41	49.54	52.24	43.06	41.60	41.31	43.63	41.01	41.70	42.87	57.14	53.35	53.50	53.35	40.28	37.73	36.62
9	A	44.30	30.90	28.40	32.96	48.13	42.64	42.13	42.69	55.22	55.67	56.67	34.13	28.79	30.26	31.98	50.08	40.10	45.53	47.89	35.05	33.26	34.55	40.43	37.87	36.05	35.52	53.61	43.47	45.60	48.25	35.82	36.28	35.16
10	A	38.51	37.90	35.89	34.99	49.36	48.37	47.83	48.15	42.63	43.56	44.73	36.32	34.72	33.57	34.06	51.23	46.40	45.95	47.55	36.55	34.77	36.74	39.64	39.19	38.37	38.80	56.14	50.94	50.68	52.84	39.73	38.57	37.45
11	F	45.58	44.30	41.96	40.24	53.39	50.79	48.22	48.48	52.22	53.86	56.19	35.69	34.71	33.73	33.78	50.15	47.57	44.18	44.03	33.21	33.56	36.80	36.47	35.81	34.92	34.48	51.47	49.43	46.26	46.70	37.12	36.74	35.64
12	E	35.42	32.73	31.98	32.83	47.04	41.02	43.25	46.15	44.55	44.85	45.29	31.70	29.75	27.84	27.68	48.79	41.27	40.95	42.69	30.71	28.93	28.72	36.09	33.88	32.92	34.71	40.40	36.27	39.11	39.17	35.72	35.08	31.77
13	F	47.70	47.76	46.90	46.59	59.54	59.02	58.07	58.13	48.30	48.41	49.16	41.21	41.18	21.22	40.27	58.24	57.62	56.05	55.69	40.35	39.20	42.09	40.26	39.90	39.18	38.96	59.21	58.41	56.97	56.34	39.18	40.18	39.05
14	A	44.90	44.37	42.58	41.46	43.75	43.81	43.70	43.61	40.61	40.96	41.47	35.85	35.34	34.49	33.88	43.36	42.65	41.08	41.08	36.05	36.39	36.93	35.51	35.15	34.47	34.07	43.81	41.53	39.40	39.42	37.55	37.70	37.77
15	C	47.91	45.32	42.71	42.40	62.34	57.20	54.25	54.35	59.15	60.58	62.24	37.38	35.52	33.80	33.54	56.08	52.66	51.44	51.73	37.17	37.31	37.57	39.18	38.69	37.95	37.89	56.73	53.48	52.52	53.18	40.48	41.37	40.27
16	C	38.02	35.73	35.74	37.65	46.36	45.12	45.93	46.50	42.42	42.63	42.94	37.38	30.86	32.28	35.38	44.22	35.76	41.57	44.34	36.46	35.30	34.92	37.34	35.08	34.58	36.18	49.29	43.41	45.51	47.38	34.65	33.50	32.40
17	D	35.40	33.85	32.45	33.33	44.48	42.11	45.31	47.39	38.99	38.09	40.50	36.70	34.88	33.71	35.47	49.07	47.40	48.28	50.98	37.30	35.86	36.33	34.66	32.65	33.00	35.36	45.30	39.88	43.89	45.43	38.64	37.74	36.63
18	A	48.81	45.45	43.10	42.15	51.47	44.52	43.48	43.92	56.22	56.77	57.15	30.45	29.13	27.25	26.44	42.40	37.82	34.81	36.10	31.55	31.88	32.04	34.34	32.96	31.45	30.96	51.45	41.87	41.76	43.40	33.64	33.10	32.00
19	B	49.18	46.31	44.03	44.27	56.66	49.27	50.95	53.00	58.68	59.59	58.86	34.45	33.74	33.52	33.93	51.34	45.19	45.03	51.00	36.19	34.74	35.97	40.48	39.17	37.71	37.10	56.09	49.98	47.44	49.49	37.82	35.31	34.21
20	D	35.56	29.73	30.25	30.24	45.11	42.76	41.62	42.60	43.53	43.33	43.42	34.19	32.53	30.91	31.05	48.73	45.58	43.49	44.68	34.49	33.04	33.68	35.36	33.54	32.49	32.87	47.90	42.51	40.89	41.09	35.09	34.67	33.29

* Run order was randomized for each subject. The run order is denoted by A-F as follows: A = Scenario A, Scenario B, Scenario C, B = Scenario C, Scenario B, Scenario A, C = Scenario C, Scenario A, Scenario B, D = Scenario A, Scenario C, Scenario B, E = Scenario B, Scenario A, Scenario C, and F = Scenario B, Scenario C, Scenario A

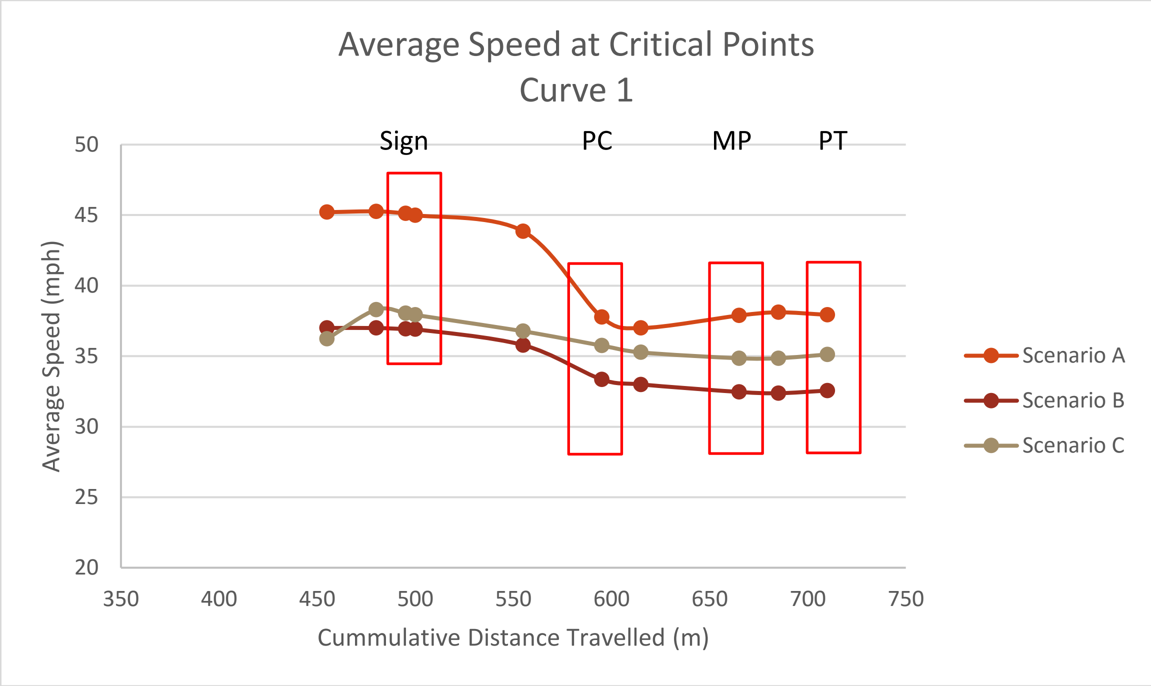


Figure 4.1 – Average speed in Curve 1.

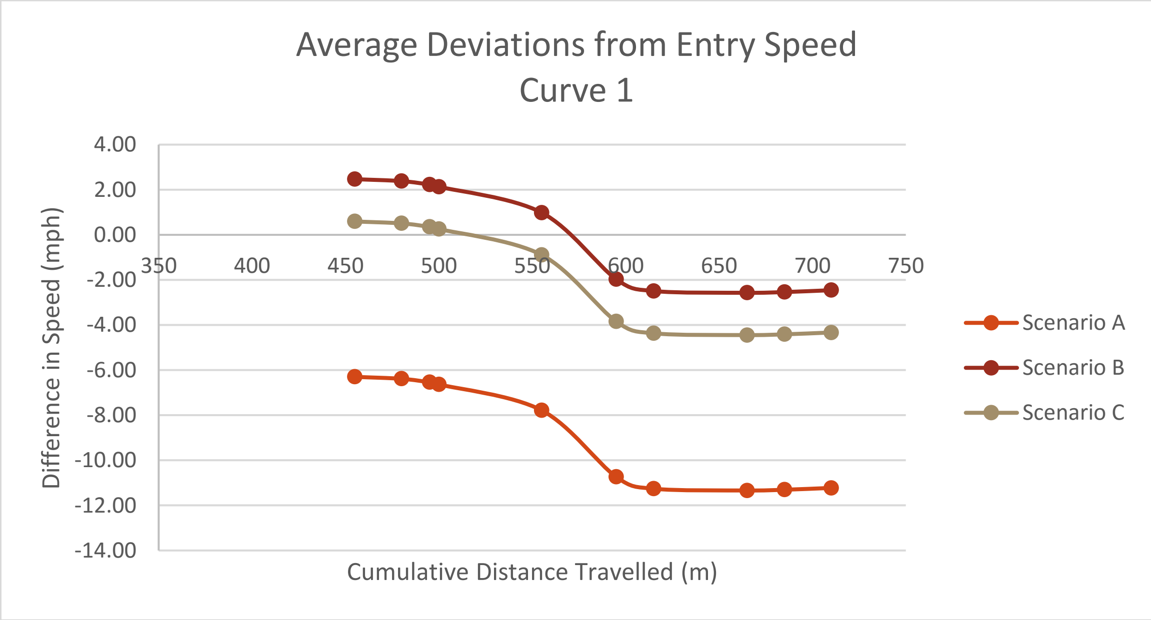


Figure 4.2 – Average deviations from entry speed in Curve Zone 1.

The comparisons for the remainder of the curves can be found in Appendix B. These results indicate that drivers behave in roughly the same manner when presented with virtual TCD information as when they are presented with the traditional post-mounted information.

Considering the p-values produced from the Wilcoxon signed-rank test, for the comparison of the critical points in the curves, sign location (sign), PC, MP, and PT, there was no statistically significant difference in the average speed at any of these points when Scenarios B and C are compared.

At Curve 1, average speeds in Scenario A are significantly different from the average speeds in Scenarios B and C. A comparison of Scenarios B and C showed statistically significant differences in average speed at both MP and PT of the curve. These differences are presented in Table 4.2 below, where red indicates p-values less than 0.05 and green indicates p-values greater than 0.05. A look at average speeds in these areas shows that drivers are operating at a higher speed through the entire curve, but that as drivers reached the MP and PT of the curve in Scenario C, they were travelling at 34.9 mph and 35.1 mph, respectively, versus 32.5 mph and 32.6 mph in Scenario B. Average speeds in Scenario B are lower at each critical point in the curve except for at the sign location.

Table 4.2 – Curve 1 p-values.

P-values in Curve 1 Comparisons			
Scenario Comparison	A vs. B	A vs. C	B vs. C
Sign	0.0000478	0.000009537	0.2024
PC	0.00573	0.01923	0.1506
MP	0.0003223	0.009436	0.01208
PT	0.0007076	0.008308	0.02389

Curve 2 shows more evidence of Scenarios B and C having no significant differences in average speeds. As shown in Table 4.3, the only exception to this is at the MP of the curve, where average speed in Scenario B is significantly different than in Scenario C, with a p-value of 0.04. The remainder of the critical points in Curve 2 show no significant difference in average speed when Scenario B is compared to Scenario C.

Table 4.3 – Curve 2 p-values.

P-values in Curve 2 Comparisons			
Scenario Comparison	A vs. B	A vs. C	B vs. C
Sign	0.0002613	0.003153	0.1536
PC	0.004221	0.03999	0.114
MP	0.001986	0.06372	0.03999
PT	0.0002613	0.01208	0.06958

With Curve 3, Scenarios B and C are not found to be significantly different at any of the critical points within the curve. This was expected from observing the average speed profiles where Scenarios B and C are almost overlaid atop one another. P-values for the comparisons made for Curve 3 can be found in Appendix C.

While this behavior was observed for Curve 3, Curve 4 had almost the opposite effect. Displayed in Table 4.4, Scenarios A and C showed significant differences only at the sign location, while Scenarios B and C were found to have no significant difference. These results can again be attributed to the average speed profile in Scenarios A and C exhibiting near identical average speeds at the remainder of the critical points.

Table 4.4 – Curve 4 p-values.

P-values in Curve 4 Comparisons			
Scenario Comparison	A vs. B	A vs. C	B vs. C
Sign	0.00003624	0.001017	0.1923
PC	0.007296	0.1231	0.001432
MP	0.004287	0.1353	0.000593
PT	0.0004826	0.1429	0.000483

Comparisons in Curve 5 again showed that Scenarios B and C are not significantly different at any of these critical points. While Curve 5 showed significant differences between Scenarios A and B and Scenarios A and C, Curve 6 showed very few significant differences across the critical points. The vast majority of the curve for all scenarios behaved as if there were no significant differences in average speed, as indicated in Table 4.5. The only exception to this was the average speed at the PC being significantly different in the A vs. C comparison and the B vs. C comparison.

Table 4.5 – Curve 6 p-values.

P-values in Curve 6 Comparisons			
Scenario Comparison	A vs. B	A vs. C	B vs. C
Sign	0.1671	0.9854	0.09731
PC	0.2455	0.04844	0.04844
MP	0.33	0.2455	0.06372
PT	0.7841	0.1258	0.2024

Curve 7 showed no statistical differences in average speeds at nearly all critical points. However, as drivers exited the curve in Scenario B, they did so at a more constant rate, not varying in average speed much from the midpoint to PT. As drivers made their exit of the curve in both Scenarios A and C, average speeds increased upon the exit of the curve at the PT. This led to Scenarios B and C showing significantly different average speeds at the MP and PT of the curve.

As drivers ended with Curve 8, no significant differences were found in Scenarios B or C at PC, MP, or PT. The comparisons can be seen in Table 4.6 below. However, the average speeds at the sign location were nearly identical for Scenarios A and C, causing a significant difference when Scenarios B and C were compared at this location.

Table 4.6 – Curve 8 p-values.

P-values in Curve 8 Comparisons			
Scenario Comparison	A vs. B	A vs. C	B vs. C
Sign	0.04998	0.866	0.002325
PC	0.01362	0.01208	0.3884
MP	0.001017	0.0003948	0.498
PT	0.000583	0.00004768	0.5459

4.2 Findings

The first item to note is the difference in speed limits for the curves. Curves 1-4 were all situated on a 35 mph speed limit section of the roadway, while Curves 5-8 were situated on a 55 mph speed limit section. Secondly, the curves within each speed limit segment were designed such that the design speed was equivalent to the posted speed. This fact can explain the average speeds. It comes as no surprise that drivers will naturally travel at operating speeds faster than an advisory if they are physically comfortable enough to do so. By designing the curves to the posted speed limit, average speeds can be expected to be around that 35 mph or 55 mph number, depending on the segment. This geometric constraint instills another method for controlling speeds and helps to confirm why, in Curves 6 and 7, there were very few significant differences found in average speed. Drivers were conforming to the geometry of the roadway and simply being reminded or aided by the signage that was presented to them.

Another interesting phenomenon that became apparent in the data is the similarity in behavior between the different curve geometries. A pairing was seen between Curves 1 and 4, Curves 2 and 3, Curves 5 and 8, and Curves 6 and 7. Each pair shared the same geometry, either a right curve or a left curve. Speed profiles as well as behaviors matched between the pairs, and not surprisingly, the significance testing revealed the same pairing results. Obviously, this pairing was not all inclusive, but could be seen subjectively from the profiles and more objectively from the comparison p-values.

Average speeds throughout all eight curves were slightly higher in Scenario C than they were in Scenario B. At first this makes sense because Scenario C is more closely related to Scenario A, where there are no signs on the roadway. Scenario C started out as if there were no signs on the road, but when they were presented in the vehicle, drivers seemed to react at a more defined location as opposed to the post-mounted case where drivers would react prior to the sign location due to their ability to see the information ahead of time. It is promising, though, that average speeds were not drastically different in Scenarios C and B.

It is important to note that the dynamic display of the chevron alignment warnings could be a candidate for future work. One hypothesis as to why average speeds in Scenario C were higher in the curves is related to the dynamic chevron display. As the chevrons flashed along the centerline of the road, it is conceivable that drivers could have felt more comfortable proceeding at higher speed because they could see the curvature relative to their position as opposed to on the outside of the roadway as they would be presented in the post-mounted case. More research would need to be undertaken to confirm or deny this hypothesis.

4.3 Eye-Tracking Data

The analysis of the collected eye-tracking data during the three scenarios for the 20 participants is still in process. The videos recorded for Scenarios B and C were divided into 22 events based on the number of the signs presented in the scenarios. For each sparse event, areas of interests were identified. In all the events, four areas of interest (AOI) were noted: dashboard, roadside, road, and sign. In addition to those four areas, another area was introduced in the pedestrian event: pedestrian crossing. The movement of the eyes and how they transitioned between those areas were tracked throughout the scenarios. Figures 4.3 and 4.4 below show the areas of interest identified in Scenarios B and C, respectively. The heat map is also shown in the figures, indicating areas where the driver fixated while navigating on a segment. The horizontal bar graphs below the figures show how much time the driver spends looking at each area.

From the videos that have been analyzed so far, it can be inferred that each participant shows a different eye movement trend from the others. In general, it was seen that the fixations on the roadside were very high in Scenario B, whereas they were very minimal in Scenario C. As seen in Figure 4.3, the driver spends a lot of time looking at the roadside (long blue bar) to comprehend the traffic sign presented. In Figure 4.4, the driver didn’t look to the roadside at all (no blue bar), but he fixated his vision on the road and the sign displayed in his line of sight at the same time.

The percentage of total time spent in each area of interest is demonstrated in the bar graphs below. Subject 14 was taken as a sample to show the results obtained for Scenario B (Figure 4.5) and Scenario C (Figure 4.6). It is clear that in Scenario B, the driver spends a big percentage of total time looking at the road side (~ 35%), while in Scenario C, the driver looks at the road side, but for a minimal percentage (less than 5%). With these results, it is possible to say that the holographic-style signs help drivers keep their attention on the road ahead of them without having to look at the roadside to search for warning or regulatory traffic signs.

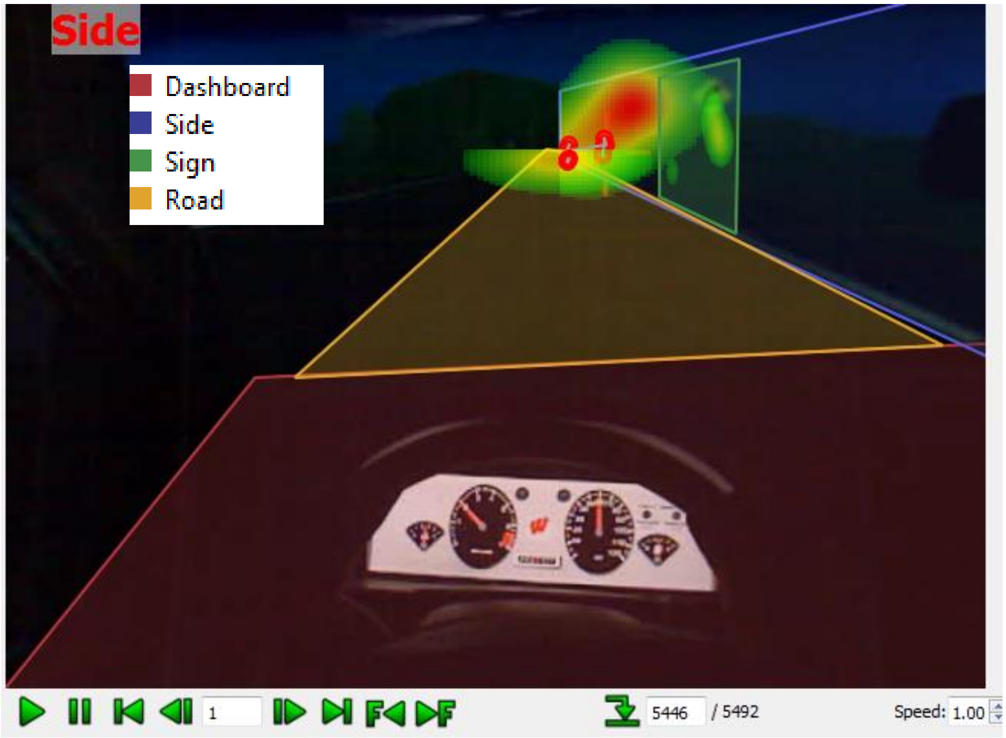


Figure 4.3 – Areas of interest in Scenario B.

Figure 4.4 – Areas of interest in Scenario C.

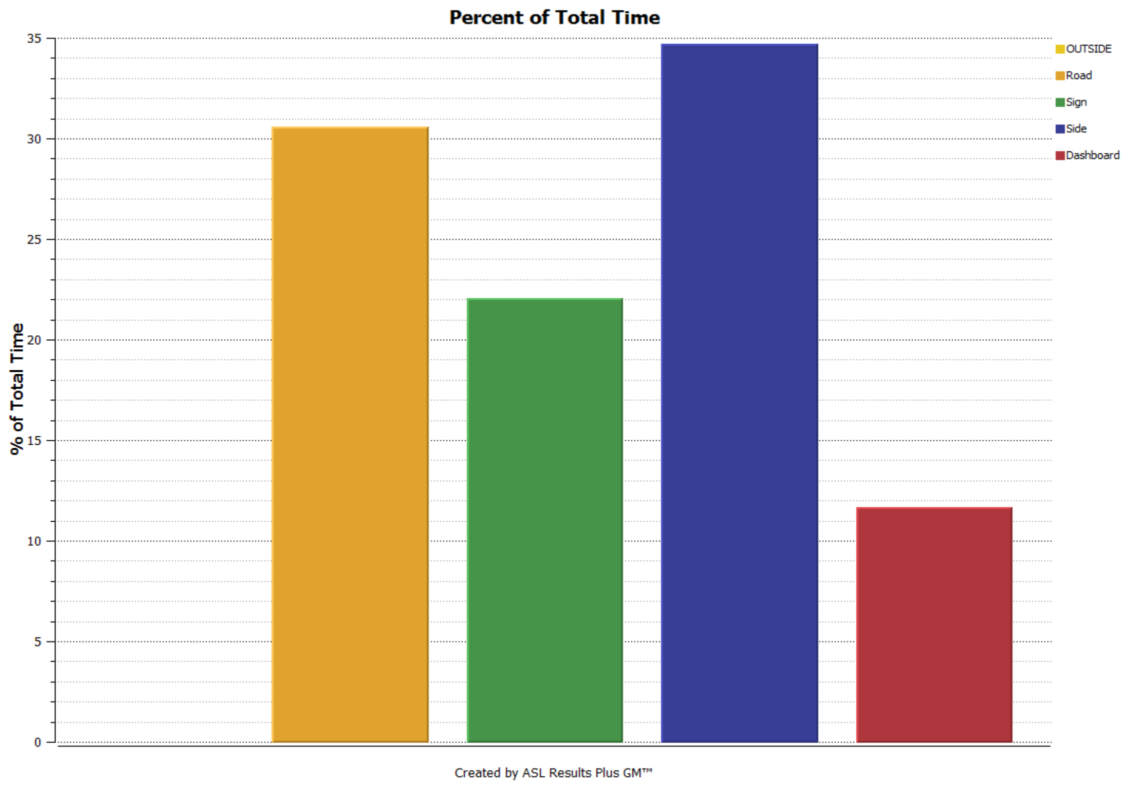


Figure 4.5 – Percentage of total time spent in AOI for Subject 14 in Scenario B.

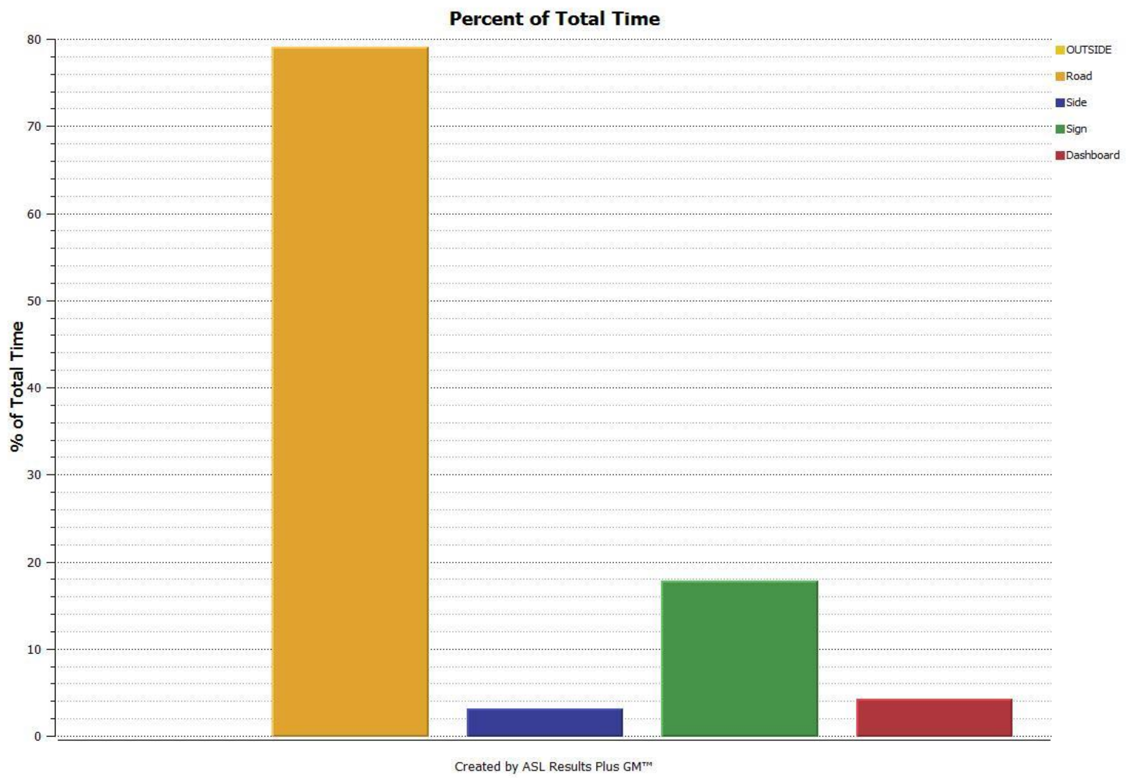


Figure 4.6 – Percentage of total time spent in AOI for Subject 14 in Scenario C.

5 Conclusions

Traffic control devices provide the primary form of communication between the roadway environment and drivers. However, many confounding factors such as clutter and traffic volume can lead to drivers missing important TCD often displayed via post-mounted signs. Advanced in-vehicle technologies may allow for a more focused presentation of TCD information, especially by displaying the information in the line of sight of drivers. Proven technologies already available in the market include the use of HUD and HDD. A natural evolution of the more advanced HUD technology is the use of holographic-style displays that can augment the reality of the roadway environment in order to support the driver, and this was the focus of the research presented in this report.

The feasibility of using holographic technology to augment the reality of the road and replace traditional post-mounted signs was studied using a full-scale driving simulator. Twenty subjects were asked to drive three different scenarios with identical geometry in the driving simulator. These scenarios took into account three roadway conditions: a signless roadway, a roadway with traditionally post-mounted signs, and a "virtually signed" roadway (no post-mounted signs). In the third scenario, virtual regulatory and warning signs were projected on the screen as if produced by a holographic display.

An analysis of the average speeds at critical points across eight curves within the scenarios suggests that virtual TCD signage could encourage driving behaviors that are similar to those observed in a traditionally signed environment. In accordance with the objective of the research presented, it was determined that in-vehicle-displayed TCD have the potential to replace post-mounted signs. However, more testing is required under an expanded number of scenarios that include different types of regulatory and warnings signs as well as guidance signs. Additionally, based on findings from the full experimental results, pedestrian safety is one area that should be explored in detail as described ahead.

5.1 Future Research

As shown in Figure 9 (Appendix A), the speed profile of most drivers remained relatively constant throughout the duration of the pedestrian zone, which included a trail crossing with potential for pedestrian activity. Although there were no pedestrians present, two subjects displayed drastically different behaviors than the others. This behavior was observed in Scenario C, when the drivers were presented with a pedestrian traffic warning sign via the holographic-style display. At the time the sign was presented, the two subjects conducted a heavy braking maneuver, decreasing their speed by more than 50%. This suggests promising work that could lead to improvements in pedestrian safety as complete streets, alternate modes, and pedestrian/bicycle accommodations are being designed and implemented across the country. Mainly, experiments should be conducted to understand how holographic-style technology can be used to increase driver awareness about the presence of pedestrians. For instance, can similar technologies effectively act as a bridge between roadside infrastructure, or in-vehicle technology, and drivers to communicate the presence of pedestrians successfully when the line of sight is blocked? Other areas to consider include the use of holographic-style augmented reality to support navigation in complex environments such as intersections and interchanges, delineate the roadway boundaries under harsh weather and lighting conditions, and convey warnings more effectively.

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Appendix A. Speed Profiles

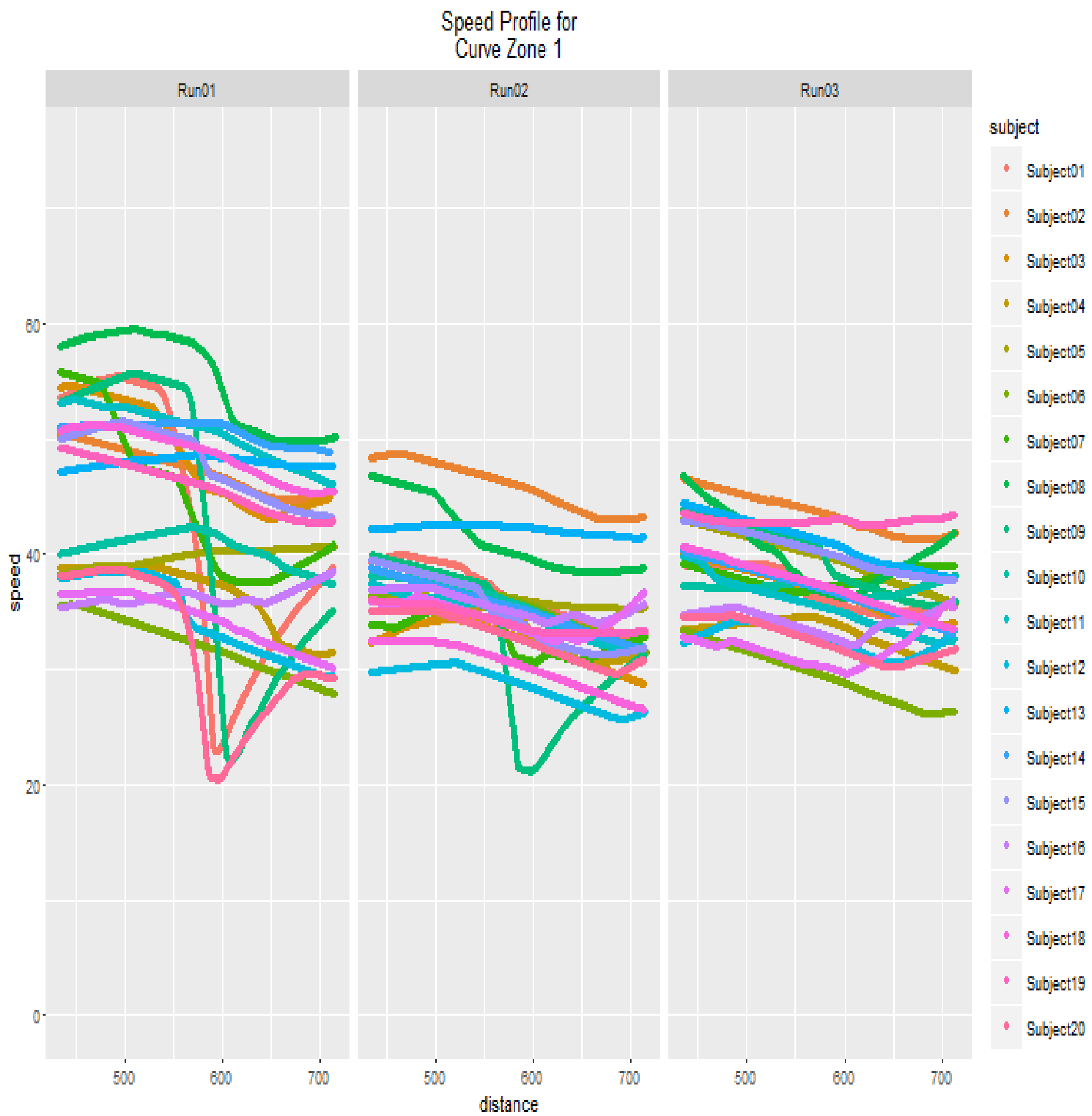

Figure A.1 – Speed profiles in Curve Zone 1.

Figure A.2 – Speed profiles for Curve Zone 2.

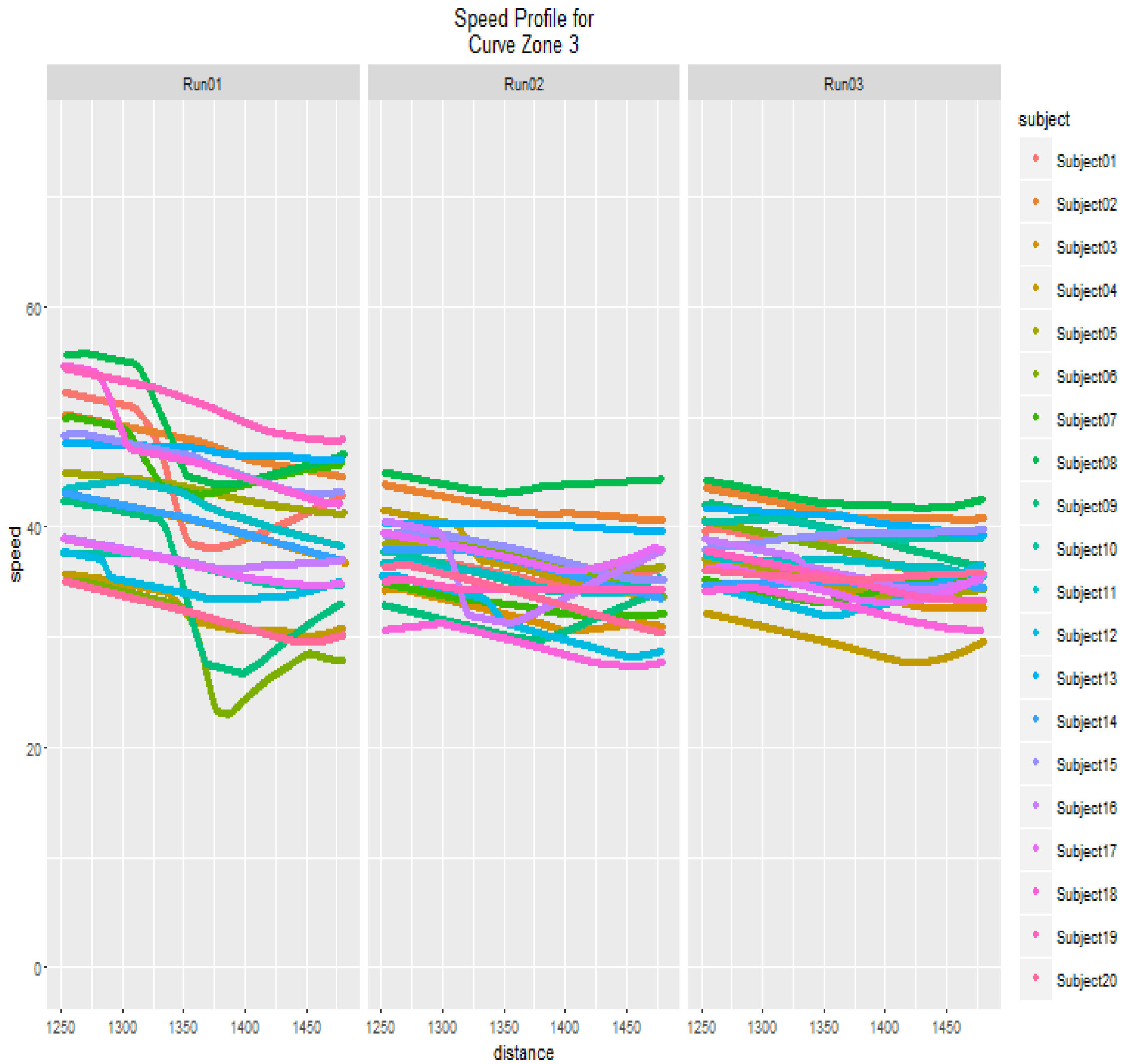

Figure A.3 – Speed profiles for Curve Zone 3.

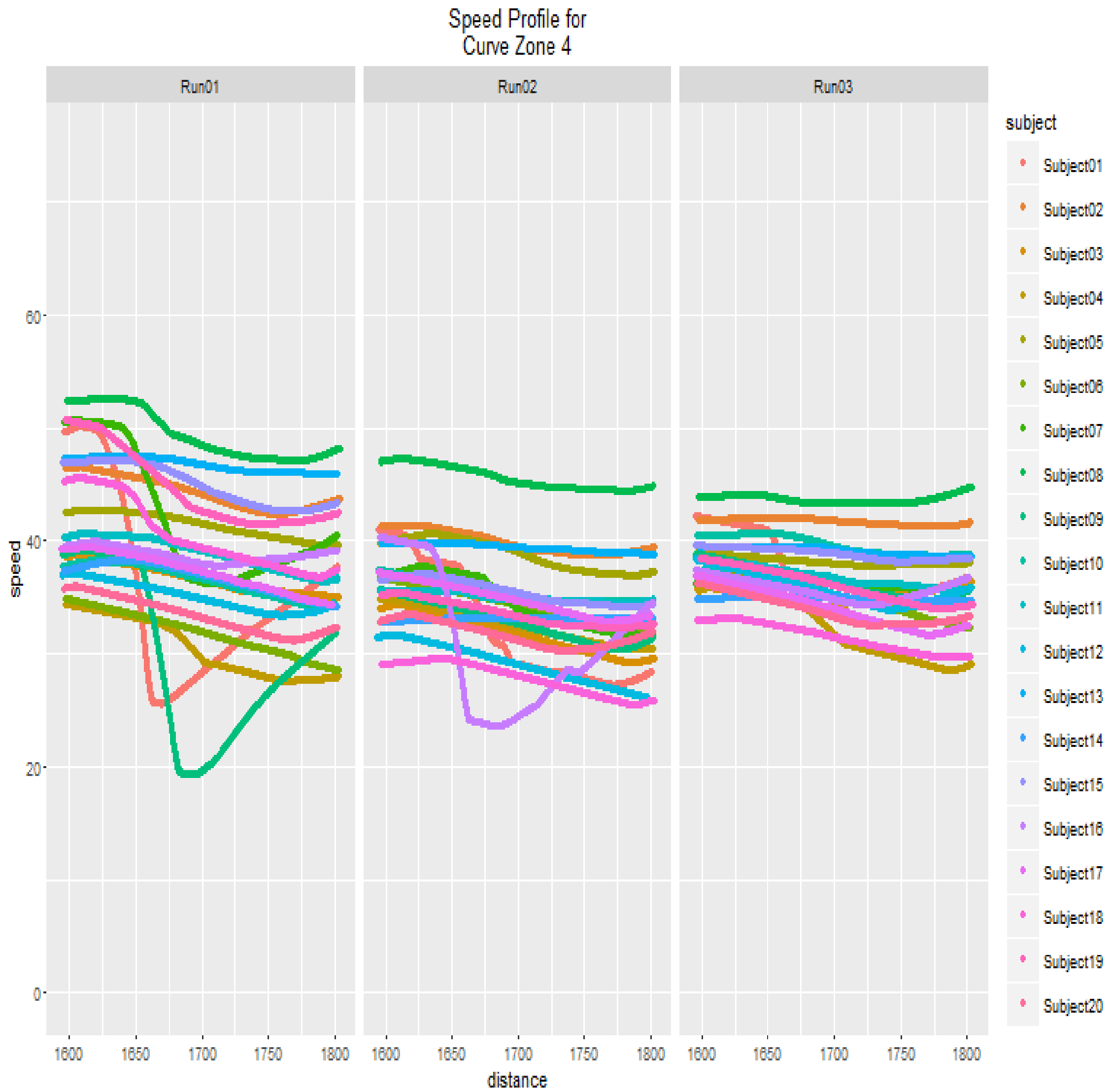

Figure A.4 – Speed profiles for Curve Zone 4.

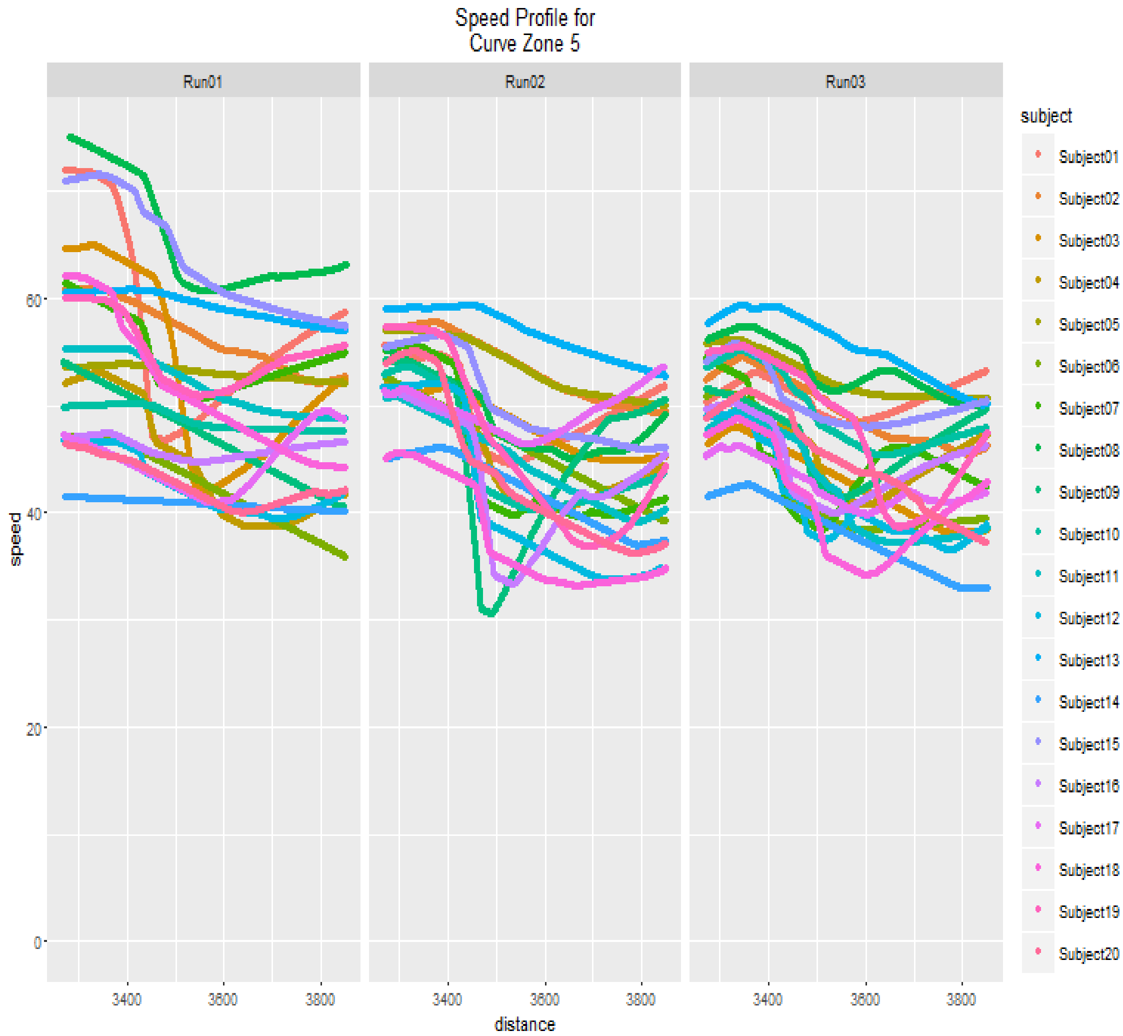

Figure A.5 – Speed profiles for Curve Zone 5.

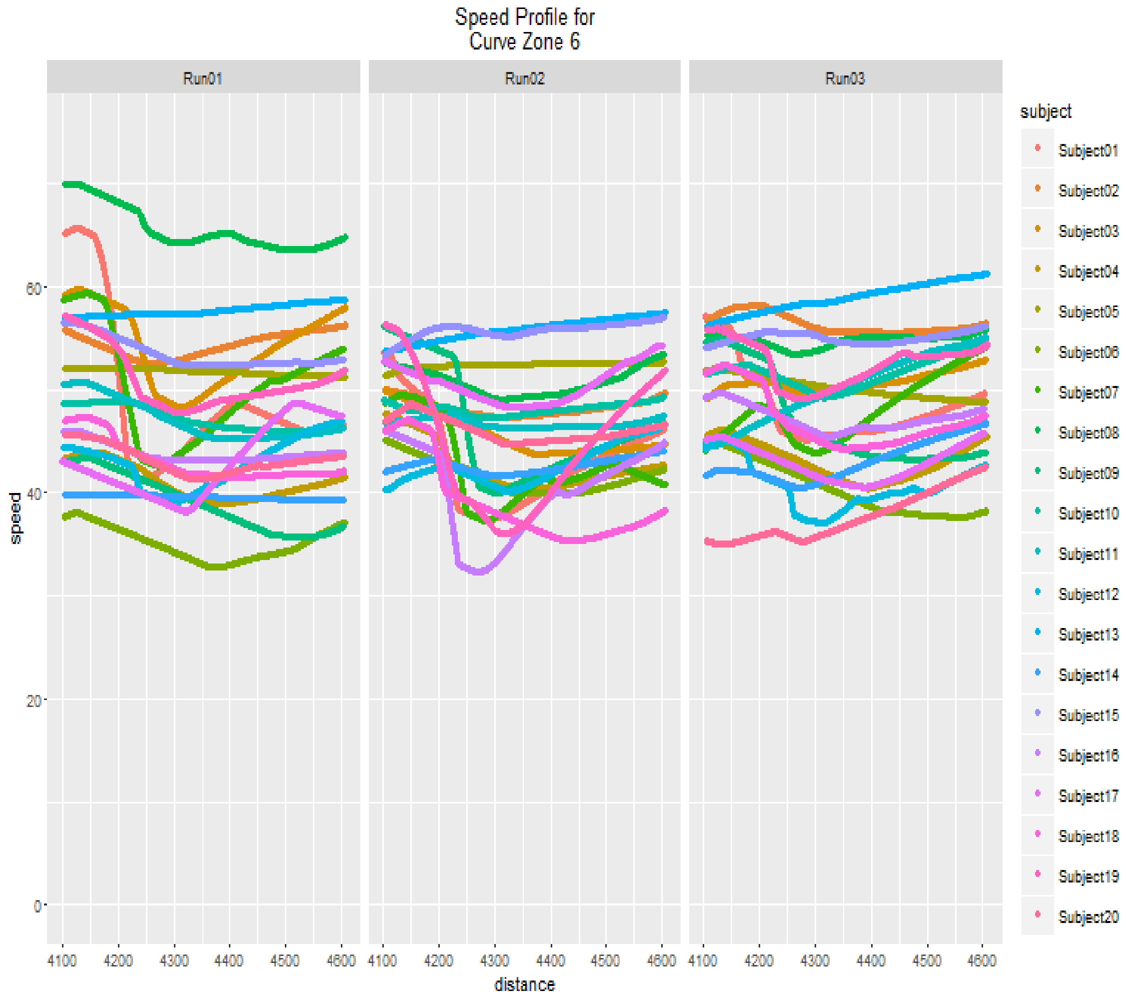

Figure A.6 – Speed profiles for Curve Zone 6.

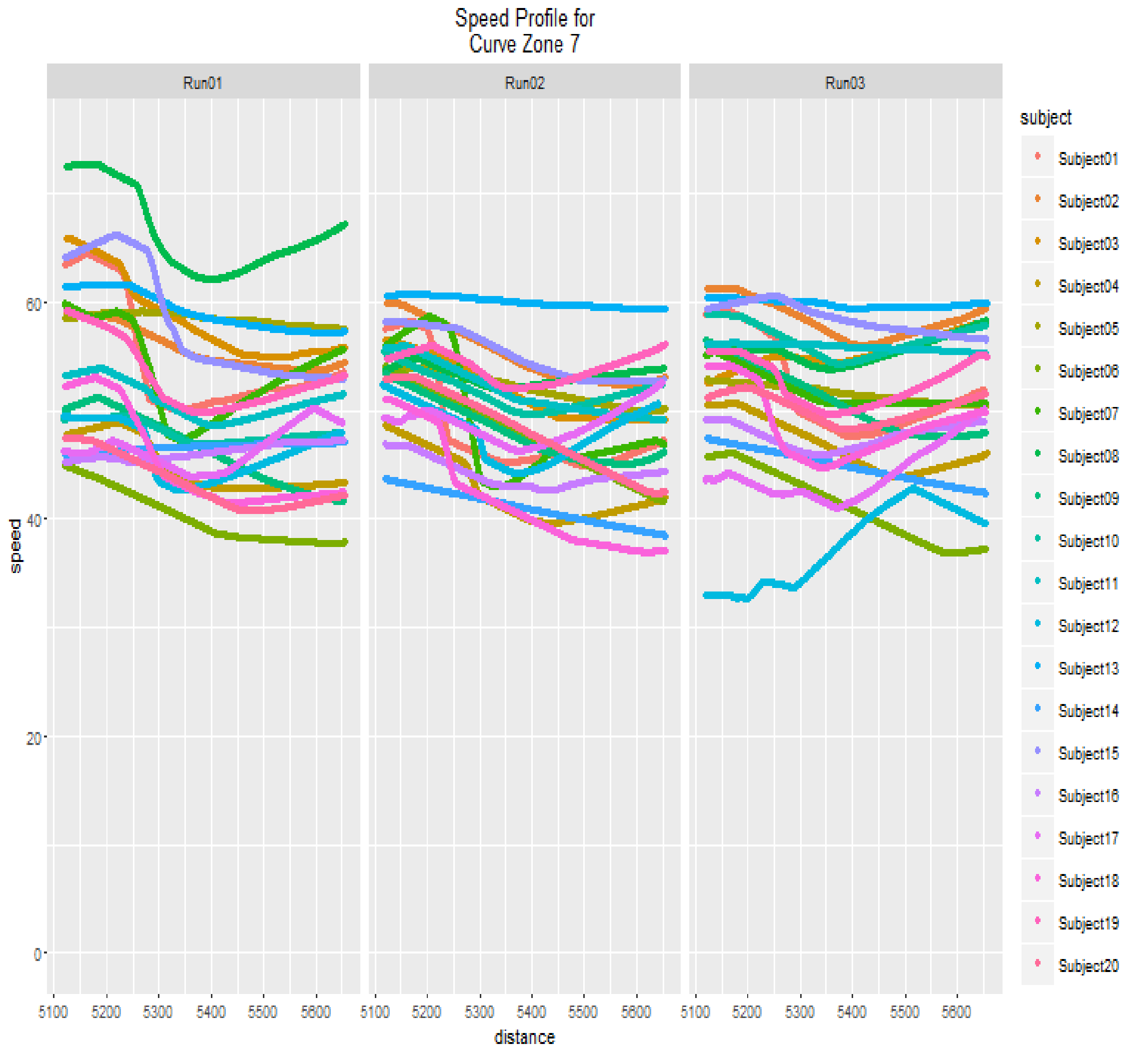

Figure A.7 – Speed profiles for Curve Zone 7.

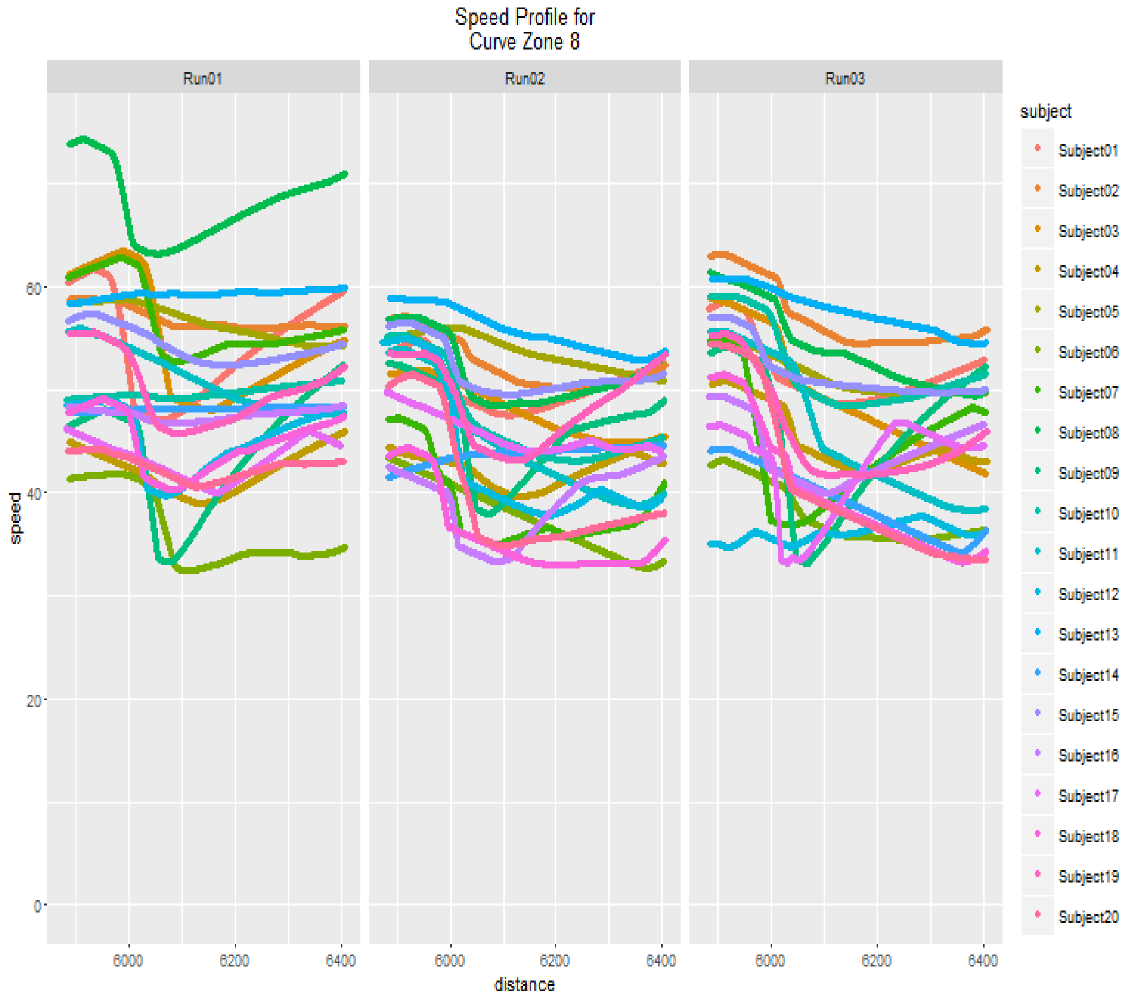

Figure A.8 – Speed profiles for Curve Zone 8.

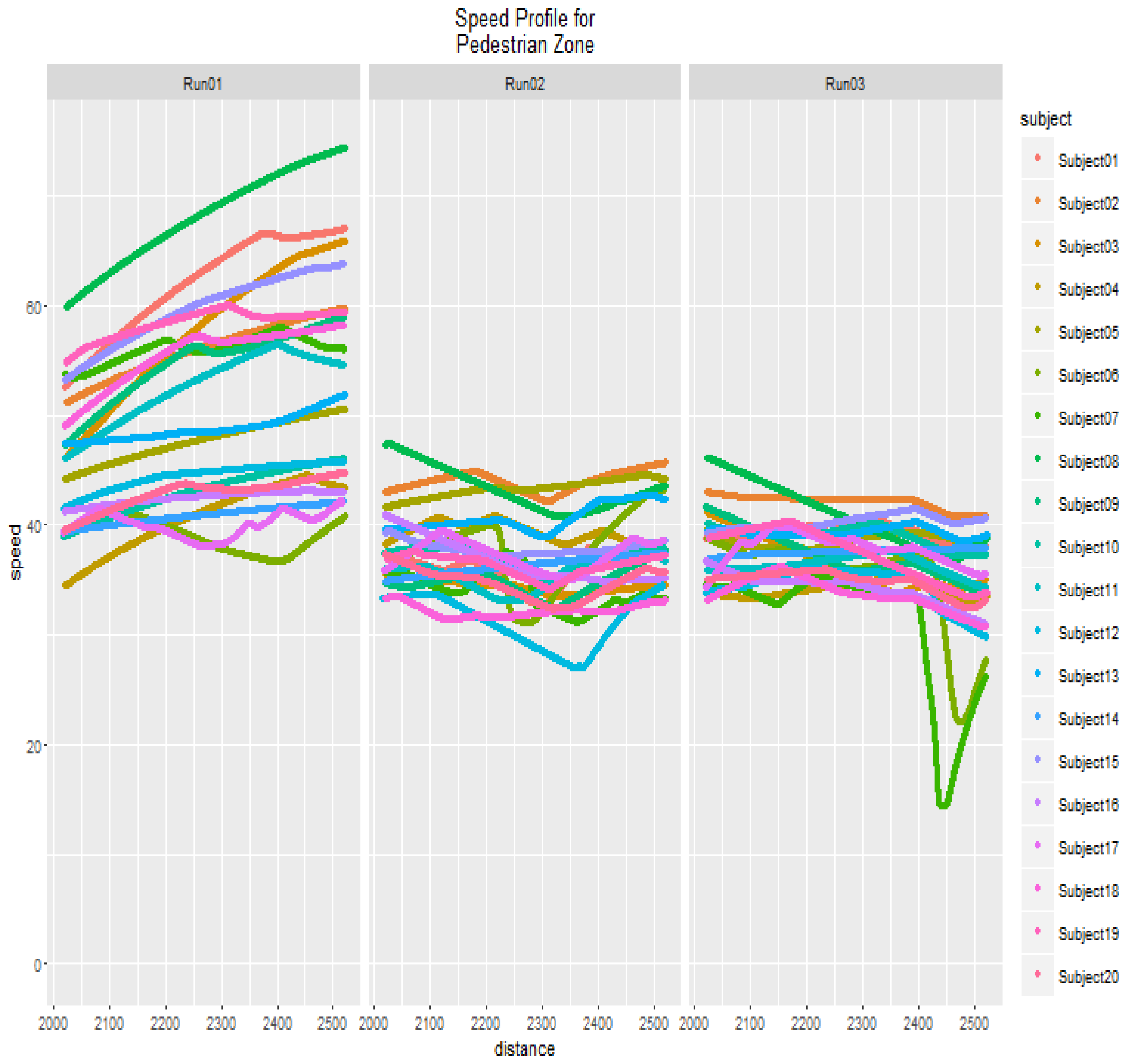

Figure A.9 – Speed profiles for pedestrian zone.

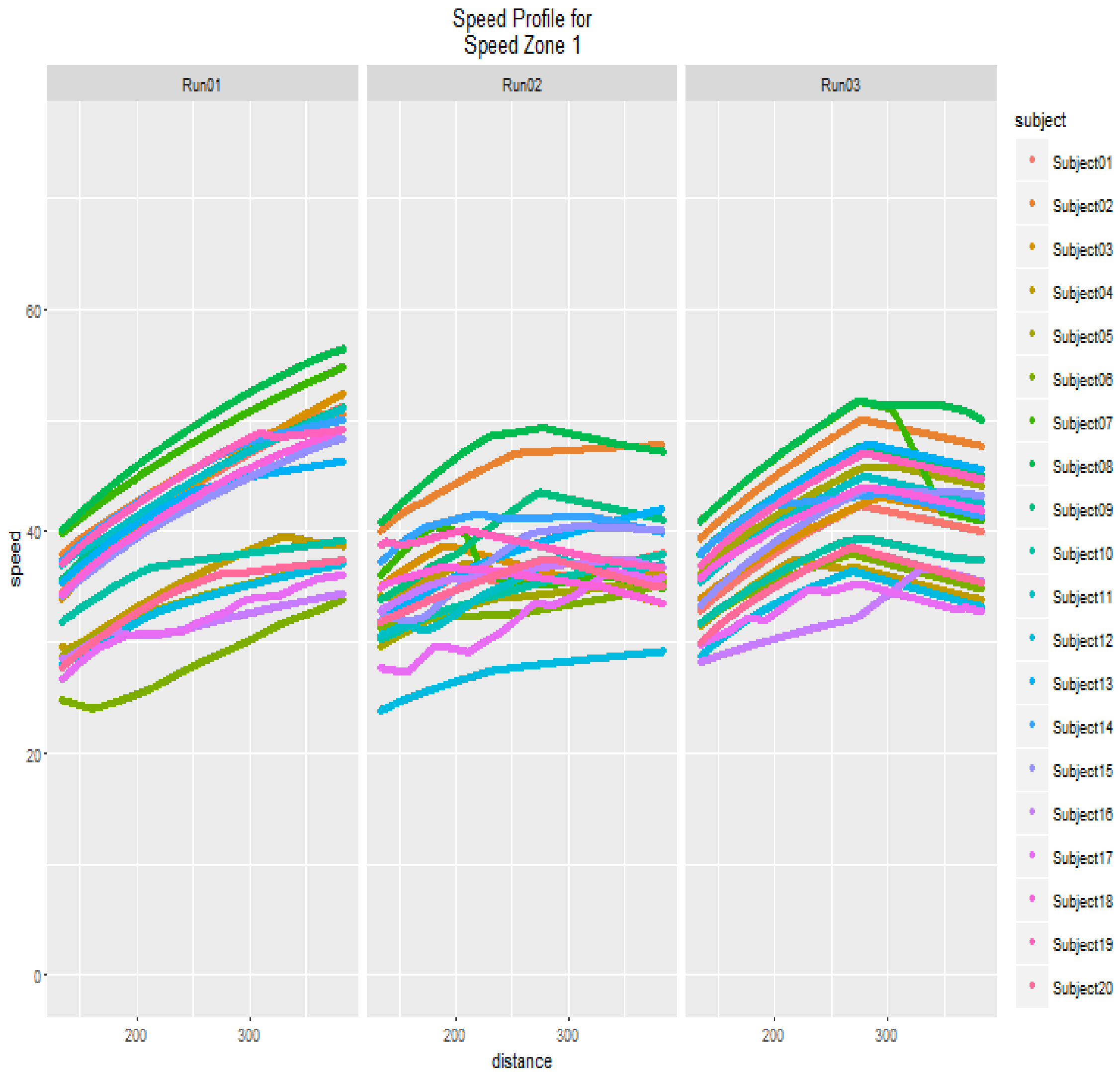

Figure A.10 – Speed profile for Speed Zone 1.

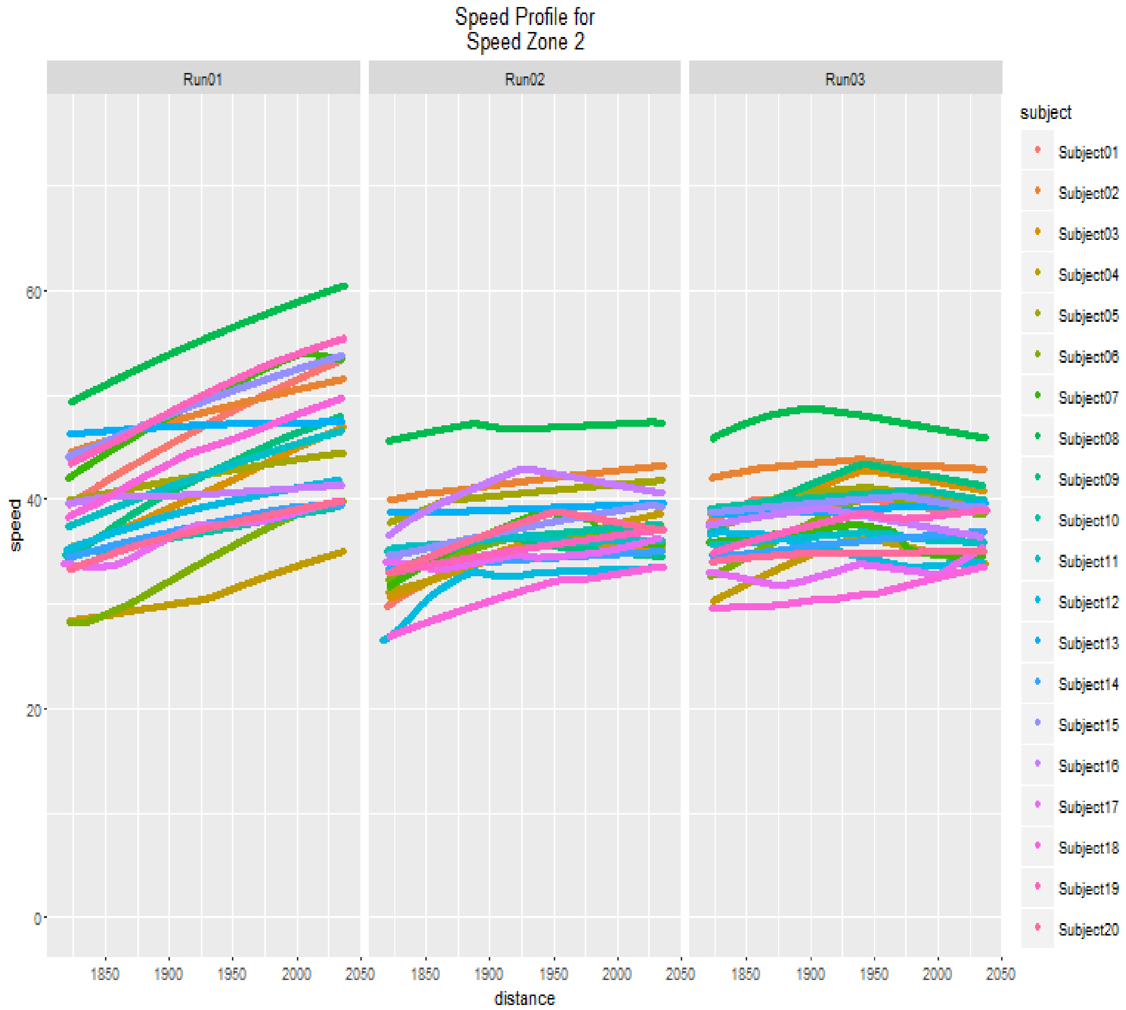

Figure A.11 – Speed profile for Speed Zone 2.

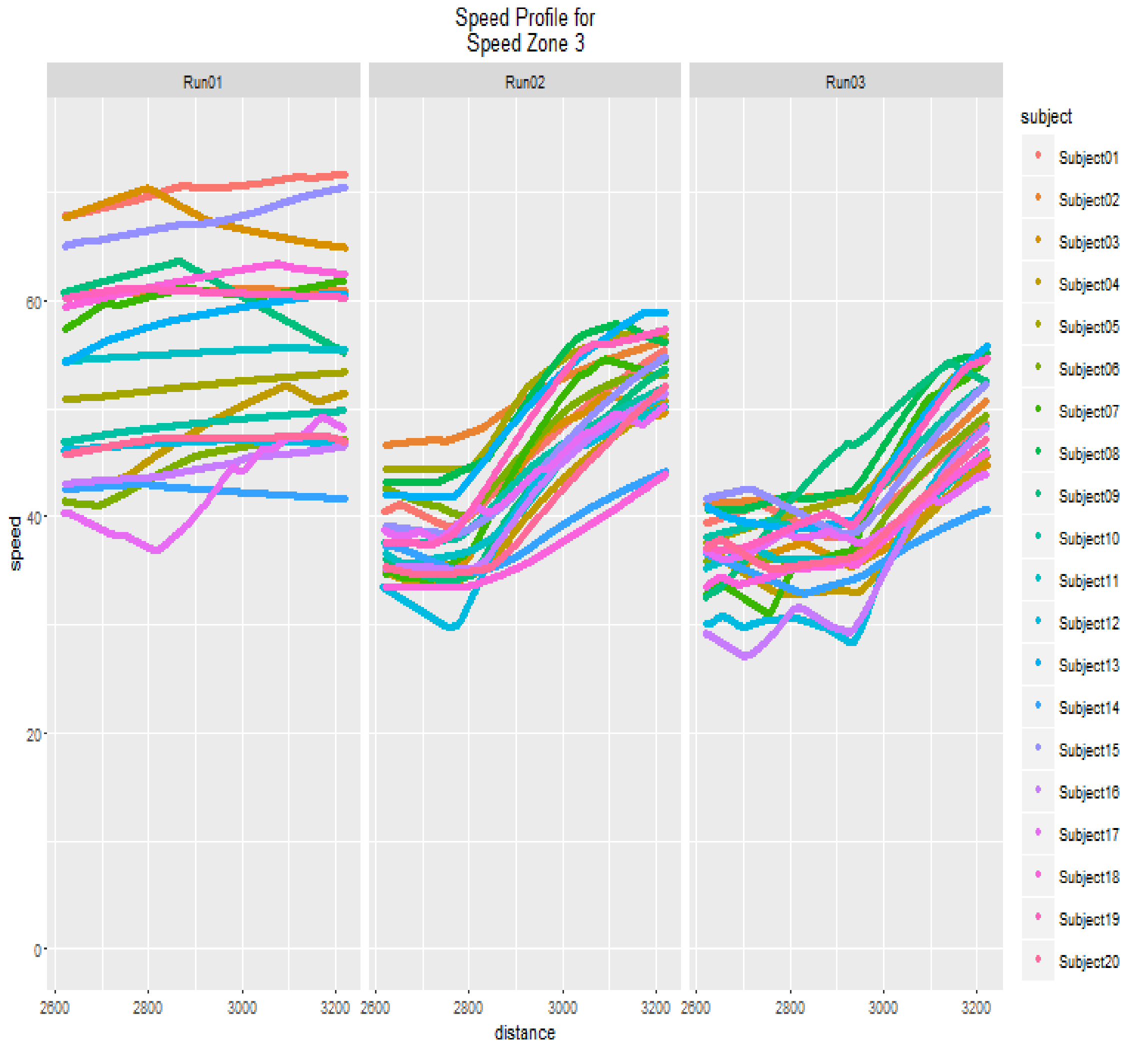

Figure A.12 – Speed profile for Speed Zone 3.

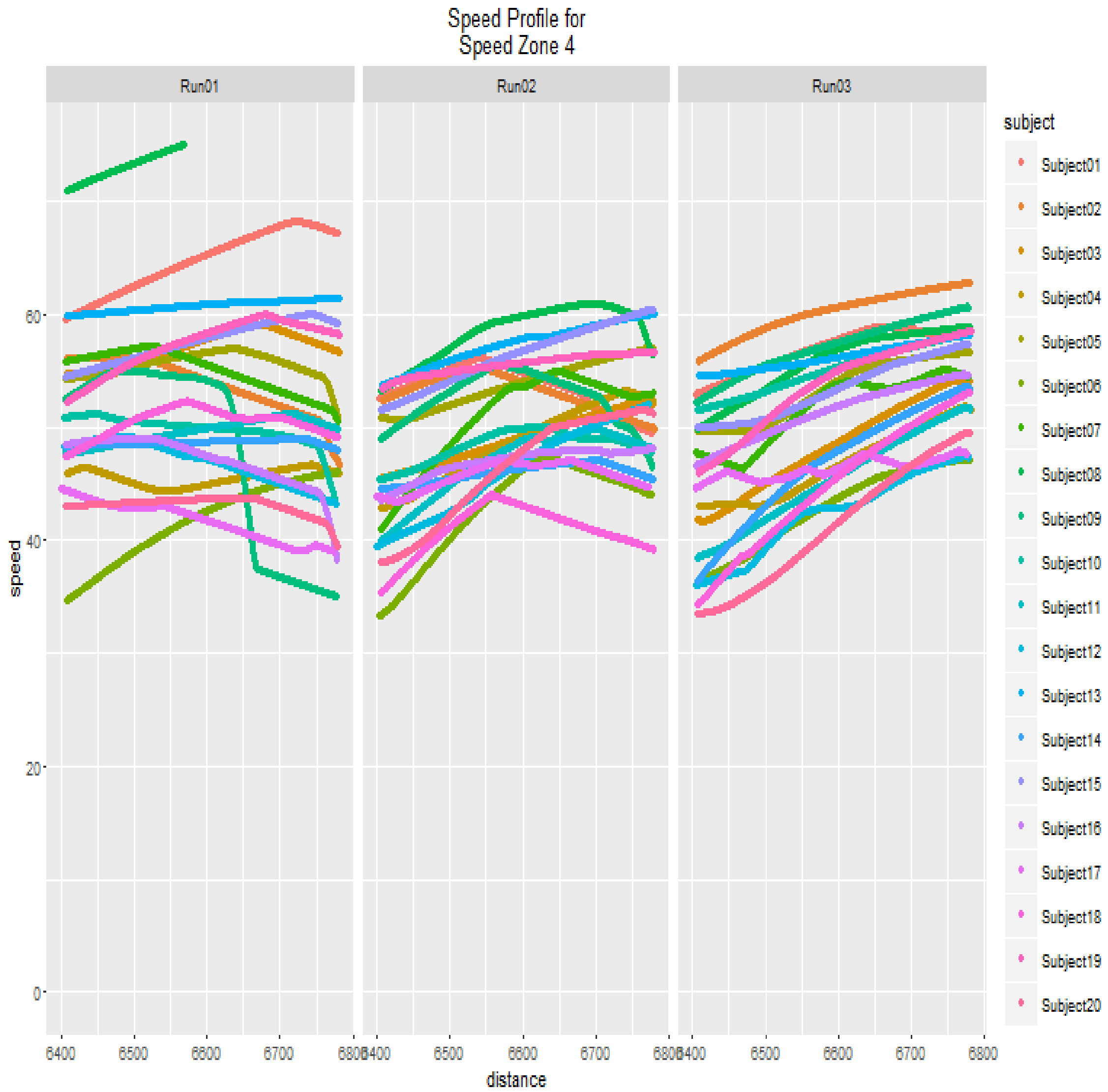

Figure A.13 – Speed profile for Speed Zone 4.

Appendix B Average Speeds & Deviations from Entry Speeds

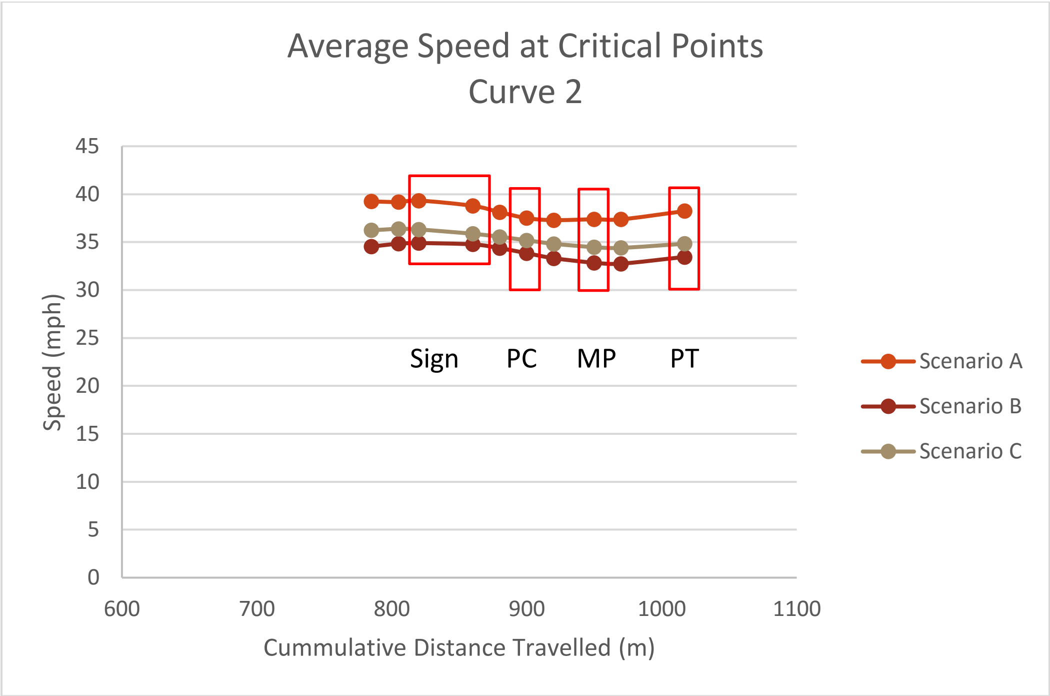

Figure B.1 – Average speed in Curve 2.

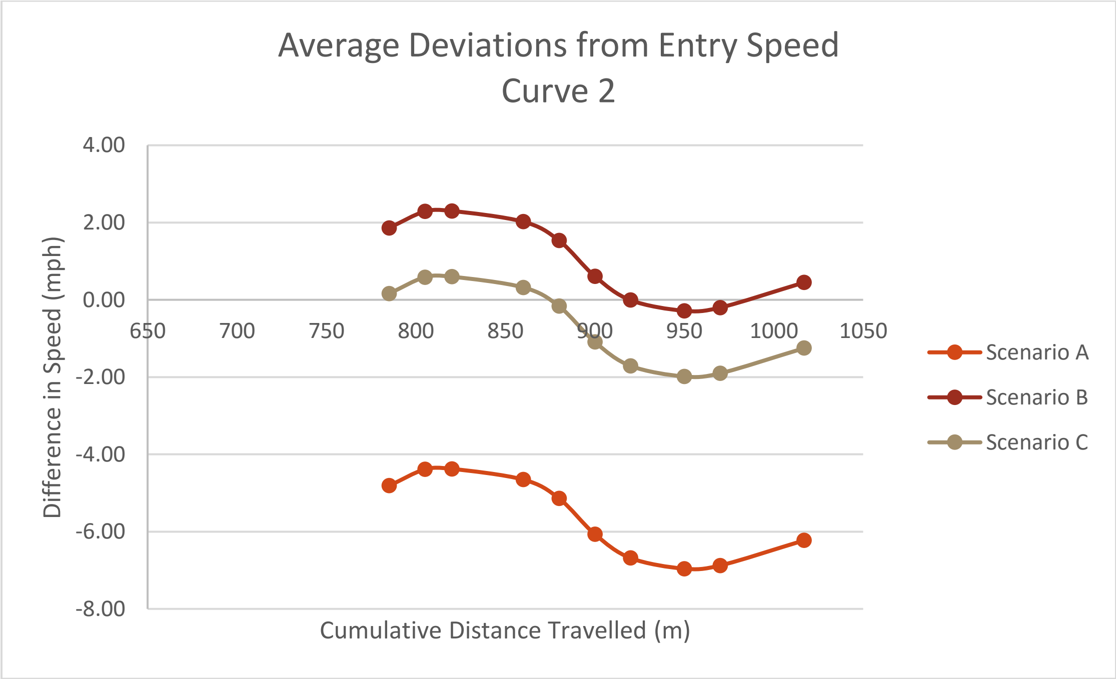

Figure B.2 – Average deviations from entry speed in Curve Zone 2.

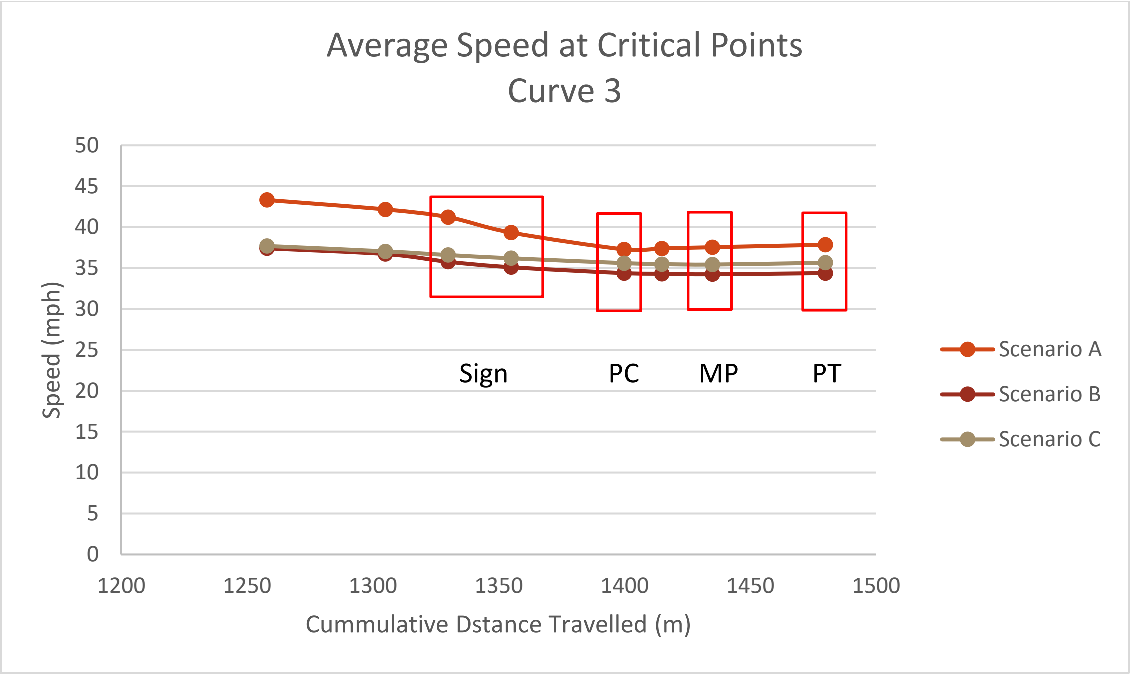

Figure B.3 – Average speed in Curve 3.

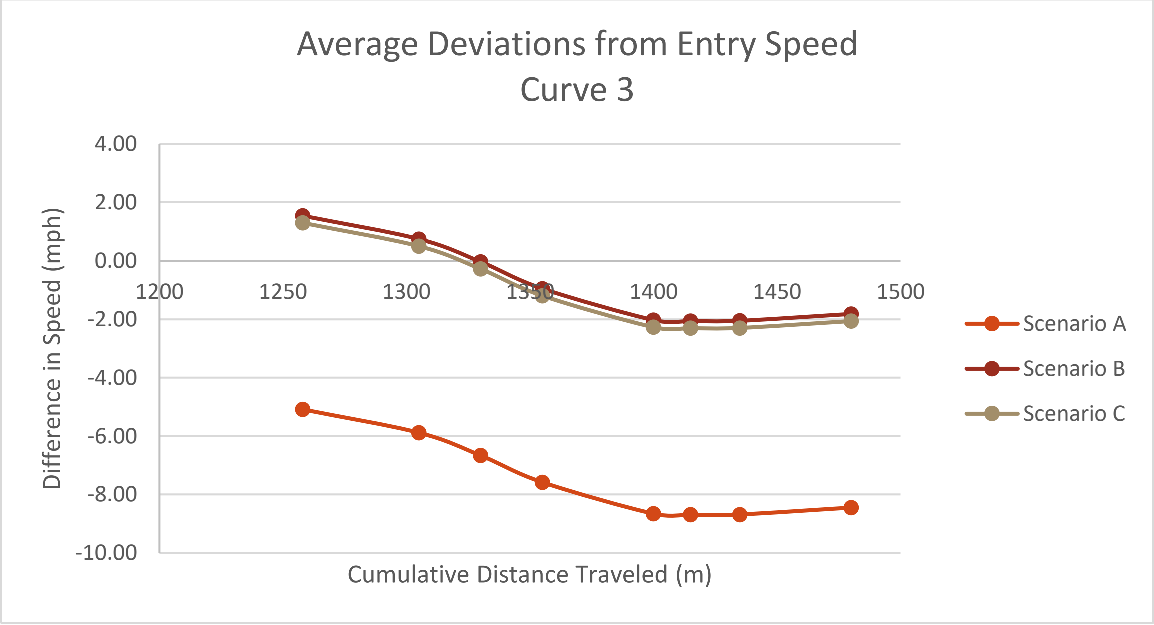

Figure B.4 – Average deviations from entry speed in Curve Zone 3.

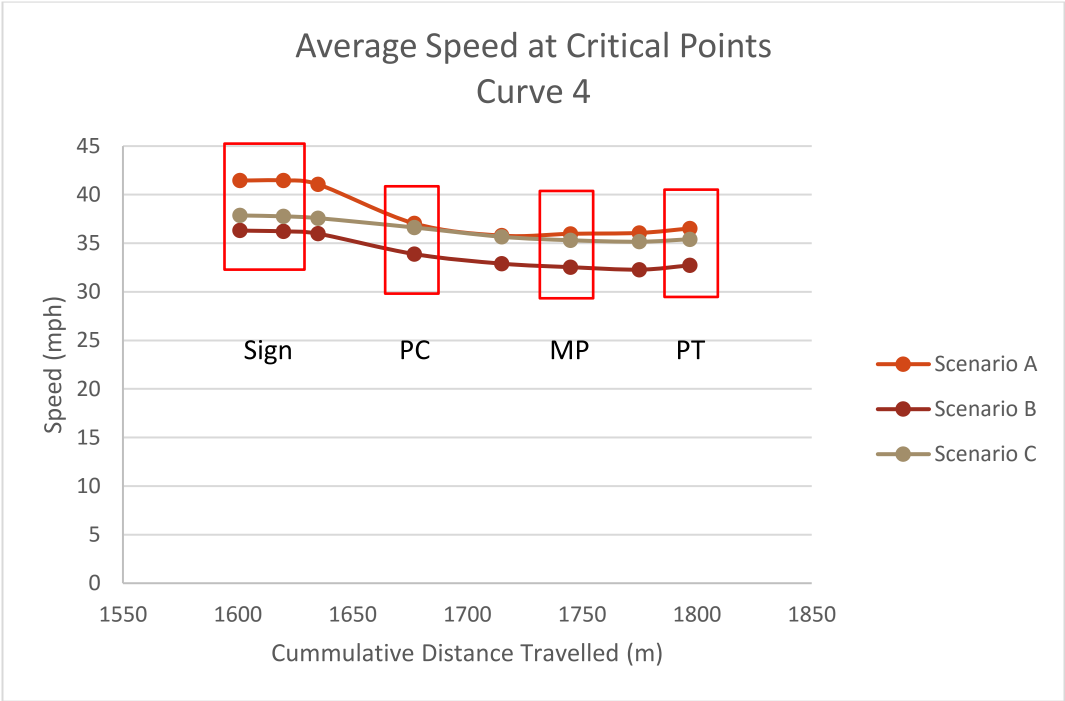

Figure B.5 – Average speeds in Curve 4.

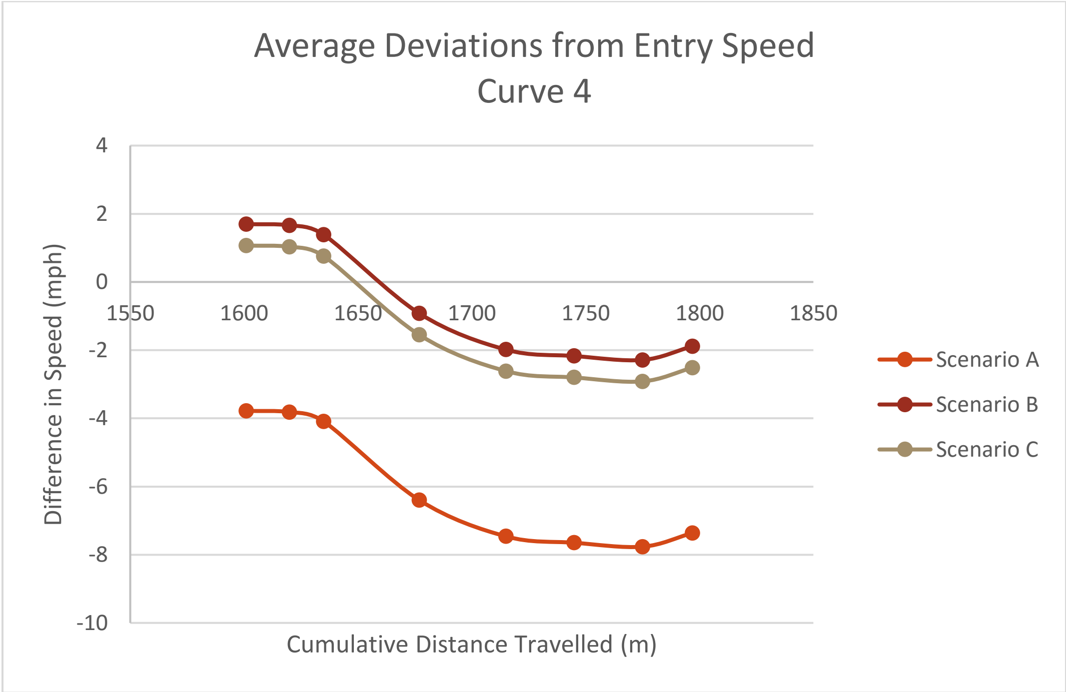

Figure B.6 – Average deviations from entry speed in Curve Zone 4.

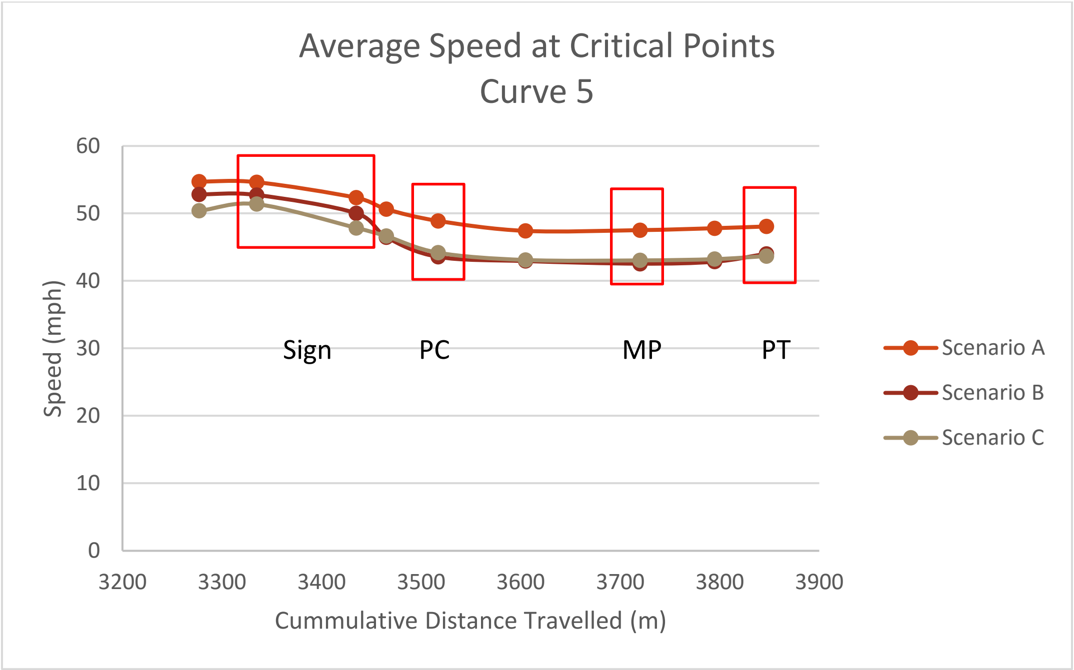

Figure B.7 – Average speeds in Curve 5.

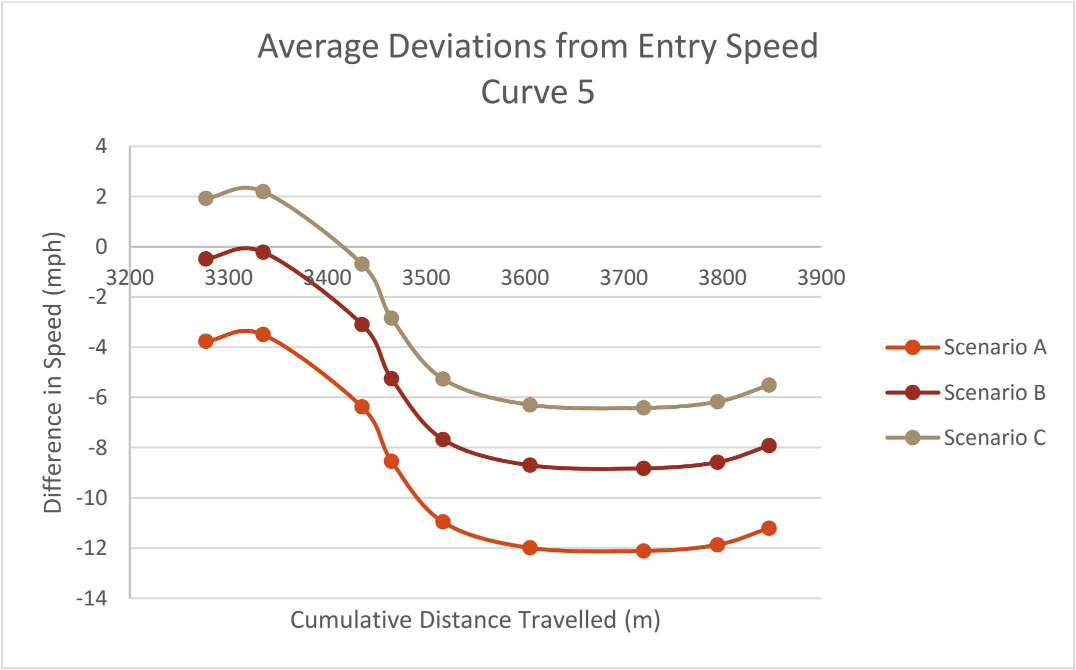

Figure B.8 – Average deviations from entry speed in Curve Zone 5.

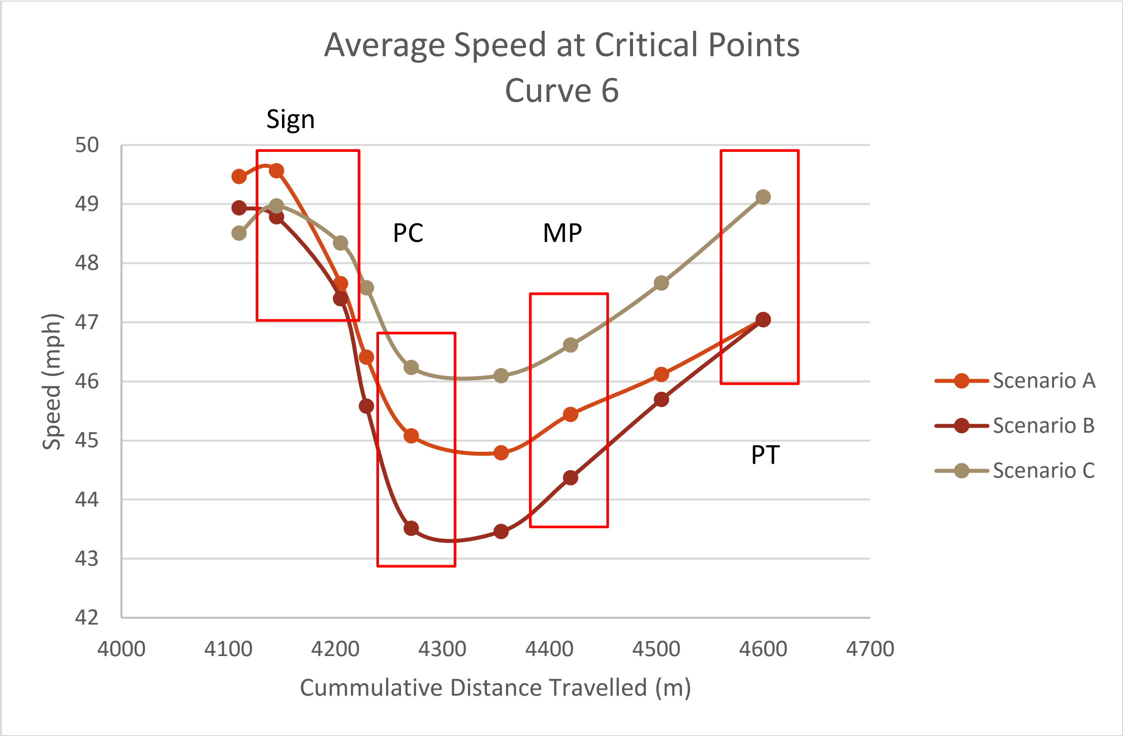

Figure B.9 – Average speeds in Curve 6.

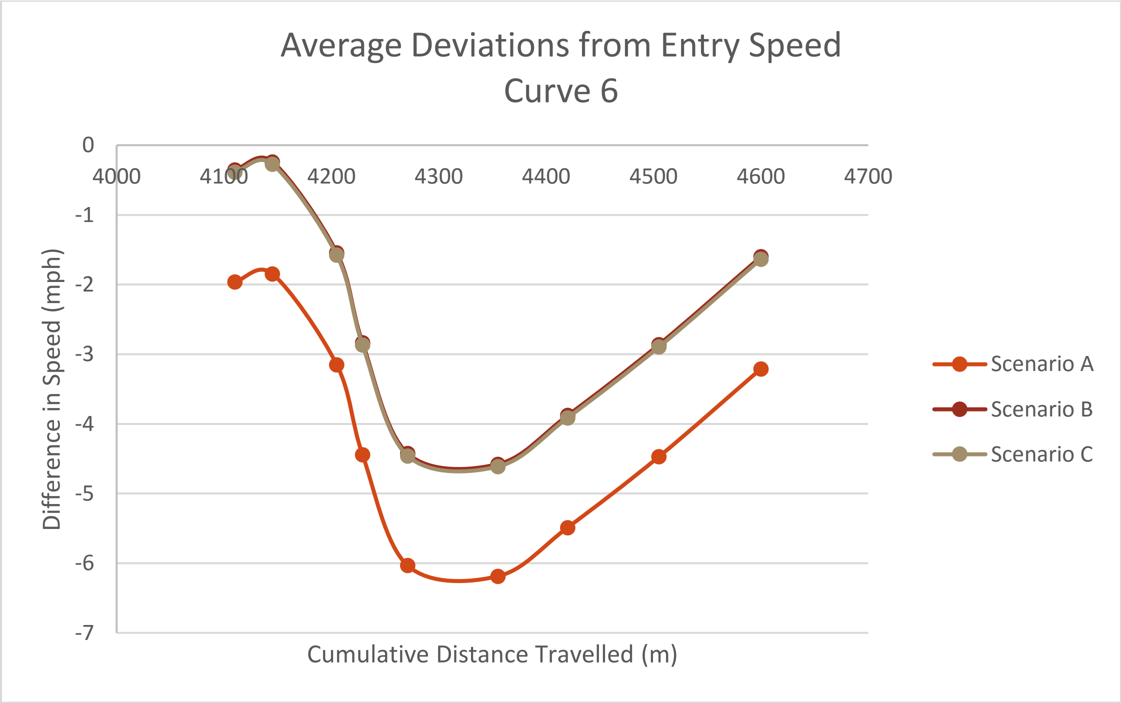

Figure B.10 – Average deviations from entry speed in Curve Zone 6.

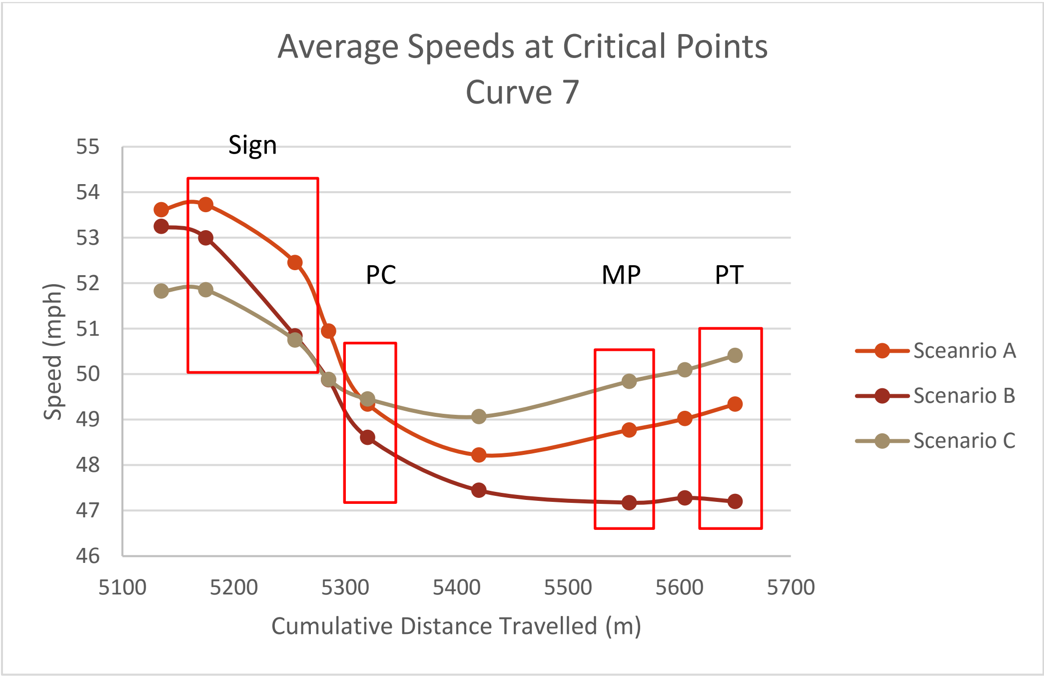

Figure B.11 – Average speeds in Curve 7.

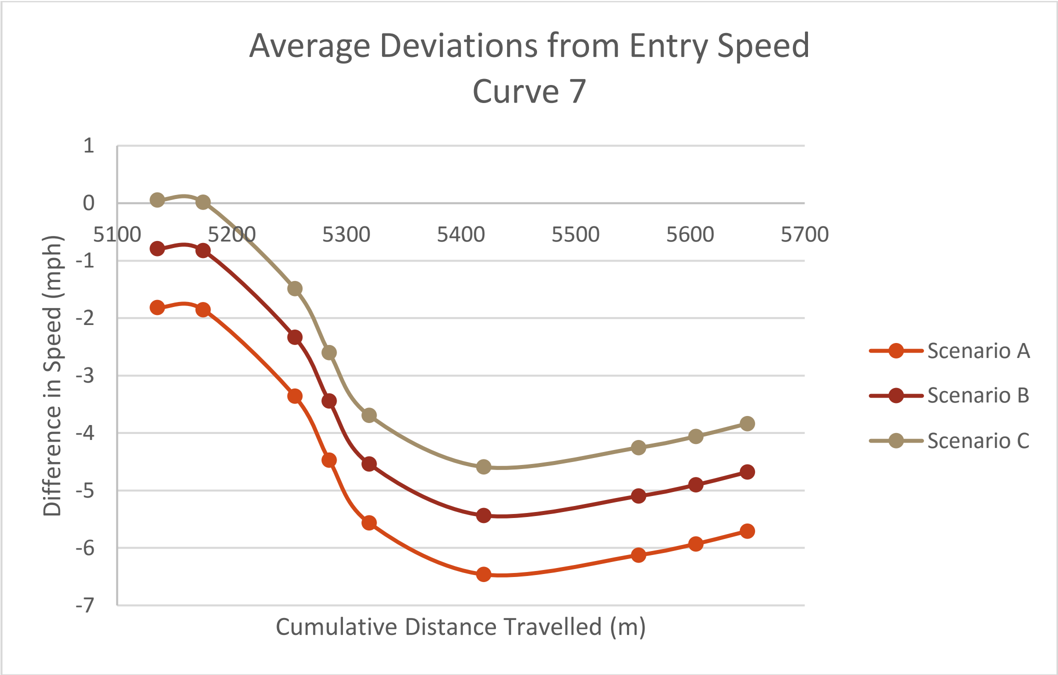

Figure B.12 – Average deviations from entry speed in Curve Zone 7.

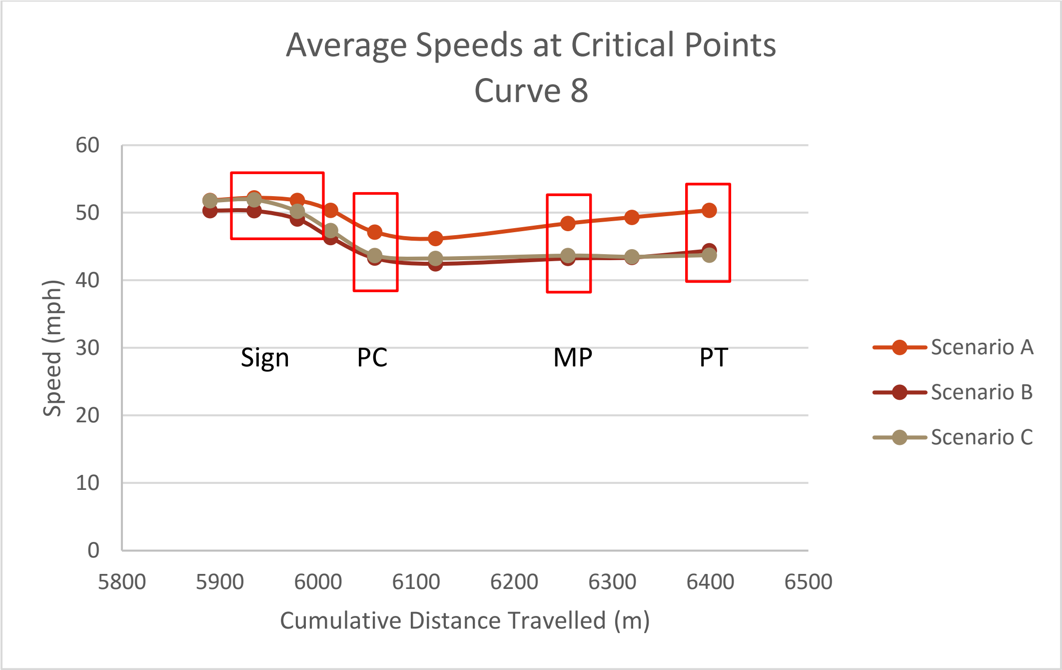

Figure B.13 – Average speeds in Curve 8.

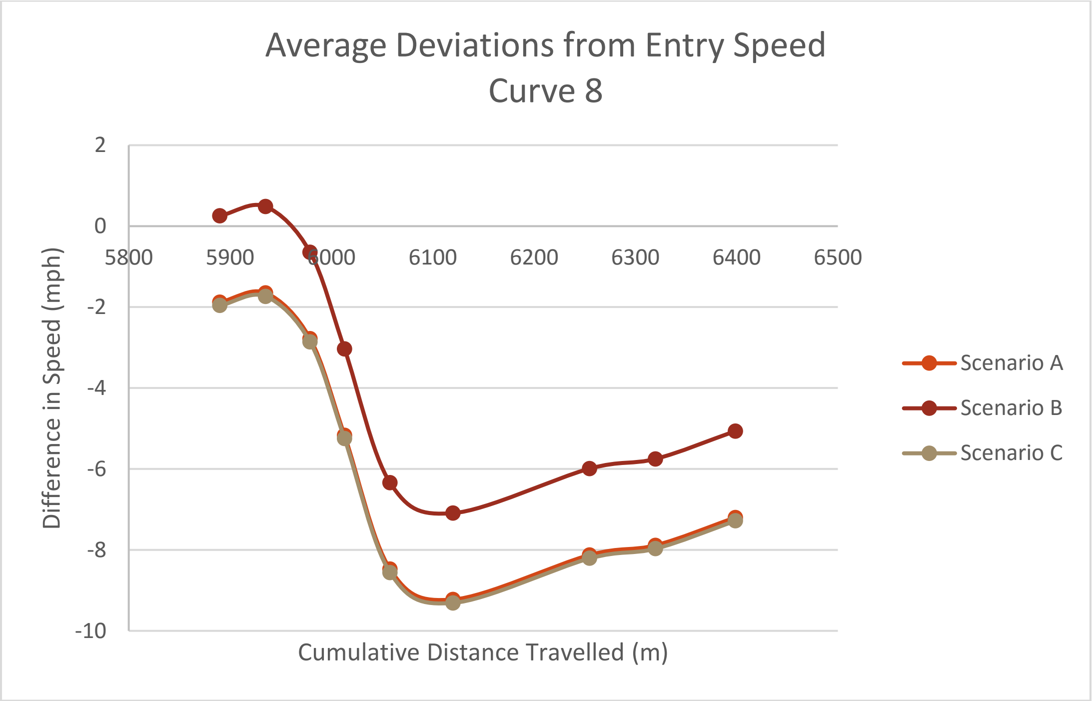

Figure B.14 – Average deviations from entry speed in Curve Zone 8.

Appendix C Standard Deviations from Average Speed

For curves within the 35 mph speed limit:

Table C.1 – Standard deviations from average speeds.

Standard Deviaitons from Average Speeds (mph)					
Scenario	Cruve	Sign	PC	Mid Point	PT
A	Curve 1	7.7	9.4	7.3	7.1
	Curve 2	7.2	8.1	7.2	6.0
	Curve 3	6.7	6.1	6.6	6.0
	Curve 4	5.8	6.7	5.6	5.4
B	Curve 1	4.1	5.0	4.2	4.3
	Curve 2	3.9	4.1	4.6	4.7
	Curve 3	3.4	3.7	3.8	4.0
	Curve 4	4.0	4.7	4.4	4.5
C	Curve 1	3.9	3.9	4.0	4.1
	Curve 2	3.9	3.9	4.0	4.0
	Curve 3	3.3	3.4	3.5	3.3
	Curve 4	2.6	2.8	3.4	3.7

For curves within the 55 mph speed limit:

Table C.2 – Standard deviations from average speeds.

Standard Deviations from Average Speeds (mph)					
Scenario	Curve	Sign	PC	MP	PT
A	Curve 5	9.1	6.6	7.1	7.4
	Curve 6	8.3	7.3	7.5	7.6
	Curve 7	8.0	6.7	6.6	6.9
	Curve 8	8.2	8.0	7.4	7.5
B	Curve 5	4.2	6.8	5.9	5.9
	Curve 6	4.2	6.3	5.5	5.3
	Curve 7	5.0	5.4	5.5	5.9
	Curve 8	5.9	6.5	5.9	6.4
C	Curve 5	4.1	5.9	5.4	5.6
	Curve 6	5.9	6.1	6.3	6.0
	Curve 7	6.8	6.4	6.0	6.5
	Curve 8	7.0	7.9	6.4	7.2

Appendix D P-Values for Curve Comparisons

Table D.1 – Curve 3 p-values.

P-values in Curve 3 Comparisons			
Scenario Comparison	A vs. B	A vs. C	B vs. C
Sign	0.0005856	0.002202	0.1231
PC	0.00169	0.02395	0.1429
MP	0.01069	0.06372	0.08254
PT	0.008308	0.06372	0.1327

Table D.2 – Curve 5 p-values.

P-values in Curve 5 Comparisons			
Scenario Comparison	A vs. B	A vs. C	B vs. C
Sign	0.029558	0.08255	0.08254
PC	0.004221	0.0004826	0.8408
MP	0.003153	0.0003948	0.6742
PT	0.00639	0.004221	0.6477

Table D.3 – Curve 7 p-values.

P-values in Curve 7 Comparisons			
Scenario Comparison	A vs. B	A vs. C	B vs. C
Sign	0.02958	0.4524	0.1213
PC	0.3884	0.6742	0.165
MP	0.1893	0.40009	0.02148

PT	0.1769	0.3118	0.01069