EXAMINING THE EFFECTS OF A SIGNLESS ROADWAY:

Virtual Traffic Control Devices and their Potential for Replacing Traditional Post-Mounted Traffic Control Devices

James G. Markosian

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EXECUTIVE SUMMARY

In recent years, there has been an ever-increasing demand for the integration of technology into vehicles. This demand comes from the expanding use and dependency on smart phones, in-vehicle entertainment, computers and the Internet, and the desire to create a "smart car" to optimize the productive use of travel time. As this expansion in in-vehicle technology continues, obvious concerns exist with the number of potential driver distractors added. Technology-based distractors have the potential to attract drivers' attention away from the driving environment and increase the probability of driver error. Nevertheless, technologies do provide the opportunity for integrating safety benefits, and it is necessary to consider how the availability of these technologies can enhance the safety of the driving task.

Traffic control devices (TCDs) provide the primary form of communication with drivers as they navigate the transportation network. Many common roadway scenarios, confounded by traffic congestion and distractors, can cause drivers to miss important TCDs, specifically post-mounted signage, and the information they convey. However, advanced in-vehicle technologies may allow for a more focused presentation of TCD information such that communication is optimized for the scenario being presented. In a recent study by the Federal Highway Administration (FHWA), elongated pavement markings (EPM) were considered as a supplement to enhance post-mounted regulatory and warning signage. 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. 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. Therefore, there is a need to determine if using in-vehicle technology to optimize the presentation of TCDs to drivers in the form of a head-up display (HUD) may lead to more effective driver communication demonstrated through TCD compliance and safer operating behavior. Furthermore, if HUDs are indeed the optimal way of presenting TCD information to drivers, a question can be explored pertaining to the future need of post mounted signs and other roadside placed TCDs.

Many studies have found in-vehicle displays using HUD to be an effective form of communicating information to drivers (7, 30, 31, 33, 35). These devices work well with various navigation and lane departure information, however, they have yet to explore the broad array of TCDs and their applications in regulating and warning drivers as they traverse the transportation network. Given these findings, the next step was taken in this research to examine the application of such in-vehicle technology by using a HUD in conjunction with TCDs to convey critical regulatory and warning information to drivers.

The objective of this research was to use HUD technology to explore presenting TCDs 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 TCDs. Twenty test subjects were recruited, ranging in age from 20-68 years old, to participate in a research experiment to evaluate a selected set of regulatory and warning sign applications. Subjects were asked to drive through three different scenarios in the full-scale driving simulator at the UW-Madison Traffic Operations and Safety Laboratory. Scenario A was a completely signless roadway environment, producing unrestricted free-flow driving and natural driving behavior without TCD communication. Scenario B was a traditionally signed roadway following the Manual on Uniform Traffic Control (MUTCD) guidance adding the appropriate sign elements of traffic control to the drive. Scenario C was a virtually signed roadway, using the capabilities of the driving simulator, in which virtual traffic control devices were displayed in the same manner that they would be in an external HUD device. No post-mounted signs were included in scenario C.

Average speeds were compared between critical points in eight curve segments (sign location, point of curvature, midpoint of the curve, and point of tangency) in an attempt to reveal the effectiveness of these virtual in-vehicle displays and their potential for replacing the traditional post-mounted roadside sign. While operating speeds were higher, on average, with virtual signage compared to post-mounted signage, statistically significant differences in speed were sparsely present. The results show that head-up displays could, in fact, be a viable option to safely and optimally replace traditional post-mounted TCD signage.

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In loving memory of:

Henry Markosian

Adam Colosimo

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1 INTRODUCTION

Since the beginning of the 21st century, there has been a massive boom in technology in the auto industry. Advancements have been demonstrated in fuel economy, alternative fuels and power modes for automobiles, and most recently, in self-driving vehicles. As the auto industry continues to drive down these technological avenues, the question remains, how will the outdated infrastructure catch up to the technological advancements that exist in the vehicles using it? In-vehicle display technologies such as head-up displays (HUDs) offer an obvious transition. Along with their current use for mostly navigation purposes, HUD offers an outlet through which more critically important information could be presented to drivers.

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 traffic control devices (TCD). TCD include post-mounted signs, pavement markings, traffic signals, and various geometric features of the roadway. TCD convey regulatory, guidance, and warning information to roadway users and act as an important tool for traffic engineers to communicate with drivers (2). Common post-mounted TCD can be seen in Figure 1 below.

Figure 1: Common Post-Mounted Traffic Control Devices (3)

Guidance and warning information and the means by which to present it have long been a topic for researchers across the country and 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 most vehicle manufacturers have developed and are now selling products that convey navigation information and environmental warnings (lane departure warnings, early collision avoidance, and automated cruise control) to drivers via a HUD (4, 5, 6). These applications of in-vehicle technology all aim at improving safety while driving and doing so in a hands-free way. This allows the driver to keep their attention and focus on the road ahead and free from having to manipulate handheld devices and in-dash controls in order to get the information that they require.

Previous research sheds light on the fact that HUD can be very effective communicative tools for drivers, especially when in a complex roadway environment (7). HUD has been used in the aviation industry for many years, so it is reasonable to believe that the same type of technology, used in the driving context, could assist drivers just like it assists pilots. However, as the roadway and surrounding environment becomes more

complex, there tends to be a disparity when it comes to seeing post-mounted signs (8). This disparity, known as visual clutter, leads to the increased potential for drivers to miss important regulatory, warning, or guidance information as they navigate these complex segments of road. As can be seen in Figure 2, the abundance of commercial signs and vehicles present on the roadway can easily lead drivers to miss the regulatory speed limit sign that is present in this roadway segment.

Figure 2: Visual Clutter in Fresno, California (9)

Previous research has shown that post-mounted signs have a low registration rate among drivers, depending on the sign type (8). Additionally, in a study by the Federal Highway Administration (FHWA), elongated pavement markings (EPM) were explored as a supplement to critical post-mounted TCD information. 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. 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 (). With the advances in technology and the continual use and production of HUD by independent 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 sign use.

1.1 Objectives

The primary objective of this research was to study the effectiveness of in-vehicle HUD displays for communicating existing TCD information to drivers. . Specifically, this research examines driver compliance with MUTCD regulatory and warning signs including speed limit signs (R2-1), horizontal alignment warning signs (W1-2 & W1-2a), and pedestrian crossing signs (W11-2). It is desired to determine if information being presented in a non-traditional way (through the use of HUD) can compare to traditional displays (post-mounted) by the way that drivers operate and react to that information presented in the driving environment.

1.2 Organization

This report consists of five chapters, references and an appendix. Chapter 1 comprises on 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, Chapter 7 is an appendix containing figures and tables relevant to the data and data collection, as well as additional information regarding the research. The figures and tables in the appendix will be referenced in the main body of this report where relevant.

2 LITERATURE REVIEW

2.1 Traffic Control Devices

Traffic control devices (TCD) 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 represent 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 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 the drivers, each TCD must contribute the drivers' expectancy that the information presented is critical and important at the time/place that it is seen.

TCD are regulated by the *Manual on Uniform Traffic Control Devices* (MUTCD). TCD 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 (i.e., Montana, Florida, New Jersey), a combination of the MUTCD and their own individual regulations (i.e., Wisconsin, Colorado, New York), or their own specific adaptation of the MUTCD for use in that particular state (i.e., 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 (Hankey reference). 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 into 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 (14).

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 ITS (intelligent transportation systems) applications (i.e., automated cruise control, navigation systems, collision warning systems, etc…) (15). The three error taxonomies are Norman's

(1981) error categorization, Reason's (1990) slips, lapses, mistakes and violations classification, and Rasmussen's (1986) skill, rule, and knowledge error classification. These three theories for human error relate to the prediction of making some type of error or violation while completing a task, either intentional or unintentional. 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 assigned various ITS applications that would help remediate errors or eliminate them.

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 actually 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, a race or impatience with slower drivers, for example (16).

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 (16). 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 or influence of 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, traffic control devices, 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 (17). Four categories were considered when performing the analyses; alignment, cross section, roadside, and traffic control device. The study found that drivers were more likely to slow down, not only because of the radius of horizontal curves, but by 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 type. Access density and roadside development caused drivers to slow most significantly when looking at roadside characteristics. Posted speed limit proved to be the most significant traffic control device. 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 (18). Further, Endsley points out that the operator of a vehicle, for example, must do more than perceive the state of their environment, but 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 makes 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. describes 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 (19). This definition relates to the nature of situation awareness during complex systems/tasks. Driving can easily be defined as

a complex system including controlling the vehicle, navigation, interpreting and addressing gauge readings, 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 requires extra mental effort. This lack of attention is attributed as one of the main factors in traffic accidents and crashes (20). As Gugerty suggests, keeping track of dynamic and changing situations is a key element of real-time tasks like driving (21). 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 conducted for the correlation between detection distance and visual noise, it was found 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 drivers 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. In-vehicle systems have become increasingly popular as technology advances. Eyesenck defines attention as the human's ability to focus on certain objects and allocate processing resources accordingly (22). 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 with 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 (23). Intention and experience relates giving higher priority to objects, which are more familiar or interesting to a person. Evaluation of demands is the concept that a person would determine what processes or objects need the most attention based on available capacity.

Attention, or lack-there-of, 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 have been introduced, studies show that the allocation of attention to these secondary tasks (e.g., talking on the phone, using 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 (24). 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 become intensified (25).

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 (26).

Within industrial engineering and human factors lie activities like aviation and driving that are both 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 (27). Chapman and Underwood further state that eye-movement and tracking allows for understanding in 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 (28). So, as diving behavior is studied, it becomes important to look at the eye of the driver to collect information about how the driver responds to different situations on or off the road. 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 (phone call with 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 a driver is 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

There are several different applications of in-vehicle displays that 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 virtual or augmented reality displays (AR). While many vehicles today are equipped with each of these technologies, there is much research done pertaining to their various applications. A deeper investigation on their uses and applications can be helpful when determining the correct use in the current study.

HDD are basically stock options in most production vehicles today. These HDD are often referred to as infotainment systems because they are capable of bring internet connectivity in to 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).

HUD 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 HUD production, offering HUD for BMW, Mercedes Benz, and Audi models (29). The concept of the HUD is the same as the HDD, however the information is presented to the driver on the windshield directly in the line of sight. HUD can portray dashboard data such as speedometer or odometer data as well as navigation aids. Another advantage of most HUD systems is the capability to display the speed limit on the specific section of road so the driver always knows how fast they are allowed to drive. These safety features, as well as the convenience they accommodate drivers is a major reason for many vehicle manufacturers including this technology in their vehicles.

Further advancements to the traditional HUD lead towards AR displays that facilitate features like land departure warnings, automated curies 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 (30). Vehicle manufacturers like Chevrolet have included these systems into its vehicles (31), but the AR displays are mostly seen in the luxury brands like the ones stated above.

The ever-growing presence of this technology and different useful applications has led to research being done using most of, if not all 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 (32). The research team used 60 participants in their 2 (drive: display system off and display system on) X 3 (condition: IVS on plus navigation, navigation only) mixed-model design, where drive was a within-subjects situation (counterbalanced) while condition was between subjects. The 60 participants were assigned to one of the three different conditions (3 groups of 20, 19, 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 from MUTCD standards, using posted speed limits and distances as the measure for when and where to display the information.

With the goal of the study to identify if drivers were better able to comply with speed limits when IVS information was present, it was seen that that drivers were prepared to adopt the changes to speed limits before entering a zone and in most cases complied with the speed limits in those zones regardless of the IVS information being there or not. 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 review 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 was 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 Linda Boyle and Fred Mannering, the effects of driving behavior using in-vehicle and out-of-vehicle traffic advisory systems was examined using a driving simulator (33). 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 for at least 12 drivers in each of the four cases. 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 sped and the standard deviation speed. It was also found that once the warning sign had either passed or become out of range, then 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 augmented reality cues (AR) in order to assist elderly drivers with various levels of cognitive impairments (34). 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 (35). 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 where the un-cued scenarios offered no aid to drivers.

Based on the results from this research, it is clear that AR cuing 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 with 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 cuing be noted while using a scene

that offers a more difficult cognitive environment (urban with heavy/constant on-coming traffic) (34).

In a similar study, Rusch and Schall examined their AR cuing 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 to be more favorable in attracting the driver's attention. Drivers became more attentive, responding to 1-2 more targets in all scenarios after the first un-cued scenario they drove through. The time to target (TTT), a measure of reaction time, provided evidence that AR cues were reducing response time for identifying targets. AR cues may lead to improving driver safety, reducing response time and increasing detection of roadway hazards (36).

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 (37). In this test, there were four possible scenarios that drivers faced; one, no HUD was used, two, a warning sign was displayed when the drivers speed exceeded the speed limit, three, a numeric warning was displayed at all times showing the drivers speed and the speed limit (eg. 43/45 in mph), four, a graphical representation clearly showing the drivers 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 from 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. EPM have been shown to significantly improved 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.

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. 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 (38).

2.9 Literature Review Summary

Through an extensive literature review, it was seen that HUDs offer an undoubtedly effective means to 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 if HUD and other in-vehicle technologies to 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 HUD 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 (39). 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 modelling 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 Figure 3 - Figure 5, consists of a full size Ford Focus body mounted on a 1-degree of freedom motion platform. This 1-degree of freedom refers to the ability for 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: UW – Madison TOPS Lab Driving Simulator (40)

To display the virtual environments, five front-facing projectors, one rear-facing projector, and 2 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 4. 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 4: Projectors Responsible for Producing the Driving Environment (40)

Figure 5: Ford Fusion Mounted on 1-Degree of Freedom Motion Platform (40)

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 vehicle at a refresh rate of 60Hz. Similarly, driver actions such as steering, braking, and accelerating behavior can also be monitored at 60Hz.

3.2 Basic 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 effects 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. 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 1, including the values described above.

Table 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 Manual of Uniform Traffic Control Devices (MUTCD) standards as laid out below in Table 2 (11). With posted speeds of 35 and 55 mph, the minimum distance was taken from Condition B in Table 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 point of curvature (PC) of the specific horizontal curve.

Table 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 design (posted) speed of 35 mph, a spacing of roughly 120 feet was used. For curves with 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.

Table 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 55mph, respectively, normal cross-section and a maximum super-elevation, as seen in. Using values from Table 1 for curve radius, the centerline and cross-section of the roadway was drawn in AutoCAD 2015, as seen in Figure 6.

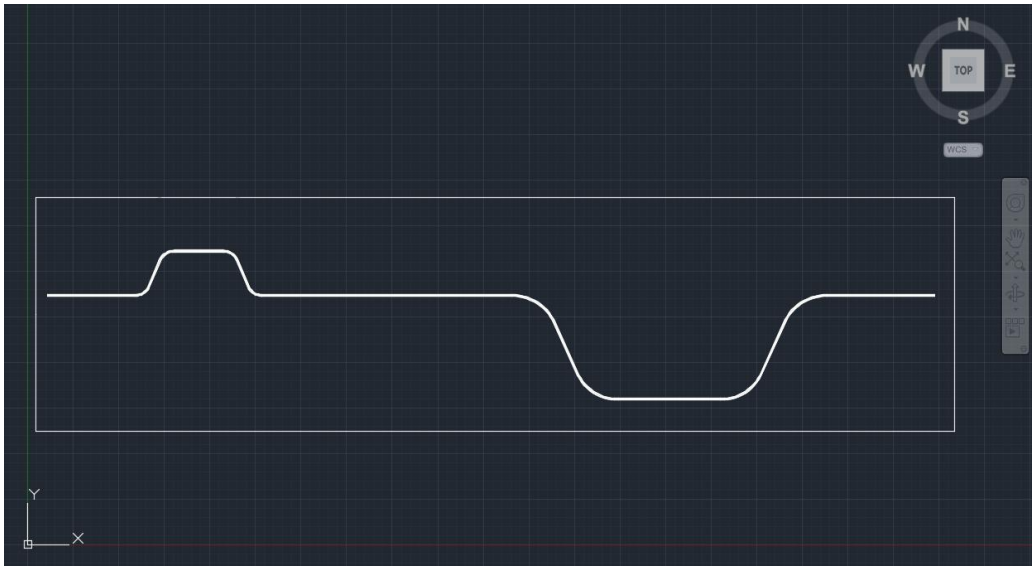


Figure 6: AutoCAD Centerline used for Scenario Creation

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 7 exhibits the 3D editing done in Blender.

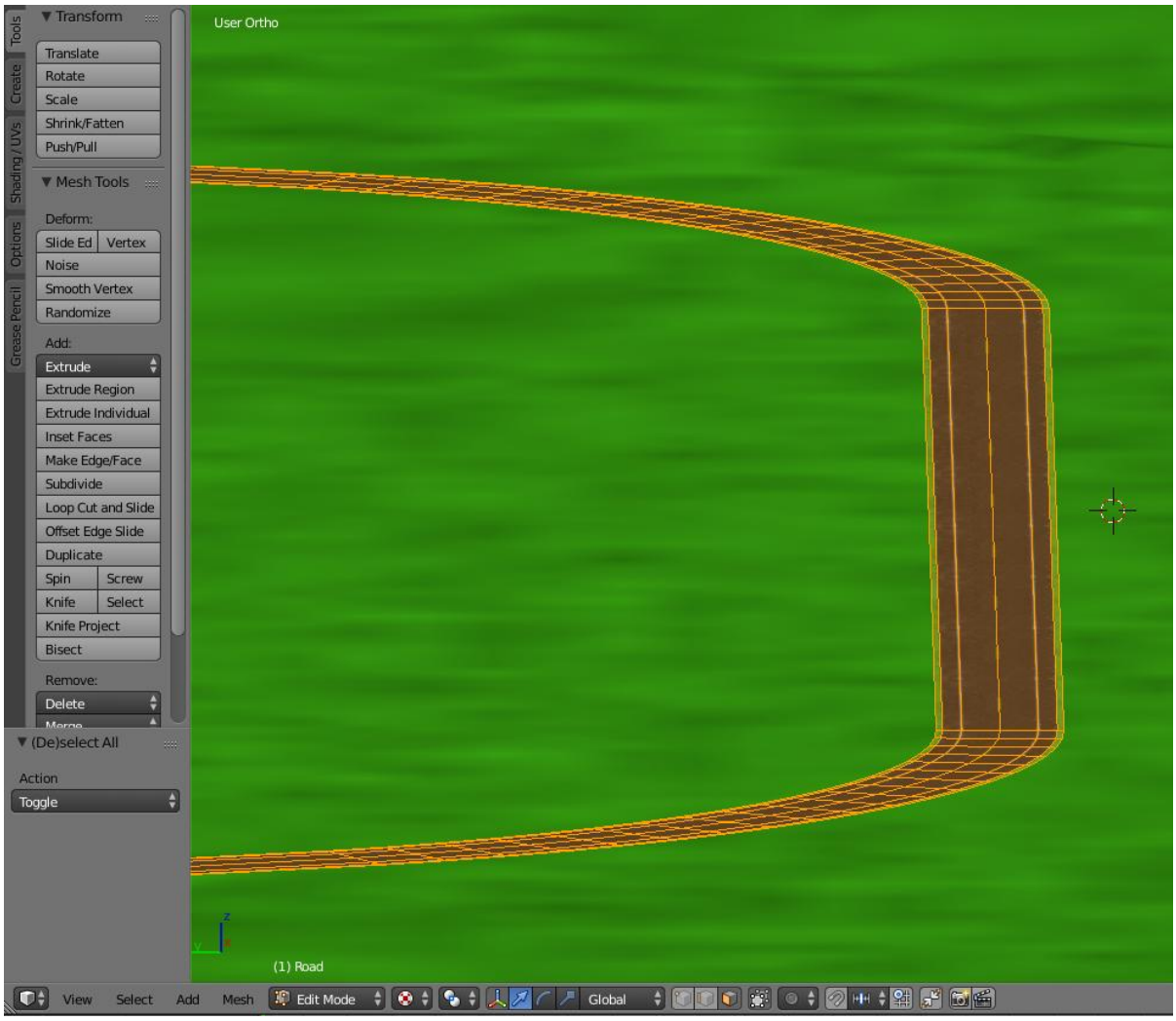


Figure 7: 3D Modeling in Blender for a Pair of Curves

To comply with 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 8 shows an example of the landscaping and sign placement using ISA.

Figure 8: Scenario Creation in ISA for a Curve Segment

3.4 Experimental Design

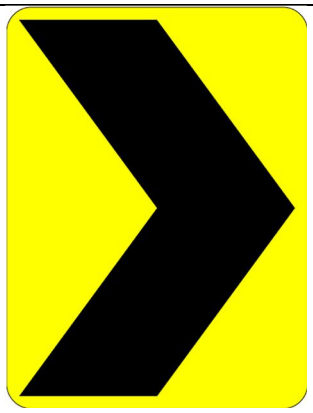
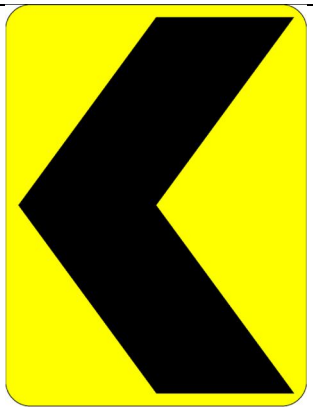
This experiment consists of three geometrically identical scenarios. Within the first scenario (Scenario A), there were no TCD or any additional signage only the roadway geometry and proper lane line markings. Scenario A was intended to serve as a baseline for determining how a driver would behave on a signless roadway. The second scenario (Scenario B) contained the identical geometry of Scenario A, however, was been fitted with the appropriate TCD. The TCD signage included can be seen in Table 4

, below. This signage offered a variety of regulatory and warning information and was selected because they are 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 a holographic Head-Up Display.

Table 4: Standard MUTCD Signage Contained Within Scenarios B and C (41 & 42).

SIGN	**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 the horizontal alignment of the roadway is moving towards the right. Installed at right-hand curves.
 W1 – 8L	Chevron alignment denoting 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 9. 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 9 only represents the end of the scenario where the subjects were prompted to stop the vehicle.

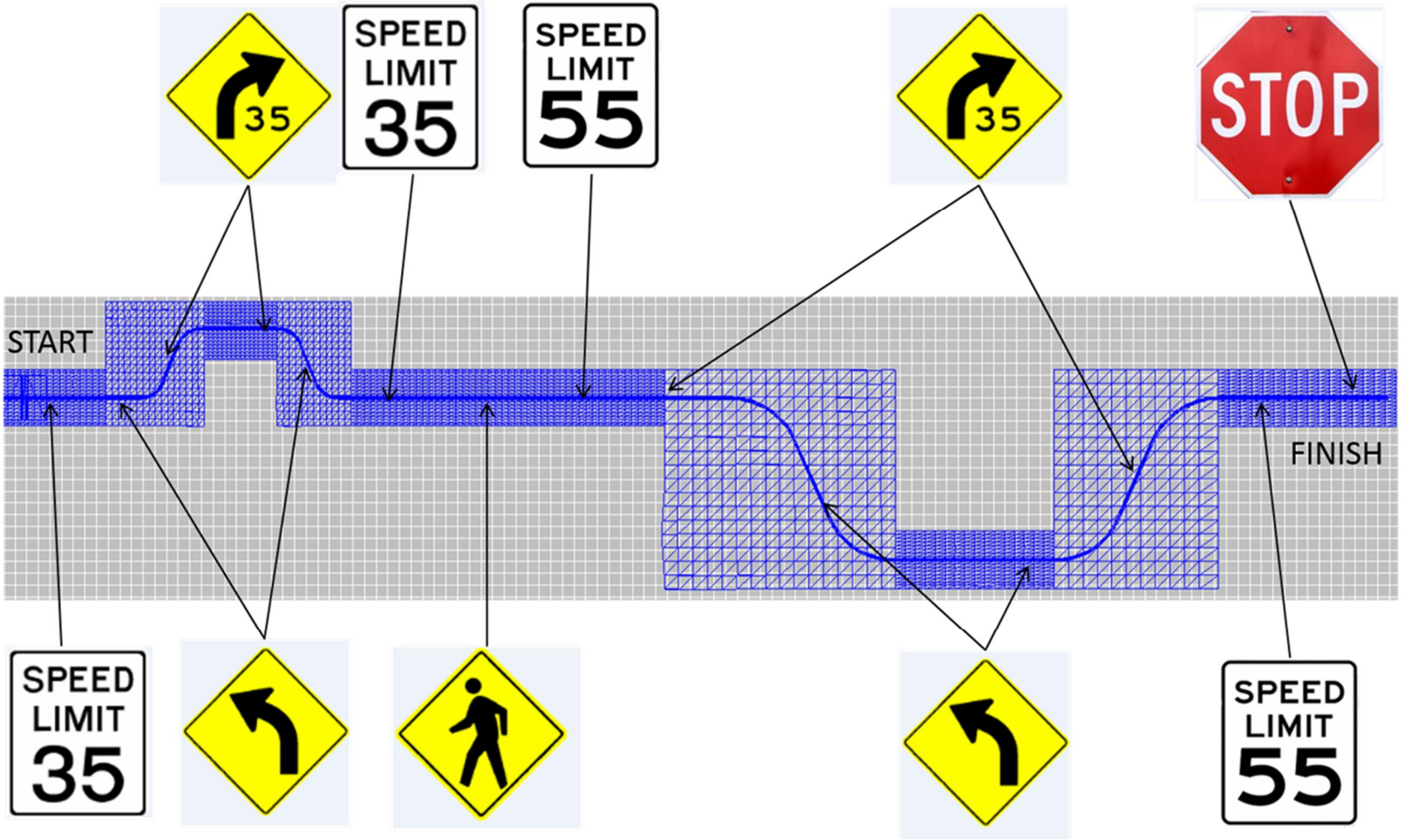


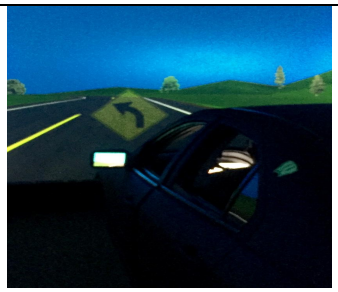
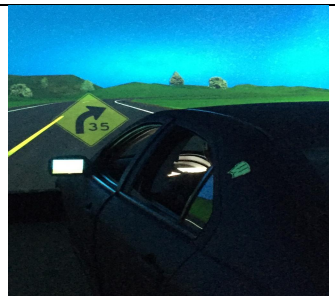
Figure 9: Sign Placement for Scenario B & C

Post location for warning signs in the traditional post-mounted scenario followed MUTCD standards as laid out in Table 2. With posted speeds of 35 and 55 mph, the minimum distance was taken from Condition B in Table 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 point of curvature (PC) of the specific horizontal curve.

The manner in which signs are displayed in Scenario C are 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 differing physiological traits of each subject). The image appears as it is seen in Table 4, but with a slight transparency and directly in the driver's line of sight, examples can be seen in Table 5. This was done in lieu of using external hardware HUD 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 (32, 34, 35, 43).

Table 5: Examples of Scenario C Signage

VIRTUAL DISPLAY	DESCRIPTION
	35 mph Speed Limit sign following MUTCD R2-1 formatting
	55mph 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 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 10, the chevrons do not follow the typical W1 – 8 layout from Table 3.

Figure 10: 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 in 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 5 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 5 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

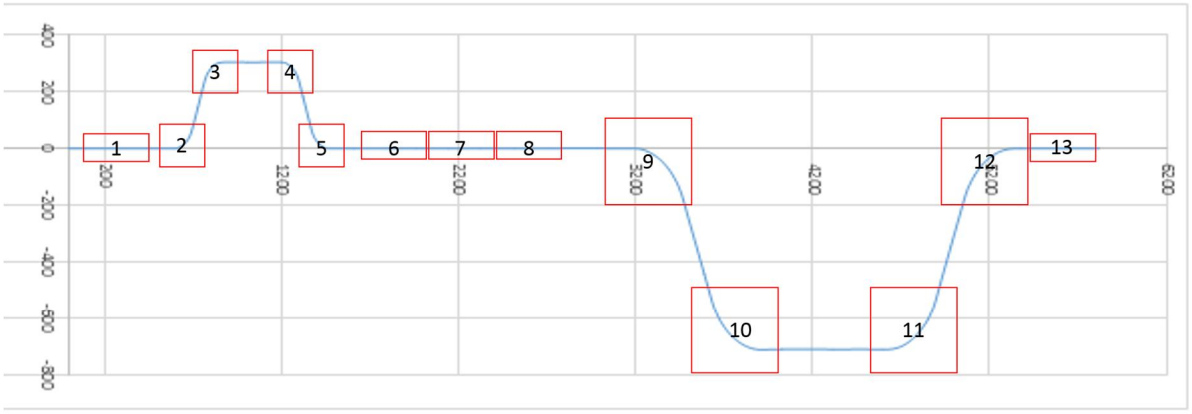
As mentioned in the previous section, 13 analysis zones were created to sort the data. Each zone corresponds to a specific feature of the scenario and are defined by X, Y position in the roadway environment. Table 6 defines the 13 zones. Within each zone, data was extracted from each simulator run and included speed readings, simulation run time, cumulative distance travelled, and vehicle trajectory.

Table 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 6 can be seen in Figure 11: Data Analysis ZonesFigure 11. These zones are uniform across all three test scenarios, meaning 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, assumed speed the driver would be travelling at the specific point (speed limit), and capturing the critical points of each analysis feature, such as the PC, midpoint, and PT of horizontal curves.



1) Speed Zone 1
2) Curve Zone 1
3) Curve Zone 2
4) Curve Zone 3
5) Curve Zone 4
6) Speed Zone 2
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 11: Data Analysis Zones

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 their driving behavior when presented with different roadway environments.

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 $\alpha = 0.05$. 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.

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

Where: N_r is the reduced sample size, x is the average speed form both comparisons, R_i is 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 Figure 14 through Figure 26 in section 7.1 of the appendix. 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 in 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 there was 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.

Table 7: 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

Average speeds and changes in speeds in Scenario A were visibly greater than either of the other scenarios. Figure 12 and Figure 13 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 the 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 either Scenario B or C. Standard deviations from average speed can be found in appendix section 7.3.

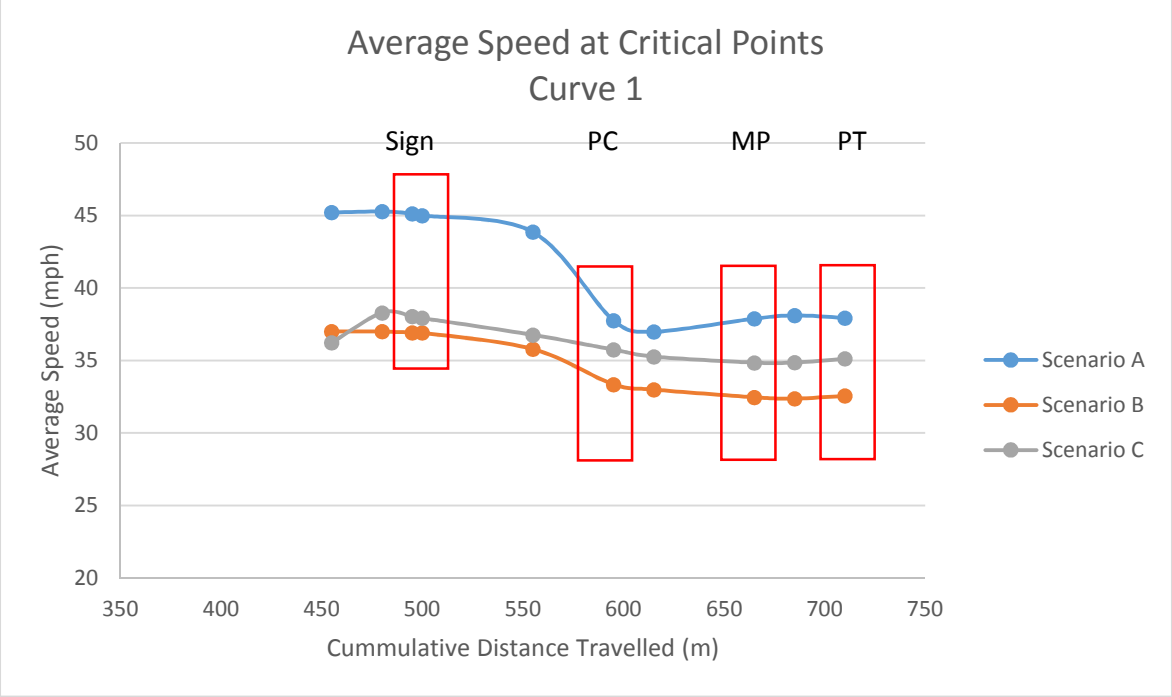


Figure 12: Average Speed in Curve 1

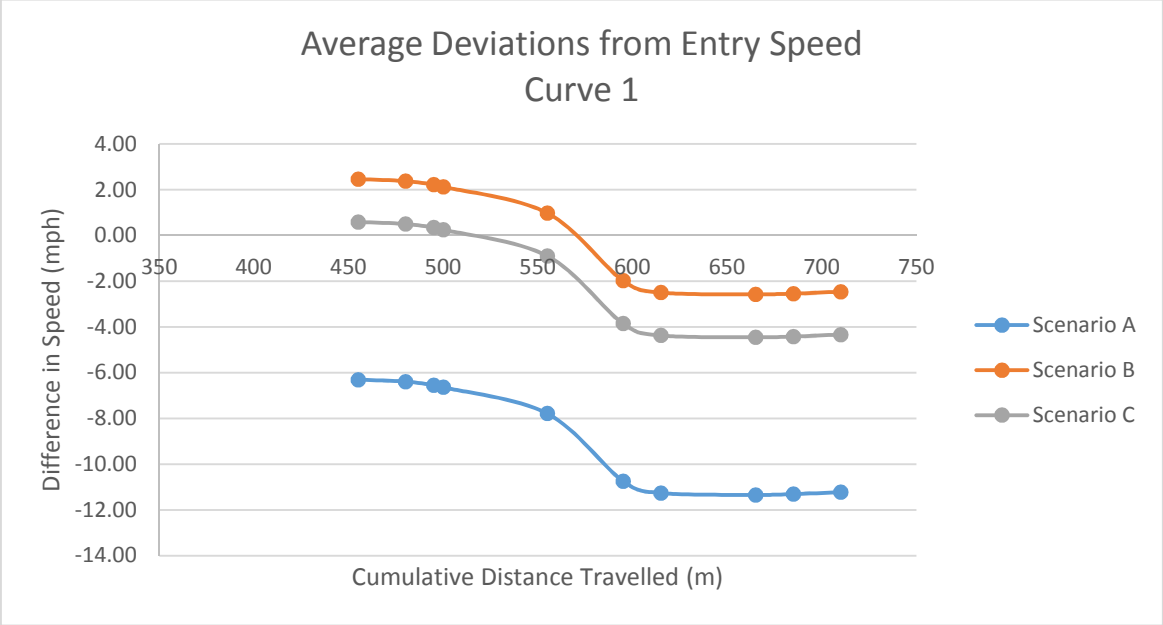


Figure 13: Average Deviations from Entry Speed in Curve Zone 1

Figure 13, above, 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 with drivers operating at higher speeds in Scenario A.

The comparisons for the remainder of the curves can be found in section 7.2 of the Appendix. These results indicate that drivers are behaving 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), Point of Curvature (PC), Midpoint of the curve (MP), and the Point of Tangency (PT), there was no statistically significant difference in the average speed at any of these points when Scenarios B and C are compared against each other.

At Curve 1, average speeds in Scenario A are significantly different from the average speeds in B and C. Comparing Scenario B and Scenario C, found statistically significant differences in average speed at both MP and PT of the curve. These differences can be seen in Table 8 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 show that drivers are operating at a higher speed through the entire curve, but as driver 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 8: 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 towards Scenario B and Scenario C having no significant differences in average speeds. As seen in Table 9 below, 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 9: 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, Scenario B and Scenario C are not found to be significantly different at any of the critical points within the curve. This was expected from observing the average speeds

profiles where Scenario B and Scenario C are almost overlaid atop one another. P-values for the comparisons made for Curve 3 can be found in appendix 7.3.

While this behavior was observed for Curve 3, Curve 4 had almost the opposite effect. Displayed in Table 10, Scenario A and Scenario C showed significant differences only at the sign location where Scenario B and Scenario C were found to have no significant difference. These results can again be attributed to the average speed profile in Scenario A and Scenario C exhibiting near identical average speeds at the remainder of the critical points.

Table 10: 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 Scenario B and Scenario C are not significantly different at any of these critical points. While Curve 5 showed significant differences between A vs. B and A vs. 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 11. 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 11: 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 scenario A and scenario C, average speeds increased upon the exit of the curve at the PT. This led to scenario B and scenario 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 scenario B or C at PC, MP, or PT. The comparisons can be seen in Table 12 below. However, the average speeds at the sign location were nearly identical for scenario A and scenario C causing a significant difference when Scenario B and C were compared at this location.

Table 12: 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

4.4 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, where 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 post 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 Curve 6 and 7, there were very few significant difference 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 phenomena that became apparent by the data is the similarity in behavior between the different curve geometries. A pairing was seen between Curve 1 and 4,

Curve 2 and 3, Curve 5 and 8, and Curve 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 paring 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 no the roadway. Scenario C start out as if there are no signs on the road, but by presenting them 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 Scenario C from Scenario 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 to believe that drivers could have felt more comfortable to proceed 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.

5 CONCLUSIONS

Traffic control devices (TCDs) provide the primary form of communication with drivers as they navigate the transportation network. Many common roadway scenarios, confounded by traffic congestion and distractors, can cause drivers to miss important TCDs, specifically post-mounted signage, and the information they convey. However, advanced in-vehicle technologies may allow for a more focused presentation of TCD information such that communication is optimized for the scenario being presented.

Many studies have found in-vehicle displays using HUD to be an effective form of communicating information to drivers (7, 30, 31, 33, 35). These devices work well with various navigation and lane departure information, however, they have yet to explore the broad array of TCDs and their applications in regulating and warning drivers as they traverse the transportation network. Given these findings, the next step was taken in this research to examine the application of such in-vehicle technology by using a HUD in conjunction with TCDs to convey critical regulatory and warning information to drivers.

Through this small sample study, 20 subjects were asked to drive three different scenarios in the UW-Madison full size driving simulator. These scenarios took into account three roadway conditions; the signless roadway, the traditionally signed roadway, and the virtually signed roadway. Where virtual signage conveyed the same TCD information that the traditional, post-mounted, signs did. From the analysis of the average speeds at critical points in the eight curves within the simulated drive, it is reasonable to conclude that the virtual TCD signage could produce driving behaviors that are similar to those displayed in a traditionally signed environment. With the objective of this research to determine if virtual,

in-vehicle, displayed TCD could replace the post-mounted sign, significance testing showed that, in fact, the virtual signage could produce behaviors similar to the post-mounted signage, meaning that it is conceivable to assume they could act as a surrogate, and perhaps a future replacement for the post-mounted TCD.

5.1 Future Research

Throughout the process of this research, some important future studies could be considered. The first candidate for future work would come from the results of the Pedestrian Zone data. As can be seen in Figure 22 in appendix section 7.1, the speed profile of most drivers remained relatively constant throughout the duration of the pedestrian zone which included a trail crossing and the potential for pedestrian activity. Although there were no pedestrians present, two subjects displayed drastically different behaviors than the others. This behavior came in Scenario C, when the drivers were presented with the pedestrian traffic warning sign via the virtual display. At the time the sign was presented, these two subjects both exercised a heavy braking maneuver decreasing their speed by more than 50%. This is cause for some 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.

The second candidate for future work involves eye-tracking data that was taken in conjunction with this study. Due to time constraints, the eye tracking data analysis was not included in this thesis. However, from this eye-tracking data, more validity could be assigned to the initial conclusion that the virtual signage could replace the post-mounted signage. By examining the eye-tracker, gaze and glance durations could be assessed between

the two methods of TCD presentation to show if the virtual signage keeps the driver's visual attention on the roadway as opposed to searching for TCD information on the side of the road in a traditional roadway environment. This could lead to a safety argument validation that the HUD-type TCD display could lead to safer driving.

A third item that could be considered for future work would be the dynamic display of the chevron alignment warnings along the centerline of the roadway. Using this technology, many applications could be created for delineation purposes or to advance lane-departure systems. By tracing the centerline (or lane-lines) researchers could provide aid to drivers in scenarios where there is poor stopping sight distance, obstacle sight distance, low-light conditions, blind corners/driveways, etc… and create a source for increasing safety in these circumstances.

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7 APPENDIX

7.1 Speed Profiles

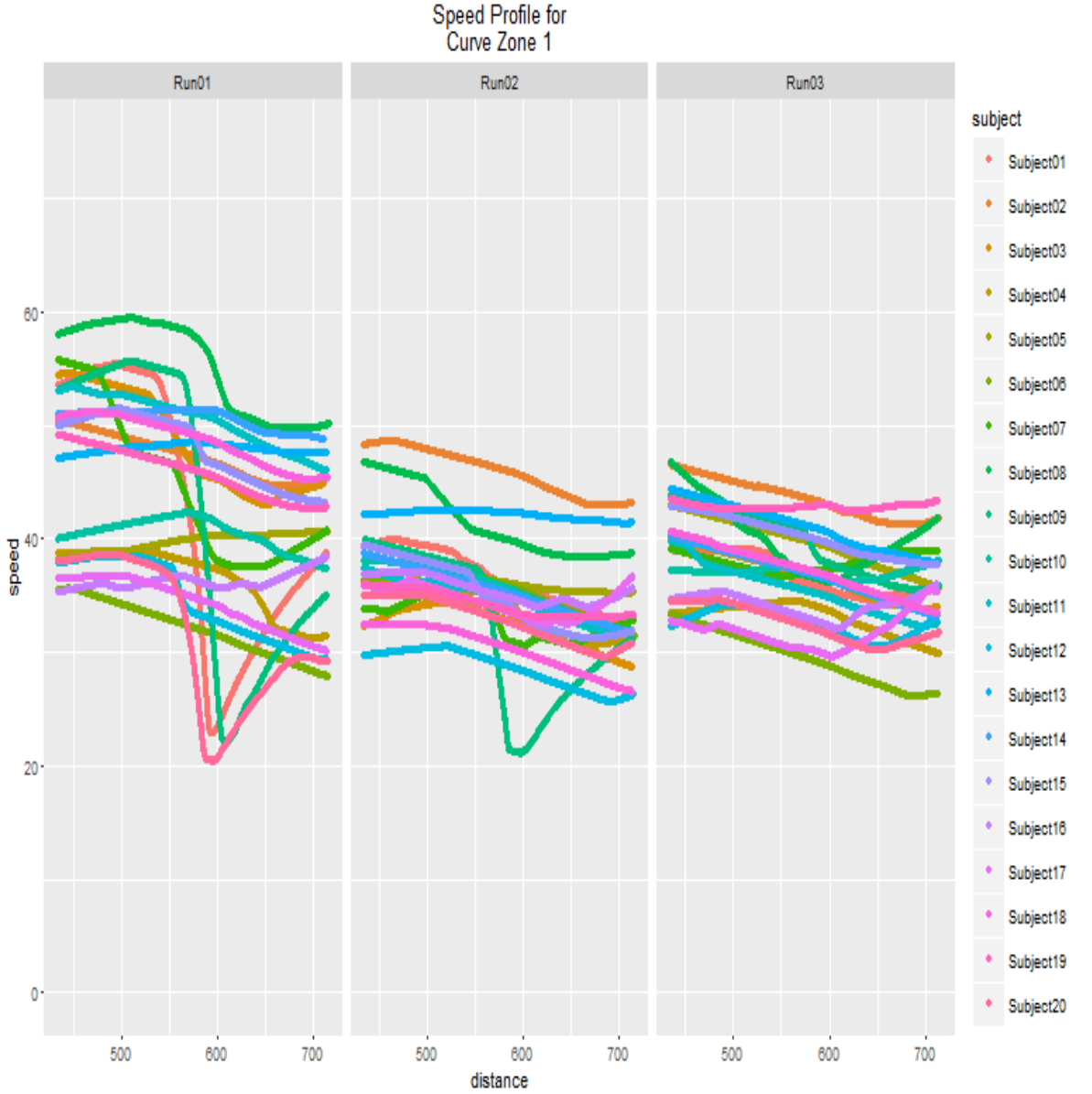

Figure 14: Speed Profiles in Curve Zone 1

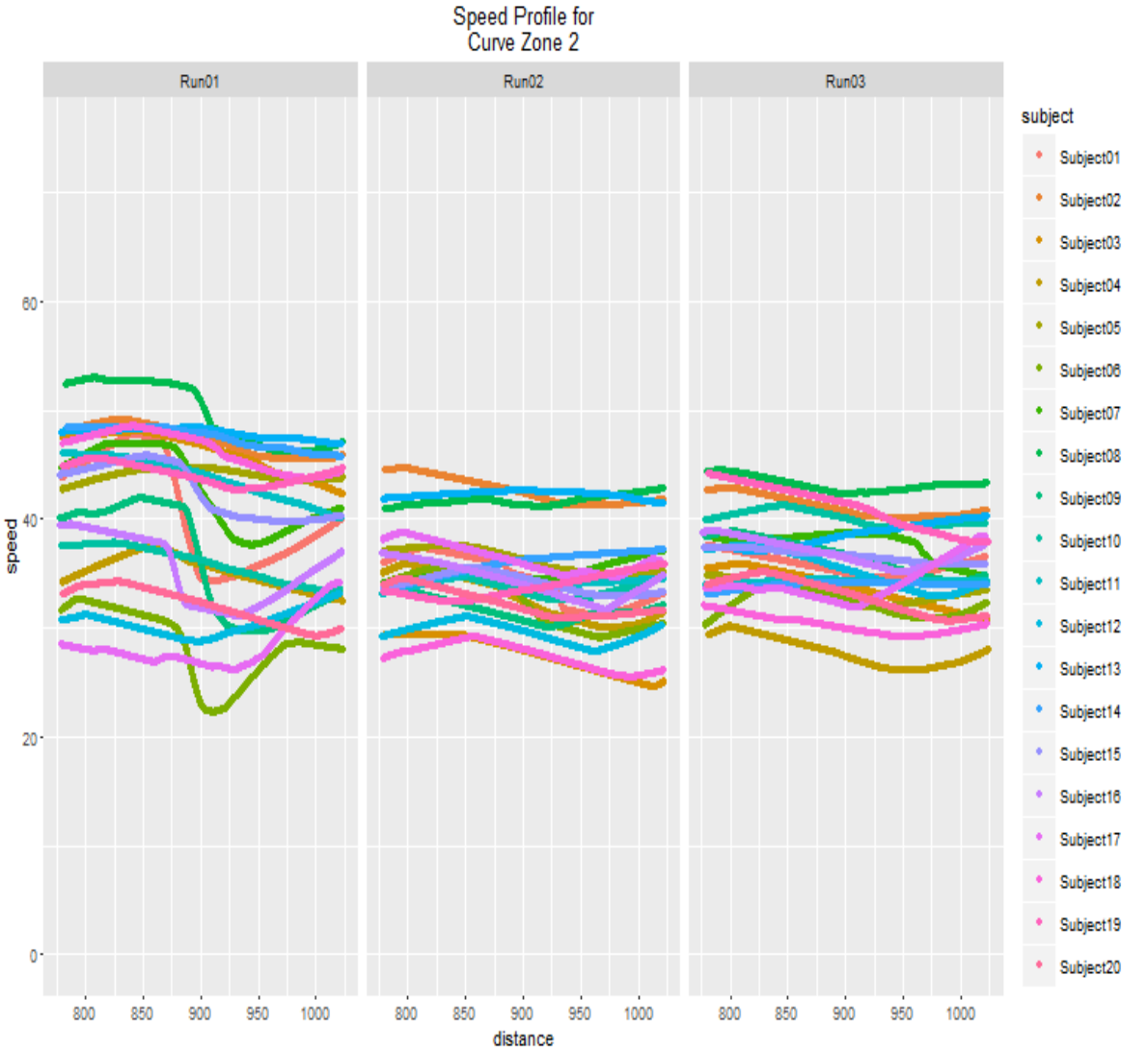

Figure 15: Speed Profiles for Curve Zone 2

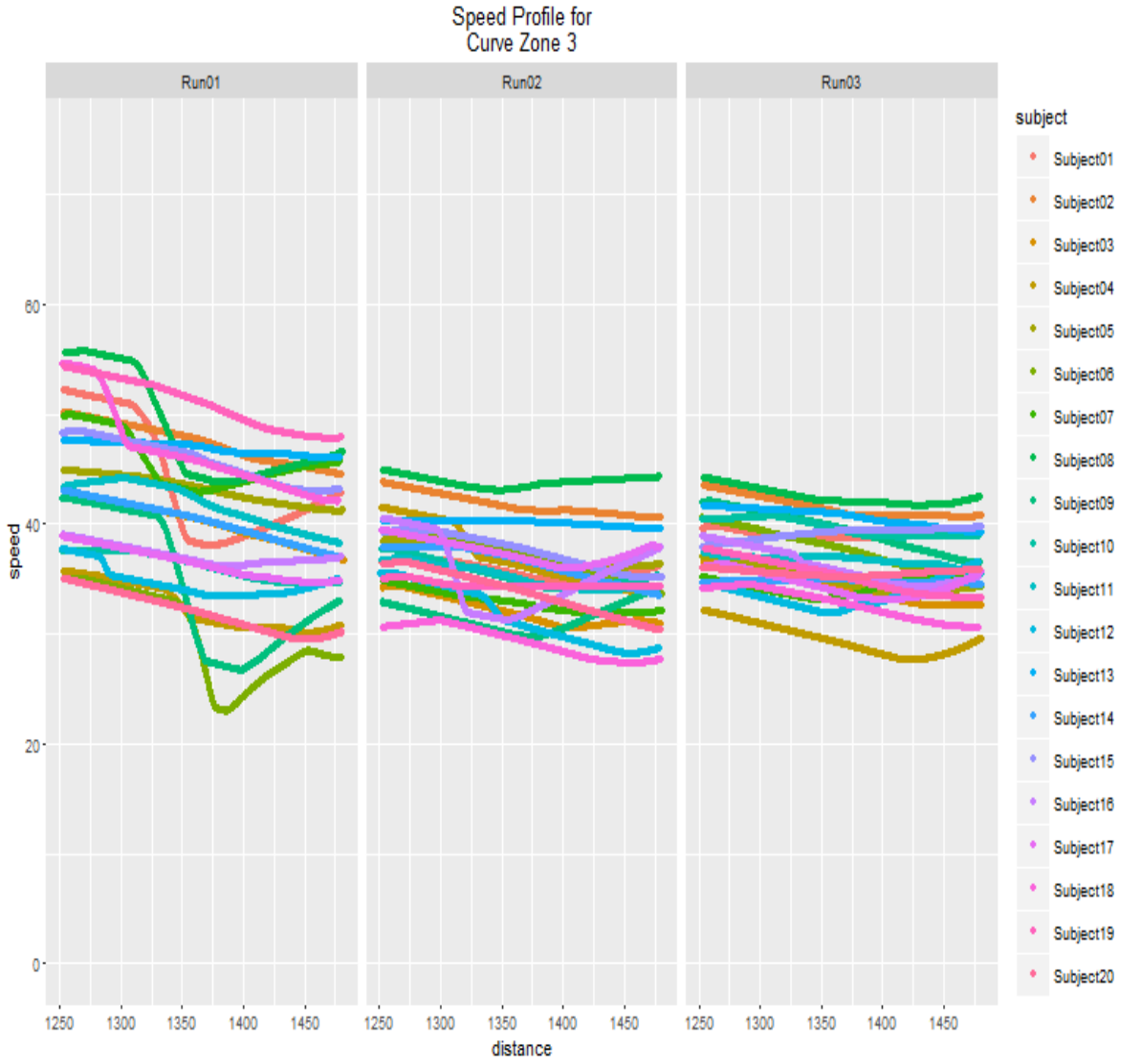

Figure 16: Speed Profiles for Curve Zone 3

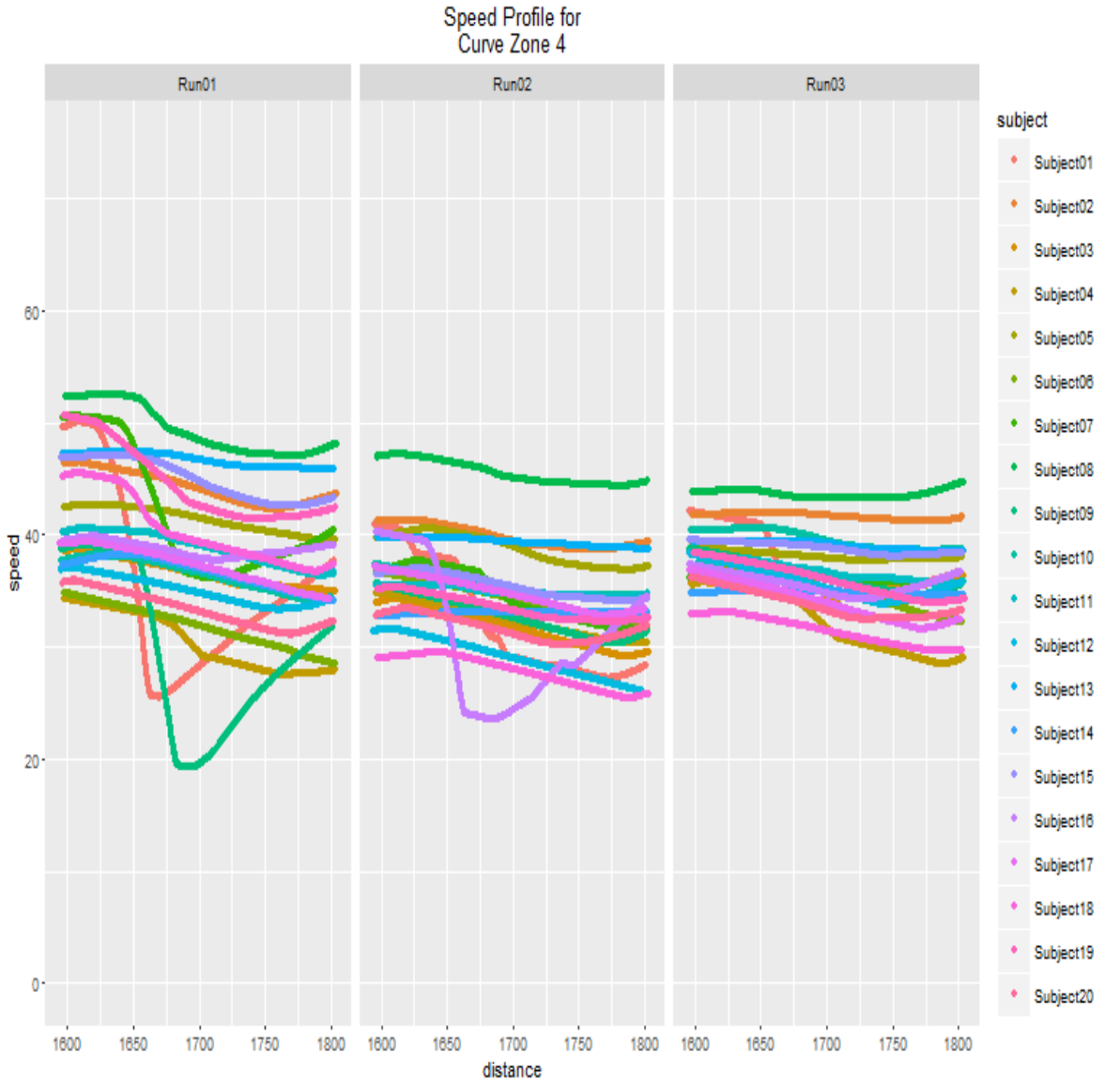

Figure 17: Speed Profiles for Curve Zone 4

Figure 18: Speed Profiles for Curve Zone 5

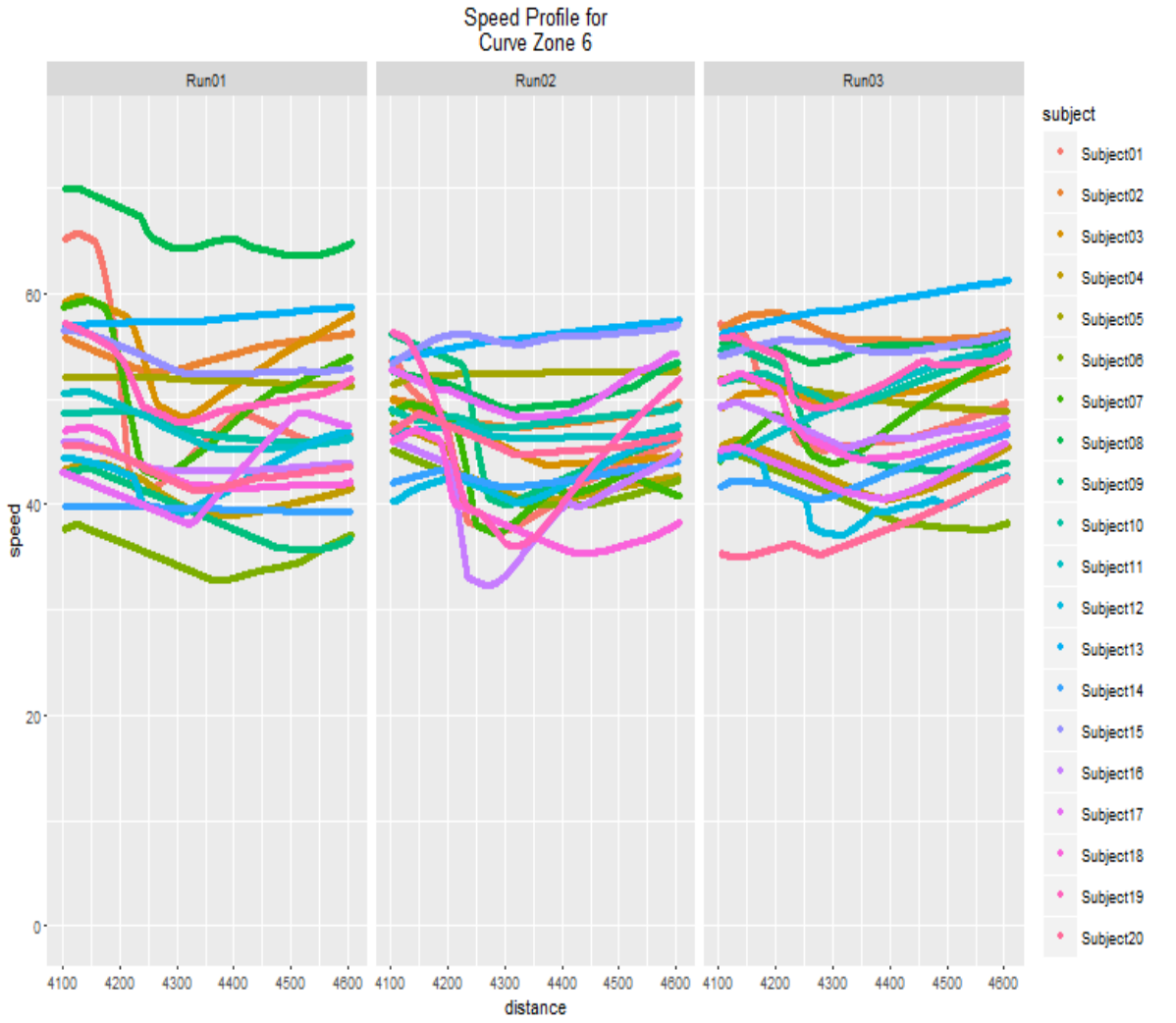

Figure 19: Speed Profiles for Curve Zone 6

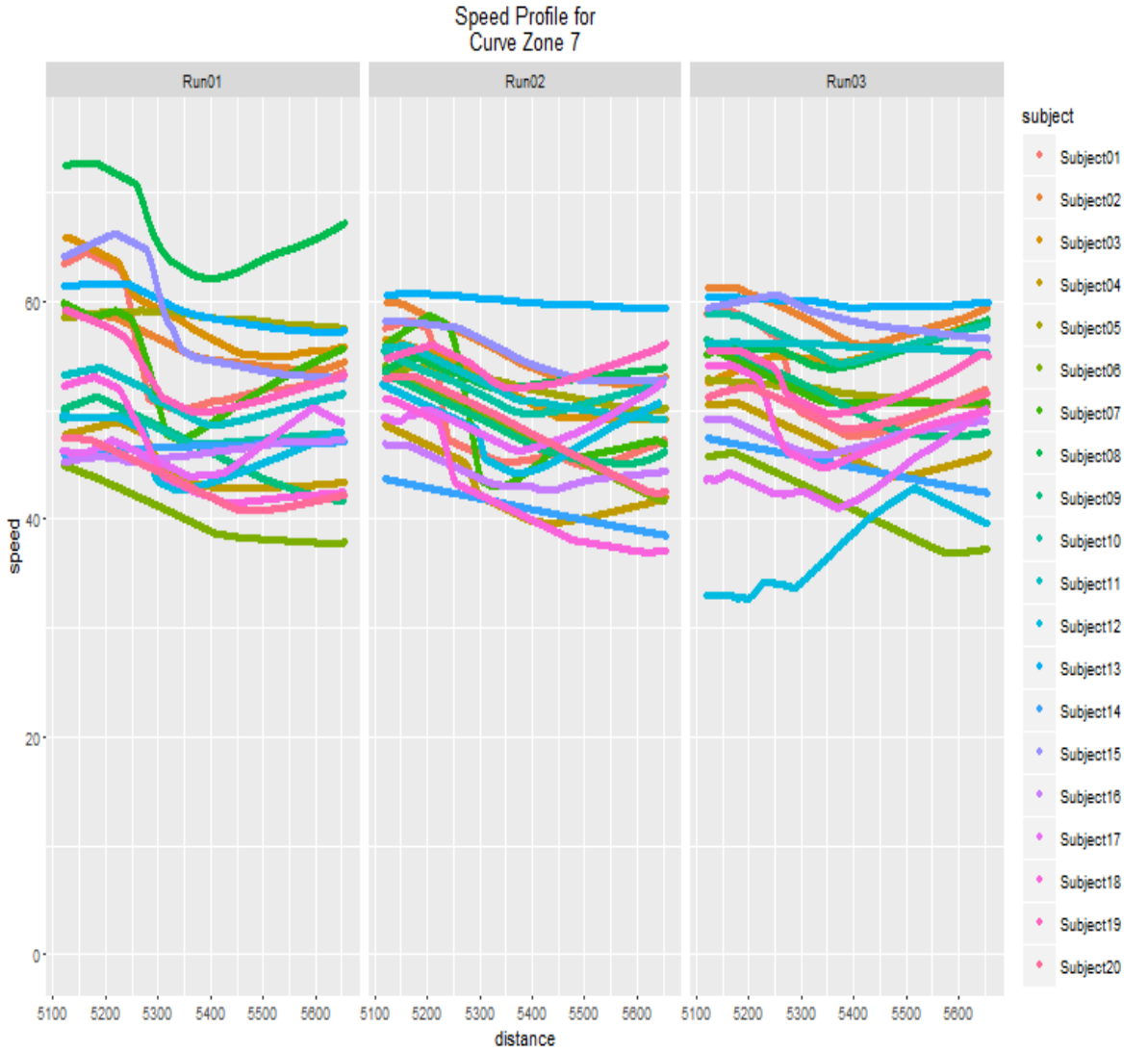

Figure 20: Speed Profiles for Curve Zone 7

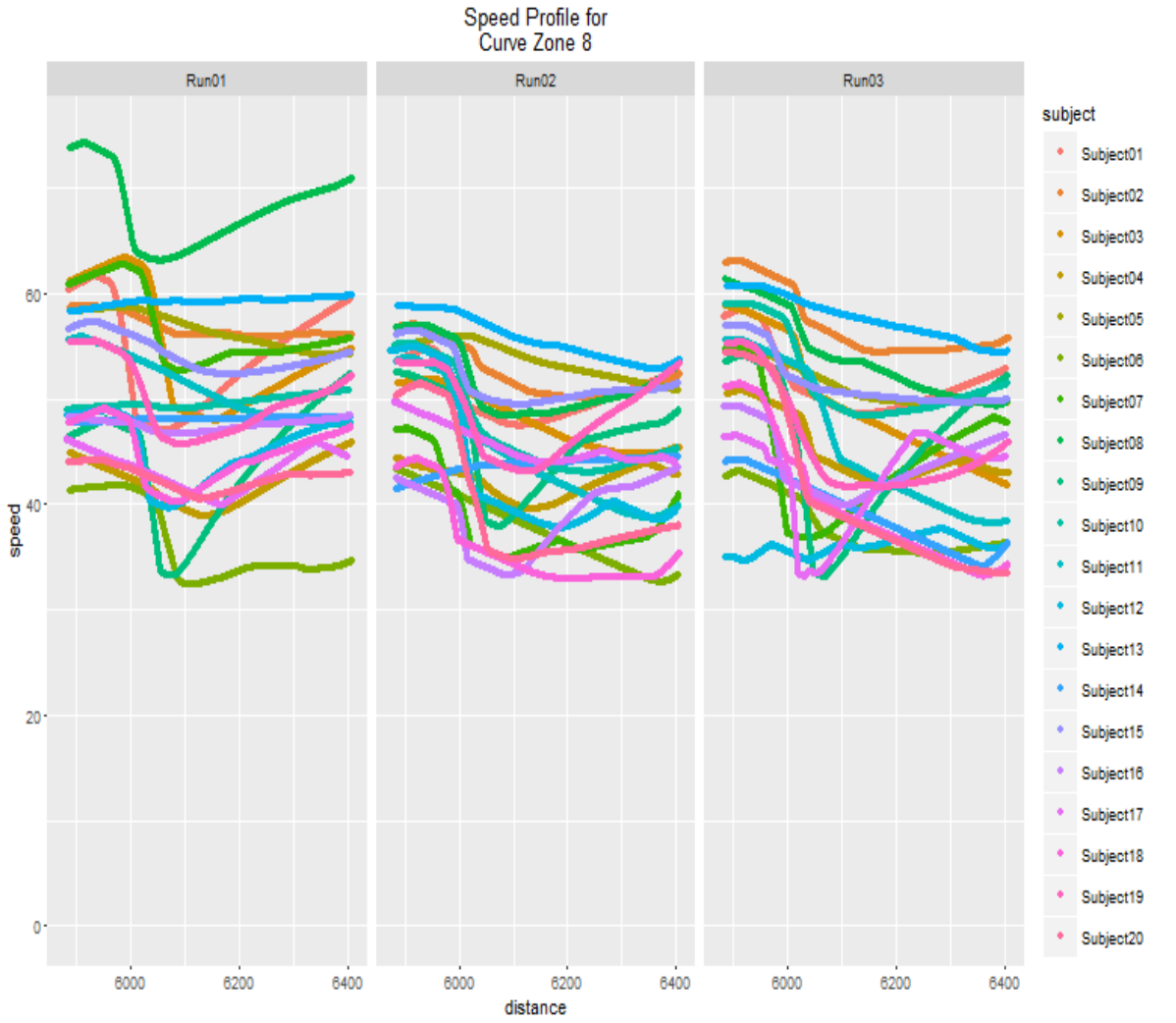

Figure 21: Speed Profiles for Curve Zone 8

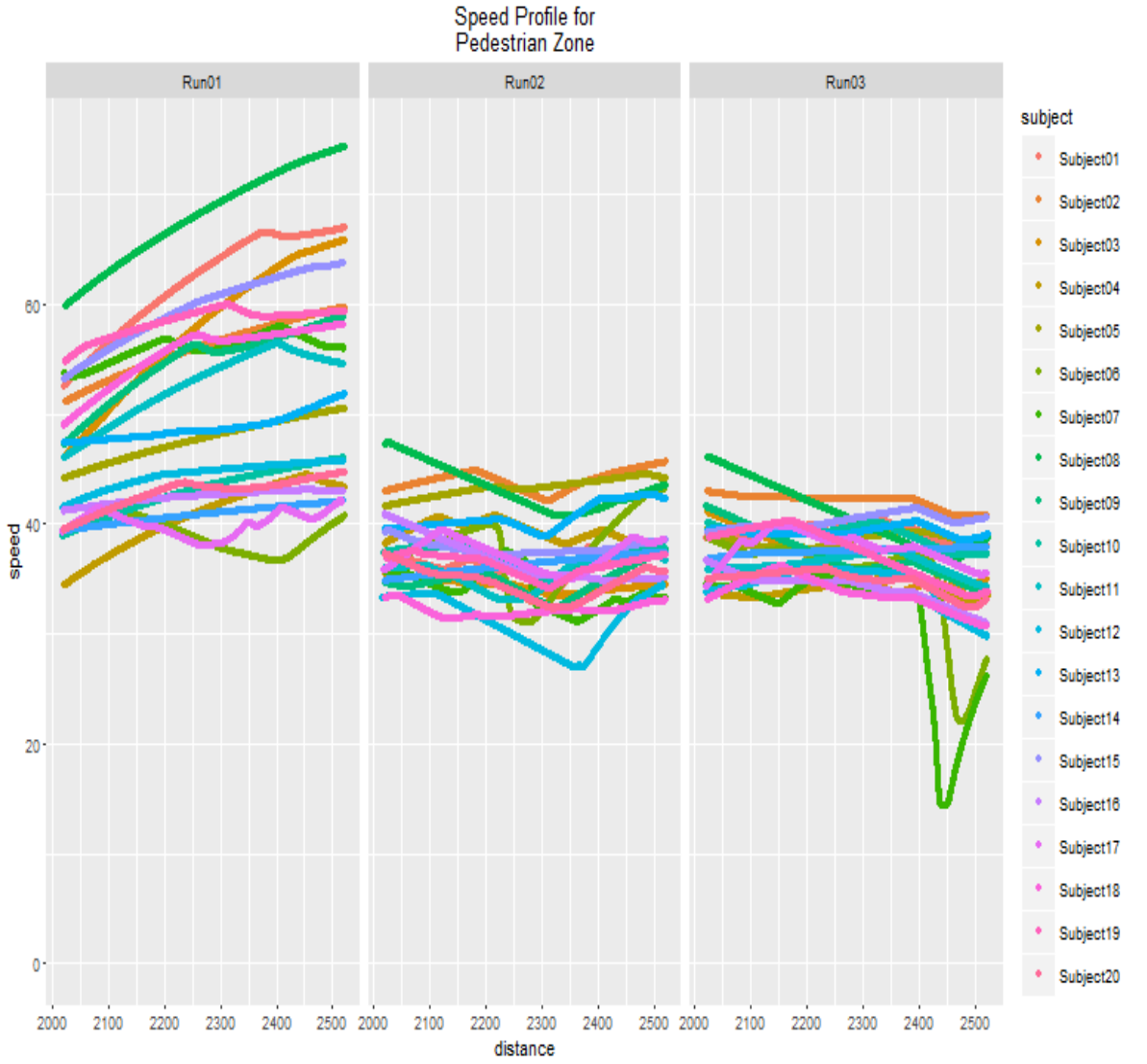

Figure 22: Speed Profiles for Pedestrian Zone

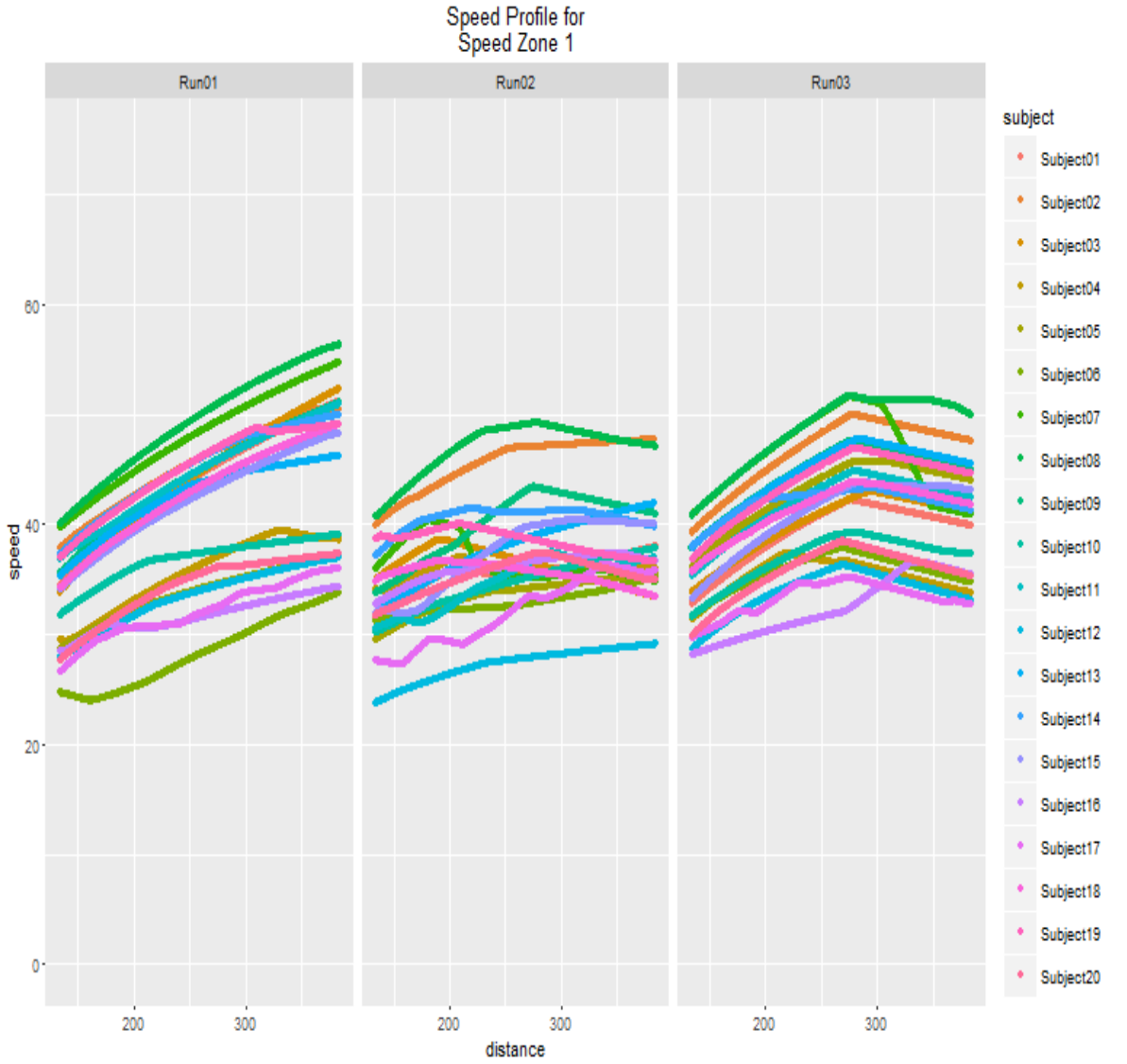

Figure 23: Speed Profile for Speed Zone 1

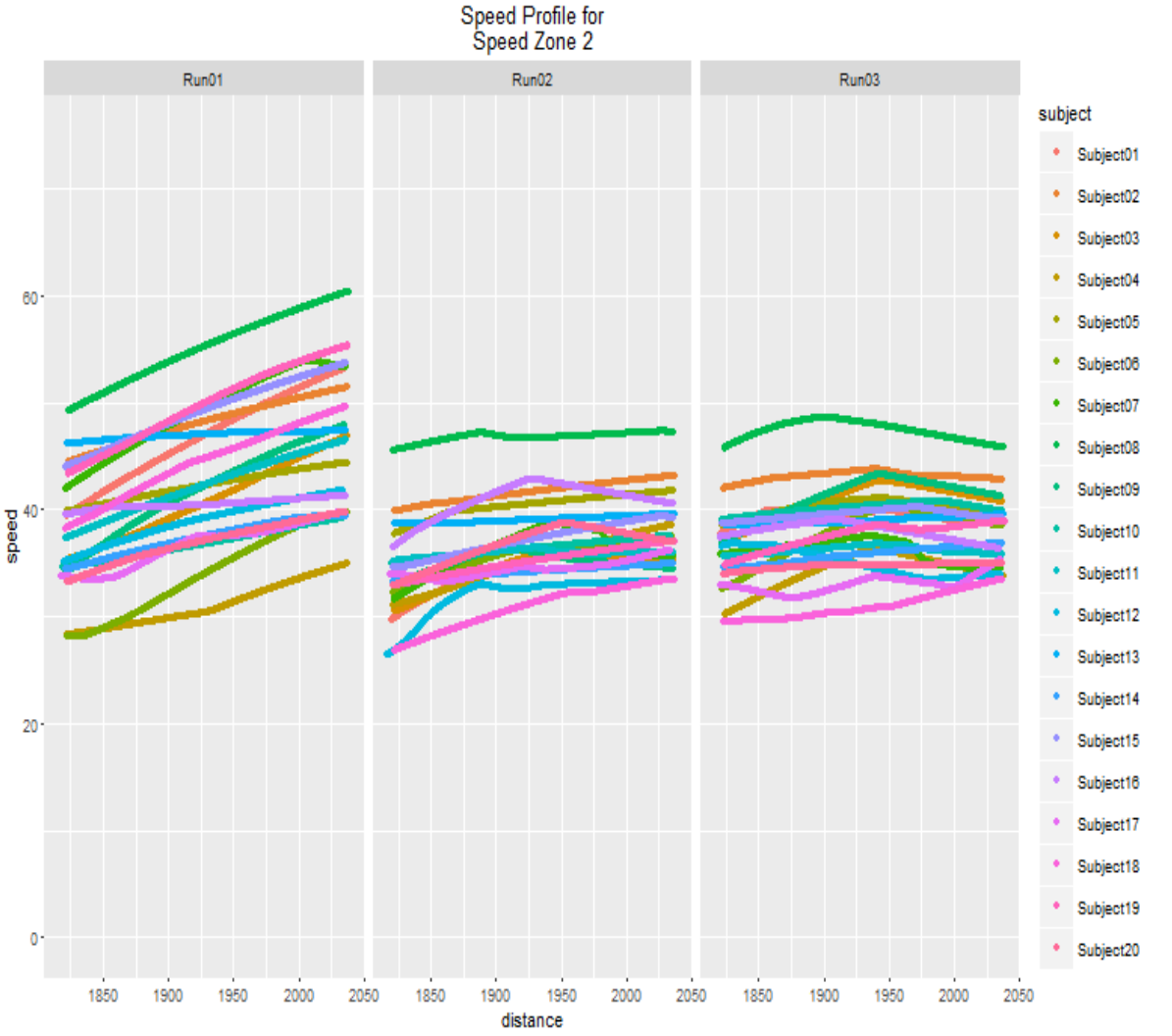

Figure 24: Speed Profile for Speed Zone 2

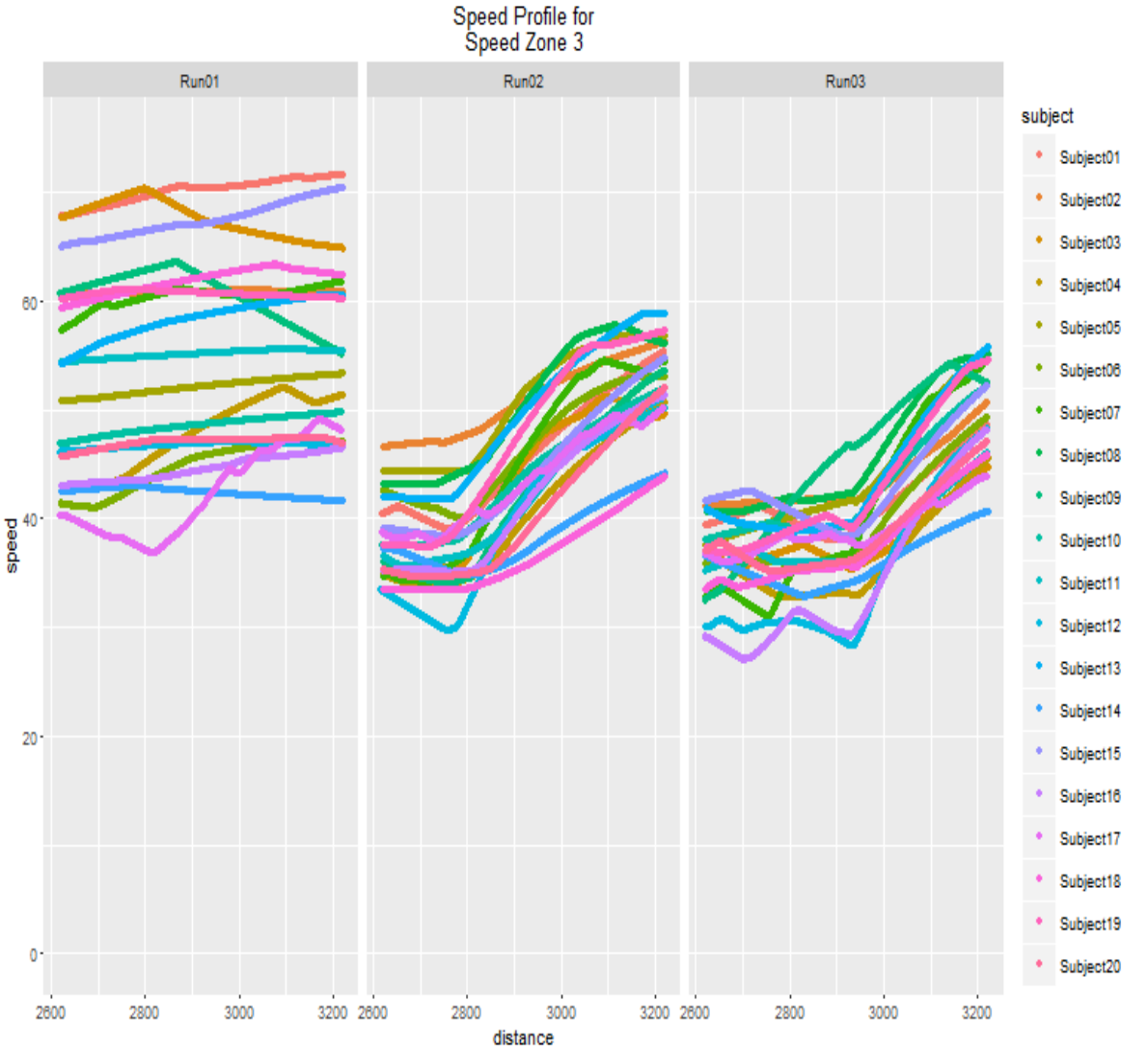

Figure 25: Speed Profile for Speed Zone 3

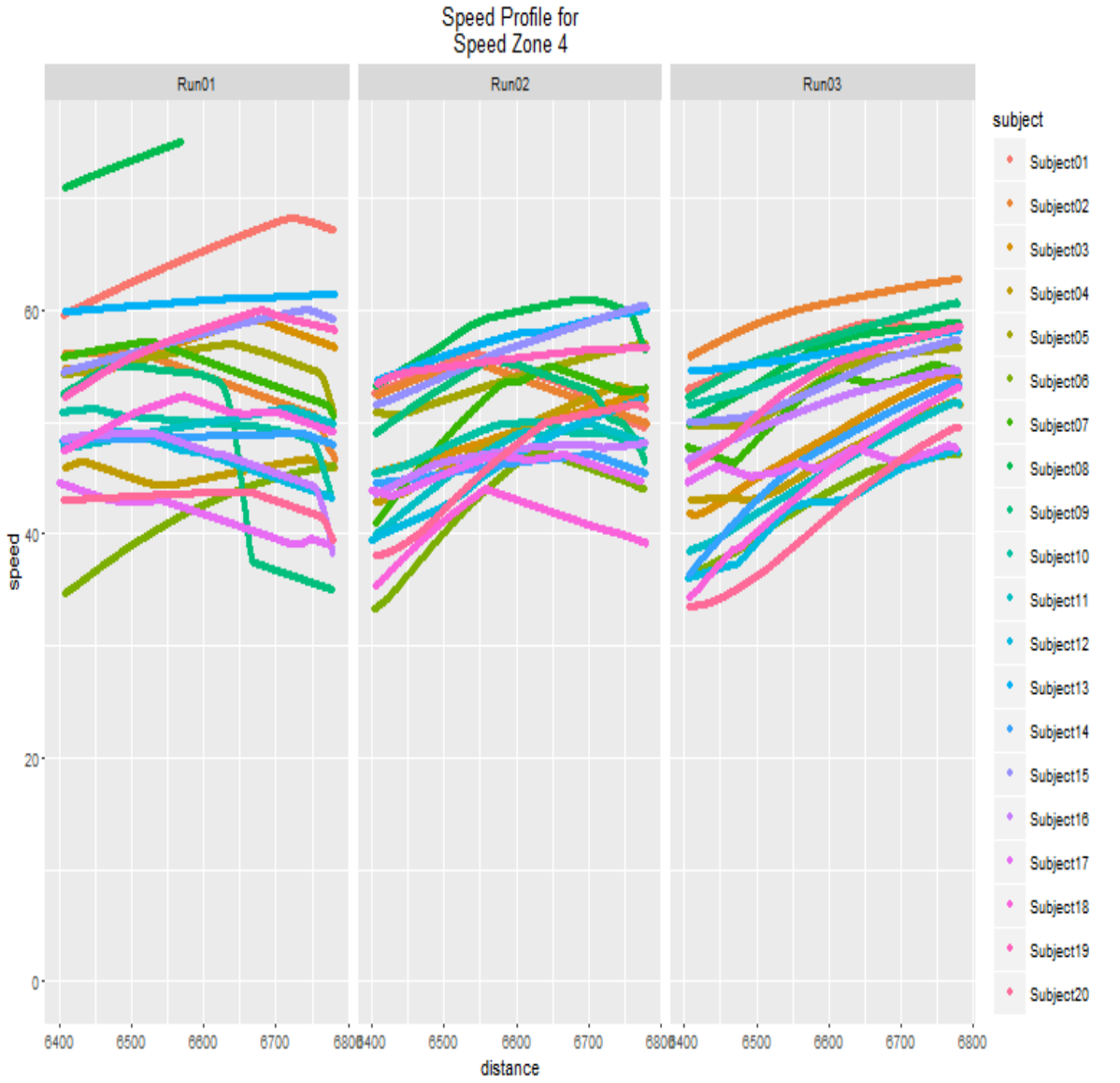

Figure 26: Speed Profile for Speed Zone 4

7.2 Average Speeds & Deviations from Entry Speeds

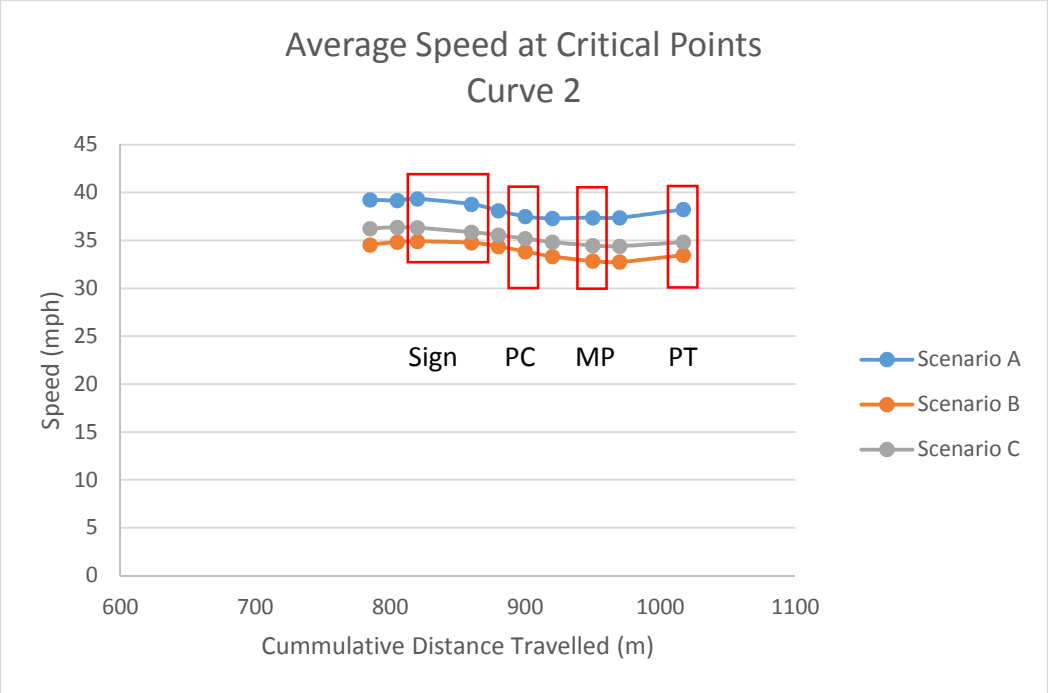

Figure 27: Average Speed in Curve 2

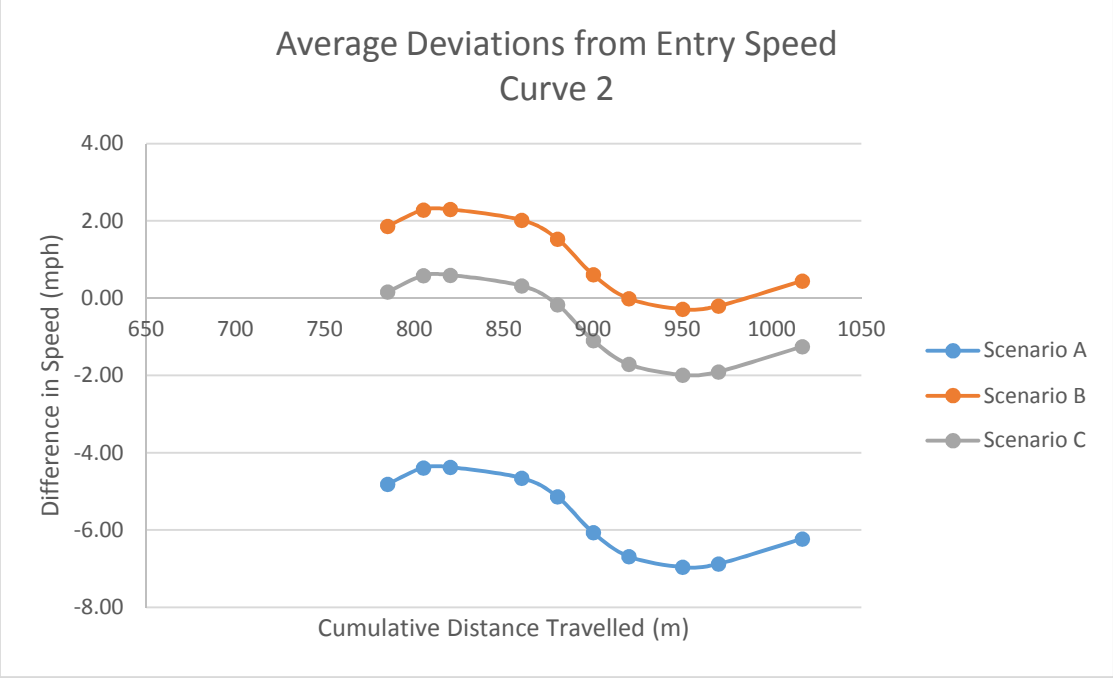

Figure 28: Average Deviations from Entry Speed in Curve Zone 2

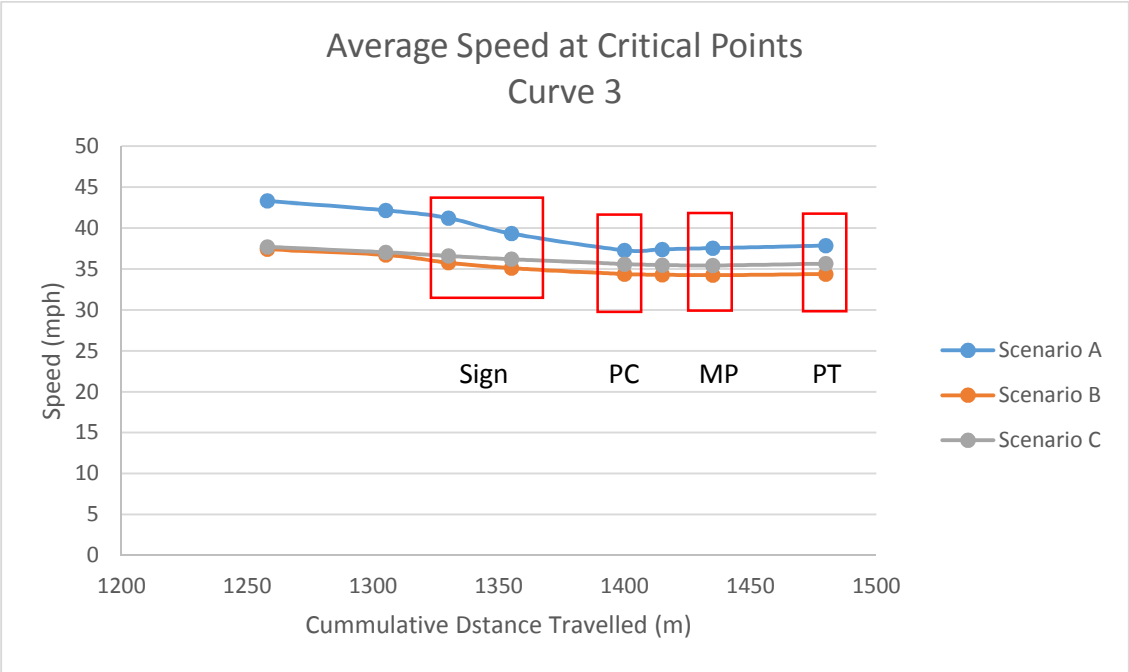

Figure 29: Average Speed in Curve 3

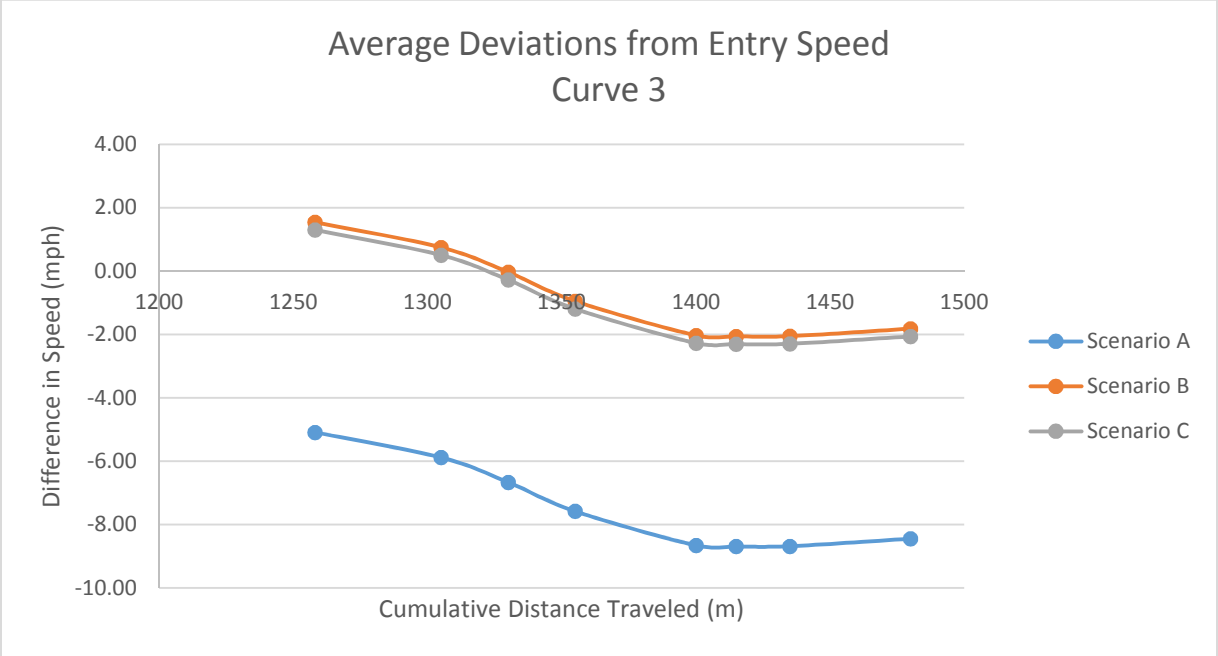

Figure 30: Average Deviations from Entry Speed in Curve Zone 3

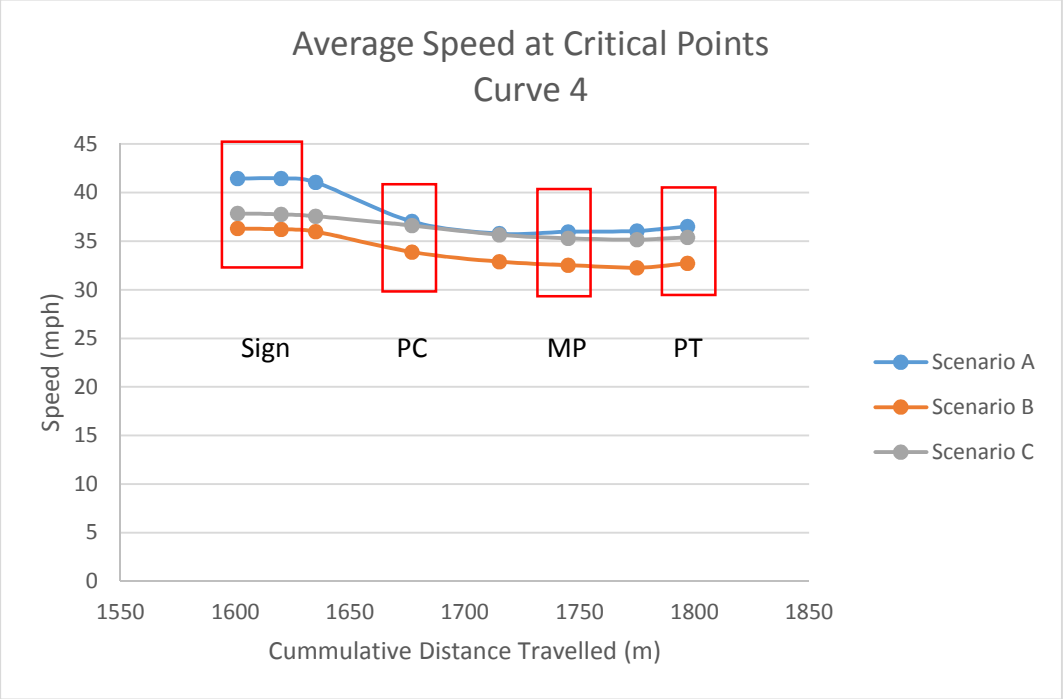

Figure 31: Average Speeds in Curve 4

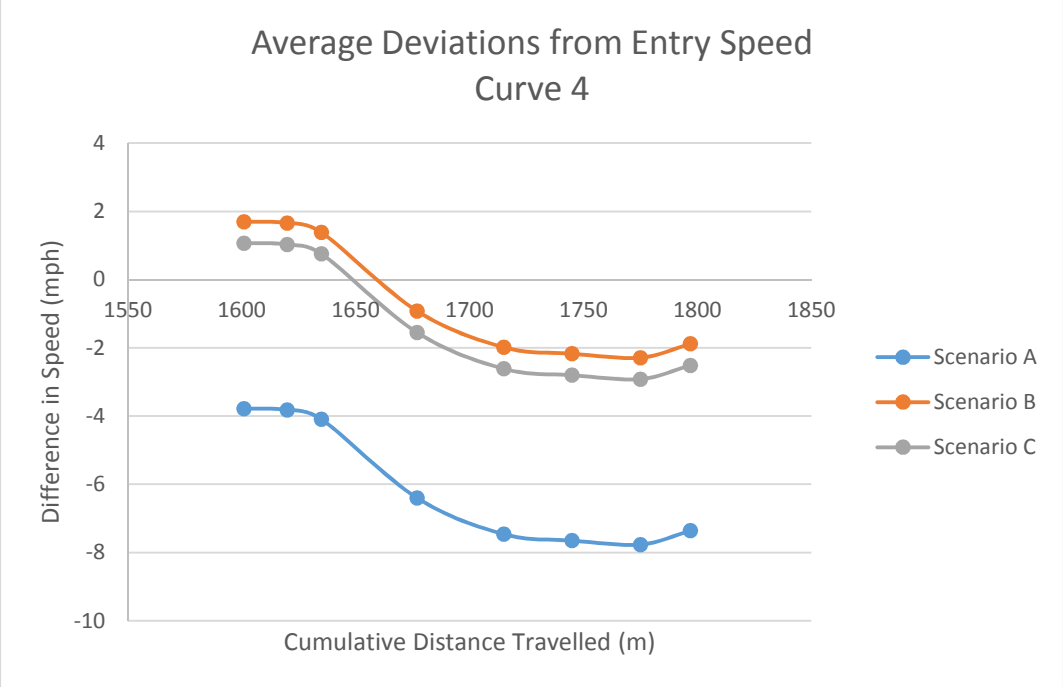

Figure 32: Average Deviations from Entry Speed in Curve Zone 4

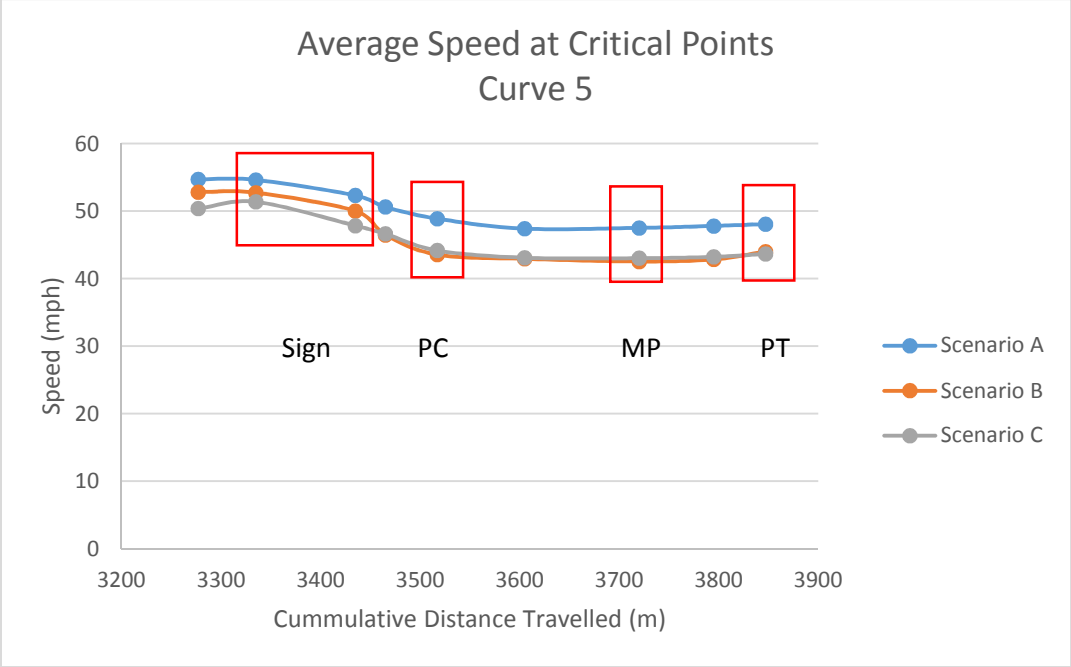

Figure 33: Average Speeds in Curve 5

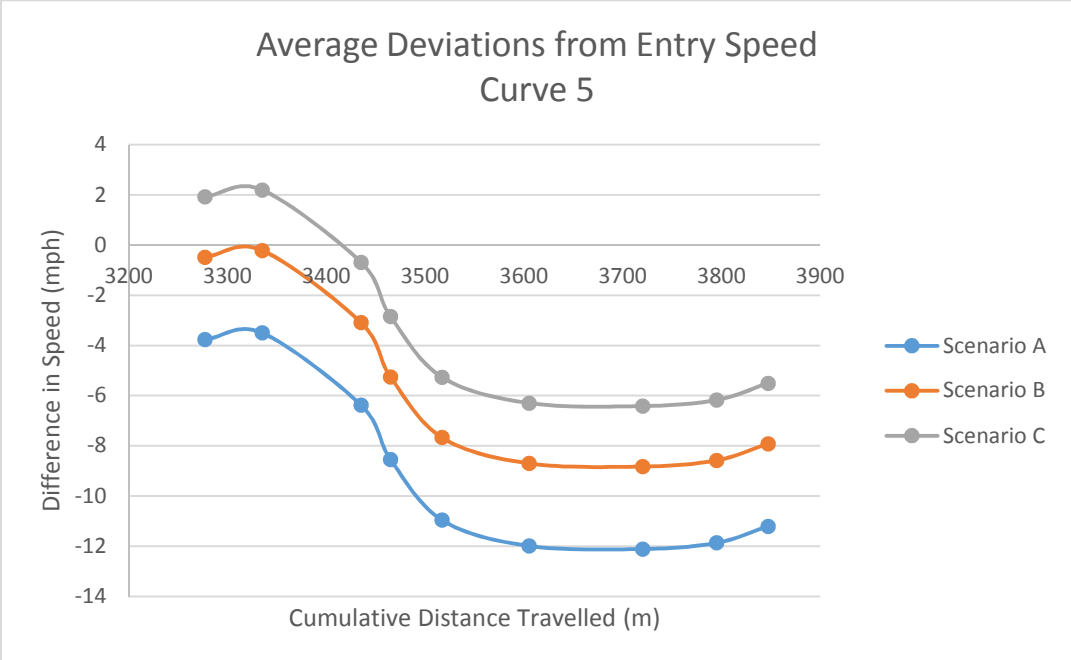

Figure 34: Average Deviations from Entry Speed in Curve Zone 5

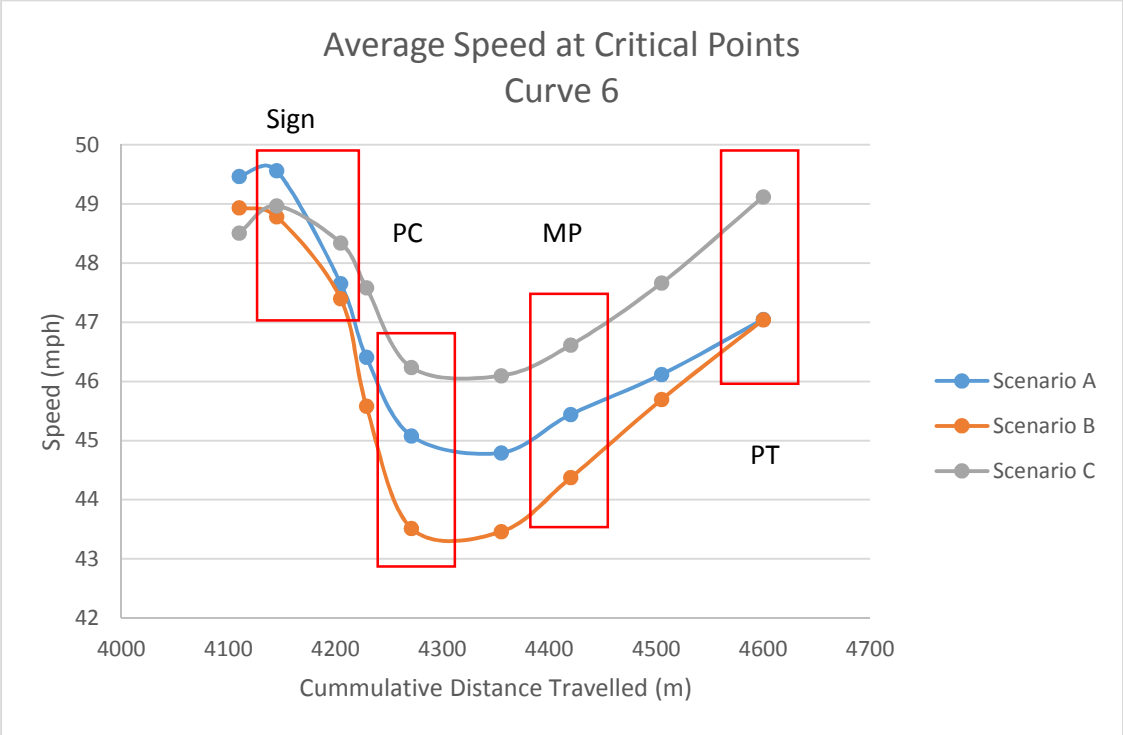

Figure 35: Average Speeds in Curve 6

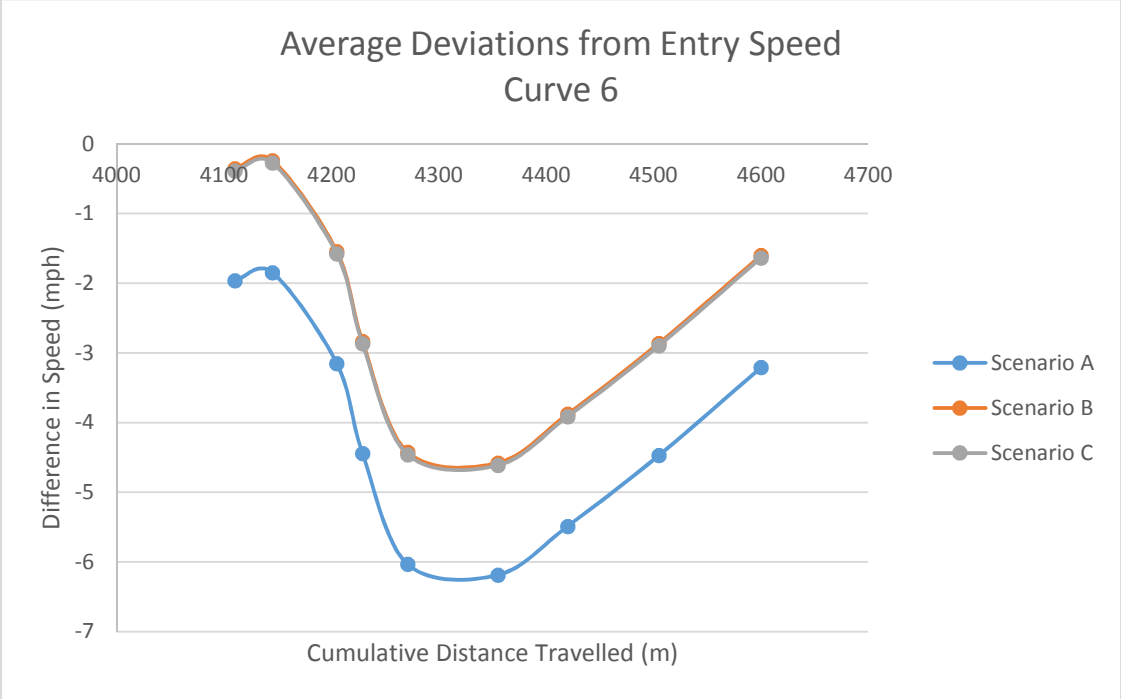

Figure 36: Average Deviations from Entry Speed in Curve Zone 6

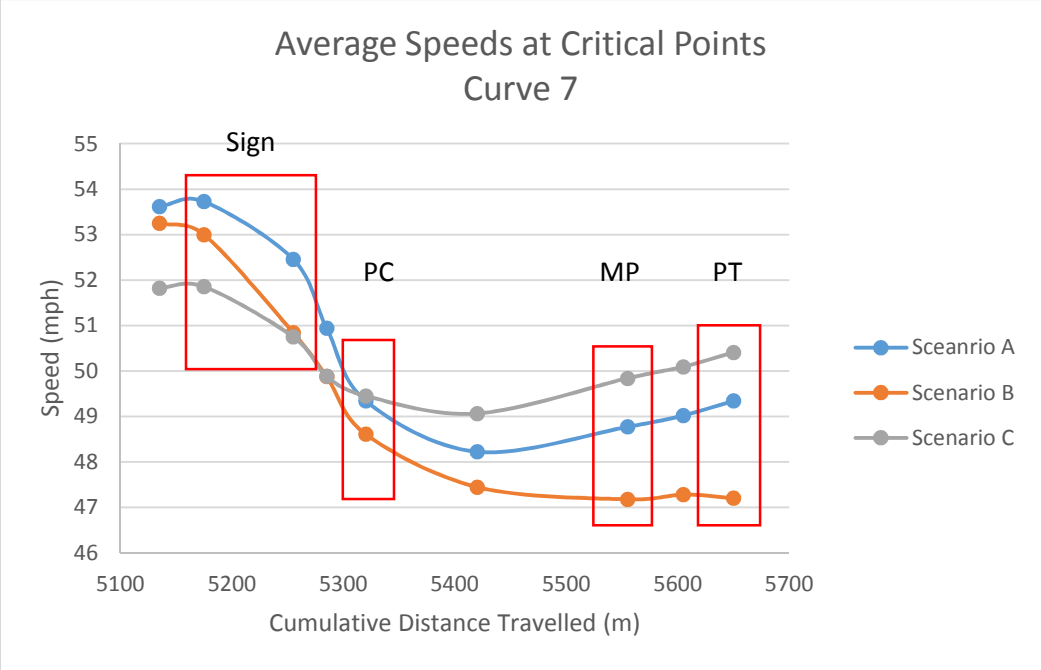

Figure 37: Average Speeds in Curve 7

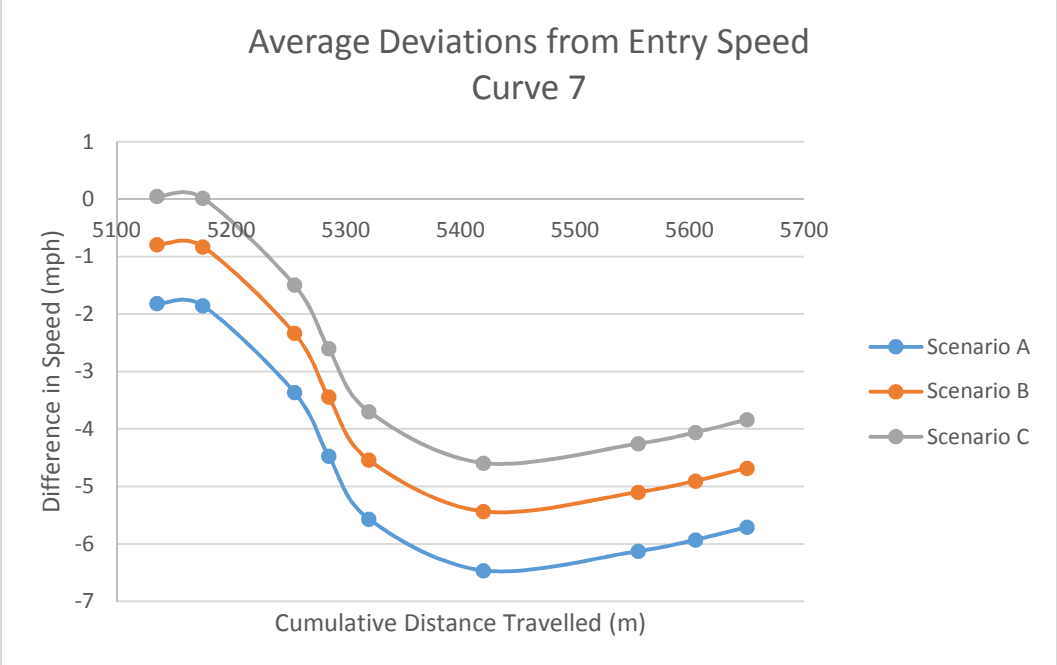

Figure 38: Average Deviations from Entry Sped in Curve Zone 7

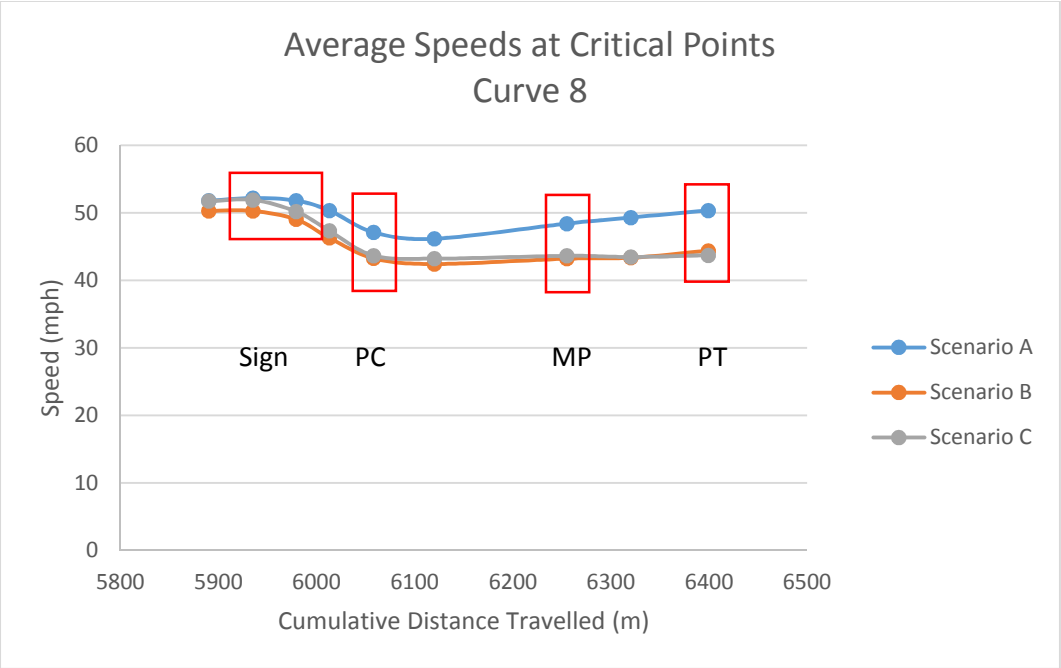

Figure 39: Average Speeds in Curve 8

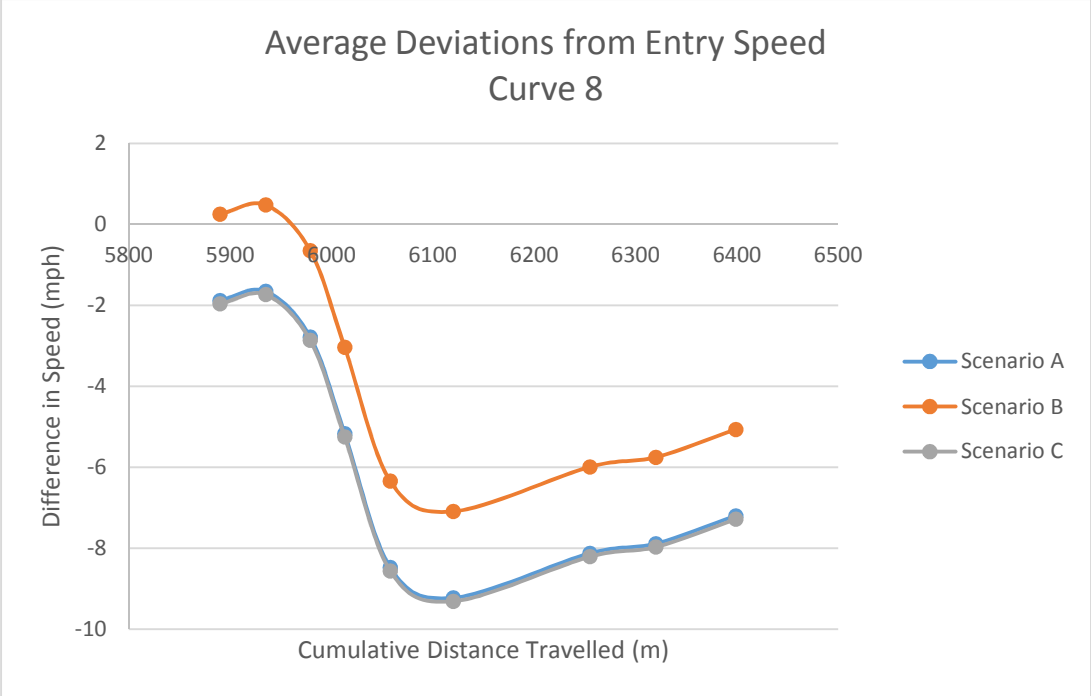

Figure 40: Average deviations from Entry Speed in Curve Zone 8

7.3 Standard Deviations from Average Speed

For curves within the 35 mph speed limit:

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

Table 13: 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 14: 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

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

7.4 P-Values for Curve Comparisons

Table 15: 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 16: 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 17: 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