VISUAL ATTENTION AND DRIVER PERFORMANCE AT HORIZONTAL CURVES

A Dissertation

by

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ABSTRACT

Despite the frequency with which drivers encounter curves on highways, curves are regularly identified as locations that experience disproportionately high crash rates. Crash data suggest that inattention is one of the leading causes of crashes at any location and on any facility. Traffic control devices (TCDs) can be installed at curves to provide drivers the information necessary for safe navigation. The research in this dissertation examines the theory that TCDs at curves are not only beneficial because they provide drivers information, but also because TCDs promote increased attention. With increased attention, drivers then navigate the curve more safely. A study of driver behavior was conducted to examine three hypotheses regarding the relationships between driver attention, navigational performance, and TCDs that are used at curves: 1) TCDs lead to improvements in operational performance at curves, 2) TCDs lead to increased attention in advance of curves, and 3) increased attention before curves leads to improved performance within the curve.

The driver-behavior study included the collection of eye-tracking and operations (speed and acceleration) data from unfamiliar drivers on a two-lane highway. Data were collected from over 100 study participants who each drove for approximately 1 hour. The hypotheses were tested using multivariable mixed models that identify relationships between the three components (TCDs, attention, and performance) while accounting for geometric and operational features at each curve. The principal findings from the study are that: 1) drivers operationally respond to TCDs by adopting a more-conservative behavior, 2) TCDs affect attention by influencing when drivers perceive relevant curve information, and 3) an earlier increase in cognition leads to a more-conservative navigation. Since TCDs influence where drivers perceive a curve, and the perception influences the operational performance, it is suggested that the selection of TCDs at curves can be based on the distance required for drivers to make a natural maneuver in advance of the curve in preparation for navigating it.

DEDICATION

To Amanda, for crossing the finish line with me. No words in a dedication could ever make up for the love and patience you have demonstrated throughout this work.

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My experience while at Texas A&M University has been distinguished by my association with my academic advisor, Gene Hawkins, and my research supervisor at the Texas A&M Transportation Institute, Paul Carlson. Working with them has been rewarding at multiple levels. Their enthusiasm for research and their expertise in the field of traffic engineering has supported me through numerous dead ends and rabbit holes, and their grasp of the complexities of issues that both policy makers and engineers have to reconcile has been enlightening. I am grateful for their dedication to me and their commitment to my personal and professional development.

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Finally, my family—extended and close—has provided unending encouragement, offered numerous prayers, and sacrificed countless hours that could have been spent together. Thank you for your patience and support throughout this effort.

NOMENCLATURE

AASHTO	American Assoc. of State Highway and Transportation Officials
deg	Degrees
FHWA	Federal Highway Administration
ft	Feet
g	Gravitational unit (32.2 ft/s^2)
GPS	Global positioning system
Hz	Hertz
in	Inches
LED	Light-emitting diode
$mcd/m^2/lx$	Millicandela per square meter per lux
mph	Miles per hour
mm	Millimeters
MP	Midpoint
MUTCD	Manual on Uniform Traffic Control Devices
PC	Point of curvature
PMD	Post-mounted delineator
PRT	Perception-reaction time
PT	Point of tangency
R_L	Retroreflectivity
s	Seconds
TCD	Traffic control device
veh/day	Vehicles per day

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1. INTRODUCTION

The horizontal components of a roadway are categorized into two types of segments: tangents, and the changes in horizontal alignment, or curves, that connect them. Both components are necessary: while tangents provide the most direct connection between two locations, curves allow the tangents to be arranged so the road avoids crossing critical areas. Drivers thus expect to encounter curves. Regardless of such an expectation, curves historically have experienced disproportionately high crash rates (Torbic et al. 2004).

Researchers and policy makers have recognized the importance for drivers to maintain adequate levels of attention during the driving task. Distracted driving was identified as a cause of approximately 25 percent of police-reported crashes 15 years ago (Ranney et al. 2000); however, and more recently, an analysis of the crashes in the 100-Car Naturalistic Driving Study attributed 78 percent of crashes to some form of inattention (Dingus et al. 2006). The prevalence of crashes that occur at curves and the importance of attention while driving suggest that there is a need to further study driver attention at curves. This dissertation documents a study of changes in driver attention at curves and examines how traffic control devices (TCDs) may be used to improve driver attention. Connections with driver performance to both attention and the use of TCDs are also investigated.

TCDs are used to provide drivers information relevant to the driving task. The *Manual on Uniform Traffic Control Devices* (MUTCD) contains guidelines for the use of TCDs, defining when they must, should, or can be used. TCDs can be applied at curves—whether required by standards or otherwise optional—as a relatively low-cost treatment for reducing crashes, and their effectiveness at doing so has been shown multiple times (McGee and Hanscom 2006; ATSSA 2006). Most previous research on TCDs has focused on showing that operational performance (traditionally measured as a vehicle's speed, position, and acceleration) improves when they are used, without investigating the human mechanism that supports the improvement. As a result, the change in behavior is assumed to be due to the information alone provided by TCDs. Figure 1.1 illustrates this relationship.

Figure 1.1: Current thought that TCDs alone affect performance.

The issue with Figure 1.1 is that it conveniently removes the human element from the response to the TCD. What if the drivers cannot see the TCD? What if they intentionally ignore it? What if the drivers are distracted? Some research on TCDs has investigated driver fixations at TCDs, suggesting that the TCDs may influence a driver's attention. It is thought that, while the actual information provided by TCDs at curves may help drivers make better decisions regarding operational behavior, some of the improvement may occur because the TCDs affect driver attention, characterized by when and where drivers process the information about the curve. This perception of information is described as a change in cognition in Figure 1.2, indicating a need for research that focuses on the cognitive aspects of drivers near curves. The resulting implication is that the change in cognition is the mechanism by which performance improves.

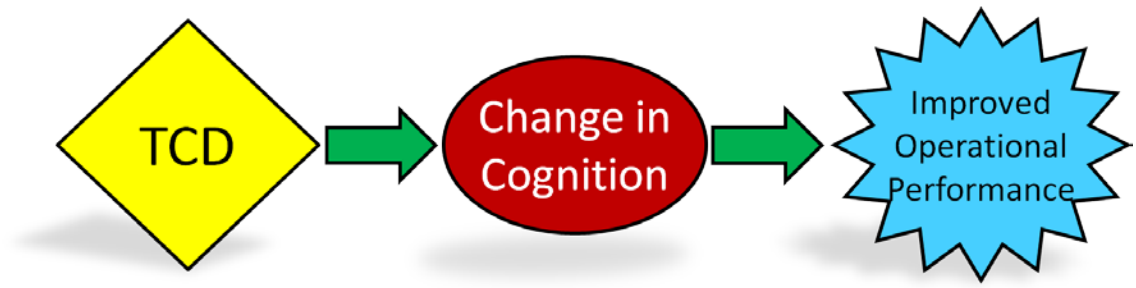


Figure 1.2: Hypothetical model that replaces the implied connection between TCDs and performance with the cognitive processes that control the driver's output.

1.1. Objectives

The objectives of this dissertation focus on the relationships represented by each of the three green arrows in Figures 1.1 and 1.2. The first objective is to show that TCDs at curves lead to improvement in driver operational performance (green arrow in Figure 1.1), supporting the primary thought that the information alone is the catalyst for improvement; the second objective is to show how TCDs affect driver cognition (or attention) before curves (first green arrow in Figure 1.2); and the third objective is to show that improved performance comes from the change in cognition (second green arrow in Figure 1.2).

There has been a substantial amount of research conducted on the effectiveness of curve TCDs (discussed in the next section) with conflicted or inconsequential findings. Such results make it difficult to identify the circumstances when a TCD at a curve should be used. If the operational performance is tied to attention, and attention tied to the use of TCDs, then TCD effectiveness may be reasonably shown by the changes in attention. Information about the human element of curve navigation and the effects of TCDs on cognition may support an overall improved understanding of multiple facets of driver behavior and can lead to better decisions regarding the use of TCDs.

In this research, a driver behavior study was conducted to obtain data regarding the operational characteristics of drivers and their attention while negotiating curves on rural two-lane highways. This dissertation describes the collection and reduction of data from the driver study and the multiple analyses that were conducted to investigate the above-mentioned relationships. Fulfillment of the above three objectives is dependent upon completion of the following tasks:

- Document driver operational performance using novel metrics that illustrate the complexities of negotiating curves.
- Evaluate how TCDs at curves affect driver operational performance.
- Show how a driver's attention changes while approaching curves.
- Identify the effects of TCDs on a driver's attention.
- Evaluate the connection between driver attention and operational performance.

Statistical models are used to illustrate the relationships between characteristics of curves, the TCDs at the curves, and the driver behavior data collected in the study. The concept of a driver's attention in this dissertation is the cognition derived from the visual behavior and physiological measures identified with eye-tracking cameras. Operational performance describes characteristics of the vehicle using measures such as speed or acceleration. The TCDs used at curves that will be tested are post-mounted delineators (PMDs), one direction large arrow signs, and chevrons, each used separately but in addition to pavement markings and advance warning signs.

1.2. Outline

This dissertation contains eight main sections. The next section provides a discussion with background information that is relevant to understanding the objectives of the dissertation. Section 3 describes the driver study that was carried out to obtain data for modeling driver behavior. Section 4 presents an analysis of operational performance with metrics that characterize the behavior of drivers as they approach and navigate curves, exclusively focusing on the effects of geometry. Section 5 expounds upon the models developed in Section 4 by including TCDs in the models of driver performance. Section 6 contains an analysis of driver visual behavior, with some models that include effects of TCDs. Section 7 investigates the connections between the measures of a driver's attention on a curve approach and the driver's operational performance, without consideration for the TCDs used at the curves. Finally, the significance and possible application of these findings are discussed in Section 8.

2. BACKGROUND

Drivers receive and process input from various stimuli in order to carry out the driving task. It has been suggested that 90 percent of the information used while driving is received visually (Sivak 1996). The remaining information is auditory (e.g., the sounds of the engine, tires on the pavement, and air against the vehicle and windows), tactile (e.g., vibration of the engine and unevenness of pavement), or vestibular (e.g., the feelings of movement and the forces that cause different forms of acceleration). One representation of a system of receiving and processing information is illustrated in Figure 2.1. The image shows how various inputs contribute to the processing (perception and integration) of information with the output being the way the brain directs a response from the motor centers. The input of information for curve navigation is the characteristics of a curve, primarily its geometry and traffic control, and any other information from the environment that assists drivers in detecting and evaluating curves. The perception and integration of the information is the cognitive processes that control how the driver responds operationally and navigates the curve. The previous experiences, memories, and emotions of each individual driver affect this perception. These personality traits, which are different for each driver, are the reason two drivers may respond to identical curves in a unique way.

A noticeable feature of the image in Figure 2.1 is the multiple sources of noise illustrated with lightning streaks. Noise is the agents that interfere with the receiving and processing of information, thus reducing the efficiency of the system. These agents include distractions and impairments that affect the cognitive capabilities of the driver. Such effects on cognition can lead to crash-causing errors, because when the driver's attention is diverted, there are fewer attentional resources available to devote to driving.

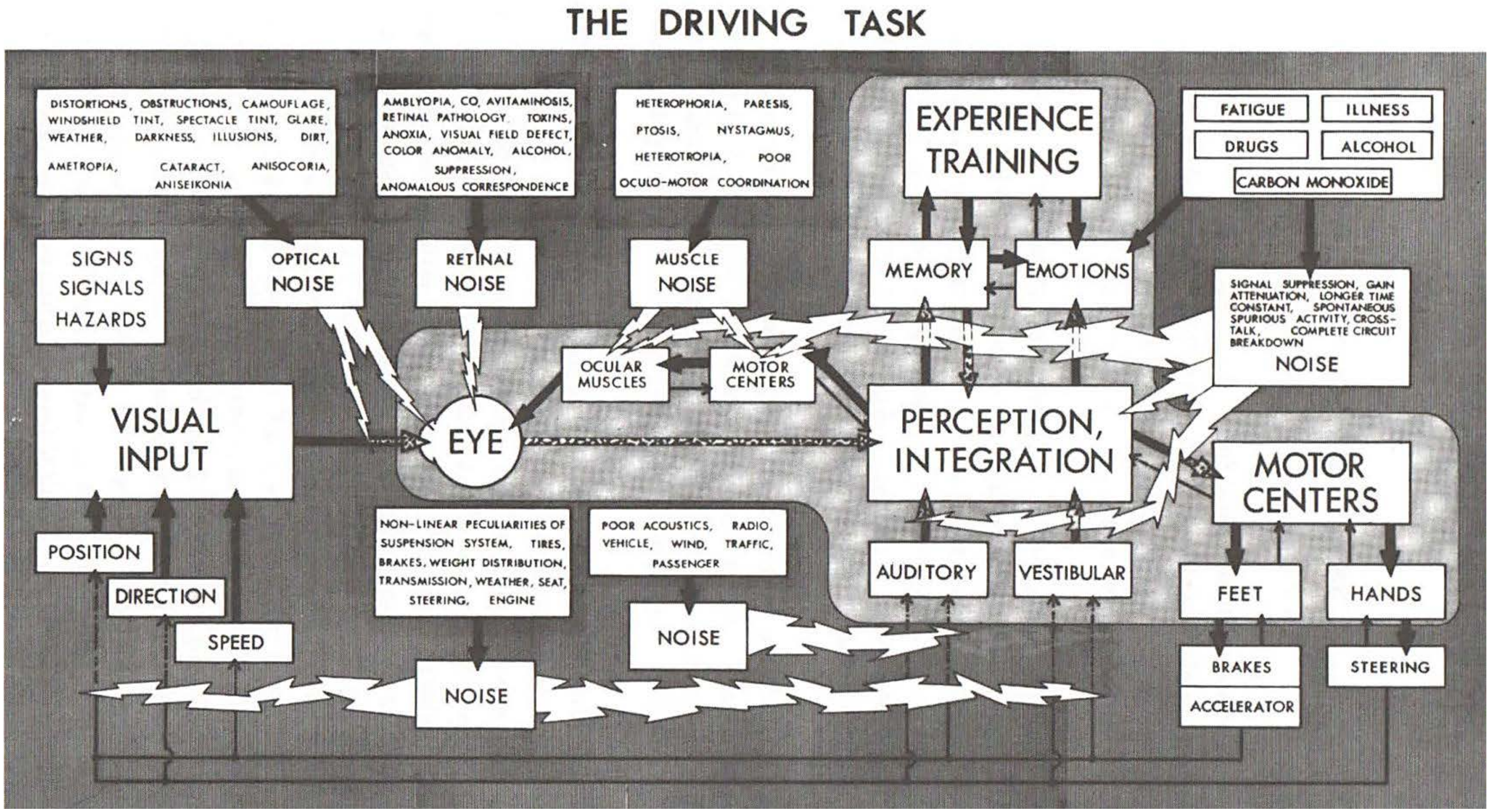


Figure 2.1: A closed-loop system of receiving and processing information during the driving task (Allen 1996).

Driver performance tends to decrease under conditions of reduced attention or increased workload (Caird et al. 2008; Horrey and Wickens 2006). Additionally, curve navigation is more visually demanding than driving on tangents (Wooldridge et al. 2000). While the alignment can be changed to reduce the severity of a curve, the removal of noise (cognitive interference) may be the simplest way to improve safety. The use of TCDs at curves has been identified as an inexpensive way to improve safety, because TCDs can provide drivers with information to help them select an appropriate behavior to safely navigate the curve. One of the principal hypotheses of this dissertation is that TCDs at curves are effective not only because they inform drivers what behavior to adopt at the curve, but they are effective because the information helps drivers eliminate noise that interferes with the cognitive processes of driving.

The output response of maneuvers appropriate for navigating a curve (executed by the motor control centers in the diagram in Figure 2.1) are not initiated until after the driver receives and processes information associated with the curve. A TCD changes the way a driver receives information about a curve, but it also may affect the time when the information is perceived. A change in the time of perception may then influence the remaining cognitive process, and, ultimately the output measured as operational performance. Only by measuring driver behavior continuously and beginning far from curves may such detailed changes in the driving task be identified.

Curve navigation is a complex part of the driving task that has been studied in many contexts. This section of the dissertation contains a review of information related to navigating curves. Specifically, it 1) explains what is known about the physical and cognitive processes associated with negotiating curves, 2) identifies the importance of attention in the driving task and shows how attention can be measured, and 3) identifies how the use of TCDs at curves may influence observed driver behavior.

2.1. Horizontal Curves: Design and Navigational Performance

The design of horizontal curves is governed by the limitations of the system comprised of the driver, vehicle, and pavement. Guidelines for design (the most common ones are set by the American Association of State Highway and Transportation Officials and published in the “Green Book” [AASHTO 2011]) are set conservatively so that the limitations of the driver, vehicle, and pavement should never be exceeded under normal operating conditions. These limitations can include the driver’s expectations and desire for comfortable navigation, the ability of the vehicle to respond to the driver’s maneuvers, and the ability of the pavement to supply the frictional forces that support the vehicle’s movements. Despite conservative guidelines, crashes continue to occur at curves in disproportionate numbers.

Three main geometric features that characterize curves are the radius, deflection angle, and superelevation. The radius defines the degree of curvature, or how quickly the direction of travel changes; the deflection angle is the total change in direction from the beginning to the end of the curve, and superelevation is the amount of banking or lateral incline. Lateral forces acting toward the center of the curve must be applied in order for a vehicle to travel in a circular path. Lateral acceleration has a quadratic relationship with the vehicle’s longitudinal speed and an inverse relationship with the curve radius. Superelevation reduces lateral forces required to support the circular movement. The deflection angle does not directly affect the forces felt by the driver, but drivers may perceive curves with large deflection angles as more severe than those with small deflection angles. Superelevation does impact operational behavior, but a curve’s superelevation is more difficult to perceive at a distance than the radius or deflection angle. Its subtlety is evident by the absence of superelevation in numerous models of operational performance (primarily curve speed). There are other geometric elements that influence the behavior of drivers, such as the lane and shoulder widths, vertical curvature, and the use of spiral transitions, but they have often been excluded from analyses, and are also excluded here.

The following discussion identifies characteristics of driver operational and visual behavior at curves, based on past research.

2.1.1. Navigational Strategies: Operational Behavior at Curves

There are many factors that affect driver operational behavior at curves. The amount of lateral acceleration experienced by a driver navigating the curve has been identified as a controlling factor for the operating speed on the curve. Research shows that drivers do not adjust their speeds on curves to consistently accept the same amount of lateral acceleration. At higher speeds, for example, drivers are more cautious and accept less lateral acceleration (Ritchie et al. 1968; Herrin and Neuhardt 1974; Bonneson 1999; Reymond et al. 2001). The geometry of the curve, which is one factor that influences lateral acceleration, will thus affect how much deceleration occurs as the driver approaches the curve. Depending on the speed at which drivers approach a curve, they may need to decelerate to a speed comfortable for navigating the curve.

Driver speed throughout a single curve is usually not constant. Figueroa Medina and Tarko (2007) observed that 66 percent of the total deceleration occurs on the tangent preceding the curve, with the remaining 34 percent of deceleration continuing after the point of curvature (PC). Generally, the minimum speed is assumed to be reached near the midpoint of the curve. Speed prediction models by Poe and Mason (2000), Donnell et al. (2001), and Islam and Seneviratne (1994) each estimate a lower speed at the midpoint than at the PC. The research that has modeled speed at the point of tangency (PT) usually identifies an exit speed close to the entrance speed.

Early research on deceleration rates at curves identified constant rates of deceleration, based on observed averages. A rate of 2.79 ft/s^2 for both deceleration and acceleration was the first proposed value that was later validated by a separate study (Lamm and Choueiri 1987; Collins and Krammes 1996). Collins and Krammes (1996) found the deceleration rate of 2.79 ft/s^2 to be an appropriate assumption, but observed that acceleration rates tend to have a lower magnitude. They noted that the assumption that deceleration and acceleration occur only on the upstream and downstream tangents is an oversimplification of true driver behavior, because deceleration and acceleration also occur within the confines of the curve. From the data evaluated by Figueroa Medina and Tarko (2007), the average deceleration and acceleration rates were approximately 2.4 and 1.6 ft/s^2, respectively. Fitzpatrick et al. (2000) also showed that acceleration and deceleration rates are not equal, and are dependent on curve geometry. A step function dependent on curve radius was produced, with deceleration rates ranging from 0 to 3.3 ft/s^2.

Drivers select a comfortable speed that is based on a number of factors associated with the design and operational characteristics of the facility. (On a two-lane highway, for example, the *Highway Capacity Manual* identifies reductions in free-flow speed when the lane or shoulder width is less than 12 or 6 ft, respectively, and if there are any access points along the segment [TRB 2010]). Upon exiting a curve, drivers will want to accelerate to a comfortable operating speed, depending on the deceleration previous to a curve and the information they have and their expectations about the upcoming curve. Hu and Donnell (2010) showed that the acceleration rate after a curve is related to the deceleration rate immediately before the curve, and that the deceleration rate before a curve is related to the earlier acceleration rate exiting the upstream curve. This should not be surprising because there will be a greater amount of potential for drivers to increase their speed after exiting a severe curve that required substantial deceleration.

From past research, there appear to be three principal phases of curve negotiation: The acceleration that occurs when exiting a curve, the deceleration that occurs when approaching a curve, and the operational behavior that occurs within a curve. Figueroa Medina and Tarko (2005) illustrated these phases with the image of a simplified speed profile shown in Figure 2.2. One of the simplified characteristics is the navigation that occurs within the curve: the curves examined in this dissertation are usually not long enough for the driver to identify an ideal comfortable speed within the curve and continue navigating at that speed.

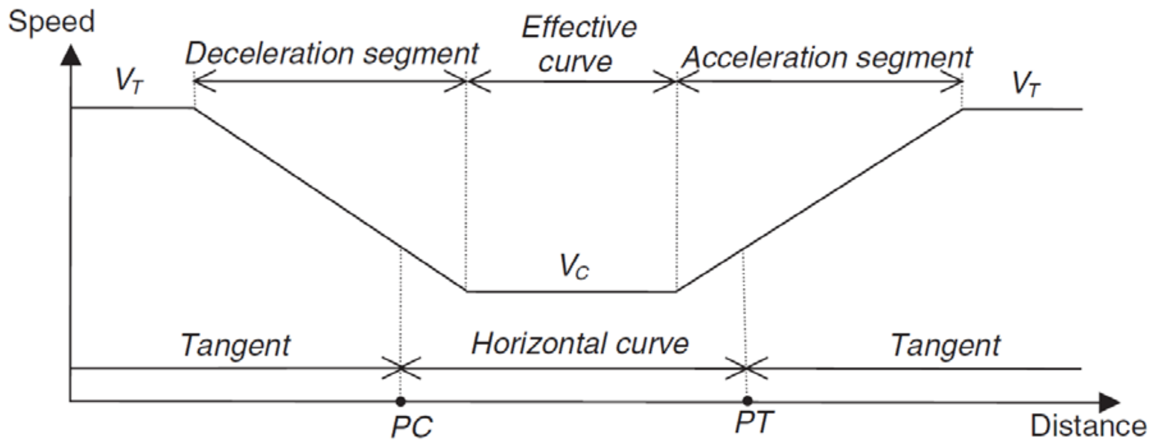


Figure 2.2: Three phases of curve negotiation: Deceleration, within-curve navigation, and acceleration (Figueroa Medina and Tarko 2005).

Figure 2.3 shows the actual speed profiles of two participant drivers at one curve from data collected in this study. The speeds are shown starting at 1,000 ft before the curve and continuing for 1,000 ft after the curve. The total length of the downstream tangent (even extending beyond 1,000 ft) is much shorter than that of the upstream tangent, which explains why the drivers do not reach their previous approach speed downstream from the curve. Small deviations in speed are visible because the data were collected at a rate of 10 Hz from a GPS receiver. A visual comparison of Figures 2.2 and 2.3 reveals some clear complexities to characterizing actual driver behavior. First, drivers do not decelerate at constant rates during the deceleration phase. The deceleration rate increases as the driver gets closer and closer to the curve. Second, the speed selected within the curve is not constant. Participant 18 (blue) does maintain a curve speed between 36 and 38 mph near the midpoint of the curve, but Participant 19 (red) decelerates to 35 mph near the end of the curve before immediately beginning to accelerate. Another interesting observation is that, while speeds of the two drivers differ by up to 8 mph on the tangents, they are quite similar within the curve.

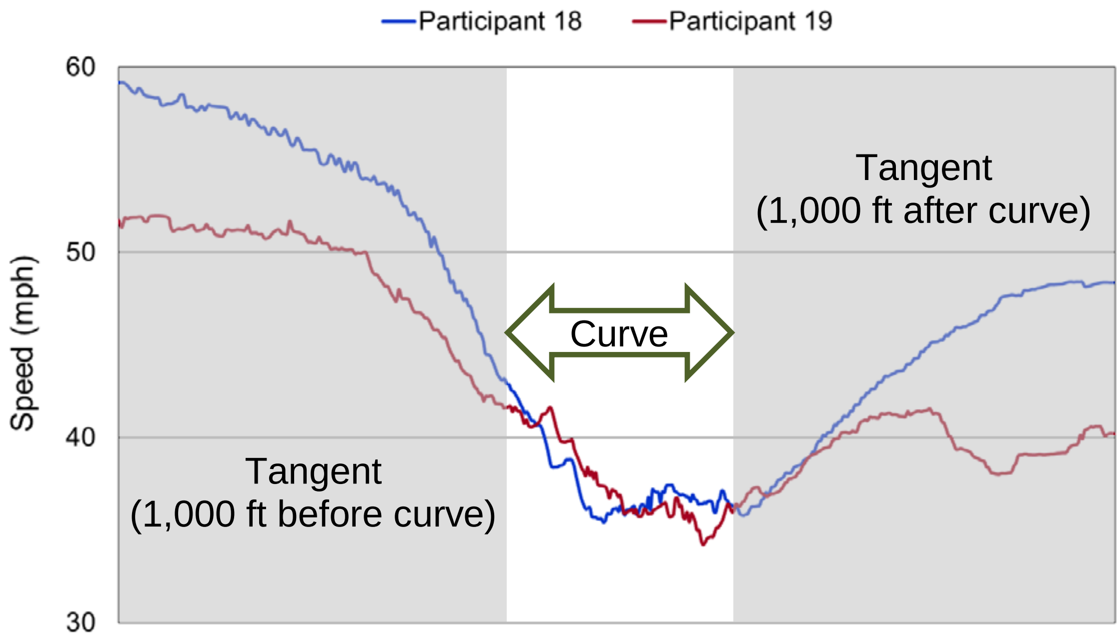


Figure 2.3: Speed profiles of two participant drivers at one curve.

Most of the models of operational metrics at curves have focused on speed and include the effect of radius (or degree of curvature) as the principal independent variable. A number of other influencing geometric factors have been identified, such as curve length, deflection angle, approach tangent length, vertical grade, superelevation, lane width, and shoulder width (Lamm and Choueiri 1987; Krammes et al. 1995; Fitzpatrick et al. 2000; Ottesen and Krammes 2000; McFadden and Elefteriadou 2000; Gibreel et al. 2001). Operational speeds on the approach tangent have also been found to significantly affect speeds within the curve (Bonneson 2000; Bonneson et al. 2007; McFadden and Elefteriadou 2000). The models indicate that if there are two curves of identical geometry, the one that has a higher approach speed will have a higher operating speed. Bonneson (2000) suggests that this happens because drivers are reluctant to decelerate at curves, even though they recognize there is a need to do so.

2.1.2. Navigational Strategies: Visual Behavior at Curves

One of the first evaluations of the visual behavior of drivers at curves was attributed to Shinar et al. (1977). They investigated how eye movements differ when drivers are on a straight road with no approaching visible curve, on an approach immediately before a curve, and on the curve. The researchers found that lateral eye movements generally follow the direction of the curve beginning 2-3 seconds before entering the curve. In terms of vertical movements, the eyes exhibited patterns of fixations far ahead of the vehicle, followed by brief fixations near the vehicle, as if the driver needs verification of lane position. Based on the fixations on the road and scenery while the driver is on approach tangents compared to fixations when on curves alone, the researchers concluded that the process of curve negotiation starts before the curve, indicating the importance of the visual behavior on the approach.

Cohen and Studach (1977) also performed an early study of driver visual behavior on curves. They evaluated the duration and location of fixations for inexperienced and experienced drivers approaching and navigating curves. Fixations were different based on curve direction, and they found that the fixations of experienced drivers compared to those of inexperienced drivers were shorter and covered a greater horizontal distribution (which indicates more searching), confirming earlier findings of Mourant and Rockwell (1972). As drivers approached a curve, the duration of the fixations decreased and they were directed in the direction of the curve, similar to findings by Shinar et al. (1977).

To reinforce the importance of previous findings regarding visual behavior on curve approaches, Lehtonen et al. (2012) studied how eye movements on approaches change under different conditions of driver cognitive workload. They suggest that glances toward the occlusion point (the location where the curve becomes hidden from view) indicate that the driver is anticipating potential hazards and searching for additional roadway information. While other points along the road are used for steering and maintaining appropriate lane placement, such as locations near to and far from the vehicle (Salvucci and Gray 2004), this focusing on the occlusion point is critical to judging curve severity and is different for each curve depending on the local conditions. In the study conducted by Lehtonen et al. (2012), the researchers presented drivers with mathematical tasks during one of three runs with each participant. Each “loaded” run included cognitive loads placed on the drivers that required use of their working memory. During the two “free” runs, drivers made anticipatory eye movements more frequently than during the one loaded run. These studies indicate that anticipatory eye movements are an important part of the driving task, specifically as they relate to noticing potential hazards (such as curves) and determining a strategy for navigating them.

2.2. Attention

The information available regarding the role of attention in the driving task has evolved as new technology provides researchers with better information about the role of a driver’s cognition. With external technology (e.g., cell phones) being used in vehicles, there has been a surge of discussion recently about distracted driving, its effect on safety, and how distractions can be reduced or eliminated. The purpose of evaluating attention in this dissertation is to identify how the driver’s cognitive state changes throughout the process of acquiring information and executing tasks associated with negotiating curves.

Some of the research on driver attention has evaluated specific eye movements and identified the objects or locations on which drivers fixate. For example, it has been found that inattentive drivers tend to experience tunnel vision, which means that they fixate less on objects in the periphery, such as their mirrors, dashboard, roadside objects, or other locations that deserve attention for safe driving (Rantanen and Goldberg 1999; Harbluk et al. 2002). In a comprehensive distracted driving study (Strayer et al. 2013) involving tasks with external workloads, drivers were less likely to make necessary glances to scan left and right for hazards at critical locations (such as four-way stops, two-way stops, and crosswalks) when placed under additional cognitive loads. Harbluk et al. (2007) similarly observed that drivers made fewer glances at traffic signals or glances to inspect the areas around intersections when drivers had to complete additional tasks. Drivers expect potential conflicts at intersections, so the visual behavior desired at intersections is easy to define because there is an expected protocol (and legal basis) for how road users interact with each other at these locations. For curves on an open highway, however, there is not a defined preferable behavior that establishes what drivers *should* fixate on.

Sayer et al. (2005) found that secondary tasks (such as eating or using a cell phone) had relatively little effect on basic measures of driver performance in a naturalistic driving study. They noted that some of these tasks affected driver visual behavior, but not enough to compromise driver safety. Sayer et al. discuss how researchers Caird et al. (2008) and Horrey and Wickens (2006) observed that the effects of secondary tasks on performance seem to be most noticeable in laboratory settings (such as a simulator or on a closed-course), with less effect as the study becomes more and more naturalistic. They suggest that effects of inattention may be more noticeable in laboratory settings, because the studies tend to include planned "unexpected" events with potential safety implications and the participants are not as motivated to perform as well. Under naturalistic conditions, the driver can choose when to perform a given task based on the challenges presented by the environment. Additionally, recognizing the real threat to safety, the driver may also exert greater attention to compensate for the cognitive load of the secondary task.

Because it cannot be determined what exactly a driver is processing, we cannot fully claim the driver is attentive or not. The driver may be exhibiting inattentional blindness, which occurs when a person's gaze is directed at an object without cognitively processing information about that object. In other words, there are some situations where a driver may fixate on the road, barely exerting the mental effort necessary to process the information, but can still drive adequately for the immediate conditions. This can occur on tangents, where the straight and continuous alignment allows the driver to relax because visual resources are not as demanding as on curves (Wooldridge et al. 2000).

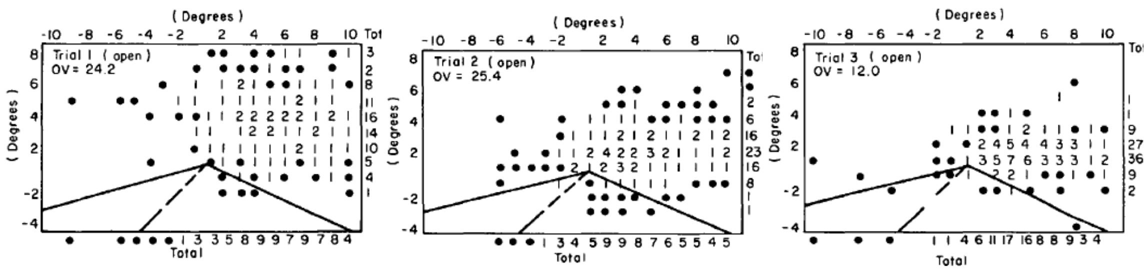
Driver attention in this research will be derived from the drivers' visual behavior and their related psychophysiological responses. The following visual behavior and physiological measures are used: fixation location, pupil size, eye closure, and blink rate. These metrics are obtained continuously along each segment rather than defined by single glances. The following subsections discuss their use in evaluating a person's cognition. Where possible, examples involving driving are given, but some of the metrics are new enough that they have not been evaluated in a driving environment. In those cases, findings from other research are discussed.

2.2.1. Measures of Visual Attention

There are a number of ways to collect data that characterize a person's cognitive state. Eye-tracking cameras have become the standard for measuring driver attention because of the implied connection between where a driver looks and what the driver is thinking. The metrics of visual attention in this dissertation are the fixation location, pupil size, percent eye closure, and blink rate. A discussion of these metrics follows.

2.2.1.1. Fixation Location

The most notable early research on driver visual behavior was performed over 40 years ago by researchers Mourant and Rockwell (1970) who identified the location of fixations of drivers who repeatedly drove the same section of road. The drivers were specifically instructed to view all of the traffic signs during the first phase of the experiment, and then fewer and fewer signs as they repeated the course. Naturally, Mourant and Rockwell were able to show that driver gazes are shifted up and to the right when the driver is unfamiliar with a road, as simulated by the participants intentionally looking at each sign. They produced the images in Figure 2.4 that show the location and concentration of the gazes based on percent time at intersecting coordinates. The dispersion in the fixations becomes smaller and smaller as the drivers become more and more familiar, having been instructed to direct fewer fixations to the traffic signs.



(a) Look at every sign (b) Look at fewer signs (c) Look at signs as little as possible

Figure 2.4: Percent fixation time by location for one driver with progressive familiarity (Mourant and Rockwell 1970).

Differences in visual patterns between novice and experienced drivers were next investigated (Mourant and Rockwell 1972). The glances of novice drivers covered a narrower horizontal field than those of the experienced drivers. Also, the vertical components of the novice drivers' fixations were lower, indicative of a shorter preview distance. The findings of Cohen and Studach (1977) similarly show that experienced drivers sample the visual field more broadly than inexperienced drivers. Research mentioned above (Shinar et al. 1977; Cohen and Studach 1977) identifies fixations near curves; other research discussed below (Zwahlen 1981; Zwahlen and Schnell 1998a; Zwahlen and Schnell 1998b) identifies fixations associated with TCDs. The fixation location is only one part of describing driver attention. Other eye-tracking data contribute to a more-complete picture.

2.2.1.2. Pupil Size

The pupil is the part of the eye through which light enters before being processed as visual information. Pupils dilate and contract as a reflex to the amount of light entering the eye: contractions occur when encountering bright conditions, dilations with dim conditions. The reflex can be as great as 2 or 3 millimeters in diameter, depending on the lighting and the size of the person's pupil. Wang's (2011) review of studies on pupil dilations discusses how pupils may dilate as one of a number of cognitive or emotional responses. Cognitively demanding processes lead to a peak dilation about 1-2 seconds after the stimulus (Beatty 1982), followed by a contraction back to a relaxed size after the task (Beatty 1982; Bernhardt et al. 1996). The involuntary contractions and dilations that occur in response to an individual's cognition tend to be smaller than the response to lighting and are often less than 0.5 mm. These small movements have been used as a metric called task-evoked pupillary response (Beatty and Lucero-Wagoner 2000).

Finley et al. (2013) observed that pupil size changes with age: older people tend to have smaller pupils. They also found that the response to light tends to decrease with age. While this dissertation does not examine separately the effects of age on pupil size and dilations, the observations by Finley et al. demonstrate the importance of accounting for the differences between subjects when analyzing pupillary responses.

Recarte and Nunes (2003) performed an open-road study that required drivers to detect small lights and their flashing pattern inside the vehicle and perform additional cognitive tasks (listening to a message and repeating it in their own words). They only found significant differences in pupil size for some of the tasks involving more complex workload, such as speaking back the message or performing calculations. One of the difficulties in evaluating pupil size is that it may be unclear when to establish starting and stopping times for pupil measurements, or how to establish a resting size of the participants' pupils. Recarte and Nunes do not state what they did with these limitations, but it seems they reported averages of the pupil diameter of all participants, which masks some of the individual changes experienced and limits what can be inferred by the results. By repeating some of the elements of that study in a laboratory, Recarte et al. (2008) showed increases in pupil size when the subject performed a visual search with no additional cognitive tasks. When the subjects were required to talk or perform a calculation (both with and without a concurrent visual search), the dilation was even greater.

In a study of participants driving a simulator while involved in a cognitively-demanding game, Palinko et al. (2010) observed pupils to increase in diameter by approximately 0.15 mm during the more-demanding tasks. A number of studies have been conducted completely outside of a driving environment. Hyönä et al. (1995) measured the pupil diameter while participants were involved in orally translating a text from English to Finnish. When interpreting, the average pupil size was almost 1 mm larger than when listening. Additionally, the pupils generally decreased in size throughout the duration of the task, indicating a degree of acclimation or comfort achieved. Klingner et al. (2008) replicated some work completed 30 years earlier, evaluating pupil size during three tasks: 1) multiplication, 2) memorizing and repeating a sequence of digits, and 3) anticipating an error in a sequence of numbers. Graphs from individual participants show pupil dilations approximately 0.3 to 0.6 mm. Greater responses occurred with increased workload.

In pupillometry, Wang (2011) emphasizes the importance of maintaining a controlled experiment to correctly interpret pupillary responses. The eye-tracking equipment used in the current study reports instantaneous pupil size as a single value of diameter in millimeters, but is only available with data collected at night. There are a number of measures that can be extracted from processing the raw data. Two of the metrics suggested by Beatty and Lucero-Wagoner (2000) will be applied in this research: the peak dilation and the latency to peak dilation. The peak dilation is calculated as the difference between the maximum diameter observed during the period of interest and a baseline value. It provides a measure of magnitude that may reflect the level of workload for a specific situation. The latency to peak is the amount of time that occurs from the start of the period of interest to the maximum value (peak). The latency to peak metric will be adapted to identify when (or, for this study, where) the drivers perceive an upcoming curve based on an observed increase in cognitive load.

2.2.1.3. Eye Closure

The percentage of the eye covered by the eyelid is another physiological measure that can be indicative of a driver's cognitive state. A large portion of driving research evaluating the eye closure of drivers has focused on drowsy driving (Bergasa et al. 2006; Sigari et al. 2013; Dasgupta et al. 2013). It is understood that as drivers become less alert, the proportion of the eye covered by the eyelid increases, or in other words, the eye becomes more closed. Investigations of eye closure while driving, outside of research on drowsy driving, have been sparse. Similar to changes in pupil size, changes in how much the eyelid covers the eye signifies a change in the subject's cognition. Wang et al. (2014) found that eye closure of drivers decreases when the traffic signal at an upcoming intersection changes to red and also while waiting for the indication to turn green. Additionally, Wang et al. show that the driver's eye closure decreases during an overtaking and passing maneuver.

2.2.1.4. Blink Rate

The primary function of blinking is to provide moisture to the eye. Drew (1951) observed that the rate at which a subject blinks tends to be approximately constant under constant conditions, but that an individual's blink rate is inversely related with the difficulty of a task (fewer blinks under higher workload). Drew comments that sometimes no blinking occurs during isolated period of maximum difficulty, while blinking occurs just before and after those periods. Other researchers have observed decreases in blink rate with more cognitively-demanding tasks (Acosta et al. 1999; Freudenthaler et al. 2003), and it has been suggested that people suppress the urge to blink to avoid gaps during the continuous flow of visual information (Nakano et al. 2009). The period of time that a blink affects information acquisition has been estimated to be near 400 ms (VanderWerf et al. 2003; Volkmann et al. 1980). Like metrics of pupil size and eye closure, changes in a driver's blink rate while on a curve approach may indicate a cognitive response associated with navigating curves.

2.2.2. Connections between Visual Attention and Performance

A large amount of resources have been directed at investigating how distractions affect driving performance. For example, in-vehicle displays, electronic devices, and activities with additional cognitive loads have been shown to negatively affect drivers, in terms of both operational performance and visual behavior (Harbluk et al. 2002; Harbluk et al. 2007; Yang et al. 2012; Strayer et al. 2013). And the 100-car naturalistic driving study (Klauer et al. 2006) successfully identified some consistent links between driver visual behavior and events directly tied to safety, whether actual crashes or near-crash occurrences. It is clear that overall performance decreases when drivers exhibit decreased levels of attention.

After characterizing the visual behavior of drivers as they approach curves, the next step is to identify the effect that cognitive measures attributed to advance preparation have on operational performance at curves. Most studies of driver performance and attention have focused both on intentional distractions (caused by additional cognitive loads) and on performance during critical events (such as at intersections or unexpected stopping and braking situations). Curves are expected road features that drivers encounter frequently and should be able to navigate smoothly and naturally. Regardless, curves remain locations of high crash rates. It is thought that if drivers exhibit greater changes in visual attention before curves or they experience the changes earlier (signifying that they perceive the curve earlier), their operational performance will improve. A confirmation of this hypothesis indicates that driver performance is a direct result of attention, which should not be surprising considering the past research summarized here. Significant value will be added if effects on visual attention and cognition are attributable to the use of TCDs.

2.3. Traffic Control Devices (TCDs)

The MUTCD identifies five basic requirements that an effective TCD should meet (FHWA 2009). They are:

1. Fulfill a need;
2. Command attention;
3. Convey a clear and simple meaning;
4. Command respect from road users; and
5. Give adequate time for a proper response.

For curve TCDs, fulfillment of the five requirements means that the TCDs provide information at the right place and time for the road user (presumably a driver) to navigate the curve with operational behavior that is comfortable and natural. If the driver has to make a sudden braking or steering maneuver in order to maintain position within the lane, it may be that the TCDs are improperly placed or inadequate for the conditions. If TCDs are present but the curve is not severe enough for them to fulfill a need, then the TCDs will lose respect from the users. The following discussion focuses on the TCDs that are traditionally used at curves and examined within this study, including their effects on both driver operational performance and visual behavior.

2.3.1. TCDs used at Curves

Guidelines within the MUTCD prescribe certain devices for curves based on severity as measured by the difference between the operating speed of the approach and the advisory speed of the curve (referred to as the speed differential). Figure 2.5 is an adaptation of the guidelines contained within Table 2C-5 of the 2009 MUTCD, identifying the TCDs to be used at changes in horizontal alignment. As shown in Figure 2.5, an advance warning sign with advisory speed plaque is required at a curve with a speed differential 10 mph or greater. Chevrons or a one direction large arrow sign are required when the speed differential is 15 mph and greater. There is a logical progression of more devices required as the severity of the curve increases.

Type of Sign	Difference Between Operating and Curve Advisory Speeds		
	5 mph	10 mph	15 mph
Advance Warning Sign (W1-1 through W1-5)	Recommended	Required	Required
Advisory Speed Plaque (W13-1P)	Recommended	Required	Required
Chevrons (W1-8) or One Direction Large Arrow (W1-6)	Optional	Recommended	Required

Figure 2.5: MUTCD Table 2C-5 (adapted from [FHWA 2009]), indicating the conditions that prescribe additional traffic control at curves.

Pavement markings are not included in Table 2C-5, although they are required on highways with traffic volumes greater than 6,000 veh/day. Regarding curves on traditional highways, Table 2C-5 in the MUTCD only specifies the use of advance warning signs, advisory speed plaques, chevrons, and one direction large arrow signs. Agencies are allowed to use other devices at horizontal curves, provided the MUTCD requirements are met. Post-mounted delineators (PMDs) are one such device. The evaluation of driver behavior in this dissertation includes consideration for the effects of PMDs, large arrows, and chevrons. Each of these devices is placed on the outside of the curve, with the spacing of PMDs and chevrons determined by the curve radius. Examples of their appearance and placement are shown in Figure 2.6. These TCDs are referred to as “supplementary” because they are traditionally used in addition to advance warning signs (from the requirements in the MUTCD). Their effects will be tested at locations where warning signs are already in use.

(a) Delineators (b) Large Arrow Sign (c) Chevrons

Figure 2.6: Supplementary TCDs used in this study.

TCDs at curves can be particularly beneficial at night when drivers do not have as many visual cues (such as the surrounding environment or traffic) that may indicate the presence or severity of curves. Retroreflective sheeting on traffic signs increases sign visibility when illuminated by headlamps. In rural areas where few other objects compete for a driver’s attention, reflective traffic signs can be very conspicuous. By dimensions, the standard height of one direction large arrow and chevron signs is 24 in, which is smaller than one side of a diamond-shaped curve warning sign. Large arrow signs, however, are quite wide (48 in), and multiple chevrons (18 in wide each) are used at curves. The signs are oriented vertically and placed on the outside of a curve in line with the approaching vehicle, which contribute to an increased brightness based on properties of retroreflectivity. A series of chevrons or a single large arrow can thus be detected by drivers several hundred feet in advance of a curve.

The retroreflective sheeting on PMDs tends to be small (usually 3 in wide and 4 in tall). To increase overall conspicuity, the spacing guidelines in the MUTCD indicate that approximately twice as many PMDs as chevrons should be used, depending on the curve radius. PMDs are not very conspicuous during the daytime, but their placement and reflective sheeting also make them quite prominent at night when illuminated by headlamps. Figure 2.7 shows examples of PMDs, a one direction large arrow sign, and chevrons on curves at night.

(a) Delineators (b) Large Arrow Sign (c) Chevrons

Figure 2.7: Supplementary curve TCDs at night.

In a study where drivers were actively searching for curve advance warning signs at night, all participants were able to recognize the sign at a distance of 600 ft, which corresponds to a legibility index of over 40 ft/in (Zwahlen and Schnell 1998b). This legibility index is greater than the index suggested by the MUTCD for word messages (30 ft/in), which is not surprising since symbolic signs tend to be easier to read. Other research has shown that drivers can recognize warning signs several hundred feet in advance of the sign (Paniati 1988; Zwahlen et al. 1991). Based on the physical similarities between warning signs, large arrows, and chevrons, large arrows and chevrons should also be visible at great distances. Due to their size, PMDs may not be quite as visible.

The value of supplementary TCDs at night may be illustrated by comparing the distance at which warning signs are visible (perhaps up to 600 ft from the sign) with the distances at which curves are visible by pavement markings alone. Zwahlen and Schnell (1999) used old and young participants to identify the visibility of pavement markings with medium (R_L = 268 mcd/m^2/lx for white markings) and high (R_L = 706 mcd/m^2/lx for white markings) retroreflectivity under low-beam and high-beam illumination. The average detection distance for older subjects with pavement markings of medium retroreflectivity illuminated by low beam headlamps was approximately 400 ft. High beams and higher retroreflectivity slightly increased the detection distance. The young participants had longer average detection distances (an increase of 200-300 ft). In an earlier study by Zwahlen and Schnell (1995), they found that 95 percent of young drivers detected a right curve at 265 ft and a left curve at 220 ft using a single right edgeline alone (radius = 800 ft). When comparing the visibility distances of pavement markings to signs or other supplementary TCDs placed at the curve, it is clear that the additional TCDs can substantially increase the distance at which an approaching driver identifies the curve.

2.3.2. Effects of TCDs on Driver Behavior

The effects of TCDs on driver behavior have been studied extensively. The following subsections summarize these findings, describing how TCDs affect behavior at an operational and visual level. Only for operational performance has there been enough research to exclusively focus on the effects of supplementary TCDs.

2.3.2.1. Effects of Supplementary TCDs on Operational Performance

Studies of PMDs have produced mixed results. Vest et al. (2005) observed increases in speed at two out of three locations, and Zador et al. (1987) and Kallberg (1993) also found that PMDs lead to an increase in speeds (about 1.5 mph in the former study). Kallberg (1993) found significant increases in speed at nighttime (with insignificant increases during the daytime) and suggested that the increase in speed due to the PMDs led to increased crashes. Chrysler et al. (2009) observed some decreases in speed, approximately 2 mph or less, though the changes were not significant.

Using a simulator, Molino et al. (2010) developed profiles for speeds on the approach and within the curve, showing that speeds were lower for curves that had delineators. They compared the effects of three traffic control treatments at curves: edge lines alone, edge lines with PMDs, or edge lines with PMDs that have light-emitting diodes (LEDs). In the simulation, drivers reduced their speeds by an average of 2 mph when only edge lines provided delineation, 7-8 mph when edge lines and PMDs were used, and 9 mph when edge lines and PMDs with LEDs were used. The simulation clearly identified increases in driver response with enhanced delineation. The LEDs also substantially increased the distance at which curves could be detected.

One direction large arrow signs tend to be used less frequently than chevrons, though the hierarchy of signs for curves in the MUTCD (see Figure 2.5) considers a large arrow sign “equal” to a series of chevrons. Perhaps because it is used infrequently compared to other devices, the large arrow sign has received quite limited attention in evaluations of driver performance. Vest et al. (2005) observed mixed results regarding changes in average speed at one curve where a large arrow sign was tested, but it was very effective at reducing extreme speeds (above the 85th percentile).

Chevrons have received much more attention by researchers than the other two devices. From a closed-course evaluation, Johnston (1983) observed chevrons to encourage decreased speeds at night. However, increased speeds during the daytime were attributed to the enhanced driver confidence and comfort provided by the chevrons. In-field tests by Jennings and Demetsky (1983) and Zador et al. (1987) near the same time identified mixed or no significant changes in speed due to chevrons. In-field and open-road tests by Agent and Creasey (1986), Chrysler et al. (2009), Re et al. (2010), and Bullough et al. (2012) found chevrons to effectively reduce driver speeds, at least during one period of the day, and usually by about 2 mph at the PC or midpoint of the curve. Using a simulator, Charlton (2007) observed that chevrons to encourage lower average speeds on curves than warning signs alone. Chevron boards (which are not used in the United States) were also tested and produced similar results. Carlson et al. (2004) observed changes in performance after increasing the number of chevrons already in place at a curve. They identified speed reductions greater than 2.6 mph, with the benefit appearing to increase as the severity of the curve increases. Researchers have also observed reductions in speed after applying reflective sheeting on chevron sign posts (Chrysler et al. 2009; Hallmark et al. 2012).

The study performed by Chrysler et al. (2009) produced important information that extends beyond observed changes in speed when PMDs or chevrons were used at curves. The investigation of speed reductions at curves was performed with data collected by vehicle sensors placed on an open road. Another part of the study involved a closed-course driving test during which drivers repeatedly approached and navigated through a series of curves that received various treatments with each repetition. The researchers recorded the distance from the curve at which the driver acknowledged being confident about the severity of the curve and the distances at which the driver stopped throttling the accelerator and first depressed the brake. When no treatment was used (pavement markings only) the distance at which the driver was confident about knowing the curve severity was approximately 220 ft from the midpoint of the curve. When vertical delineation was used, the distance increased by 100-250 ft. The distances at which drivers stopped throttling the accelerator and began to depress the brake also increased, though not by much. The maximum lateral acceleration observed at the curves was also greater when no treatment was present.

It is interesting to note that when speeds decreased in response to delineation devices, researchers have commented that the effect is due to drivers becoming more cautious from receiving critical alignment information. In cases where speeds increased, researchers have attributed the increase to drivers having more confidence due also to the alignment information provided by the devices. It is possible that both explanations can be correct depending on the specific characteristics of the curves and drivers, but the findings (and explanations) seem to be in conflict. It is suggested that these studies of TCD effectiveness using driver speeds are limited by the simplicity of only measuring speed at few locations near and within the curve. Vehicle speed at one location poorly captures the complexity of driver behavior. Metrics with greater detail are needed to better represent the operational nuances of curve navigation.

An example of one metric that provides more detail than the speed alone at the PC is the difference in speed between the PC and midpoint. An improvement in performance is a reduction in that speed differential, which likely indicates a shift of even more speed change occurring in advance of the curve. Chrysler et al. (2009) observed that chevrons and delineators both mostly led to reductions in speed changes. The treatments were not tested at the same curves, so direct comparisons may not be appropriate, but chevrons produced lower speed differentials more consistently than delineators. This is one example of how the complexity of driver behavior can be better characterized with more-descriptive metrics.

2.3.2.2. Effects of TCDs on Visual Behavior

Drivers generally do not seek out warning devices in the same way they might search for directional or guidance devices. Curve warning devices fit with the description of “real-world” warnings by Wickens et al. (2009). According to Wickens et al., real-world warnings can be described by the NT-SEEV model, where attention to them is based on the time to be noticed (*NT*), the salience (*S*) of the object or event, the effort (*E*) to direct attention to the object, the expectancy (*E*) of there being new information, and the value (*V*) of that information. For TCDs, these factors are affected by the material properties of the device, the device’s location, and characteristics specific to each driver. If, for example, the device is not in the proper location or made from proper material, it may poorly attract attention.

Traffic signs, like all TCDs, are expected to command attention, so some fixations should be directed at them. Zwahlen (1995) found that the duration of fixations directed at signs is quite short, but that drivers do look at signs multiple times. It is thus expected that the majority of fixations are primarily directed at the immediate road scene (including pavement markings) while drivers search for and then anticipate upcoming changes in alignment. Zwahlen (1987) also evaluated the differences in driver fixations on curve warning signs when there is and is not an additional advisory speed. The distance at which drivers first looked at the signs ranged from 250 to 550 ft before the sign, and fixations lasted about 0.5 seconds. There were not consistent differences between daytime and nighttime fixations or when there was an advisory speed displayed.

In a similar study of fixations as drivers approached a stop sign (Zwahlen 1988), longer fixation durations and greater first look distances were observed, perhaps a result of the importance of the message and size of the stop sign compared to the curve warning signs. Other studies have employed similar metrics to describe driver behavior in different scenarios (Zwahlen 1981; Zwahlen and Schnell 1998a; Schnell and Zwahlen 1999; Zwahlen et al. 2003). The difficulty in applying the metrics used in these studies is that they are somewhat uninformative. The number of fixations on a device, their duration, or the distance from the target when they are made are descriptions of visual behavior, but difficult to apply in understanding attention or defining a desirable response. Supplementary TCDs at curves should not require long fixations because the message is not complex. These devices convey different information than other warning devices, so there should be a different method of analyzing their effectiveness.

In a study conducted by TTI (Theiss et al. 2013), driver visual behavior was evaluated as participants drove through work zones that were delineated by different types of barriers. One objective was to compare how channelizing drums with warning lights affect drivers compared to drums without warning lights. Another objective was to compare the effects of retroreflective delineators and warning lights on concrete barriers. The researchers divided the visual field into separate areas to evaluate whether or not attention allocation based on fixations to those areas changed for a given condition. They had trouble identifying consistencies because participants within the same test condition had substantially different fixation durations and locations. Some of the difficulty was attributed to the time change between participants that resulted in a different number of opposing vehicles within the field of view. Also, they observed that the number of fixations to the right may be directly related to the driveway density of that segment. These differences indicate there were some changes in visual behavior; however, it seems that confounding factors affected the ability to identify any substantive meaning.

Consistent changes in visual behavior when approaching a curve should indicate when anticipatory glances begin, signaling the start of the cognitive component of curve negotiation. Early work (Brimley et al. 2014) using data relevant to this dissertation showed that the location or time when drivers make these fixations with respect to a curve may change when chevrons are used. The distribution of fixations was more concentrated when chevrons were used at curves. A consistent change in fixation distribution, or perhaps fixation location, would be indicative of a change in the driver's attention.

Whether a device is installed with the intent for it to receive foveal fixations or be viewed peripherally, it is clear that objects placed within the visual field affect driver attention in some way. For TCDs, the attention should be toward the condition represented by the device. It seems, however, that the metrics that have been used to describe visual behavior under these circumstances poorly describe the cognitive element of attention. Other parameters associated with cognition may better represent driver attention.

2.4. Summary

The state of the knowledge concerning what is currently known about the behavior of drivers navigating curves, the importance of attention, how attention can be measured in the driving task, and the effects TCDs have on driver operational performance and attention has been presented in this section of the dissertation. The following is a summary of the information about driver behavior compiled in this section and recommendations for the use of innovative performance metrics that may overcome the limitations of previous research in a more-comprehensive study of driver behavior. The driver behavior study that is introduced in the Section 3 was designed to address the gaps in information that can be filled by collecting continuous observational and attentional data while drivers navigate an unfamiliar and curvy rural highway.

2.4.1. Overview of Driver Behavior

The operational behavior of drivers near curves is governed by the specific features of the curves and how the drivers perceive those features, as well as the operating characteristics of the facility. The connections between lateral acceleration and driver comfort and safety influence drivers to decelerate to reduce the lateral acceleration experienced within the curve. Driver speed within a curve is not constant, with deceleration continuing within the curve and acceleration beginning before the end of the curve. The driver continues to accelerate until reaching a desired speed. TCDs can be used at curves to provide information to drivers about the upcoming change in alignment, thus affecting the drivers' perception. Driver responses to curve TCDs have been investigated numerous times, and TCD effectiveness seems to increase as the level of warning or amount of delineation increases.

Driver fixations tend to be directed as far downstream as possible in order to anticipate changes in alignment and respond to any unexpected events. Not all time is spent fixating on the distant scene, however, because other objects within the field of view attract attention and the driver acquires information for the driving task from a variety of sources. Driver visual behavior is also influenced by the TCDs and other objects within the field of view. Decreases in driver performance have been observed when driver attention is diverted to other tasks.

2.4.2. Alternative Metrics of Operational Performance

Most of the operations data collected in previous research were obtained at one or more fixed locations within or on the approach to a curve using tools such as traffic classifying sensors, RADAR, and cameras. That information, though accurate, may not adequately describe the multi-phased process of curve negotiation that is unique to each driver and curve. For example, single speed measurements before and on a curve may not capture the full deceleration phase that can begin and end outside of the locations where the measurements are made, thus not conveying the entire response. If use of a TCD results in reduced speed at the curve, it would then be impossible to determine whether that reduction occurred because the deceleration rates of drivers were higher, they began decelerating earlier, their speeds on the tangent were lower, or some combination of the three. Figure 2.3 shows how characterizing driver speed on a curve can be quite complex.

Based on characteristics associated with negotiating curves and the images shown in Figures 2.2 and 2.3, it is suggested that the process of curve negotiation be divided into three phases: 1) acceleration after exiting the upstream curve, 2) deceleration before entering a curve, and 3) navigation within the curve. The simplest way to collect data within each of these phases is through measurements that are continuously made while drivers navigate a sequence of segments with multiple curves. The study described in this dissertation collected operational and visual behavior data continuously rather than at single points to identify in detail the way TCDs influence driver performance throughout the phases of curve negotiation. Details of the study are provided in Section 3. Continuous data allow for the use of alternative performance metrics to overcome some of the limitations of previous work. The suggested operational performance metrics are divided into each of the phases of curve navigation as discussed below.

2.4.2.1. Acceleration Exiting an Upstream Curve

Two metrics are used to characterize driver behavior when departing a curve: 1) The location at which the driver reaches maximum speed (measured as the distance downstream from the previous PT) and 2) the total increase in speed. With changes in alignment as the main highway feature that triggers changes in speeds, the location of a driver's maximum speed on a tangent and the increase in speed are the first indication of where and how a driver responds to information relevant to an upcoming curve. The location where the driver reaches a maximum speed and the magnitude of the increase characterize the point where the driver's desire for efficient travel is either satisfied by having reached a comfortable speed or suppressed by the desire to drive safely after recognizing the need to decelerate on the approach to a curve. Due to the visibility of the TCDs, it is hypothesized that their effects on driver behavior will be observed with these measures even several hundred feet from the curve.

2.4.2.2. Deceleration Entering a Curve

While approaching a curve, most drivers begin decelerating (if necessary) to a speed comfortable for navigation. Previous research has shown that an average of 66 percent of the total deceleration at curves occurred on the tangent (Figueroa Medina and Tarko 2007), with observed deceleration rates ranging from 0 to 4.4 ft/s^2 (Lamm and Choueiri 1987; Collins and Krammes 1996; Fitzpatrick et al. 2000; Figueroa Medina and Tarko 2007; Hu and Donnell 2010). Three metrics are used to evaluate driver operational performance during the deceleration phase: 1) the speed reduction that occurs before the curve, 2) the proportion of speed change that occurs before the curve compared to the total observed speed change, and 3) the maximum deceleration rate observed on the approach. The metrics of speed change are indicative of the preparation drivers make before entering the curve. More speed reduction before the curve (rather than within the curve) is preferred, particularly at sharp curves. If a larger portion of the total deceleration is completed before the curve, the driver can concentrate more on the steering component of maneuvering rather than on other tasks. At the same time, a more-conservative deceleration rate is desirable, which may negatively affect the amount of deceleration that can occur before entering the curve.

2.4.2.3. Within-Curve Performance

The speed at the PC has been investigated numerous times in previous research and reflects one element of driver behavior. Operational behavior at curves is evidently quite complex, and the use of data collected continuously along a corridor allow for other characteristics of performance within the curve to be used that may better relate to the preparation drivers make in advance of the curve. This dissertation will include prediction models for the speed at the PC as well as two other metrics of within-curve driver performance: the maximum longitudinal deceleration rate and the maximum lateral acceleration rate. The limits of the pavement-tire interface that support lateral acceleration justify using maximum lateral acceleration as a performance metric. The longitudinal deceleration rate within a curve is important because it represents how drivers continue the deceleration that began before the curve and how they respond to conditions while within the curve itself.

2.4.3. Metrics of Visual Attention

Driver attention has been evaluated in multiple contexts, but primarily only during occasions when the driver was intentionally distracted by secondary tasks. Driver visual attention can be measured with eye-tracking technology that captures metrics such as the location of a driver's fixation and physiological measurements associated with the eyes. The physiological measurements are: pupil size, eye closure, and blink rate. Changes in these measures (whether in magnitude or location where the change occurs) may reveal details about the processing of information related to the upcoming curve. As TCDs contribute to the information provided to drivers, it is hypothesized that some of the attentional changes can be attributed to the use of TCDs.

3. OPEN-ROAD DRIVING STUDY

This section documents the open-road driving study that was conducted to fulfill the objectives of the dissertation. The following subsections include a description of the study and explain how the data collected in the study were reduced for the analyses in this document.

3.1. Description of Study

As documented here, the study protocol involved having participants navigate an unfamiliar, rural two-lane highway in an instrumented vehicle. The vehicle contained equipment that collected data characterizing operational performance and parameters associated with the participant's visual attention. Data were collected in multiple states: Oregon, Idaho, and Texas.

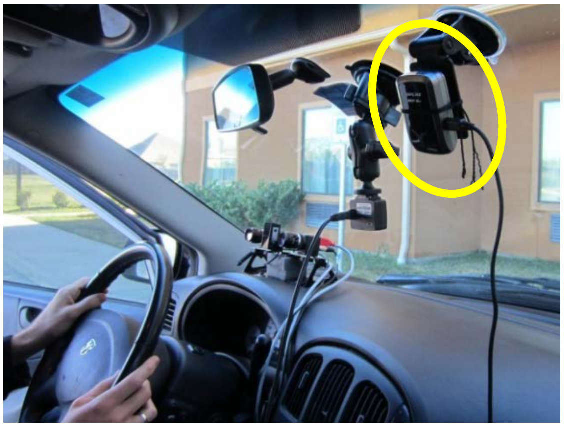
3.1.1. Study Participants

Study participants were recruited to drive an instrumented vehicle over an extended length of a rural and *unfamiliar* two-lane highway. There were 103 total participants (approximately 34 in each state). The age distribution of participants represented the demographics of drivers involved in fatal crashes on curves. As there are more "young" than "old" drivers involved in fatal crashes, there were more young than old study participants (approximately a 2:1 ratio). The median age of all participants was 23 years and the mean was 30.4 years. All were younger than 71 and more participants drove at night than during the day. Demographic data are summarized in Appendix A. Nighttime driving was emphasized because the need for TCDs as a source of information is greater at night. In order to replicate a driving experience that is as normal as possible, the participants were not required to complete any tasks other than driving on the highway. Drivers were paid $50 for their participation.

The selection of unfamiliar drivers was a fundamental component of this study. Many of the previous investigations of driver performance at curves involved collecting data in the field from drivers who are familiar, regular drivers. Drivers who are familiar with a highway and its changes in alignment are generally not the ones in need of the information curve TCDs provide, which may be one reason many in-field studies of TCDs did not produce substantial results. The effectiveness of TCDs should be determined based on the drivers who rely on them the most. That information can best be produced by monitoring the behavior of drivers who are unfamiliar with a highway.

3.1.2. Equipment

The vehicle was a 2005 Dodge Caravan equipped with various instruments to record data relevant to the driving task. Two infrared cameras mounted to the dashboard were used to track the drivers' eyes using faceLAB software produced by Seeing Machines. Eye movements were recorded at 60 Hz. A GPS receiver operating at 10 Hz was used to track the position and speed of the vehicle, and a bi-axial accelerometer also operating at 10 Hz collected measurements of longitudinal and lateral acceleration. Data collected by the eye-tracking cameras, GPS receiver, and accelerometer were stored in separate files on a laptop computer operating in the rear of the vehicle. A computer time stamp was recorded with each entry that was used to synchronize the data sources, thus identifying the simultaneous visual and operational behavior. Images of the equipment used in the vehicle for collecting data are shown in Figure 3.1.



(a)

(b)

(c)

(d)

Figure 3.1: Data collection equipment—(a) GPS receiver, (b) accelerometer, (c) eye-tracking cameras, and (d) laptop.

3.1.3. Experiment Protocol

The study was conducted during July and August 2013 in Oregon and Idaho and February 2014 in Texas. Weather conditions during data collection were optimal for driving (good visibility and no precipitation). The participants were greeted in the lobby of a nearby hotel where they were given instructions regarding the driving study. A vision test was administered, and 75 percent of all participants had a measured acuity of 20/20 or better, as documented in Appendix A. They were allowed to wear corrective lenses if necessary. One daytime participant (with a valid license) had a measured acuity of 20/50. The participants were then placed in the study vehicle and allowed to adjust basic driver comfort settings before being guided through a procedure to calibrate fixations with the infrared cameras. Following the eye-tracking calibration, they were directed to drive to the study site, allowing them to become accustomed to the new vehicle. The participants were instructed to follow all traffic laws as they drove to the end of the highway, having little information about the purpose of the study.

When the participants reached the end of the designated study route, they were instructed to return to the hotel where the study began. During the return trip, the drivers were led to believe the instrumentation in the vehicle was no longer collecting data, while all devices were actually still running and data being stored on the computer. This element of deception for the return trip was incorporated into the study to further encourage the participants to drive as naturally and comfortably as possible. The analyses reported later do not differentiate for when drivers were aware they were being monitored and when they believed the instrumentation was not operating. Though preliminary analysis has shown the drivers are more aggressive (or, perhaps, more comfortable) during the return trip, it is not believed that a differentiation is meaningful to fulfill the objectives of this dissertation.

Throughout the drive, the participants were discouraged from using the vehicle's cruise control, and the frequency and severity of some of the curves encountered generally made it impractical to do so anyway. This made it possible to obtain distinct periods of acceleration (as drivers exited curves) and deceleration (as drivers approached curves). Because traffic was very light, the participants were usually able to drive under free-flow conditions. There were occasions, however, when a participant encroached upon another vehicle traveling in the same direction. When that occurred, the participant was instructed to stop at the first reasonable location and wait to generate a substantial distance between the vehicles. During post-processing, any data collected when a participant driver was following another vehicle were discarded.

3.1.4. Study Sites

From the three study corridors, 167 total changes in alignment were identified as study curves. Each corridor was divided into various segments that begin at the end of an upstream curve where a tangent begins and continue until the PT of the downstream study curve. Because data were collected in both directions on the highway, each study curve can potentially appear in the analysis twice as two different curves, because the alternative direction of the curve and operational characteristics of the two different approaches produce two unique experiences for the unfamiliar driver. Not every change in alignment was identified as a curve suitable for inclusion in the analysis.

The following geometric data were collected for each curve/segment:

- Radius (ft)
- Deflection (deg)
- Superelevation (percent)
- Curve direction
- Curve length (ft)
- Approach tangent length (ft)

Table 3.1 contains a descriptive summary of the study curves identified in the three states. Note that data regarding vertical curvature were not explicitly collected. The site in Texas had gently rolling hills, while the sites in Idaho and Oregon were reasonably flat, as they were next to rivers. Due to the elevation changes at some of the horizontal curves in Texas, some of the curves were not included in the database which would have clearly influenced the visibility of the TCDs at the curve and the drivers' responses.

Table 3.1: Characteristics of Study Sites

	Oregon		Idaho		Texas	
Number of Curves	39		70		58	
Posted Speed Limit (mph)	55		45–55		60	
	Min.	Max.	Min.	Max.	Min.	Max.
Radius (ft)	690	5,670	420	2,150	55	1,250
Deflection Angle (deg)	22	151	14	123	7	90
Tangent Length (ft)	490	10,400	140	6,300	140	5,900
Posted Advisory Speed (mph)*	40	45	35	45	15	50

*Represents only the curves treated with a warning sign and posted advisory speed. The posted advisory speeds were not validated.

3.1.5. Installation of Delineators and One Direction Large Arrow Signs in Texas

Inspection of the radii reported in Table 3.1 reveals that the curves on the selected highway in Texas tend to be more severe than the curves on the two highways in Oregon and Idaho. In fact, there are seven locations on the Texas corridor treated with chevrons and one location treated with one direction large arrow signs. In Oregon, two locations had been treated with chevrons, and none in Idaho. There are several untreated curves in Texas whose geometry is similar to those that are treated with chevrons. It was determined that the corridor in Texas was suitable for an evaluation of supplementary devices, and the installation of PMDs and large arrow signs at these untreated curves would create an opportunity to model driver behavior under different conditions.

Eight locations in Texas were selected to receive a treatment of either PMDs or one direction large arrow signs during the study. Each treatment, however, was in place for only half of the participants, which allowed data to be collected for each of those curves under conditions when the treatment was and was not present. Chevrons remained at the locations where they were originally installed. In order for the participants to navigate some curves with PMDs or a large arrow sign present, and other drivers to navigate the same curves without the treatment, the data collection was divided into two phases as outlined in Table 3.2. PMDs were temporarily installed at three locations for the first phase and two locations for the second phase. Large arrow signs were temporarily installed at two different locations during each phase. One location (Location 6 in Table 3.2) received a different treatment during both phases; all other locations were treated only once.

Table 3.2: Treatments Installed on Curves in Texas

Location	Phase 1	Phase 2
1	Delineators	Nothing
2	Nothing	Delineators
3	Delineators	Nothing
4	Large Arrow	Nothing
5	Nothing	Large Arrow
6	Large Arrow	Delineators
7	Delineators	Nothing
8	Nothing	Large Arrow

It was mentioned that data were not analyzed for both directions of navigation at every curve. The selection of data for analysis was based on identifying appropriate subsets of curves that are similar in physical and operating characteristics. In the analyses that include the effects of supplementary devices (Sections 5 and 6), there are seven curves treated with PMDs, four with one direction large arrow signs, and ten with chevrons. Eleven curves with warning signs that never received a supplemental treatment were included in the analyses. For identifying the effects of supplementary TCDs, warning signs are considered the “base” condition. Supplementary TCDs in addition to the warning signs are the test condition.

3.2. Data Reduction

A discussion of the data collected by the different pieces of equipment is provided below, followed by a discussion of how the measures of effectiveness were extracted from the data to perform the analyses in the subsequent sections.

3.2.1. Raw Data

The data collected in this study were divided into two categories: operations and eye-tracking. The operational data are derived from the raw data provided by the GPS receiver and accelerometer and include the vehicle's speed and longitudinal and lateral acceleration. The visual attention data are derived from the eye-tracking output files and include the fixation angle displacement, pupil diameter, eye closure, and blinks for each eye.

3.2.1.1. Data Sources

The GPS receiver and accelerometer operated at 10 Hz, each providing one data entry per tenth of a second. The Eye-tracker operated at 60 Hz, providing one entry per 0.0167 s. Each trip with the study participants lasted at least 1 hour. Over the course of an hour, the GPS receiver and accelerometer log 36,000 entries and the eye-tracker logs 216,000 entries. There are several extraneous data values logged by each data source. The critical values of raw data used in the study are listed below.

GPS receiver:

- Computer time stamp
- Longitude and Latitude
- Speed (mph)

Accelerometer:

- Computer time stamp
- Longitudinal acceleration (g)
- Lateral acceleration (g)

Eye-tracker:

- Computer time stamp
- Video frame (for reference to the forward-facing camera)
- For each eye:
  - Horizontal angle of fixation displacement (radians)
  - Vertical angle of fixation displacement (radians)
  - Pupil diameter (mm)
  - Eye closure percentage
  - Blinking state (0 [not blinking] or 1 [blinking])
  - Gaze quality (1 [low], 2, or 3 [high])

3.2.1.2. Data Extraction

With driving behavior quite complex, as explained in Section 2, it was necessary to extract the information in a way that preserves the complexity of driver behavior throughout all phases of negotiating curves. The object of the analysis is to identify relationships between changes in driver behavior (visual attention and operational performance) and characteristics of each curve. The data that had been collected continuously by separate units thus needed to be combined and identified based on the location of the vehicle with respect to a curve.

The first step to combine the data values and associate them with a curve was to identify various "points of interest" along each segment with a study curve. The values of longitude and latitude were identified for the following points of interest on each segment: the PC, the curve midpoint, the PT, and continuous 100-ft intervals from the start of the curve moving upstream to the previous change in alignment. Depending on the length of the approach tangent, each segment was comprised of several points of interest. Figure 3.2 shows part of one segment with various points of interest. Each point of interest with location defined by latitude and longitude were recorded in an Excel spreadsheet and ordered consecutively as they would be encountered by a participant, starting with the first point of interest encountered (several hundred feet from the first curve), to the end of the route, and back to the beginning.

Figure 3.2: Points of interest used in extracting data.

The points identified in the first step are the same for each driver on that corridor. The second step involved identifying the exact time the vehicle was located at a point of interest. A simple distance formula and a Visual Basic macro was used to identify which GPS data entry represents when the vehicle is closest to each point of interest. The timestamp of that location was extracted from the GPS data, as well as the speed of the vehicle.

The third step was to identify the longitudinal and lateral acceleration from the accelerometer data. This was done by finding the accelerometer entry whose timestamp is nearest to the GPS timestamp when the vehicle was at the point of interest. Rather than report a single acceleration entry recorded at one instant, five values were averaged to smooth the data that were often noisy due to small deflections in the pavement or quick steering corrections. The value of the longitudinal acceleration was multiplied by 32.2 to convert the value from units of gravity (*g*) to ft/s^2, which is more conventional. Lateral acceleration remained in units of *g*.

The fourth step was to extract the eye-tracking data. Of interest were the fixation location (recorded as horizontal and vertical rotation angles), pupil size, eye closure, and blinks. It was determined that an interval of 4 seconds would accurately represent the cognitive state of the driver at a small moment in time, striking a balance between the need for a robust measure of visual attention while preventing short-lived deviations that create a noisy dataset. Earlier work (Brimley et al. 2014) combined 6 seconds of eye-tracking data; a different study of pupillometry used an average of 3 seconds (Hyönä et al. 1995).The identified parameters were averaged for both eyes over a 4-second interval (240 total frames for each eye at 60 frames per second). After each average value was extracted for each eye at an identified point of interest, the average of the two eyes was reported. Entries when the recorded gaze quality was lower than 3 for each eye were excluded.

The fifth step in reducing the data was to find the operational extremes that occurred on each segment. The following data were extracted from the GPS and accelerometer files: the maximum speed on the tangent, the location of the maximum speed, the maximum deceleration rate on the tangent, the minimum speed within the curve, the maximum deceleration rate within the curve, and the maximum lateral acceleration within the curve. These values are characteristics of driver performance that are not observed when making point-to-point measurements at select locations.

The final step was to clean the data. It was discussed above that, despite driving on low-volume highways, there were occasions when the participant encroached upon a vehicle traveling in the same direction. These instances of following would affect both the operational and visual behavior, because the participants were limited by the actions of the vehicle in front and they also tended to fixate on the lead vehicle. Any time the participant encroached upon another vehicle, the participant was instructed to pull over at the nearest reasonable location and create a sufficient amount of distance between the two vehicles. Data collected during these occasions were removed from the dataset. It was also observed that visual behavior was significantly affected by encounters with opposing vehicles. Participants tended to fixate on the opposing vehicle until it passed, as if to ensure no conflict occurs with the other vehicle. At night, the pupils would also substantially contract due to the opposing vehicle’s headlamps. There appeared to be no significant effects on operational behavior; therefore, the visual behavior data during these encounters with opposing vehicles were eliminated, but the operational data preserved.

3.2.2. Organization of Reduced Data

The data were recorded continuously from the time the participant exited the hotel parking lot to the time the participant returned, resulting in thousands of entries from each data source for each participant. The discussion above identifies how the process of data reduction involved extracting the data from the three sources in a way that identifies various complex parts of a driver's behavior while on an individual segment. The reduced data set contains one entry for each study curve. Each entry contains information about the curve (radius, deflection angle, approach tangent length, TCDs, etc.) and information about the operational and visual behavior on the approach and within the curve (maximum tangent speed, maximum deceleration rate, initial pupil diameter, maximum pupil diameter, blink rate at the PC, etc.).

3.3. Conclusion

The study was designed to obtain a large sample of data collected continuously while study participants navigated an unfamiliar, rural two-lane highway in one of three states. Speed and acceleration data were collected by a GPS receiver and bi-axial accelerometer and visual behavior data were collected by eye-tracking cameras. The data were collected at a high frequency with many participants over prolonged periods, resulting in an extensive dataset. The data were reduced in a way that facilitates analysis in statistical models to show the effects and interactions of multiple independent variables. Having described the manner of collecting and reducing data, the following sections present analyses of the data. Section 4 presents models of driver operational performance using the combined data collected in all three states without considering the effects of TCDs. The purpose of Section 4 is to establish strong relationships between geometry and operations upon which the models in Section 5 will build. Section 5 contains operations models generated exclusively from data collected in Texas to identify the effects of TCDs with consideration for the effects of geometry. Section 6 focuses on the visual attention of drivers on curve approaches, identifying influences from both geometry and TCDs. Models in Section 7 evaluate the relationships between attention and operational performance and are based on data collected in all three states.

4. CHARACTERIZING THE EFFECTS OF CHANGES IN HORIZONTAL ALIGNMENT ON DRIVER OPERATIONAL PERFORMANCE

The relationships between geometric elements of horizontal curves and operational characteristics have been the subject of numerous research studies. Ten years ago, Misaghi and Hassan (2005) identified 27 publications with various speed prediction models for driving on horizontal curves; the number of curve speed prediction models continues to grow. Traditionally, the curve geometry has been the primary independent variable, with other geometric and operational characteristics producing additional effects. Perhaps because speed is a relatively-simple measure of performance, it has received the most attention in studies of operations. A smaller amount of research has investigated factors such as rates of deceleration and longitudinal and lateral acceleration (Bonneson 2000; Fitzpatrick et al. 2000; Reymond et al. 2001; Figueroa Medina and Tarko 2007; Hu and Donnell 2010).

It was discussed in Section 2.4.2 that most of the previous operations research reported data that were collected at fixed locations within or on the approach to a curve. Driver behavior, however, is much more complex than single measurements of speed that do not capture the entire picture of curve navigation. Point-to-point speed differences over long distances can mask the instantaneous changes that may occur at critical locations, such as immediately before a curve. Additionally, as the speed of a vehicle changes within a curve, it is difficult to concretely define a curve's "operating speed".

Section 2.3.2.1 introduced a number of studies that evaluated the operational effects of TCDs used at curves. It is hypothesized that the TCDs evaluated in this study positively influence the operational behavior of drivers, if only by 1 or 2 mph within the curve, as found multiple times previously. The total effects of the TCDs, however, are much more complex than a small observed speed change. Specifically, there may still be questions of where a driver initiates a response, based on visibility of a device or the information provided, as well of the magnitude of the response. More-descriptive data and metrics that better characterize the driver's behavior near curves are needed in order to more-fully understand these details.

The purpose of this section is to establish basic relationships between curve features and operational performance using metrics suggested in Section 2.4.2. Since some of these measures have not been investigated by previous research, it is necessary to first identify characteristics of driver behavior based on the curve alone. Accordingly, this section does not include consideration for the TCDs used. The next section expounds upon the analyses contained in the current section by including consideration for the supplementary TCDs used in the study. The analyses include multivariable mixed linear models that estimate parameters of the performance metrics introduced in Section 2. A brief review of the phases of curve negotiation and the operational metrics associated with them is provided below, followed by the analyses.

4.1. Background

The data used in this section of the dissertation were obtained from the multi-state dataset effort that involved local drivers navigating a rural and unfamiliar two-lane highway in an instrumented vehicle. Section 3 documents how the data were extracted from the continuous operations data obtained from the GPS receiver and accelerometer. From research summarized in Section 2 (Background), the process of curve negotiation is divided into three phases: 1) acceleration after exiting the upstream curve, 2) deceleration before entering a curve, and 3) navigation within the curve. The performance metrics analyzed in the current and following sections will be divided into these phases. The performance metrics for each phase are listed below.

Acceleration after exiting curve:

- Distance (ft) traveled downstream to reach maximum speed
- Increase in speed (mph)

Deceleration before entering curve:

- Speed reduction (mph) before curve
- Proportion (percent) of speed change before curve compared to total observed speed change
- Maximum deceleration rate (ft/s^2) on approach

Within-curve navigation:

- Speed (mph) at PC
- Maximum deceleration rate (ft/s^2) in curve
- Maximum lateral acceleration rate (*g*)

4.2. Methodology

The eight performance metrics are evaluated as dependent variables in multivariable mixed models to identify how various geometric features of curves influence driver operational behavior. The purpose of these models is to establish basic relationships from a very robust sample (up to 4,800 entries). All of the data are used without consideration for traffic control, time of day, or location (3 states, day and night driving, all subjects), though some exclusions for specific models are applied where necessary and specifically mentioned. For the analyses in this section, the significance level was set at $\alpha = 0.0001$. Such a high level of significance was used to keep the models as simple as possible, ensuring that the most important variables are included in the models. It was anticipated that the relationships identified in the next section, where TCDs are investigated, would not be as strong because a smaller dataset is used. A very high level of significance at this stage ensures that the relationships identified when

TCDs are investigated would still be within acceptable levels. Interactions between main effects were tested and are included when they are significant. The study participants were incorporated as random effects to account for the variation across different participants. There were several instances where transformations were performed on the data or where weighted least squares regression was necessary to account for non-constant variance within the data. The adjustments that were made are identified when appropriate. R^2 correlation values are not provided for the models generated by the weighted regression because they tend to be a poor representation of the unweighted correlation. The models were developed with JMP software; Appendix B contains figures with residual plots and distributions of the residuals; the script used for each final model is provided in Appendix C.

4.3. Results

The multivariable models presented below are separated into subsections for each of the three phases of curve navigation. The models in this section establish important relationships between the geometric elements associated with curves and operational performance. To illustrate the trends described in the models, graphs are presented when practical with model fit lines superimposed over the data used to generate the model.

4.3.1. Acceleration Exiting an Upstream Curve

The two metrics characterizing the acceleration phase are the distance traveled before the driver reaches a maximum speed on the tangent and the actual increase in speed observed on the tangent. These two metrics depend on the length of the tangent, the vehicle’s initial speed at the end of the upstream curve, and the speed at which the driver desires to travel on the entire facility (which is likely to be near the speed limit, though unique to each driver). The desired speed of an individual driver is the maximum speed of that driver observed throughout the study. A new variable called the potential speed increase is used, which is the difference between the desired speed of the driver and the speed when exiting the upstream curve. The potential speed increase represents how much the driver would accelerate if there were a sufficient distance before the next curve. It thus depends upon the severity of the previous curve (because low exit speeds are expected at severe curves) and the desired speed of the individual driver. The potential speed provides a perspective of how much the driver would accelerate if the approach tangent were sufficiently long. If there is a long tangent between two curves and there is a large potential to increase speed, then the distance traveled during the acceleration phase and the speed change experienced should be greater.

Table 4.1 presents the prediction parameters for the models characterizing the acceleration phase using two main effects of tangent length and potential speed increase. Approximately half of all available data (2,300 total observations) were used in these models because not all study curves had operational data reduced at the PT of the previous curve, and only curves with preceding tangents 250 to 2,500 ft in length were used. The *p* values of the t-test for the fixed effects are all less than 0.0001. The correlation coefficients (adjusted R^2) for the two models are 0.73 and 0.84.

Residual plots from initial models in Appendix B (Figures B.1 and B.4) indicated that the assumption of constant variance in the error terms is not met, evident by the "megaphone" pattern in the figures. To correct for this failure, models using transformed (square root) dependent variables were tested and used as alternatives for the raw values. In the first model (the acceleration distance), a square root transformation was also applied to the fixed effect of tangent length, which also reduced some of the heteroscedasticity of the residuals. Table 4.1 present the final models. Figures B.2 and B.5 in Appendix B are residual plots of the final models.

Table 4.1: Regression Models Characterizing Acceleration after Exiting a Curve

	Estimate	t Ratio	Prob>|t|
Sqrt [Distance Traveled (ft) to Maximum Tangent Speed] (R^2=0.73)			
Intercept	-3.57	-8.20	<0.0001
Sqrt [Tangent Length(ft)]	0.71	60.22	<0.0001
Potential Speed Increase (mph)	0.27	16.6	<0.0001
Sqrt [Speed (mph) Increase after Curve] (R^2=0.84)			
Intercept	-0.32	-7.00	<0.0001
Tangent Length (ft)	0.00090	44.2	<0.0001
Potential Speed Increase (mph)	0.091	48.2	<0.0001

Equations 4.1 and 4.2a (simplified in Equations 4.1b and 4.2b) are formulas for the two models from Table 4.1.

$$\sqrt{D_{Accel}} = -3.57 + 0.71\sqrt{L_{Tan}} + 0.27Potential \qquad 4.1$$

$$\sqrt{\Delta_{Speed_{Accel}}} = -0.32 + \frac{9L_{Tan}}{10{,}000} + 0.091Potential \qquad 4.2$$

where

D_{Accel} = distance traveled (ft) before reaching maximum tangent speed,

$\Delta_{Speed_{Accel}}$ = increase in speed (mph) during acceleration phase,

L_{Tan} = tangent length (ft), and

Potential = potential speed increase (mph) based on the difference between the driver's desired speed and the initial speed on the tangent.

The data used to generate the models in Table 4.1 include observations on tangents 258–2,496 ft (average 871 ft) in length and potential speed increases of 0.2–51.6 mph (average 16.9 mph). The observed distances traveled while accelerating ranged from 0 to 2,400 ft (average 440 ft) and the observed speed increases ranged from 0 to 42 mph (average 4.7 mph).

Because the models include data for curves with preceding tangents up to 2,500 ft in length, which is a distance at which the curve geometry is not visible, the models in this phase do not account for the specific geometry of the downstream curve. It was found that the effects of curve geometry (i.e., radius and deflection angle) can be identified within the acceleration phase, but they are quite small in comparison to the effects of tangent length and potential speed increase. Graphical representations of the models are shown in Figures 4.1 and 4.2. The data in both figures are quite dispersed for observations with low potential speed changes, but the data outside of the clusters help to define the relationships.

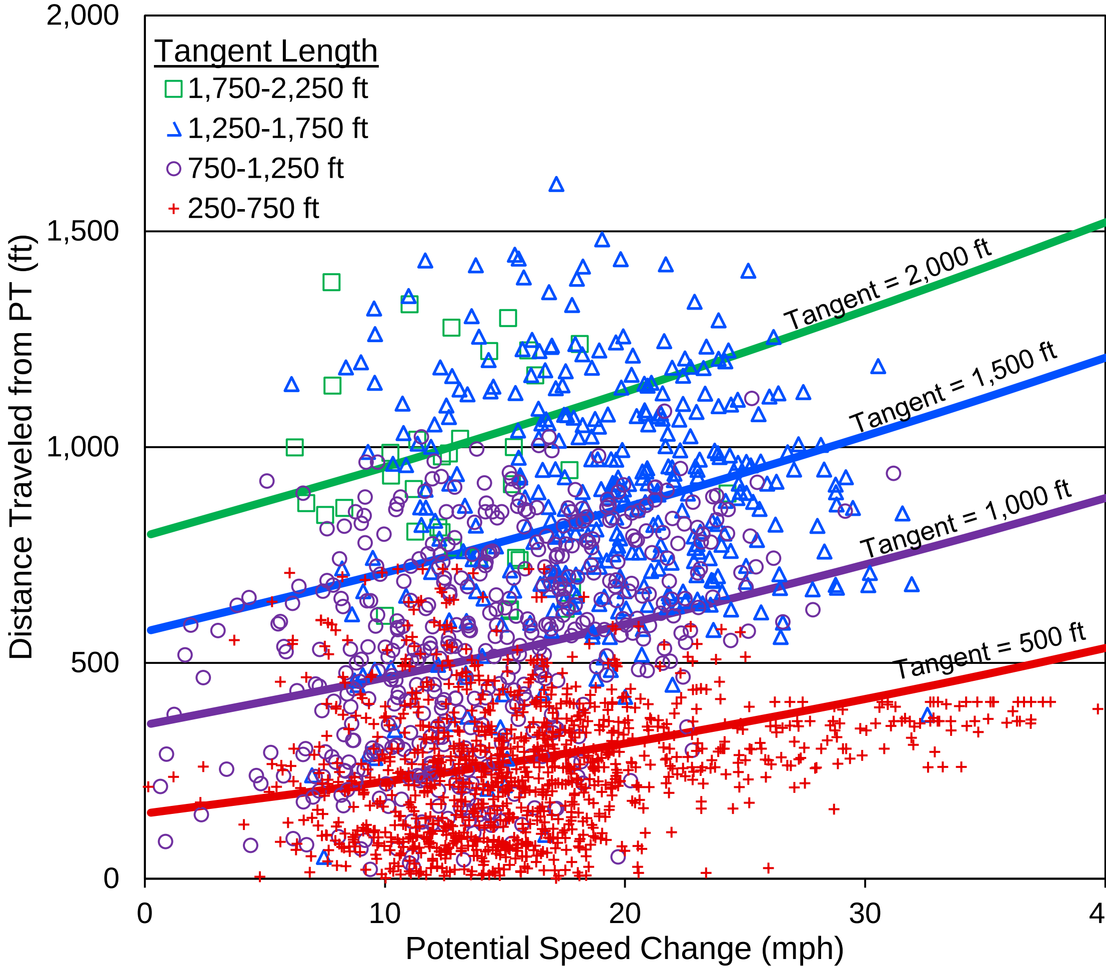


Figure 4.1: Distance (ft) traveled on a tangent to reach maximum speed.

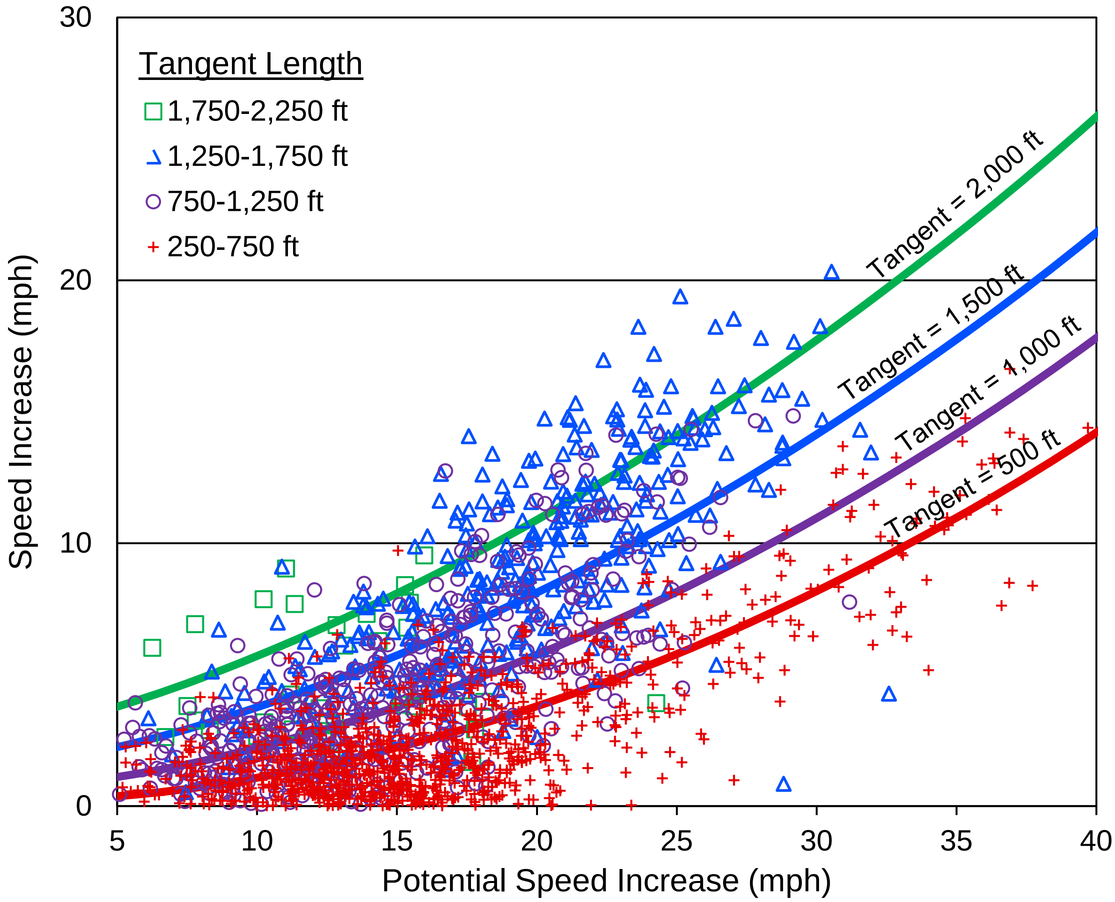


Figure 4.2: Increase in speed (mph) observed on a tangent.

4.3.2. Deceleration Entering a Curve

The geometry of the downstream curve was not included in models for the acceleration phase, because of the inability to detect the geometry so far from the curve. Geometry is included in models for deceleration because the driver is at a location where the appearance of the curve's severity can clearly affect a response. The performance measures to characterize the deceleration phase are the reduction in speed that occurs before the PC, the proportion of total speed change that occurs before the curve, and the maximum deceleration rate that is observed on the approach.

Table 4.2 presents the parameters and fixed effects of the models characterizing the deceleration phase. These models were generated from the 4,800 observations in the dataset. The first model predicts the speed reduction that occurs before a curve, and includes factors for geometry (radius) and the operational performance identified with the acceleration models in Table 4.1 (the maximum tangent speed and the location of that maximum speed where the deceleration begins). The assumption of unequal variance was not met in the first model of the change in speed before the curve, as documented in Figure B.7 in Appendix B, and it was found that transformations alone would not be enough to correct the observed patterns in the residuals. The model estimates were determined using weighted least squares regression based on the residuals of the original model to give less weight to the observations far from the prediction. Even though the variance is still heterogeneous, the model estimates are now adjusted for this condition.

The proportion of total speed reduction that occurs before a curve was investigated as another performance measure associated with the pre-curve deceleration phase. Unfortunately, all potential models identified a very weak correlation, so no specific models are reported here. An average 53 percent of the total speed reduction at each curve occurred before the curve, which is less than (though reasonably similar to) the 66 percent observed elsewhere (Figueroa Medina and Tarko 2007).

The second model developed in this phase estimates the greatest deceleration rate (in ft/s^2) observed on the approach to a curve. The deceleration rate is a driver's intentional reaction based on the driver's risk-taking habits and the information provided on the tangent. A lower deceleration rate is considered conservative and desirable. This model shows that the deceleration rate is primarily dependent upon the total change in speed associated with the curve. The relationship between total speed reduction and maximum observed deceleration rate is strongly correlated (R^2=0.76). Other variables were investigated in this model, specifically the effects of radius, deflection angle, and tangent length. It was found that the speed differential by itself accounts for such a large portion of the variance in the response that other measures such as geometry simply do not provide much benefit in addition to the total speed change. Additionally, the speed differential is by itself a function of those and other variables. The second model estimating the maximum deceleration rate appears to meet the assumption of equal variance based on the residuals plotted in Figure B.10. No transformations were performed.

Table 4.2: Regression Models Characterizing Pre-Curve Deceleration Phase

	Estimate	t Ratio	Prob>|t|
Speed Reduction (mph) Before Curve			
Intercept	-11.5	-6.58	<0.0001
Maximum Tangent Speed (mph)	0.22	3.91	<0.0001
Distance Before Curve at Maximum Speed (ft)	0.0051	39.2	<0.0001
1 / Radius (ft)	1287	52.7	<0.0001
Maximum Deceleration Rate (ft/s^2) on Tangent (R^2=0.76)			
Intercept	0.89	10.7	<0.0001
Total Speed Reduction (mph)	0.22	81.3	<0.0001

Equations 4.3 and 4.4 are formulas for the performance metrics based on the modeling results in Table 4.2.

$$\Delta_{Speed_{Decel}} = -11.5 + 0.22 Speed_{Max} + \frac{51D}{10{,}000} + \frac{1287}{R} \qquad 4.3$$

$$Decel_{Rate_{Tan}} = 0.89 + 0.22\Delta_{Speed} \qquad 4.4$$

where

$\Delta_{Speed_{Decel}}$	=	change in speed (mph) before the curve,
$Decel_{Rate_{Tan}}$	=	maximum deceleration rate (ft/s^2) on the tangent,
$Speed_{Max}$	=	maximum speed (mph) on the tangent,
D	=	distance (ft) from curve at maximum speed,
R	=	radius (ft), and
Δ_{Speed}	=	total speed differential at the curve.

The maximum observed tangent speed in the data ranged from 32.5 to 77.7 mph (average 51 mph); the distance from the curve at maximum speed ranged from 0 ft (at the PC of the curve) to 1,500 ft upstream from the curve (average 400 ft, though dependent upon the tangent length); the curve radius ranged from 55 to 2,150 ft (average 800 ft); and the speed differential ranged from 0 to 50 mph (average 8.0 mph). Regarding the dependent variables in Equations 4.3 and 4.4, the speed change on the tangent ranged from 0 to 43 mph (average 4.6 mph) and the maximum deceleration rate ranged from 0 to 17 ft/s^2 (average 2.7 ft/s^2).

The first deceleration model (Equation 4.3) is not plotted due to the complexity of graphically representing four effects. The fit line and data for the second model (Equation 4.4) are shown in Figure 4.3. Note that the deceleration rate for some of the observations was equal to or near 0 although there was a small observed speed change at the curve. Those are instances when deceleration occurred only within the curve, whereas this model represents the maximum deceleration rate observed on the tangent. One of the most valuable insights provided by the model of the maximum observed deceleration rate is that it identifies a simple relationship characterized by one component of a much more complex behavior. The total speed differential is a complex decision based on the perception of multiple sources of information. The deceleration rate is just one part of accomplishing that behavior.

In order to execute a greater speed change for a curve, drivers can either accept a greater deceleration rate or begin decelerating earlier. The model for Equation 4.4 and Figure 4.3 shows drivers are willing to accept increased deceleration rates. Though no model is shown here, it was found (unsurprisingly) that deceleration rates are lower when the deceleration phase begins earlier. The effect of the location where the deceleration phase begins is much weaker than the effect for the total speed change, and is thus not incorporated into the model. This finding suggests that drivers are willing to sacrifice comfort (and potential safety) for the efficiency that comes from decelerating later.

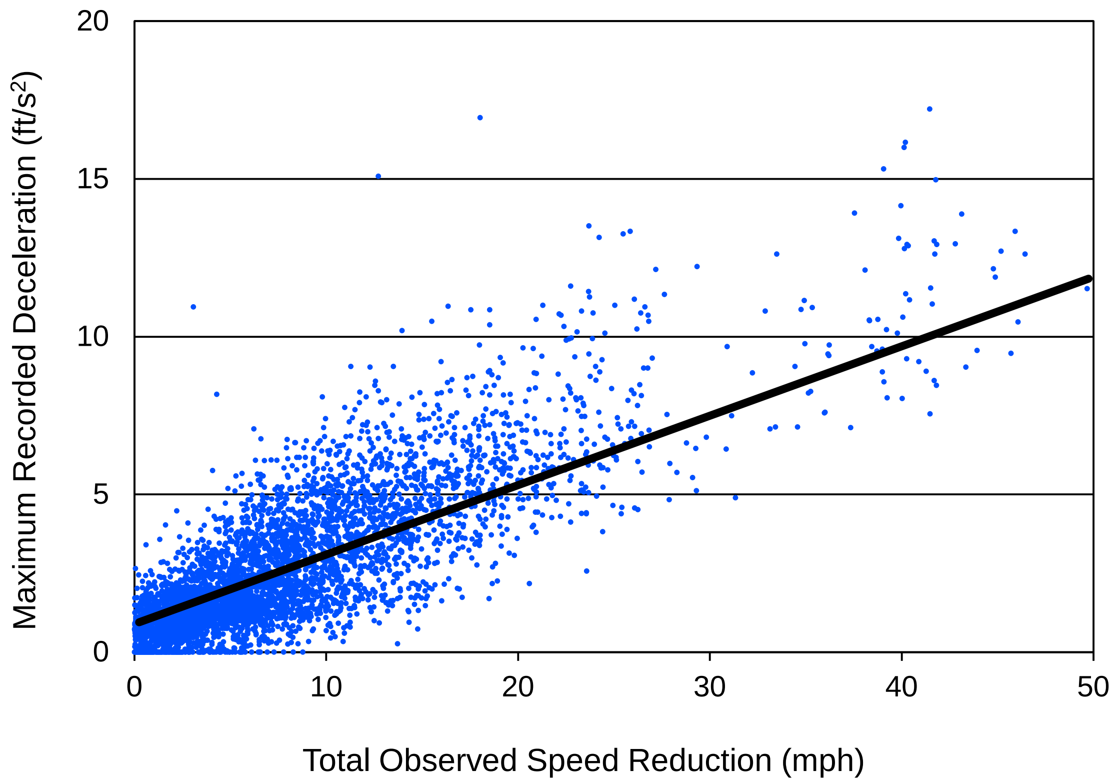


Figure 4.3: Maximum observed deceleration rate (ft/s^2) on an approach tangent estimated by total speed differential at the curve.

4.3.3. Within-Curve Performance

The navigation within the curve is characterized in this study by three metrics: the speed at the PC, the maximum deceleration rate observed within the curve, and the maximum lateral acceleration rate observed within the curve. Models estimating these three metrics are given in Table 4.3. The speed at the PC is estimated by the curve radius and maximum approach speed. The relationships (unsurprisingly) indicate that a higher speed at the PC occurs with a higher tangent speed and larger radius. All parameters are significant and the correlation is strong (R^2 = 0.88). The final model of speed at the PC presented in Table 4.3 was developed after investigating potential transformations of the main effects. The initial model included the maximum approach speed and the reciprocal of the curve radius. A plot of the actual observations of the initial model fit by their predicted values and the residual plot are given in Appendix B (Figures B.12 and B.13). The curve in the data shown in Figures B.12 and B.13 suggest that a different model form may better reflect the driver behavior at these curves. A log transformation of the radius, rather than the reciprocal, led to substantial improvements in the form of the residuals, indicating a better overall prediction (Figures B.14 and B.15).

It has been discussed that not all deceleration occurs in advance of a curve, but continues after the PC. The previous models showed that the deceleration rate is easily relatable to the total observed speed change. The second model in Table 4.3 extends the simple relationship discussed previously, identifying the effect of total speed change on the maximum rate of deceleration within the curve. The correlation coefficient is 0.66, which is weaker than the model estimating the deceleration rate on the tangent. No adjustments were made to the initial model because there were no violations of normality or homoscedasticity. The residual of the model are shown in Figures B.17 and B.18.

An algebraic comparison of the two models of deceleration rates reveals that for speed reductions greater than 4.5 mph, the deceleration rate on the tangent will be greater than the rate within the curve. The significance of the relationship between the deceleration rate observed in the curve and the speed differential is not unlike that of the model for the deceleration rate on the tangent: severe curves (unsurprisingly) lead to greater rates of deceleration, which drivers are more willing to accept than beginning the deceleration phase earlier.

It was found that one of the simplest relationships for estimating lateral acceleration is with a ratio of curve deflection (in degrees) to radius (in feet). The third model in Table 4.3 identifies the relationship, which is best described by a log function of deflection/radius. It has been observed (Emmerson 1969) that the ability of drivers to reduce lateral acceleration through cornering is limited by the deflection angle of the curve. The inclusion of deflection thus gives a novel perspective of severity that is not described by radius alone. The speed of the vehicle could have been included in the model, but it would have led to a near-perfect prediction of lateral acceleration. Without speed, there is room for estimating effects of other variables, such as TCDs. The model of lateral acceleration was created with a weighted least squares regression using the inverse of the model residuals as weights. This was done because of the pattern of the residual plot of the original model shown in Figure B.19. Possible transformations of the dependent variable were investigated, but it was determined that a transformation reduces the effect of the clear logarithmic relationship shown below in the plot of the lateral acceleration model. The weighted least squares regression thus maintains the form of the original model, but gives less influence to the observations that are far from their predicted value, accounting for the increase in variance as the lateral acceleration increases.

Table 4.3: Regression Models Characterizing Within-Curve Navigation Phase

	Estimate	t Ratio	Prob>|t|
Speed (mph) at PC (R^2=0.86)			
Intercept	-14.5	-20.8	<0.0001
Ln[Radius (ft)]	5.49	60.5	<0.0001
Maximum Tangent Speed (mph)	0.50	60.5	<0.0001
Maximum Longitudinal Deceleration (ft/s^2) Within Curve (R^2=0.66)			
Intercept	1.00	15.2	<0.0001
Total Speed Reduction (mph)	0.19	64.4	<0.0001
Maximum Lateral Acceleration (g) Within Curve			
Intercept	0.30	80.6	<0.0001
Ln[Deflection/Radius] (deg/ft)	0.046	66.0	<0.0001

Mathematical equations for the models in Table 4.3 are given as Equations 4.5 through 4.7. The following are the ranges of the data used to generate the models. The radius ranges from 55 to 2,150 ft (average 800 ft); the deflection angle ranges from 7 to 120 deg (average 56 deg); the maximum tangent speed ranges from 32 to 77 mph (average51 mph); and the total speed change ranged from 0 to 50 mph (average 8 mph). For the dependent variables, the speed at the PC ranged from 17 to 74 mph (average 46 mph); the maximum deceleration rate within the curve ranged from 0 to 17 ft/s^2 (average

2.5 ft/s^2); and the maximum lateral acceleration ranged from 0.03 to 0.49 g (average 0.19 g).

$$Speed_{PC} = -14.5 + 5.49 \ln R + 0.50 Speed_{Max} \tag{4.5}$$

$$Decel_{Rate_{Curve}} = 1.00 + 0.19 \Delta_{Speed} \tag{4.6}$$

$$Accel_{Lat} = 0.30 + 0.046 \ln \frac{I}{R} \tag{4.7}$$

where

$Speed_{PC}$	=	speed (mph) at the PC,
$Decel_{Rate_{Curve}}$	=	maximum longitudinal deceleration rate (ft/s^2) in the curve,
$Accel_{Lat}$	=	maximum lateral acceleration (g) in the curve,
R	=	radius (ft),
L_{Tan}	=	tangent length (ft),
$Speed_{Max}$	=	maximum speed (mph) on the tangent,
Δ_{Speed}	=	change in speed (mph) observed at the curve, and
I	=	curve deflection angle (deg).

Figures 4.4 and 4.5 are graphs of the data and model lines for the maximum longitudinal deceleration and lateral acceleration rates observed within a curve.

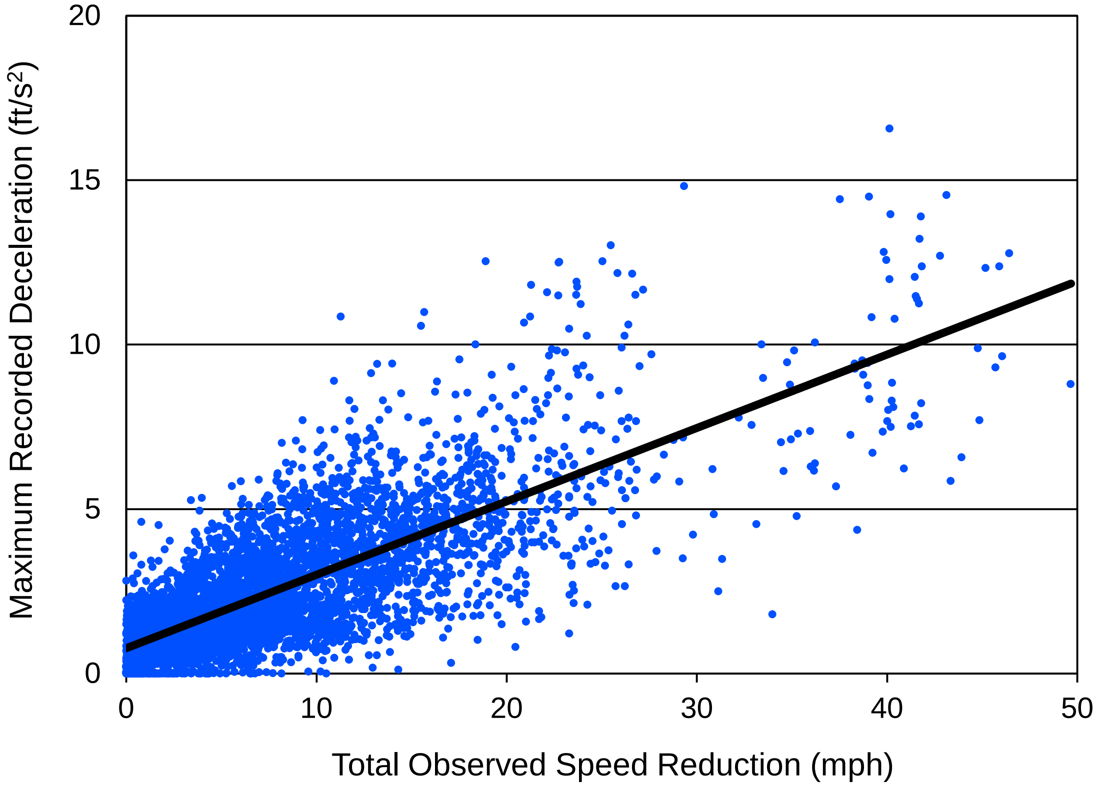


Figure 4.4: Maximum longitudinal deceleration (ft/s^2) observed within a curve estimated by total speed differential at the curve.

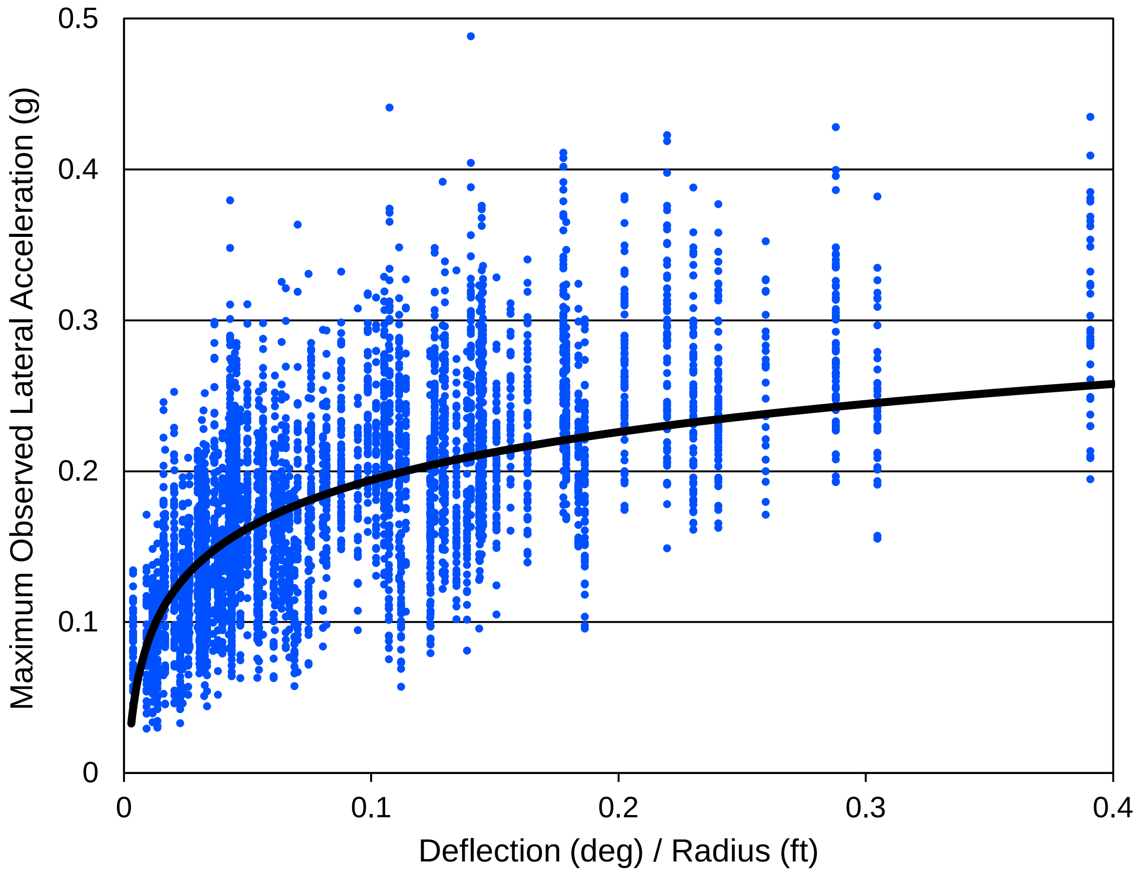


Figure 4.5: Maximum lateral acceleration (g) estimated by deflection/radius.

4.4. Summary

The basic relationships presented in this section show how various operational parameters of unfamiliar drivers are affected by changes in horizontal alignment on two-lane rural highways. Most of the models either characterize measures of operational behavior that have previously not been investigated or they present relationships that explain driver behavior in a unique way. The data came from measures of speed and acceleration collected throughout the course. Key observations regarding operational performance are summarized below:

1. During the acceleration phase after a curve, the maximum speed of a driver on a tangent and the location when that speed is observed are primarily dependent

upon the length of the tangent, the driver's initial speed, and the driver's desired speed.

2. The total decrease in speed before a curve is primarily dependent upon the driver's speed on the approach tangent, the distance from the curve when the deceleration begins, and the geometry of the curve.
3. The deceleration rates of a driver both on the tangent and in the curve are not uniform at each curve, but are primarily dependent upon the total speed change experienced at the curve.
4. The lateral acceleration experienced within curves is correlated with the geometry of the curve. A log function with the ratio of deflection angle to radius can be used to describe the relationship.

The patterns of operational behavior presented in this section are not original from a conceptual perspective that curve negotiation can be divided into three phases and that driver performance within each phase is primarily dependent upon characteristics associated with the roadway alignment. In other words, the key points above should not conflict with scientific reasoning or common sense. Previous research has identified some parameters associated with these phases (especially the operations within curves), but few have examined the entire process that begins with acceleration on a tangent and ends within the curve as one segment where the behavior in one phase affects what is observed in another. This section presents findings of operational performance that show where drivers respond to a change in alignment and the magnitude of the response.

4.5. Conclusion

This section shows that performance in the curve is affected by the operations on the approach. There is a logical progression of how what happens in one phase influences what happens in the next. This is important to establish because TCDs do not immediately affect performance within the curve without there being some change in behavior leading up to the curve. The inclusion of analyses of the phases often ignored in this type of research produces a more-comprehensive view of driver behavior than has previously been produced.

Throughout the research, emphasis was placed on ensuring the results are applicable to a broad range of conditions and are relatively easy to understand. That is particularly evident by the absence of TCDs from the models. The driving routes and study curves were carefully selected for that purpose, and the models were developed such that they are as simple as possible while maintaining significance. None of the models presented here account for the influence of TCDs used at changes in alignment. The purpose of the analyses here, and in using such an extensive database, is to establish relationships that will be investigated in more detail in Section 5, where data limitations may affect the ability to identify such strong relationships. Most of the curves in the data used in this section had been treated with advance warning signs, and a smaller number had been treated with any of the supplementary devices used in the analyses later. The following section introduces variables for supplementary TCDs into the models, to show how they influence driver performance when accounting for the geometric effects discussed in this section.

5. EFFECTS OF TRAFFIC CONTROL DEVICES ON OPERATIONAL PERFORMANCE AT CURVES

As each type of curve TCD has a unique design, each likely affects drivers in a unique way. Based on physical properties, chevrons or a one direction large arrow sign are likely visible at a greater distance than PMDs. Such a visibility distance also may affect how a driver responds while approaching a curve. Previous studies have generally focused on driver operational behavior within or very near the confines of a curve, but the previous analyses in Section 4 identified how drivers may begin responding to curves farther away than often assumed. If information about a curve can be perceived at a long distance, the drivers will likely respond at a long distance.

This section contains analyses of the effects of TCDs that build upon the models and findings presented in Section 4. The analyses exclusively use the data collected in Texas at night. The supplementary TCDs were only applied in Texas, and they tend to be most useful at night due to the absence of other visual information. By excluding the data collected outside of Texas or during the day, there will be no identifiable influence of location or time of day in the models.

5.1. Background

The phases of negotiating curves (discussed in Sections 2 and 4) are: 1) acceleration after exiting a curve, 2) deceleration before entering a curve, and 3) navigation within the curve. In Section 4, multivariable linear mixed models with very significant ($\alpha = 0.0001$) fixed effects identified the operational effects of curve geometric elements alone. The models included no factors that indicate whether or not TCDs are used because the purpose of these models is to establish basic relationships of driver performance with respect to changes in horizontal alignment. The purpose of this section is to identify the effects of TCDs at curves by using models that have the same functional form and variables as those in the previous section, but with the addition of TCDs. The effects of TCDs are on operational behavior hypothesized to be small in comparison to the effects of some of the geometric elements, though still noticeable. In other words, the models in this paper focus on the effects of TCDs in addition to the effects of geometry. Consideration for the effects of both devices and geometry together, rather than as separate entities, during the three phases of curve negotiation may result in a more-complete understanding of operational performance than has been previously produced.

The following patterns, identified in Section 4, are worth reprinting here because the effects of TCDs will be evaluated within the context of these findings:

1. During the acceleration phase after a curve, the maximum speed of a driver on a tangent and the location when that speed is observed are primarily dependent upon the length of the tangent, the driver's initial speed, and the driver's desired speed.
2. The total decrease in speed before a curve is primarily dependent upon the driver's speed on the approach tangent, the distance from the curve when the deceleration begins, and the geometry of the curve.
3. The deceleration rates of a driver both on the tangent and in the curve are not uniform at each curve, but are primarily dependent upon the total speed change experienced at the curve.
4. The lateral acceleration experienced within curves is correlated with the geometry of the curve. A log function with the ratio of deflection angle to radius can be used to describe the relationship.

It was discussed in Section 4 that the findings regarding operational performance are overall quite consistent with previous research. The real value comes not in that consistency, or even the exact estimate of each parameter, but in the way the models attribute specific elements of a driver's response to the change in alignment. A driver's behavior during a given phase of curve negotiation is based on a number of factors: the driver's personal experience, expectations, and tolerance for risk; the vehicle's current operational characteristics; and the available information regarding immediate and upcoming roadway features. The models did not account for all the information drivers were presented with regarding the changes in alignment, because there was no consideration for the use of TCDs. At some curves, the only information regarding the change in alignment came from the road, pavement markings, and the surrounding environment. Other curves had warning signs, and a select few had supplementary devices placed within the curve. It is anticipated that the inclusion of TCDs in the models in this section will not substantially alter the relationships identified in the previous section.

5.2. Methodology

The original dataset used in Section 4 included approximately 4,800 unique observations of drivers approaching and navigating curves. Because the focus of this section is the effects on operational performance from supplementary TCDs, it was necessary to only include curves in the analyses with characteristics similar to those treated with supplementary TCDs. The exclusion of observations at curves with characteristics not within a particular range would remove some of the potential for bias. The reduced dataset used in this analysis has 555 observations. The reduction was based on limiting the data to the following values:

- State = Texas
- Time of Day = Night
- Radius = 55–860 ft
- Deflection = 27–90 deg
- Tangent Length = 200–2,820 ft

Table 5.1 contains descriptive statistics about the curves and observations, grouped by the treatment used. Some of the curves treated with delineators and large arrow signs (listed in Table 5.1) received the TCDs during the first half of the study, and the others during the second half. These treated curves are represented in both the treatment and baseline group.

Table 5.1: Characteristics of Curves in Supplementary Device Analysis

	Baseline		Treatment					
	Warning Sign Only		Warning + Delineators		Warning + Arrow Sign		Warning + Chevrons	
Number of Curves	19		7		4		10	
Curve-Driver Observations	283		60		34		178	
	Min	Max	Min	Max	Min	Max	Min	Max
Radius (ft)	55	860	370	815	55	390	55	500
Deflection (deg)	27	90	30	90	83	90	40	90
Tangent Length (ft)	209	2,820	700	2,770	800	2,820	485	2,500
Average Speed Differential (mph)	5.8	38	5.8	17	16	38	6.6	41

The data in this section are analyzed with multivariable linear mixed models that identify relationships between the same performance metrics used in Section 4 and the fixed effects of the geometric and traffic control variables of interest. The focus of this section is the effects that supplementary TCDs have on the output measures of driver performance while accounting for the effects of other factors (such as geometry). The participants are again included in the models as random effects and the independent variables of interest are fixed effects.

The dataset used to generate the models in Section 4 was extensive enough that the main effects in the models were very significant ($\alpha = 0.0001$). The estimates of the model effects in this section are expected to be less significant and slightly different, because only a subset of the data is analyzed and factors for the traffic control are introduced. The level of significance is relaxed in these models ($\alpha = 0.05$) and the fixed effects that do not significantly contribute to the prediction of the performance metric are excluded. Interactions are included when significant and practical. As with Section 4, transformations or weighted regression were applied as necessary when issues with normality or constant variance were encountered. Again, R^2 values are not given when they are inflated in a weighted regression. Appendices B and C contain residual plots and scripts for generating the models, taken from the JMP software used for modeling.

5.3. Results

Multivariable linear mixed models were created using the subset of the data described in Table 5.1. These models use the same fixed effects as the related models in Section 4, but with the inclusion of the appropriate supplementary TCD (if any) used for each curve and observation. The models are again separated into the three phases of curve negotiation. The effects of the individual type of supplementary TCD (PMDs, large arrow sign, or chevrons) are separated, though their individual t-ratios were often not significant. The overall effect of the use of supplementary devices, however, is significant in each model based on the analysis of variance F-ratio. Full equations are not provided each model in this section because their form and the estimates for their main effects are similar to the models in Section 4. Some equations illustrating the effects of the supplementary TCDs are provided where useful.

5.3.1. Acceleration Exiting an Upstream Curve

The two metrics characterizing driver performance while accelerating after exiting a curve are the location at which the vehicle reaches a maximum speed and the total increase in speed. Previous research (Chrysler et al. 2009) showed that when delineation devices are used, drivers can more-confidently identify the severity of a curve and they stop accelerating and start braking slightly earlier. Based on those results and the assumption that unfamiliar drivers are likely to respond to the stimulus provided by the TCDs, it is hypothesized that the acceleration phase will be shortened when TCDs are used.

The two fixed effects from the original models for the acceleration phase are the tangent length and the potential speed increase, defined as the difference between the driver's desired speed (maximum speed observed throughout the study) and the speed at the PT of the previous curve where the tangent begins. Unsurprisingly, these main effects in both models are positive. Effects for the TCDs, on the other hand, were negative as was hypothesized. There was no significant interaction in the first model. The new models of the acceleration phase with the inclusion of the supplementary TCDs are identified in Table 5.2. Residual plots of the two models are given in Appendix B (Figures B.21 and B.23). There is no clear pattern in the residual plots, indicating the assumption of constant variance is met. The residuals appear normally distributed (Figures B.22 and B.24).

Table 5.2: Regression Models of Acceleration after Exiting a Curve (Supplementary Devices)

	Estimate	**t Ratio**	**Prob>|t|**
Distance Traveled (ft) to Maximum Tangent Speed (R^2=0.91)			
Intercept	-174	-4.4	<0.0001
Tangent Length (ft)	0.64	26.0	<0.0001
Potential Speed Increase (mph)	8.6	4.94	<0.0001
Supplementary Devices:			
Delineators (if yes)	-76	-2.14	0.034
Arrow Sign (if yes)	-81	-2.07	0.040
Chevrons (if yes)	-137	-4.80	<0.0001
Speed (mph) Increase after Curve (R^2=0.96)			
Intercept	-12.5	-14.3	<0.0001
Tangent Length (ft)	0.0052	14.8	<0.0001
Potential Speed Increase (mph)	0.752	17.9	<0.0001
Interaction:			
(Tangent Length – 1,490) × (Potential Increase – 23.0)	0.00013	2.98	0.0033
Supplementary Devices:			
Delineators (if yes)	-0.7	-1.39	0.167
Arrow Sign (if yes)	-1.9	-3.39	0.0009
Chevrons (if yes)	-1.3	3.28	0.0013

The results of the model of the acceleration distance indicate that the supplementary devices lead drivers to stop accelerating between 76 and 137 ft earlier than when they are not used. The model of the increase in speed identifies a reduction in speed gained by 0.7 to 1.9 mph when supplementary TCDs are used. If the acceleration distance is reduced, it should not be surprising that the total increase in speed is reduced as well. The models are written in Equations 5.1 and 5.2a (Equation 5.2b is a simplification of Equation 5.2a).

$$D_{Accel} = -174 + 0.64L_{Tan} + 8.6Potential + TCD \qquad 5.1$$

$$\Delta_{Speed_{Accel}} = -12.5 + \frac{52L_{Tan}}{10{,}000} + 0.75Potential + \frac{1.3(L_{Tan} - 1{,}490)(Potential - 23)}{10{,}000} + TCD \qquad 5.2a$$

$$\Delta_{Speed_{Accel}} = -8.04 + \frac{22L_{Tan}}{10{,}000} + 0.56Potential + \frac{1.3(L_{Tan})(Potential)}{10{,}000} + TCD \qquad 5.2b$$

where

D_{Accel}	=	distance traveled (ft) before reaching maximum tangent speed,
$\Delta_{Speed_{Accel}}$	=	increase in speed (mph) during acceleration phase,
L_{Tan}	=	tangent length (ft),
Potential	=	potential speed increase (mph), the difference between the driver's desired speed and the initial speed on the tangent, and
TCD	=	influence of a supplementary device, obtained from Table 5.2.

The models were generated from data with the following ranges. The tangent length ranged from 210 to 2,500 ft (average 1,060 ft); and the potential speed increase ranged from 10.6 to 50.5 mph (average 23.6 mph). Actual observations of the dependent variables ranged from 167 to 2,040 ft for the distance traveled while accelerating (average 927 ft), and 1.7 to 40.6 mph for the total increase in speed on the tangent.

A graphical representation of the models are illustrated in Figures 5.1 and 5.2. The light lines represent the projected distance traveled before reaching the maximum speed when chevrons are used at curves; the dark lines represent the distance when only warning signs are used (the base condition). Based on the first model in Table 5.2, the effects of PMDs and large arrow signs are between each light and dark line. There are substantially fewer data points in these figures than the graphs shown in Figures 4.1 and 4.2. This is a result of limiting the dataset to nighttime conditions and curves suitable for the analysis of supplementary TCDs. The effects of the TCDs are generally subtle, though noticeable at this phase of curve negotiation.

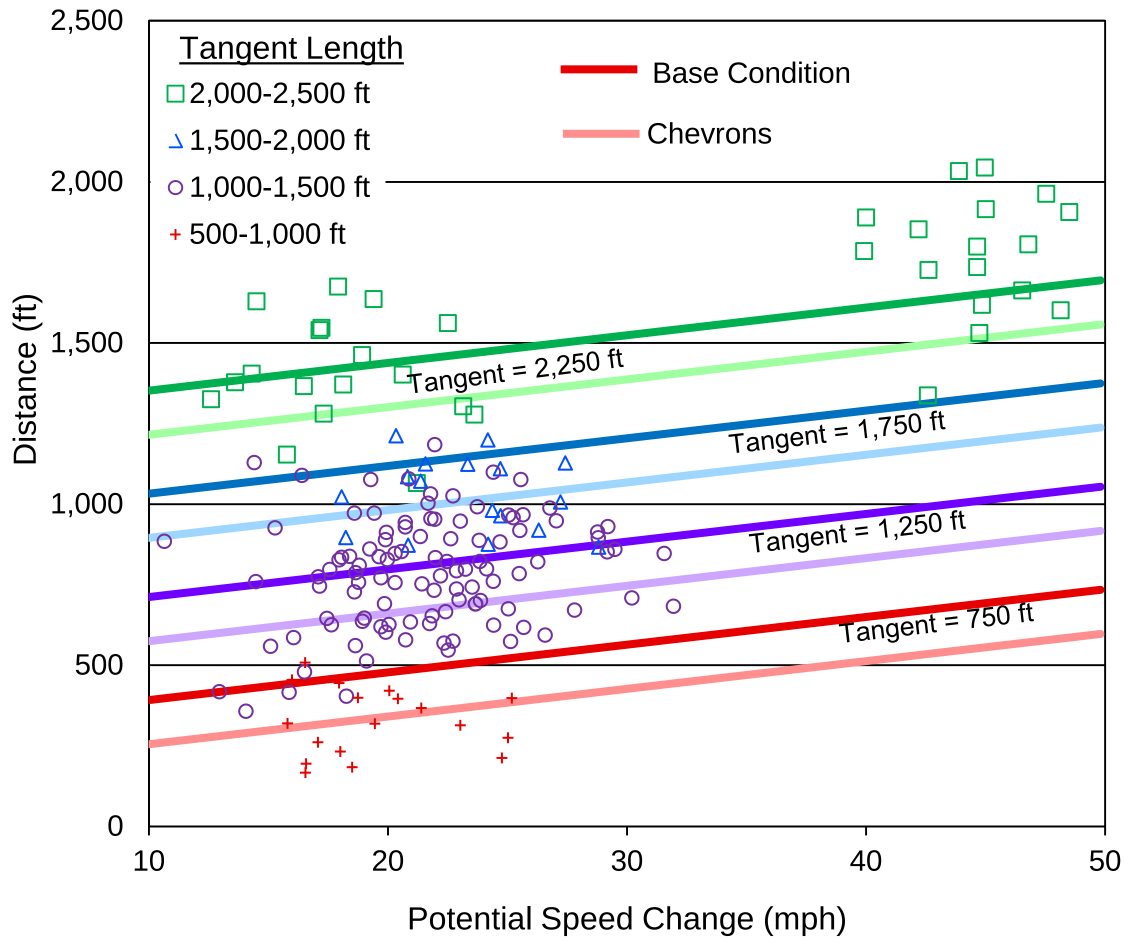


Figure 5.1: Distance (ft) traveled on a tangent to reach maximum speed, with influence from TCDs.

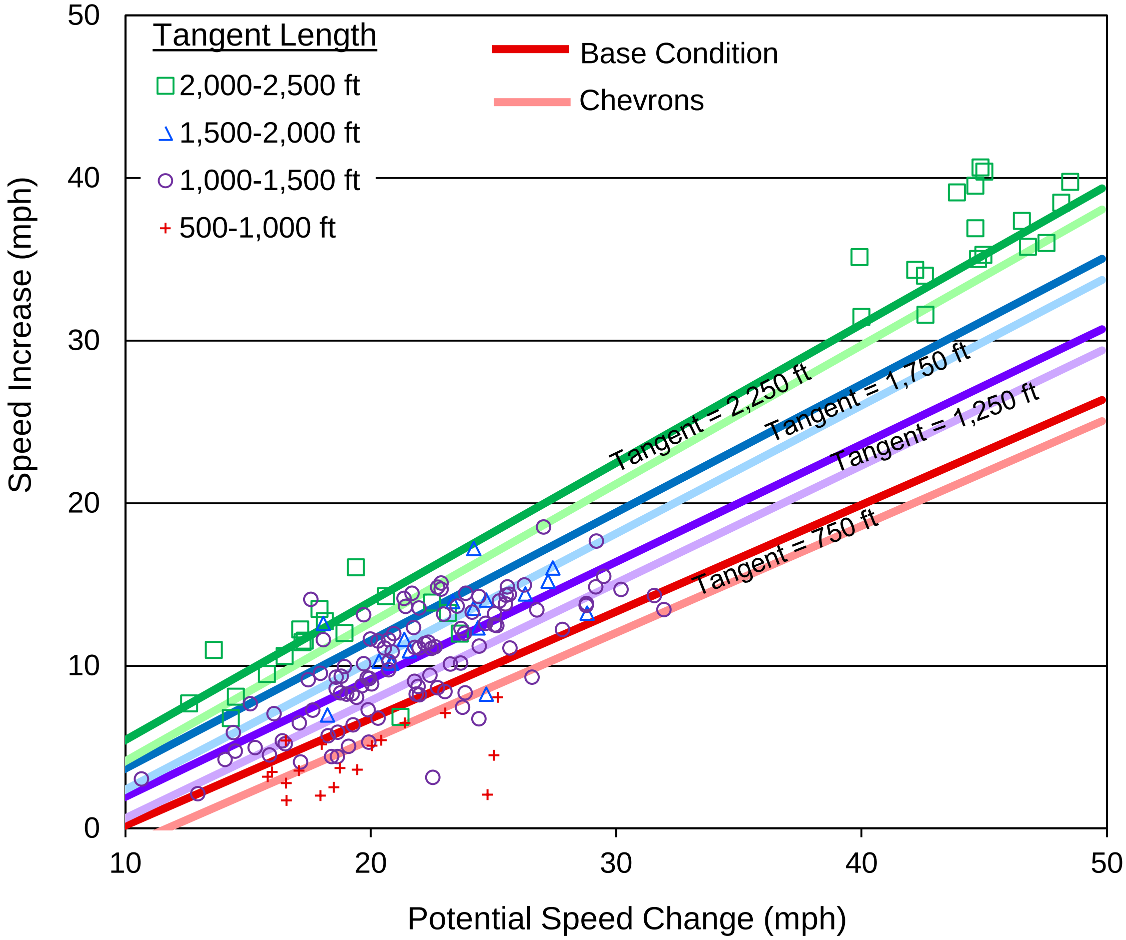


Figure 5.2: Increase in speed (mph) observed on a tangent with influence of TCDs.

5.3.2. Deceleration before Entering a Curve

As described in Section 4 three performance metrics associated with the deceleration phase were tested. Only two proved useful for modeling behavior: the total speed reduction that occurs on the tangent and the maximum deceleration rate observed. The speed reduction before the PC was shown to be dependent upon the maximum speed observed on the tangent, the distance before the curve when that maximum speed occurs, and the radius. The second metric, the maximum observed deceleration rate, is dependent upon the total speed reduction at the curve. The effects of supplementary devices are incorporated into the models in Table 5.3. Based on the residuals for the models in Figures B.25 through B.28, it appears that assumptions of constant variance and normality are met for both models without needing any transformations or other adjustments.

Table 5.3: Regression Models of Pre-Curve Deceleration (Supplementary Devices)

	Estimate	t Ratio	Prob>|t|
Speed Reduction (mph) on Tangent (R^2=0.80)			
Intercept	-17.1	-11.3	<0.0001
Maximum Speed on Tangent (mph)	0.42	14.8	<0.0001
1 / Radius (ft)	1187	34.8	<0.0001
Supplementary Devices:			
Delineators (if yes)	2.3	5.25	0.0039
Arrow Sign (if yes)	2.7	4.65	0.0562
Chevrons (if yes)	2.5	8.31	0.104
Maximum Deceleration Rate (ft/s^2) on Tangent (R^2=0.70)			
Intercept	2.0	9.59	<0.0001
Speed Differential (mph)	0.24	18.8	<0.0001
Supplementary Devices:			
Delineators (if yes)	-0.46	-2.40	0.0167
Arrow Sign (if yes)	-0.13	-0.52	0.0188
Chevrons (if yes)	-1.29	-9.48	<0.0001

The model for the speed reduction that occurs before the curve indicates that a greater change in speed occurs when any of the three supplementary devices are used. The acceleration models in Section 5.3.1 showed that drivers reach a lower speed on the tangent when a device is used. Since the factor for the maximum speed on the tangent is carried over into this model, drivers will be entering the curve at an even lower speed when supplementary TCDs are used. The indicators show delineators contribute approximately 2.3 mph, an arrow sign approximately 2.7 mph, and chevrons approximately 2.5 mph to the change in speed. The model of the maximum observed deceleration rate indicates that the effects of delineators, arrows, and chevrons on deceleration rates are approximately 0.46, 0.13, and 1.29 ft/s^2. Equations 5.3 and 5.4 are mathematical representations of the models in Table 5.3.

$$\Delta Speed_{Decel} = -17.1 + 0.42 Speed_{Max} + \frac{1187}{R} + TCD \qquad 5.3$$

$$Decel_{Rate_{Tan}} = 2.0 + 0.24 \Delta_{Speed} + TCD \qquad 5.4$$

where

$\Delta_{Speed_{Decel}}$	=	change in speed (mph) before the curve,
$Decel_{Rate_{Tan}}$	=	maximum deceleration rate (ft/s^2) on the tangent,
$Speed_{Max}$	=	maximum speed (mph) on the tangent,
R	=	radius (ft),
Δ_{Speed}	=	total speed differential at the curve, and
TCD	=	influence of a supplementary device obtained from Table 5.3.

The data used to generate the models in Equations 5.3 and 5.4 had the following ranges. The radius ranged from 55 to 860 ft (average 460 ft); the maximum speed observed on the tangent ranged from 35 to 66 mph (average 51 mph); and the total observed speed change ranged from 0.6 to 46 mph (average 15 mph). For the dependent variables, the speed change in advance of the curve ranged from 0 to 37 mph (average 9.5 mph) and the maximum observed deceleration rate on the tangent ranged from 0.6 to 17 ft/s^2 (average 5.2 ft/s^2).

A graph of the deceleration rates observed and predicted for the base condition (with warning sign) and condition with chevrons is provided in Figure 5.3. The graph illustrates how, when accounting for the total speed differential at the curve, chevrons encourage deceleration rates to decrease by approximately 1.3 ft/s^2.

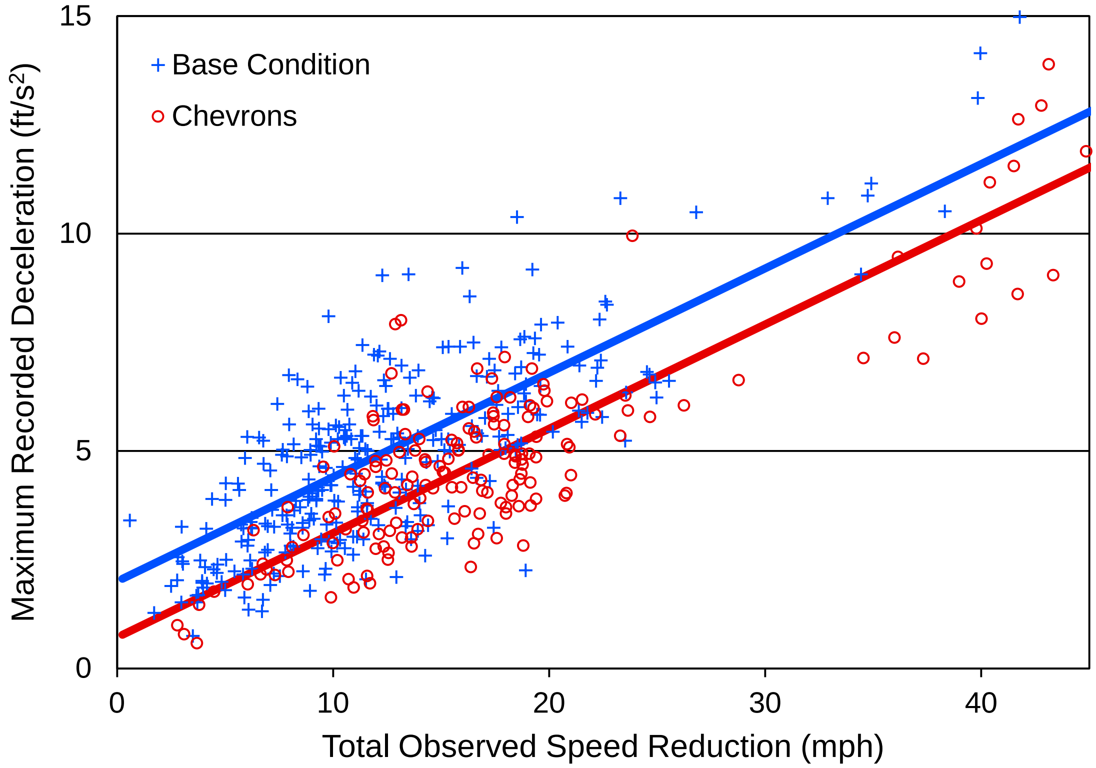


Figure 5.3: Maximum deceleration rates on a tangent under base conditions (warning sign only) and with chevrons.

5.3.3. Within-Curve Performance

The performance of drivers within curves was evaluated with three metrics in Section 4: the speed of the vehicle entering the curve (at the PC), the maximum deceleration rate observed within the curve, and the lateral acceleration rate within the curve. From these models, the radius and the speed on the tangent were found to be the primary factors influencing the speed at the PC; the speed differential was the primary factor affecting the deceleration rate within the curve; and the geometry influences the maximum lateral acceleration within the curve. The models that include effects of supplementary devices are provided in Table 5.4.

No transformations to the dependent variables were necessary to generate the models in Table 5.4. The residuals from the model of the speed at the PC are plotted in

Figure B.29 and appear normally distributed in Figure B.30. Three outliers were removed from the model of the maximum deceleration rate whose residuals were affecting the assumption of normality. The residuals of the resulting model are shown in Figures B.31 and B.32 in Appendix B. Two outliers were removed when creating the model of the maximum lateral acceleration, also to ensure normality. Model residuals are shown in Figures B.33 and B.34. Assumptions of constant variance appear to be met in all three models.

Table 5.4: Regression Models of Within-Curve Performance (Supplementary Devices)

	Estimate	t Ratio	Prob>|t|
Speed (mph) at PC (R^2=0.81)			
Intercept	17.1	11.3	<0.0001
Maximum Speed on Tangent (mph)	0.58	20.22	<0.0001
1 / Radius (ft)	-1187	-34.8	<0.0001
Supplementary Devices:			
Delineators (if yes)	-2.3	-5.25	<0.0001
Arrow Sign (if yes)	-2.7	-4.65	<0.0001
Chevrons (if yes)	-2.5	-8.31	<0.0001
Maximum Deceleration Rate (ft/s^2) in Curve (R^2=0.54)			
Intercept	2.39	12.2	<0.0001
Speed Differential (mph)	0.18	21.1	<0.0001
Supplementary Devices:			
Delineators (if yes)	-1.02	-4.84	<0.0001
Arrow Sign (if yes)	-1.16	-4.17	<0.0001
Chevrons (if yes)	-0.88	-6.12	<0.0001
Maximum Lateral Acceleration (g) (R^2=0.50)			
Intercept	0.30	34.3	<0.0001
Ln[Deflection (deg) / Radius (ft)]	0.036	15.3	<0.0001
Supplementary Devices:			
Delineators (if yes)	-0.016	-2.59	0.0099
Arrow Sign (if yes)	-0.005	-0.60	0.552
Chevrons (if yes)	-0.023	-5.09	<0.0001

Each model Table 5.4 contains the supplementary devices as main effects, which are shown to reduce speeds at the curve and rates of deceleration and lateral acceleration within the curve. Equations 5.5 through 5.7 are representations of the models from Table 5.4

$$Speed_{PC} = 17.1 + 0.58Speed_{Max} - \frac{1187}{R} + TCD \tag{5.5}$$

$$Decel_{Rate_{Curve}} = 2.39 + 0.18\Delta_{Speed} + TCD \tag{5.6}$$

$$Accel_{Lat} = 0.30 + 0.036 \ln\frac{I}{R} + TCD \tag{5.7}$$

where

$Speed_{PC}$	=	speed (mph) at the PC,
$Decel_{Rate_{Curve}}$	=	maximum longitudinal deceleration rate (ft/s^2) in the curve,
$Accel_{Lat}$	=	maximum lateral acceleration (g) in the curve,
$Speed_{Max}$	=	maximum speed (mph) on the tangent,
R	=	radius (ft),
Δ_{Speed}	=	change in speed (mph) observed at the curve,
I	=	curve deflection angle (deg).
TCD	=	influence of a supplementary TCD obtained from Table 5.4.

The data used to generate the models in Equations 5.5 through 5.7 contained observations with the following ranges. The radius ranged from 55 to 860 ft (average 460 ft); the maximum speed observed on the tangent ranged from 35 to 66 mph (average 51 mph); the total observed speed change ranged from 0.6 to 46 mph (average 15 mph); and the deflection angle ranged from 27 to 90 deg. Regarding the dependent variables, the speed at the PC ranged from 18 to 59 mph (average 41 mph); the maximum deceleration rate in the curve ranged from 1 to 17 ft/s^2 (average 4.7 ft/s^2); and the maximum lateral acceleration rate ranged from 0.1 to 0.42 g (average 0.22 g).

From the models in Table 5.4 and Equations 5.5 through 5.7, it is apparent that supplementary TCDs do encourage drivers to adopt a more-conservative behavior at curves. The connections between the effects of TCDs in these models are quite logical—with reduced speed at the curve, there is a reduced need to decelerate while within the curve. There should also be reduced lateral acceleration, which is directly dependent upon the speed of the vehicle. Figures 5.4 and 5.5 graphically represent the models of the speed of the vehicle at the curve entrance and the maximum deceleration rate in the curve under base conditions (warning sign only) and with a treatment of chevrons.

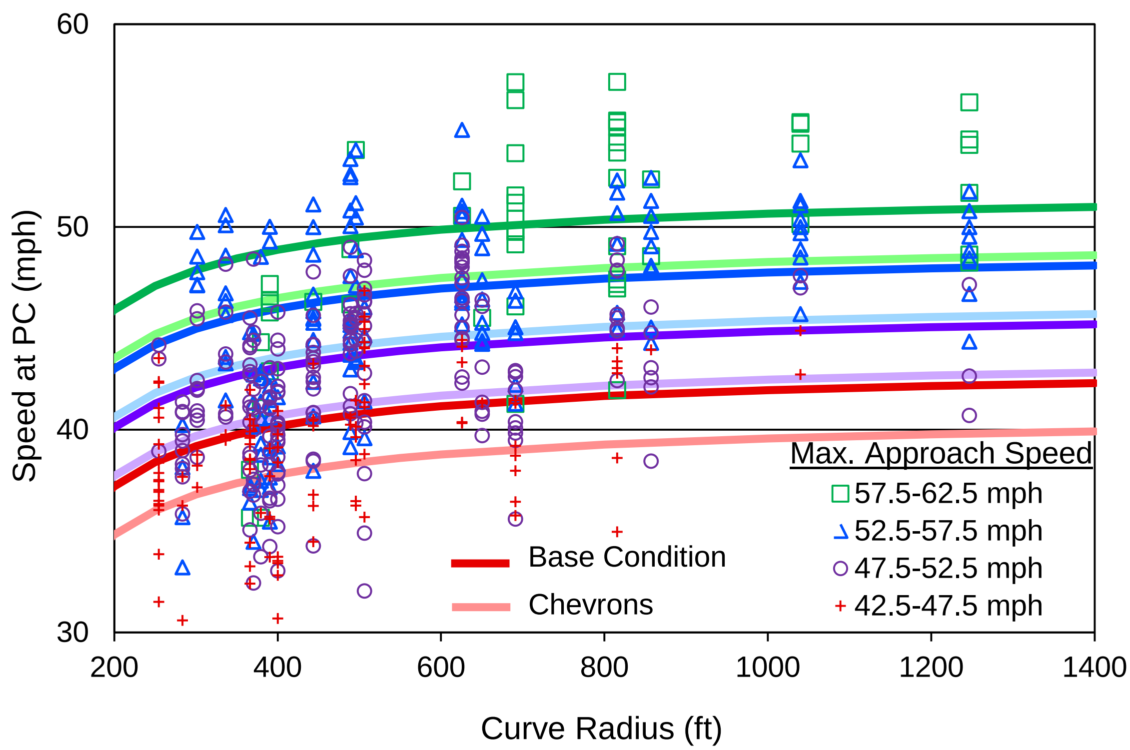


Figure 5.4: Speeds at a curve entrance based on radius and approach speed under base conditions (warning sign only) and chevrons.

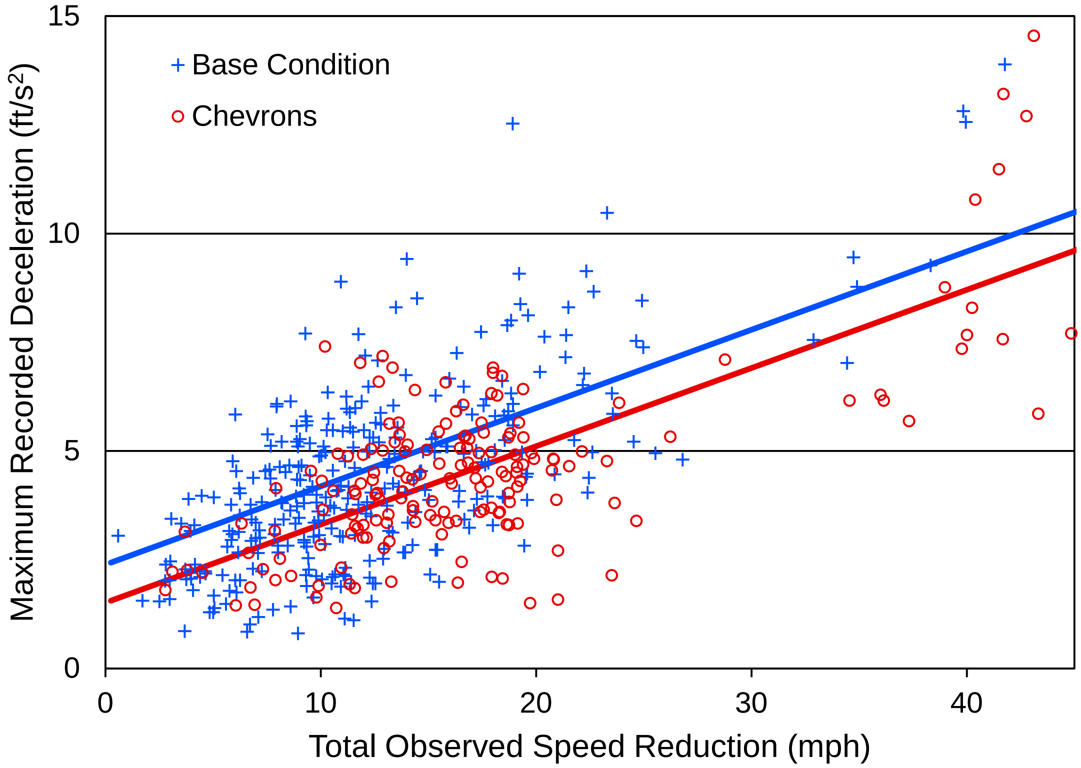


Figure 5.5: Maximum deceleration rates in a curve under base conditions (warning sign only) and with chevrons.

5.4. Summary

This section presents multivariable models of driver performance that identify the effects of curve supplementary TCDs (PMDs, large arrow signs, or chevrons) while taking into account the strong relationships of geometry as identified in Section 4. Within each model, the effect of TCDs was found to be significant based on the F-test, indicating that the use of a supplementary device does significantly affect performance. The *p* values from the t-test sometimes indicate there is no significant difference among the different devices used, which explains why some of the specific TCD effects in the models are quite similar. Based on the models above and Equations 5.1 through 5.7, the following observations can be made regarding the effects of the TCDs:

1. Drivers respond to supplementary devices by ending the acceleration phase earlier (76–137 ft) and with reduced speed on the tangent (about 0.7 to 1.9 mph).
2. Deceleration rates are reduced when supplementary devices are used. This is true for all speed differentials when delineators and chevrons are used, but only for speed differentials less than 24 mph when a large arrow is used.
3. Driver speed upon entering a curve is reduced for all conditions when supplementary TCDs are used. The effect for PMDs is 2.3 mph; chevrons, 2.5 mph; and arrow signs, 2.7 mph.
4. When supplementary devices are used, drivers have reduced deceleration rates within the curve. Chevrons and large arrow signs are effective for all reasonable speed differentials; delineators are effective when the speed differential is greater than 8.8mph.
5. The maximum lateral acceleration rate generally decreases when supplementary devices are used. The effectiveness at reducing lateral acceleration increases as curve severity increases.

Section 4 identifies seven basic models of driver operational behavior, focusing on the effects of geometry throughout the 3 phases of curve negotiation. The curves used for those analyses had a very diverse range of characteristics. The dataset used in this section was a subset of that larger, original dataset that needed to be constrained to fit the characteristics of curves treated with supplementary TCDs. When geometry and other operational factors are considered, it is apparent that the TCD effects are quite small, based on the estimates for the effects and the tests for significance

A significant benefit of this research is the applicability of the results to a relatively-broad set of conditions, since multiple curves were evaluated and effects of geometry were considered in the results. Most previous operations-based studies identified the effects of TCDs by measuring speed at select points within a small number of curves. In many cases, the researchers were able to claim a small reduction in speeds, not unlike what is shown in the models here (Agent and Creasey 1986; Carlson et al.

2004; Chrysler et al. 2009; Re et al. 2010; Bullough et al. 2012). There seems to be overall consistency of findings regarding within-curve operational performance, at least as measured by speed.

One important finding that connects to previous work is related to the model estimating the distance traveled during the acceleration phase. The model in this section (Table 5.2) suggests that drivers reach a maximum speed between 75 and 135 ft earlier when a supplementary device is used. Chrysler et al. (2009) showed that drivers were confident about the severity of the curve 100-250 ft earlier when vertical delineation treatments were used. They also found that the distance from the curve when drivers stop throttling the accelerator and depress the brake increases when TCDs are used. The findings in this section seem reasonably consistent with the earlier research.

5.5. Conclusion

In comparison to previous research, the models in this section do not present any specific finding that alters the consensus of how drivers respond operationally to TCDs. A reduction in observed speed at the PC by approximately 2.5 mph when a TCD is used is not that surprising, and by itself is not that important. (A difference of 2.5 mph will rarely be what determines whether or not a crash occurs at a curve on a rural highway.) The other within-curve metrics were similarly lackluster. If the devices have an overall subtle effect within the curve, perhaps their real value may be found in the models that identify the operational behavior leading up to the curve. For the nighttime conditions, drivers stopped accelerating approximately 137 ft earlier at curves when chevrons were used compared to other similar curves without supplementary devices. PMDs or arrow signs also prompted drivers to respond to the presence of the curve at an earlier time.

Chevrons are very conspicuous when illuminated by headlamps at night, and their message regarding the alignment is quite clear. Arrow signs are similarly salient and also have a direct message, though perhaps not as strong (usually only one sign is used per direction); the message provided by PMDs is less clear and prominent. (There seems to be a progression of TCD severity, though the model results do not always reflect that.) The principal reason drivers would stop accelerating earlier or start decelerating earlier is that information is provided to drivers earlier and/or their perception of the information leads to a quicker or stronger response. The increased visibility of the supplementary TCDs over pavement markings at night supports the idea that drivers are responding to the information about the curve at an earlier time. While 2.5 mph in the curve may not be a crash-saving difference by itself, the proper acquisition of information at an appropriate, if not earlier, time may be the factor that does prevent one.

It is understood that the best decisions are made with the information available in that moment. The way the devices influence the operational performance is thus a reflection of the perception of information available to drivers. So much of the previous research has focused on driver performance within curves, which is understandable considering the historical concern for safety at curves. But curve negotiation is clearly a more-dynamic and complex process than is implied by a single, simple value, such as curve speed. The presentation of the performance metrics here and in Section 4 in a chronological manner helps in explaining where a device begins influencing driver behavior and how that response on the approach affects the performance within the curve—it is a more complete picture of the way TCDs influence performance. Drivers clearly do not respond to TCDs just within the limits of the curve, nor is their perception of information about the curve exclusive to the message of the device. They use all available information in context of the setting to make adjustments that reflect their experience, expectations, and tolerance for risk.

It must be emphasized that operational behavior is a reflection of the motor center output shown in the closed-loop system in Figure 2.1. It cannot be said with certainty, based on the output alone, that TCDs help drivers process information about curves earlier. That certainty can only come from measures that directly reflect the drivers' cognition. These measures, investigated through eye-tracking technology, are discussed in the next section.

6. VISUAL BEHAVIOR AND COGNITIVE LOAD OF DRIVERS APPROACHING AND NAVIGATING CURVES

This section details the analysis of eye-tracking data collected during the driver behavior study. The results include patterns that show how visual and cognitive load changes while drivers approach curves and how TCDs influence these changes. Visual behavior can be characterized by how the driver views the forward scene, and the cognitive load is reflected in the physiological changes to the driver's eyes as measured through eye-tracking technology. These changes are indicative of the driver's perception of information. A cognitive response, manifest through the visual behavior, provides a perspective of the driving experience that cannot be characterized by vehicle operations alone.

6.1. Background

With the exception of instances of inattentional blindness, drivers tend to fixate on the objects they consider to provide the most important information at that moment. Early eye-tracking driving research was aimed at identifying general characteristics of visual behavior, such as where drivers fixate and overall fixation patterns. Since then, more-specific scenarios have been defined, including some related to the use of TCDs. Notable research on the visual behavior of drivers has included studies of where drivers look (Mourant and Rockwell 1970; Land and Lee 1994), how characteristics of fixations change for different driving situations (Shinar et al. 1977), how separate cognitive loads, distractions, or changes in complexity of the driving scene affect these behavioral patterns (Luoma 1987; Miura 1990; Lehtonen et al. 2012), and the influence of driving experience (Mourant and Rockwell 1972; Cohen and Studach 1977; Chapman and Underwood 1998; Crundall and Underwood 1998; Falkmer and Gregersen 2005).

It has been shown that as drivers approach curves they concentrate on the occlusion point (where the curve becomes hidden from view), anticipating potential hazards and searching for additional roadway information at the earliest possible time (Shinar et al. 1977; Cohen and Studach 1977; Lehtonen et al. 2012). While visual behavior of drivers approaching and navigating curves has been documented multiple times by evaluating fixations, current eye-tracking technology allows other measures to be investigated. Such measures included in this study are the size of the pupils, the amount of closure of the eyes, and the blink rate.

The purpose of TCDs at curves is to provide drivers with the information necessary for safe and efficient curve navigation. Tracking the visual behavior of drivers as they drive on a tangent and approach a curve may help identify when drivers perceive curves and the factors (such as TCDs) that affect the temporal aspects of the cognition. Each supplementary TCD has different physical characteristics that affect the messages conveyed to drivers. Section 5 identified how the use of the different TCDs may result in small, though noticeable, operational changes at curves. It would not be surprising if the effects of TCDs on visual attention as identified in this section are similarly subtle.

6.2. Methodology

The data for this section were obtained from the multi-state open road driving study described in Section 3. The measures of visual behavior and cognitive load were compiled over 4-second intervals at 100-ft increments along the approach tangent to the study curves. The first results in this section are general patterns in those metrics observed as drivers approach and navigate curves. Though with little detail, these patterns serve a similar purpose as the operational behavior models in Section 4, introducing the reader to the behavior that will then be examined more thoroughly. The patterns were identified from data collected in all three states, using 22 curves to the left and 14 curves to the right. Only curves with approach tangents longer than 1,000 ft are included. There were 519 total observations of drivers approaching and navigating curves in the patterns.

While the first portion of the results that show patterns of visual behavior are based on data collected in all states, the effects of TCDs are analyzed using data collected only in Texas at night, as was done with the operational analyses in the previous section. The exclusive use of nighttime data is crucial for limiting the influence of light on the physiological measurements of pupil size and eye closure and for capturing the responses of the drivers at the time when they are most reliant on TCDs. Like the analyses of TCD effects on operational behavior, the analysis of visual behavior employs multivariable mixed linear models that estimate the fixed effects of geometric factors and the supplementary TCDs (if any) used at the curves. Participant drivers are incorporated as random effects. The analyses of TCDs are based only on nighttime data collected on the same segments and curves that were used in Section 5 (described in Table 5.1). The curves in the analysis thus have similar features but may have received different traffic control treatments. Again, JMP was used to generate the models. When necessary, transformations or weighted regression techniques were used.

6.3. Results

The operational analyses presented in Sections 4 and 5 detail how drivers accelerate after exiting the curve and then decelerate before entering a curve. Those findings are congruent with decades of operations research. The acceleration and deceleration phases at curves shown in Figure 2.2 should not be an unfamiliar concept to the average reader because their patterns have been investigated through decades of research. Patterns associated with fixations at curves have been previously investigated, as discussed above, but the physiological measures of pupil diameter, eye closure, and blink rate at curves have not received much attention, if any. Like the operations analyses, the analyses in this section also employ multivariable mixed linear models to assess changes in these measures to familiar parameters associated with curves.

Section 4 used novel performance metrics to characterize operational performance, and the previous section analyzed the effects of TCDs. In a similar way, Section 6.3.1 below introduces the reader to patterns of visual behavior observed from the entire dataset using various images to illustrate the parameters of interest and how they change while drivers approach and then navigate curves. Section 6.3.2 then uses the same segments as the analyses in the previous section to isolate the effects of supplementary TCDs.

6.3.1. Patterns in Visual Behavior at Curves

This subsection introduces various measures of visual behavior and shows how they change as drivers approach and navigate curves. The patterns discussed here are based on a large dataset and are illustrated in figures that are useful for identifying trends associated with the perception of information relevant to navigating curves.

6.3.1.1. Patterns of Fixation Location

Previous research has shown that driver fixations at night are distributed across a smaller area and directed lower than during the day, due to the drivers' reliance on headlamps (Brimley et al. 2014). The eye-tracking data in this study contain vertical and horizontal components of the fixation angle, which indicate the location where the eyes are fixating at a single point in time. Each component (horizontal or vertical angle) represents the off-center displacement of the fixations.

Changes in this location of focus are shown in Figure 6.1, displaying graphs of the average horizontal displacement angle of driver fixations for curves of two different directions. The angular displacement, mapped against the location of the drivers with respect to the curves, shows that driver fixations tend to be slightly off-center to the right when far away from curves, and begin moving (on average) toward the direction of the curve at about 600-700 ft before the curve. Figure 6.1 uses curves from all three states with different geometry and traffic control treatments. As such, it is impossible to identify specific effects of those factors from the figure alone. The shaded areas in Figure 6.1 represent one standard deviation of the data.

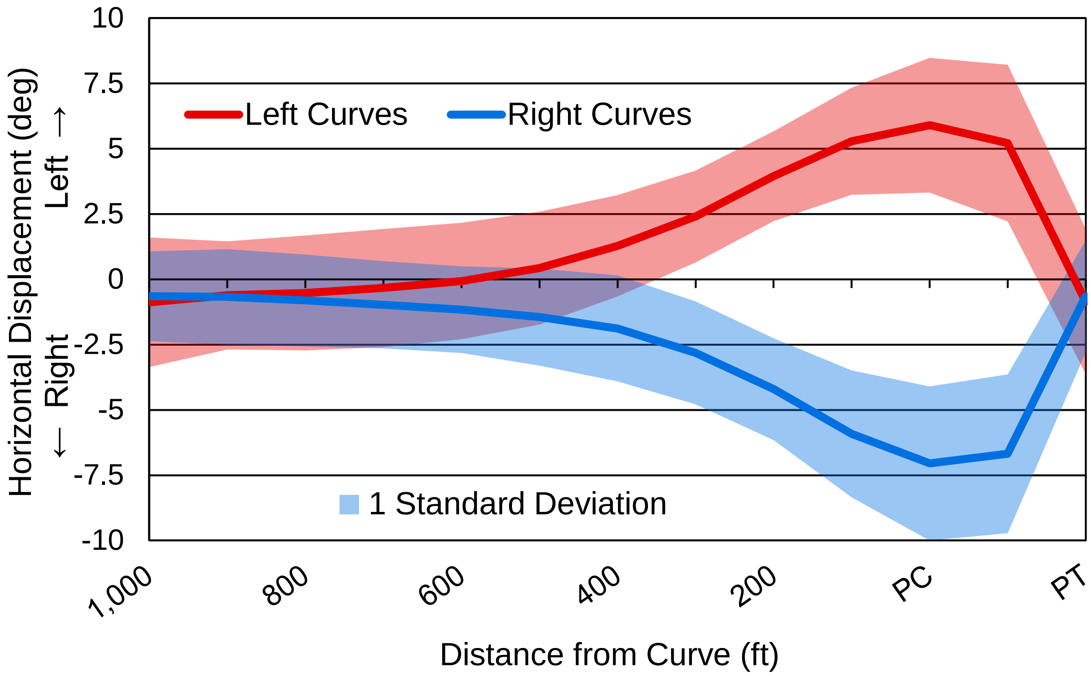


Figure 6.1: Average horizontal gaze displacement by distance from curve.

The vertical displacement of fixations is indicative of how far in front of the vehicle the drivers are viewing the forward scene. The viewing distance increases as vertical displacement increases. Without analyzing the exact position and orientation of the eye-tracking cameras and drivers, it is impossible to translate the vertical displacement angle to actual viewing distance. The general trends are still valuable. Figure 6.2 shows the average vertical displacement of fixations for drivers approaching and navigating the same curves used in Figure 6.1. One clear observation about Figure 6.2 is the variability in the vertical displacement, indicated with the shaded standard deviation. The average value is quite small compared to the standard deviation. It appears that the average preview distance begins to increase around 800 ft before each curve, likely indicating a change in visual behavior while approaching the upcoming curve, but it is difficult to definitively state much more simply because of the variability in the data. For the change in the average at that distance, it may be that drivers acknowledge the presence of the curve and are adjusting their fixation location to give themselves as much preview time and distance as possible to become aware of other possible hazards.

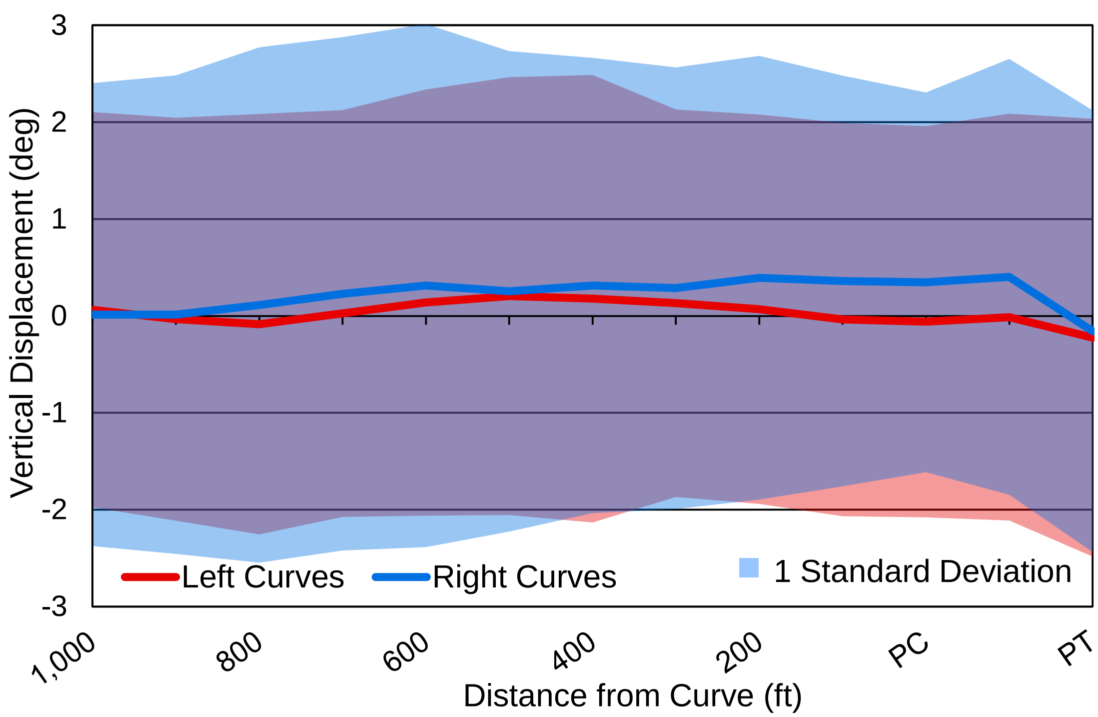


Figure 6.2: Average vertical gaze displacement by distance from curve.

One of the difficulties of examining fixation location based on an average is that drivers tend to scan an entire area with overall quick fixations, rather than concentrate on an isolated point. Figures 6.1 and 6.2 show averages, but a reader may incorrectly interpret that the figures identify the actual fixation locations. Previous research by Zwahlen (1987; 1988; 1995) shows that drivers do not fixate on signs for long periods of time. Once the relevant information is obtained (and confirmed, if necessary, by a subsequent fixation), there is no reason for drivers to continue fixating on it. The same is true for other objects or road features. Repeated fixations along the alignment however, are necessary because the driver is anticipating changes in the alignment.

The average vertical fixation angle appears discontinuous compared to the average horizontal fixation angle. The horizontal fixation angle for Figure 6.1 is primarily controlled by the direction of the curve and it would be expected that drivers do not allow their gazes to vary much outside of the roadway alignment. Regarding vertical fixation displacement, previous research has shown that drivers alternate between near- and far-field fixations, even at curves (Shinar et al. 1977). Patterns of fixation distance were evaluated by Zwahlen (1993) who found no consistent or preferred pattern for drivers. With drivers inconsistently rotating between near- and far-field fixations, the result is substantial variability in the vertical displacement of gazes, evident in Figure 6.2 , Ultimately, there is a limit to how much can be interpreted from an average of fixations.

6.3.1.2. Patterns of Pupil Diameter

As a physiological and involuntary response, changes in pupil size reflect cognitive processes of a driver. The task-evoked pupillary response is a measure of cognitive load. For drivers, pupil dilations are indicative of the workload associated with performing search tasks and anticipating and carrying out driving maneuvers. Section 2 identifies multiple ways to characterize the response, such as the latency to peak dilation or the magnitude of the dilation. One of the complexities of the pupillary response in this study is that the stimulus (the information about the curve from the TCDs) is not presented to the drivers at a uniform time. Drivers have unique visual abilities and patterns regarding the objects that are fixated on. Rather than suddenly being presented with a stimulus or task (as is often done in other studies) the TCDs gradually come into view as the drivers approach the curve.

Figure 6.3 shows the difference between the drivers' measured pupil on the tangent and within the curve and their respective average diameter, averaged over the 36 curves. The shaded area represents one standard deviation of the data for that location. There is a substantial amount of variability illustrated with the standard deviation, but that may be expected with 36 different curves and most of the nighttime drivers included. There is no distinction for direction in Figure 6.3; 321 total observations are represented for each 100-ft location. There are fewer total observations in Figure 6.3 than were used in the diagrams for fixations above because the eye-tracking cameras were able to measure the pupils for only a select number of participants. In Figure 6.3, the eyes begin to dilate (on average) several hundred feet in advance of the curve, which is near the location where the fixations started to change in Figures 6.1 and 6.2. The average pupil diameter reaches a peak near the entrance of the curve, and then contracts by the end of the curve.

It is important to note that, like the previous figures, the primary line in Figure 6.3 represents an average of multiple participants at multiple curves. The pupils of each participant at each curve may dilate earlier or later than what appears here (which begins near 800 ft before the curve). While the average change in diameter in Figure 6.3 shows a quasi-sinusoidal pattern with total average change in diameter near 0.2 mm, the experience of an individual driver at a single curve may be quite different and is masked by using an average. Individual changes were often between 0.2 and 1.0 mm, a consistent range for task-evoked pupil responses in previous work.

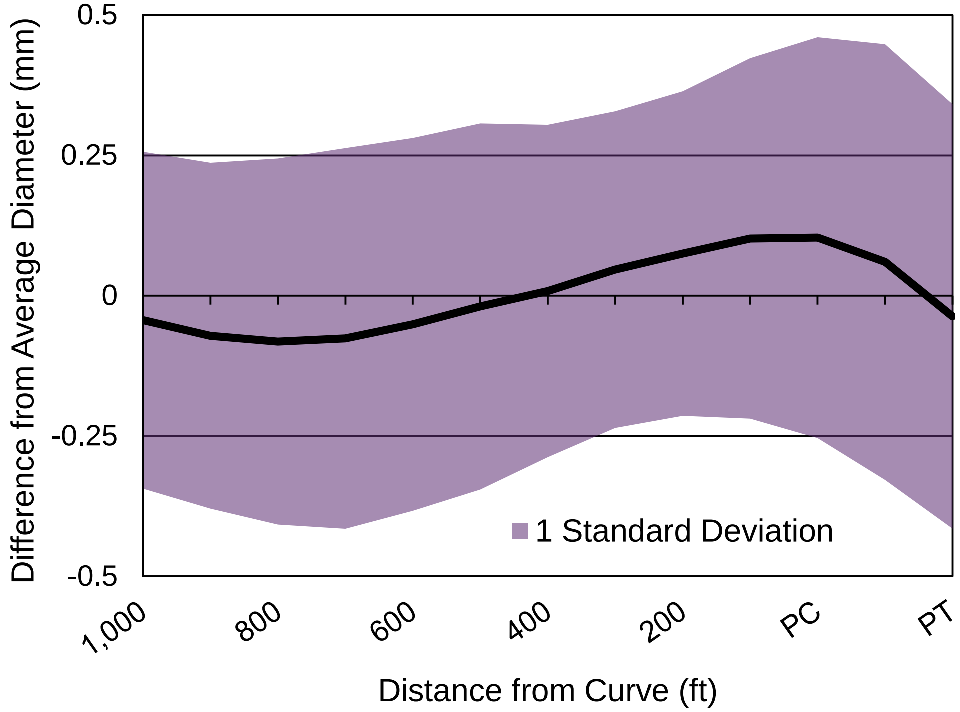


Figure 6.3: Average difference between participants' measured and average pupil diameter (mm).

6.3.1.3. Patterns of Eye Closure

The eye closure is a measure of the amount of the eye covered by the eyelid, given as a percentage. Most driving research employing eye closure has used it as a measure of drowsiness. It is investigated in this research as a measure of alertness. Figure 6.4 shows the pattern of the difference between a driver's actual eye closure on a segment and average eye closure throughout the experiment. The trend in Figure 6.4 shows the eyes becoming wider as the driver approaches the curve. Although there is substantial variability shown in the figure (like the previous figures, it was created from all the nighttime participants at multiple curves), the eyes are (on average) closed the most near 800 ft before the curves. The biggest changes occur when the driver is approximately 400 ft from the curve and the eyes are widest at the beginning of the curve. It was mentioned that a change in pupil size is an involuntary physiological response indicative of visual search tasks and changes in cognition. While a person can control eye closure more easily than pupil size, it is still a natural reflection of visual behavior. There is clearly a similarity in the patterns of eye closure and pupil size with respect to the task of navigating curves.

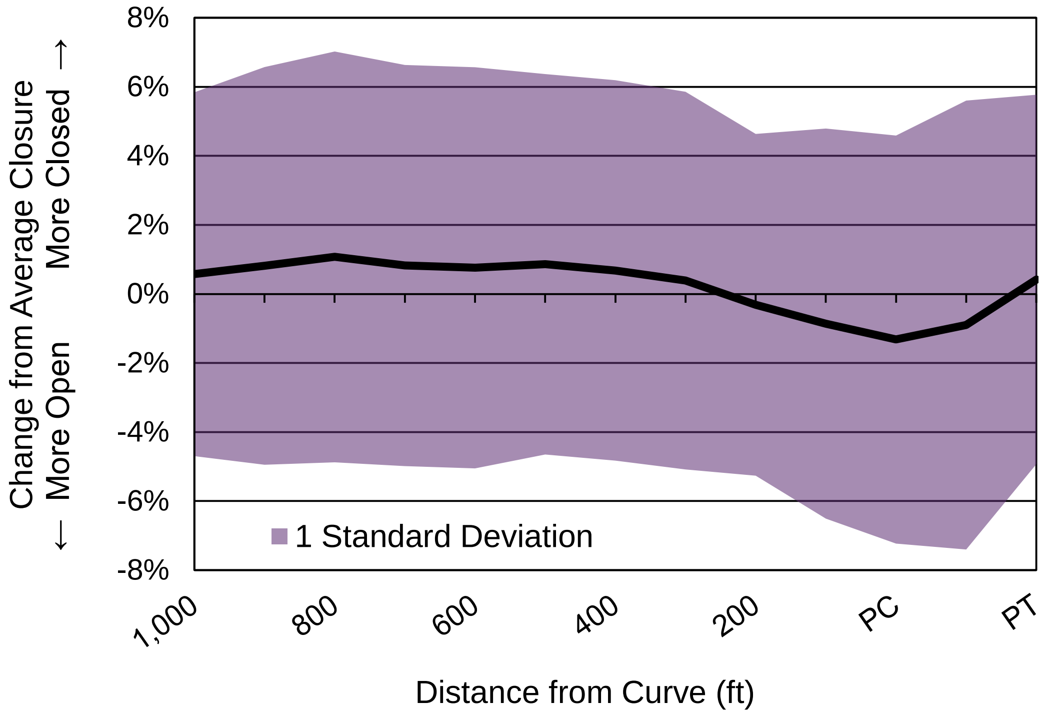


Figure 6.4: Difference between measured eye closure and average eye closure by distance from curve.

6.3.1.4. Patterns of Blink Rate

Blinks are recorded by the eye-tracker as binary occurrences through time, either as a 1 or 0 to indicate that a subject is blinking or not blinking. By totaling the number of blinks over a 4-second interval, the blink rate (over 4 seconds) becomes more like a continuous metric. The variable is still difficult to use because it is not normally distributed within a reasonable range for each participant like the pupil size (3-7 mm) or eye closure (20-80 percent). Some drivers may go several seconds without blinking (blink rate = 0) or may blink quite frequently.

Like the pupil size and percent eye closure, each person has a unique blink rate observed when under normal and relaxed conditions. Previous research discussed in Section 2 has shown that blink rate decreases when a person is under additional workload. A decrease in blink rate is thus expected as the driver approaches the curve. Figure 6.5 shows the average blink rate observed for the participants as they approached curves starting at an approach distance of 1,000 ft, using an average of 434 observations for each data point. One standard deviation is also shown shaded in grey. The pattern in Figure 6.5 should now be familiar as one period of a quasi-sinusoidal function that is evident in the pupil and eye-closure data. The blink rate (on average) is at a maximum at 900 ft before the curve and then increases after reaching a minimum near the PC.

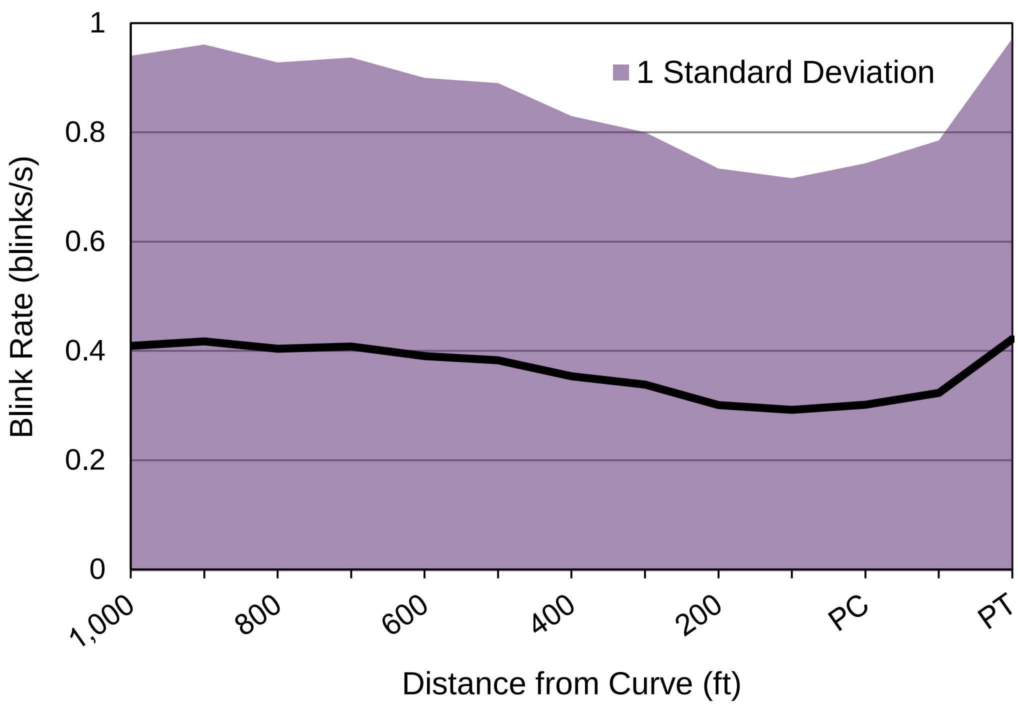


Figure 6.5: Average blink rate by distance from curve.

6.3.1.5. Summary of Visual Behavior Patterns

The graphs provided in the previous figures indicate patterns of visual behavior and measures of cognitive load that are consistently observed as drivers approach and navigate curves. Specifically, changes in fixation location, pupil size, eye closure, and blink rate were shown. These changes can be observed beginning several hundred feet in advance of the curve, returning to “normal” either while within the curve or shortly after exiting. The graphs are based on averages of all the participants (between 300 and 600 observations for each data point) at the specific 100-ft increment, which overshadow the actual experience of an individual driver. Because the change for each driver occurs at a unique location, the actual magnitude of the changes in each measure tends to be greater than the averages shown.

The horizontal component of the fixation location is consistent with previous research (Shinar et al. 1977), showing where drivers fixate while approaching and navigating curves. The small changes in average horizontal displacement beginning several hundred feet in advance of the curve indicate the driver is making brief fixations toward the occlusion point on the curve, while the majority of fixations are still directly in front of the vehicle. At that distance, the occlusion point on the curve is also not far off-center. Changes in the average vertical displacement of fixations indicate that drivers increase their average viewing distance as they anticipate the upcoming curve. The sudden change that occurs near 800 ft may indicate the (average) location where the driver is aware of the presence of the upcoming curve. Within the curve, the average viewing distance decreases due to the visible constraints of the geometry and the need for more guidance during the navigation process.

In the patterns of the physiological measurements (pupil diameter, eye closure, and blink rate) driver workload begins to increase (on average) 800-900 ft from the curve. The increase in workload is associated with the tasks of searching for and perceiving information related to the upcoming curve. It seems that the pupil dilating may be more of a reflection of the cognitive load, while the blink rate and eye closure relate more to the visual demand, since their changes occur later near the curve where the visual demands significantly increase.

The locations where the visual behavior and cognition change are quite consistent among each other. This should not be surprising since they each come from the drivers' eyes. Such correlation is desirable considering these measures have previously not been analyzed together in an evaluation of drivers approaching and navigating curves. Since some of these measures are quite novel, the patterns shown above are meant to only introduce the reader to how they fluctuate and can be used in characterizing visual attention. There was no consideration for the specific curve characteristics and TCDs, which are evaluated in models discussed in the next subsection.

6.3.2. Models of TCD Effects on Visual Behavior

The patterns shown in Figures 6.1 through 6.5 identify changes in cognition associated with approaching and navigating curves that start several hundred feet in advance of the curve. The initiation of these changes can only happen when drivers perceive information about an upcoming curve. The purpose of the analyses here is to identify the effects that various forms of information (TCDs and geometry) have on the visual behavior of drivers. Effects on fixation location, pupil diameter, and eye-closure are reported, with models identifying where the change in cognition occurs and the magnitude of the response. The blink rate was not evaluated due to the complexity associated with the blink data.

6.3.2.1. Models of Fixation Location

Figures 6.1 and 6.2 show the average angular deviation of fixations generated from the eye-tracking data. Statistical analysis was not able to identify an effect on horizontal displacement due to the use of TCDs. Even though TCDs were not found to significantly impact the horizontal displacement of fixations, it is still valuable to investigate the factors that influence where a driver looks. For example, it appears in Figure 6.1 that drivers start visually responding to the curve around 600 or 700 ft from the curve, based on the split of the average fixation location by direction. A further analysis may verify this observation. Models based on the fixation data were developed to identify the factors that contribute to the horizontal component. In order to declare that the driver is visually responding to the curve, there must at least be a noticeable effect of curve direction on the fixation displacement. Additional influence from the geometry of the curve is desirable. Equation 6.1 shows the model structure. Estimates for the parameters are given in Table 6.1.

$$Hort.Displacement = \beta_0 + Direction \times \left(\beta_1 \times I_R + \frac{\beta_2}{R}\right) \quad 6.1$$

where

Hort. Displacement	=	horizontal fixation displacement (deg),
β_0	=	intercept,
Direction	=	indicator for direction {Right = +1; Left = −1},
β_1	=	estimate for right curve indicator,
I_R	=	indicator for right curve {Right = +1; Left = 0},
β_2	=	estimate for effect of geometry, and
R	=	radius (ft).

Rather than include a variable for distance, which may have been impossible considering the pattern shown in Figure 6.1, the average horizontal displacement was modeled at each 100-ft increment leading up to the curve. The resulting multivariate model, with different parameter estimates for each location, is given in Table 6.1. The parameters in the table are in bold text when significant, meaning they contribute to the horizontal fixation displacement when at that location. Because supplementary TCDs were not significant, the observations where they were applied at the curve were removed. This means the responses of the visual behavior in the models are not influenced by the use of supplementary TCDs.

Table 6.1: Multivariate Model of Horizontal Gaze Displacement (Curves without Supplementary TCDs)

Distance (ft) from Curve	β_0 (Intercept)	β_1 (for right curves)			β_2 (geometric effect)		
		Effect	t-Ratio	Prob>|t|	Effect	t-Ratio	Prob>|t|
1,000	-0.01	1.82	1.59	0.11	-332	-1.23	0.22
900	0.40	1.63	1.22	0.22	-296	-0.94	0.35
800	**0.99**	0.008	0.02	0.99	**132**	**2.35**	**0.020**
700	**0.80**	-0.13	-0.23	0.82	103	1.46	0.145
600	0.39	0.78	1.65	0.10	71.9	1.13	0.26
500	-0.27	**2.0**	**5.15**	**<0.0001**	8.01	0.15	0.88
400	**-1.24**	**3.63**	**11.4**	**<0.0001**	-54.6	-1.22	0.22
300	**-2.48**	**5.52**	**19.2**	**<0.0001**	-33.7	-0.80	0.42
200	**-4.04**	**8.62**	**28.7**	**<0.0001**	**89.3**	**2.09**	**0.038**
100	**-4.83**	**10.8**	**29.4**	**<0.0001**	**550**	**10.7**	**<0.0001**
0	**-4.93**	**11.4**	**27.7**	**<0.0001**	**845**	**14.6**	**<0.0001**

Note: Values in **Bold** indicate the parameter is significant at that location.

The eleven models shown in Table 6.1 are not written out in equation form (which would take the form of Equation 6.1) because the value of these models is not in the actual effects of the parameters, but in identifying where the driver is when the effect becomes significant. As the driver gets closer to the curve, the ability to estimate the horizontal gaze displacement improves. The direction of the curve (with estimate β_1) becomes significant at 500 ft before the curve, and the geometry (with variable 1/Radius) becomes significant at 200 ft before the curve. Figure 6.1 shows that the direction of average fixations split near 700 ft in advance of the curve. These models, however, show that direction isn't a significant factor until 500 ft, which is likely a result of substantial variability in the data. At 500 ft, however, the data are consistent enough to attribute the drivers' fixation location to the curve direction. It is possible that there is also some influence from the warning signs, which indicate the direction of the curve.

It should not be surprising that the significance of the effects (especially curve direction) increases with each 100-ft increment. Driver fixations are quite scattered far from the curve and generally become more confined as the driver advances closer and closer to the curve. Near the curve, the visual behavior becomes more and more controlled by the geometry.

Investigations of models for the vertical component of the gaze fixation did not produce noteworthy results. No factors, including both geometry and use of TCDs were found to significantly influence the vertical fixation angle.

6.3.2.2. Models of Pupil Diameter

The general pattern of changes in pupil diameter was discussed earlier and illustrated with Figure 6.3. Starting at the beginning of a tangent, the pupils may still be in a dilated state from the change experienced at the previous curve. Pupil contractions represent a decrease in cognitive load, which may occur when there is no immediate information about approaching hazards. The pupils begin to dilate with increased cognitive load when the driver perceives information about the downstream curve. The dilation reaches a maximum near the curve and the pupils begin to contract within the curve once the main maneuvers are all but complete.

Models characterizing the contraction of the pupils are described below with parameter estimates given in Table 6.2. The models identify the distance the driver travels while the pupils contract and the total measure of the contraction. Effective supplementary TCDs should increase the driver's cognitive load earlier, reducing the duration and total magnitude of the contraction. Similar to the models in Sections 4 and 5 that characterize the acceleration of vehicles after departing curves, it was determined that the best effects to include in the models of pupil contraction are tangent length and the potential pupil contraction, which describes the change in pupil size that could occur based on an individual participant's smallest observed pupil. Based on the data in these models, the average potential contraction was 1.2 mm, with standard deviation 0.46 mm. It is also believe that on extremely long tangents, the patterns of visual behavior will simply not be consistent. The models here are valid only for tangents with length between 200 and 2,000 ft.

The first model in Table 6.2 estimates the distance the driver travels while the pupils contract to a minimum size on the tangent. It is hypothesized that supplementary TCDs, by influencing cognitive load, reduce the duration of the contraction, similar to the reduction in acceleration distance observed with the use of TCDs. In the acceleration models from Sections 4 and 5, fixed effects of tangent length, potential speed increase, and supplementary TCDs (if applicable) were used to estimate the duration of the acceleration phase. The model of the distance the driver travels until the pupil fully contracts is quite similar, with fixed effects for tangent length and the potential contraction, defined as the difference between the size of the pupil at the beginning of the tangent and the driver's overall smallest recorded pupil size. An interaction between these fixed effects was tested, but not significant. Effects of supplementary TCDs on the distance to minimum pupil size were also, unfortunately, not significant. The main effects of this model indicate that pupils contract over a longer distance when there is a longer tangent, but that the contraction is shortened when the pupil is already small. The correlation in the model is quite weak, as identified by a low R^2 value (0.38).

Investigation of the residuals from the initial model indicated that the assumption of equal variance was violated, as shown by the residual plot in Figure B.35. Various transformations of the independent and dependent variables were investigated, with no improvements to the observed pattern in the residuals. The final model thus maintained the form of the original model, but was created with weighted least squares regression using the inverse of the residuals from the original model as a weight for each observation. The distribution of the residuals is shown in Figure B.36.

The second model in Table 6.2 is the total contraction of the pupil. The main effects again are the tangent length and the potential contraction. For this model, square root transformations were applied to both the dependent variable of the total contraction and the independent variable of tangent length. Residual plots of the initial (without transformations) and final models are given in Appendix B (Figures B.37 through

B.40).Supplementary TCDs were again not significant. The signs (positive or negative) for the estimates of the main effects are the same for both models in Table 6.2: The pupils tend to contract more on long tangents and when there is greater potential for contracting. The correlation coefficient for the second model is 0.31.

Table 6.2: Models of the Pupil Contraction

	Estimate	t Ratio	Prob>|t|
Distance Traveled (ft) to Minimum Pupil Size			
Intercept	-320	-3.96	0.0011
Tangent Length (ft)	0.362	11.4	<0.0001
Potential Contraction (mm)	270	5.71	<0.0001
Sqrt[Pupil Contraction (mm) after Curve] (R^2=0.33)			
Intercept	-0.34	-4.49	0.0001
Sqrt[Tangent Length (ft)]	0.0099	6.53	<0.0001
Potential Contraction (mm)	0.301	8.15	<0.0001

The models from Table 6.2 are written as Equations 6.2 and 6.3.

$$D_{Max\ Pupil} = -320 + 0.362 L_{Tan} + 270 Potential \qquad 6.2$$

$$\sqrt{Contraction} = -0.34 + \frac{99\sqrt{L_{Tan}}}{10{,}000} + 0.301 Potential \qquad 6.3$$

where

$D_{Max\ Pupil}$	=	distance traveled (ft) before reaching maximum pupil size,
Contraction	=	contraction (mm) occurring before the dilation,
L_{Tan}	=	tangent length (ft), and
Potential	=	potential contraction in pupil size (mph) based on the difference between the driver's minimum recorded pupil diameter and the initial diameter on the tangent.

The data used to create the models in Equations 6.2 and 6.3 have the following ranges. Tangent length ranged from 209 to 1,937 ft (average 946 ft); and potential pupil contraction ranged from 0 to 2.8 mm (average 1.2 mm). The dependent variables of the distance traveled on a tangent until the pupil is contracted and the magnitude of the contraction ranged from 0 to 1,500 ft (average 350 ft) and 0 to 1.7 mm (average 0.2 mm).

The acceleration models in Sections 4 and 5 used the variable Potential Speed Increase to describe the how much the driver could comfortably accelerate if the conditions were conducive to such a speed change. The variable of potential contraction, representing the difference between the initial and minimum observed pupil diameters, is the amount the pupil could contract if the conditions were appropriate. Similar to the variable Potential Speed Increase used in the acceleration models, the effect of potential contraction reflects the cyclical nature of the changes in pupil diameter. It is an effective variable for identifying the likely initial pupillary response of drivers who have just exited a curve.

After contracting, the pupil dilates in response to the cognitive load of preparing to navigate the curve. While it was found that supplementary TCDs have no effect on the phase of contraction, it is still hypothesized that supplementary TCDs affect the dilation of the pupils, both in duration and magnitude. An effective TCD should shorten the duration of the dilation because it provides drivers with the desired information quicker, and it should increase the magnitude of the dilation due to increased cognitive load from the perception of information.

A model for the dilation phase is presented in Table 6.3. The parameter of interest is the distance from the downstream curve at which the driver's pupils are fully dilated. In this model, effects of geometry (the ratio of deflection to radius) and operations (total speed differential) are used. The correlation identified in this model (R^2=0.20) is quite low, though the effects from supplementary TCDs are significant. Residuals from the initial model, shown in Figures B.41 and B.42 violated assumptions of normality and constant variance. Transformations were tested but they did not improve the model. A weighted least squares regression was performed that weighted each observation in the final model based on the inverse of the original residual. In the model, the TCDs increase the distance from the curve at which the dilation concludes by approximately 100–171 ft. The negative estimate for the effect of the geometry indicates that the dilation concludes closer to the curve for sharp curves, while the estimate for speed differential indicates the dilation concludes earlier with greater speed changes.

A second model estimating the magnitude of the dilation was investigated, but failed to meet critical criteria regarding the model parameters and assumptions of normality and constant variance. Unfortunately, these issues were not resolved with transformations of any of the parameters or performing a weighted regression as was done with previous models.

Table 6.3: Model of the Pupil Dilation

	Estimate	t Ratio	Prob>|t|
Distance (ft) from Downstream Curve at Maximum Pupil Size			
Intercept	100	4.55	<0.0001
Deflection (deg) / Radius (ft)	-337	-6.75	<0.0001
Speed Differential (mph)	13.4	6.39	<0.0001
Supplementary Devices:			
Delineators (if yes)	101	2.62	0.0093
Arrow Sign (if yes)	137	5.90	0.0007
Chevrons (if yes)	171	7.53	<0.0001

The equation for the model in Table 6.3 is provided below.

$$D_{Dilation} = 100 - \frac{337I}{R} + 13.4\Delta_{Speed} + TCD \qquad 6.4$$

where

$D_{Dilation}$ = distance (ft) from the curve when the pupil is dilated,

I = curve deflection angle (deg),

R = curve radius (ft),

Δ_{Speed} = total speed differential at the curve, and

TCD = influence of a supplementary device, obtained from Table 6.3.

The data used in the model is described as follows. Radius ranged from 55 to 1,250 ft (average 509 ft); deflection ranged from 27 to 90 deg (average 53 deg); and speed differential ranged from 0.6 to 42 mph (average 14 mph). The actual observed distance from the curve when the pupil was dilated ranged from 0 to 1,500 ft (average 309 ft).

One of the limitations to applying and interpreting the pupillary models is the physical range within which a pupil may naturally dilate or contract. Just as a driver's speed is not likely to be observed outside of a normal range, the pupils will not naturally contract or dilate beyond these limits (usually about 3–8 mm).

6.3.2.3. Models of Eye Closure

Changes in the percent eye closure for drivers at two different curves were shown in Figure 6.4. The overall trend is characterized by an increase in eye closure early on the tangent, followed by a widening of the eyes as the driver nears the curve. Beyond the midpoint of the curve, the eyes tend to return to the original level of closure. Similar to the models identifying the periods of contraction and dilation of the pupils, the models associated with changes in eye closure are separated into periods of closure and opening. It is hypothesized that these changes will occur earlier when TCDs are used. The increase in information about the upcoming curve should lead to an increase in cognitive load and earlier initiation of the search tasks associated with curve navigation.

Table 6.4 contains a model investigating the changes in eye closure of drivers on the study segments. The model is the distance traveled until the eyes reach a period of maximum closure. Perhaps because the changes in eye closure tend to be quite subtle, no models estimating the magnitude of the change in eye closure could be developed.

The model in Table 6.4 is quite similar to the model of distance traveled to minimum pupil size in that it uses the tangent length and difference between average and initial values as main effects. Potential eye closure is not used because the maximum closure can be 100 percent, which is a full blink (though closure measurements when blinking were discarded). Early generations of the model indicated that the error is not normally distributed with constant variance (shown in Figures B.43 and B.44). The final model in Table 6.4 was created with weighted least squares regression based on the inverse of the residuals in the original model, reducing the influence of the observations that are far from their predictions. Even though the form of the model does not substantially change, the weighted regression accounts for the heteroscedasticity of the residuals. The distribution of the residuals from the final model in Figure B.46 indicates some improvement in normality.

The model indicates that as the length of the tangent increases, the eyes reach a state of maximum closure later. Also, the effect for the difference between the average and initial eye closure indicates that the eyes will take longer to reach maximum closure when the eyes are initially wide. On the other hand, if they are initially quite closed, the eyes will more quickly reach a level of maximum closure. This cyclical pattern was identified with the changes in pupil size discussed above. The only substantial effect from TCDs is for the large arrow sign, which reduced the distance at which the eyes reach a maximum closure by approximately 210 ft.

An additional model of the location where the eyes are at minimum closure was tested, the results of which showed marginal effects of TCDs. Additionally, the model failed to meet critical assumptions in regression, specifically normality and constant variance of the error terms, and transformations or a weighted least squares regression did not sufficiently correct these issues or even lead to significant estimates.

Table 6.4: Model for Changes in Eye Closure

	Estimate	t Ratio	Prob>|t|
Distance Traveled (ft) to Maximum Eye Closure			
Intercept	13.3	0.76	0.451
Tangent Length (ft)	0.43	26.3	<0.0001
Average Eye Closure – Initial Eye Closure (%)	2,470	16.1	<0.0001
Supplementary Devices:			
Delineators (if yes)	15	0.48	0.63
Arrow Sign (if yes)	-213	-7.7	<0.0001
Chevrons (if yes)	-51	-3.11	0.0020

An equation for the model in Table 6.4 is given below.

$$D_{Max\ Closure} = 13.3 + 0.43L_{Tan} + 2{,}470\Delta_{Avg_{Closure}} + TCD \qquad 6.5$$

where

$D_{Max\ Closure}$ = distance (ft) traveled until the eyes reach maximum closure,

L_{Tan} = tangent length (ft),

$\Delta_{Avg_{Closure}}$ = difference between the driver's average eye closure and the initial eye closure on the tangent,

TCD = influence of a supplementary device, obtained from Table 6.4.

The model was generated from data with tangent lengths ranging from 209 to 1,937 ft (average 946 ft) and difference from average eye closure ranging from -15 to +15 percent (average 0 percent. The distance downstream from the curve at which the eye was most closed ranged from 0 to 1,500 ft (average 373 ft).

6.3.2.4. Summary of Effects of TCDs on Visual Behavior

The models above identify parameters and their effects on visual behavior while drivers approach curves. The horizontal fixation displacement noticeably changes (based on the curve geometry alone) starting near 500 ft in advance of the curve. This is reasonable considering the research on where drivers are able to detect changes in alignment by using pavement markings alone. (The curves used in the models of fixation location had advance warning signs but no supplementary devices) The models predicting the location of the driver when the maximum pupil size or minimum eye closure are observed do not identify consistent effects of TCDs. Each supplementary TCD was found to significantly increase the distance from the curve at which the pupil is fully dilated. When approaching curves with large arrow signs, drivers' eyes tend to reach a maximum level of closure earlier. When approaching curves with PMDs or chevrons, the eyes tend to be fully widened earlier.

The correlation coefficients of each of the mixed models were quite weak in contrast to the correlation observed in the operations models of the previous two sections. It should be noted that the variables for geometry (radius or deflection-to-radius ratio) and operations (speed differential or lateral acceleration) as used in the models are highly correlated. While the inclusion of these effects in the models does not detract from the ability to predict each dependent variable, the multicolinearity of the correlated variables does reduce the ability to assess their individual contribution.

6.4. Conclusion

This section documents the changes in visual behavior and visual load observed as drivers approach and navigate curves. The visual behavior is characterized by the fixation location, pupil size, eye closure, and blink rate of drivers. Changes in visual behavior were observed to start several hundred feet before curves. Physiological measurements of pupil diameter, eye closure, and blink rate indicate that drivers tend to relax on tangents until perceiving an upcoming curve. Increases in cognitive load are identified through increases in pupil size, decreases in eye-closure (widening of the eyes), and decreases in blink rate. Generally, the pupil is fully dilated, the eyes are widest, and the blink rate is at a minimum close to the curve.

The location of the driver when a change in cognition can be detected is indicative of when the driver is perceiving information about the upcoming curve. It was hypothesized that supplementary TCDs used at curves affect the location at which these changes are observed. It was found that TCDs do not influence the horizontal or vertical component of the location of a driver's fixations. Based on the models analyzing pupil size and eye closure, supplementary TCDs may affect the distance at which drivers cognitively respond to the curve by approximately 170 ft, though there were some inconsistencies in the models.

There are a number of reasons why the models of visual behavior and cognition of drivers were not as strong in terms of correlation compared to the operations models in the previous sections. And only some select models in this section were able to identify significant effects of TCDs. Some thoughts regarding these issues are provided below.

When evaluating a model based on correlation, it is important to keep in mind what the correlation indicates—that it is based on all the variables included in the model and does not negate or confirm the significance of an individual variable. Based on the findings in this section, the variables selected for the models of attention are simply poorly correlated to the effect they are predicting. Is (are) there some other variable(s) that may improve the correlation? Most definitely. Driver age, gender, experience, or aggressiveness; length of time in the study; time of day; characteristics of the previous curve; other features of the present segment; etc. could each contribute to the correlation of the model. Though there are implications regarding the applicability of the model (including the threat of overfitting the data), any number of variables can be added to increase the correlation. On the other hand, a variable that substantially improves the overall fit may not exist, suggesting that the visual attention of drivers cannot simply be matched to any specific condition or characteristic. Regardless, it is maintained that the purpose of these models is not to predict the dependent variable, but to identify the effects of the variables that do significantly affect the measure of interest.

One reason the supplementary TCDs appeared generally ineffective when evaluating the pupil size and eye closure is that the supplementary TCDs are not the only source of visual information about an upcoming curve available to drivers. The first source is the warning sign that is placed in advance of the curve (usually 300-400 ft). Other visual information may come from the landscape or surrounding environment (with visible tree lines or fences offset from the alignment) and the pavement and pavement markings. But not all information used in the driving task is visual. The interference of other types of information (auditory, tactile, and vestibular) further disrupts the ability to isolate the influence of specific visual information.

The lack of correlation and significance in some of the models of cognition, compared to the operations models, may be due to the distances over which the visual information is received and the operational output executed. TCDs are visible for long distances in advance of curves, and that visibility distance fluctuates based on the driver's vision and attention and the conditions at each curve. Such variability (between and within subjects) over long distances makes it difficult to identify consistent relationships. But regardless of where or when that information is acquired, there is a limited area where the operational response tends to be carried out. Figure 6.6 illustrates how the perception of information occurs over an extended length, but that the response, when comparing length, is quite truncated.

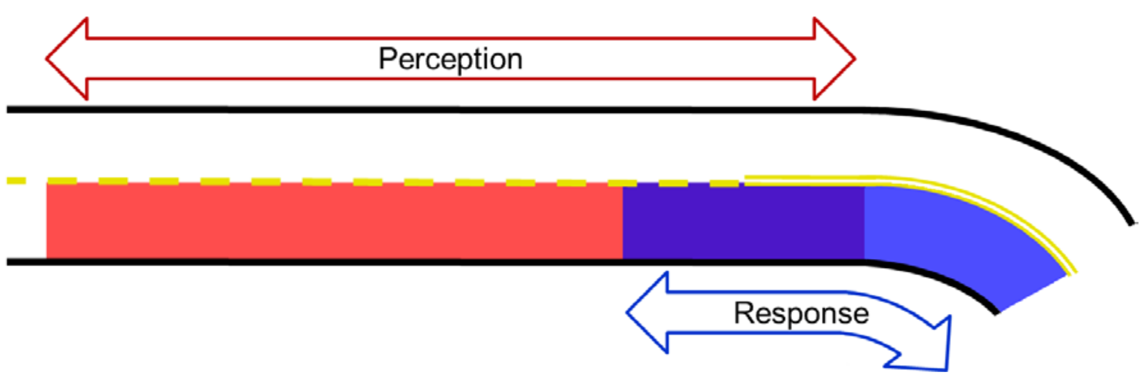


Figure 6.6: Locations on a segment where the primary components of the perception of information and operational response occur.

The models in this section were not able to consistently identify how TCDs affect the *magnitude* of the cognitive load, but only affected the location where the driver experienced the change in cognition. With no effect on the magnitude of the cognitive load, it seems that the measured workload will be the same regardless of the method by which the information is conveyed. The effects on the location when the cognitive change occurs suggests that TCDs help drivers acquire information (such as curve location or severity) earlier than they otherwise would.

Based on the patterns shown in this section, it is clear that curve navigation is more cognitively demanding than driving on tangents. The lack of demands on the driver while on a tangent leaves cognitive capacity for other tasks. In other words, drivers can multitask on tangents by maintaining reasonable operational characteristics while they think about other things, regardless of relevance to the driving ask. Unfortunately, the eye-tracking cameras are unable to ascertain what information the drivers are specifically processing, so the difficulty with some of the analyses of cognition also comes from having no restrictions on what the drivers are actually *thinking*. Some of the actual peaks or troughs in the data for an individual's cognition may be due to anything the driver is processing: the thoughts, emotions, and memories associated with past, present, and future events. These personal experiences interfere with identifying the cognition specifically attributed to the driving task.

There are some similarities between the findings in this section and those of the operational analyses. The patterns of the physiological measures of pupil size, eye-closure, and blink rate can be compared to patterns of speed near curves. The acceleration phase after a driver exits a curve seems to match with a relaxation in cognition. This occurs because the driver is comfortable with the straight alignment until the driver perceives the upcoming curve. The increase in cognitive load indicates the driver is acquiring and processing the information related to the upcoming curve, which initiates the deceleration phase.

The connections between a driver's visual behavior and operational performance seem rational based strictly on observations presented in this and previous sections.

What is not known is how much a driver's operational behavior at curves is influenced by the driver's cognition. Does an improvement in cognition affect operational output? Previous research on attention and the components of the model of the driving task in Figure 2.1 suggest there are relationships between these measures. The next section investigates them in detail.

The primary benefit of the analyses in this section is an identification of *when* drivers perceive information about an upcoming curve. The findings suggest that drivers begin processing information several hundred feet in advance of the curve. Though somewhat inconclusive, TCDs likely increase the distance at which this perception begins and ends. When these results are combined with the results regarding the operational behavior observed at curves, there is a complete model describing the actual perception of and reaction to information at curves. One use of such a synthesis of information can be to identify the traffic control that should be used at a curve based on the characteristics of the curve and the actual needs and behavior of drivers. The selection of TCDs at curves could then be based more on whether or not a device is actually needed.

7. EFFECTS OF MEASURES OF ATTENTION ON OPERATIONAL PERFORMANCE

The previous sections document the results of studies of driver operational and visual behavior of drivers while approaching and navigating curves. Section 4 presents general patterns and specific models characterizing operational performance near curves; Section 5 contains models illustrating the effects of TCDs on these operational patterns; and Section 6 identifies both patterns of visual attention associated with the presence of curves and the influence that TCDs have on visual attention. The final step in analyzing the behavior of drivers at curves and the influence of TCDs is to evaluate the relationships between visual attention and operational performance. The primary question to answer is, based on the data collected in this research, how does a driver's attention, using measures of cognitive load, influence operational performance? The purpose of this section is to answer that question.

7.1. Background

Before evaluating the relationships between visual behavior and operational performance, the following is a summary of findings from the research documented in the previous sections, a discussion of the purpose and potential significance of the research in this section, and the methodology used for the analysis.

7.1.1. Summary of Findings in Previous Sections

Section 4 presents significant relationships between the operational performance of drivers and the presence and characteristics of curves. None of the models identify behavior that is unusual: the presence of a curve leads drivers to adjust their speed in advance of and within the curve, and the specific operational changes are influenced by the geometric characteristics of the curve. TCDs were found to also influence driver operational behavior. Section 5 presents models of operational performance, patterned after the structure of the models in Section 4, with inclusion of the use of supplementary TCDs (PMDs, one direction large arrow signs, and chevrons). The significant findings of Section 5 show that, in response to these TCDs, drivers:

- limit the distance traveled during the period of acceleration,
- restrict how much they accelerate after exiting a curve,
- reduce their speed more before entering the curve,
- accept a lower deceleration rate while approaching the curve,
- navigate the curve with reduced speed,
- accept a lower deceleration rate while within the curve, and
- accept a lower rate of lateral acceleration within the curve.

There are obvious connections between some of these operational performance metrics. The deceleration rate on a tangent, for example, will be lower if the driver starts decelerating earlier and/or the vehicle's initial speed is lower. Also, less lateral acceleration within the curve should be expected with a reduced speed. What is important from the models in Section 5 is the consistency in the "positive" influence of the TCDs and the clear documentation of where that influence is observed (for example, finding that the deceleration phase begins earlier when TCDs are used). Much of the previous research on TCDs summarized in Section 2 was not able to identify effects in such detail.

Based on the models in Section 6, it can be concluded that driver visual behavior is much more variable and difficult to model than operational behavior. Significant changes in measures of visual behavior and cognitive load were found, but the effects of TCDs are simply not as clear and consistent as their influence on operational behavior. The physiological measurements of pupil size, eye closure, and blink rate are particularly important for understanding where drivers begin perceiving information about curves. Patterns indicate that driver workload increases on curve approaches, then decreases within the curve. Models examining the changes in pupil size and eye closure suggest that TCDs may lead to an earlier increase in cognitive load and earlier completion of the perception of information on the tangent; however, the results were somewhat inconclusive.

It was observed that there may be some similarities among the patterns of operational and visual behavior of drivers at curves. For example, drivers tend to accelerate after exiting a curve and then decelerate before entering a curve, while the pupil tends to contract after exiting a curve and then dilate before entering a curve. Figure 7.1 illustrates these behaviors with data collected from one driver on one segment in Texas. The pupil data are noticeably not smooth in the figure because they were not reduced (averaged over four seconds) as they were in the other analyses. But the inverse relationship between speed and pupil size is quite apparent with the lines crossing near 40 mph and 6.5 mm. The recurrence of these patterns at curves indicates that the changes in both operational and cognitive measures are cyclical.

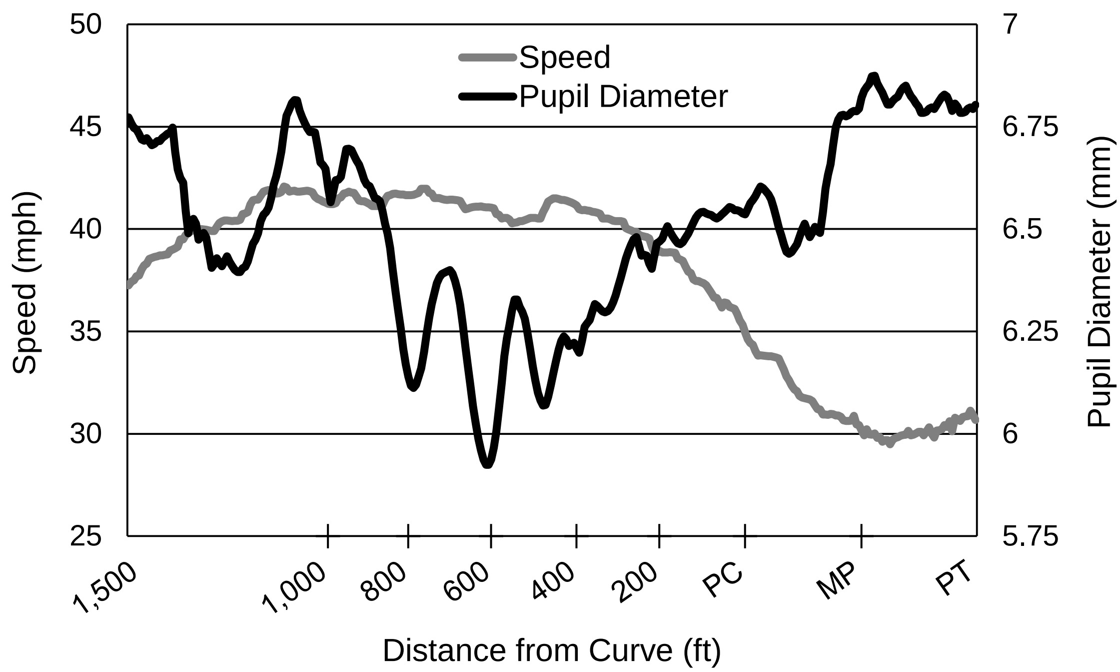


Figure 7.1: Speed (mph) and pupil diameter (mm) of one driver approaching and navigating one curve.

7.1.2. Purpose of this Section

Figure 7.1 illustrates the changes in pupil size and speed while drivers approach and navigate curves. It has been suggested that the cognitive and operational metrics are related. The purpose of this section of the dissertation is to investigate in detail the possible relationships between them. With the effects of TCDs documented extensively in Sections 5 and 6, the analyses in this section ignore their effects.

The data in Figure 7.1 suggest that the instantaneous measures of speed and pupil diameter are related. The first part of the analyses documents how cognitive measures may be a reflection of the current operational characteristics. The second part of the analyses will be to investigate whether or not operational performance improves with a desirable change in visual behavior, which is the principal hypothesis of this section. Improvements in operational performance were observed when TCDs were used (as listed above), but the weak relationship between TCDs and visual behavior may be a foreshadowing of the difficulty connecting visual behavior and operational performance. That connection may prove to be elusive. Sample questions to answer in this research may be “does performance improve with an earlier pupil dilation?” and “does performance improve when the dilation is greater in magnitude?”

From the seven measures of operations modeled in Sections 4 and 5, desirable improvements in performance are defined by an earlier response to the curve and a more-conservative operational behavior. The significance of the research questions is that if they are proven correct, it can be said that performance improves when the information is processed earlier. Also, if increased cognitive load leads to improved performance, then it may be inferred that the most effective TCDs are the ones that lead to the greatest increases in workload.

7.1.3. Methodology

The relationships between attention and operational performance will be primarily tested through multivariable linear mixed models, as was done in Sections 4-6. The tested variables are the metrics of cognition and operational behavior developed in the previous sections, so the variables for the models are the same as were described and used before. Only nighttime data are used, but there is no consideration for the TCDs used at the curves or the state where data were collected. The patterns identified in Section 6 suggest that there may be enough consistency between curve features and visual behavior that the instantaneous visual behavior may be attributed to operational characteristics of the vehicle. The first part of the results identifies models that include visual behavior as a variable dependent on operational behavior. The second part of the results focus on the principal hypothesis of this section, that performance improves with greater visual attention. Models with operational performance at each curve were tested as dependent variables that are influenced by the visual behavior observed on the tangent.

7.2. Results

The analyses in the previous sections have centered on the creation of multivariable linear mixed models. Mixed models have been necessary to account for the variation between subjects that each have a natural range of visual behavior (with physiological measures such as pupil size or blink rate) and preferred range of operational characteristics (such as a normal speed or deceleration rate). The analyses in this section are divided into two groups. The first group identifies how the metrics of visual behavior is related to the instantaneous operational characteristics. The second group identifies the relationships between a driver’s cognition and operational performance at curves.

7.2.1. Characterizing Visual Behavior and Cognitive Load with Operational Metrics

The data represented in Figure 7.1 suggest that there may be a relationship between the measures of visual and operational behavior. The first part of the analysis in this section is to investigate the correlation between some of these metrics, which is given in Table 7.1. The correlation values were determined from the reduced data compiled at each 100-ft increment on a study segment in Texas, representing numerous instantaneous characteristics rather than just one observation per study curve. There are 5,279 observations used to create the correlation matrix.

Table 7.1: Correlation Matrix of Select Operations and Eye-Tracking Data

	Speed	Acceleration	Pupil Size	Eye Closure	Vertical Fixation Component
Speed	1.00				
Acceleration	-0.091	1.00			
Pupil Size	0.121	-0.069	1.00		
Eye Closure	0.019	0.028	**-0.378**	1.00	
Vertical Fixation Component	0.119	-0.047	**-0.251**	0.018	1.00

The only notable correlation (though fairly weak) among the variables is between the pupil diameter and the percent eye closure and vertical fixation angle. The inverse relationship between pupil size and eye closure is not surprising considering the patterns of pupil diameter and eye closure at horizontal curves discussed in Section 6 (pupils contract and became more closed after exiting a curve, then dilate and widen upon approaching the next curve). Figure 7.2 shows the data with a linear fit line. Table 7.1 also identifies an inverse relationship between pupil size and vertical fixation component. The inverse relationship between pupil size and vertical fixation angle is also best explained within the context of navigating curves. The pattern of the vertical fixation angle in Figure 6.2 shows that the fixations of drivers become directed downward toward the near field while approaching a curve. During that time, there tends to be an increase in pupil size. After the curve, drivers revert back to fixating in the far field while their pupils contract.

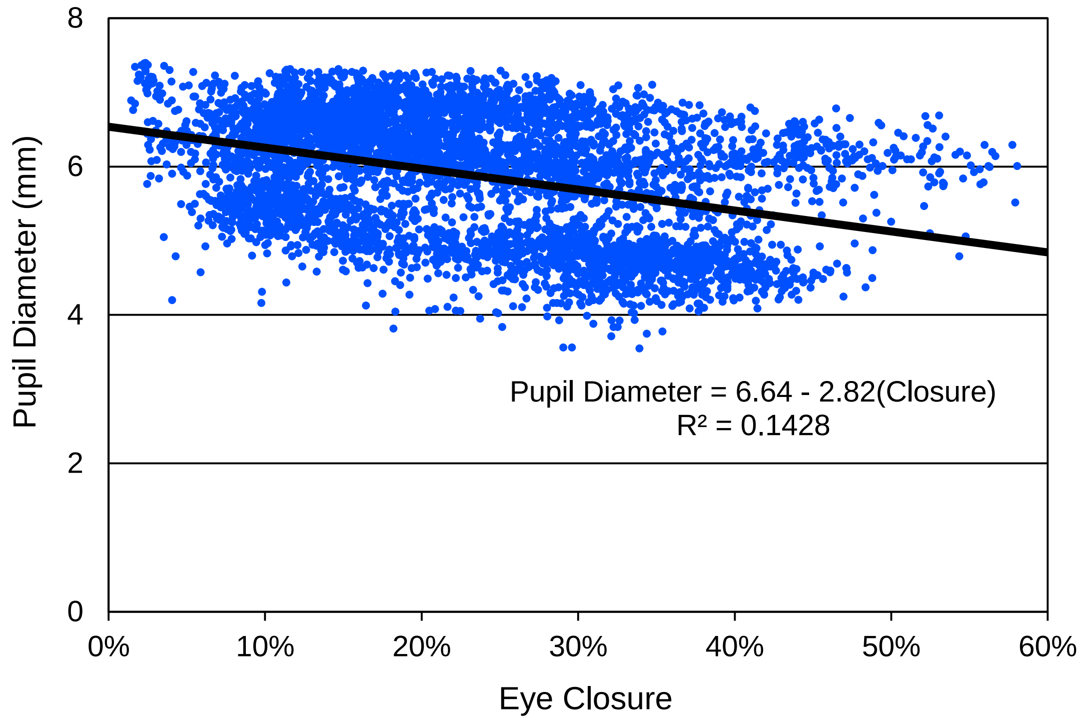


Figure 7.2: Weak relationship between eye closure and pupil diameter.

Despite the relationships observed by visual inspection of Figure 7.1 or the patterns from Section 6, the correlation of the data at individual moments is generally quite weak. Fortunately, with mixed models including the participants as random effects, the ability to identify significant relationships among the data substantially increases. The models here examine how the instantaneous measures of visual attention may be characterized by operations. They are based on the data used to generate the correlation matrix in Table 7.1. The models are given in Table 7.2 and discussed below.

The first model in Table 7.2 identifies the vertical component of the fixation location. The horizontal component is not analyzed in this analysis because of the complexity introduced by the strong influence of curve direction. Changes in the vertical angle are indicative of changes in the driver's preview distance. The correlation coefficients in Table 7.1, though weak, indicate that the vertical fixation angle has a positive relationship with speed and an inverse relationship with acceleration. Those relationships are maintained in the model in Table 7.2. Speed is the dominant factor, with longer preview distance (higher vertical angle) estimated for higher speeds, which in the context of curve navigation occurs when drivers are on the tangent. Within the curve, where speeds and visibility are dependent upon the curve geometry, drivers have the shortest preview distance. As with previous models, residual plots are provided in Appendix B (Figures B.47 and B.48). The residuals appear to be homoscedatic but not normal due to the wide-tailed distribution.

The second model in Table 7.2 estimates the pupil diameter using only the speed and acceleration. An interaction between speed and acceleration was tested but is not significant. The model estimates a larger pupil with lower speeds and during periods of deceleration, which is reasonable based on the behavior of drivers at curves. The model indicates that the pupil should be constricted when the vehicle is at higher speeds and when accelerating. Based on the diagram of speed and pupil size shown earlier in Figure 7.1, one would think that the size of the pupil is more dependent (inversely) on the observed speed. The t Ratio and p values indicate that acceleration is the dominant factor. Despite the image in Figure 7.1, the stronger connection between pupil size and acceleration is reasonable because speed is a product of the acceleration (over time). For negotiating curves, the deceleration in advance of a curve corresponds with the pupils dilating from the perception of information; the acceleration after a curve corresponds with the relaxation in cognitive load (and pupil contraction), as discussed in Section 6. Without any stimulus, the speed and pupil size would both likely remain constant. Despite the strong correlation of the model (R^2=0.82), the distribution of the residuals in Figure B.50 indicates the model fails the assumption that the error is normally distributed. Transformation of the data was unproductive and the model remains in Table 7.2 with the understanding that the overall relationships should be valid, but there are some limitations in its applicability.

The third model in Table 7.2 estimates the eye closure using only acceleration. Eye closure has an inverse relationship (though somewhat weak based on Table 7.1 and Figure 7.2) with pupil size, so it is not surprising that the sign for the estimate of the effect of acceleration on eye closure is positive while negative for pupil size. Because speed is not a significant effect in the model, it seems the driver's cognitive load is related more to the immediate stimuli and their responses than by the overall operating conditions. Because the distribution of the residuals in an original model estimating eye closure was not normal, a square root transformation of the dependent variable was applied, which led to improvements in the distribution of the error terms (Figure B.52).

Table 7.2: Models Estimating Visual Behavior with Metrics of Operations

	Estimate	**t Ratio**	**Prob>|t|**
Vertical Fixation Angle (deg) (R^2=0.33)			
Intercept	-1.05	-2.11	0.0471
Speed (mph)	0.0379	8.73	<0.0001
Acceleration (ft/s^2)	-0.0500	-3.15	0.0017
Pupil Diameter (mm) (R^2=0.82)			
Intercept	5.92	25.0	<0.0001
Speed (mph)	-0.00135	-1.97	0.0494
Acceleration (ft/s^2)	-0.0219	-8.71	<0.0001
Sqrt[Eye Closure (percent)] (R^2=80)			
Intercept	0.423	14.4	<0.0001
Acceleration (ft/s^2)	0.00238	6.99	<0.0001

Equations for the models from Table 7.2 are given below.

$$Fixation_Y = -1.05 + 0.0379Speed - 0.050Accel \quad 7.1$$

$$Pupil\ Diameter = 5.92 - 0.00135Speed - 0.0219Accel \quad 7.2$$

$$\sqrt{Eye\ Closure} = 0.423 + \frac{23.8Accel}{10{,}000} \quad 7.3$$

where

$Fixation_Y$	=	vertical component (deg) of the average fixation,
Pupil Diameter	=	pupil size (mm),
Eye Closure	=	proportion of the eye covered by the eyelid,
Speed	=	instantaneous speed (mph) of the vehicle, and
Accel	=	instantaneous acceleration (ft/s^2) of the vehicle.

Valid ranges for the data used in these models include speeds of 22-65 mph (average 44 mph), acceleration rates of -14 ft/s^2 (deceleration) to 4.0 ft/s^2 (average -1.1 ft/s^2), vertical fixation component -10 to 26 deg (average 0.67 deg), pupil diameter 3.1 to 7.4 mm (average 5.9 mm), and eye closure 2 to 63 percent (average 19 percent). The models shown in Table 7.2 are quite useless without the context of curve navigation. They essentially take the patterns and models in Section 6 and attribute them to instantaneous operational features. One of the most useful contributions of these models is the comparison of significance between the main effects of speed and acceleration. The first model indicates that the vertical displacement of fixations is mostly dependent upon speed. This is reasonable because drivers need greater preview distance at higher speeds. In the models that estimate measures of cognitive load (pupil size and eye closure), however, acceleration, rather than speed, is the most significant effect. The consistency in the patterns identified in the previous sections suggests that the real connection between these two cognitive measures and acceleration comes from the presence of curves. On the highways used in this study, curves are the agent that leads to changes in cognition and the subsequent response of acceleration.

7.2.2. Estimating Operational Metrics with Visual Behavior

With the visual behavior metrics evaluated in the previous subsection, this section inverts the analyses, modeling the operational metrics of the study with effects from the visual behavior. The approach, however, is not to evaluate instantaneous measures, but to identify whether or not specific attributes of the cognitive metrics observed on an approach affect the operational behavior. The visual behavior metric that most consistently identified benefits from the use of TCDs at curves in Section 6 was the distance from a curve at which the pupil is fully dilated. The location of a pupil dilation (either the initiation or conclusion) is indicative of a change in cognition. The analyses in Section 6 were unable to identify any significant impact from TCDs on the magnitude of the dilation. It was thought that a greater dilation would occur when TCDs are used, signifying heightened workload due to the TCD. Unfortunately, only effects of geometry or operations were found to affect the magnitude.

The location of the pupil dilation was identified as the choice variable for identifying the effects of visual behavior on operations. The operational metrics modeled in Sections 4 and 5 are used again as performance metrics. The main effects of geometry and operations used in the original models are included here because of their importance in estimating the parameter of interest. Because of the dependence of the location of the pupil dilation and the length of the tangent, the variable for tangent length will be included in the models. Each performance metric is partitioned into one of the three phases used in the previous sections: acceleration, pre-curve deceleration, and within curve navigation.

7.2.2.1. Acceleration Exiting an Upstream Curve

The acceleration phase was characterized operationally in Sections 4 and 5 using measures that describe the duration of the acceleration in terms of distance traveled before the vehicle reaches a maximum speed on the individual approach tangent and the total increase in speed (difference between the speed upon exiting the curve at the PT and the maximum speed). It was hypothesized that drivers are likely to accelerate until they reach a location where they can perceive information about the upcoming curve, thus the location of the minimum pupil size (signifying the beginning of the dilation) should have an effect on the acceleration phase. Various models of the distance traveled while accelerating and the total speed change were attempted, but no significant effect from the location of the dilation could be found when accounting for the original initial variables of tangent length or potential speed change.

There was success in modeling a substitute parameter in place of the distance traveled during the acceleration phase. Rather that examining how far the drivers travel from the start of the tangent to the maximum speed, the distance of their location at maximum speed from the downstream curve provides a similar view of where the drivers are at when they start the process of curve navigation. The model of the distance from the curve at maximum speed in Table 7.3 uses only two fixed effects, the tangent length and the location where the pupils are dilated, represented as the distance from the downstream curve when the pupils are at a maximum size. Though the significance is not as strong as the tangent length, the cognitive measure indicates that the vehicle reaches maximum speed earlier when the pupil dilates earlier. The model in Table 7.3 was created from a weighted least squares regression with weights based on the residuals from an original prediction. The residual plots from the initial and final models are shown in Figures B.53 through B.56.

Table 7.3: Acceleration Model with Metrics of Cognitive Load

	Estimate	**t Ratio**	**Prob>|t|**
Distance from Downstream Curve at Maximum Speed			
Intercept	20.5	8.27	<0.0001
Tangent Length (ft)	0.424	78.9	<0.0001
Distance from Maximum Pupil to Curve (ft)	0.0704	12.9	<0.0001

The model in Table 7.3 is written in Equation 7.4.

$$D_{Decel} = 20.5 + 0.424L_{Tan} + 0.0704D_{Dilation} \qquad 7.4$$

where

D_{Decel}	=	distance (ft) of the vehicle from the curve at maximum speed, or deceleration distance,
L_{Tan}	=	tangent length (ft), and
$D_{Dilation}$	=	distance (ft) from the curve when the pupil is dilated.

The data used to generate the model have the following ranges. The tangent length ranged from 138 to 1,445 ft (average 584 ft); the distance from the downstream curve when the pupil was dilated ranged from 0 to 1,000 ft (average 185 ft); and the distance from the downstream curve when the vehicle is at maximum speed ranged from 0 to 1,227 ft (average 283 ft).

7.2.2.1. Deceleration Before Entering a Curve

Sections 4 and 5 identified two performance measures associated with the deceleration phase: the speed reduction that occurs before the curve and the maximum deceleration rate experienced on the tangent. The investigation of models with these performance metrics incorporates the primary variables of geometry and operations first identified in Section 4 to preserve the basic structure of the model and isolate the effect of cognition. Models tested the distance before the downstream curve at which the pupil is fully dilated, representing the time the driver has completed processing information regarding the curve.

The speed reduction that occurs in advance of the curve was the only metric of the deceleration phase that was successfully modeled. The primary geometric effects in the corresponding model in Section 4 are the radius and maximum speed on the tangent. The model in Section 4 (Table 4.2) also included an effect for the distance from the curve at which the vehicle is at a maximum speed. The effect for that variable indicates that the speed reduction before curves increases when the maximum speed is reached earlier, which should not be surprising. That variable is not included in this model because there is a connection between the location at which the driver reaches a maximum speed and the location at which the pupils are fully dilated. Though the relationship is not as strong, the effect of the location when the pupil is dilated indicates that the speed reduction increases with an earlier dilation. One reason this speed reduction is so small is that the geometry and operations account for most of the variance in the observations, leaving little to be attributed to the pupil dilation. In the initial model of the speed reduction, residual plots indicated that the error terms are not characterized by constant variance, illustrated by the megaphone pattern in Figure B.57. Transformations of the data were not productive. Some outlier residuals were discarded and a weighted least squares regression model was developed and is represented in Table 7.4.

Unfortunately, no valid model could be developed that identified how the location where the pupil dilation occurs with respect to the curve affects the deceleration rate on the tangent. This should not be surprising given the small effect of the dilation location on the model for the total deceleration.

Table 7.4: Deceleration Models with Metrics of Cognitive Load

	Estimate	**t Ratio**	**Prob>|t|**
Speed Reduction (mph) Before Curve			
Intercept	-5.52	-16.0	<0.0001
1 / Radius (ft)	1449	55.8	<0.0001
Maximum Speed on Tangent (mph)	0.105	14.2	<0.0001
Tangent Length	0.00255	21.8	<0.0001
Distance from Maximum Pupil to Curve (ft)	0.00104	6.44	<0.0001

The model in Table 7.4 is provided in Equation 7.5.

$$\Delta_{Speed_{Decel}} = -5.52 + \frac{1449}{R} + 0.105 Speed_{Max} + \frac{25.5 L_{Tan}}{10{,}000} + \frac{10.4 D_{Dilation}}{10{,}000} \quad 7.5$$

where

$\Delta_{Speed_{Decel}}$ = change in speed (mph) before the curve, R = radius (ft),

$Speed_{Max}$ = maximum speed (mph) on the tangent,

L_{Tan} = tangent length (ft), and

$D_{Dilation}$ = distance (ft) from the curve when the pupil is dilated

The data used to generate the model have the following ranges. Radius ranges from 55 to 2,380 ft (average 791 ft); the maximum tangent speed ranges from 35 to 73 mph (average 50 mph); and the tangent length ranges from 138 to 1,445 ft (average 584 ft); and the distance to the downstream curve from the location where the pupil is dilated ranged from 0 to 1,000 ft (average 186 ft). The dependent variable, the actual observed speed reduction that occurs before the curve, ranged from 0 to 35 mph (average 3.4 mph).

7.2.2.2. Within-Curve Performance

The performance measures for within-curve navigation are the speed at the PC and the maximum lateral acceleration observed within the curve. Sections 4 and 5 identified the maximum rate of deceleration within the curve as a viable performance measure, but no significant relationship between measures of cognition and within-curve deceleration could be identified. Again, the distance from the curve at which the pupils are fully dilated is the identified measure of cognition, and the models also contain the primary geometric features used in Section 4. Table 7.5 contains the models and significant main effects.

The first model in Table 7.5 contains the same geometric and operational parameters estimating the speed at the PC as the corresponding model in Section 4 (Table 4.3). The distance from the curve at which the pupil is dilated has an inverse relationship with speed, indicating that drivers tend to enter the curve at a lower speed when they process the information about the curve earlier. This relationship is significant in the model (though weak compared to the other parameters) despite the inclusion of tangent length, which maintains the same sign as the previous model based on geometry alone. No transformations were necessary; residual plots are shown in Figures B.61 and B.62.

The second model in Table 7.5 indicates that an increased distance from the curve at which the pupil is dilated leads to a reduced lateral acceleration experienced within the curve. As was discussed previously, lateral acceleration is based on the instantaneous speed of the driver and the geometry of the curve, but it was shown that curve geometry alone produces a strong estimation of lateral acceleration. In the model of maximum lateral acceleration in Table 7.5, the cognitive measure of the distance from the curve at which the pupil is dilated indicates that less lateral acceleration is expected when the pupil is dilated earlier. Surprisingly, the tangent length was not significant despite the strong correlation with the location of the pupil dilation. Again, no transformations were necessary; residual plots are shown in Figures B.63 and B.64.

Table 7.5: Within-Curve Models with Metrics of Cognitive Load

	Estimate	t Ratio	Prob>|t|
Speed (mph) at PC (R^2=0.90)			
Intercept	10.1	13.1	<0.0001
Maximum Speed on Tangent (mph)	0.821	55.9	<0.0001
1 / Radius (ft)	-1499	-40.2	<0.0001
Tangent Length (ft)	-0.00280	-12.6	<0.0001
Distance from Maximum Pupil to Curve (ft)	-0.00121	-4.54	<0.0001
Maximum Lateral Acceleration (g) (R^2=0.68)			
Intercept	0.311	45.2	<0.0001
Ln[Deflection (deg) / Radius (ft)]	0.049	39.0	<0.0001
Distance from Maximum Pupil to Curve (ft)	-1.2×10^{-5}	-2.82	0.0048

Equations for the models in Table 7.5 are provided below.

$$Speed_{PC} = 10.1 + 0.821 Speed_{Max} - \frac{1499}{R} - \frac{28L_{Tan}}{10{,}000} - \frac{12.1 D_{Dilation}}{10{,}000} \quad 7.6$$

$$Accel_{Lat} = 0.311 + 0.049 \ln\frac{I}{R} - \frac{0.12 D_{Dilation}}{10{,}000} \quad 7.7$$

where

$Speed_{PC}$ = speed (mph) at the PC,

$Accel_{Lat}$ = maximum lateral acceleration (g) in the curve,

$Speed_{Max}$ = maximum speed (mph) on the tangent,

R = radius (ft),

L_{Tan} = tangent length (ft),

$D_{Dilation}$ = distance (ft) from the curve when the pupil is dilated, and

I = curve deflection angle (deg).

The data used to generate the models have the following ranges. Radius ranges from 55 to 2,380 ft (average 791 ft); the deflection angle ranges from 14 to 151 deg; the maximum tangent speed ranges from 35 to 73 mph (average 50 mph); the tangent length ranges from 138 to 1,445 ft (average 584 ft); the distance to the downstream curve from the location where the pupil is dilated ranged from 0 to 1,000 ft (average 186 ft). The observed dependent variables ranged from 18 to 70 mph for speed at the PC (average 46 mph) and 0.05 to 0.43 g for maximum lateral acceleration (average 0.18 g).

The consistency of the effects that the location of the pupil dilation has on the two models in Table 7.5 should not be surprising. Since the lateral acceleration experienced within a curve will be strongly correlated with the speed of the vehicle at the PC, a decrease in speed at the PC (observed with an earlier pupil dilation) will naturally lead to decreased lateral acceleration. The parameter for the location of the dilation is not nearly as significant as the other variables in these models, which is a consistent observation for the other models as well.

7.3. Summary

Sections 7.2.1 and 7.2.2 identify relationships between the measures of operational performance and visual behavior. Regarding measures of cognition (pupil size and eye closure) the models in Section 7.2.1 suggest that the pupils contract and the eyes become more closed while accelerating. Someone who evaluates these models may mistakenly conclude that the cognitive measures are dependent upon operational features alone. Such findings are quite meaningless, however, without considering the context of the study—that the drivers were on a curvy highway. Because of the correlation between features of the highway and how the drivers tend to respond operationally, the relationship between cognition and operations is actually a support for the relationship between the road features and cognition.

To elaborate, imagine a driver on a stretch of road that extends for miles straight in each direction. There are no apparent hazards such as traffic, obstacles, or visibility restrictions. If the driver voluntarily decelerates or accelerates at random and with no constraints on the parameters of deceleration and acceleration other than the physical capabilities of the vehicle, would the relationships between cognitive and operational parameters be similar to the ones identified in this research? Probably not, because the operational behavior of the driver on that road would not be in response to the perception of information crucial to the driving task. The behavior would be really a response to the whims of the driver that involve minimal processing. Thus the relationships documented in Section 7.2.1 are not so much cause-effect as they are a way to characterize the visual attention of drivers observed at curves using operational metrics.

The relationships in Section 7.2.2 are more valid from a perspective of cause and effect, identifying (with relatively weak terms) how the processing of inputs affects the system's response. The distance from the curve when the pupil is at a maximum dilation, indicating the location at which cognitive load is the greatest, was the preferred cognitive parameter. The model of speed reduction that occurs before the curve identifies a small increase in speed reduction when the pupil is dilated earlier. The earlier pupil dilation was unexpectedly found to lead to an increased deceleration rate. Earlier pupil dilations were successfully found to lead to lower speeds at the PC (which is not surprising considering the predicted increase in speed reduction and deceleration rate) and reduced lateral acceleration experienced within the curve. Variables associated with eye closure were generally not significant, or at least not as significant as those of pupil size, so eye closure was not included in the models in Section 7.2.2.

7.4. Conclusion

This section investigates relationships among the measures of cognitive load and operational performance for drivers at curves. It was found that the magnitude of the dilation (in mm) has no significant impact on any measure of operational performance at curves. The most influential cognitive measure is the location where the pupil dilates, which is a derivative of the latency of the dilation discussed in other research (Beatty and Lucero-Wagoner 2000). This appears to relate to the findings in the previous section, that TCDs generally do not affect the magnitude of the cognitive response, but do affect the location. In the data, the location of the pupil dilation is defined with two different parameters: the location of the vehicle when the pupil is at a minimum size (representing the initiation of the dilation) and the location of the vehicle when the pupil is at a maximum size (representing the conclusion of the dilation). Surprisingly, the location of the vehicle when the pupil is at a minimum size and fully contracted had no significant effect on the operational parameters tested. Only the location at the end of the dilation (measured as the distance from the downstream curve) was significant. Generally, operational performance improved when the dilation occurred earlier.

The results of Sections 4 and 5 indicate that an earlier initiation of the deceleration on a tangent leads to improved performance at the curve. In fact, the operational behavior observed at each stage carries over to influence the operational behavior in the next stage. The first analyses in this section show how the cognitive measures at any time may be a reflection of the immediate operational characteristics. But the second part identifies how the changes in cognition later affect the operational performance. There is an interesting pattern that links the relationships between the instantaneous measures of cognition and operations, the relationships between the operational measures on a tangent and the operations within a curve, and the relationships between the cognitive measures on a tangent and the operations within a curve. In a sense, this link is not unlike a transitive property (if A = B and B = C, then A = C). In this case, if operations on the tangent affect the operations in the curve, and operations on the tangent are related to cognition on the tangent, then cognition on the tangent affects operations in the curve.

The analyses of the operational and attentional relationships illustrate the complexity of determining whether or not driver attention actually affects performance at curves. The models in Table 7.2 would suggest that the visual attention is actually a product of the operational measures, that drivers are responding cognitively based on their speed and acceleration. There would thus be a question of which comes first—the cognition or the operational response. Of course, the possibility of there being such a question regarding this ordering is rather absurd given our understanding of the processes involving the steps of informational input, perception of information, *then* an output response. With that foundation (presented as a continuous system of the driving task in Figure 2.1), it is clear that the perception (and associated attention) does affect operational performance.

It is interesting that the magnitude of the pupil dilation—often identified as the cognitive load—was not found to have any influence on behavior. It was hypothesized that greater pupil dilations, which are indicative of greater cognitive load, would lead to better performance, as if a result of the driver processing the information about the curve in a more-serious way than he/she otherwise would. It was observed that curves of higher severity would usually have a larger dilation, regardless of the TCDs used. This seems to suggest that a driver's pupils will dilate to a certain amount for a curve whether or not the information comes from TCDs. The models in Section 6 indicate that, rather than increasing the actual cognitive load, TCDs encourage the change in cognition to occur at an earlier time. The success in these models with using the location of the dilation, rather than the magnitude, is congruent with that finding. In other words, it may be that drivers obtain the same amount of information related to curves no matter what supplementary devices are used; the value of TCDs is in influencing when that information is perceived.

8. CONCLUSION

This dissertation documents a study completed to investigate driver operational and visual behavior associated with navigating horizontal curves. Components of operational behavior were documented in Sections 4 and 5 and components of visual behavior were documented in Section 6. Relationships between the two were also investigated and analyses were presented in Section 7. A substantial amount of the research has focused on the effects of TCDs used at curves. Models in Section 5 identified consistent effects of TCDs on operational behavior that would be considered desirable (e.g., reduced speeds). Though not as clear as the effects on operations, the models in Section 6 identified effects on driver visual behavior that indicate that TCDs encourage the perception of information to occur earlier.

This research has examined parts of the driving task relating to the visual input, perception of that information, and the output of the motor centers within the context of navigating horizontal curves. In the study, the visual input of supplementary TCDs was investigated, with acknowledgement that the curve geometry and other features also serve as sources of information for drivers. The models analyzing the visual behavior included metrics of driver cognition that characterize how the driver perceives the visual input. And models evaluating the operational behavior of drivers identified how the drivers respond after the perception of the information. Though models measuring the magnitude of the cognitive load were not robust, the most useful product may be the models that identify when the perception of information occurs. Analyses of the relationship between the cognitive and operational measures suggest that earlier perception of information leads to improved performance.

The research presented in this dissertation is large in scope. Not only is driver operational behavior evaluated at curves that have various features (such as geometry and the presence of TCDs), but it is evaluated at different stages of curve navigation. In addition to the operational behavior, the visual behavior and cognition of drivers is also evaluated throughout the various stages. The synthesis of these results produces a comprehensive view of the processes involving the input and perception of information and the output of operational behavior within the context of curve navigation. The analyses are complex, requiring the testing of multiple hypotheses, but the information produced is quite rich in detail and applicability.

There are a number of ways this research expands upon the current understanding of driver behavior and can improve the way engineering decisions are made and driving research is conducted. The following discussions identify the contributions of this research, how the findings can be applied in practice, and what work can be done to overcome some of the limitations of this research and further examine the relationships between attention and performance. The section concludes with some final thoughts.

8.1. Contributions of this Research

The literature summarized in Section 2 includes multiple studies that have evaluated driver visual behavior at curves, but it seems that few, if any, have evaluated the cognitive processes associated with navigating curves. Even fewer have incorporated the effects of TCDs on perception. Although the models of cognitive load in Section 6 were not as robust as was desired, it is believed that these metrics are still useful in future work. Research that exclusively employs operational measures to evaluate performance implicitly disregards the importance of understanding how drivers perceive information. The pupil diameter, eye closure, and blink rate are measures that directly relate to the cognitive load of the driver and can thus be a window to the internal processes of the driving task. Most important has been their use in identifying when a stimulus first becomes relevant. It is suggested that the effectiveness of TCDs or other objects or situations that involve the perception of information may likewise be evaluated in terms of the cognitive response identified with these measures.

The analyses of driver operational performance were executing using some metrics measures that have not received widespread use. These measures were identified as the best way to utilize the continuous data collected in the study. With the exception of one new metric (the proportion of total deceleration occurring in advance of the curve), each was successfully modeled with overall strong correlation using geometric and other operational features. When the metrics were modeled with effects of TCDs at curves, each operational effect was observed to lead to a more-conservative maneuver.

The successful use of alternative operational performance metrics in this dissertation shows that the complexities of driver behavior can be illustrated by using more than just single measures of speed at single locations. Measures that extend beyond the traditionally small area of interest near curves can provide a better picture of how drivers respond to various situations. It has been discussed that each of these operational measures for evaluating performance at curves are related. For example, a shorter acceleration phase leads to a reduced maximum speed attained on the tangent; a reduced maximum speed on a tangent should lead to a reduced deceleration rate in advance of the curve and lower speed at the PC; a lower speed at the curve should lead to a reduced rate of lateral acceleration, etc. The effects of the TCDs are also observed beginning in the acceleration phase and continue until exiting the curve. Since effects of TCDs were identifiable in most of the new performance metrics, it is suggested that future research involving driving at curves include some of the metrics derived here.

The synthesis of the cognitive response of drivers and the operational behavior shows how the perception of information does influence the observed output, specifically, that the time of perception affects the operational response. Such a finding should not be surprising when considering the requirement to execute a deceleration maneuver in advance of a curve, and it emphasizes the importance of providing drivers with the right information at the right place and time. The function of TCDs at curves is to do that. The TCDs evaluated in this research resulted in the earlier perception of information, as observed in the pupillary and eye closure data, and earlier initiation of the operational response, as observed by the earlier termination of the acceleration phase.

It is not uncommon for a researcher tasked with identifying whether or not a treatment is effective to perform the requisite tests and simply conclude that the treatment is or is not effective. Engineers may then inquire under what conditions the treatment should be used. In this research, the supplementary TCDs were found to be effective under almost all conditions (and using numerous performance measures). But the simple proof of effectiveness does not justify the application of these TCDs at all curves. That should be done employing principles of engineering that factor in the economic use of resources based on the needs of the system and its users. The following discussion illustrates how the results can be applied in practice.

8.2. Applying Findings to Engineering Practice

The current guidelines in the MUTCD identify in simple terms the conditions for which TCDs (currently only signs) should be used at curves (FHWA 2009). For conventional curves, advance warning signs with an advisory speed plaque are required at curves where the approach speed (whether speed limit or prevailing speed) and the curve advisory speed differ by 10 mph or greater. Chevrons are required when the speed differential is 15 mph or greater. Unfortunately, this guideline does not allow for flexibility in considering the actual conditions at a curve or the needs of drivers to properly respond to curve information.

The results of the driver behavior study indicate that TCDs at curves lead to improved performance under all practical conditions. Even though improved performance may result from the use of a device, that improvement alone may not be enough to justify its use when considering the limitations of agency resources. From the evaluations of the drivers' cognitive and operational responses, the findings documented in Sections 4-6 contain information about when (or where) drivers receive information at curves and how they respond. By using these findings, engineers can make decisions about the devices that should be used in order to provide drivers the information needed to make a proper response and comfortably navigate the curve. In other words, the engineer should ask, “What information, and delivered through which means, should be provided so drivers will navigate the curve at a speed consistent with their expectations and desired level of comfort?”

The models in this research identify where drivers are able to identify curves, what characteristics of operational behavior they adopt (such as deceleration rates and lateral acceleration), and the potential influence of supplementary TCDs on both the ability to detect a curve and the selected operational response. Without considering the MUTCD guidelines for TCDs at curves, the proper selection of a supplementary device can be based on whether or not a driver needs additional information within the distance provided to naturally respond to the curve and avoid unnecessary or extreme maneuvers. This discussion suggests a way to integrate the findings from the various models in selecting appropriate TCDs at curves.

The results of previous research suggest that drivers are able to detect curves several hundred feet before the curve, relying only on pavement markings. Advance warning signs, which are legible several hundred feet in advance of the sign (Paniati 1988; Zwahlen et al. 1991), provide additional information that aids in the identification of curves. The results of this research (Section 6) suggest that 500 ft is the distance at which drivers can identify a curve, based on the direction of their fixations. The results in Section 6 show that supplementary TCDs increase the detection distance by up to 170 ft from the location of the vehicle when the pupil is fully dilated. Unfortunately, the findings of the effects of TCDs are not perfectly consistent. While chevrons, for example, were identified to contribute an additional 170 ft to the detection of the curve, from the pupillary changes, PMDs were observed to add 100 ft. Based on the operational findings, however, the increased distance at which a response begins (determined by the termination of the acceleration phase) is 137 ft for chevrons and 76 ft for PMDs. Regardless of the specifics, however, the most common trend indicates the supplementary TCDs increase the distance from the curve at which drivers cognitively and operationally respond. Based on the physical properties of the devices and the visual acuity of drivers, a detection distance for chevrons of 670 ft (500 ft from the curve alone and an additional 170 ft from the chevrons) seems reasonable.

With various detection distances possible with the multiple TCDs, the next step is to identify the distance required for a driver to execute a natural response at a curve. A suitable TCD will provide a detection distance at least as great as the necessary response distance. The response distance can be determined by the models of driver operational behavior—whether in this research or elsewhere—that identify the deceleration that occurs before a curve. These models use various inputs from in-field data or reasonable assumptions (if necessary) that identify values such as the approach speed (maximum tangent speed in this research), curve speed (speed at the PC or within the curve), and deceleration rates or total observed deceleration. Some reasonable modifications may need to be made to the equations used. For example, it was observed in this research that the deceleration rate is not constant, but tends to be greater near the curve. Also, 55 percent of the total speed change at curves (on average) occurs on the tangent. These two observations illustrate how some assumptions or models may need to be adjusted to better reflect natural driving habits.

It should be noted that, as with other engineering applications, there are multiple ways in which the system may fail because its components (in this case, the drivers) do not respond as expected. Drivers may exhibit inattentional blindness, be distracted visually and cognitively, have poor vision, or simply react slowly. The visibility may be compromised by weather or the presence of other vehicles, and the conditions of the road may also be inadequate to support a projected response. Various *factors of safety* can be added into the models to account for these effects, such as additional PRT, limited device effectiveness due to reduced visibility, and less total deceleration occurring in advance of a curve. The point is that there needs to be consideration for the unique behaviors that drivers exhibit which are not accounted for in some of the models from the experimental data. The models in this study predict driver behavior using least-squares regression, so the extremes tend to not be fully represented.

While the models may not be perfect, the recommended approach for applying this research is valuable to practitioners because it illustrates how principles of engineering can be used to select TCDs at curves. Perhaps the most important findings of the study relate to the locations at which changes in cognition and operational responses are observed and the effects supplementary curve TCDs have on these values. By considering the distance drivers need to operationally respond to a curve, and matching that distance with an appropriate treatment, the engineer is able to make decisions based on the specific conditions at each curve and the actual needs of drivers. Such an approach may be a significant improvement upon the way TCDs are selected over the current guidelines in the MUTCD.

8.3. Recommendations for Future Work

This research has quite thoroughly investigated driver cognition and operational behavior associated with navigating curves, including an investigation of the effects of supplementary curve TCDs. Despite how comprehensive the analyses seem, there are some limitations of the research findings and areas of related research where gaps in information have not yet been filled. This subsection presents some recommendations for future research that can address these shortcomings.

During the process of data reduction in this study, most of the measures of cognition and operations were identified separate from each other, with later efforts to integrate the measures. For example, the locations where the vehicle is at a maximum speed on the tangent (an operational measure) and the pupil dilation occurred (a cognitive measure) were assumed to be related (and confirmed in the analyses). But the data, unfortunately, were not reduced in a way that automatically integrates the measures. By adjusting the way the data are compiled, the moment when the curve information is perceived (e.g., when a dilation occurs), and the measures of operations at that instant can be extracted to identify the "initial" driver behavior on the tangent. By having these different data sources integrated together more consistently, rather than relying on the assumed link that may actually be delayed several seconds, the information produced would more accurately reflect the true cognitive and operational states at the time when such changes in the parameters are observed. Future work involving cognitive and operational measures should consider integrating the various parameters of interest from the onset of the data collection rather than connecting them in a post-processing stage that loses some of the richness of the data.

The reduction of eye-tracking data in this study involved averaging data over 4 seconds beginning at each 100-ft interval on tangent approaches. This method was selected in order to condense the amount of eye-tracking data (collected at 60 frames per second) into a manageable size for analysis. The identification of changes in cognition is thus based on changes in the averaged data between each 100-ft point of interest, rather than the actual inflections that more-likely occur between the 100-ft locations. Additionally, the 4-second average, which was used as a way to control some of the brief incongruities in the eye-tracking data, affects how changes in visual behavior and cognition are observed. The observed changes as averages over time are dampened compared to the actual driver's experience. This effect is illustrated with data for the pupil diameter shown in Figure 8.1.

The data in Figure 8.1 show pupil size averaged over 4 seconds compared to the size when averaged over only 1 second. Some of the inflections in the size of the pupils when averaged over only 1 second are clearly missing when averaged over a 4-second period, though the averaging makes the overall pattern of increased cognitive load clearer. It appears that the minimum pupil size is almost 0.25 mm smaller when averaged over 1 second than when averaged over 4 seconds. In hindsight, it is believed that, while an averaging of the eye-tracking data is effective for identifying consistent patterns, 4 seconds is longer than necessary and produces in a less-dynamic picture of driver visual behavior and cognition. For future research, an interval of 2 seconds seems long enough to not be impaired by missing or incongruous data, but not too long to dramatically dampen the observation.

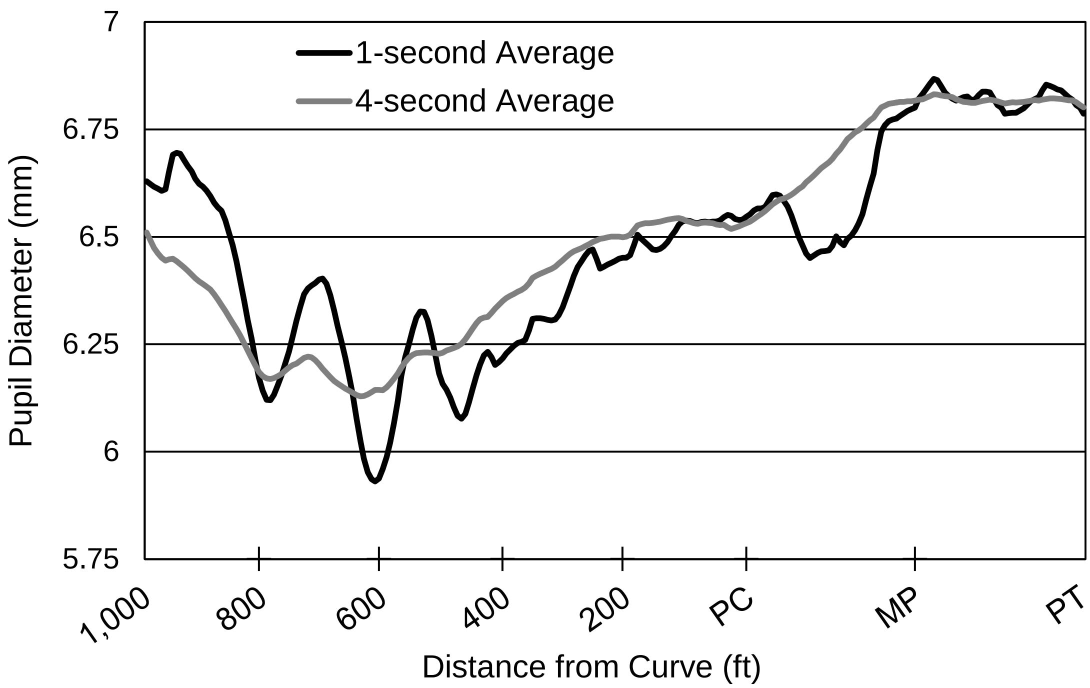


Figure 8.1: Pupil sizes when averaged over 1 second and 4 seconds.

At the start of this research, it was not known what patterns, if any, would be identified in the eye-tracking data. The 100-ft locations for averaging the eye-tracking data were useful for simplifying the amount of data and exploring patterns in visual behavior. Unfortunately, this further reduced the ability to identify the changes in cognitive parameters that occur while negotiating curves. A study incorporating changes in cognition should identify the native maximums and minimums, with some averaging if done consistently, but not based on predefined locations which diminishes the true response. While the reduced eye-tracking data in this study were still dynamic enough to identify significant effects of TCDs on cognition and effects of cognition on operational performance, it is believed that such an approach would substantially improve future analyses.

Overall, the TCDs evaluated in this study produced the “desired” responses of earlier perception of information and more-conservative operational behavior. But this study only evaluated the effects of supplementary TCDs, which are traditionally used in addition to advance warning signs (not to mention the pavement markings, which tend to be taken for granted). As a prominent source of information, especially at night when sign conspicuity increases, advance warning signs likely affect the responses of drivers at curves. While the effects of the supplementary TCDs in this study were significant, it is likely their effects in an isolated condition (without an advance warning sign) will be even more apparent. Additionally, a study of the cognitive and operational responses to warning signs may produce information that helps identify the conditions for which advance warning signs should be used. A combination of the findings of these analyses, and the application of their meaning in practice, can lead to systematic improvements in how curves are treated with TCDs.

It has been observed that crash-causing conditions tend to be observed in the tails of a distribution rather than the mean (Horrey and Wickens 2007). In other words, although crashes have come to be expected, they are not an expected result when drivers exhibit “average” behavior. They occur when a driver’s attention is diverted to secondary tasks or tolerance for risk exceeds what the conditions of the facility can handle. While this research has extensively documented driver behavior during various parts of the driving task, the results more-closely describe average behavior than what is observed at the unsafe extremes of the distribution. Fortunately, the results of this research were generally consistent enough that the modeling technique was able to successfully attribute changes in behavior to TCDs. But the use of these models means that the extreme data are obscured by the observations closer to the average behavior. A different approach should be taken in order for a conservative design to appropriately account for extreme situations. Future work in this area may benefit from focusing on the behavior of drivers in the extreme tail of a distribution rather than attempting to describe characteristics that fit all drivers.

This research primarily emphasized the performance of drivers that are young. Though some data were collected by old drivers, there was an intentional emphasis on young drivers so the results would be most applicable to the demographic of drivers most-often involved in fatal crashes at curves. While it is important for engineers to account for the characteristics of old drivers, especially for situations involving visibility, it is thought that the driving habits of young drivers are more important to observe because they tend to lean toward the aggressive end of the distribution. The results would certainly change (though the amount is debatable) if a different sample of drivers were used.

8.4. Final Thoughts

The three objectives of this research stated in Section 1.1 are to (1) show that TCDs at curves lead to improvement in operational performance, (2) show how TCDs affect driver attention (cognition) before curves, and (3) determine whether or not improved performance comes from the change in cognition. From the successful completion of these objectives, it can be stated that improvement in operational performance at curves does consistently occur when TCDs are used. It can also be concluded that TCDs lead to improved attention in advance of the curve and that an earlier increase in cognition leads to improved operational performance. Each of the three green arrows in Figure 8.2 is individually found in the research findings.

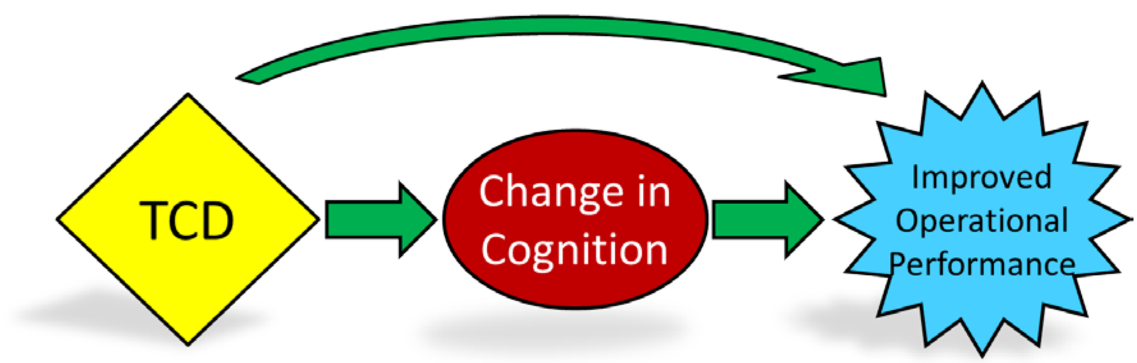


Figure 8.2: TCDs appear to directly affect operational performance at curves, but the more-likely path is through a change in cognition.

When talking about the function of TCDs, it is often assumed that the information they provide is what helps drivers better execute the driving task. The analyses in this dissertation suggest that the information alone may not be as important as the simple fact that the TCDs command attention at a great distance. For example, PMDs do not have an explicit message, but their arrangement around a curve and the luminance reflected to the driver may be valuable, if not to provide information about the curve, then to at least attract a driver's attention to a feature of the road. To a "regular" driver, PMDs may not mean anything more than the outlining of the alignment that is visible at a great distance. But they attract driver attention at a greater distance, encouraging an increase in workload related to the driving task. That increase in workload appears to be the trigger that translates into improved performance. One of the benefits of TCDs may then be to simply increase the alertness of drivers. Such an effect will be particularly important for drivers who may be exhibiting a suboptimal level of attention within the driving task.

The increase in cognitive load at curves also shows that curve driving is (unsurprisingly) more demanding than driving on tangents. This supports the consensus that distractions associated with secondary tasks are unsafe. If a driver's attention is split with another task, there may not be enough spare cognitive capacity to properly navigate the curve (or maneuver through a different hazard). The natural increase in observed cognitive load associated with curve navigation also supports the use of TCDs under certain circumstances. Severe curves are more demanding operationally and cognitively. The right TCD at the right place will support an increase in driver cognitive workload earlier so there is enough distance to execute an appropriate maneuver. Curves that are more demanding should be treated with the devices that increase cognitive load earlier so drivers are properly prepared for the curve.

Our understanding of the role that attention plays in the driving task is expanding as research continues to identify links between attention and performance. And until autonomous vehicles become available, the driving task will always require the integration of perceiving information and response through operational changes. The research in this dissertation illustrates how TCDs can influence driver attention, aiding in the task of navigating curves. When selecting traffic control treatments, engineers and policy makers should consider the cognitive demands on drivers and how the perception of TCDs may bring about an increase in cognitive load. With an increase in attention at the right place and time, drivers will better execute a maneuver that fits with the operational demands of the specific situation.

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APPENDIX A

INFORMATION ABOUT DRIVER STUDY

This appendix contains information about the driver study, specifically, the demographic characteristics of the drivers, a photocopy of the directions provided to the drivers at the beginning of the study, and a photocopy of the debriefing form signed at the end of the study.

A.1. Demographic Data

The minimum, average, and maximum ages of the drivers are given in Table A.1. The number of participants by gender is also identified. Except for the data collected in Idaho, the balance between male and female participants was generally equal. Figure A.1 is a plot of the cumulative distribution of the participants' corrected visual acuity. The visual acuity on the X-axis of the plot decreases from left to right. Approximately 75 percent of all participants had a visual acuity of 20/20 or better. No participant was color blind.

Table A.1: Demographic Statistics of Study Participants

Study Location and Time		Total	Age			Gender	
			Min	Avg.	Max	Male	Female
Idaho	Day	13	18	26.5	66	10	3
	Night	22	18	24.4	66	10	12
Oregon	Day	12	18	38.3	71	6	6
	Night	20	18	26.9	62	9	11
Texas	Day	19	21	36.6	60	9	10
	Night	18	21	33.9	74	8	10

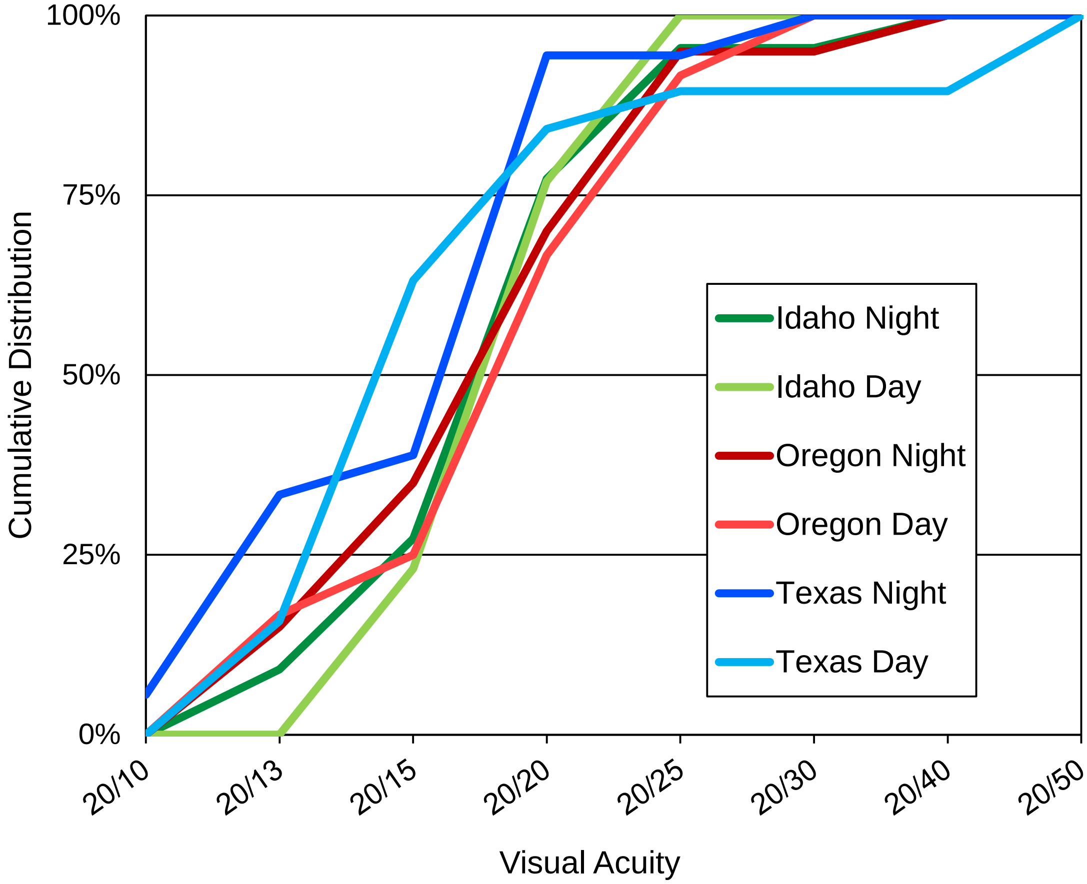

Figure A.1: Cumulative distribution of the visual acuity of study participants.

As shown in Figure A.1, two participants in Texas had a measured visual acuity of 20/50, which is substandard for driving. It should be noted that the participants only drove during the daytime, so they did not contribute any eye-tracking data to the models of visual attention. With a mix of participants that have both exceptional and poor vision, overall the data appear to be representative of the driving population.

Analyses of the driver demographics (age and gender) suggest that, overall, marginal differences in driver behavior can be attributed to these characteristics. Depending on the variables included in operations models, male drivers are observed to navigate curves approximately 0.4 mph faster than female drivers ($p<0.05$) and young drivers approximately 1.0 mph faster than old drivers ($p<0.0001$). There are also differences attributable to the state, up to 5 mph total, which is likely more a reflection of the characteristics of the highway (including its alignment and terrain) than qualities of the state's drivers.

These demographic factors become insignificant when the participants are included as random effects in the models. This should not be surprising, because in order for a demographic effect to be identified as significant when the participants are included as random effects, there must be consistency in the observations of the participants in that demographic. An additional complication occurs when one operational characteristic is used to predict another operational characteristic. For example, the speed on a curve was predicted with one factor being the maximum speed upstream of the curve. Inclusion of a demographic factor in this case may not be productive because some of the contribution of that demographic will be a part of the speed on the tangent. A similar difficulty was encountered in Section 7, where effects of attention were included in addition to the original effects used to predict an operational measure. The contribution of a demographic characteristic (or in Section 7, an attentional metric) will be small compared to the influence of the original variables.

A.2. Study Instructions

A copy of the instructions read to the participants is provided on the next page, followed by a copy of the debriefing form signed after participation in the study.

Project 03-106 (479430) *September, 2012*

In-Vehicle Project Verbal Instruction

Subject # 34 *Researcher:* ______
Weather: clear

Visual Acuity: 20/20 **Color Blind: Yes No**
Special Considerations (circle all that apply): Glare Coating on Glasses Tinted Glasses Bi-Tri-Focals with Lines

NOTE: check:
Seat belt is on
Mirrors adjusted in car
No bright lights

This survey is being conducted by the Texas Transportation Institute, which is part of the Texas A&M University System. It is being sponsored by the National Cooperative Highway Research Program (NCHRP). The purpose of the survey is to evaluate traffic control devices used on rural two-lane roadway. It is hoped with this information we may increase motorist safety.

Before we begin remember that while the vehicle is specially equipped to record and measure various driving characteristics, it drives just like a normal car. I will be in the vehicle with you at all times. While you are driving the test vehicles please obey all traffic laws.

We will first drive for a few minutes so that you may get comfortable driving this vehicle. Then you will be asked to drive through a predetermine roadway. We want you to drive like you normally do, obeying all traffic control devices. I will be in the car with you telling when and where you will need to drive.

After the drive through there may be some follow up questions. If you are ready to begin you will need to (*researcher will instruct each participant the route that they should go.)* **Remember, while we want you to focus on your driving tasks, your most importation job is to drive safely, and always pay attention to the road ahead.**

IRB NUMBER: IRB2012-

Version: November 19, 2012

DEBRIEFING FORM
Project No. 03-106 Traffic Control Device Guidelines for Curves

First, I would like to thank you for participating in our study. You have provided TTI with valuable information that hopefully will increase driver safety.

Researchers told you that the study would be conducted as you drive along the study site in one direction. However, researchers believe that people tend to drive with more caution when they are being observed, in order to encourage you to be more relaxed and drive more to your day to day driving behavior, researchers continued to collect data during the drive back to the starting point. TTI needs your approval to use this data. You are free to deny TTI the use of this data with no ramifications to you. If you have no objection to TTI using this additional data, please check below that you understand that the data was collected during part of the driving task without your knowledge and that you agree to allow TTI to use this additional data.

✓ I understand that data was collected during part of the driving task without my knowledge (the drive back to the office), and agree to allow TTI to use this additional data.

Signature of Participant: [redacted] Date: [redacted]

Printed Name: [redacted]

APPENDIX B

MODELING INFORMATION

This appendix documents some of the processes of creating the models (in Sections 4–7) as discussed in the body of the dissertation. Primarily, figures are provided that illustrate how the various forms of the models were selected, including the tests for verifying modeling assumptions. Each subsection below corresponds with a section in the dissertation.

B.1. Models for Section 4

The models in Section 4 characterize driver behavior at curves without including factors for TCDs. It was documented how the models of the operational effects of geometric characteristics were intended to be as simple as possible (with few parameters) at this stage in order to then test the effects of TCDs. The results of the section are based on data collected at almost all study curves during both daytime and nighttime, so there is substantially more data here than is used in the other sections. The statistical analyses were performed with JMP software. The figures here are plots of the residuals based on output from the software. Each model is represented by a figure of the residual plot and a distribution of the residuals to investigate normality. For models that required transformations or were developed with a weighted least squares regression, plots from the initial, untransformed model are given to document the patterns observed before transforming the observations.

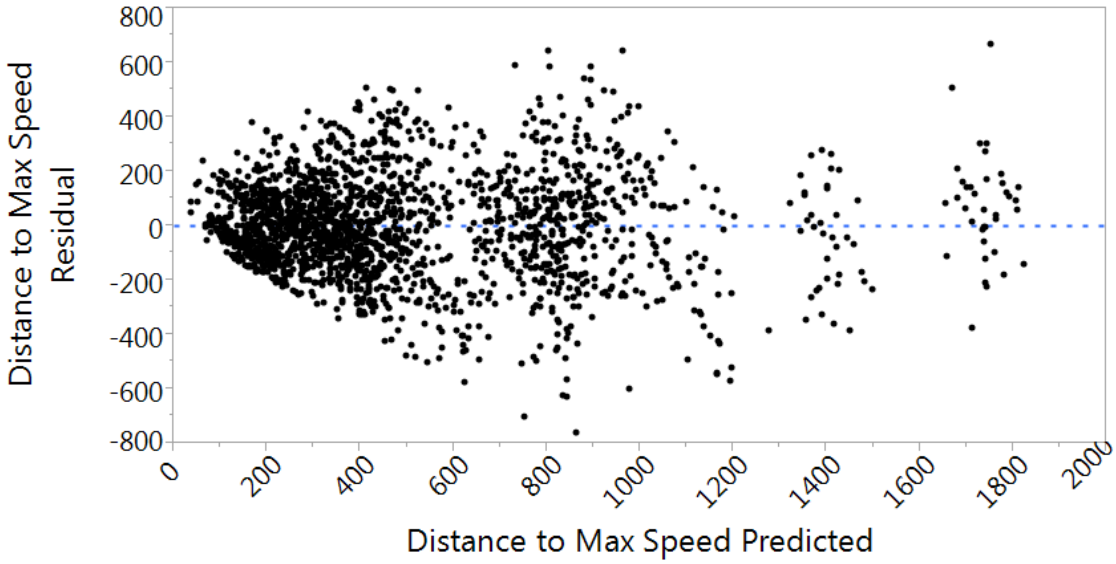

Figure B.1: Residual plot of the initial model for the distance to maximum speed.

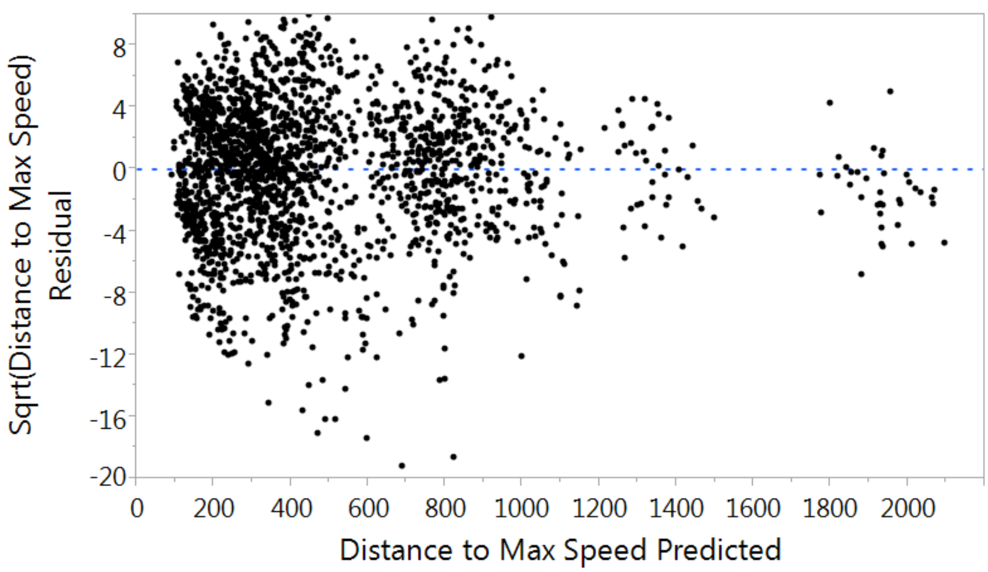

Figure B.2: Residual plot of the transformed (final) model for the distance to maximum speed.

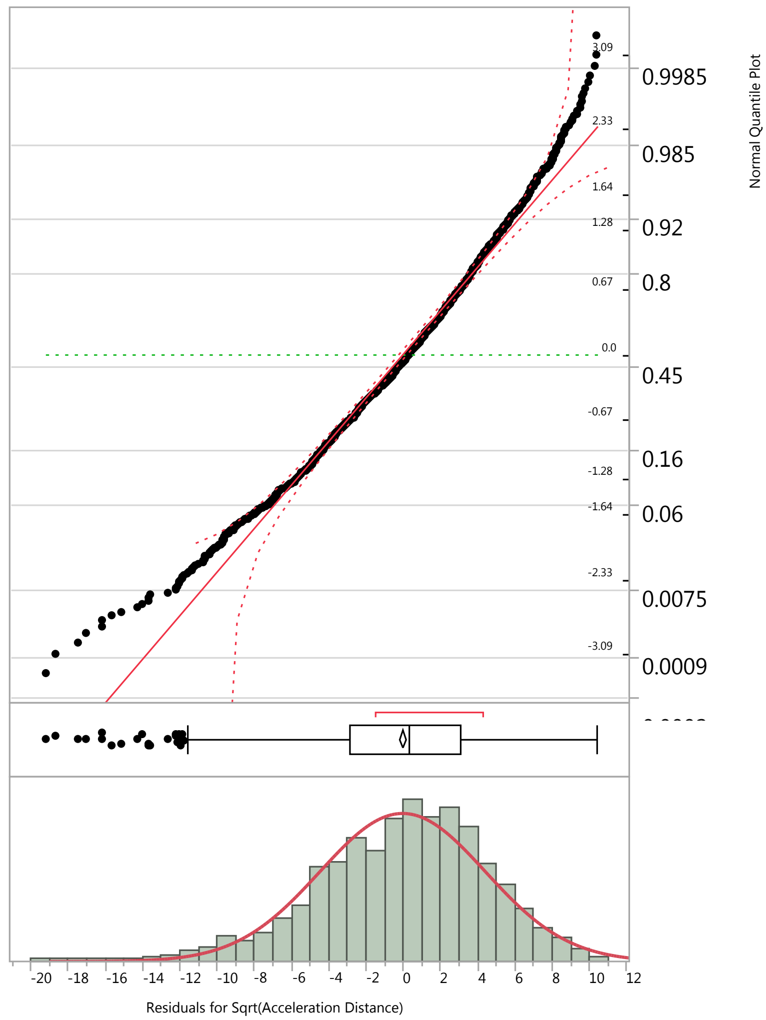

Figure B.3: Residuals for the final model of the distance to maximum speed.

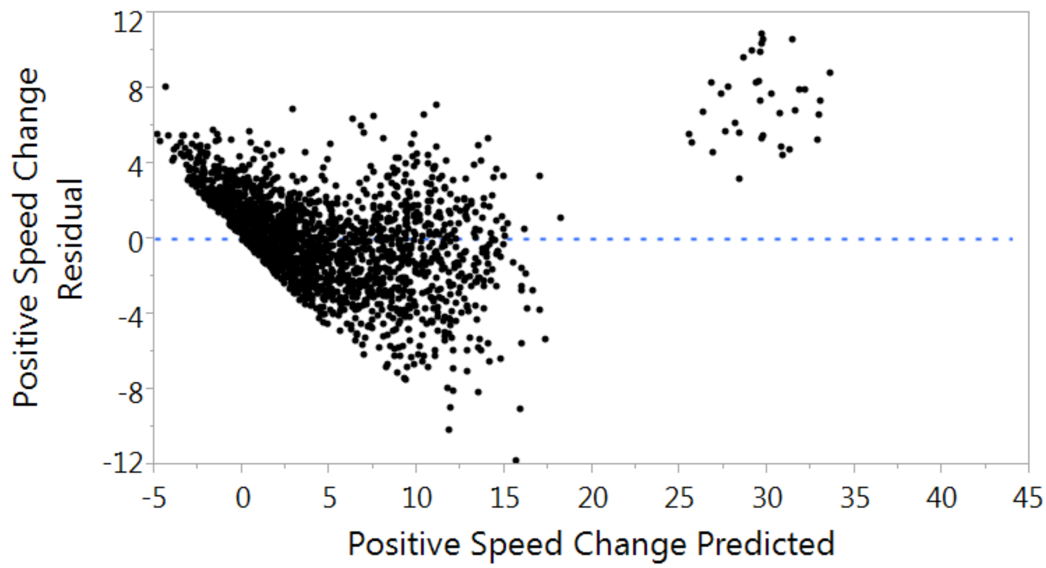

Figure B.4: Residual plot of the initial model for the increase in speed after exiting a curve.

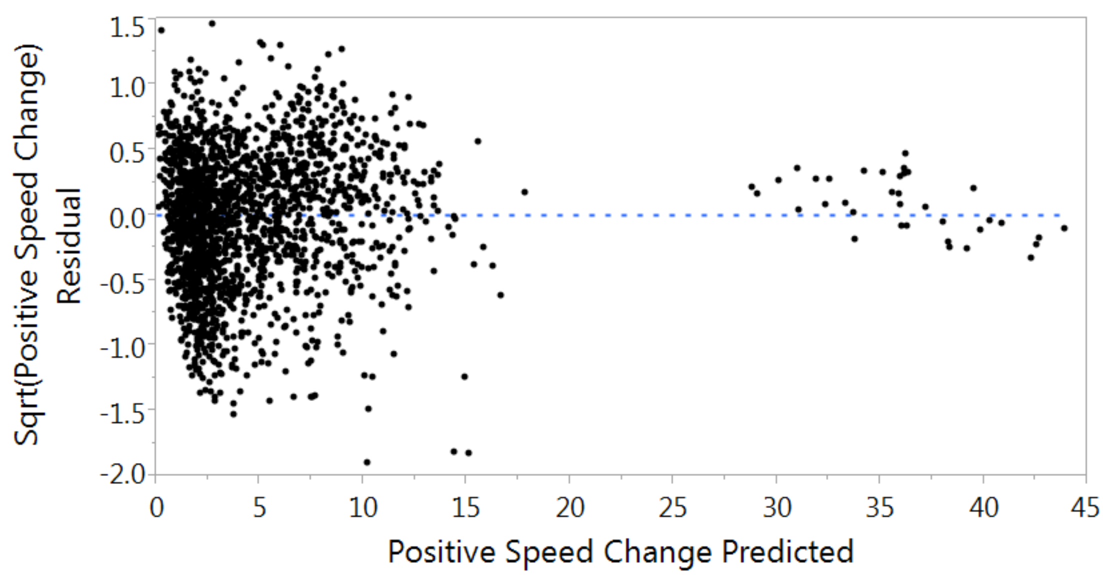

Figure B.5: Residual plot of the transformed model (final) for the increase in speed after exiting a curve

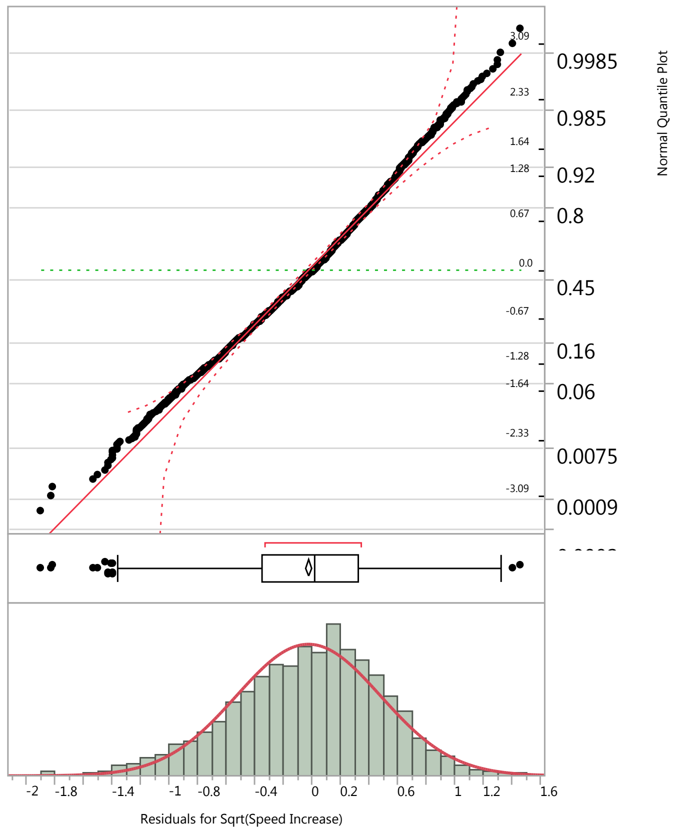

Figure B. 6: Residuals for the final model of speed increase on a tangent.

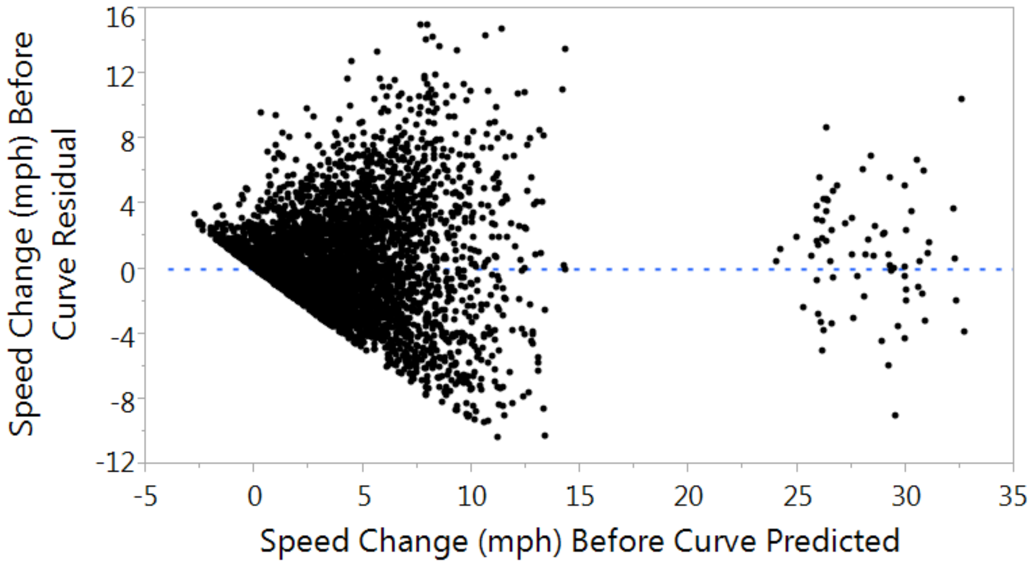

Figure B.7: Residual plot of the initial model for the decrease in speed before entering a curve.

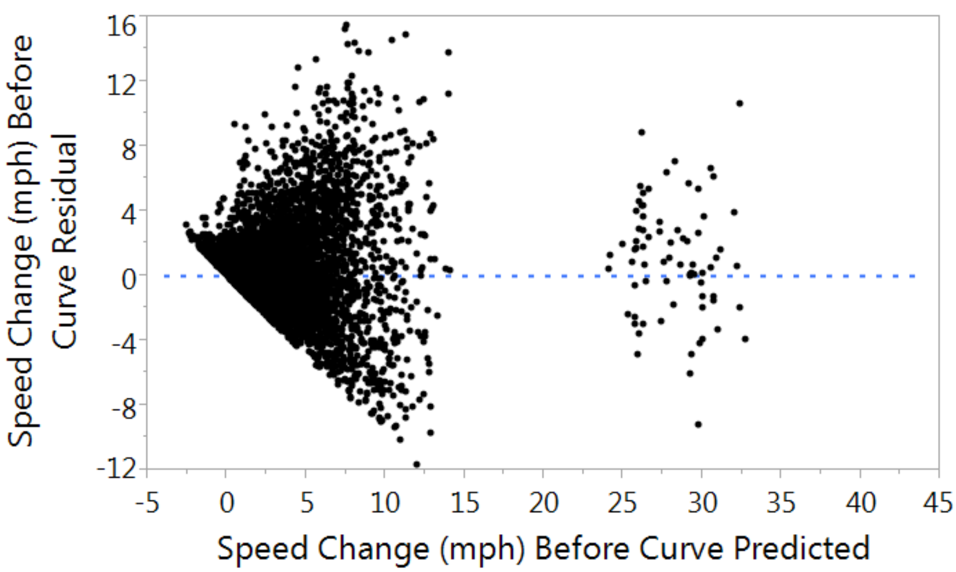

Figure B.8: Residual plot of the final model for the decrease in speed before entering a curve.

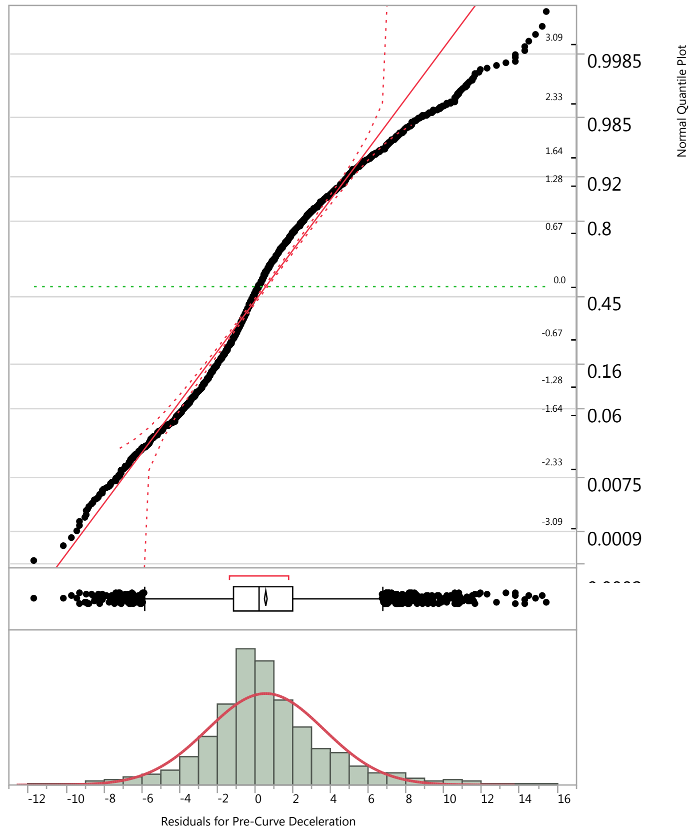

Figure B.9: Residuals for the model of the decrease in speed before entering a curve.

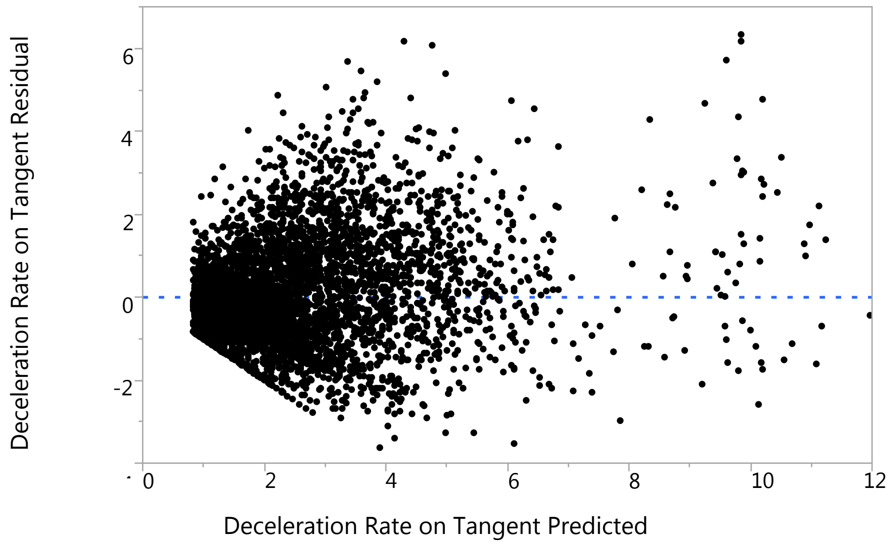

Figure B.10: Residual plot of the model for the maximum deceleration rate on the tangent.

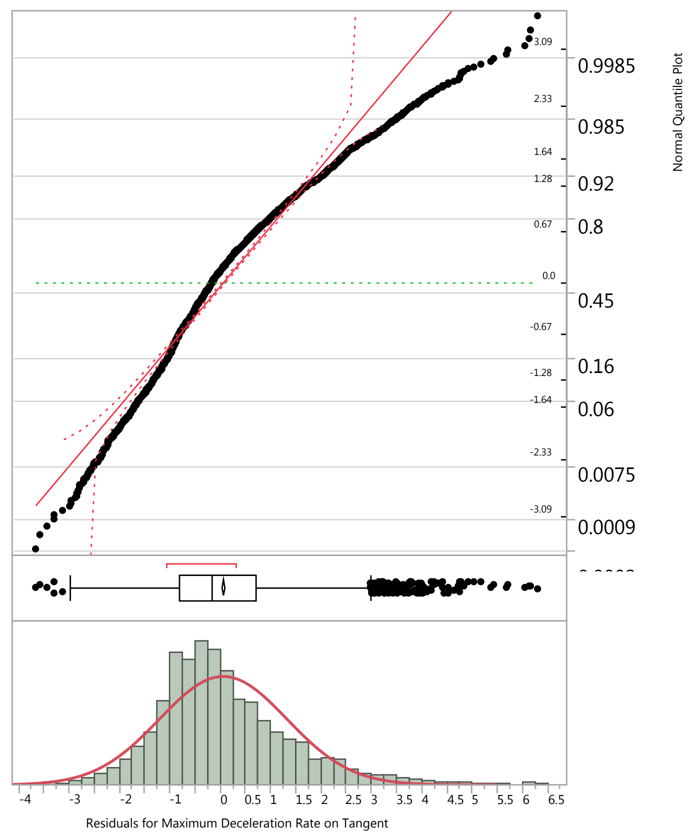

Figure B.11: Residuals for the model of maximum deceleration rate on the tangent.

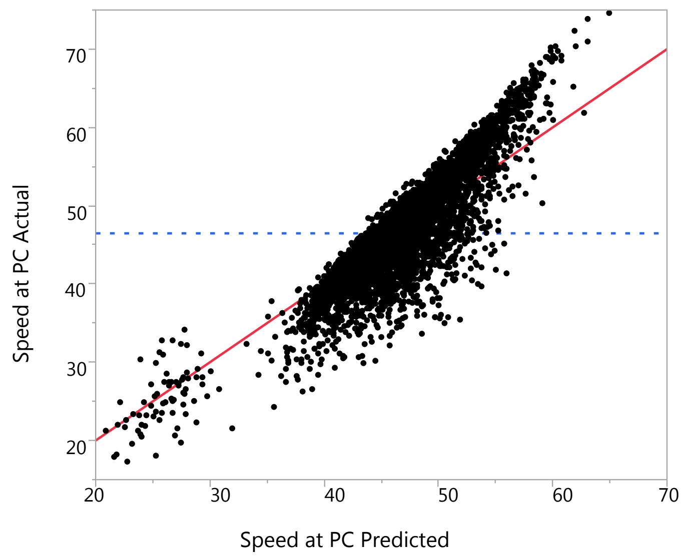

Figure B.12: Plot of actual by predicted values of the initial model for speed at the curve entrance.

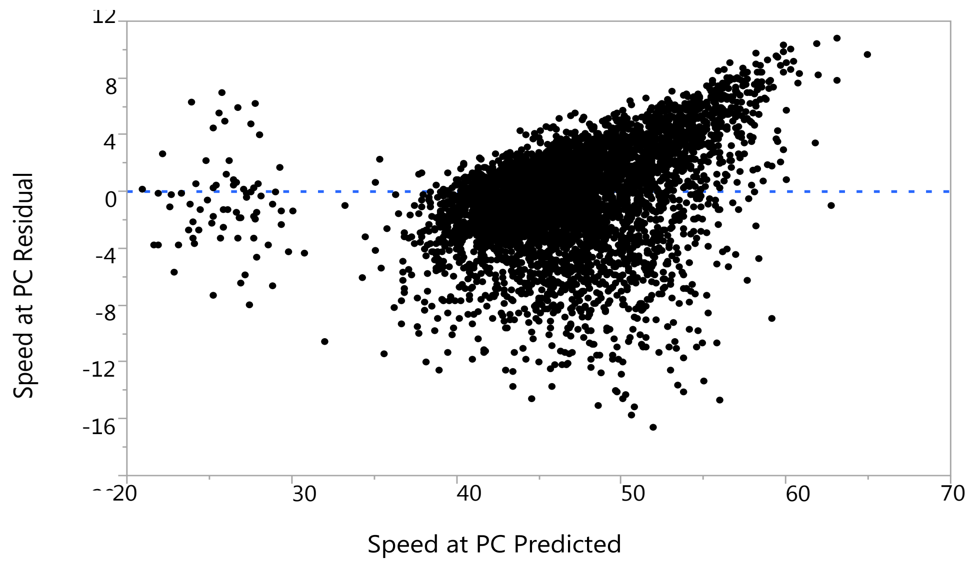

Figure B.13: Residual plot of the initial model for speed at the curve entrance.

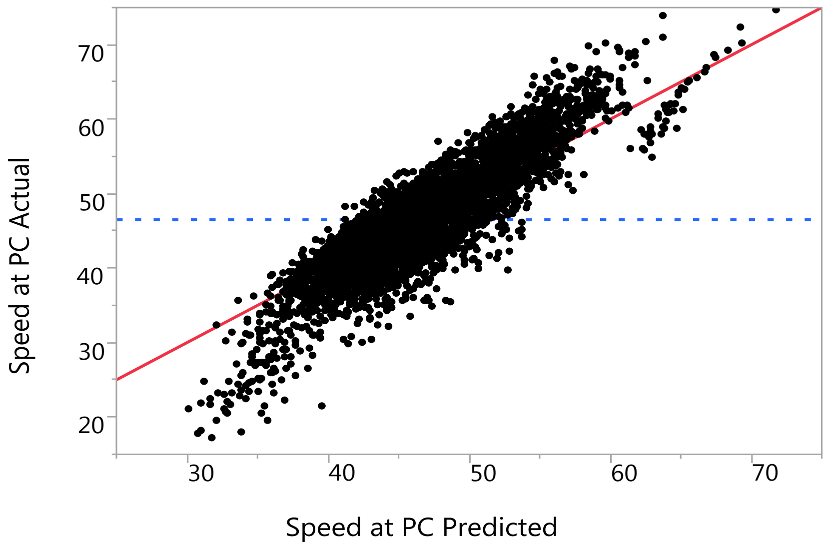

Figure B.14: Plot of actual by predicted values of the final model for speed at the curve entrance.

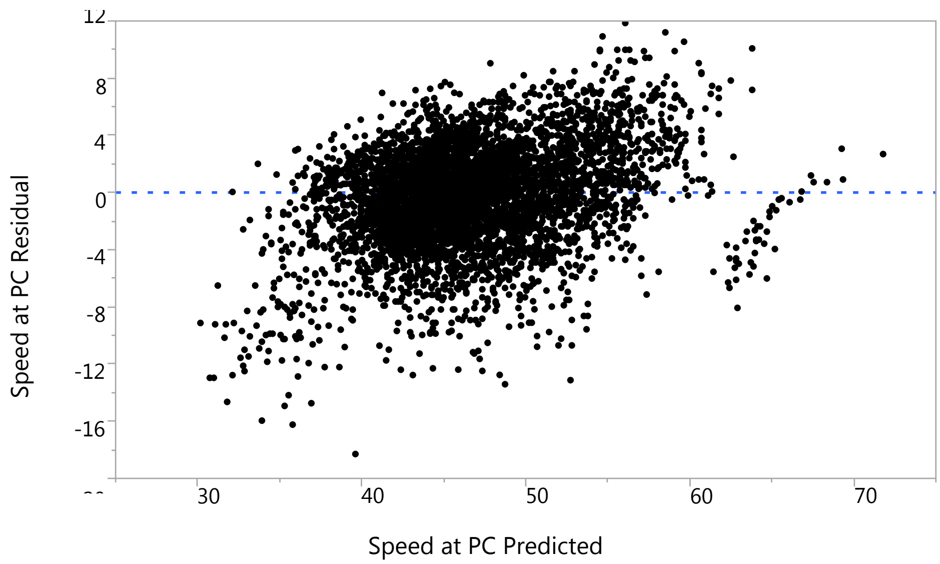

Figure B.15: Residual plot of the final model for the speed at the curve entrance.

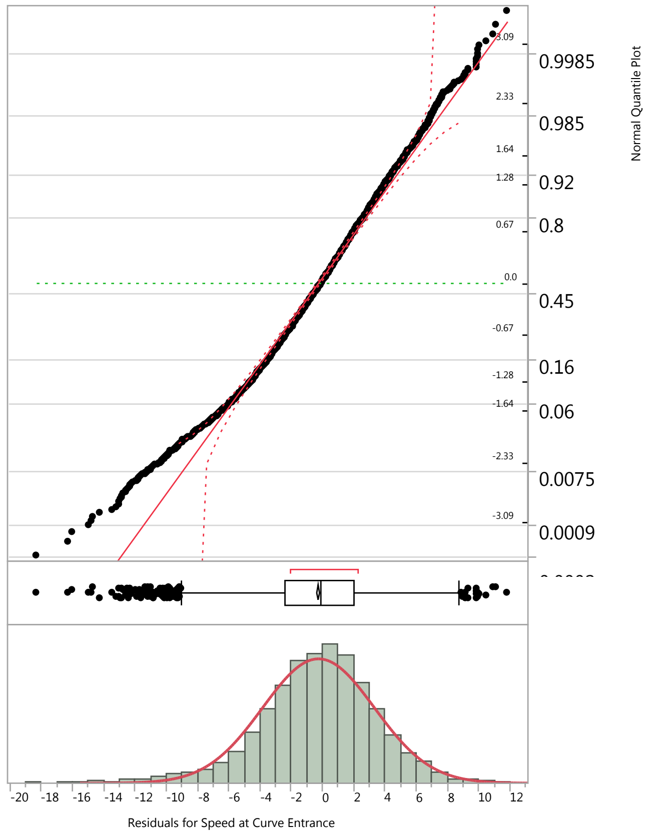

Figure B.16: Residuals for the final model of speed at the curve entrance.

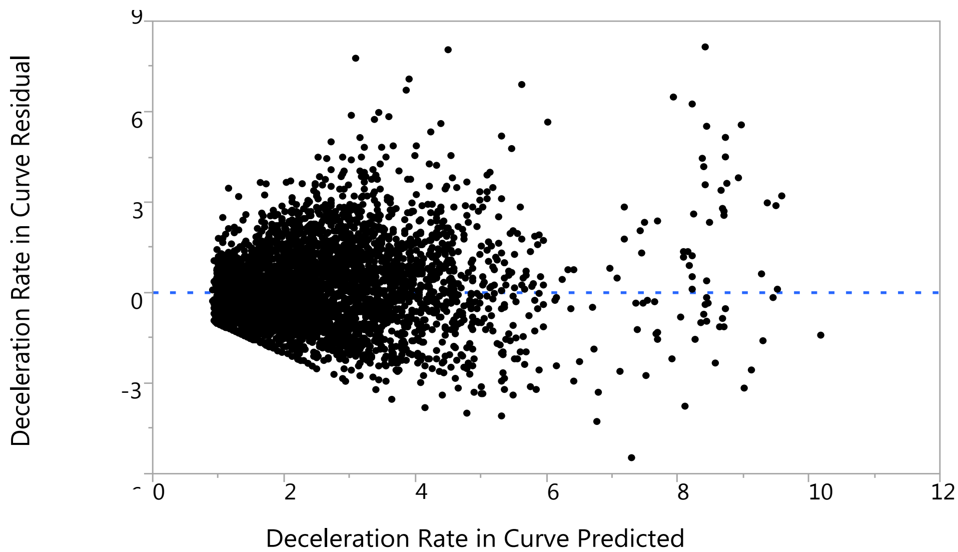

Figure B.17: Residual plot of the model for the maximum deceleration rate in the curve.

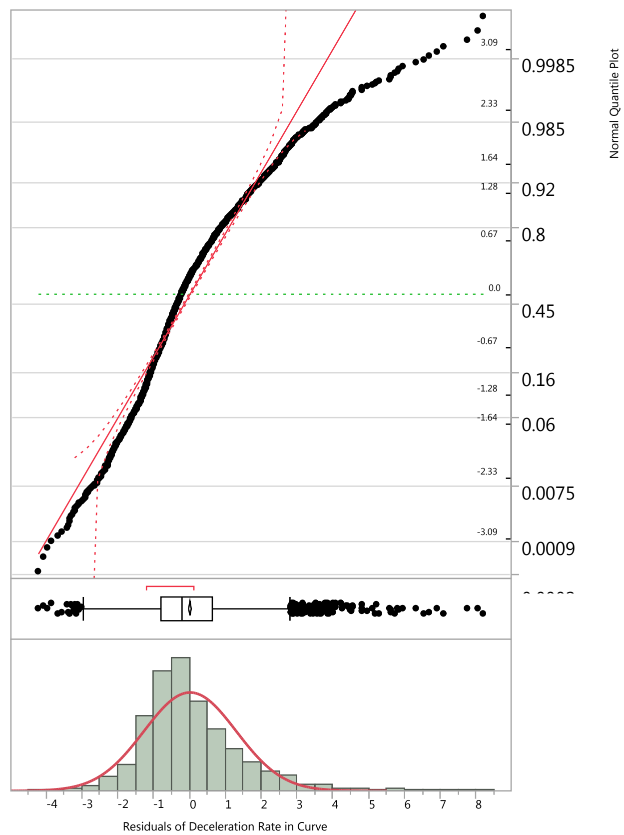

Figure B.18: Residuals for model of maximum deceleration rate in curve

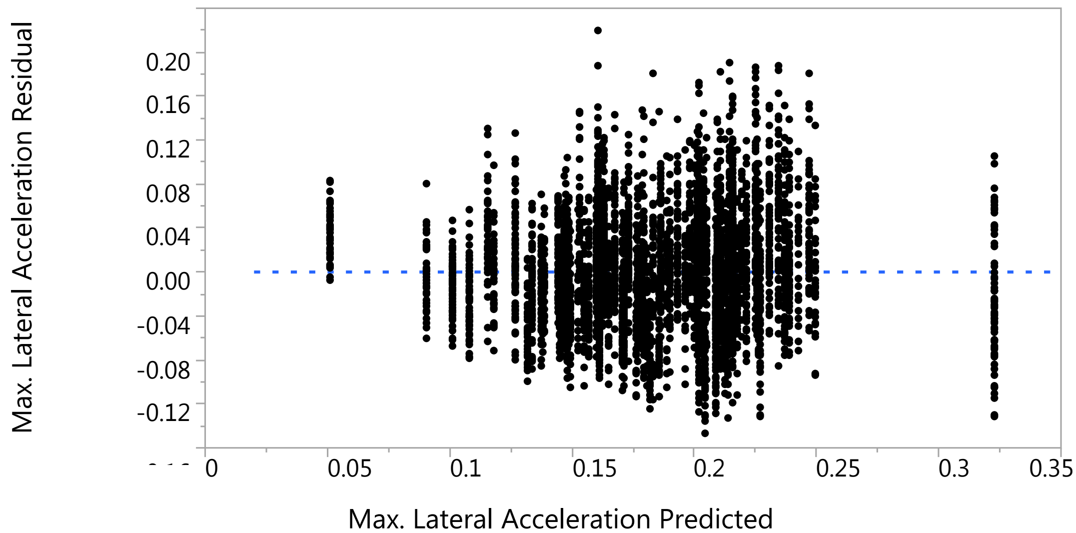

Figure B.19: Residual plot of the model for the maximum lateral acceleration observed in the curve.

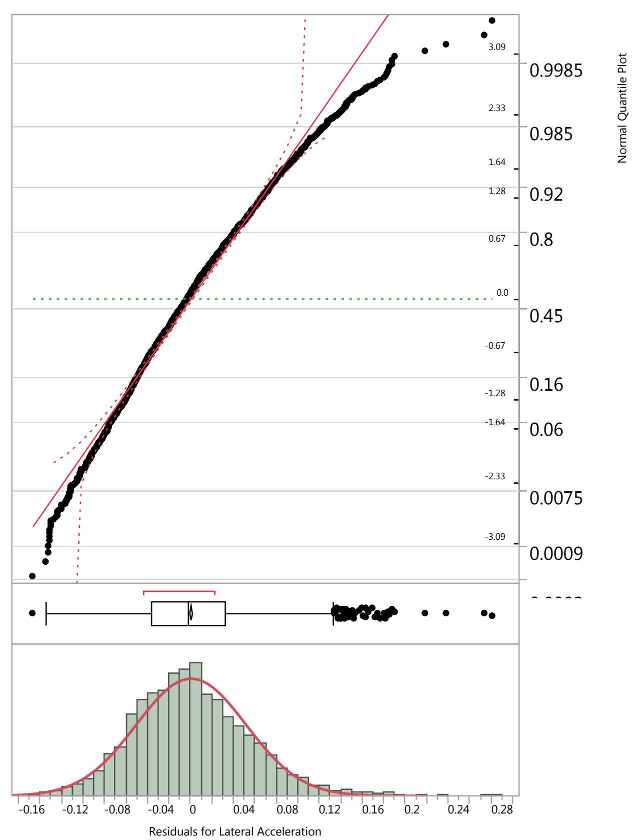

Figure B.20: Residuals for model of maximum lateral acceleration.

B.2. Models for Section 5

The models in Section 5 characterize driver behavior at curves and include factors for TCDs. The results of the section are based on data collected at a restricted number of study curves in Texas only at night, so there is substantially less data here than is used in Section 4. The statistical analyses were performed with JMP software. The figures here are plots of the residuals based on output from the software. Each model is represented by a figure of the residual plot and a distribution of the residuals to investigate normality. For models that required transformations or were developed with a weighted least squares regression, plots from the initial, untransformed model are given to document the patterns observed before transforming the observations.

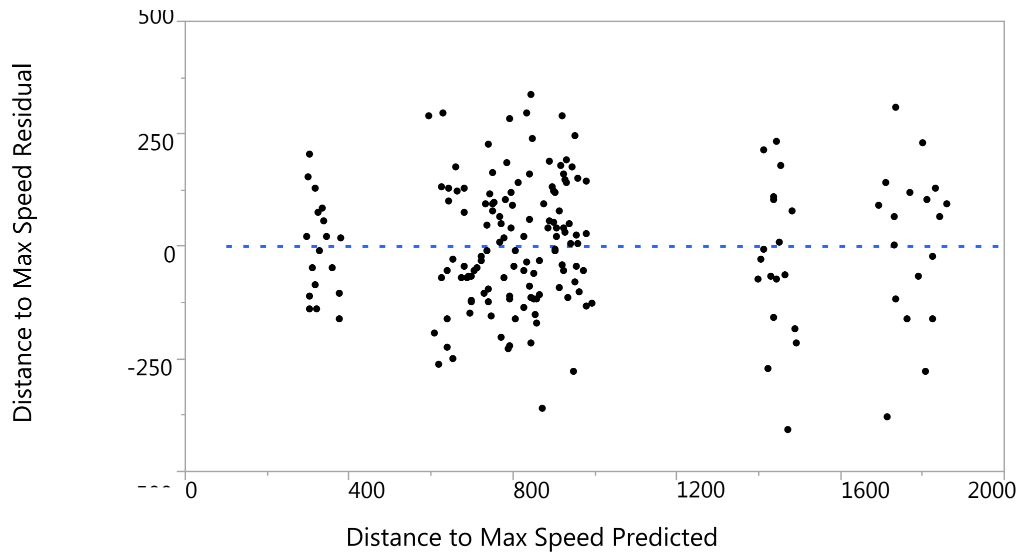

Figure B.21: Residual plot of the model for the distance to maximum speed with influence of TCDs.

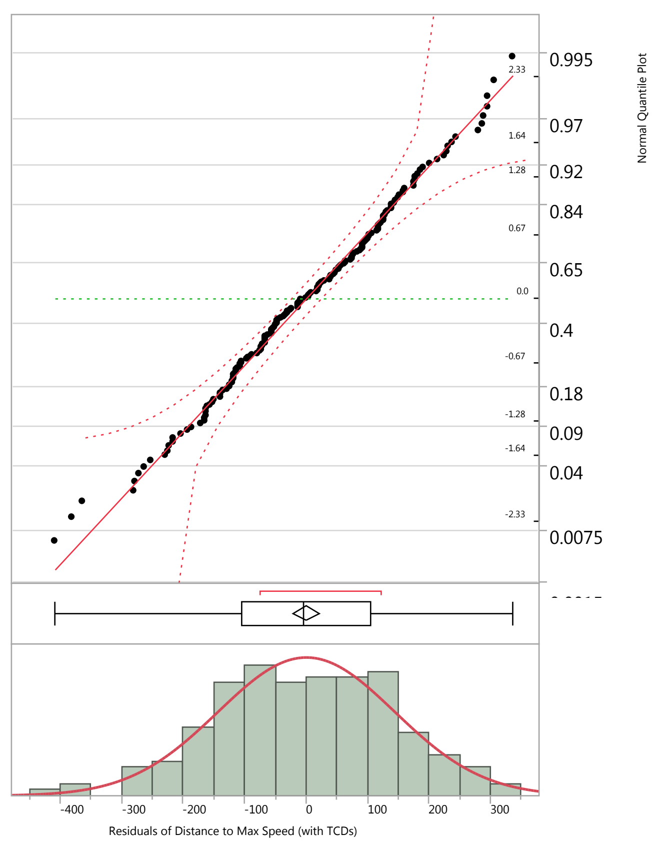

Figure B.22: Residuals from the model of distance to maximum speed (with TCDs).

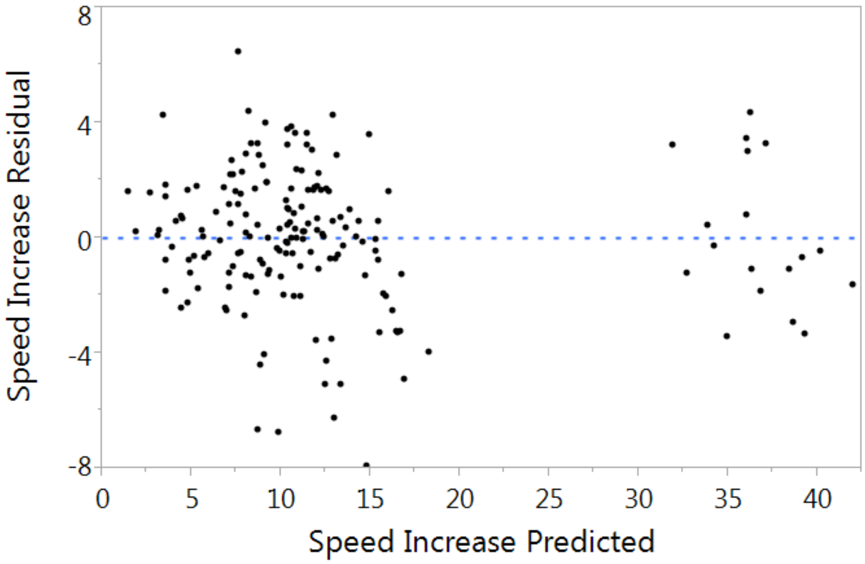

Figure B.23: Residual plot of the model for the increase in speed on a tangent (with TCDs).

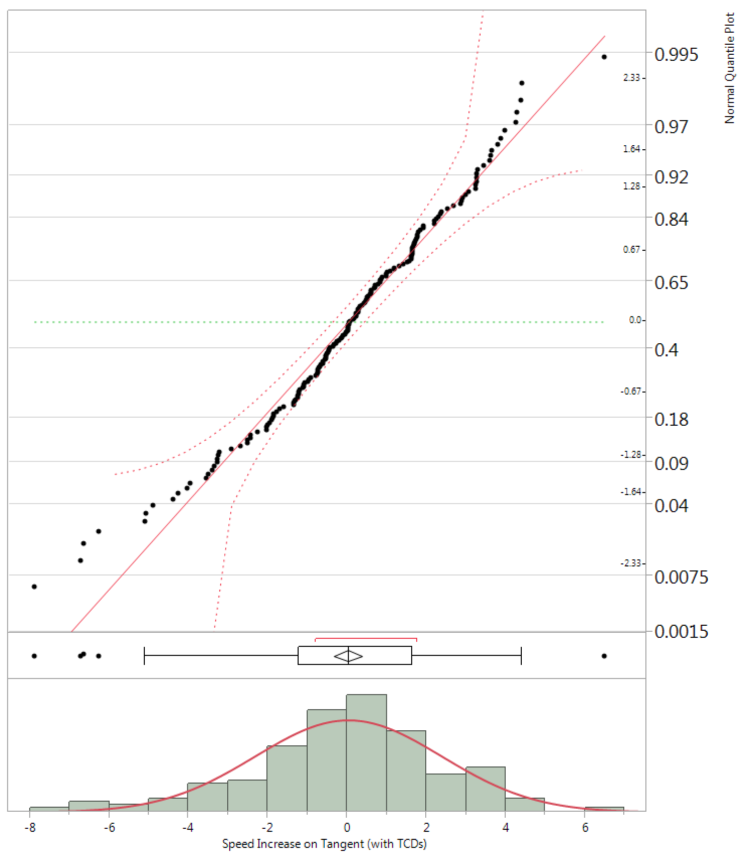

Figure B.24: Residuals from the model of speed increase (with TCDs).

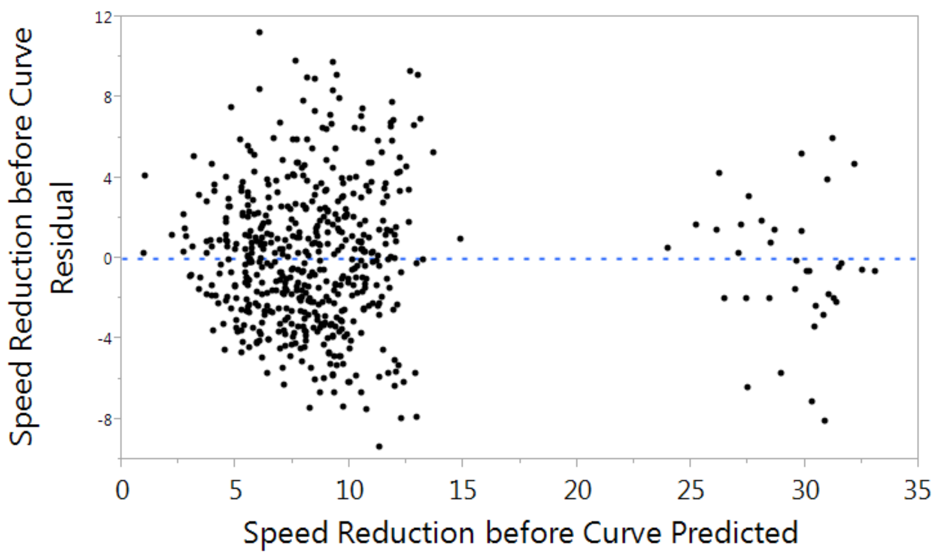

Figure B.25: Residual plot of the model for the reduction in speed occurring before a curve (with TCDs).

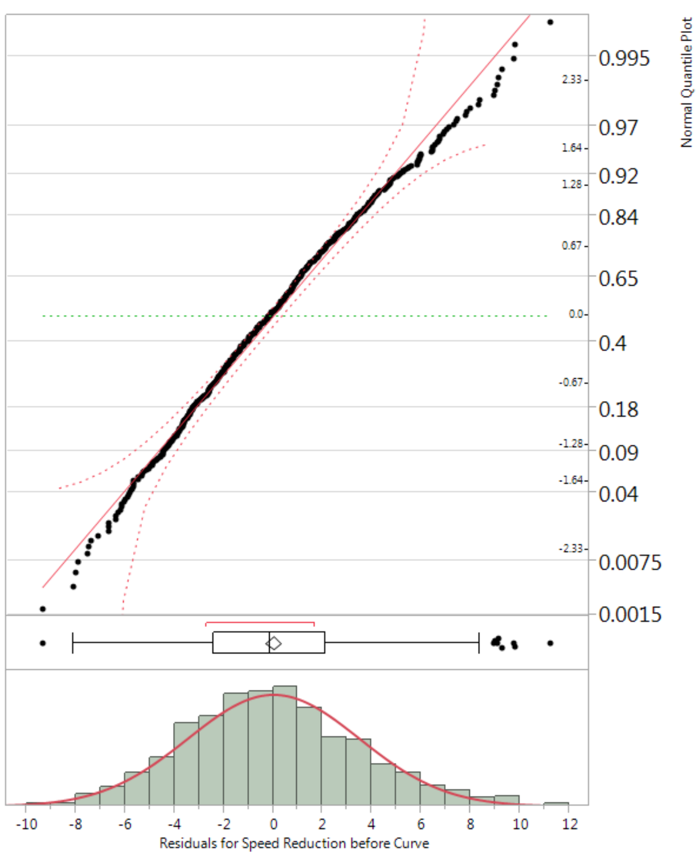

Figure B.26: Residuals for the model of speed reduction completed before a curve (with TCDs).

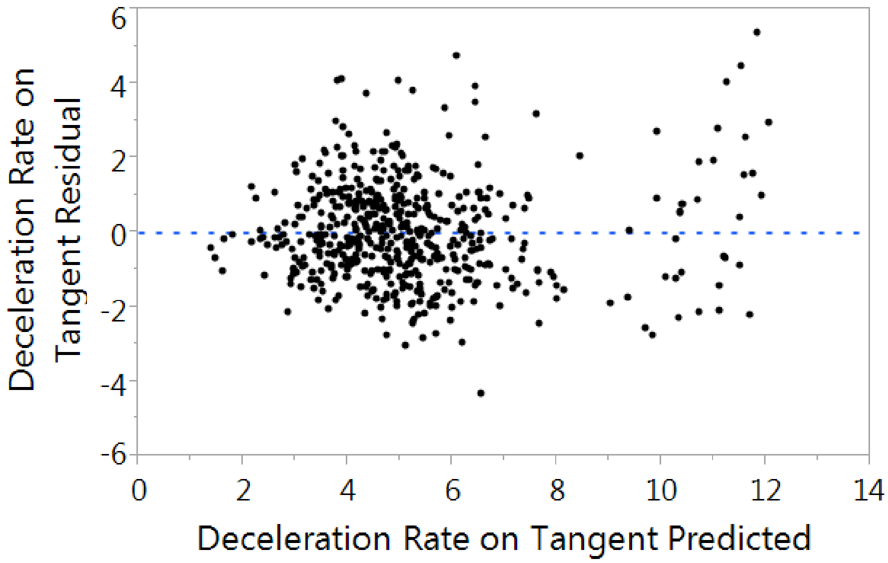

Figure B.27: Residual plot of the model for the maximum deceleration rate on the tangent (with TCDs).

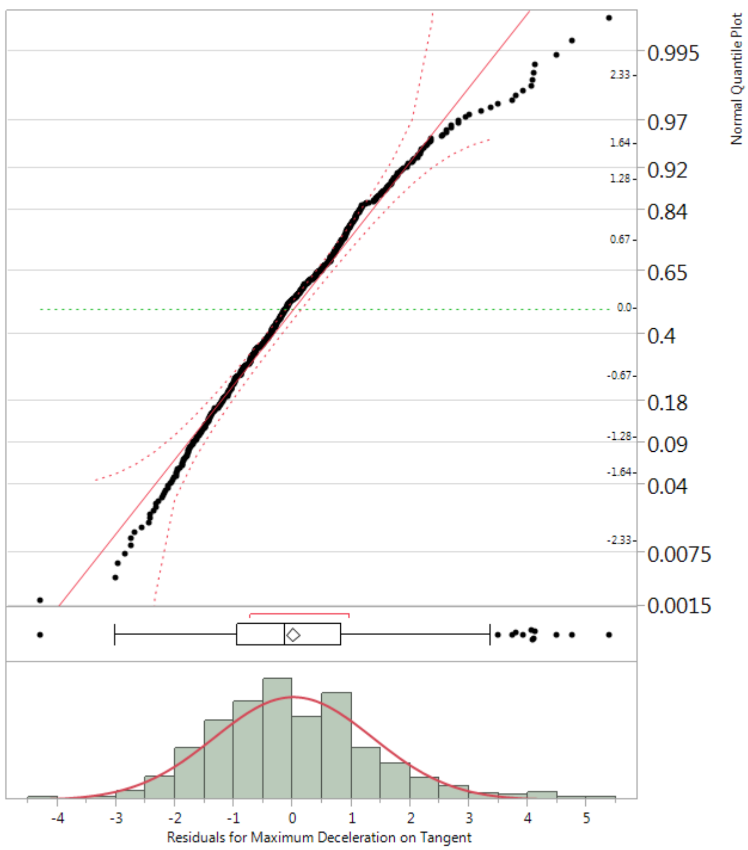

Figure B.28: Residuals from the model for the maximum deceleration rate on the tangent (with TCDs).

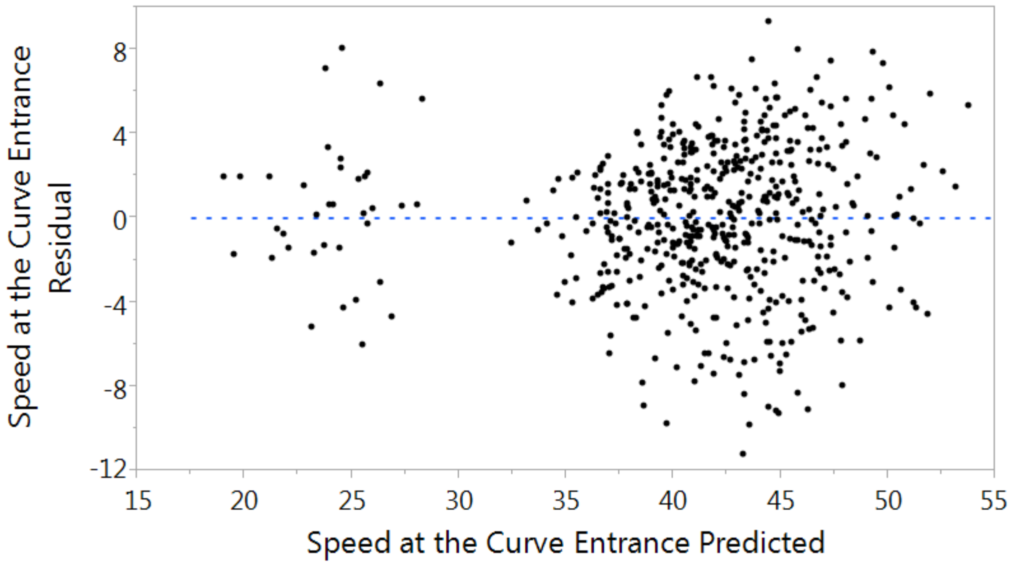

Figure B.29: Residual plot from model of speed at the curve entrance with influence of TCDs.

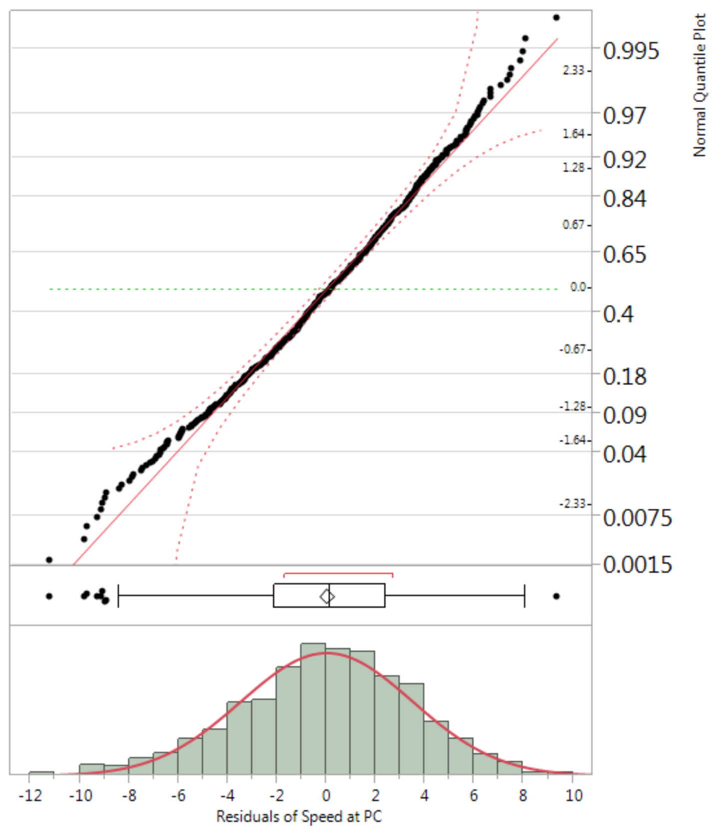

Figure B.30: Residuals of the model for speed at the curve entrance with effects of TCDs.

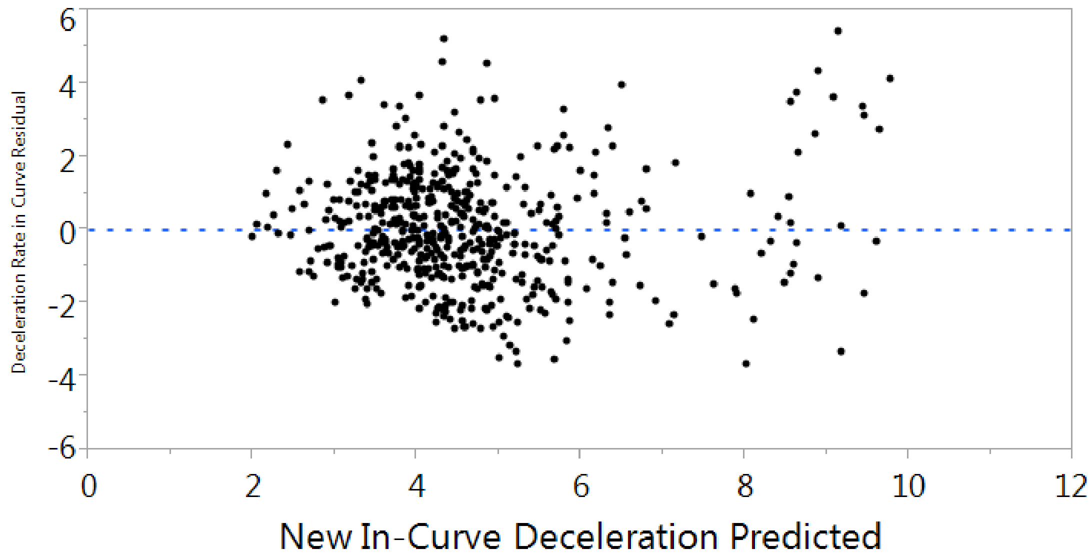

Figure B.31: Residual plot for the model of the maximum deceleration rate in the curve with effects of TCDs.

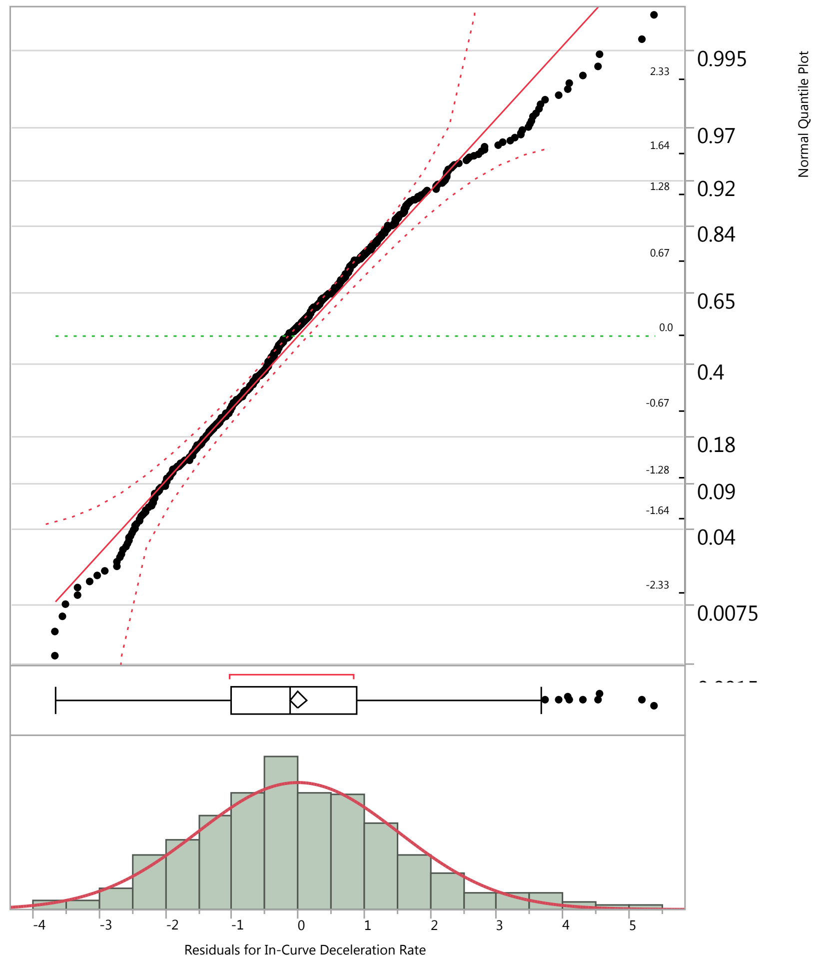

Figure B.32: Residuals for the model of maximum deceleration rate in curve with effects of TCDs.

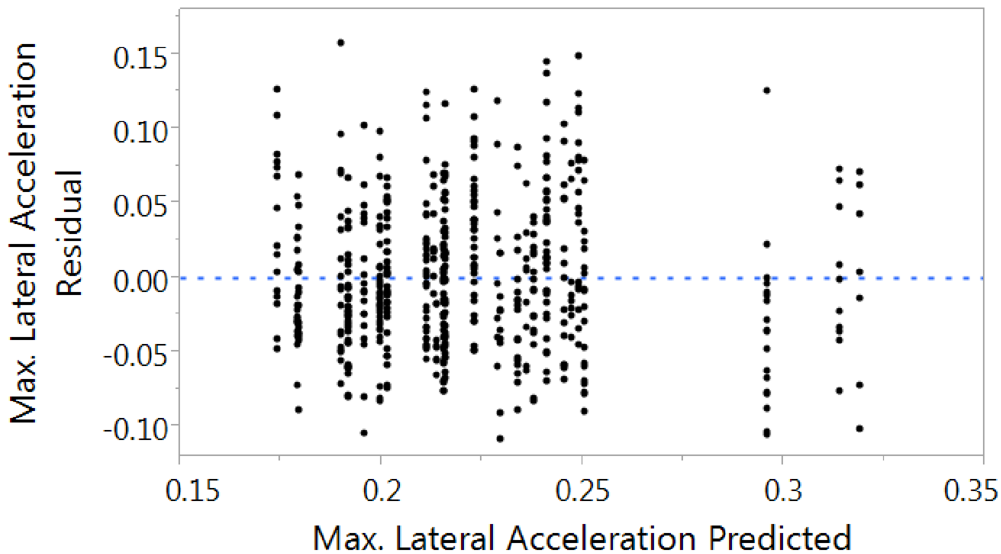

Figure B.33: Residual plot of the model for maximum lateral acceleration (with TCDs).

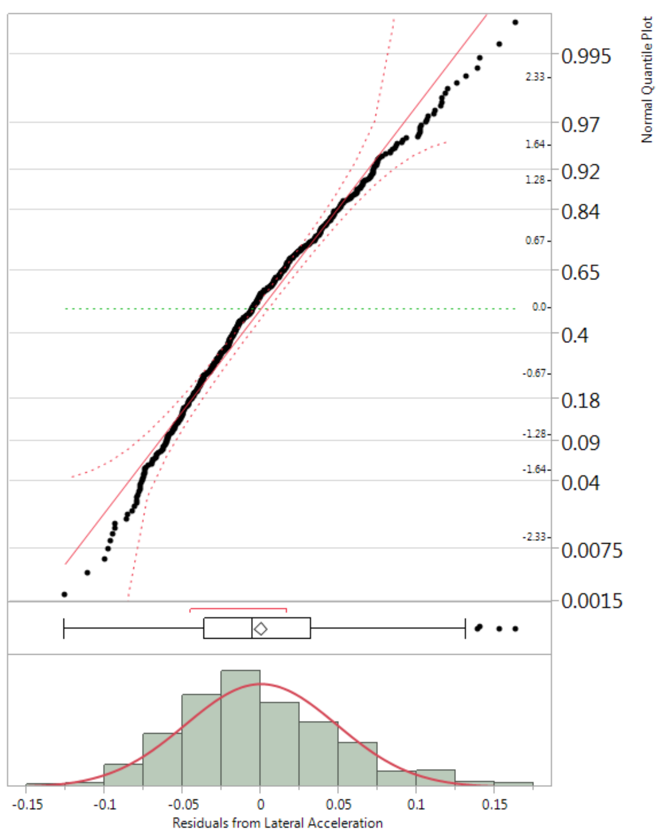

Figure B.34: Residuals from the model for maximum lateral acceleration rate (with TCDs).

B.3. Models for Section 6

The models in Section 6 characterize how driver visual attention near curves can be influenced by the use of supplementary TCDs. Like Section 5, the results of the section are based on data collected at a restricted number of study curves in Texas at night. The statistical analyses were performed with JMP software. The figures here are plots of the residuals based on output from the software. Each model is represented by a figure of the residual plot and a distribution of the residuals to investigate normality. For models that required transformations or were developed with a weighted least squares regression, plots from the initial, untransformed model are given to document the patterns observed before transforming the observations.

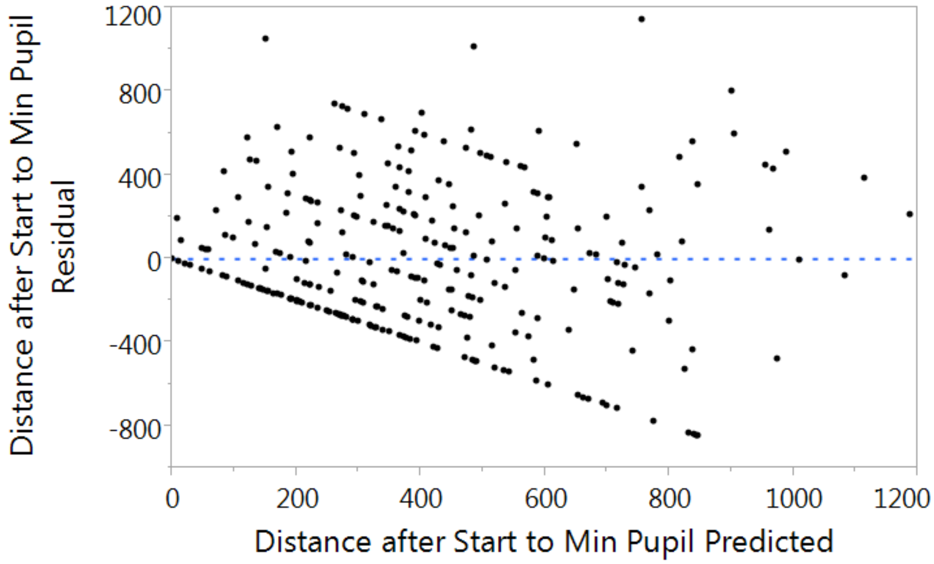

Figure B.35: Residual plot for the model of the distance traveled from the upstream curve until the pupils are contracted.

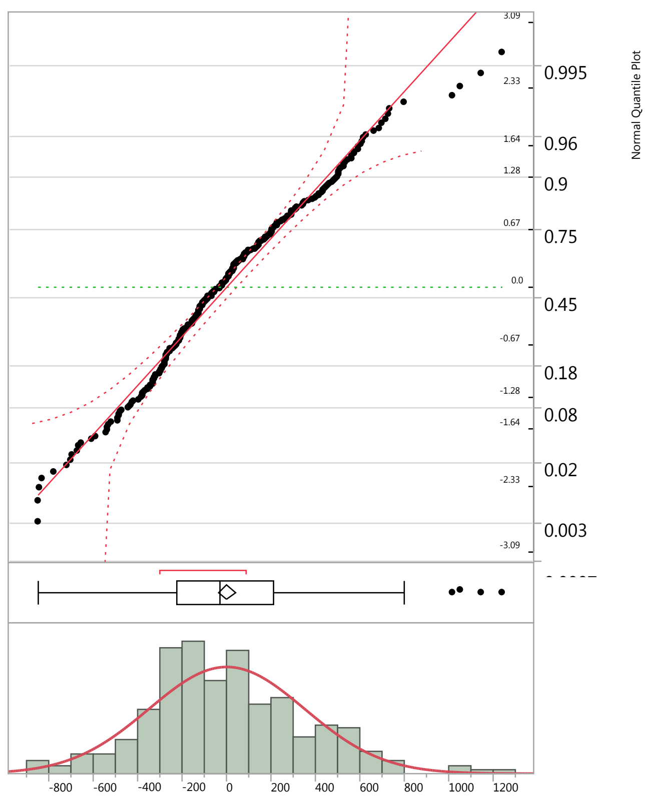

Figure B.36: Residuals of the model for the distance traveled from the upstream curve until the pupils are contracted.

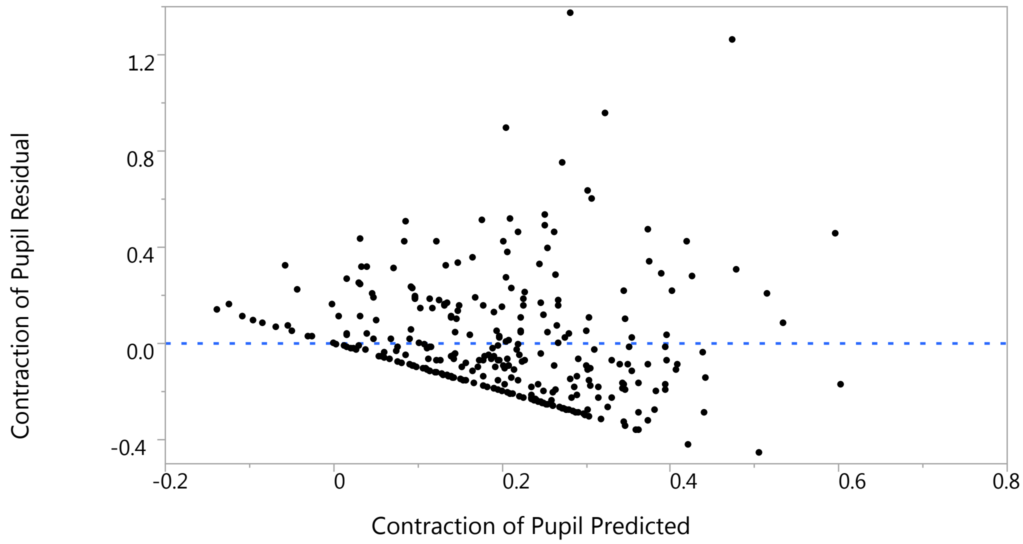

Figure B.37: Residual plot from the initial model of the magnitude of the pupil contraction.

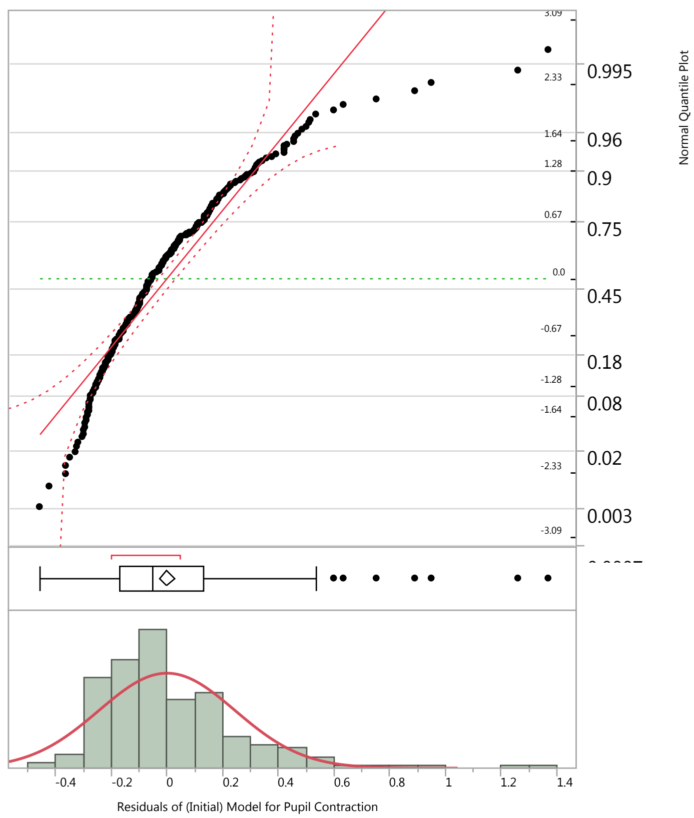

Figure B.38: Residuals from the initial model for the magnitude of the pupil contraction.

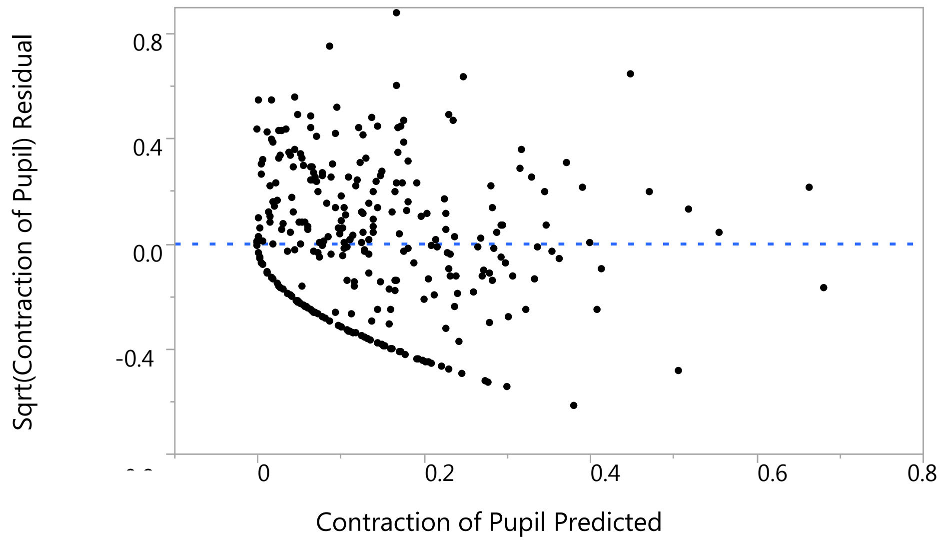

Figure B.39: Residual plot from the final model estimating the magnitude of the pupil contraction.

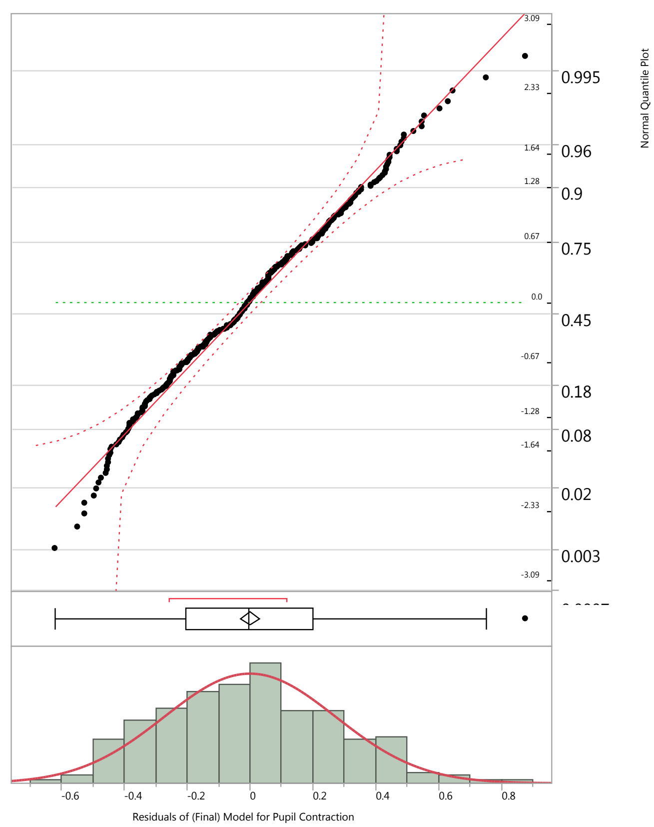

Figure B.40: Residuals from the final model (with square root transformation) of the pupil contraction.

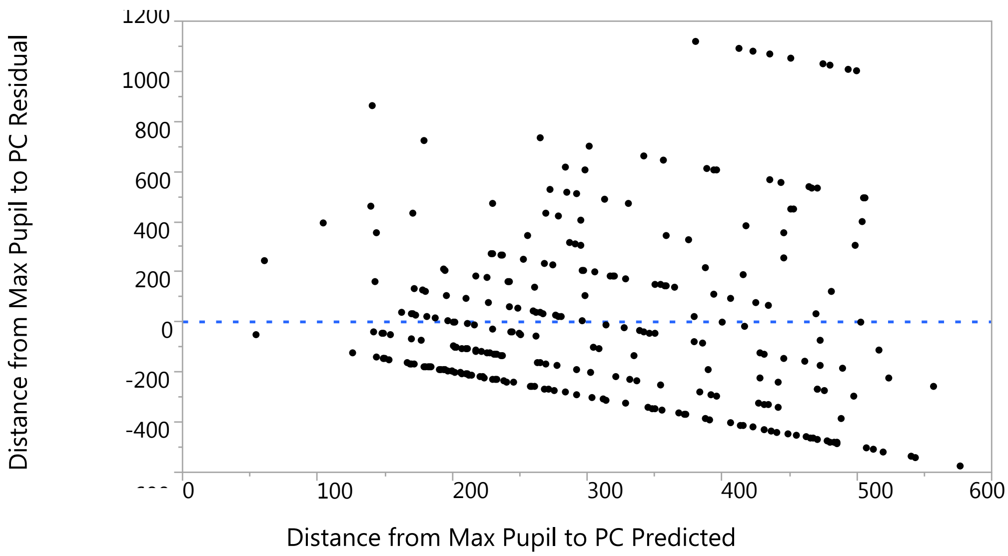

Figure B.41: Residual plot from the initial model estimating the distance from the downstream curve at which the pupil is fully dilated.

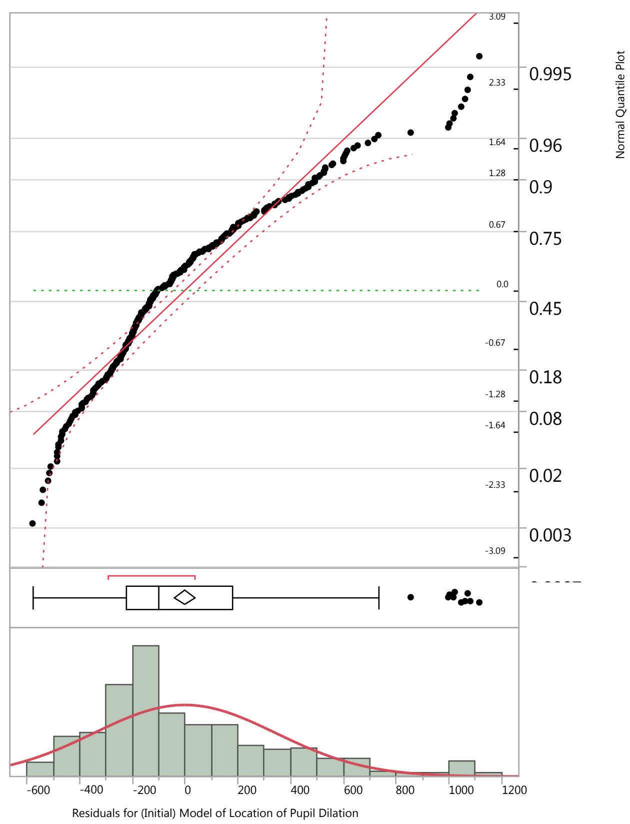

Figure B.42: Residuals from the initial model estimating the distance from the downstream curve at which the pupil is fully dilated.

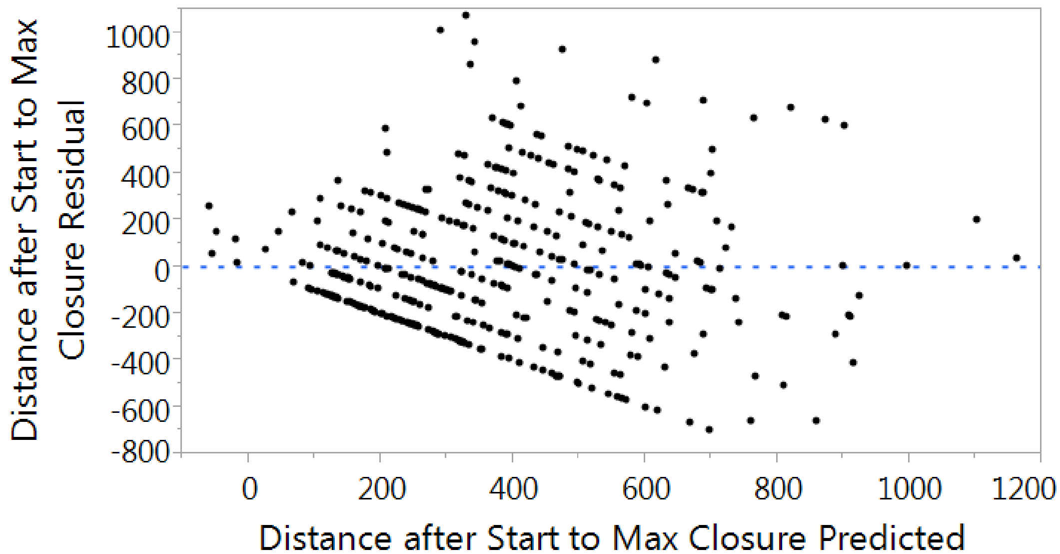

Figure B.43: Residual plot for the initial model of the distance traveled downstream of a curve when the eyes are most closed.

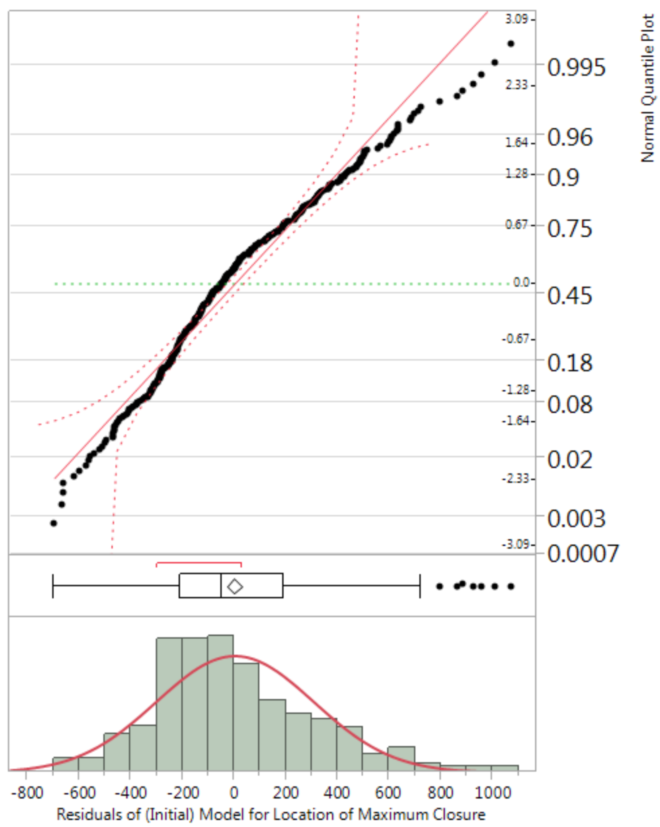

Figure B.44: Residuals of the initial model for the distance traveled downstream of a curve when the eyes are most closed.

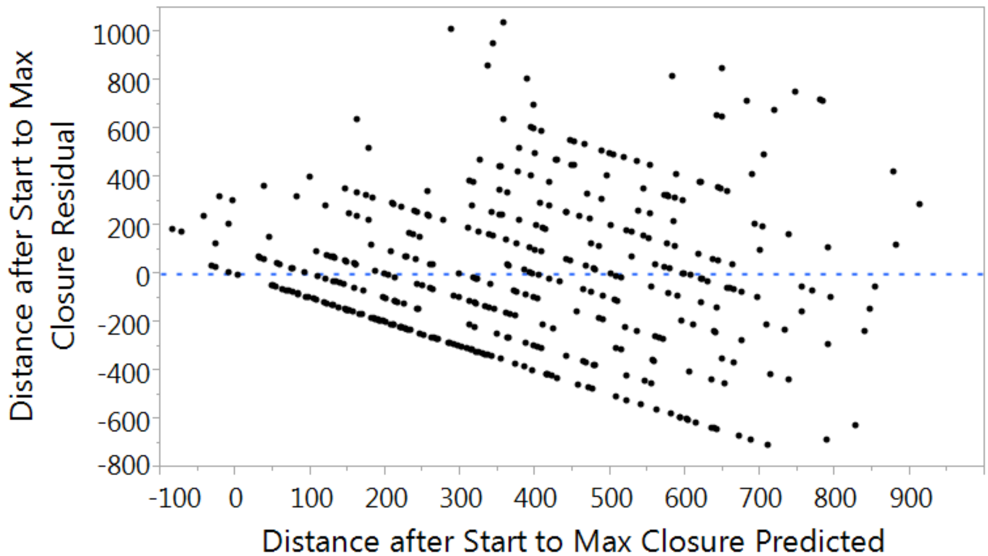

Figure B.45: Residual plot for the final model of the distance traveled downstream of a curve when the eyes are most closed.

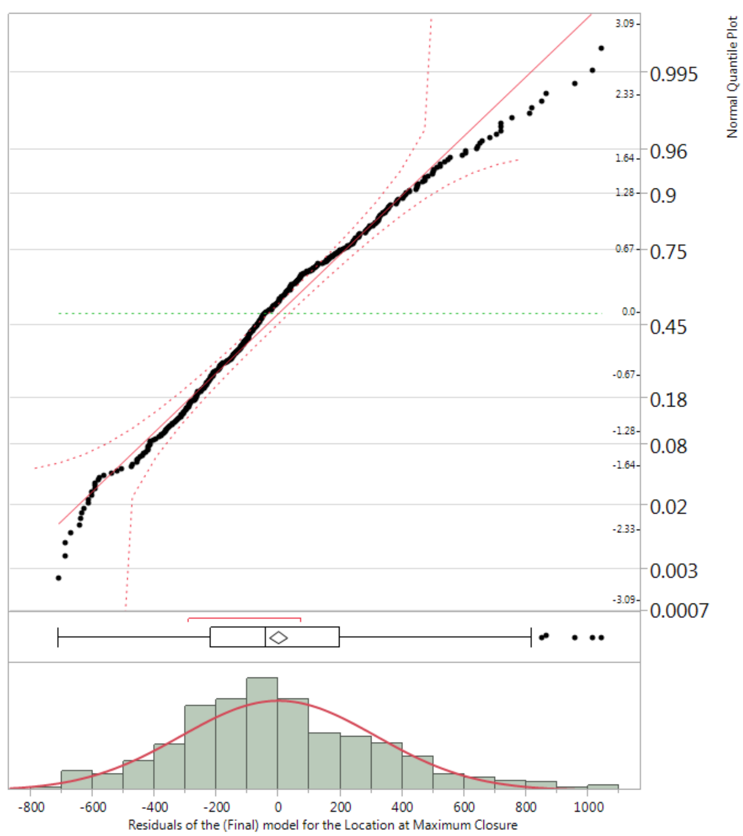

Figure B.46: Residuals of the final model for the distance traveled downstream of a curve when the eyes are most closed.

B.4. Models for Section 7

The models in Section 7 characterize how driver visual attention near curves influences operational performance. The results of the section are based on data collected in all three states but primarily with a restriction on the length of the tangent at each curve. Again, only nighttime data are used. The statistical analyses were performed with JMP software. The figures here are plots of the residuals based on output from the software. Each model is represented by a figure of the residual plot and a distribution of the residuals to investigate normality. For models that required transformations or were developed with a weighted least squares regression, plots from the initial, untransformed model are given to document the patterns observed before transforming the observations.

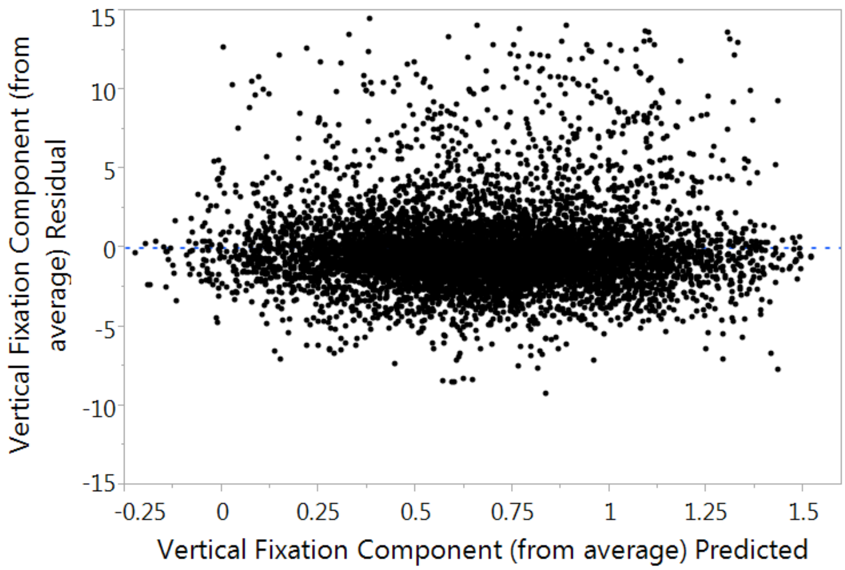

Figure B.47: Residual plot of the model estimating the vertical component of driver fixations using instantaneous operational metrics.

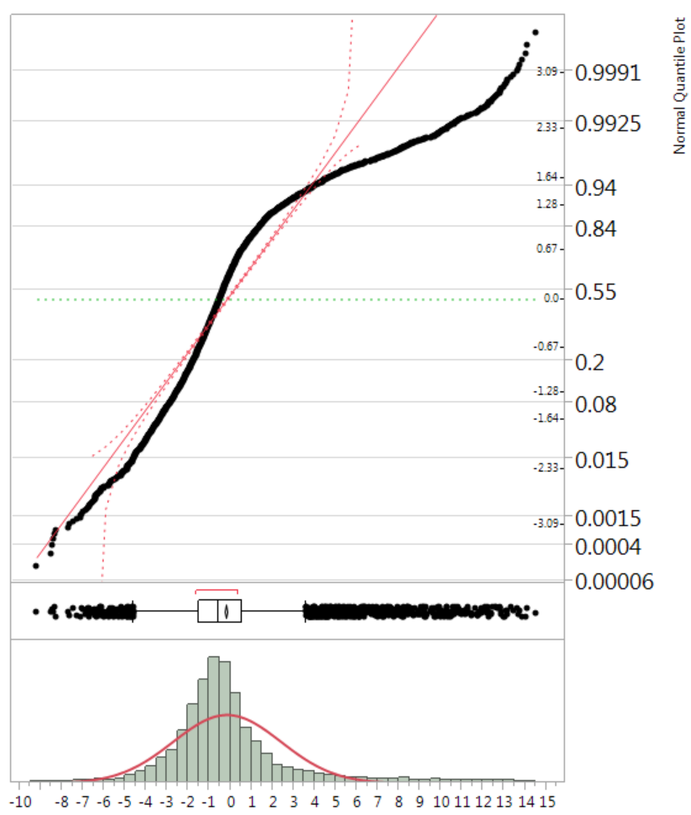

Figure B.48: Residuals from the model estimating the instantaneous vertical component of fixations.

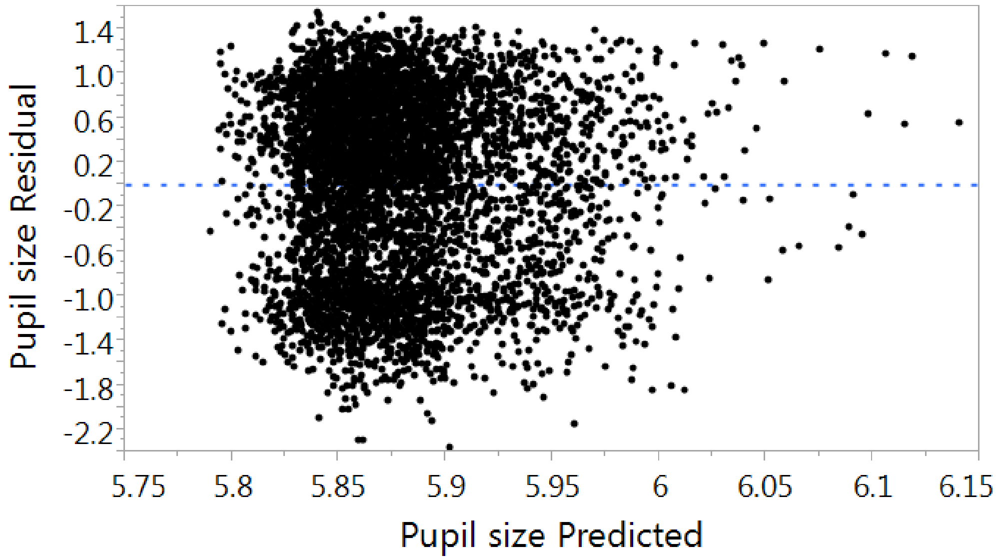

Figure B.49: Residual plot for the model of the instantaneous pupil diameter.

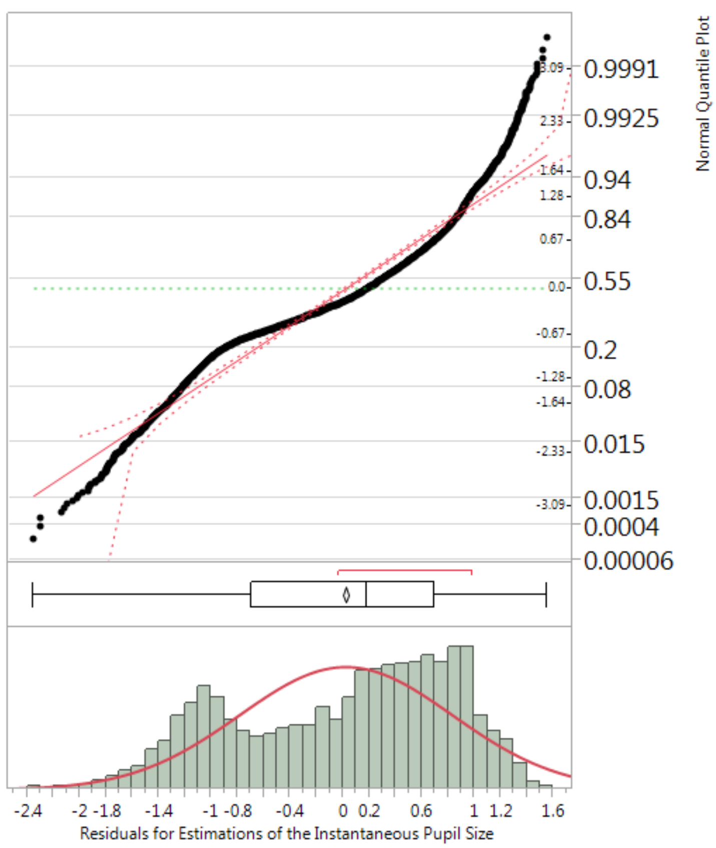

Figure B.50: Residuals of the model for the instantaneous pupil diameter.

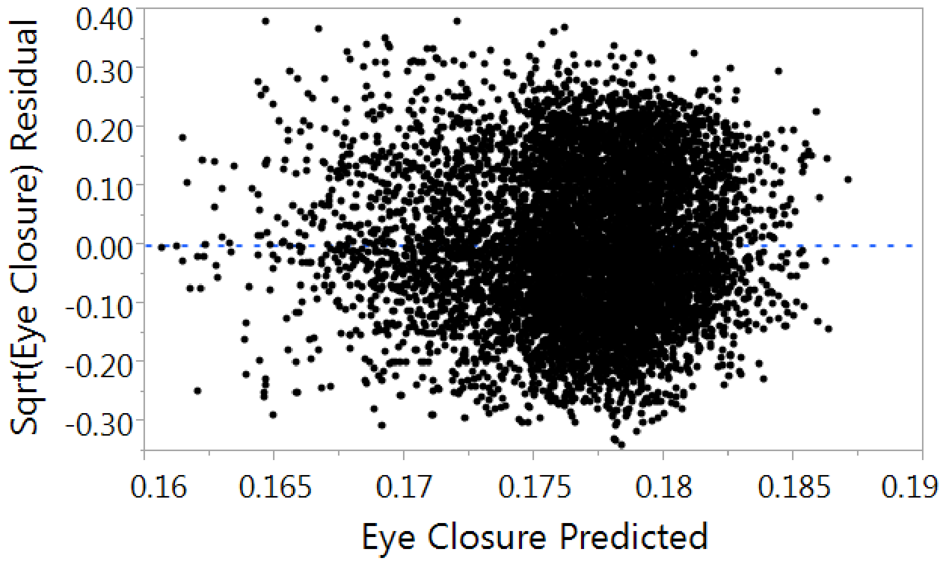

Figure B.51: Residual plot of the (final) model for instantaneous eye closure.

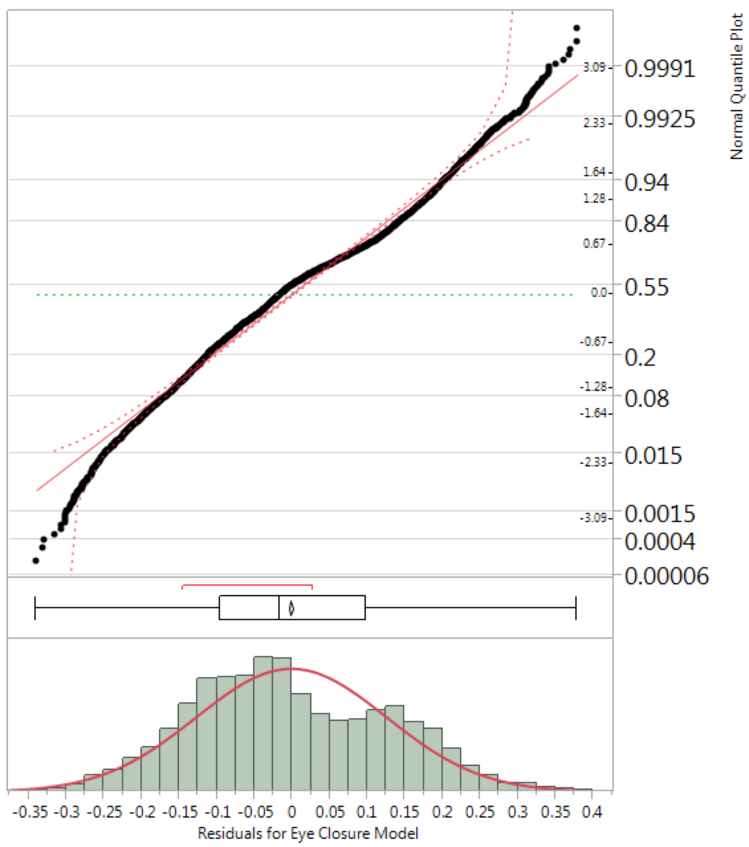

Figure B.52: Residuals for the (final) model of instantaneous eye closure.

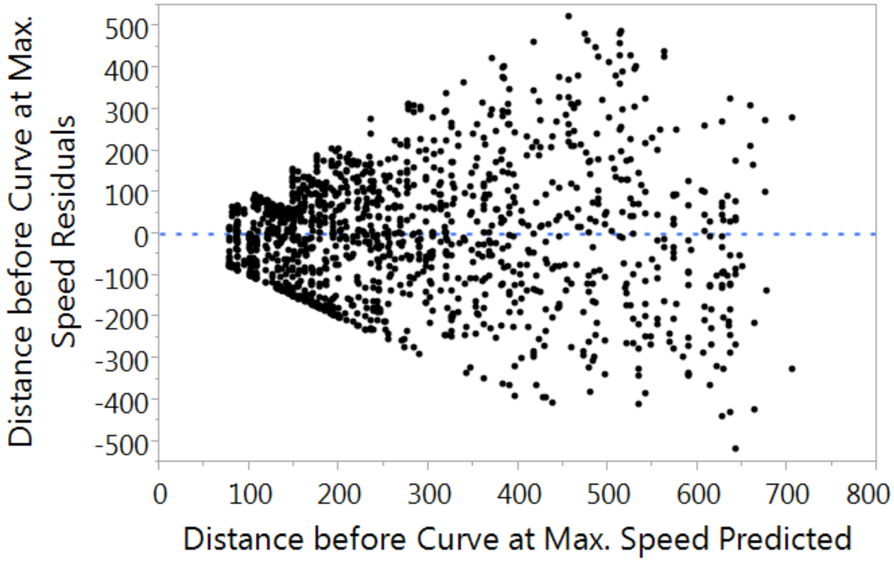

Figure B.53: Residual plot for the (initial) model predicting the location where maximum speed occurs before the downstream curve.

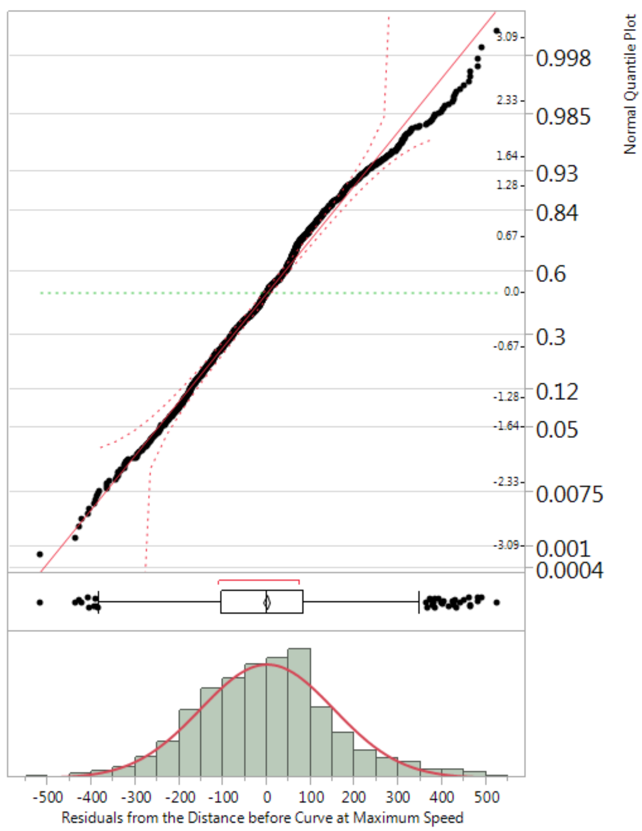

Figure B.54: Residuals from the initial model predicting the location of the vehicle at maximum speed before a curve.

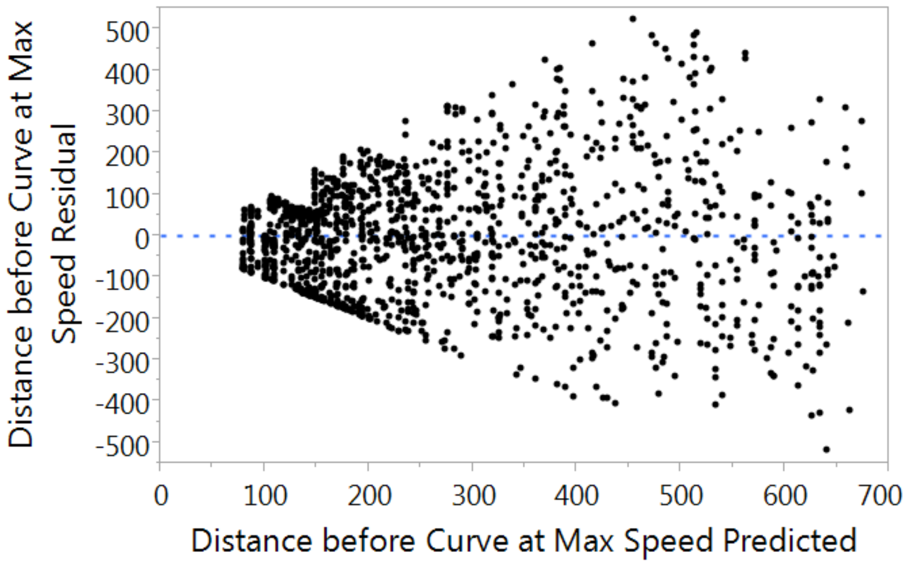

Figure B.55: Residual plot for the (final) model estimating the distance before the curve when the vehicle is at maximum speed.

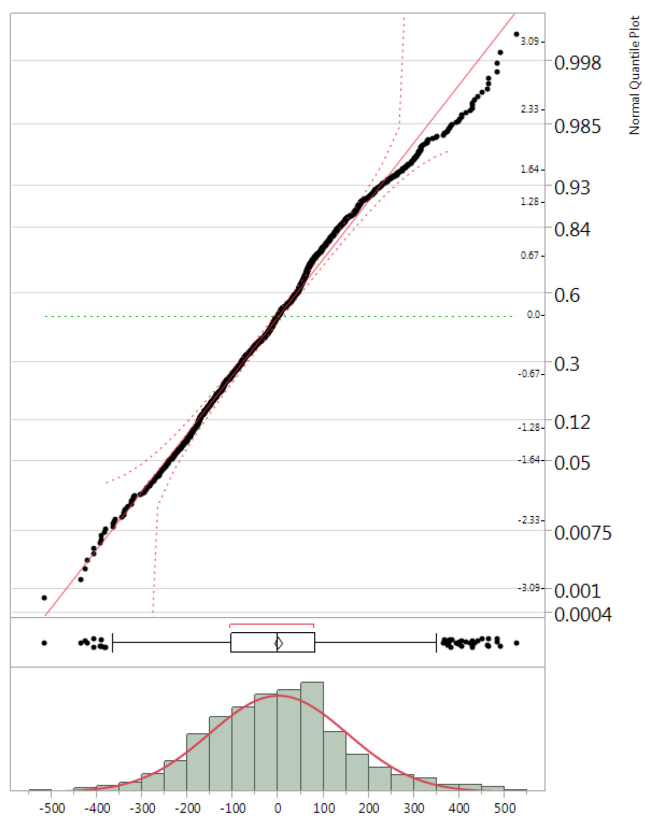

Figure B.56: Residuals from the (final) model estimating the distance before the curve when the vehicle is at maximum speed.

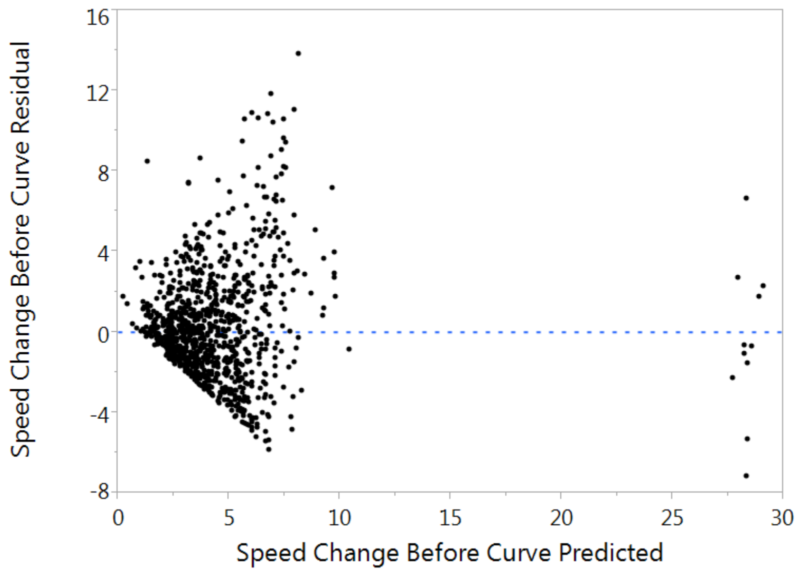

Figure B.57: Residual plot for the initial model of speed change before a curve with effects from the location of pupil dilation.

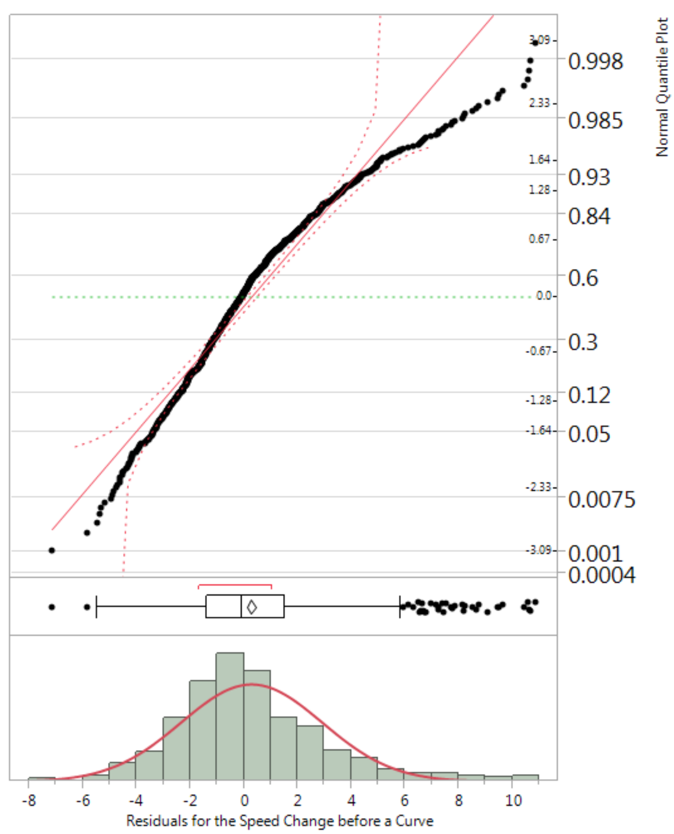

Figure B.58: Residuals for the initial model of speed change before a curve with effects from the location of pupil dilation.

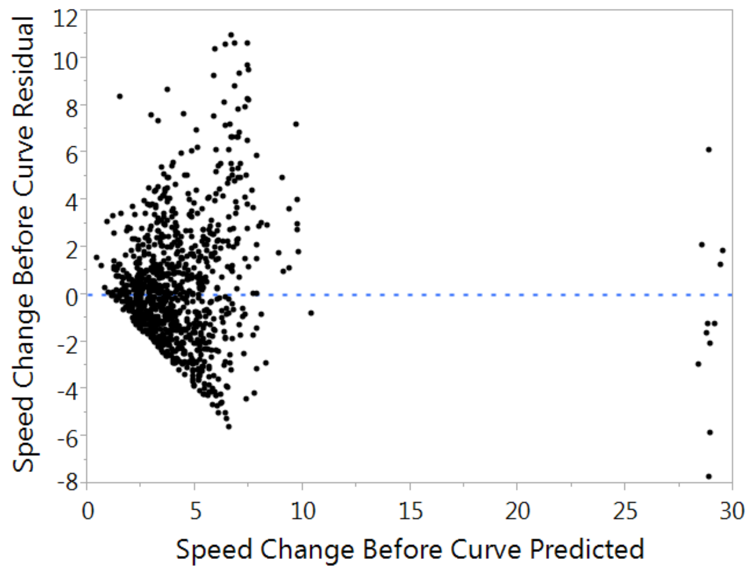

Figure B.59: Residual plot for the final model of the speed change before a curve with effects for the location of the pupil dilation.

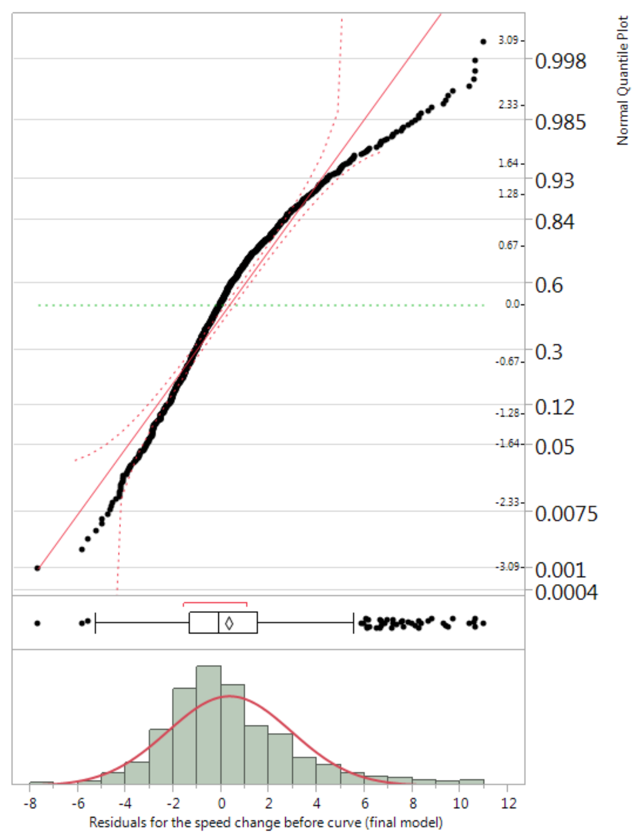

Figure B.60: Residuals from the final model estimating the speed change before a curve with effects for the location of pupil dilation.

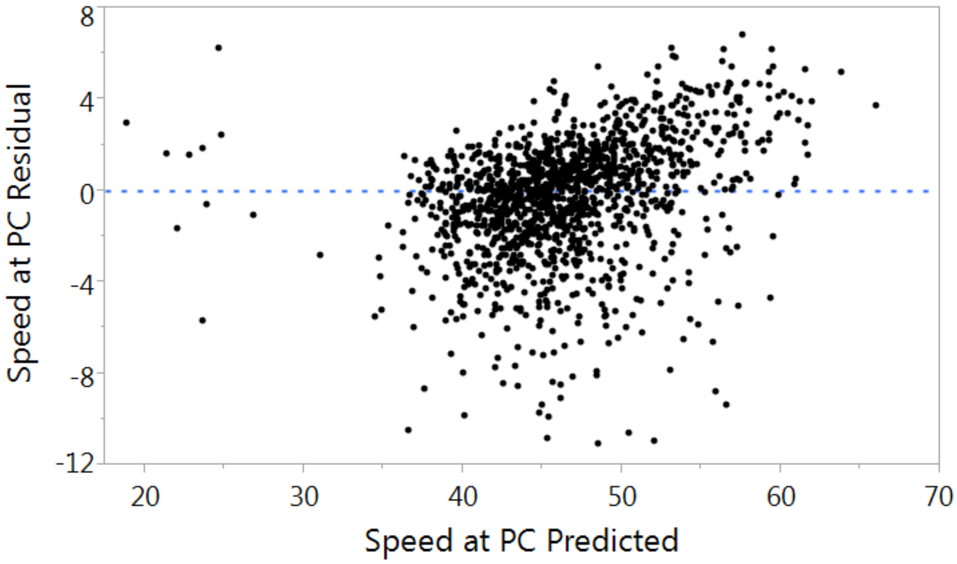

Figure B.61: Residual plot of the model predicting the speed at the PC with influence for location of dilation before a curve.

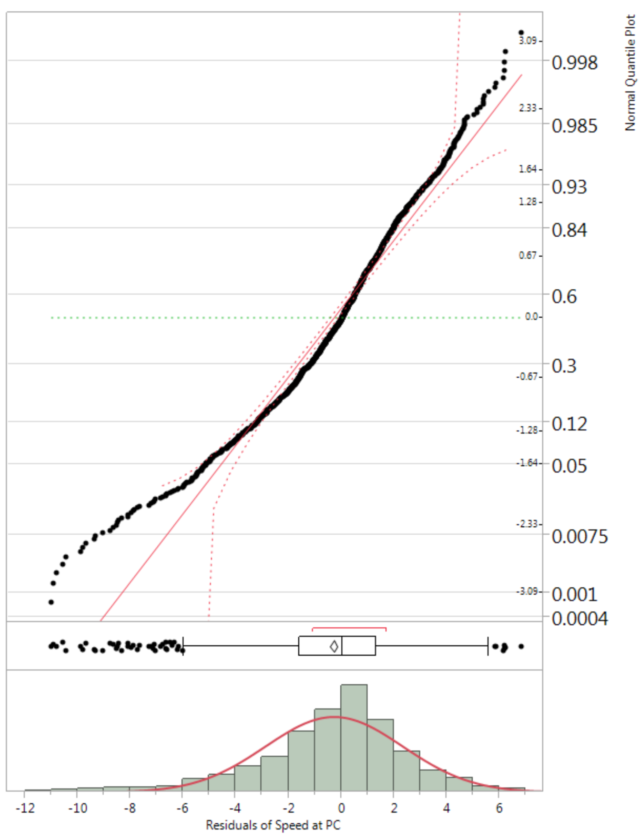

Figure B.62: Residuals of model predicting the speed at the PC with effects of pupil dilation with respect to the curve.

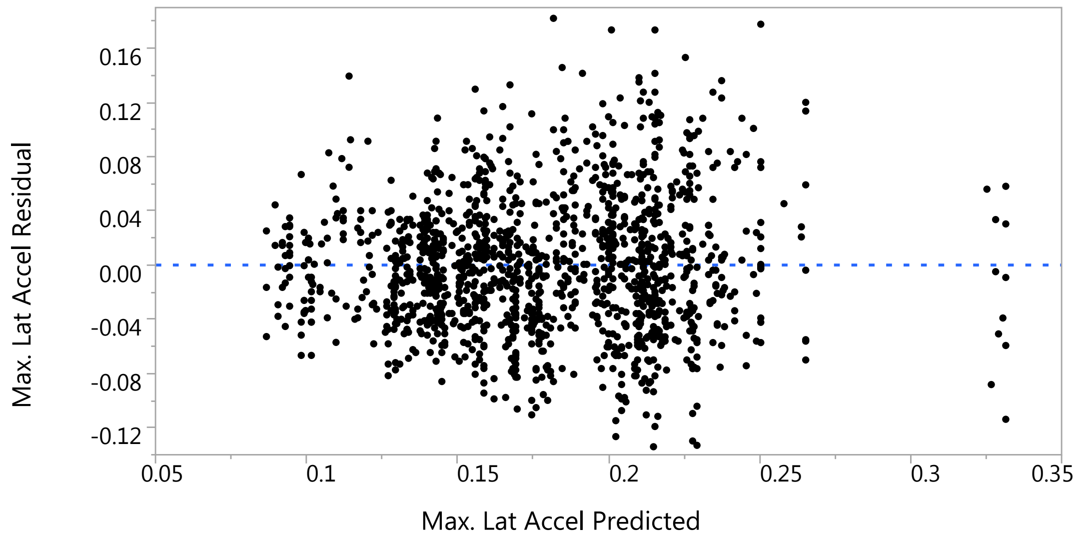

Figure B.63: Residual plot for the model predicting lateral acceleration with effects of pupil dilation.

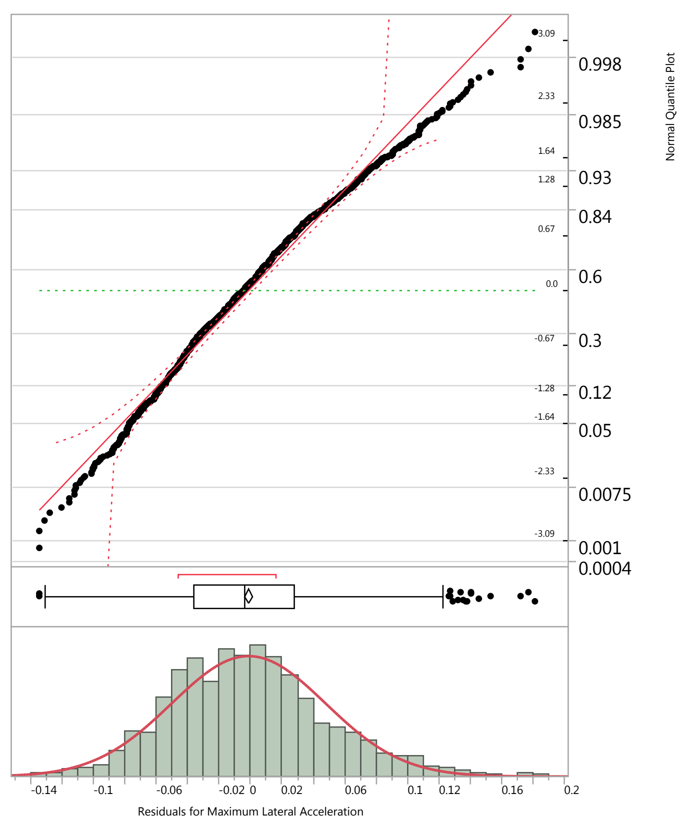

Figure B.64: Residuals of the model for lateral acceleration with effects of pupil dilation.

APPENDIX C

MODEL SCRIPTS

C.1. Code for Section 4 (Operations at Curves)

Distance to Maximum Speed

```
Fit Model(
	Y( Sqrt( :Distance to Max Speed ) ),
	Effects( Sqrt( :Tangent Length ), :Potential Speed Increase ),
	Random Effects( :Participant ),
	Personality( Standard Least Squares ),
	Method( REML ),
	Emphasis( Minimal Report ),
	Run(
		:Distance to Max Speed << {Analysis of Variance( 0 ), Lack of Fit( 0 ),
		Plot Actual by Predicted( 0 ), Plot Regression( 0 ),
		Plot Residual by Predicted( 0 ), Plot Effect Leverage( 0 )}
	)
)
```

Speed increase on tangent:

```
Fit Model(
	Y( Sqrt( :Speed Increase ) ),
	Effects( :Tangent Length, :Potential Speed Increase ),
	Random Effects( :Participant ),
	Personality( Standard Least Squares ),
	Method( REML ),
	Emphasis( Minimal Report ),
	Run(
		:Speed Increase << {Analysis of Variance( 0 ), Lack of Fit( 0 ),
		Plot Actual by Predicted( 0 ), Plot Regression( 0 ),
		Plot Residual by Predicted( 0 ), Plot Effect Leverage( 0 )}
	)
)
```

Speed Reduction before Curve

```
Fit Model(
```

```
	Weight( :Weight for speed reduction before curve ),
	Y( :Name( “Speed Change (mph) Before Curve” ) ),
	Effects( :Max Speed on tangent, :Distance at Max Speed, 1 / :Radius ),
	Random Effects( :Participant ),
	Personality( Standard Least Squares ),
	Method( REML ),
	Emphasis( Minimal Report ),
	Run(
		:Name( “Speed Change (mph) Before Curve” ) << {Analysis of
Variance( 0 ),
		Lack of Fit( 0 ), Plot Actual by Predicted( 0 ), Plot Regression( 0 ),
		Plot Residual by Predicted( 0 ), Plot Effect Leverage( 0 )}
	)
)
```

Maximum Deceleration Rate on Tangent

```
Fit Model(
	Y( :Name( “Max Decel Rate on Tangent” ) ),
	Effects( :Speed Change ),
	Random Effects( :Participant ),
	Personality( Standard Least Squares ),
	Method( REML ),
	Emphasis( Minimal Report ),
	Run(
		:Name( “Max Decel Rate on Tangent” ) <<
		{Analysis of Variance( 0 ), Lack of Fit( 0 ), Plot Actual by Predicted( 0 ),
		Plot Residual by Predicted( 0 ), Plot Effect Leverage( 0 )}
	)
)
```

Speed at PC

```
Fit Model(
	Y( :Speed_PC ),
	Effects( 1 / :Radius, :Max Speed on tangent ),
	Random Effects( :Participant ),
	Personality( Standard Least Squares ),
	Method( REML ),
	Emphasis( Minimal Report ),
	Run(
		:Speed_PC << {Analysis of Variance( 0 ), Lack of Fit( 0 ),
		Plot Actual by Predicted( 0 ), Plot Regression( 0 ),
		Plot Residual by Predicted( 0 ), Plot Effect Leverage( 0 )}
```

```
	)
)
```

Maximum Deceleration Rate in Curve

```
Fit Model(
	Y( :Name( “Max Decel Rate in curve” ) ),
	Effects( :Speed Change ),
	Random Effects( :Participant ),
	Personality( Standard Least Squares ),
	Method( REML ),
	Emphasis( Minimal Report ),
	Run(
		:Name( “Max Decel Rate in curve” ) <<
		{Analysis of Variance( 0 ), Lack of Fit( 0 ), Plot Actual by Predicted( 0 ),
		Plot Residual by Predicted( 0 ), Plot Effect Leverage( 0 )}
	)
)
```

Maximum Lateral Acceleration Rate

```
Fit Model(
	Weight( :Weight for maximum lateral acceleration ),
	Y( :Max. Lat accel ),
	Effects( Log( :Name( “Defl/Radius” ) ) ),
	Random Effects( :Participant ),
	Personality( Standard Least Squares ),
	Method( REML ),
	Emphasis( Minimal Report ),
	Run(
		:Max. Lat accel << {Analysis of Variance( 0 ), Lack of Fit( 0 ),
		Plot Actual by Predicted( 0 ), Plot Residual by Predicted( 0 ),
		Plot Effect Leverage( 0 )}
	)
)
```

C.2. Code for Section 5 (Inclusion of TCDs)

Distance to Maximum Speed

```
Fit Model(
	Y( :Distance to Max Speed ),
	Effects(
		:Potential Speed Increase,
		:Tangent Length,
		:Supplementary Devices
```

```
	),
	Random Effects( :Participant ),
	Personality( Standard Least Squares ),
	Method( REML ),
	Emphasis( Minimal Report ),
	Run(
		:Distance to Max Speed << {Analysis of Variance( 0 ), Lack of Fit( 0 ),
		Plot Actual by Predicted( 0 ), Plot Regression( 0 ),
		Plot Residual by Predicted( 0 ), Plot Effect Leverage( 0 )}
	)
)
```

Speed Increase on Tangent:

```
Fit Model(
	Y( :Speed Increase ),
	Effects(
		:Potential Speed Increase,
		:Tangent Length,
		:Potential Speed Increase * :Tangent Length
	),
	Random Effects( :Participant ),
	Personality( Standard Least Squares ),
	Method( REML ),
	Emphasis( Minimal Report ),
	Run(
		:Speed Increase << {Analysis of Variance( 0 ), Lack of Fit( 0 ),
		Plot Actual by Predicted( 0 ), Plot Regression( 0 ),
		Plot Residual by Predicted( 0 ), Plot Effect Leverage( 0 )}
	)
)
```

Speed Reduction before Curve

```
Fit Model(
	Y( :New Tangential Deceleration ),
	Effects( :Speed Change, :Supplementary Devices),
	Random Effects( :Participant # ),
	Center Polynomials( 0 ),
	Personality( Standard Least Squares ),
	Method( REML ),
	Emphasis( Minimal Report ),
	Run(
```

```
			:New Tangential Deceleration << {Analysis of Variance( 0 ), Lack of Fit(
0 ),
			Plot Actual by Predicted( 1 ), Plot Regression( 0 ),
			Plot Residual by Predicted( 1 ), Plot Effect Leverage( 1 )}
	)
)
```

Maximum Deceleration Rate on Tangent

```
Fit Model(
	Y( :New Tangential Deceleration ),
	Effects( :Speed Change, :Supplementary Devices),
	Random Effects( :Participant # ),
	Personality( Standard Least Squares ),
	Method( REML ),
	Emphasis( Minimal Report ),
	Run(
			:New Tangential Deceleration << {Analysis of Variance( 0 ), Lack of Fit(
0 ),
			Plot Actual by Predicted( 0 ), Plot Regression( 0 ),
			Plot Residual by Predicted( 0 ), Plot Effect Leverage( 0 )}
	)
)
```

Speed at PC

```
Fit Model(
	Y( :Speed_PC ),
	Effects(
			:Max Speed on tangent,
			1 / :Radius,
			:Supplementary Devices
	),
	Random Effects( :Participant # ),
	Center Polynomials( 0 ),
	Personality( Standard Least Squares ),
	Method( REML ),
	Emphasis( Minimal Report ),
	Run(
			:Speed_PC << {Analysis of Variance( 0 ), Lack of Fit( 0 ),
			Plot Actual by Predicted( 1 ), Plot Regression( 0 ),
			Plot Residual by Predicted( 1 ), Plot Effect Leverage( 1 ), AICc( 1 ),
			Show All Confidence Intervals( 1 )}
	)
```

)

Maximum Deceleration Rate in Curve

```
Fit Model(
	Y( :Name( “Max Decel Rate in curve” ) ),
	Effects( :Speed Change, :Supplementary Devices ),
	Random Effects( :Participant ),
	Personality( Standard Least Squares ),
	Method( REML ),
	Emphasis( Minimal Report ),
	Run(
		:Name( “Max Decel Rate in curve” ) <<
		{Analysis of Variance( 0 ), Lack of Fit( 0 ), Plot Actual by Predicted( 0 ),
		Plot Regression( 0 ), Plot Residual by Predicted( 0 ),
		Plot Effect Leverage( 0 )}
	)
)
```

Maximum Lateral Acceleration

```
Fit Model(
	Y( :Max. Lat accel ),
	Effects(
		Log( :Name( “Defl/Radius” ) ),
		:Supplementary Devices,
	),
	Random Effects( :Participant # ),
	Center Polynomials( 0 ),
	Personality( Standard Least Squares ),
	Method( REML ),
	Emphasis( Minimal Report ),
	Run(
		:Max. Lat accel << {Analysis of Variance( 0 ), Lack of Fit( 0 ),
		Plot Actual by Predicted( 1 ), Plot Regression( 0 ),
		Plot Residual by Predicted( 0 ), Plot Effect Leverage( 1 )}
	)
)
```

C.3. Code for Section 6 (Visual Attention)

Distance from Upstream Curve to Reach Minimum Pupil Size

```
Fit Model(
        Weight( :Weight for distance at minimum size ),
        Y( :Distance after Start to Min Pupil ),
        Effects( :Tangent Length, :Potential Pupil Contraction ),
        Random Effects( :Participant # ),
        Personality( Standard Least Squares ),
        Method( REML ),
        Emphasis( Minimal Report ),
        Run(
                :Distance after Start to Min Pupil << {Analysis of Variance( 0 ),
                Lack of Fit( 0 ), Plot Actual by Predicted( 1 ), Plot Regression( 0 ),
                Plot Residual by Predicted( 1 ), Plot Effect Leverage( 1 )}
        )
)
```

Total Pupil Contraction

```
Fit Model(
        Y( Sqrt( :Contraction of Pupil ) ),
        Effects( Sqrt( :Tangent Length ), :Potential Pupil Contraction ),
        Random Effects( :Participant # ),
        Personality( Standard Least Squares ),
        Method( REML ),
        Emphasis( Minimal Report ),
        Run(
                :Contraction of Pupil << {Analysis of Variance( 0 ), Lack of Fit( 0 ),
                Plot Actual by Predicted( 0 ), Plot Regression( 0 ),
                Plot Residual by Predicted( 0 ), Plot Effect Leverage( 0 )}
        )
)
```

Distance from Downstream Curve at Maximum Pupil Size

```
Fit Model(
        Weight( :Weight for distance at dilation ),
        Y( :Distance from Max Pupil to PC ),
        Effects( :Speed Change, :Name( “Defl/Radius” ), :Supplementary Devices ),
        Random Effects( :Participant # ),
        Personality( Standard Least Squares ),
        Method( REML ),
```

```
        Emphasis( Minimal Report ),
        Run(
                :Distance from Max Pupil to PC << {Analysis of Variance( 0 ),
                Lack of Fit( 0 ), Plot Actual by Predicted( 0 ), Plot Regression( 0 ),
                Plot Residual by Predicted( 1 ), Plot Effect Leverage( 1 )}
        )
)
```

Distance Downstream from Starting Point at Maximum Eye Closure

```
Fit Model(
        Weight( :Weight for distance at max eye closure ),
        Y( :Distance after Start to Max Closure ),
        Effects(
                :Tangent Length,
                :Name( “Average-First Eye Closure” ),
                :Tangent Length * :Name( “Average-First Eye Closure” ),
                :Supplementary Devices
        ),
        Random Effects( :Participant # ),
        Personality( Standard Least Squares ),
        Method( REML ),
        Emphasis( Minimal Report ),
        Run(
                :Distance after Start to Max Closure << {Analysis of Variance( 0 ),
                Lack of Fit( 0 ), Plot Actual by Predicted( 0 ), Plot Regression( 0 ),
                Plot Residual by Predicted( 0 ), Plot Effect Leverage( 0 )}
        )
)
```

C.4. Code for Section 7 (Attention and Performance)

Vertical Fixation Component

```
Fit Model(
        Y( :Name( “X rotation” ) ),
        Effects( :mph, :Name( “Ax (ft/s/s)” ) ),
        Random Effects( :Participant ),
        Personality( Standard Least Squares ),
        Method( REML ),
        Emphasis( Minimal Report ),
        Run(
                :Name( “X rotation” ) << {Analysis of Variance( 0 ),
```

```
			Lack of Fit( 0 ), Plot Actual by Predicted( 1 ), Plot Regression( 0 ),
			Plot Residual by Predicted( 1 ), Plot Effect Leverage( 1 )}
		)
)
```

Pupil Diameter

```
Fit Model(
		Y( :Pupil size ),
		Effects( :mph, :Name( “Ax (ft/s/s)” ) ),
		Random Effects( :Participant ),
		Personality( Standard Least Squares ),
		Method( REML ),
		Emphasis( Minimal Report ),
		Run(
			:Pupil size << {Analysis of Variance( 0 ), Lack of Fit( 0 ),
			Plot Actual by Predicted( 1 ), Plot Regression( 0 ),
			Plot Residual by Predicted( 0 ), Plot Effect Leverage( 1 )}
		)
)
```

Eye Closure

```
Fit Model(
		Y( Sqrt( :EyeClosure ) ),
		Effects( :Name( “Ax (ft/s/s)” ) ),
		Random Effects( :Participant ),
		Personality( Standard Least Squares ),
		Method( REML ),
		Emphasis( Minimal Report ),
		Run(
			:EyeClosure << {Analysis of Variance( 0 ), Lack of Fit( 0 ),
			Plot Actual by Predicted( 0 ), Plot Residual by Predicted( 1 ),
			Plot Effect Leverage( 1 )}
		)
)
```

Distance from Downstream Curve at Maximum Speed

```
Fit Model(
		Y( :Distance at Max Speed ),
		Weight( :Weight for distance at max speed ),
		Effects( :Tangent Length, :Distance from Max pupil to PC ),
		Random Effects( :New Participant Number ),
		Personality( Standard Least Squares ),
```

```
        Method( REML ),
        Emphasis( Minimal Report ),
        Run(
                :Distance at Max Speed << {Analysis of Variance( 0 ), Lack of Fit( 0 ),
                Plot Actual by Predicted( 0 ), Plot Regression( 0 ),
                Plot Residual by Predicted( 0 ), Plot Effect Leverage( 0 )}
        )
)
```

Speed Reduction before a Curve

```
Fit Model(
        Weight( :Name( “Weight for Speed Chg (1/Resid)” ) ),
        Y( :Speed Change Before Curve ),
        Effects(
                :Max Speed on tangent,
                1 / :Radius,
                :Tangent Length,
                :Distance from Max pupil to PC
        ),
        Random Effects( :New Participant Number ),
        Personality( Standard Least Squares ),
        Method( REML ),
        Emphasis( Minimal Report ),
        Run(
                :Speed Change Before Curve << {Analysis of Variance( 0 ), Lack of Fit(
0 ),
                Plot Actual by Predicted( 0 ), Plot Regression( 0 ),
                Plot Residual by Predicted( 1 ), Plot Effect Leverage( 1 )}
        )
)
```

Speed at the PC

```
Fit Model(
        Y( :Speed_PC ),
        Effects(
                :Max Speed on tangent,
                1 / :Radius,
                :Tangent Length,
                :Distance from Max pupil to PC
        ),
        Random Effects( :New Participant Number ),
        Personality( Standard Least Squares ),
```

```
	Method( REML ),
	Emphasis( Minimal Report ),
	Run(
		:Speed_PC << {Analysis of Variance( 0 ), Lack of Fit( 0 ),
		Plot Actual by Predicted( 0 ), Plot Regression( 0 ),
		Plot Residual by Predicted( 0 ), Plot Effect Leverage( 0 )}
	)
)
```

Maximum Lateral Acceleration

```
Fit Model(
	Y( :Max. Lat accel ),
	Effects( Log( :Name( “Defl/Radius” ) ), :Distance from Max pupil to PC ),
	Random Effects( :New Participant Number ),
	Personality( Standard Least Squares ),
	Method( REML ),
	Emphasis( Minimal Report ),
	Run(
		:Max. Lat accel << {Analysis of Variance( 0 ), Lack of Fit( 0 ),
		Plot Actual by Predicted( 0 ), Plot Regression( 0 ),
		Plot Residual by Predicted( 1 ), Plot Effect Leverage( 1 )}
	)
)
```