A THEORETICAL MODEL OF VISUAL ATTENTION TO PREDICT
DRIVER PERFORMANCE AT CURVES

A Doctoral Dissertation Proposal

by

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INTRODUCTION

The horizontal components of a roadway can be divided into two types of sections: tangents, and the changes in alignment, hereafter referred to as curves, which connect tangents. 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. For the inattentive driver, a curve can be a potential hazard. Research has shown that in order to navigate a curve safely drivers must satisfy increased visual demands within the curve (1). But little has been done to show the importance of driver visual behavior on curve approaches, where drivers obtain important information about the upcoming curve. If the visual behavior of drivers is different on curves than on tangents, there should be some measurable change on an approach as drivers notice and then anticipate a curve.

The effects of a driver’s attention on the approach to a curve will likely be reflected in how well he navigates it. If a driver’s performance while navigating a curve is related to his preceding visual behavior or attention, it is important to encourage an increase in driver attention at an appropriate time before these critical locations. It is hypothesized that the visual attention exhibited by drivers in anticipation of a curve increases when traffic control devices (TCDs) are used. Since TCDs provide visual information that may not otherwise be obtained from the curve itself or its surrounding environment, it is thought that this stimulus alerts drivers of the upcoming hazard, leading to a change in visual attention. When attention increases, performance should improve.

This proposal describes a plan to evaluate how driver visual behavior changes near curves and identify the relationship between visual attention before curves and operational performance while navigating curves.

PROBLEM STATEMENT

There are three hypotheses that will be tested in the dissertation: (1) driver visual behavior on a tangent changes as the driver approaches a curve, (2) driver visual behavior can be influenced by the use of TCDs at the curve, and (3) driver visual behavior prior to a curve affects performance while navigating the curve.

Visual behavior, which is a reflection of attention, will be characterized by parameters measured by eye-tracking equipment. Navigational performance is characterized by vehicle operational measures that are derived from values of speed or acceleration. In this study, the speed and acceleration data will be measured continuously, which allow for the development of new metrics that may be more descriptive of driver behavior than speed or acceleration at one location alone.

The TCDs that will be tested are post-mounted delineators and large arrows, each used separately but in addition to pavement markings and advance warning signs. If these three hypotheses can be successfully proven, the resulting implication is that the tested TCDs can lead to better driving performance because they support improved attention. This investigation can
lead to improvements in how the effectiveness of a TCD is measured; if a particular device leads to increased attention, and an increase in attention leads to safer navigation, there is justification to use that device at more-severe hazards. At a curve, for example, the level of attention supported by a particular device should be consistent with the severity of the curve.

SPECIFIC RESEARCH OBJECTIVES

There are three objectives to the research that need to be met in order to test the three hypotheses. For the written dissertation, it is anticipated that each objective will be fulfilled in a separate chapter. The three objectives are:

1. Using data collected from study participants, develop a model that characterizes how a driver’s visual attention changes as the driver approaches and navigates a curve and identifies how that attention is influenced by TCDs, if any, used at the curve. This objective tests the first two hypotheses.
2. Develop metrics of driving performance on curves that characterize driving behavior better than traditional operations-based measures. Evaluate the driving performance of the study drivers using these metrics. This objective alone does not test a dissertation hypothesis, but it is thought that the new metrics will be beneficial in testing the third hypothesis.
3. Using the data from Objectives 1 and 2, identify the components of a driver’s visual attention prior to a curve that affect performance while navigating the curve. Identifying this relationship will test the third hypothesis.

BACKGROUND

The scientific literature is filled with evaluations of driver performance under a number of circumstances and in many different settings. For curves specifically, the research question has usually been whether or not a particular geometric element or TCD results in a measurable improvement in terms of vehicle operations. Rather than viewing the problem solely as a matter of operations, however, there may be a more important issue related to driver attention and the relationship between attention and operations. The purpose of this dissertation is to establish that relationship, which would identify the real mechanism that makes TCDs effective by investigating processes that are more internal to the driver. This section of the proposal discusses aspects of driver behavior in terms of operations and visual attention, the use of TCDs on curves, the effects of TCDs on driver behavior, and connections between visual attention of drivers and their driving performance. The section concludes with a discussion of research needs that support the hypotheses of the dissertation.

Driver Behavior

Though specifics in the literature vary by location and characteristic studied, curves experience higher crash rates than tangents (2–4). The prevalence of crashes at curves has long justified
extra attention from researchers attempting to better understand driver behavior. The process of navigating a curve is more complicated than driving on a tangent because the driver is required to make steering and speed adjustments that fit with the changing road alignment. This section contains a discussion of operational and visual behavior relevant to the driving task as a driver approaches and navigates a curve.

**Operational Metrics for Curve Driving**

Speed has been identified as a principal factor in crash frequency and severity (5, 6), making it the primary measure of interest when evaluating safety on curves. From a simple design perspective, the “design speed” of a horizontal curve is controlled by the radius, side-friction, and superelevation of the roadway. Because unique drivers have different levels of experience and risk-taking habits, vehicles differ by design and type, and curves are unique based on local conditions that restrict their design, speeds on curves can be variable. Predictions of driver speeds on curves have been done many times using different geometric elements such as radius, lane width, and grade.

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 longitudinal speed and an inverse relationship with radius (without considering superelevation). The lateral acceleration felt by the driver is sustained by sideways friction between the tires and pavement, typically referred to as the sidefriction demand. Design guidelines for horizontal curves are set conservatively so that the sidefriction demand should never exceed what is available. With many crashes at curves identified as run-off-road, however, the lateral acceleration experienced by drivers is still an important element of safe navigation.

Research shows that drivers do not adjust their speeds on curves to consistently accept the same amount of lateral acceleration. At higher speeds, drivers are more cautious and accept lower levels of acceleration (7–10). If approach speeds are high, which is especially common at isolated curves, and drivers generally do not accept high levels of lateral acceleration at high speeds, they will need to decelerate to a speed appropriate for navigating the curve. This process begins after the driver becomes aware of the curve and begins formulating a strategy to navigate it. Driver speed throughout a single curve is usually not constant. Generally, the minimum speed is reached near the midpoint of the curve. Speed prediction models by Poe and Mason (11), Donnell et al. (12), and Islam and Seneviratne (13) each estimate a lower speed at the midpoint than at the point of curvature (PC), and those that also modeled speeds at the point of tangency (PT) estimate an exit speed close to the entrance speed. Medina and Tarko (14) and Hu and Donnell (15) observed that 66 percent of the total deceleration occurs on the tangent preceding the curve, with the remaining 34 percent occurring after the PC.

Though not receiving as much attention as speed, the placement of vehicles within the lane is an important component of curve navigation. When possible, drivers tend to “cut” curves (also called “cornering” or “flattening”), adjusting their position within the lane in order to navigate the curve at a radius larger than that of the actual alignment. For left curves, the vehicle encroaches upon the centerline. For right curves, the vehicle encroaches upon the edgeline.
Cutting the curve is intentional because the driver sacrifices position within the lane to reduce forces of lateral acceleration without having to reduce speed.

The operational effects of curves as discussed in this section show that the decisions made by drivers near curves are both intentional and natural. This is important because the decisions drivers make regarding how they navigate a curve are based on the unique characteristics of their vehicles and driving habits, their previous experiences, and the information obtained about the curve, usually in advance of the curve. That information comes from both the visible road scene and surrounding environment, including the TCDs, if any, used. The information obtained by the drivers is dependent upon their behavior on the approach to the curve, defined by the attention the devoted to the forward scene.

**Visual Attention**

Our understanding of the role of visual attention in the driving task has evolved as new technology provides researchers with better information about the interaction between drivers and the driving environment at a visual level. 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 it can be reduced or eliminated. This dissertation does not deal with distracted driving per se (defining distracted as failing to exhibit attention), but rather identifying the situations where drivers may exhibit different levels of attention. It seems that the concept of attention and its effect on driver behavior are too complex to be reduced to a dichotomy of attention vs. inattention.

The most notable early research on driver visual behavior was performed over 40 years ago by researchers Mourant and Rockwell (16) who worked to identify the general location of driver gazes as they 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 they are unfamiliar with a road, as simulated by the participants intentionally looking at each sign. They produced the images in Figure 1 that show the location and concentration of the gazes based on percent time at intersecting coordinates. Where the concentration is high enough, a whole percent is given. A single dot represents locations with less than a whole percent of gazes. Note that in the image for the third drive, there are values as high as 5, 6, and 7 percent at some locations.
Mourant and Rockwell later identified differences in visual patterns between novice and experienced drivers (17). The glances of novice drivers covered a narrower horizontal field than those of the experienced drivers. Also, the vertical components of the novice drivers’ glances were lower, indicating that their preview distances were shorter than those of the experienced drivers.

In 1977, Shinar and McDowell teamed up with Rockwell on a study of visual behavior of drivers navigating curves (18). 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 supplemental verification of his 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 actually starts before the curve, indicating that the visual behavior on the approach is extremely important. Also, drivers tended to fixate on the road more while navigating right curves than left curves, which supports the need to evaluate visual behavior on curves differently by direction.

At the same time that Shinar, McDowell, and Rockwell were studying where drivers look on curves, Cohen and Studach were performing a similar study (19). Cohen and Studach 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 the earlier findings of Mourant and Rockwell (17). As drivers approached a curve, the duration of the fixations decreased and they were directed in the direction of the curve, similar to results of Shinar et al. (18).

To reinforce the importance of visual behavior on curve approaches established by Shinar et al. (18) and Cohen and Studach (19), Lehtonen et al. (20) 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 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 (21), 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. (20), the researchers presented drivers with mathematical tasks during one of three runs with each participant. These “loaded” runs were affected by 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 and more often 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. But it has not yet been determined whether or not the anticipatory movements affect driving performance. This dissertation thus will attempt to answer the following two questions: (1) do curve TCDs lead to an improvement in the anticipatory eye movements made before curves? and (2) do anticipatory eye movements affect how well drivers navigate curves?

Traffic Control Devices at Curves

The Manual on Uniform Traffic Control Devices (MUTCD) states that one of five basic requirements of a TCD is that it should “command attention” (22), indicating that a TCD should direct driver attention to the condition it represents. It is thus suggested that the purpose of a TCD at a curve is to help the driver begin the anticipatory glances discussed by Lehtonen et al. (20) at an earlier time, providing more distance and time for the driver to make an appropriate response before entering the curve. The most common devices are curve and turn advance warning signs, which may be supplemented by an advisory speed plaque, and chevrons, which are placed along the outside of the curve (similar to post-mounted delineators). While an advance warning sign can notify a driver of a change in alignment, it does not announce exactly where that change occurs. That information can be provided by chevrons, delineators, or a large arrow sign, which are placed within the field of view of the driver on the approach to notify the driver of the curve and provide relevant information regarding the alignment. There currently is no regulation in the MUTCD requiring delineators be used at curves, though some jurisdictions use them. Either chevrons or a large arrow sign are required where the operating speed on the curve represents a deceleration of 15 mph or greater. The specific devices studied in this dissertation are post-mounted delineators and a large arrow sign. Examples of these devices are shown in Figure 2.
Generally, drivers 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. (23). According to Wickens et al., real-world warnings can be described by the N-SEEV model, where attention to them is based on the time to be noticed, the salience of the object or event, the effort to direct attention to the object, the expectancy of there being new information, and the value 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.

The effects of curve-related TCDs on driver behavior have been studied extensively. The following sections summarize some of these findings, describing how TCDs affect behavior at an operational and visual level.

**Effects of TCDs on Operations**

Chevrons and post-mounted delineators are categorized as delineation devices. The literature that reports effects of TCDs consistently hypothesizes (at least initially) that delineation devices lead to a decrease in driver speeds. This hypothesis has been both successfully proven and refuted in many studies. In open- and closed-course tests, Johnston (24), Agent and Creasey (25), Chrysler et al. (26), Re et al. (27), and Bullough et al. (28) found chevrons to be effective in reducing driver speeds, at least during one period of the day. Johnston (24) observed speeds to increase during daytime conditions with chevron use. No changes in speed due to chevrons were found by Jennings and Demetsky (29) and Zador et al. (30). A study using a simulator showed speeds to be consistently reduced before and within the curve when chevrons are used (31).

Studies of delineators have also had mixed results. An in-field study by Vest et al. (32) found speeds to increase at two out of three locations, and Kallberg (33) found significant increases in
speed at nighttime (with insignificant increases during the daytime). Chrysler et al. (26) found speeds to decrease, similar to their finding for chevrons. From work with a simulator, Molino et al. (34) developed profiles for speeds on the approach and length of the curve and showed that speeds were lower for curves that had delineators.

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. Likewise, in cases where speeds increased, researchers have attributed the increase to drivers having more confidence due 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, 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 in the curve. Vehicle speed at one location poorly captures the complexity of driver behavior and also implies that “slower is better” without any thought for other conditions or factors. For example, the speed at the PC alone provides no information about driver behavior before and after entering the curve. This dissertation will suggest that more-detailed metrics are needed to better represent the nuances of operations at curves.

As one measure of effectiveness, Chrysler et al. (26) used the speed differential between the speed at the PC and the midpoint, suggesting that an improvement is a reduction in the speed change that occurs between the PC and midpoint. While chevrons and delineators both mostly led to reductions in speed changes, chevrons were more consistent than delineators. The chevrons and delineators were not tested at the same curves, however, so direct comparisons may not be appropriate, but this is one example of the complexity of investigating operational behavior at curves.

Effects of TCDs on Visual Behavior

Since the early research with eye-tracking by Mourant and Rockwell, many researchers have defined more-specific scenarios for evaluating driver visual behavior. For example, Zwahlen (36) 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 durations lasted between 0.5 and 0.6 seconds. Unfortunately, there were not consistent differences between daytime and nighttime fixations or when there was an advisory speed displayed, so it was difficult to draw conclusions specifically related to effects on driver behavior.

In a similar study of fixations as drivers approached a stop sign (37), 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 (38—41). The difficulty in applying the metrics used in many of those previous 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 behavior, but difficult to use in understanding
attention. Devices at curves should not require long fixations as if a complex legend must be read and comprehended. 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 (42), driver visual behavior was evaluated as participants drove through work zones that were delineated by different types of barriers. One objective was to compare the effect on drivers from channelizing drums with warning lights vs. drums without warning lights. Another objective was to evaluate retroreflective delineators on concrete barriers vs. warning lights in a different work zone. 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. It was suggested that some of the difficulty was due to the time change between participants that resulted in fewer 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. The researchers did identify some changes in visual behavior; however it seems the confounding factors affected the ability to identify any substantive meaning for the changes.

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 traffic control devices, 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 attention. What is needed is a method of evaluating visual behavior that can show how attention changes under changing conditions.

**Connecting Visual Attention and Driver Behavior**

For important reasons, a large amount of resources have been directed at addressing the problem of distracted driving. It is clear that inattentive drivers perform poorer than attentive ones. For example, in-vehicle displays and other electronic devices have been shown to negatively affect drivers, both in terms of attention and performance (43—45). One limitation of applying results from distracted-driving studies to evaluating attention under normal conditions is that those studies usually add external distractions or other workloads that are not present during most driving tasks. Before fully understanding how intentional distractions affect drivers, there is a need to understand how changes in driver attention under normal conditions affect driver performance. In identifying these connections, there should be no need to distinguish between different devices used at a curve, because the question is restricted to only whether or not the attentional parameters are linked to operational performance. The devices may act as a stimulus for a change in attention, but the hypothesis is strictly that attention affects performance.

**Research Needs**

TCDs are installed at curves in order to provide drivers with additional information that will help them better navigate the curves. The primary measures of effectiveness of these TCDs have strictly been operational, with little thought for how the TCDs affect internally-based processes,
such as a driver’s visual behavior. Attention and driving performance have generally been previously measured within separate spheres. This has left little to show the effect of attention on performance under normal driving conditions. A defined connection between attention (while free from additional workloads or intentional distractions) and performance is important because it represents conditions that drivers are under for most driving tasks. This understanding provides a foundation for deciding when to install devices at certain curves based on the conditions specific to each curve.

RESEARCH PLAN

The data for the research will come from an open-road study of unfamiliar drivers on a rural, curvy two-lane road. The drivers will be in an instrumented vehicle equipped with eye-tracking cameras and devices for recording the vehicle’s position, speed, and instantaneous acceleration (both longitudinal and lateral). There will be two phases in the study during which delineators or large arrow signs will be used at select study curves. This section discusses the specific tasks of the dissertation. A proposed schedule for task completion is also included.

Task 1: Literature Review

The literature review will be focused on identifying research that has been conducted related to the two primary components of the dissertation: driver attention and operational performance. The literature review will provide a summary of the current knowledge and justification for the proposed methodology. Though the process is continually ongoing, an extensive amount of literature has already been reviewed.

Task 2: Conduct Driving Experiment

Data will be collected from an experiment of unfamiliar drivers navigating a rural two-lane road during daytime and nighttime conditions. The selected road is FM 3090, which has many isolated curves. During each drive, instruments in the vehicle will collect and store data from three sources: eye-tracking cameras, an accelerometer, and a GPS receiver. Specific study curves have been selected based on their location and geometric features. The study curves will be given a different treatment, during the second phase of the study than the first phase, using either delineators or large arrow signs.

Study Protocol

Unfamiliar drivers will navigate FM 3090 while the equipment measures the vehicle’s instantaneous speed and acceleration and tracks the drivers’ eyes. Researchers will be present in the vehicle to operate the equipment and ensure the study is conducted properly. The road is approximately 15 miles long (one way) and drivers will be instructed to drive at a comfortable and legal speed. At the end of the road, they will be instructed to return to the beginning. The study protocol has been approved by the Texas A&M University Institutional Review Board.
Two Phases of the Open-Road Test

TCDs installed at the study curves will be changed during two phases of the study, as shown in Table 1. There are three comparisons presented in Table 1: Nothing vs. delineators; nothing vs. large arrow; and delineators vs. large arrow sign. Four of the seven curves are isolated enough at both ends to justify using data collected from both directions of travel, resulting in eleven study curves. The devices in Table 1 were assigned systematically to ensure that the devices are tested at curves of different severity, based on observed speed changes.

<table>
<thead>
<tr>
<th>Curve Number</th>
<th>Phase 1</th>
<th>Phase 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Delineators</td>
<td>Nothing</td>
</tr>
<tr>
<td>2</td>
<td>Nothing</td>
<td>Delineators</td>
</tr>
<tr>
<td>3</td>
<td>Large Arrow</td>
<td>Nothing</td>
</tr>
<tr>
<td>4</td>
<td>Delineators</td>
<td>Large Arrow</td>
</tr>
<tr>
<td>5</td>
<td>Large Arrow</td>
<td>Delineators</td>
</tr>
<tr>
<td>6</td>
<td>Delineators</td>
<td>Nothing</td>
</tr>
<tr>
<td>7</td>
<td>Nothing</td>
<td>Large Arrow</td>
</tr>
</tbody>
</table>

Study Participants

It is anticipated that 32 study participants will be used throughout the experiment, with 16 participants in each phase. No specific evaluation will be made based on any demographic factors such as age or gender. Table 2 illustrates the breakdown of participants that will drive during each phase and time period. Each participant will driver only one time during the course of the study.

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Phase I</th>
<th>Phase II</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day</td>
<td>8</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>Night</td>
<td>8</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>Total</td>
<td>16</td>
<td>16</td>
<td>32</td>
</tr>
</tbody>
</table>

Task 3: Analyze Eye-Tracking Data and Develop Visual Attention Model

The eye-tracking equipment provides the following data at 30 Hz:
- Percent closure of each eye (the fraction of the iris covered by the eye lids—0.0 is wide open, 1.0 is completely closed)
- Blinks (an indicator of whether or not a blink is occurring)
- Pupil size (diameter, only available on nighttime participants)
- Gaze rotation (orientation of the eyes in Euler angles representing a vector from the center of the eye)
- Pixel coordinates of gaze position on video screen

The following sections discuss how the eye-tracking data will be analyzed, and how the visual attention model will be presented.

**Proposed Analysis of Eye-Tracking Data**

The goal of the eye-tracking analysis is to create a representation of a driver’s visual attention. One suggested method is graphical. In a preliminary analysis, fixation intensity maps were developed to show how the position of a driver’s gaze changes under different scenarios, such as driving on a curve or tangent. Two such maps are shown in Figure 3. These images, developed for a paper accepted for publication in a Transportation Research Record (46), graphically show the distribution of drivers’ gazes, collected over a total of 72 seconds. The use of intensity maps in studying visual behavior has been done recently by Diem (47), who evaluated drivers in rural and urban areas during daytime and nighttime conditions. Figure 4 shows the images created by Diem.

![Figure 3: Heat map examples showing eye rotations of participants under different conditions.](image)

(a) Nighttime tangent section  
(b) Nighttime right curve approach
The contour heat maps show (in two dimensions with a color component) a visualization of where drivers’ gazes are fixated, but it is still necessary to quantify the data for an objective analysis. The clearest quantifiable metrics to describe these images are the dispersion measured by area in degrees$^2$ that covers a specific percentage of gazes (such as the 50th or 85th percentile) and the location of the centroid. The gaze area in degrees$^2$ was used by Lehtonen et al. (20) and is a metric similar to one developed by Zhang et al. (48) that multiplied the standard deviations of the pitch and yaw eye angles as a measure of variability.

Research has shown that the eyes dilate, eyelids become more open, and people blink more under conditions of higher workload and attention. The amount the eyelids cover the eye (measured by percent eye closure) has been studied as a way of detecting drowsy driving (49); pupil size (measured by the diameter in millimeters) has been shown to increase under cognitive and search tasks (50, 51); and blinking has been used as a metric of driver mental and visual demand (44). It is hypothesized that as a driver approaches a curve, those physiological changes
will occur. When devices are used at the curve, it is hypothesized there will be an even greater change.

From the eye-tracking data described above, the following metrics will be calculated using 4-second intervals at specific points of interest relative to each study curve:

- Percent eye closure
- Number of blinks
- Blink rate
- Pupil size
- Total eye movement
- 85th percentile gaze area
- Percent of gazes outside a 5-degree viewing area
- Percent of gazes outside a 10-degree viewing area
- Percent of gazes outside a 15-degree viewing area

While all of the values for these metrics are evaluated over a 4-second period, only a select few of them are explicitly given in the raw eye-tracking data files. A substantial amount of processing is needed to derive the eye movement and different gaze areas. Those metrics are new to driving research, first hypothesized in this dissertation as a reasonable way to measure driver attention. They have been synthesized based on the available data. When drivers are more attentive, it is suggested that there should be less measured eye movement and a more confined gaze area. If there are successful results from this experiment, it is likely they will be used more in future visual behavior research.

**Visual Attention Model**

The purpose of the visual attention model is to describe how a driver’s attention changes when approaching and then navigating curves of different characteristics and with different devices. At this time, it is unclear which metrics will prove useful in identifying changes in driver visual attention. Undoubtedly, some metrics will not be effective, but they still need to be tested in an effort to make a contribution to the body of knowledge regarding driving behavior. The model completed in this task will fulfill the first objective of the dissertation.

**Task 4: Analyze Driver Performance**

As presented in the Background, there are a number of deficiencies with the metrics often used to evaluate performance on curves. In this study, a GPS receiver and accelerometer will be used to track the location of the vehicle and give instantaneous readings of speed and acceleration (10 times per second). Utilizing the high-fidelity data provided by a GPS receiver and accelerometer, the following metrics will be derived for each study curve and TCD:

- Minimum speed reached in the curve
  - Location where minimum speed occurs
- Speed change (reduction) that occurs within the curve, measured as the difference between the speed at the PC and the minimum speed in the curve
Specific energy dissipated within the curve, measured as one half the difference between the squared minimum speed and the speed at the PC
- Reduction in speed that occurs after the midpoint, if any occurs
- Maximum deceleration rate (longitudinal acceleration) within the curve
  - Location where maximum deceleration rate occurs
- Maximum lateral acceleration experienced in the curve
  - Location of maximum lateral acceleration in curve
- Maximum speed on approach tangent
  - Location of maximum speed on tangent
- Maximum deceleration rate on approach tangent
  - Location of maximum deceleration rate on tangent

Generally, these metrics have not been used by previous studies, and few have even had data from accelerometers. It is anticipated that a chapter in the dissertation will be devoted to discussing these new metrics and providing a sound theoretical justification for their use. Some brief thoughts follow: Speed change from the PC to the midpoint has been used in the past (35), but the minimum speed does not always occur at the midpoint; the idea for using specific energy comes from recommendations by Pratt and Bonneson (52) that curve TCDs be determined based on energy measures rather than speed differences alone (the squared speed term in calculating specific energy “penalizes” higher speeds over lower speeds, which is thought to provide an improved perspective on safety); and deceleration that occurs after the midpoint may indicate that the driver was inadequately prepared to navigate the curve.

The new performance measures discussed in this section are not perfect metrics, but they provide a perspective on navigating curves that is more descriptive of driving behavior than many of the measures that have been used in the past. Their potential as viable metrics has not been tested and it is possible that there will be little usable information to make significant comparisons. In case that happens, speed, longitudinal acceleration, and lateral acceleration will still be extracted from the raw data at individual points of interest. These unmodified data will be used if the “new” metrics presented above are not successful. The development and testing of performance measures in Task 4 will fulfill the second objective of the dissertation.

**Task 5: Putting it Together: Identifying Relationships between Visual Attention and Driver Performance**

Tasks 3 and 4 create models that describe driver visual attention when approaching a curve and the vehicle operational output (performance) experienced at the change in alignment. The next step is to find connections between attention and operational performance. Each category of interest (attention and performance) has a large number of relevant metrics that have been defined in a qualitative way suitable for identifying relationships. Task 5 will include statistical analyses that test these correlations, fulfilling the third objective of the dissertation.
Task 6: Report Findings

It is anticipated that the chapters within the body of the dissertation will independently function as journal papers. Suggested publication outlets include TRB, the Human Factors and Ergonomics Society, and Transportation Research Part F. The following is a proposed list of chapters within the dissertation.

- Chapter 1: Introduction and background
- Chapter 2: A model of driver visual attention on curve approaches
- Chapter 3: Driver performance metrics in curve negotiation
- Chapter 4: Predicting curve driving performance from a driver’s visual attention
- Chapter 5: Conclusion

Proposed Schedule

It is anticipated that the tasks outlined above will be completed by the end of June 2014. Figure 5 outlines when work on each task is suggested to occur.

<table>
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<tr>
<th>Task</th>
<th>February</th>
<th>March</th>
<th>April</th>
<th>May</th>
<th>June</th>
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<td>Task 1: Literature Review</td>
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<td>Task 2: Conduct Driving Experiment</td>
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<td>Task 3: Develop Visual Attention Model</td>
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<td>Task 4: Analyze Operational Performance</td>
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<td>Task 5: Test Relationships between Attention and Performance</td>
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<td>Task 6: Report Findings</td>
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<td>Dissertation Defense</td>
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Figure 5: Proposed schedule for dissertation work.

CONCLUSION

Safety concerns, especially at curves, continue to influence the way engineers design roads and policy makers establish standards. This dissertation proposal contains a discussion of many of the findings of behavioral research relevant to the experience of navigating curves and presents hypotheses that may improve our knowledge of the connections between driver attention and performance. If the goals of this dissertation are met, we will have information that can lead to (1) improvements in safety due to better design standards and policies and (2) better methods that researchers can use to evaluate and describe how people drive.
REFERENCES


4. Sarbaz, O., R. Thomson, and L. Gunnar. Identifying Critical Road Geometry Parameters Affecting Crash Rate and Crash Type. 53rd Annual Scientific Conference of the Association for the Advancement of Automotive Medicine, Baltimore, MD.


