Effects of Horizontal Curvature, Vertical Curvature, and Guardrail on Passing Choice and Safety

A Thesis

Presented in Partial Fulfillment of the Requirements for the

Degree of Master of Science

with a

Major in Civil Engineering

in the

College of Graduate Studies

University of Idaho

by

Regan K. Hansen

Major Professor: Kevin Chang, Ph.D.

Committee Members: Brian Dyre, Ph.D.; Michael Lowry, Ph.D.

Department Administrator: Patricia J. S. Colberg, Ph.D.

December 2017

Authorization to Submit Thesis

This thesis of Regan K. Hansen, submitted for the degree of Master of Science with a major in Civil Engineering and titled "Effects of Horizontal Curvature, Vertical Curvature, and Guardrail on Passing Choice and Safety," has been reviewed in final form. Permission, as indicated by the signatures and dates below, is now granted to submit final copies to the College of Graduate Studies for approval.

Major Professor: ______________________________ Date: ____________
Kevin Chang, Ph.D.

Committee Members: ______________________________ Date: ____________
Brian Dyre, Ph.D.

______________________________ Date: ____________
Michael Lowry, Ph.D.

Department Administrator: ______________________________ Date: ____________
Patricia J. S. Colberg, Ph.D.

Abstract

Passing maneuvers on rural two-lane highways are complex maneuvers requiring drivers to enter the opposing traffic lane to overtake an impeding vehicle. A successful maneuver requires correctly judging the distance to the oncoming vehicle, speed of the oncoming vehicle, and the time it will take to complete the maneuver. Previous studies have shown that the type and speed of impeding vehicle, traffic volume, roadway cross-section, horizontal curvature, and driver characteristics influence passing behavior. This study expands on the previous research by investigating the effects of vertical curvature and guardrail on passing behavior as well as distinguishing between left- and right-direction horizontal curvature. The study was conducted by designing and conducting two driving simulation experiments based on two-lane rural highways in the state of Alaska. Data from the first experiment were analyzed to infer the effects of curvature on driver choice to pass, characterize passing maneuvers under different geometric configurations, and compare safety outcomes of pass attempts under different geometric configurations. Horizontal and vertical curvature had significant effects on driver choice to pass but no effects on safety outcomes of pass attempts. Data from the second experiment were analyzed to infer the effects of guardrail on passing behavior and collision avoidance. The presence of guardrail did not have significant effects on driver passing choice or safety outcomes of pass attempts. However, the presence of guardrail was found to significantly decrease the likelihood that drivers would avoid a head-on collision. The results of this study have implications for capacity and safety analysis of rural two-lane highways.

Acknowledgments

This thesis would not have been possible without the contributions of several people and organizations.

First, I would like to express my deepest gratitude to Dr. Kevin Chang. He provided guidance throughout the process of designing, executing, analyzing, and reporting the research that this thesis is based on. In addition to his contributions to this thesis, Dr. Chang has provided invaluable insight into the transportation engineering field and has been a great professional mentor. Without him, I could not have completed my Master's degree or this thesis.

I would like to thank Dr. Brian Dyre for his expertise on designing and analyzing the driving simulation experiments and Dr. Mike Lowry for his time and guidance in writing this thesis.

I would like to thank Isaiah Samuel for coordinating the participant scheduling for the second stage of this study, spending hours in the lab collecting data for both stages, and helping develop and troubleshoot the driving simulation experiments. Likewise, I would like to thank Jacob Rember and Kushal Patel for guiding me through the simulation development process and showing me how to get started.

I would like to thank the Alaska Department of Transportation & Public Facilities (ADOT&PF) and the Pacific Northwest Transportation Consortium (PacTrans) for funding the research studies that this thesis is based on. Finally, I would like to thank the Department of Civil & Environmental Engineering and the National Institute for Advanced Transportation Technology (NIATT) for enabling me to continue my education!

Table of Contents

List of Figures

List of Tables

Chapter 1: Introduction

On rural two-lane roads, passing maneuvers occur when one vehicle overtakes a slower-moving vehicle (hereafter referred to as the “impeding” vehicle) by occupying the lane used by opposing traffic. To accomplish this maneuver, the driver of the overtaking vehicle must be able to see a sufficient distance ahead, judge the distance to the oncoming vehicle or sight restriction, and correctly determine whether there is enough time and space to complete the maneuver without interfering with the oncoming vehicle or the impeding vehicle. The passing maneuver is very complex because it is difficult to correctly judge the distance and speed of the oncoming vehicle and the time and distance required to complete the maneuver (1-6).

Part of the difficulty in determining the distance and time that it takes to complete the passing maneuver is that the maneuver can vary substantially in terms of how much acceleration occurs (i.e. whether it is a “flying” or “accelerative” pass) (7), what the top speed will be, and how much gap is given to the impeding vehicle at the initiation and completion of the pass (8). The acceleration also depends on the power-to-weight ratio of the overtaking vehicle (9-10) as well as driver behavioral characteristics. Because of the complexity of the passing maneuver, it is one of the most difficult driving behaviors to model in microsimulations of two-lane rural roads (10). This study expands on the previous research by investigating the effects of vertical curvature and guardrail on passing choice as well as distinguishing between the effects of left- and right-direction horizontal curvature. The effects of horizontal curvature, vertical curvature, and guardrail on passing maneuvers and safety outcomes are also investigated.

Since the passing maneuver on a rural two-lane road is a complex maneuver that involves entering the opposing lane of traffic, a driver’s choice to initiate a pass also has implications for the other vehicles in the traffic stream, especially vehicles in the oncoming lane. An unsafe passing choice could lead to a head-on collision. This study investigates the effects of the presence of guardrail on the ability of drivers to avoid a head-on collision when an oncoming driver has made an unsafe passing choice and is unable to terminate the passing maneuver safely.

1.1 Research Objectives

The objectives of the research presented in this thesis are to:

- Assess the effects of horizontal curvature, vertical curvature, and guardrail on driver choice to pass,
- Assess the effects of horizontal curvature and vertical curvature on passing maneuvers,
- Assess the effects of horizontal curvature, vertical curvature, and guardrail on the safety outcomes of passes, and
- Assess the effects of guardrail on the ability of a driver to avoid a collision with an oncoming vehicle that is in the driver's travel lane.

1.2 Thesis Organization

This thesis is organized into five chapters. After the current introductory chapter, a literature review on topics relating to driver passing behavior and driving simulation is presented in Chapter 2. Chapter 3 describes the driving simulation methodology, including descriptions of the driving simulator apparatus, simulation development process, experimental design, experiment procedure, and data reduction. The results of the driving simulation experiments are presented in Chapter 4. Finally, Chapter 5 discusses the research conclusions and suggestions for future research.

Chapter 2: Literature Review

This chapter includes a literature review of research pertaining to passing behavior and driving simulation.

2.1 Passing Behavior

Early studies on passing behavior used field studies to observe how accurately drivers perceived the speed of the oncoming vehicle (1), estimated the distance to complete the maneuver (2), and made correct judgments regarding the safety of a passing maneuver (3).

Clarke et al. studied data from 973 police road-accident file describing overtaking crashes (4-5). The authors concluded that most crashes were a result of an incorrect decision at the start of the maneuver rather than poor handling or execution (4-5). The two most frequent types of error were overtaking a vehicle that then turned into the path of the overtaking vehicle followed by head-on collisions. The authors suggested that the most common error in head-on collisions was the difficulty of judging the time required to complete a passing maneuver (4-5).

Bar-Gera and Shinar investigated the speed differential at which drivers would pass an impeding vehicle on a divided highway (11). They found that drivers passed the impeding vehicle most of the time (66%-92% depending on speed differential) if the impeding vehicle was traveling at a speed equal to or less than the driver’s average speed, and even passed in 50% of the cases in which the impeding vehicle was traveling at a higher speed than the driver’s average speed, so long as the impeding vehicle was traveling at a speed within the driver’s range of preferred speeds.

Many of the studies regarding passing on rural two-lane highways have focused on describing the passing maneuver. Farah modelled the distance and duration of passing maneuvers and found significant effects for the following distance, distance to the oncoming vehicle at the initiation of the pass, gap to the oncoming vehicle at the end of the pass, age of the driver, and speeds of the driver, impeding vehicle, and opposing vehicle (12). Vlahogianni modelled the duration of passing maneuvers using hazard-based models and found significant effects for speed differential, oncoming vehicle spacing, opposite vehicle speed, number of vehicles overtaken in the maneuver, and the gender of the driver (13).

Jenkins and Rilett investigated the effects of the length and speed of the impeding vehicle on the length and duration of the passing maneuver as well as the start- and end-gaps to the impeding vehicle (8). Finally, Papakostopoulos et al. investigated how the appearance of an oncoming vehicle during a passing maneuver changed the driver's choice of lane positioning and how much gap to provide between the impeding vehicle at the end of the passing maneuver; they found that the appearance of an oncoming vehicle tends to cause the driver to reduce the rear safety margin to the impeding vehicle (14).

Several studies have investigated the effect of traffic volume on the number of passes initiated and, intuitively, have found that higher traffic volumes in the opposing lane reduce the number of pass attempts (15-16). Moreno et al. showed that the most passes occur when there is a moderate traffic volume (600-700 vehicles per hour) balanced roughly equally between the directions (16). Increased opposing traffic volume has been shown to increase a driver's propensity to accept a shorter gap due to impatience from waiting for a safe gap (15, 17).

Several studies have investigated how driver characteristics, traffic, and geometry affect driver willingness to accept a gap in the oncoming traffic and initiate a pass (18-21). The first study showed significant effects for the following distance, driver speed, driver driving style, and driver age (18). The second study showed significant effects for geometric design, driver characteristics, and the speeds of the driver, impeding vehicle, and oncoming vehicle (19). The third study developed a model based on two sub-models: one that calculated the probability of the desire to pass, and another that calculated the probability of accepting the passing gap. The "desire to pass" model showed significant effects for the following distance and the difference between the impeding vehicle speed and the driver's desired speed. The "gap acceptance" model showed significant effects for the driver's speed, impeding vehicle speed, opposing vehicle speed, horizontal curvature, type of impeding vehicle (truck or car), and driver age (20). Finally, Vlahogianni and Golias developed Bayesian classifiers to model the probability of overtaking and found significant effects for the relative speeds of the driver, impeding vehicle, and oncoming vehicle, and the distances to the impeding vehicle and oncoming vehicle (21).

One application of passing research is microsimulation programs, which rely on an understanding of the characteristics of passing maneuvers and gap acceptance decisions to model overtaking behavior on two-lane roads. Although most microsimulation software is designed to model urban and freeway road configurations and do not include decision models for overtaking slower-moving vehicles on two-lane roads, some microsimulation programs, such as TWOPAS (22-23), TRARR (24), VTIsim (9, 26), RuTSim (10), and TWOSIM (25), have been specifically developed to model rural roads and therefore include overtaking models. The overtaking models in each of these programs include decision models that are primarily based upon the speed differential between the overtaking and impeding vehicles and the lesser of the gap to the oncoming vehicle or the available sight distance. The available gap must be larger than the required time and distance to complete a passing maneuver. Some of the models (9, 22-25) are deterministic, meaning that the maneuver will be completed if it is initiated, while others (10, 26) continue to check the gap during the maneuver and abort the maneuver if the time-to-collision is lower than the time required to complete the maneuver. The models may also rely on driver characteristics assigned to each vehicle (24) and vehicle capabilities (9-10, 22-24). Geometric variables are not directly modelled in any of the passing decision models reviewed, although geometry does influence some of the other variables in the models such as available sight distance, maximum acceleration, and desired speed.

2.2 Driving Simulation

There are many difficulties in obtaining passing maneuver data in field studies (8, 18, 20, 27). Field study methods are limited by lack of control over environmental conditions and traffic conditions and the inability to collect driver information (8, 19-20). Using direct observation has many limitations including imprecise measurements/human error and relatively few observations. Another common field study method is using cameras, which has the limitations of limited field of view and lack of efficient and automated data extraction (28). In contrast, driving simulation allows for precise and high-resolution data collection, knowledge of driver characteristics, low-cost and low-risk repetition, and control over confounding variables such as weather, lighting, and traffic (29). Some of the tradeoffs of using driving simulation to collect data are simulator fatigue (19-20), lack of realism in the simulation (7-8, 29), and how drivers may accept more risk because they are not subject to the consequences of risky maneuvers such as property damage and personal injury (6).

Bella discussed the effectiveness of using driving simulation for research (27). The author discussed the difference between absolute and relative validity, where absolute validity is the numerical correspondence between simulation results and real-world results and relative validity is the correspondence of effects between simulation results and real-world results; the former is not necessary in many cases such as when the goal of the research is to infer an effect of a given treatment and not to quantify the effect in absolute terms. An overview of simulation validation studies is also included in the study (27).

Chapter 3: Methodology

This chapter describes the driving simulator apparatus, simulation development process, experimental design, experiment procedure, and data reduction and analysis.

3.1 Apparatus

The driving simulator at the University of Idaho, shown in Figures 3.1 and 3.2, is a medium fidelity fixed-base driving simulator. The simulation software is National Advanced Driving Simulator (NADS) Minisim version 2.0 installed on a Windows 7 workstation. The hardware is composed of cab-mounted controls for realistic user-interaction, a single workstation for all simulation processing, data collection, and graphics rendering, and additional components for audiovisual output and to facilitate transmission of information between the primary hardware components.

Figure 3.1: Driving Simulator Cab

The cab for user-interaction is from a 2001 Chevrolet S10 pickup truck. The vehicle controls are connected to the Minisim via a Suzo-Happ model 95-0800-10k USB Game Controller Interface (UGCI). The steering wheel is the original steering wheel from the S10 pickup; it is self-centering and has a 540-degree steering range. The brake and accelerator pedals are also original equipment from the S10 pickup and provide haptic feedback similar to the feedback of a normal automobile. An automatic gear selector from a 2001 Honda Civic was installed in the center console to provide users with a standard interface for gear selection.

Figure 3.2: Driving Simulator Controls

The simulation visuals are displayed via a 7-channel display configuration. The first three channels are displayed by three Canon REALiS SX800 projectors, which project the front view of the simulation environment onto three 90-inch screens at a combined resolution of 4200 x 1050 pixels. The three screens form 3 sides of an octagon centered at the projected eye-point of the simulation for a field of view of 135 degrees horizontally and

34 degrees vertically. The cab is positioned so the driver's eyes are at the projected eye-point of the simulation. The fourth video channel displays the dashboard instrument cluster including a speedometer, tachometer, engine temperature, gear selection, and fuel gauge. This channel is displayed by a 10-inch liquid crystal display (LCD) screen with a resolution of 1280 x 800 pixels that is mounted in place of the original instrument cluster. The final three channels display the rear view of the simulation. Eight-inch LCD screens with a resolution of 800 x 600 pixels are mounted on the driver side and passenger side mirror housings of the cab. A 65-inch plasma screen with a display resolution of 1280 x 720 pixels is mounted on the rear of the cab and is visible through the original center rear-view mirror.

The workstation contains a six-core Intel Core I7 processor running at 3.9 GHz, 32 GB of RAM, and two NVidia video display adapters. A GeForce GTX680 GPU processes the three main screens, which are routed through a Matrox T2G-D3D-IF multi-display adapter, as well as the instrument cluster and the passenger side mirror. A GeForce GTX660TI GPU processes the driver side mirror and rear screen. Finally, a 4.1-channel audio system used four speakers mounted in the cab doors and a subwoofer mounted behind the driver's seat to produce engine, environmental, and road noise.

The MiniSim simulation software is a part of the driving simulation suite developed at the National Advanced Driving Simulator (NADS) and The University of Iowa, which also includes the Tile Management Tool (TMT) and Interactive Scenario Authoring Tool (ISAT) for simulation development. The MiniSim utilizes NADSDyna high-fidelity vehicle dynamics software to model vehicle dynamics in the simulation. During the simulation, MiniSim uses information from the terrain visual database, terrain logical database, and scenario to render the simulation. Additionally, the software records vehicle input, vehicle dynamic, and scenario related variables at a collection frequency of 60 hertz (30).

3.2 Scenario Development: First Stage

The first stage of the driving simulation experiment focused on the effects of horizontal and vertical curvature on driver passing behavior. Three sections, each approximately five miles in length, of two-lane rural highway in the State of Alaska were chosen based on crash history. The three sections were:

- Seward Highway (between Milepost 108 and Milepost 114),

- Parks Highway (between Milepost 154 and Milepost 160), and
- Sterling Highway (between Milepost 145 and Milepost 151).

The highway sections were modeled in a virtual environment and driven by twenty-four participants to collect and analyze data regarding their passing behavior. The centerline striping for this stage of the experiment was dashed (permissive) for the full length of each track so that driver choice to pass was based on geometric cues rather than regulatory cues. The following section describes how the driving simulation scenarios were developed, the traffic characteristics in the simulation, and the statistical design of the experiment.

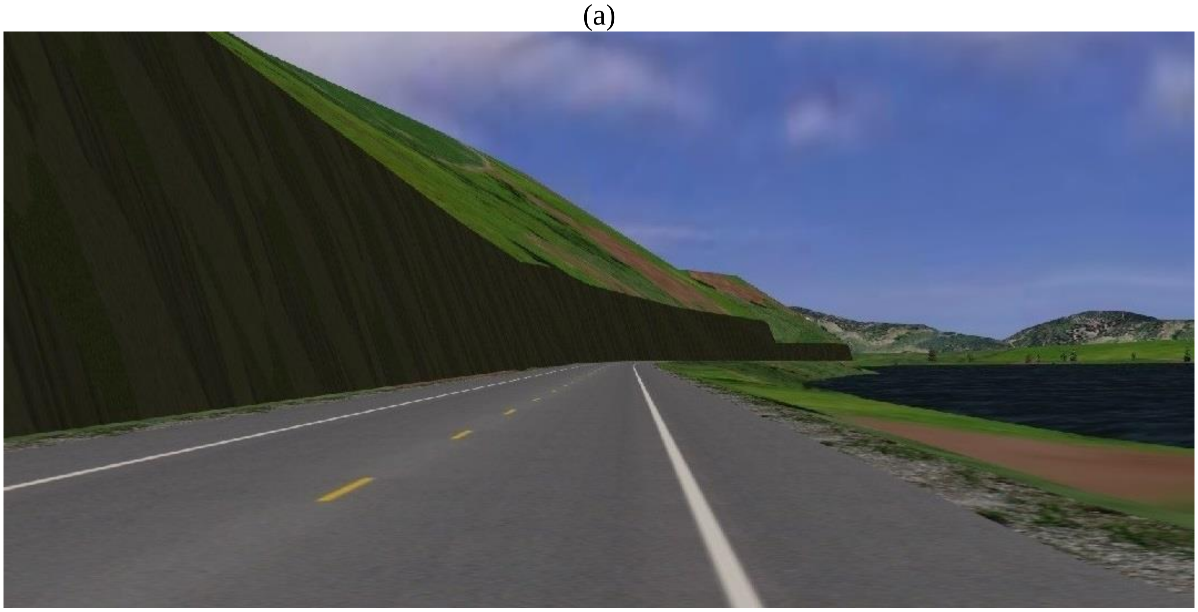
3.2.1 General Summary

To develop the required scenarios for each participant, multiple software applications were used along with the Minisim simulation program to test these scenarios. Every scenario was composed of multiple tiles that displayed the appropriate roadway geometries and the surrounding environment. These roadway geometries were based on the three real-world alignments of the Alaskan highway system.

Autodesk AutoCAD Civil 3d software was used to create the alignment, profile, and corridor for each test section based on as-built plans provided by the Alaska Department of Transportation. The corridors consisted of a 51-foot wide planar cross-section projected along the alignment and profile. The corridors were exported from Civil 3d and imported into Autodesk 3ds Max.

In 3ds Max, an image texture was applied to the roadway, resulting in a 24-foot wide paved roadway with a centerline and foglines as well as six-foot paved shoulders with gravel and grass edges. A dashed centerline (i.e. permitted passing) was provided for the entire roadway regardless of sight distance. The surrounding environment was then created in consultation with staff from the Alaska Department of Transportation. The environment included a cliff and waterbody for Seward Highway and forest, rolling highway, and mountains for the Parks and Sterling highways. Example comparisons between each simulated environment and Google Street View screenshots are shown in Figures 3.3 to 3.5. Each road section and surrounding environment was exported as a tile to be combined into a visual database by NADS Tile Management Tool (TMT) software. The surrounding environment was also exported to Civil 3d for sight distance analysis. Finally, a 3ds Max script was used to extract the coordinates of the centerline of each section to be used for roadway logic and to calculate geometric variables for each track.

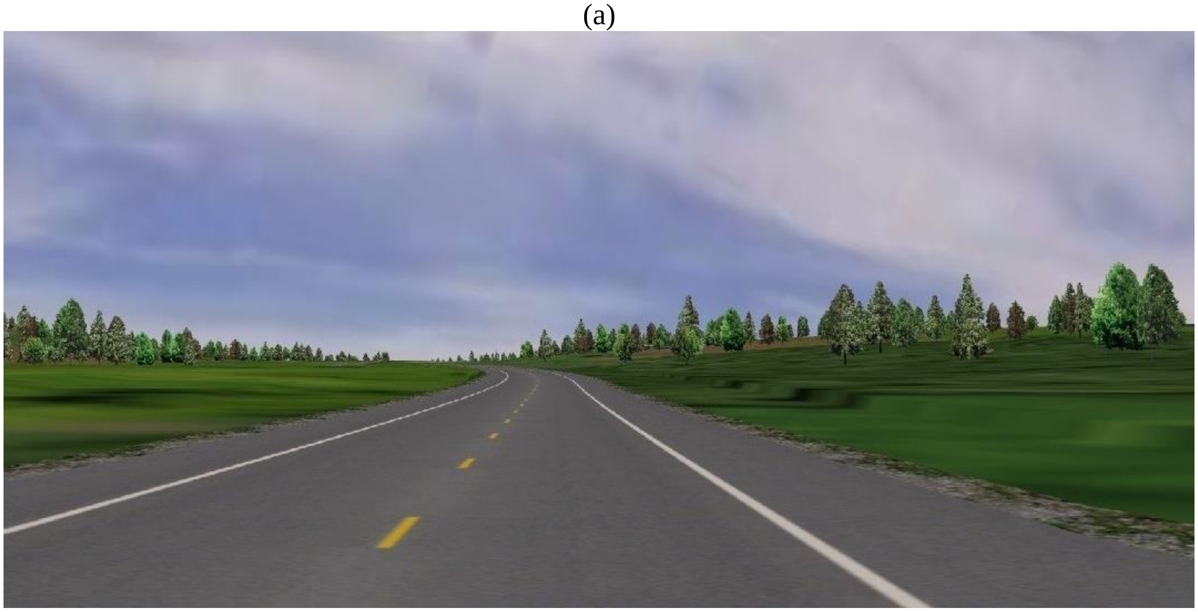
(a)



(b)

Figure 3.3: Seward Highway: (a) Actual Highway and (b) Simulation Highway

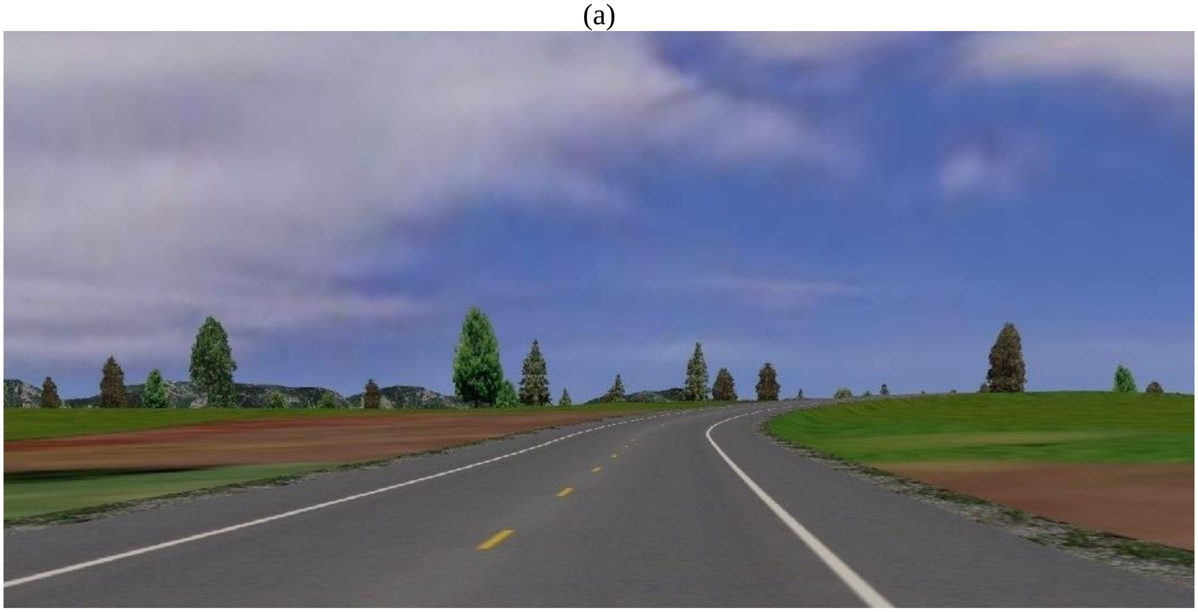
(a)



(b)

Figure 3.4: Parks Highway: (a) Actual Highway and (b) Simulation Highway

(a)



(b)

Figure 3.5: Sterling Highway: (a) Actual Highway and (b) Simulation Highway

The tiles for each section were combined with each other and with background filler tiles in TMT. The exported visual databases were then installed into the Minisim visual directory to be rendered during the simulation. Text files containing the centerline coordinates for each tile were combined and exported by TMT. The resulting logical databases were installed into the Minisim directory to be used for the roadway logic during the simulation. The logical database files also served as the basis for the NADS Interactive Scenario Authoring Tool (ISAT) scenario files.

Python scripts were developed to write the scenario files, which consist of information regarding the locations and characteristics of the vehicles, speed limit signs, and data collection triggers in the simulation. The scenario files were then opened in ISAT to visually inspect the object locations and verify that the Python scripts worked correctly. Finally, the scenario files were imported into the Minisim directory. Each scenario was tested multiple times to verify the correct placement and behavior of scenario and environment objects. The output data from the trial runs were also analyzed and validated before any data were collected.

3.2.2 Simulated Traffic

The speed of the opposing traffic was set to the posted speed limit (55 miles per hour) and the vehicles were created at half-mile spacing along each track. This density was low enough to provide ample opportunity for drivers to pass, yet dense enough to prevent drivers from passing indiscriminately (i.e. they had to look ahead and verify that an oncoming vehicle would not interfere with a passing maneuver). The speed of the same-lane traffic was set to 43 miles per hour, which was based on the assumptions in the AASHTO passing sight distance guidelines that the speed differential between the overtaking and impeding vehicles is 12 miles per hour and the overtaking vehicle is traveling at the posted speed limit (31). The same-lane vehicles were spaced at quarter-mile spacing which was close enough to provide the drivers with ample opportunity to overtake the vehicles yet far enough to prevent platooning and allow the drivers to pass a single vehicle and return to their lane. For this study, all vehicles in the simulation were sedans to eliminate differences in choices to pass long or short vehicles, sight restriction differences between large and small impeding vehicles, and perception differences between large and small oncoming vehicles.

3.2.3. Experimental Design

The statistical experimental design of a Latin square was carried out to control for order effects in the experiment. In a Latin square design treatment, sections were assigned to rows and columns in such a way that each treatment occurred once. Table 3.1 shows an example of the experimental design used for this study.

Table 3.1: Latin Square Experimental Design for First Stage

Track	Tile Order						
Track 1	1	2	3	Break	6	5	4
Track 2	2	3	1	Break	4	6	5
Track 3	3	1	2	Break	5	4	6

Each track was driven by eight participants. The tracks were coded as follows:

- Northbound: 1 = Seward; 2 = Parks; and 3 = Sterling
- Southbound: 4 = Seward; 5 = Parks; and 6 = Sterling

3.3 Scenario Development: Second Stage

The second stage of the driving simulation experiment focused on the effects of guardrail and centerline striping on driver passing behavior. Results from the first stage were used to prioritize shorter sections of highway so more repetitions could be completed. The targeted sections were:

- Seward Highway (between Milepost 109 and Milepost 112),
- Parks Highway (between Milepost 158 and Milepost 160), and
- Sterling Highway (between Milepost 149.5 and Milepost 150.5).

This stage of the experiment also included a short experiment to test the effects of guardrail on collision avoidance. Each participant encountered an opposing vehicle that was executing a passing maneuver and was in the participant's travel lane. To avoid a head-on collision, the participant needed to move out of the oncoming vehicle's trajectory by moving toward the edge of the road. The shoulder was clear (i.e. no guardrail was present) for half of the participants and not clear (i.e. guardrail on the shoulder) for the other half of the participants. Since this portion of the experiment yielded only one data point per participant (i.e. one chance to either avoid or fail to avoid a collision), the number of participants for the second stage experiment was doubled to 48 participants to increase the statistical power of the experiment.

The scenario development, traffic characteristics, and statistical design of the second stage of the experiment are described in the following sections.

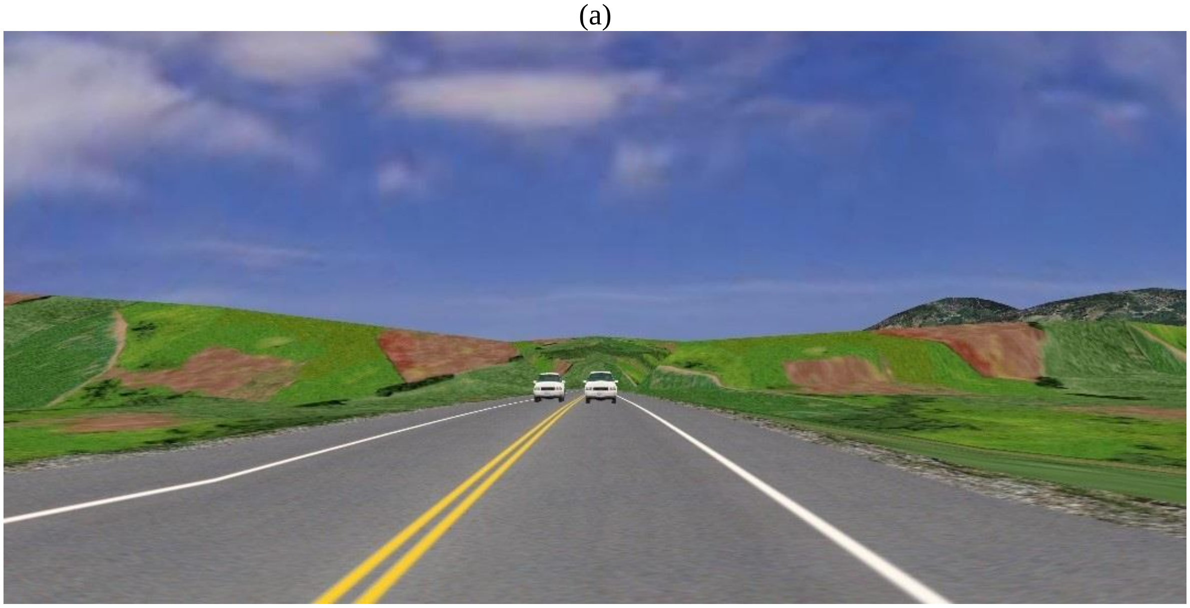
3.3.1 General Summary

The procedure for developing the simulation scenarios for the second stage was the same as for the first stage with the additions of changing the centerline striping and adding guardrail. Google Streetview was used to identify the locations of the passing zones and guardrail sections. The appropriate image texture (striped for no passing, two-way passing, or one-way passing) was then applied to the roadway in 3ds Max to match the observed striping. Guardrail sections were inserted with the 3ds Max Civil View extension with dimensions taken from the Alaska Department of Transportation Standard Drawings Manual (32). An example screenshot with centerline striping and guardrail is shown in Figure 3.6.

Figure 3.6: Seward Highway with Guardrail and Field-Matched Striping

In addition to the three sections of Alaskan highway, a short roadway section was designed to test the effects of guardrail on collision avoidance. The section consisted of a straight and level section of road for 2000 feet followed by a 600-foot crest vertical curve (K = 205). The section was marked with a double yellow centerline for its entirety. The tile was created with and without guardrail at the curve. Screenshots of the collision avoidance portion of the experiment are shown in Figure 3.7.

(a)



(b)

Figure 3.7: Collision Avoidance Experiment: (a) Guardrail and (b) no Guardrail

3.3.2 Simulated Traffic

Adjustments to the traffic were made based on preliminary results from the field data collection and results from the first stage. The speed of the same-lane traffic was increased to 57 miles per hour based on field data. The posted speed limit was increased to 60 miles per hour to encourage participants to pass and as a compromise between the actual posted speed limits of 55 miles per hour for Seward Highway and Sterling Highway and 65 miles per hour for Parks Highway. The speed of the oncoming vehicles was set at the posted speed limit. Since there were few unsafe pass attempts in the first stage, the density of the oncoming traffic was increased so that drivers had to accept shorter gaps. Vehicles were created at an average distance of one-quarter mile along each track; these distances were drawn from a normal distribution with a standard deviation of 300 feet. This variation was added to prevent participants from realizing that the traffic was regularly spaced and making passing decisions accordingly. The spacing between the same-lane vehicles was kept at one-quarter mile.

To test the effect of guardrail on collision avoidance, an oncoming vehicle was programmed to be in the participant's travel lane overtaking another vehicle when the participant traveled over a crest vertical curve. The overtaking vehicle was programmed to travel at 65 miles per hour and the overtaken vehicle was programmed to travel at 60 miles per hour.

3.3.3 Experimental Design

A standard Latin-square design for three track sections would have resulted in the Seward section with no guardrail (section 1) preceding the Seward section with guardrail (section 2) in 2 out of 3 conditions (see tracks 1-3 in Table 3.2). A counterbalancing Latin-square design in which the Seward section with guardrail (section 2) preceded the Seward section with no guardrail (section 1) in 2 out of 3 conditions (see tracks 4-6 in Table 3.2) was added to eliminate order effects.

Table 3.2: Latin Square Experimental Design for Second Stage

Track	**Tile Order**						
Track 1	1	2	3	Break	6	5	4
Track 2	2	3	1	Break	4	6	5
Track 3	3	1	2	Break	5	4	6
Track 4	2	1	3	Break	6	4	5
Track 5	1	3	2	Break	5	6	4
Track 6	3	2	1	Break	4	5	6

Each track was driven by eight participants. The tracks were coded as follows:

- Northbound: 1 = Seward – No GR; 2 = Seward – GR; and 3 = Parks and Sterling
- Southbound: 4 = Seward – No GR; 5 = Seward – GR; and 6 = Parks and Sterling

At the end of the second drive (after all of the passing data were recorded) each participant encountered the collision avoidance portion of the experiment. Guardrail was present for half of the participants and no guardrail was present for the other half of participants.

3.4 Participant Recruitment

For each stage, participants with unrestricted valid driver's licenses were tested. Participants were recruited from the community by posted advertisements on community bulletin boards, Craigslist classifieds, and word of mouth. Participants were required to be 18 years of age or older for this study, and were paid $20 per hour. Participants recruited for the study were handled in accordance with the University of Idaho's Institutional Review Board (IRB) protocol governing the use of human subjects in research.

3.5 Procedure

Basic instructions were read to all drivers prior to participation. The instructions stated that the driver's goal was to keep their vehicle centered in their lane and to travel at an appropriate speed, just as they would in everyday driving. To induce a sense of urgency and increase the number of passing maneuvers, the participants were instructed to drive as if they were in a hurry. In the first stage, the instructions said that the participants were in a hurry "to get home from a weekend long trip." In the second stage, the instructions stated that the participants were in a hurry "for a family emergency"; this heightened urgency was deemed necessary to encourage participants to pass vehicles at higher speeds than in the previous stage.

The participants then completed a short test drive to become familiar with the controls of the vehicle. Each participant then drove the sequence of tracks indicated in the experiment design, with a short break between the two scenarios. After the completion of both test scenarios, the participants completed a brief questionnaire regarding the simulation, their driving history, and selected personal demographics.

3.6 Data Reduction

Each session recorded about one gigabyte of data that was stored in a data acquisition (.daq) format. These data contained microscopic information related to vehicle dynamics, user input, and position. Data related to vehicle dynamics included speed and acceleration. User input data included steering wheel angle, accelerator position, brake pedal position, turn signal position, and gear selector position. Position data included the vehicle's coordinates, lane position, and following distance, as well as the coordinates of every vehicle in the scenario. All .daq files were converted into a hierarchical data format (hdf5) for data reduction.

A script was written using an IPython interface to identify when passes were attempted. Several variables related to each pass attempt were either recorded directly from the raw data or calculated, including the location of the participant's vehicle at the initiation and conclusion of the maneuver, distance to the impeding vehicle and oncoming vehicle at the initiation and conclusion of the maneuver, the total time and distance spent in the opposing lane, the vehicle's speed when abreast of the impeding vehicle, and the time to contact to the oncoming vehicle at the initiation and conclusion of the maneuver. The location of the vehicle at the time of initiation was then used to extract data such as sight distance, slope, and horizontal and vertical curvature.

A script was also written to extract frames from each drive to build a dataset that included the pass attempts from the pass counting script as well as frames at which the drivers chose not to pass. The script looped through each drive and sampled frames from a uniform distribution of 10-30 seconds; if a pass attempt occurred within the next 20 seconds, the script would record geometric and situational variables for the frame at which the pass attempt was initiated and record "attempt" for the outcome variable. If no attempt occurred, the variables were recorded for the frame that was sampled and "none" was recorded for the outcome variable. The frames were also only sampled if the driver was within 250 feet of an impeding vehicle so that a pass attempt was possible; of the observed pass attempts, this distance represented the 98th percentile of the following distance distribution.

Finally, a script was written to extract information regarding how each participant in the second stage reacted to the vehicle in their lane. Specifically, the script recorded whether the driver collided with the oncoming vehicle and how far the driver moved toward the edge of the road (lane deviation).

Chapter 4: Results

In this chapter, a breakdown of the participant demographics is detailed first. A comparison of the passing locations under dashed centerline (first stage) and field-matched centerline (second stage) conditions is then shown. The first stage results, including a logistic model of driver passing choice, characterization of passing maneuvers, and analysis of passing safety under different geometric conditions are then presented. Finally, the causal effects of guardrail on passing behavior and collision avoidance are presented; the second stage analysis was limited to a comparison of guardrail vs. no-guardrail conditions within the experiment because it was determined that there were too many differences between the first and second stage experiments to make valid comparisons between experiments.

4.1 Participant Information

A total of 72 participants were recruited to complete simulation testing for both stages. Table 4.1 provides a summary of the demographics for the participants.

Table 4.1: Participant Demographics

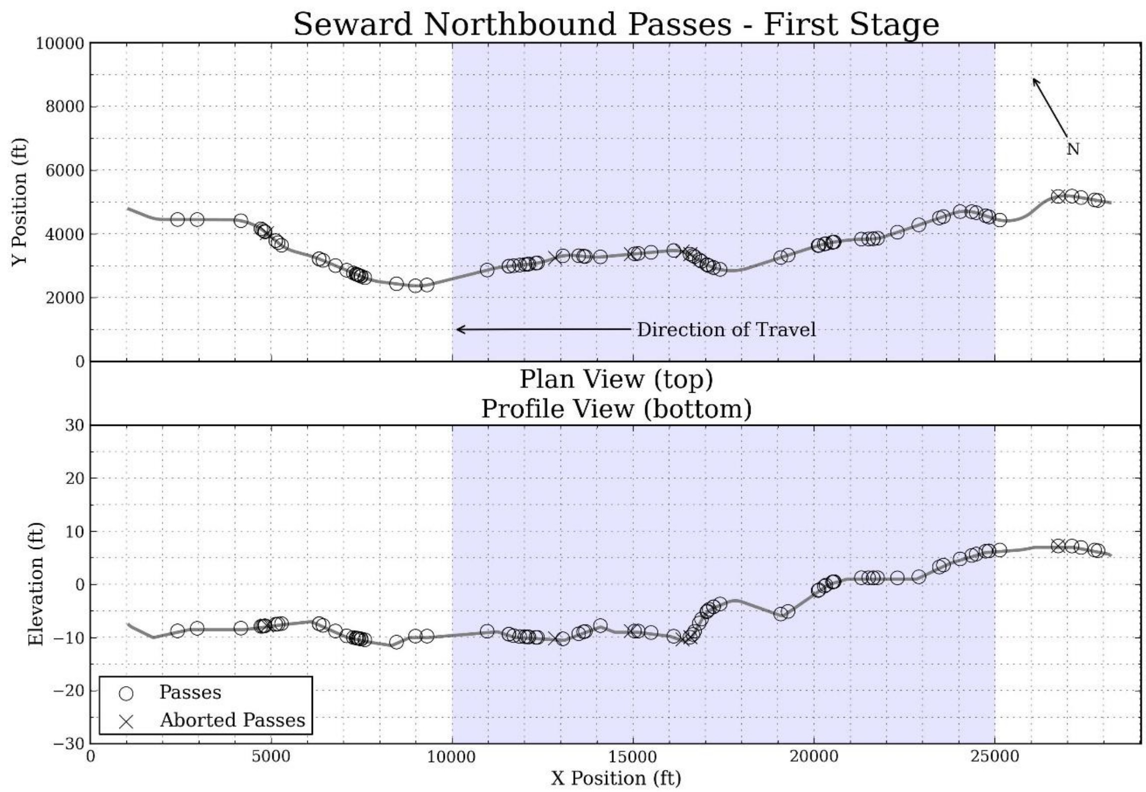
	1st Stage	2nd Stage
Age		
Minimum	18	18
Maximum	60	78
Mean	27.5	28.6
Driving Experience		
Minimum	3	2
Maximum	45	60
Mean	11.5	13.2
Sex		
Male	16	27
Female	8	21
Marital Status		
Single	19	34
Married	5	14

4.2 Passing Locations

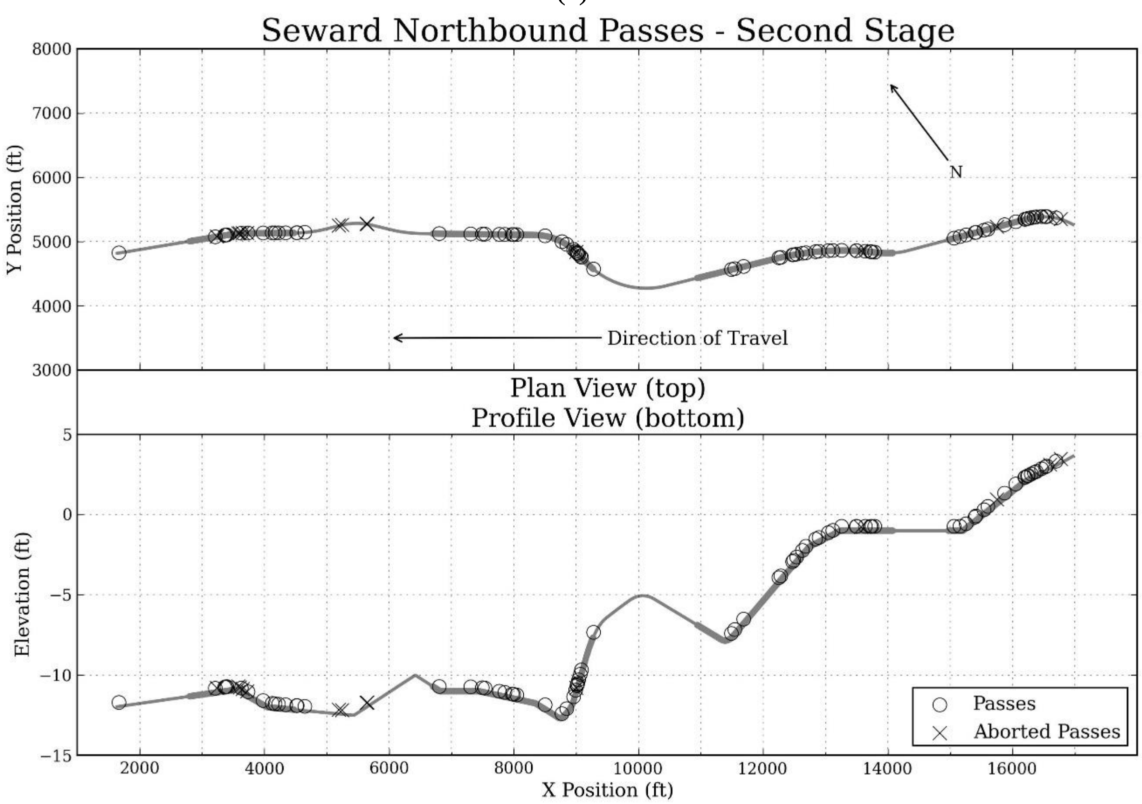
The initiation location of each completed and aborted passing maneuver was plotted on plan-view and profile-view plots of each highway section and the results are shown in

Figures 4.1 to 4.6 (pages 23 to 28). Part (a) of each figure shows the pass attempts in the first stage (unrestricted passing) and part (b) of each figure shows the pass attempts in the second stage. The gray-highlighted portion of the first stage plots corresponds to the shortened sections tested in the second stage. The passing zones in the second stage are indicated by wider centerlines in the plots. Each figure identifies the horizontal curvature (shown in the top section in plan view) and the accompanying vertical curvature (shown in the bottom section in profile view) for both the northbound and southbound directions. The coordinates indicated in each figure correspond to how the road alignment was positioned in the simulator files and are arbitrary in terms of real-world position; however, the scale is correct and units are in feet.

On the Parks and Sterling highway test sections, there is not a clear relationship between horizontal curvature and pass attempt locations, though the attempts appear to cluster downstream from crest vertical curves. In contrast, the pass attempts appear to cluster downstream from horizontal curves along the Seward highway test section as the vertical curvature on this section is minimal. These patterns are consistent with the expectation that drivers are less likely to pass when sight distance is restricted; sight distance is primarily restricted by crest curves on the Parks highway and Sterling highway test sections and is primarily restricted by the horizontal curves on the Seward highway test section.

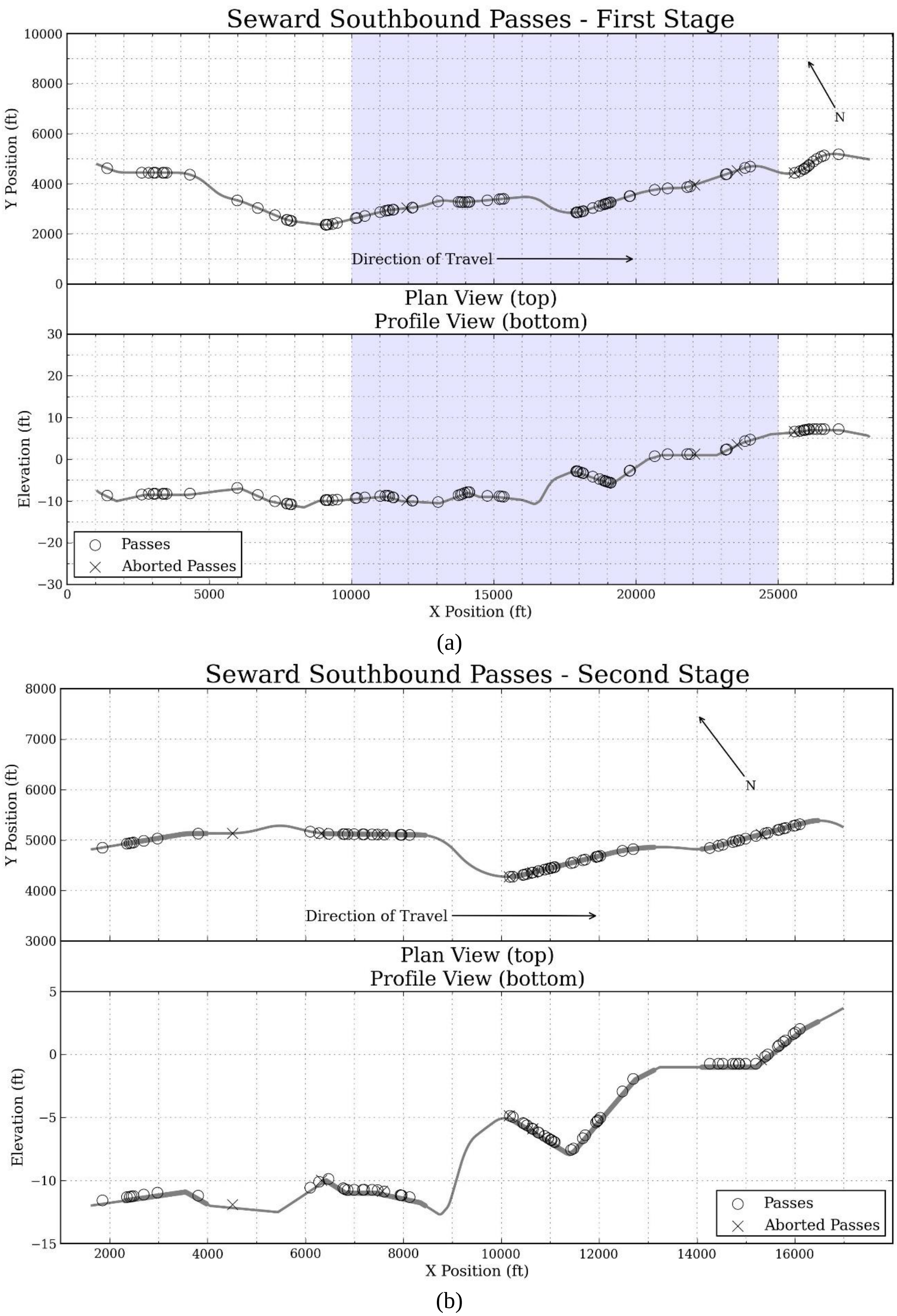


(a)



(b)

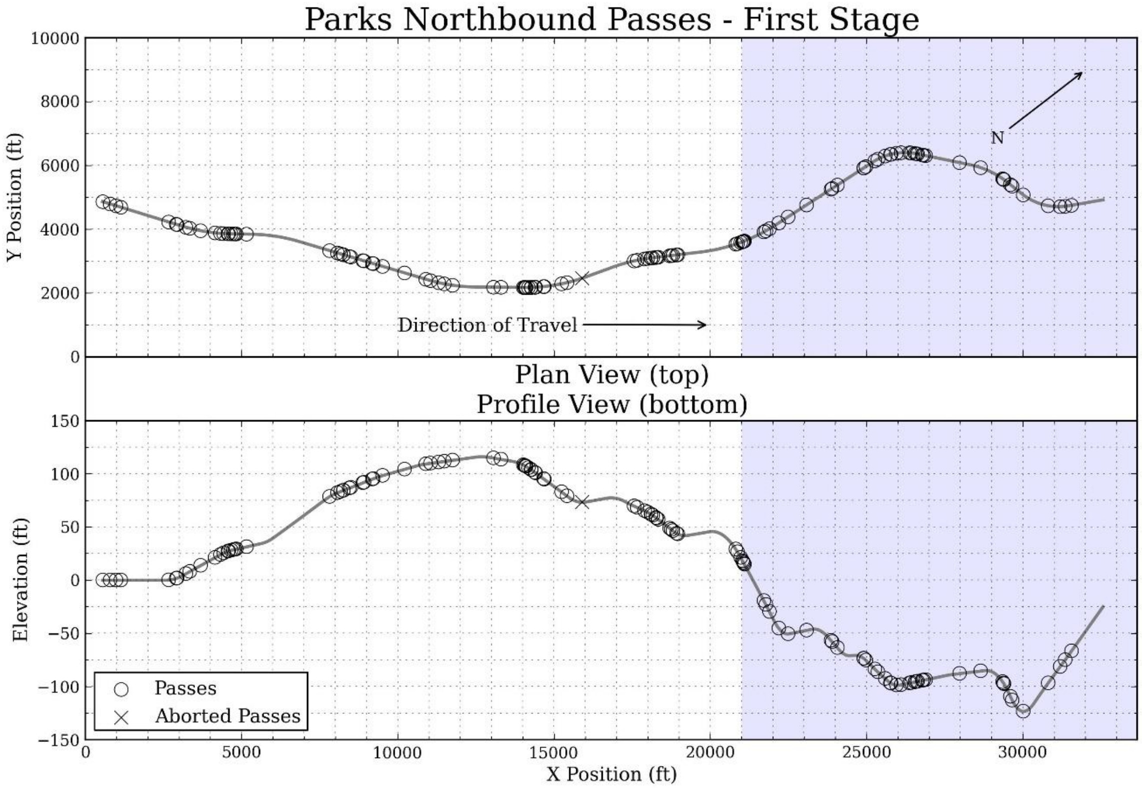
Figure 4.1: Pass Locations (Seward - NB): (a) First Stage and (b) Second Stage



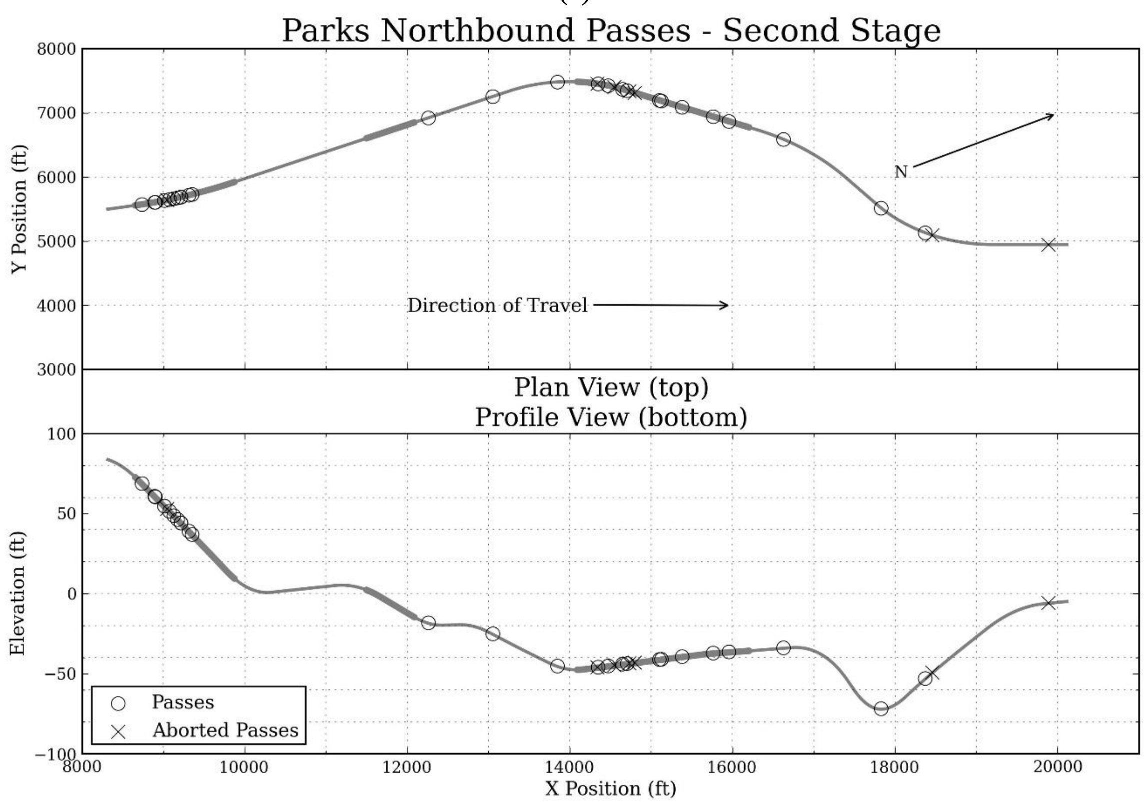
(a)

(b)

Figure 4.2: Pass Locations (Seward - SB): (a) First Stage and (b) Second Stage

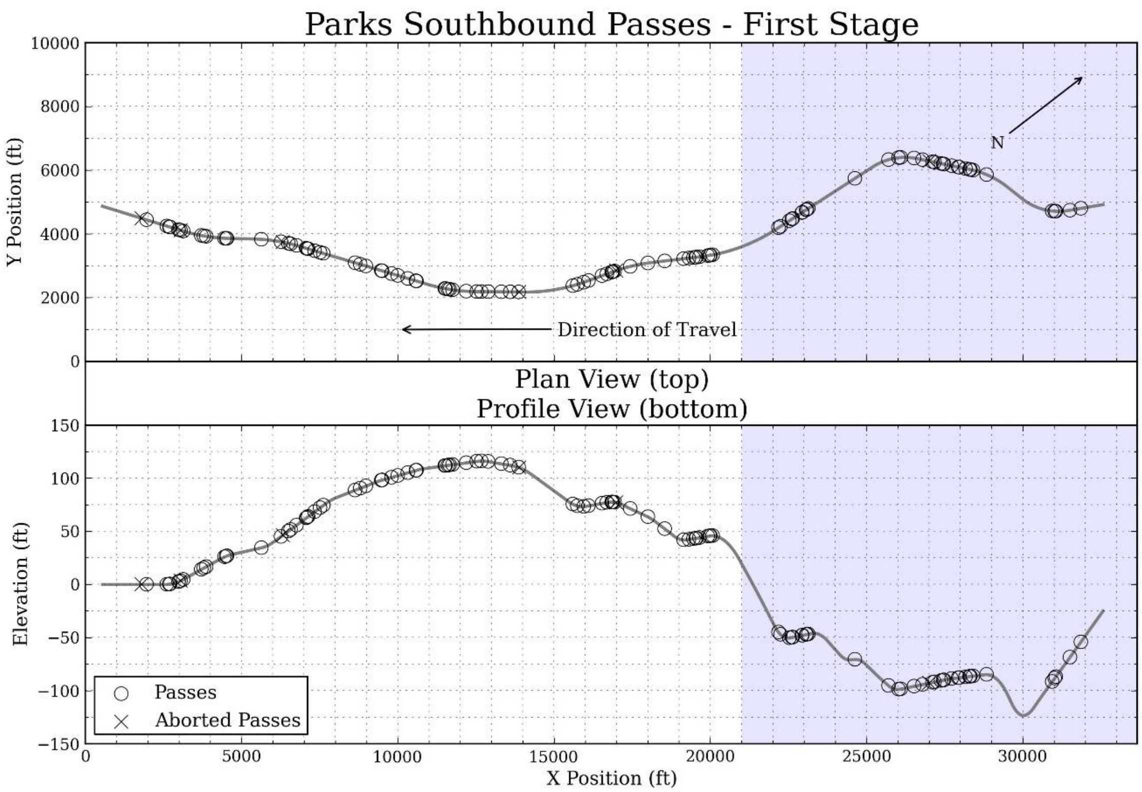


(a)

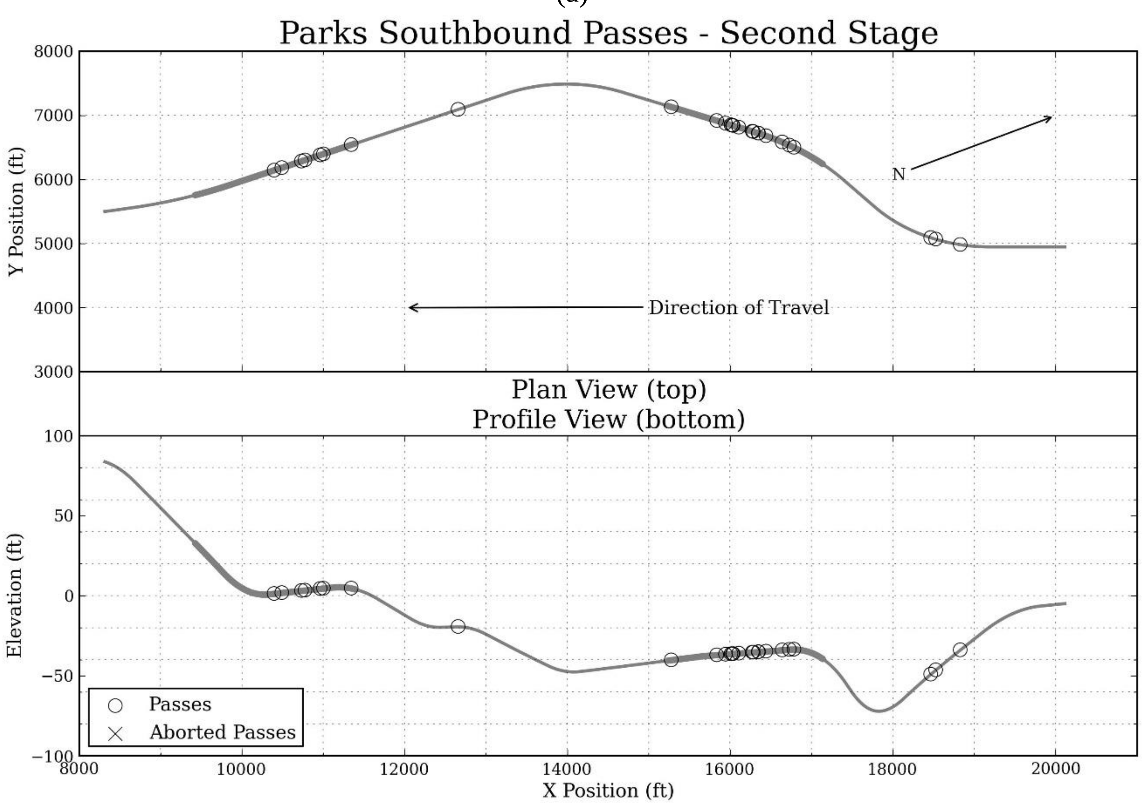


(b)

Figure 4.3: Pass Locations (Parks - NB): (a) First Stage and (b) Second Stage

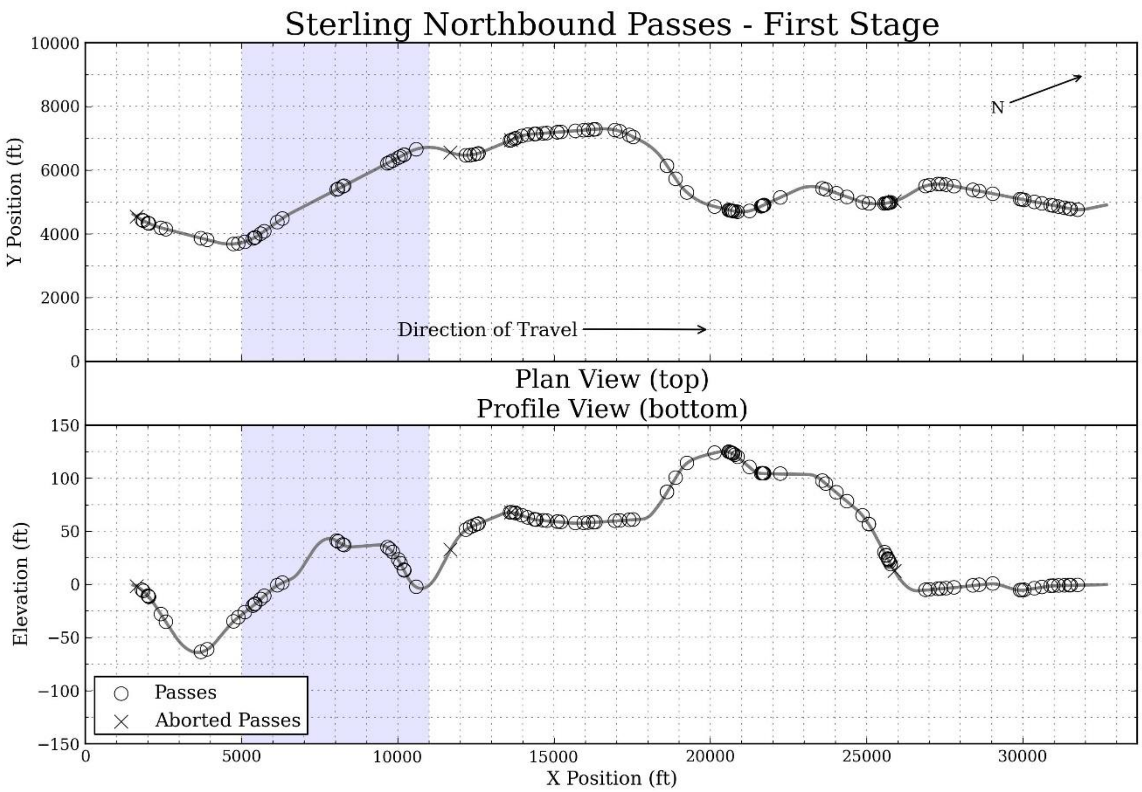


(a)

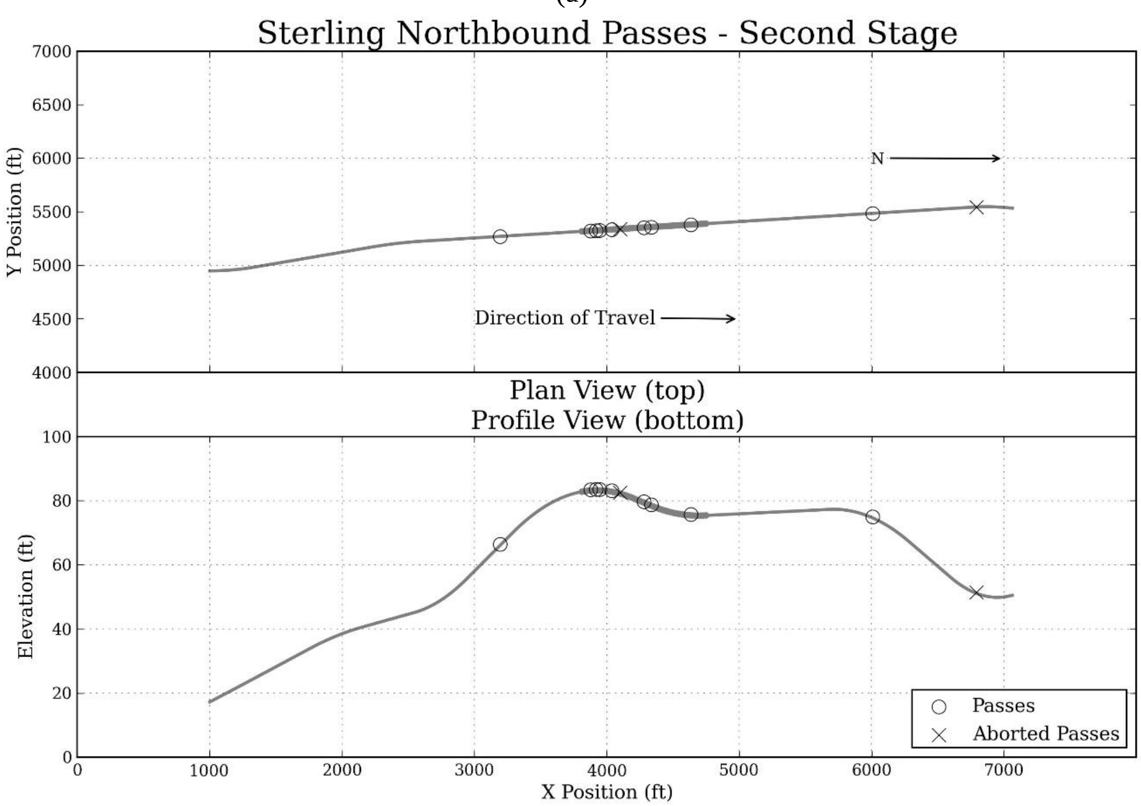


(b)

Figure 4.4: Pass Locations (Parks - SB): (a) First Stage and (b) Second Stage

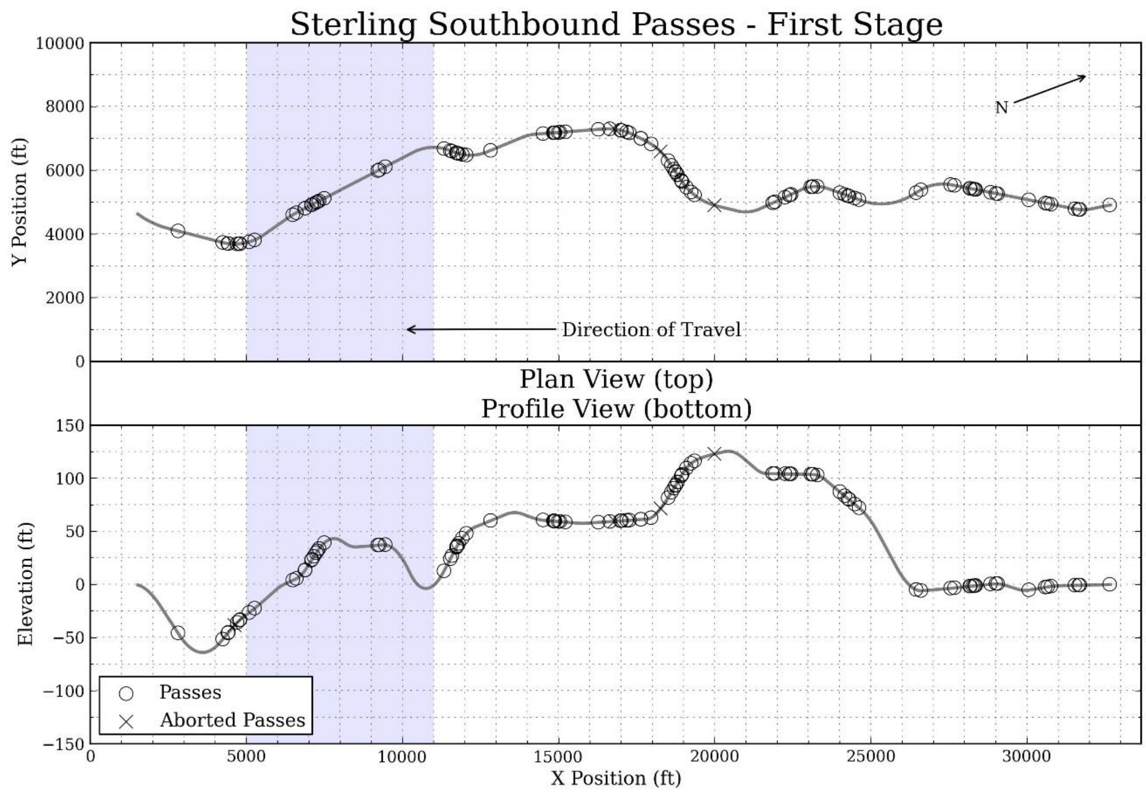


(a)

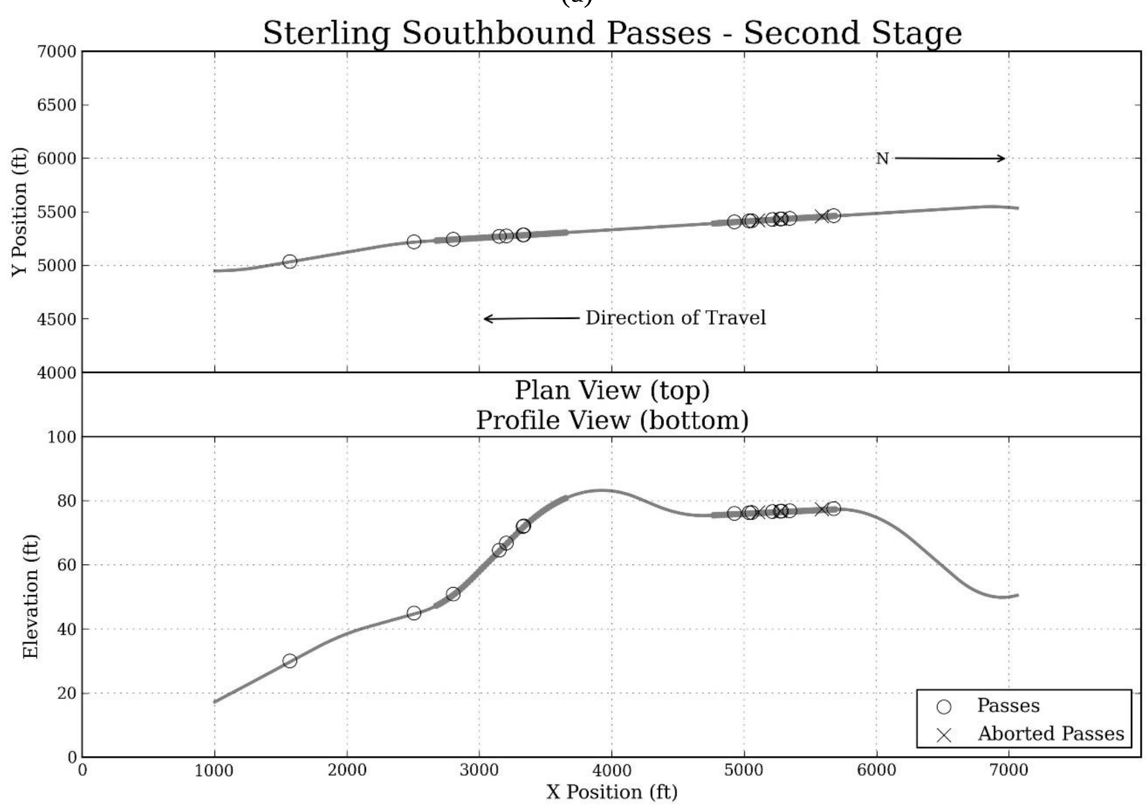


(b)

Figure 4.5: Pass Locations (Sterling - NB): (a) First Stage and (b) Second Stage



(a)



(b)

Figure 4.6: Pass Locations (Sterling - SB): (a) First Stage and (b) Second Stage

4.3 Data Analysis: First Stage

4.3.1 Passing Choice Logistic Model

A mixed-effects logistic regression model was developed to infer the effects of geometric configuration on the choice to pass. Situational variables and driver characteristic variables were also included in the model to control for variability. The geometric variables included the slope, horizontal curvature, and vertical curvature, which were recorded as the change in curvature (heading in degrees and slope in percent) in the previous and subsequent 500-foot and 1000-foot segments of road. The 1000-foot length was chosen because 1000 feet was the approximate average distance that a passing maneuver took to complete and the 500-foot distance was chosen to quantify how much of the curvature occurred in the early or late portions of the maneuver. Situational variables included the following distance (i.e. distance to impeding vehicle), distance to sight obstruction, and whether the sight obstruction was a natural sight obstruction or an oncoming vehicle. Driver characteristic variables included demographic variables and average speed. The participant identification (PID) was also included in the model as a random effect. The variables that were considered for the model are summarized in Table 4.2. The distance to sight obstruction variable was transformed by taking the square root, which resulted in an improved model fit.

Table 4.2: Description of Variables Considered for Passing Choice Logistic Model

Variable	Description
event (dependent variable)	1 = pass attempted; 0 = otherwise
Sterling	1 = Sterling; 0 = otherwise
Seward	1 = Seward; 0 = otherwise
right500, left500	change in heading in 500 feet of road from driver's location [degrees]; if < 0 absolute value was taken and this was *left* variable, if > 0 then *right* variable; 0 = if road was straight or curved in opposite direction
right1000, left1000	change in heading in 1000 feet of road from driver's location [degrees]; if < 0 absolute value was taken and this was *left* variable, if > 0 then *right* variable; 0 = if road was straight or curved in opposite direction
sag500, crest500	change in slope in 500 feet of road from driver's location; if < 0 absolute value was taken and this was *crest* variable, if > 0 then *sag* variable; 0 = if road was flat or curved in opposite direction
sag1000, crest1000	change in slope in 1000 feet of road from driver's location; if < 0 absolute value was taken and this was *crest* variable, if > 0 then *sag* variable; 0 = if road was flat or curved in opposite direction
up, down	slope at driver's location; if < 0 absolute value was taken and this was *down* variable, if > 0 then *up* variable; 0 = if road was level or sloped in opposite direction
b_right500, b_left500	change in heading in 500 feet of road previous to driver's location [degrees]
b_right1000, b_left1000	change in heading in 1000 feet of road previous to driver's location [degrees]
b_sag500, b_crest500	change in slope in 500 feet of road previous to driver's location
b_sag1000, b_crest1000	change in slope in 1000 feet of road previous to driver's location
follow	distance from driver to impeding vehicle [feet]
obdist	distance from driver to sight distance obstruction (either natural obstruction or oncoming vehicle) [feet]; defined as minimum between distance to oncoming vehicle (*dist*) and sight distance (*SD*)
obtype	type of sight distance obstruction: 1 = oncoming vehicle (*dist* < *SD*); 0 = natural sight distance obstruction (*SD* < *dist*)
avg_speed	driver average speed while traveling in own lane unimpeded
sex	1 = male; 0 = female
mar_stat	1 = married; 0 = single

The final model was chosen based on backwards elimination by removing the variables with the highest probability that did not meet the chosen significance criterion (p <

0.10). The 500-foot and 1000-foot segment alternatives of the horizontal and vertical curvature variables were compared and the more-significant alternative was chosen to remain in the model. The 500-foot alternatives were more significant for the horizontal curvature variables and the previous sag curvature, while the 1000-foot alternatives were more influential for the vertical curvature. The final model is summarized in Table 4.3.

Table 4.3: Summary of Final Logistic Model

Variable	**Scaled Coefficient**	**Standard Error**	**z Value**
Intercept	-0.729	0.205	-3.558 ***
Seward	-0.987	0.187	-5.274 ***
up	-0.390	0.086	-4.524 ***
right500	-0.182	0.088	-2.065 *
left500	0.170	0.076	2.229 *
crest1000	-0.781	0.139	-5.626 ***
sag1000	0.188	0.092	2.047 *
b_sag500	-0.249	0.083	-3.004 **
follow	-0.679	0.098	-6.925 ***
sqrt(obdist)	1.293	0.099	13.020 ***
obtype	-0.531	0.168	-3.162 **
avg_speed	1.156	0.176	6.566 ***
age	-0.509	0.183	-2.776 **

Random effects: *(Intercept | PID) Variance = 0.627, Standard Deviation = 0.792*
Model fit: *Null LL = -907.7, Final LL = -606.6, McFadden's* R^2 *= 0. 332*
Significance: * = ($p < 0.05$) ** = ($p < 0.01$) *** = ($p < 0.001$)

The model showed significant effects for the highway section, slope, horizontal curvature, vertical curvature, following distance, distance to sight obstruction, and type of sight obstruction, as well as the age and average speed of the driver. Drivers were less likely to pass on the Seward Highway section than on the Parks Highway or Sterling Highway sections. The reason for this is unclear, although there are several possible contributing factors. First, it is possible that the highway section variable interacts with some of the other geometric variables in complex ways that are not described by this model. Other iterations of the model showed weak interactions between the section variables and geometric variables that were discarded because the effects were not shown to be statistically significant, although the cumulative effect of these interactions may be significant. Additionally, 41.7% of participants reported that the cliff decreased their likelihood to choose to pass, with some citing the sight distance restriction and others noting the discomfort due to driving between a cliff and a body of water.

Drivers were less likely to pass when the road turned to the right in the next 500 feet than if the road was straight, and were more likely to pass if the road turned left than if the road was straight. Two factors are likely to contribute to a preference for passing on left-hand curves; first, passing on a left-hand curve flattens the overtaking vehicle's path and shortens the path length through the curve and, second, the impeding vehicle often obstructs the sight distance for the overtaking driver on straight sections and right-hand curves.

Drivers were also less likely to pass when there was a crest curve within the next 1000 feet than if the road was flat, and were more likely to pass if the road had a sag curve within the next 1000 feet than if the road was flat. Drivers were less likely to pass if there was a sag curve within the previous 500 feet than if the road was flat. Finally, drivers were less likely to pass when they were traveling uphill than if they were traveling on level road or downhill.

Of course, drivers were also more likely to pass as the distance to the sight obstruction increased, and were less likely to pass if the sight obstruction was a vehicle than if it was a natural sight restriction. Drivers were more likely to pass as the follow distance decreased, which makes sense because drivers close the gap when they are preparing to pass. Finally, drivers were more likely to pass if their average speed was higher and less likely to pass as their age increased.

4.3.2 Passing Maneuver Characterization by Geometric Configuration

The vehicle speed when abreast of the impeding vehicle, total time spent in opposing lane, total distance traveled in the opposing lane, following distance at the initiation of the pass, and distance from the impeding vehicle at the end of the maneuver were calculated for each passing maneuver (see Figure 4.7). T_i is the time when the vehicle breaches the centerline, T_a is the time when the vehicle is abreast of the impeding vehicle, and T_f is the time when the vehicle returns fully to its own lane. Speed abreast is the speed at T_a, total time spent in opposing lane is the time in seconds between T_i and T_f, distance traveled is the distance traveled between times T_i and T_f, following distance at the initiation is d_i, and distance from the impeding vehicle at the end of the maneuver is represented by d_f.

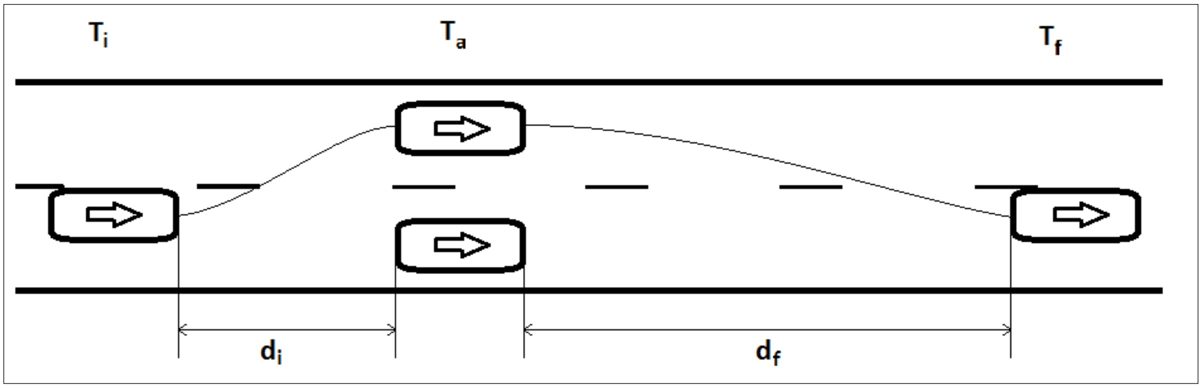


Figure 4.7: Passing Maneuver Characteristics

The data were subdivided into geometric configurations based on the change in heading (left, right, and straight) and slope (sag, crest, and flat) in the 500-foot and 1000-foot segments of road following the initiation of each pass. Pairwise comparisons of the means of each variable for each geometric configuration were performed using a t-test at the 0.05 significance level. The results are summarized in Tables 4.4 and 4.5; significant differences are denoted as indicated in the footnotes of each table. For example, the mean speed when the road was straight for at least 500 feet from pass initiation, 64.9 miles per hour, is statistically significantly greater than the mean speed when the road curved to the right within 500 feet from pass initiation, 63.5 miles per hour, which is indicated by an asterisk (*). Likewise, the mean speed when the road was straight for at least 1000 feet from pass initiation, 65.4 miles per hour, is statistically significantly greater than the mean speed when the road curved to the left within 1000 feet from pass initiation, 63.8 miles per hour, which is indicated by a cross (†).

Horizontal curvature affected every measure that was compared. During passing maneuvers drivers tended to reach higher speeds when passing on straight sections of road than on curves. These differences were small (less than 2 miles per hour, on average) so little practical significance was gained. Vehicles were in the oncoming lane for shorter times and distances on average when the road was curved to the right than when the road was straight or curved to the left; this difference corresponds to a substantial reduction in distance between the vehicle and the passed vehicle when the pass was finished and the vehicle returned to its own lane, which averaged 176.7 feet on left curves, 188.8 feet on straight sections, and 148.2 feet on right curves. Similarly, when the roadway curved to the right within 500 feet of the initiation of the pass, the average following distance at the initiation of the pass was 101.7 feet compared to 115.4 feet when the road was straight.

Table 4.4: Passing Maneuver Characteristics by Horizontal Curvature

	500ft			**1000ft**		
	Left N=218	**Straight N=256**	**Right N=143**	**Left N=289**	**Straight N=151**	**Right N=177**
Vehicle Speed (when abreast, in mph)	64.0	64.9*	63.5	63.8	65.4†	64.0
Total Time Spent (opposing lane, in seconds)	11.4*	11.1	10.6	11.4*	11.3*	10.4
Total Distance Traveled (opposing lane, in feet)	1035.2*	1024.1*	957.6	1036.5*	1049.8*	941.9
Finish Distance (to impeding vehicle, in feet)	174.2*	178.7*	152.8	176.7	188.8	148.2
Initial Follow Distance (to impeding vehicle, in feet)	112.0	115.4*	101.7	110.5	117.1	106.6

Significant ($p < 0.05$) differences indicated by: ** > Right* *† > Left*

Table 4.5: Passing Maneuver Characteristics by Vertical Curvature

	500ft			**1000ft**		
	Crest N=158	**Flat N=286**	**Sag N=173**	**Crest N=179**	**Flat N=161**	**Sag N=277**
Vehicle Speed (when abreast, in mph)	63.6	63.6	65.8*†	64.3	63.5	64.7
Total Time Spent (opposing lane, in seconds)	11.5‡	11.3‡	10.4	11.2	11.4	10.9
Total Distance Traveled (opposing lane, in feet)	1037.8‡	1024.0‡	970.8	1013.6	1035.0	999.0
Initial Follow Distance (to impeding vehicle, in feet)	109.6	108.3	116.7	110.0	106.6	114.2
Finish Distance (to impeding vehicle, in feet)	170.8	173.3	169.1	168.2	178.7	169.4

Significant ($p < 0.05$) differences indicated by: ** > Flat* *† > Crest* *‡ > Sag*

When the road had a sag curve within 500 feet of the pass initiation, the average speed of the vehicle while abreast of the impeding vehicle was 65.8 miles per hour compared to 63.6 miles per hour when the road was flat or had a crest curve. The higher speed on sag curves corresponds to less time spent and distance traveled in the opposing lane. Each of these differences only occurred when the sag curve was in the early portion (less than 500 feet from initiation) of the passing maneuver and diminished if the sag curve was within 1000 feet of the initiation of the maneuver.

4.3.3 Passing Safety by Geometric Configuration

The most important variable regarding passing safety is the final time to contact (TTC), which is the most direct measure of how close a driver executing a passing maneuver comes to colliding with a vehicle in the oncoming lane. A common criterion used to determine whether a pass is excessively risky is if the final time to contact is less than three seconds (18). The proportion of passes that ended in an unsafe time to contact was calculated for each section. The most important factor influencing the outcome of a passing maneuver is the distance to the oncoming vehicle when the driver chooses to initiate the pass. To compare passing safety in this experiment, the average final time to contact, proportion of unsafe passes, and average initial distance to an oncoming vehicle were recorded for each pass and a pairwise comparison was performed by geometric configuration. A subset of the data for which the initial sight distance is greater than 1000 feet, which is the minimum passing sight distance for a 60 mile-per-hour highway recommended by the MUTCD, was also compared to control for unsafe events that would have occurred in no-passing zones had the centerline been striped per MUTCD guidance. The mean values of the initial distance and time to contact variables were compared using a t-test and the proportions of unsafe passes were compared using a chi-square contingency test; all tests were performed at the 0.05 significance level. The results are summarized in Tables 4.6 and 4.7; significant differences are denoted as indicated in the footnotes of each table.

Table 4.6: Passing Safety Characteristics by Horizontal Curvature

	500ft			**1000ft**		
	Left	**Straight**	**Right**	**Left**	**Straight**	**Right**
Initial Distance $^{\alpha}$ (to oncoming vehicle, in feet)	3846.4	4008.9	3970.1	3844.1	4035.9	4025.9
Initial Distance $^{\beta}$ (SD > 1000 feet, in feet)	3903.9	4019.2	4011.5	3882.0	4052.4	4072.8
Time to Contact $^{\alpha}$ (in seconds)	10.6	12.8†	12.1†	10.7	13.1†	12.7†
Time to Contact $^{\beta}$ (SD > 1000 feet, in seconds)	11.0	12.4	12.4	10.9	12.6†	13.0†
Proportion of Unsafe Passes $^{\alpha}$ (defined as TTC < 3 seconds)	0.106	0.116	0.089	0.115	0.110	0.089
$^{\alpha}$N = (217,249,135), (287,145,169) *$^{\beta}$N = (195, 237, 123), (264, 137, 154)*	*Significant (p < 0.05) differences indicated by: * > Right † > Left*					

The time to contact on passes was lower on average when the pass occurred on a left curve than when the road was straight or curved right. The difference in these averages diminished for cases when the sight distance was above the minimum sight distance of 1000 feet and the left curve was in the early portion of the maneuver (within 500 feet of initiation). Despite the overall lower average of time to contact on left curves, there was not a higher proportion of unsafe passing maneuvers.

Table 4.7: Passing Safety Characteristics by Vertical Curvature

	500ft			1000ft		
	Crest	**Flat**	**Sag**	**Crest**	**Flat**	**Sag**
Initial Distance $^{\alpha}$ (to oncoming vehicle, in feet)	3858.2	3975.0	3963.5	3848.2	4159.4†‡	3875.2
Initial Distance $^{\beta}$ (SD > 1000 feet, in feet)	3932.5	3993.5	3984.7	3859.9	4213.9†‡	3908.5
Time to Contact $^{\alpha}$ (in seconds)	10.9	11.6	13.2†	11.1	12.5	11.9
Time to Contact $^{\beta}$ (SD > 1000 feet, in seconds)	11.1	11.7	12.9	11.2	12.7†	11.9
Proportion of Unsafe Passes $^{\alpha}$ (defined as TTC < 3 seconds)	0.109	0.125	0.072	0.124	0.096	0.101
$^{\alpha}$N = (156, 279, 166), (177, 157, 267) *$^{\beta}$N = (127, 268, 160), (160, 150, 245)*	*Significant ($p < 0.05$) differences indicated by: * > Flat † > Crest ‡ > Sag*					

When the road was flat for at least 1000 feet from pass initiation, the average distance to the oncoming vehicle at initiation was 4159.4 feet compared to 3848.2 feet when there was a crest curve and 3875.2 feet when there was a sag curve. When the sight distance was more than 1000 feet, the average time to contact of 12.7 seconds was higher when the road was flat compared to 11.2 seconds when the road had a crest curve, which corresponds to the higher initial distance. When the road had a sag curve within 500 feet of the initiation of the pass, the time to contact averaged 13.2 seconds which was higher than the average of 10.9 seconds when there was a crest curve in the early portion of the pass, although this difference diminished when sight distance was greater than 1000 feet. The higher average time to contact in both of these cases did not correspond to a significant difference in the proportions of unsafe passes.

4.4 Data Analysis: Second Stage

4.4.1 Effects of Guardrail on Passing Behavior

The effects of guardrail on passing behavior were examined by comparing the number and characteristics of pass attempts on the Seward section only in order to isolate the effects of the guardrail from the confounding effects of geometry. To assess how the presence of guardrail affects driver choice to pass, the number of pass attempts and the proportion of completed versus aborted passes were compared between conditions. To assess how the presence of guardrail affects the safety outcomes of passes, the average time-to-contact for attempted and completed passes and the proportion of safe (TTC > 3 seconds) versus unsafe (TTC < 3 seconds) passes were compared between conditions. The results are summarized in Table 4.8; as shown, none of the probabilities (p) were significant at a 0.05 significance level.

Table 4.8: Effects of Guardrail on Passing Behavior

		Guardrail		**p**
		No	**Yes**	
Pass Attempts	attempts/ participant	2.61	2.45	0.80
	Completed	72	74	0.16
	Aborted	14	7	
	TTC (s)	3.53	3.48	0.88
Completed Passes	passes/ participant	2.40	2.47	0.82
	Safe	32	31	0.87
	Unsafe	40	43	
	TTC (s)	3.05	3.10	0.88

For the 33 participants that attempted to pass on the Seward section, the average number of attempts with no guardrail present was 2.61 and the average number of attempts with guardrail present was 2.45. These averages were compared with a paired t-test and were not found to be different at a significance of $p < 0.05$. In the no-guardrail condition, 72 passes were completed and 14 were aborted; in the presence of guardrail, 74 passes were completed and 7 were aborted. These proportions were compared using Fisher's exact test and were not found to be different at a significance of $p < 0.05$. The average final time-to-contact (TTC) for pass attempts in the no-guardrail condition was 3.53 seconds and the average final time-to-contact (TTC) for pass attempts in the presence of guardrail was 3.48 seconds. These averages were compared with a t-test and were not found to be different at a significance of $p < 0.05$.

For the 30 participants that completed at least one pass on the Seward section, the average number of completed passes with no guardrail present was 2.40 and the average number of passes with guardrail present was 2.47. These averages were compared with a paired t-test and were not found to be different at a significance of $p < 0.05$. In the no-guardrail condition, 32 passes were safe and 40 were unsafe; in the presence of guardrail, 31 passes were safe and 43 were unsafe. These proportions were compared using Fisher's exact test and were not found to be different at a significance of $p < 0.05$. The average final time-to-contact (TTC) for completed passes in the no-guardrail condition was 3.05 seconds and the average final time-to-contact (TTC) for passes in the presence of guardrail was 3.10 seconds. These averages were compared with a t-test and were not found to be different at a significance of $p < 0.05$.

4.4.2 Effects of Guardrail on Collision Avoidance

The effects of guardrail on collision avoidance were examined by comparing the proportion of drivers that collided with the oncoming vehicle and the distance that the drivers moved toward the edge of the roadway (measured from the center of the driver's travel lane) under the conditions of no guardrail and in the presence of guardrail. The results are summarized in Table 4.9.

Table 4.9: Effects of Guardrail on Collision Avoidance

	Guardrail		**p**
	No	**Yes**	
Collision	4	16	0.0005
No Collision	20	8	
Lane Deviation (ft)	7.53	4.71	0.01

In the no-guardrail condition, 4 participants collided with the oncoming vehicle and 20 participants avoided a collision; in the presence of guardrail, 16 participants collided with the oncoming vehicle and 8 participants avoided a collision. These proportions were compared using Fisher's exact test and were significantly different at a significance of $p < 0.05$. In the no-guardrail condition, the average lane deviation was 7.53 feet and in the presence of guardrail the average lane deviation was 4.71 feet. These averages were compared using the Mann-Whitney U test and were significantly different at a significance of $p < 0.05$. The Mann-Whitney U test was chosen because the two distributions (guardrail versus no-guardrail) of maximum lane deviation were independent and were found to be non-normal.

Chapter 5: Conclusion

This chapter includes a discussion of practical implications of the passing behavior and collision avoidance portions of this study as well as study limitations and future research that could be conducted to validate and build upon this study.

5.1 Discussion

5.1.1 Passing Behavior

The passing maneuver is one of the most complex maneuvers in rural-highway driving and is consequently very difficult to model. Existing models are based primarily on vehicle speeds and available gaps and fail to directly account for roadway geometry (9-10, 22-26). Previous studies have shown that roadway geometry affects driver willingness to accept a gap and initiate a pass, although these studies did not consider vertical curvature or specify directionality in the horizontal curvature (19-20). The present study showed that horizontal curvature, vertical curvature, and slope have significant effects on driver choice to pass. The presence of guardrail was not found to have a significant effect.

The results of this study have practical implications for microsimulation of rural highways, highway design, and highway safety. After the effects of geometric variables on passing choice are better understood and modeled more precisely, microsimulation can incorporate these effects to more accurately model the expected locations of passes. This would likely have ramifications for highway design because highway capacity could be modeled more effectively and the locations of passing zones and passing lanes could be designed accordingly. Additionally, the ability to accurately predict where passing is most likely to occur on a section of highway could have implications for prioritization of safety treatments and signage.

Horizontal and vertical curvature were both shown to have significant effects on the characteristics of passing maneuvers including the speed of the passing vehicle, the total time and distance of the maneuvers, and the distance between the passing vehicle and the impeding vehicle at the initiation and termination of the maneuvers. These differences may have implications for capacity and safety analysis of rural two-lane highways. The implementation of improved models of vehicle trajectories during passing maneuvers may lead to more accurate microsimulation models of rural two-lane highways and would enable improved capacity analyses, which could inform the design of passing zones and passing lanes. The distance to the impeding vehicle at the initiation and termination of a passing maneuver may have safety implications with regard to the risk of rear-end collisions and same-direction sideswipe collisions of the passing and impeding vehicles.

Despite differences in passing choice and passing maneuvers, roadway geometry was not shown to significantly affect the safety outcomes of passes. Although there were conditions in which the average time to contact were different (e.g. lower when the road curved to the left than when straight or curved to right, and higher when the road had a sag curve than when flat or had a crest curve), none of these differences corresponded to a significantly higher proportion of passes ending with an unsafe time to contact. Guardrail was also not shown to have a significant effect on the proportion of safe versus unsafe passes.

5.1.2 Collision Avoidance

The results of the collision avoidance experiment indicate that the presence of guardrail may increase the occurrences of head-on collisions because drivers do not correctly perceive the risks involved in colliding with a vehicle versus colliding with guardrail. While it is clear that colliding with guardrail is preferable given the undesirable options available, drivers may not have time to process the risks with the urgency required to avoid a collision.

This finding has implications for safety analysis of rural two-lane highways. If the presence of guardrail significantly impedes the ability of drivers to safely avoid head-on collisions then this effect should be taken into account in the prioritization of safety projects. For example, safety features such as centerline rumble strips or centerline barriers may have a greater impact in reducing the prevalence of head-on collisions and reducing the average severity of collisions on roadway sections with guardrail. Additionally, this finding may have implications for lane width, shoulder width, and the lateral placement of the guardrail; more research should be conducted to determine whether the impediment diminishes when the guardrail is further from the centerline.

5.2 Limitations

One limitation of this study is that the use of real-world alignments precluded an experimental design in which the horizontal and vertical curvature were systematically varied to isolate and infer effects. This added variation to the test variables due to unknown interaction effects and possible order effects. An experiment with a track specifically designed with systematic changes in curvature should be conducted to validate and strengthen the results of this study.

Another limitation of this study is that the data were collected via a driving simulator. Consequently, the developed passing choice model would not have predictive validity on real-world alignments. However, since the purpose of the model was to infer effects rather than to make predictions, the results are likely valid in terms of relative validity. Field studies should be used to validate these findings and calibrate any models developed for prediction on real-world highways. Similarly, the differences in visual perception and vehicle controls in the simulation versus real-world vehicles likely lead to differences in the passing maneuvers in the simulator versus real-world, so the passing maneuver characterization may lack absolute validity; again, however, the purpose of the characterization was to compare the relative effects of curvature, and the results are likely valid in terms of relative validity. Finally, the perceived risk in the driving simulator is much less than in real-world driving because the consequences of crashing are nonexistent in the simulator and potentially catastrophic in the real-world. The results of the passing safety and collision avoidance analyses should therefore be viewed with these limitations in mind and should be validated using real-world data.

5.3 Future Research

There are several possible studies that could extend the results of this study. As mentioned, an experiment with a well-designed track with systematic variation of horizontal and vertical curvature could validate and strengthen the findings of this study, particularly with regard to passing choice, maneuver characterization, and safety outcomes. Some additional variables that could be tested in relation to passing choice are other types of roadside features (e.g. concrete barrier, signage, posts, etc.) and vegetation that cause minor sight obstructions and regulatory guidance such as different centerline striping configurations and signage.

The collision avoidance portion of this study also has several extensions. The effect of roadway geometry on avoidance behavior could be investigated in a driving simulator by designing a similar study under different geometric configurations. Likewise, the effects of different types of barrier (e.g. galvanized guardrail, weathering steel guardrail, concrete barrier, etc.) could be investigated to determine if the visual prominence of the barrier affects drivers' ability to avoid head-on collisions. The placement of barrier under different lane-width and shoulder-width conditions could also be investigated.

As mentioned, field studies and other studies that capture the behavior of drivers on real-world road sections are important to validate the findings of this study. Some possible studies include setting up cameras and observing real-world passing maneuvers, comparing the rates of passing in passing zones with different geometric configurations, and comparing the safety outcomes of passing maneuvers in different passing zones. Finally, the safety outcomes of passes and the ability of drivers to avoid head-on collisions could be investigated using crash data; the prevalence of passing-related crashes or head-on collisions could be analyzed in conjunction with roadway geometry, roadside infrastructure, and terrain variables from a GIS, digital imagery, or site assessment.

References

1. Farber, E., and C. A. Silver. Knowledge of Oncoming Car Speed as a Determiner of Drivers' Passing Behavior. *Highway Research Record,* Vol. 195, 1967, pp. 52–65.
2. Gordon, D. A., and T. M. Mast. Drivers' Decisions in Overtaking and Passing. *Highway Research Record,* Vol. 247, 1968, pp. 42–50.
3. Jones, H. V., and N. W. Heimstra. Ability of Drivers to Make Critical Passing Judgments. *Journal of Engineering Psychology,* Vol. 3, 1964, pp. 117-122.
4. Clarke, D. D., P. J. Ward, and J. Jones. Overtaking Road-Accidents: Differences in Maneuver as a Function of Driver Age. *Accident Analysis & Prevention*, Vol. 30, No. 4, 1998, pp. 455–467.
5. Clarke, D. D., P. J. Ward, and J. Jones. Processes and Countermeasures in Overtaking Road Accident. *Ergonomics*, Vol. 42, No. 6, 1999, pp. 846-867.
6. Gray, R. and D. M. Regan. Perceptual Processes Used by Drivers During Overtaking in a Driving Simulator. *Human Factors,* Vol. 47, No. 2, 2005, pp. 394-417.
7. Jenkins, J. M., and L. R. Rilett. Classifying Passing Maneuvers: A Behavioral Approach. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1937, 2005, pp. 14–21.
8. Jenkins, J. M. and L. R. Rilett. Application of Distributed Traffic Simulation for Passing Behavior Study. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1899, 2004, pp. 11-18.
9. Brodin, A. *VTI Traffic simulation model: A Program for the Monte Carlo Simulation of Vehicle Traffic along Two-Lane Rural Roads (Revised ed.).* Swedish Road and Traffic Research Institute, Linkoping, Sweden, 1983.
10. Tapani, A. A Traffic Simulation Modeling Framework for Rural Highways. Department of Science and Technology, Linköping University, Sweden, 2005.
11. Bar-Gera, H. and D. Shinar. The Tendency of Drivers to Pass Other Vehicles. *Transportation Research Part F,* Vol. 8, No. 6, 2005, pp. 429-439. http://dx.doi.org/10.1016/j.trf.2005.06.001.
12. Farah, H. Modeling Drivers' Passing Duration and Distance in a Virtual Environment. *IATSS Research*, Vol. 37, No. 1, 2013, pp. 61-67. http://dx.doi.org/10.1016/j.iatssr.2013.03.001.

13. Vlahogianni, E. I. Modeling Duration of Overtaking in Two Lane Highways. *Transportation Research Part F,* Vol. 20, 2013, pp. 135-146. https://doi.org/10.1016/j.trf.2013.07.003.
14. Papakostopoulos, V., D. Nathanael, E. Portouli, and N. Marmaras. The Effects of Changes in Traffic Scene During Overtaking. *Accident Analysis & Prevention,* Vol. 79, 2015, pp. 126-132. http://dx.doi.org/10.1016/j.aap.2015.02.025.
15. Bella, F. How Traffic Conditions Affect Driver Behavior in Passing Maneuver. *Advances in Transportation Studies*, 2011, pp. 113-126.
16. Moreno, A. T., C. Llorca, A. Garcia, A. Perez-Zuragia. Operational Effectiveness of Passing Zones Depending on Length and Traffic Volume. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2395, 2013, pp. 57-65. http://dx.doi.org/10.3141/2395-07.
17. Pollatschek, M. A., and A. Polus. Modeling Impatience of Drivers in Passing Maneuvers. *Transportation and Traffic Theory: Flow, Dynamics and Human Interaction* (H. S. Mahmassani, ed.), Emerald Group Publishing, Bingley, United Kingdom, 2005, pp. 267–279.
18. Farah, H., A. Polus, S. Bekhor, and T. Toledo. Study of Passing Gap Acceptance Behavior Using a Driving Simulator. *Advances in Transportation Studies,* 2007 (Spec. Iss.), 2007, pp. 9-16.
19. Farah, H., A. Polus, S. Bekhor, and T. Toledo. A Passing Gap Acceptance Model for Two-Lane Rural Highways. *Transportmetrica*, Vol. 5, No. 3, 2009, pp. 159–172.
20. Farah, H. and T. Toledo. Passing Behavior on Two-Lane Highways. *Transportation Research Part F,* Vol. 13, No. 6, 2010, pp. 355-364. http://dx.doi.org/10.1016/j.trf.2010.07.003.
21. Vlahogianni, E. I. and J. C. Golias. Bayesian Modeling of the Microscopic Traffic Characteristics of Overtaking in Two-Lane Highways. *Transportation Research Part F,* Vol. 15, No. 3, 2012, pp. 348-357. https://doi.org/10.1016/j.trf.2012.02.002.
22. McLean, J. R. *Two-Lane Highway Traffic Operations*. Gordon and Breach Science Publishers, Amsterdam, 1989.

23. Leiman, L., A. Archilla, A. May. *Twopas Model Improvements, NCHRP PROJECT 3-55(3) Capacity and Quality of Service of Two-Lane Highways.* Midwest Research Institute, University of California, Berkeley, 1999.

24. Hoban, C.J., G.J. Fawcett, G.K. Robinson. *A Model for Simulating Traffic on Two-Lane-Rural Roads: User Guide and Manual for TRARR Version 3.0.* Australian Road Research Board, Victoria, Australia, 1985.

25. Kim, J. and L. Elefteriadou. Estimation of Capacity of Two-Lane Two-Way Highways Using Simulation Model. *Journal of Transportation Engineering*, Vol. 136, No. 1, 2010, pp. 61-66. http://dx.doi.org/10.1061/(ASCE)0733-947X(2010)136:1(61).

26. Olstam, J.J. Generation and Simulation of Surrounding Vehicles in a Driving Simulator. Presented at Driving Simulator Conference, Paris, France, 2006.

27. Bella, F. Can Driving Simulators Contribute to Solving Critical Issues in Geometric Design? *Transportation Research Record: Journal of the Transportation Research Board*, No. 2138, 2009, pp. 120-126. http://dx.doi.org/10.3141/2138-16.

28. Llorca, C. and A. Garcia. Evaluation of Passing Process on Two-Lane Rural Highways in Spain with New Methodology Based on Video Data. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2262, 2011, pp. 42-51. http://dx.doi.org/10.3141/2262-05.

29. Lee, J.D. et al. Matching Simulator Characteristics to Highway Design Problems. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2248, 2011, pp. 53-60. http://dx.doi.org/10.3141/2248-07.

30. *MiniSim User's Guide: National Advanced Driving Simulator, Version 17.* National Advanced Driving Simulator, Iowa City, IA, 2011.

31. *A Policy on Geometric Design of Highways and Streets, 6th edition*. American Association of State Highway and Transportation Officials, Washington, DC, 2011.

32. Alaska Department of Transportation and Public Facilities. *Alaska Standard Drawings Manual.* http://www.dot.alaska.gov/stwddes/dcsprecon/stddwgeng.shtml. Accessed Mar. 8, 2017.

Appendix A: Study Documents

A.1 Consent Form

CONSENT FORM
Idaho Visual Performance Laboratory
Department of Psychology and Communication Studies
College of Liberal Arts and Social Sciences
University of Idaho

The University of Idaho Institutional Review Board has approved this project.

During this experiment you will be presented a simulated virtual environment. Various parameters of the environment will be manipulated to examine the processes underlying vision and decision making. The experimental tasks will require you control your movement in the virtual world using input devices like a steering wheel and brake/gas pedals.

Your participation will help increase knowledge of visual processes underlying locomotion and aid in the design of visual displays used in transportation. Subsequent to your participation the purpose and methods of the study will be described to you and any questions you have about the study will be answered. It is our sincere hope that you will learn something interesting about your visual system from this debriefing.

We believe the risks in this study are minimal, however displays simulating movement through virtual environments may on rare occasion cause motion sickness or eye fatigue. If at any time during the experiment you feel any discomfort, eye fatigue, dizziness, headache or nausea, please let the experimenter know immediately so that you can prevent these symptoms from becoming more intense. We endeavor to design our virtual environments to minimize eye fatigue and motion sickness. We also schedule periodic breaks to further reduce the occurrence of these risks. As a result, these risks are generally avoided, but it is important for you to inform us immediately if they do occur. At such time we will immediately terminate the experiment and provide you with a comfortable place to rest. If your discomfort is mild and passes quickly you will be given the opportunity to continue the experiment if you so desire. Any new information developed during the course of this research which might affect your willingness to continue participation will be provided as soon as it is available.

Your participation will require 1 session of approximately 60 minutes. You may withdraw from this study at any time without penalty. If you do wish to withdraw, simply inform the experimenter; you will receive full compensation for your time spent in the experiment up to that point. However, please be aware that your data will have the greatest scientific value if you complete the experiment in its entirety.

The data you provide will be kept anonymous. There will be absolutely no link between your identity and your particular set of data.

If you have further questions or issues please contact:

Dr. Brian P. Dyre
Department of Psychology and Communications Studies
University of Idaho
(208) 885-6927
bdyre@uidaho.edu

I have reviewed this consent form and understand and agree to its contents.

Participant Name ____
Date of Birth ________________________________
Signature ___________________________________
Date ______________________________________

Experimenter Name_______________________________
Signature____________________________
Date ______________________________

Thank you for your participation.

Figure A.1: Participant Consent Form

A.2 Instructions

A.2.1 Stage 1 Instructions

Driving Study Instructions

Ask the participant has participated in any other driving study.

If they say “yes,” inform them that this simulation is an independent study and has no correlation with the previous study.

Read the following prompt:
This experiment examines how people drive on rural highways.

Your task will be to steer a simulated vehicle over a road through a simulation of the American countryside. Just like with any car, to turn right you move the top of the steering wheel to the right. To turn left you move the top of the steering wheel to the left. To accelerate you press the gas pedal. To slow down, you press the brake pedal. Turn signals operate just like in a real vehicle.

In this experiment you will go through 1 trial lasting approximately 60 minutes which will simulate a 40-mile drive returning from a weekend long trip. There will be vehicles ahead of you and behind you as well as in the oncoming lane. You should pay careful attention to other vehicles just as you would if you were driving on a real rural highway, and in a **hurry to get home.**

Do you have any questions?

Now please explain to me, in your own words, what you will be doing in this study.

After approximately 20 miles, a message will appear on the screen asking you to pull over and take a break. At this time, we want you to park the car on the shoulder, placing the transmission in “Park” and exit the vehicle so that you can get up, walk around, and stretch your legs for a few minutes.

Upon entering the vehicle, please adjust the center rear view mirror and seat to your preference (the side mirrors do not adjust). To begin each trial you will need to depress the brake pedal to release the transmission lock and shift the gear shift into “D” or “drive.”

Do you have any questions?

First you will go through a test drive lasting approximately 5-10 minutes. The test drive is meant for you to get comfortable with the controls of the car. Feel free to ask questions after the test drive if you have any. Make sure the steering wheel is centered before the simulation starts.

Remember that you are in a hurry to get home from a weekend long trip.

Figure A.2: Stage 1 Instructions

A.2.2 Stage 2 Instructions

Driving Study Instructions

Ask the participant has participated in any other driving study.

If they say “yes,” inform them that this simulation is an independent study and has no correlation with the previous study.

Read the following prompt:
This experiment examines how people drive on rural highways.

Your task will be to steer a simulated vehicle over a road through a simulation of the American countryside. Just like with any car, to turn right you move the top of the steering wheel to the right. To turn left you move the top of the steering wheel to the left. To accelerate you press the gas pedal. To slow down, you press the brake pedal. Turn signals operate just like in a real vehicle.

In this experiment you will go through 1 trial lasting approximately 20 minutes which will simulate a 20-mile drive. There will be vehicles ahead of you and behind you as well as in the oncoming lane. You should pay careful attention to other vehicles just as you would if you were driving on a real rural highway, and in a **hurry to get home for a family emergency.**

Do you have any questions?

Now please explain to me, in your own words, what you will be doing in this study.

After approximately 10 miles, a message will appear on the screen asking you to pull over and take a break. At this time, we want you to park the car on the shoulder, placing the transmission in “Park” and exit the vehicle so that you can get up, walk around, and stretch your legs for a few minutes.

Upon entering the vehicle, please adjust the center rear view mirror and seat to your preference (the side mirrors do not adjust). To begin each trial you will need to depress the brake pedal to release the transmission lock and shift the gear shift into “D” or “drive.”

Do you have any questions?

First you will go through a test drive lasting approximately 5-10 minutes. The test drive is meant for you to get comfortable with the controls of the car. Feel free to ask questions after the test drive if you have any. Make sure the steering wheel is centered before the simulation starts.

Remember that you are in a hurry to get home for a family emergency.

Figure A.3: Stage 2 Instructions

A.3 Debriefing Form

Section 1 - Participant's Driving History

1.1 Types of roadway driven (approximate % of time driven)

	Less than 20%	20% - 40%	40% - 60%	60% - 80%	80% +	None
Interstates/Freeways	○	○	○	○	○	○
City Roads	○	○	○	○	○	○
Town Roads	○	○	○	○	○	○
Rural Highways	○	○	○	○	○	○
Others	○	○	○	○	○	○

1.2 How would you describe your real-life driving style?

- Careful
- Defensive
- Passive
- Aggressive
- Fast
- Slow
- Other:

1.3 While driving on rural highways in real life how often do you pass other vehicles? (ask to elaborate and record it in Other... section)

- Never
- Almost Never
- Sometimes
- Often
- Very Often
- Other:

1.4 What types of vehicles have you driven on two-lane rural highways?

- Car
- SUV
- Minivan
- Pickup
- Full-size Van
- Commercial
- Motorcycles
- Other:

Section 2 - Simulation

2.1 Did the simulation make you feel as if you were driving through a three-dimensional Environment? (ask "why?" and record it in Other... section)

- Yes
- No
- Other:

2.2 Did you notice anything unusual about the simulated environment? (ask to elaborate and record it in Other... section)

- Yes
- No
- Other:

Section 3 - Vehicles in Simulation

3.1 In terms of other vehicles in the simulation study, which factors influenced your decision to pass? (ask "why" and record it in Other... section)

- Speed of vehicles ahead of you
- Number of vehicles traveling ahead of you
- Amount of traffic in opposing Lane
- Vehicle traveling behind you
- None of the above
- Other:

3.2 Which factors influenced your driving in general? (ask to elaborate and record it in Other... section)

- Speed of vehicles ahead of you
- Number of vehicles traveling ahead of you

- Amount of traffic in opposing Lane
- Vehicle traveling behind you
- None of the above
- Other:

Section - 4 Simulation Environment/Layout

4.1a In terms of simulated environment layout in study, what influenced your general driving? (ask "why?" and record it in Other... section)

- Left Direction Curve
- Right Direction Curve
- Straight Sections
- Crest Curve (i.e. going over a hill)
- Sag Curve (i.e. a dip)
- Guardrail
- Trees/Forests
- Rolling hills
- Mountains
- Cliff
- Water/Lake/Sea
- None
- Other:

4.1b In terms of simulated environment layout in study, which of the following factors decreased the likelihood of a choice to pass other vehicles? (ask "why?" and record it in Other... section)

- Left Direction Curve
- Right Direction Curve
- Straight Section
- Driving up-grade (i.e. uphill)
- Driving down-grade (i.e. downhill)
- Crest Curve (i.e. going over a hill or hump)
- Sag Curve (i.e. a dip)
- Guardrail
- Trees/Forests
- Rolling hills

- Mountains
- Cliff
- Water
- None
- Other:

Please provide any other comments/experience sharing you might have.

Demographic Information

Age

Sex

- Male
- Female
- Other:

Years of Driving Experience

Marital Status

- Single
- Married
- Other:

Parent

- Yes
- No