Modeling Passing Behavior on Two-Lane Rural Highways:
EVALUATING CRASH RISK UNDER DIFFERENT GEOMETRIC CONFIGURATIONS

FINAL PROJECT REPORT

by

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16. Abstract

Passing maneuvers on rural two-lane highways are a complex task with a significant effect on safety, capacity, and service quality. This maneuver, which involves driving in the lane of the opposing traffic, is associated with simultaneously increasing crash risk and increasing the driver's speed. Understanding drivers' passing behaviors and their decision-making on two-lane rural highways can significantly contribute to accurately predicting risk and service quality. Only limited research has been conducted to capture and document drivers' perception of when they need to pass and passing decision-making. This is partly because it is difficult to collect detailed data on driver perceptions and passing behavior in the real-world environment. Furthermore, field studies offer little control over the intervening variables, and usually no information on the drivers being observed. Evidence showing the effects of this limited research lies in recent work assessing passing sight distance (PSD) standards for two-lane highways in two preeminent manuals. One is the American Association of State Highway and Transportation Officials (AASHTO) Green Book, which states minimum PSD and the other is the Manual on Uniform Traffic Control Devices (MUTCD). Marking of passing and no-passing zones is based on PSD criteria presented in the MUTCD. The National Highway Cooperative Highway Research Program (NCHRP) Report 605 presented recommendations regarding current procedures and guidelines used to estimate minimum PSD requirements for highway design and pavement marking.
The report concluded that the MUTCD PSD criteria for marking passing and no-passing zones should also be used for PSD design. It also concluded that although the longer AASHTO PSD criteria might provide improved traffic operational efficiency, the AASHTO PSD are so long they are often impractical. As a result of the report recommendations, the PSD values in the 2011 AASHTO Green Book were modified and brought closer to the MUTCD PSD values. The field data used to validate different PSD models in NCHRP 605 were based on video data collection. Videos were used to study distance traveled by the passing vehicle in the opposing lane, the speed differential between the passed and passing vehicles, and the deceleration rate used by the passing vehicle when the passing maneuver was aborted. No relationship was established between driver perception of quality of service, passing behavior, and the present highway conditions. Finally, the only tool available for estimating two-lane highway performance resides in the Highway Capacity Manual (HCM). This tool is not based on any relationship between observed user perception, documented driver passing behavior, and two lane highway conditions. As a result, the Transportation Research Board's Committee on Highway Capacity and Quality of Service identified researching two-lane highway traffic operations as a high priority research subject, as did the AASHTO.

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Table of Contents

List of Figures

List of Tables

Executive Summary

General Background

Passing maneuvers on rural two-lane highways significantly affect safety, capacity, and service quality. Safe execution of two-lane passing maneuvers allows rural highways to provide improved capacity and quality of service to the public. However, passing-related crashes on two-lane highways pose a particular challenge for transportation system operators in the Pacific Northwest (and the nation) because of their social and economic cost.

Problem Statement

To better understand how humans manage crash risk in passing decisions, this project aimed to establish an initial set of data to foster further empirical research for developing and refining models for quantifying drivers' passing decisions on rural two-lane highways. Such a passing decision model will provide highway engineers better understanding and prediction of drivers' passing behaviors and risk-taking on two-lane rural highways. Properly applied, this knowledge could lead to significant improvements in the safety, capacity, and quality of service of rural highways, and reduce both the social and economic costs of high-impact crashes.

Key Methodology

The investigation collected two different sets of data: a) driver-simulator-based data and b) video-based field observations collected for a stretch of US 95 just south of Ferdinand, Idaho.

The driving simulator study allowed us to study both strategic and tactical factors associated with passing decisions. On a strategic level, we examined whether the density of oncoming traffic affected drivers' passing decisions by either raising or lowering the frequency and acceptable risk of passing. On a tactical level, we examined the effects of road geometry and gap distance on passing decisions. Furthermore, we examined samples of both experienced and inexperienced drivers. By comparing the driving simulator results to the field data, we were able to validate whether our research participants' behaviors in the driving simulator were representative of real-world driving.

Our study aimed to address the following questions:

1. Do research participants drive the simulator in a manner that represents real-world driving? Are their speeds and passing decisions comparable?
2. What gap sizes do drivers consider safe for passing and do these preferred gaps vary under different road geometries or oncoming traffic conditions?

Major Findings and Implications

The primary findings of this study were that both oncoming traffic density between passing zones and road geometry influence passing decisions in driving simulation. Higher traffic densities lower the number of passes made, particularly at shorter gap distances. This "calming" effect may be due to priming of the expectation of denser traffic when a driver enters a passing zone. Drivers experiencing lower oncoming traffic densities were more likely to make risky passing maneuvers with shorter time to collision (TTC). We recommend that such effects be included in macrosimulation models of highway capacity and quality of service.

Finally, straight and level road geometry also increases the likelihood of passing, even when horizontal and vertical curves do not produce sight obstructions. In addition, passing on straight stretches of highway is typically done at lower maximum speed. Taken together, these findings suggest that quality of service in passing zones is enhanced for straight and level road geometries.

Chapter 1: Introduction

1.1 General Background

Passing maneuvers on rural two-lane highways significantly affect safety, capacity, and service quality. Safe execution of two-lane passing maneuvers allows rural highways to provide improved capacity and quality of service to the public. However, passing-related crashes on two-lane highways pose a particular challenge for transportation system operators because of their social and economic cost.

As a highway feature, passing zones represent a compromise between capacity and safety, factors that together affect overall quality of service. Perhaps more than any other highway feature, the broken yellow centerlines that mark passing zones hand over responsibility for safety to individual drivers, who must safely execute a complex and potentially dangerous driving task requiring sound strategic decision making and strong tactical skills. Because drivers on two-lane highways must temporarily pull into the oncoming lane, approaching vehicles approach at speeds sometimes in excess of 120 mph. Split-seconds matter, and when drivers— who are arguably the weakest link in the overall chain of highway safety—make poor passing decisions or fail to execute passing maneuvers, horrific, high-impact, and often fatal crashes may result.

Quality of service in passing decisions can be inferred from the traffic gap sizes (and corresponding time-to-contact of the oncoming vehicle or platoon of vehicles) for which drivers execute passing maneuvers. Passing zones that do not afford adequate sight-distance for drivers to perceive a gap in oncoming vehicles sufficient for a safe pass could lead to frustration and lessen perceived quality of service. Similar frustration and lowered perceived quality of service could result from non-passing zones that afford adequate sight-distance for a pass yet do not allow passing to occur. Hence, understanding of what gaps are deemed acceptable by drivers under different conditions should aid highway engineers in marking safer and more efficient two-lane passing zones on rural highways that will improve quality of service.

1.2 Problem Statement

Research examining drivers' passing behavior in field studies has been limited. This is partly because it is difficult to collect detailed data on driver perceptions and passing behavior in the real-world environment. Furthermore, field studies offer little control over the intervening variables and usually no information on the drivers being observed.

Evidence showing the effects of this limited research lies in recent work assessing passing sight distance (PSD) standards for two-lane highways in two preeminent manuals. One is the American Association of State Highway and Transportation Officials (AASHTO) Green Book, which states minimum PSD, and the other is the Manual on Uniform Traffic Control Devices (MUTCD). Marking of passing and no-passing zones is based on PSD criteria presented in the MUTCD.

National Cooperative Highway Research Program (NCHRP) report 605 presented recommendations regarding current procedures and guidelines used to estimate minimum PSD requirements for highway design and pavement marking. The report concluded that the MUTCD PSD criteria for marking passing and no-passing zones should also be used for PSD design. It also concluded that although the longer AASHTO PSD criteria might provide improved traffic operational efficiency, the AASHTO PSD are so lengthy that they are often impractical. As a result of the report recommendations, the PSD values in the 2011 AASHTO Green Book were modified and brought closer to the MUTCD PSD values.

The field data used to validate different PSD models in NCHRP 605 were based on video data collection. Videos were used to study distance travelled by the passing vehicle in the opposing lane, the speed differential between the passed and passing vehicles, and the deceleration rate used by the passing vehicle when the passing maneuver was aborted. No relationship was established between driver perception of quality of service, passing behavior, and the present highway conditions.

Finally, the only tool available for estimating two-lane highway performance resides in the Highway Capacity Manual (HCM). This tool is not based on any relationship between observed user perception, documented driver passing behavior, and two-lane highway conditions.

As a result, the Transportation Research Board's Committee on Highway Capacity & Quality of Service identified researching two-lane highway traffic operations as a high priority research subject, as did the AASHTO.

1.3 Project Goal

To better understand how humans manage crash risk in passing decisions, this project aimed to establish an initial set of data based on both simulation and field measurements that will foster further empirical research and development of models for quantifying drivers' passing decisions on rural two-lane highways. Such a model will provide highway engineers with a better understanding and ability to predict drivers' passing behaviors and risk-taking on two-lane rural highways. Properly applied, this knowledge could lead to significant improvements in the safety, capacity, and quality of service of rural highways, and reduce both the social and economic costs of high-impact crashes.

1.4 Project Approach

In this project, we investigated how traffic conditions influence passing maneuvers on two-lane rural highways under different geometric configurations and for different driver groups. The investigation collected two different sets of data: 1) driver-simulator-based data and 2) two-lane highway driving videos of varying highway conditions in the field.

Chapter 2: Literature Review

A handful of studies have examined passing behavior or measured the subjective impressions of drivers regarding safety and quality of service. This chapter reviews this previous research.

2.1 Simulation Studies of Passing Behavior

Passing on two-lane highways is a complex task that places high mental demand on drivers (Cantin, Lavalliere, Simoneau, & Teasdale, 2009). Over the past 10 to 20 years, the development of driving simulators has allowed for research into factors affecting passing decisions and behavior. This research has focused on two aspects of passing behavior, the desire to pass and the acceptable gap for passing, which represent strategic and tactical concerns in passing decisions, respectively.

Factors affecting the strategic aspect of passing behavior, the desire to pass, include the speed of and distance to the leading vehicle, variability in driver speed, and the use of automated systems such as adaptive cruise control or overtaking assistants (Bar-Gera and Shinar, 2005; Farah and Toledo, 2010; Hegeman, Tapani, Hoogendoorn, 2009; Jamson, Chorlton, and Carsten, 2012). Demographic factors also influence the desire to pass. Younger drivers typically pass more often than older drivers, and young men pass more often than young women, perhaps reflecting more aggressive and impulsive driving styles (Vlahogianni and Golias, 2012).

The choice of acceptable gap distance between a driver's vehicle and the nearest oncoming vehicle has also been studied in simulation. "Gap" is generally defined as the distance to oncoming vehicles; however, this definition does not take into account vehicle closing rates, which are affected by both distance and speed. Toledo and Farah (2011) concluded that for passing decisions, drivers pick acceptable gaps based on time-to-collision (TTC) and consider the time in seconds before an oncoming vehicle would impact their vehicle.

Shariat-Mohaymany, Kashani, Nosrati, and Kazemzadehazad (2013) determined influential factors leading to head-on traffic conflict on two-lane highways. The definition of head-on traffic conflict used in the study is a TTC of less than 3 seconds. A model predicting the probability of a head-on conflict (p) was developed. Increases in percentage of time spent following (PTSF), surface width, and horizontal roadway curvature (straight or curved roadway) *increased* collision probability, while increases in mean vehicle speed, directional distribution of traffic, and grade *decreased* collision probability.

Farah, Bekhor, and Polus (2009) evaluated the causes of risk during two-lane highway passing maneuvers using a driving simulator. The study used TTC as the risk measure, with lower TTC values indicating higher risk. Factors associated with higher risk were found to be higher opposing vehicle speed, higher subject speed, longer time spent behind a slow vehicle, and poor geometry (lower design speed, narrow lane and shoulder widths, lower curve radii, and steeper side-slopes). Factors associated with greater risk were higher passing vehicle speed, opposing traffic volume, following headway, and time waiting behind a slow vehicle. The effects of road geometry were not clear from the results and necessitated further study.

Two potentially important factors in two-lane passing decisions that require further study are traffic density of oncoming vehicles and road geometry (straight and level vs. horizontal and vertical curves). Oncoming traffic density could affect drivers' expectations of passing opportunities, which in turn could affect their strategic desire to pass. For example, higher oncoming traffic density might influence more aggressive drivers to strategically lower their threshold for acceptable risk in passing and promote passing attempts with smaller gap sizes.

Conversely, higher oncoming traffic density might cause less-aggressive drivers to abandon actively searching for passing opportunities by invoking a form of learned helplessness (Maier, S.F. and Seligman, 1976). The tactical choice of acceptable gap may be influenced by road geometry. Horizontal and vertical curves produce more complicated oncoming vehicle dynamics that potentially impair or aid drivers' ability to judge acceptable gaps based on TTC (Garcia, Moreno, Llorca, and Camacho-Torregrosa, 2013). Understanding how these factors affect passing decisions was one aim of this study.

2.2 Measuring Perception of Quality of Service

Previous research has also examined drivers' perception of quality of service. Given its subjective nature, quality of service is challenging to measure. Stephens and Groeger (2009) assessed quality of service by asking drivers in a simulator to rate their emotional state in response to probes occurring at different times of the drive. Malta et al. (2011) measured quality of service in real-world drivers using measures of electro-dermal skin conductance and videos of facial expressions. Other studies (Qin et al., 2011; Ko, Wahburn, and McLeod, 2009) have used survey methods to measure perception of safety and quality of service.

With respect to two-lane highways, factors affecting perceived quality of service include percentage of time spent following, percentage of time being followed, lane width, and shoulder width (Ko, Washburn, and McLeod, 2009). Al-Kaisy and Durbin (2008) proposed that quality of service based on percentage of time spent following (PTSF) be defined relative to following vehicles with headways of less than or equal to 6 seconds, as compared to the standard 3-second follower headway cutoff. They reasoned that, according to car following models, leading vehicles influence following vehicles at headways of up to 6 seconds. Studies by the Facility Analysis and Simulation Team (2010), Karjala (2008), and Hashim and Abdel-Wahed (2011) investigated alternative service measures and found strong correlations between follower density (FD) and vehicle platooning. Since platooning is considered to be a strong negative indicator for two-lane highway service quality, follower density can be used to assess service quality.

Chapter 3: Field Study Site/Data

Field data were obtained from video footage collected from an approximately 2 mile, two-lane rural highway segment of U.S. 95 near Ferdinand, Idaho, illustrated as the red line in figure 3.1. Video was collected from roughly 3:50 pm to 6:15 pm on a Friday in September 2013 using two 640x480 resolution cameras that were directed at the roadway (see figure 3.1).

Figure 3.1 Ferdinand segment location

Vehicle trajectories were constructed by recording the time each vehicle passed four data collection points along the study segment. These four points are shown in figure 3.2. Highway geometry information for each segment between data points is provided in table 3.1.

Figure 3.2 Study segment data points and segments

Table 3.1 Study segment geometry

Segment	Length (miles)	Number of NB Lanes	Number of SB Lanes
1	0.66	1	1
2	0.67	1	1
3	0.60	1	2

Passing in the opposing lane was allowed in all segments except SB Segment 3, where a climbing lane was present. For this reason SB Segment 3 data were not used in this study.

Four two-lane highway performance measures were calculated from the vehicle trajectory data:

1. Average Travel Speed (ATS) (mph)
2. Follower Density (FD) (following vehicles/mile)
3. Percentage of Following (PF)
4. Time-to-Collision (TTC) (sec)

Followers were defined as vehicles traveling behind another vehicle with a headway of less than or equal to 3 seconds. It is important to note that it was not possible to measure typical TTC (measured from when the passing vehicle returns to its original lane) from video recordings. Therefore, TTC was measured from when the passing vehicle was abreast of the leading vehicle.

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Chapter 4: Results of Field Study

Data from the Ferdinand study segment, including 0.46 miles of highway north of the segment and 1.10 miles south of the segment, were modeled in CORSIM. Field data from the first hour of video was used to calibrate the model.

Several parameters in CORSIM were used to calibrate the model to field conditions. The effects of these parameters on performance measures were determined via sensitivity tests. The results of the sensitivity tests are summarized in table 4.1.

Table 4.1 Effects of CORSIM calibration parameters on performance measures

Change in Calibration Parameter	Change in Performance Measures
↑ Pass clearance distance (ft)	↓ Passing frequency
↑ Min/Max TTC (sec)	↑ TTC, ↓ Passing frequency
↑ Follower threshold (sec)	↑ Passing frequency, ↑ PF, ↑ FD
↑ Impatience factor	↑ Passing frequency at upstream end of segment
↑ Differential passing speed (mph)	No significant effect
↑ Mean free-flow speed (mph)	↑ ATS
↑ Free-flow speed variation	↑ Passing frequency, ↑ PF, ↑ FD

The values of the final calibration parameters that were adjusted from the default values are shown in table 4.2.

Table 4.2 Final non-default calibration parameters

Parameter	Calibrated Value	Default Value
Minimum separation for generation of vehicles (sec)	1.0	1.6
Time to complete a lane-change maneuver (sec)	4.0	2.0
Minimum TTC (after pass completion) (sec)	2	5
Clearance gap (ft)	50	75
Free-flow speed (mph)	68	65

Vehicle entry headways followed an Erlang distribution with a shape parameter of 1. Freeflow speeds for each of the ten vehicle types were determined by calculating the average of each observed free-flow speed decile. No-passing zones were also added to the north and south ends of the modeled segment to facilitate vehicle bunching and higher passing frequency, percentage of following, and follower density. In general, calibration parameters were adjusted to encourage a higher percentage of following, follower density, and passing frequency.

Performance measures from the field and from CORSIM are shown in table 4.3. CORSIM was calibrated to achieve mean performance measures within 10% of the mean field measures after 50 1-hour simulation runs.

Table 4.3 Observed field and calibrated CORSIM performance measures

Performance Measure	Field			CORSIM
	Mean	-10%	+10%	Mean
Average Travel Speed (mph)	67	61	74	67
Follower Density (followers/mile)	0.47	0.43	0.52	0.49
Percentage of Following (percent)	19.2	17.3	21.1	19.8
Time-to-Collision (abreast of leading vehicle, sec)	18.7	16.8	20.6	17.9
Time-to-Collision (at completion of pass, sec)	-	-	-	13.7

Modeling the study segment in CORSIM allowed measurement of both TTC measures, which can be used to develop a function relating TTC (abreast of leading vehicle) to TTC (at completion of pass).

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Chapter 5: Simulation Method

We presented each driver a 50-mile stretch of two-lane rural highway using the University of Idaho's National Advanced Driving Simulator (NADS) Minisim (see figure 5.1).

5.1 Experimental Design

The 12 passing zones were created from a factorial combination of three road geometries and four oncoming vehicle gap sizes. Details of the configuration of these stimuli are provided in section 4.2. In addition, drivers were divided into groups. A high-density group experienced a higher oncoming traffic density between passing zones (5.5 vehicles per minute), while a low-density group experienced lower oncoming traffic density between passing zones (2.75 vehicles per minute). This experiment thus used a mixed factorial design, with the variables of passing zone gap and road geometry manipulated within subjects (repeated measures), and the variable of traffic density manipulated between subjects.

Our primary performance measures included the driver's control inputs to the steering wheel, brake pedals, and accelerator pedal, as well as the simulated speed and position of the vehicle on the roadway. In addition, the trajectories of all other simulated vehicles were measured, which allowed calculation of time-to-contact of the nearest oncoming vehicle while abreast of the vehicle being passed.

Figure 5.1 Overhead view of Chevy S-10 simulator cab

5.2 Stimuli

The simulated rural stretches of two-lane highway contained a mix of both straight and level roadways and roadways with horizontal curves and vertical terrain. The speed limit for all roadways was posted at 65 miles per hour, with speed limit signs at various locations along the highway. The simulation also included advisory signs for curves ahead. In the stretches of highway between the passing zones, oncoming traffic appeared regularly, with half the participants experiencing low traffic density (2.75 vehicles per minute) or high traffic density (5.5 vehicles per minute). To examine passing behavior, traffic was placed in front and behind the driver. The traffic in front of the driver was scripted to travel 5 MPH below the speed limit to encourage passing, while the traffic behind the driver was scripted to maintain a close following distance to also pressure the driver to pass.

The middle line markings were configured so that legal passes could occur only within our 12 experimentally defined passing zones. Each driver experienced each passing zone configuration once. Factorially combining three road geometries (straight, Ferdinand northbound, Ferdinand southbound) and four gap distances (1/4, 1/2, 3/4, and 1 mile; or in SI units 402.25, 804.50, 1206.75, and 1609.00 m, respectively) created 12 unique passing zone conditions, which we presented in an order determined with a partial Latin square (see table 5.1). This ordering procedure ensured that each trial scenario a) occurred equally often in each place of the order, and b) preceded and followed every other scenario an equal number of times. Any effects of passing gap length or road geometry were thus independent of scenario order effects. The first three scenarios appeared in a fixed order to provide a baseline for driver behavior and included the three possible passing zone geometries with a ¼-mile gap. It was expected that drivers would not often pass during these first three scenarios with ¼-mile gaps, due to the maximum time-tocontact (TTC) being 6.92 s (Farah and Toledo, 2010).

Table 5.1 Orders of passing zone conditions assigned to participants

PID*	ORDER OF PRESENTATION FOR PASSING ZONE CONDITIONS											
1, 13	1	2	3	4	12	8	11	7	6	5	9	10
2, 14	1	2	3	7	6	11	5	10	9	8	12	4
3, 15	1	2	3	10	9	5	8	4	12	11	6	7
4, 16	1	2	3	4	9	11	8	10	6	5	12	7
5, 17	1	2	3	7	12	5	11	4	9	8	6	10
6, 18	1	2	3	10	6	8	5	7	12	11	9	4
7, 19	1	2	3	4	12	8	11	7	6	5	9	10
8, 20	1	2	3	7	6	11	5	10	9	8	12	4
9, 21	1	2	3	10	9	5	8	4	12	11	6	7
10, 22	1	2	3	4	9	11	8	10	6	5	12	7
11, 23	1	2	3	7	12	5	11	4	9	8	6	10
12, 24	1	2	3	10	6	8	5	7	12	11	9	4

Key to Passing Zone Conditions

1	Straight 1/4 mile gap	7	Straight 3/4 mile gap
2	Ferdinand Northbound 1/4 gap	8	Ferdinand Northbound 3/4 mile gap
3	Ferdinand Southbound 1/4 gap	9	Ferdinand Southbound 3/4 gap
4	Straight 1/2 mile gap	10	Straight 1 mile gap
5	Ferdinand Northbound 1/2 mile gap	11	Ferdinand Northbound 1 mile gap
6	Ferdinand Southbound 1/2 gap	12	Ferdinand Southbound 1 gap

*PID refers to Participant ID Number. Participants 1-6 and 13-18 experienced low oncoming traffic density between passing zones. Participants 7-12 and 19-24 experienced high oncoming traffic density between passing zones.

5.3 Participants

We tested 24 participants with valid unrestricted driver's licenses in this experiment. Two different methods were used to recruit and compensate participants. For the first method, we recruited drivers with more than nine9 years of driving experience through a local classified advertisement placed on Craigslist. These drivers received $40 for their participation. The second method recruited less experienced (younger) drivers from the population of University of Idaho students signed up in the research participant pool set up by the Department of Psychology and Communications Studies. These drivers received course extra credit for their participation.

5.4 Materials and Apparatus

A seven-video channel National Advanced Driving Simulator (NADS) MiniSim rendered the simulations and collected our behavioral data. Participants "drove" the simulations from an instrumented cab based on a 2001 Chevrolet S10 pick-up truck. The cab was located such that the driver's eyes were located at the projected eye-point of the simulated environment. Three Canon REALiS SX800 projectors front-projected the main forward view of the environment onto three white screens arranged as three sides of an octagon (see figure 4.1). The projected viewpoint of the simulation was located at the center of the octagon, 1.8 m from the center of each screen. These screens created a 135 x 33.75 degree (horizontal x vertical) field of view with a spatial resolution of 4200 x 1050 pixels (H x V) and a refresh rate of 60 Hz.

In addition to the main view, two 0.203 m (8 in.) liquid crystal display (LCD) screens, each with a spatial resolution of 800 x 600 pixels (H x V), were mounted to the left and right side rearview mirror housings of the S10 cab (the right-side mirror is visible in figure 4.1). The center—windshield-mounted—rearview mirror of the cab reflected the view out the rear window of the cab, which was filled by imagery displayed on a 1.65-m (65-in.) plasma screen with 1280 x 720 pixel resolution and 60-Hz refresh rate located directly behind, and completely filling, the window opening. The seventh MiniSim video channel displayed the dashboard instrument cluster (tachometer, speedometer, engine temperature gauge, gear selection, fuel gauge) on a 0.254-m (10-in.) LCD with a spatial resolution of 1280 x 800. This display was mounted in place of the normal mechanical analog instrument cluster of the S10.

All seven displays were rendered by the NADS MiniSim software running under the Windows 7 operating system on a single graphics workstation containing 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 routed through a Matrox T2G-D3D-IF controlled the three main displays. This video adapter also rendered the dashboard and right side-mirror displays. A GeForce GTX660TI video adapter rendered the left side-mirror and center rearview mirror displays. A 5.1-channel audio system used the four speakers mounted in the cab doors and B pillars and a sub-woofer mounted behind the driver's seat to produce automobile and road sounds.

A US Digital USB4 Analog to Digital (DAC) interface with a rotary encoder connected the steering wheel, gear selector, turn signals, and brake and accelerator pedals to the MiniSim. The original S10 steering wheel provided 540 degrees of steering range and was self-centering. The original S10 brake and throttle controls provided touch displacement feedback similar to a normal automobile. A center console housed an automatic gear selector from a 2001 Honda Civic to provide participants with a standard interface for gear selection.

5.5 Procedure

Participants were treated in accordance with a university-approved protocol governing the use of human subjects in research. Prior to participation, all participants received a general description of the study, including warnings of potential risks (primarily motion sickness), and signed a consent form. Next, participants received the experimental instructions listed in Appendix A.

After the instructions, participants drove a 5-minute test drive on a two-lane rural highway to familiarize themselves with the driving simulator, and the sensitivity of the controls. Once participants felt comfortable with the controls, the test drive was terminated. Following the test drive, the experimental trial began. To reduce fatigue, after 35 miles, participants took a 5-minute break to walk around. Following the simulation, participants completed a post-simulation questionnaire and were informed of the nature and purpose of the study. The entire experimental session lasted 120 minutes.

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Chapter 6: Simulation Results

Our measures included vehicle speed and lane deviations as well as vehicle headway relative to other simulated vehicles in the environment. Figures 6.1 and 6.2 summarize vehicle speeds and lane deviations for each of the 12 passing zone configurations. Each light blue line represents the trace for one trial through the passing zone. Darker blue lines represent the mean speed or lane deviation at any given point, and the red shaded areas represent the 95 percent confidence intervals about those means of the distribution of speeds and deviations. From visual examination of the figures it is clear that both speed and lane deviation increased with longer gaps between oncoming vehicles. Indeed, there was a visible increase in number of blue tracks at a deviation of 12 feet for the 1-mile gap, which indicates that drivers spent more time in the opposing traffic (passing) lane than they did in their own lane for those conditions. There were no visually obvious effects of the different road geometries

Individuals differed significantly in the total number of vehicles passed (see table 6.1). Four of our 24 participants never passed a vehicle under any conditions, while one participant passed 36 out of the 48 possible vehicles. We were not able to conduct factorial analyses of variance on these data because some conditions in our design never produced any passes, thereby producing empty cells in the factorial design. Therefore, data will be described, but no inferences about significant differences can be made.

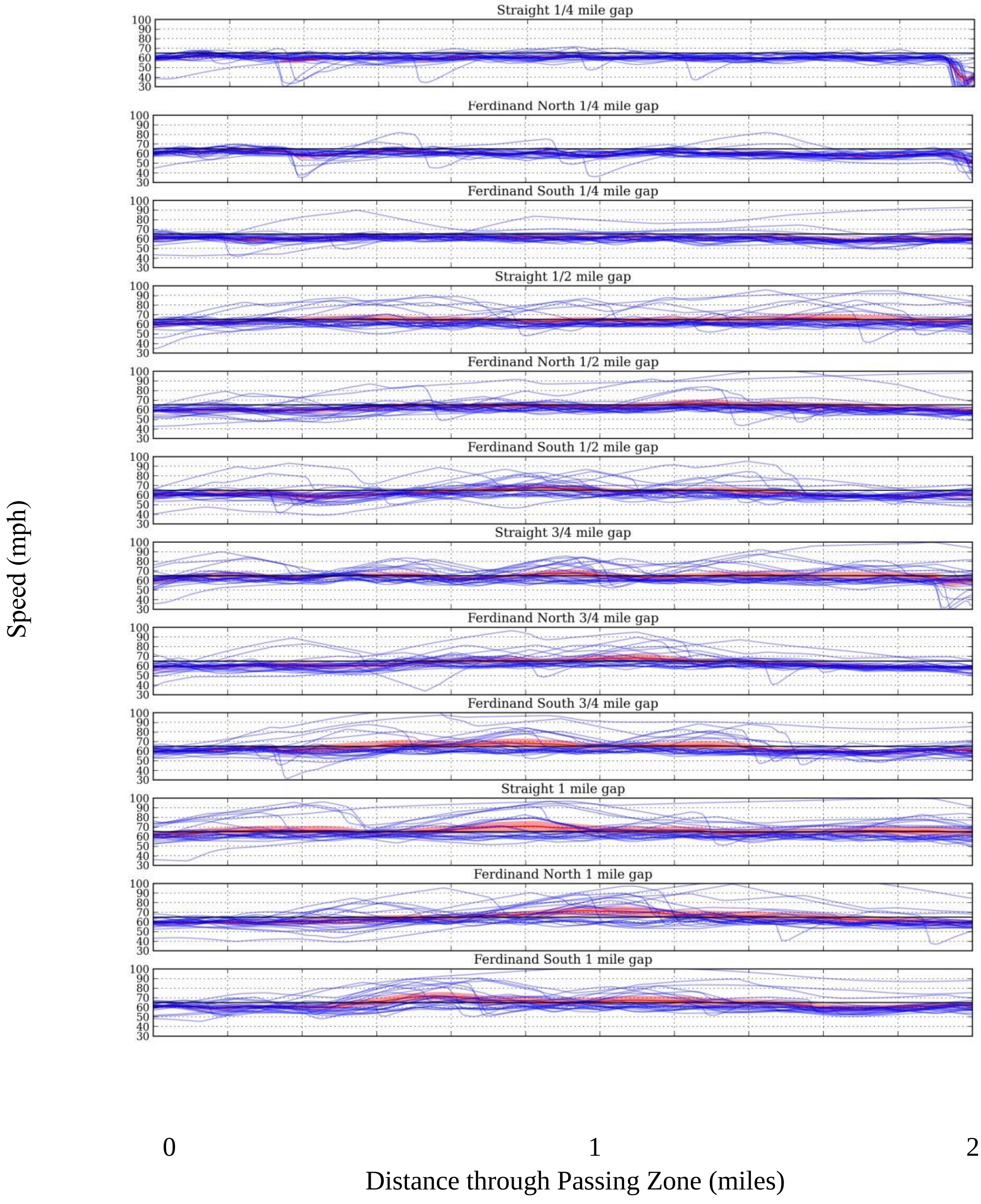

Figure 6.1 Ensemble plots of vehicle speed by passing zone condition.

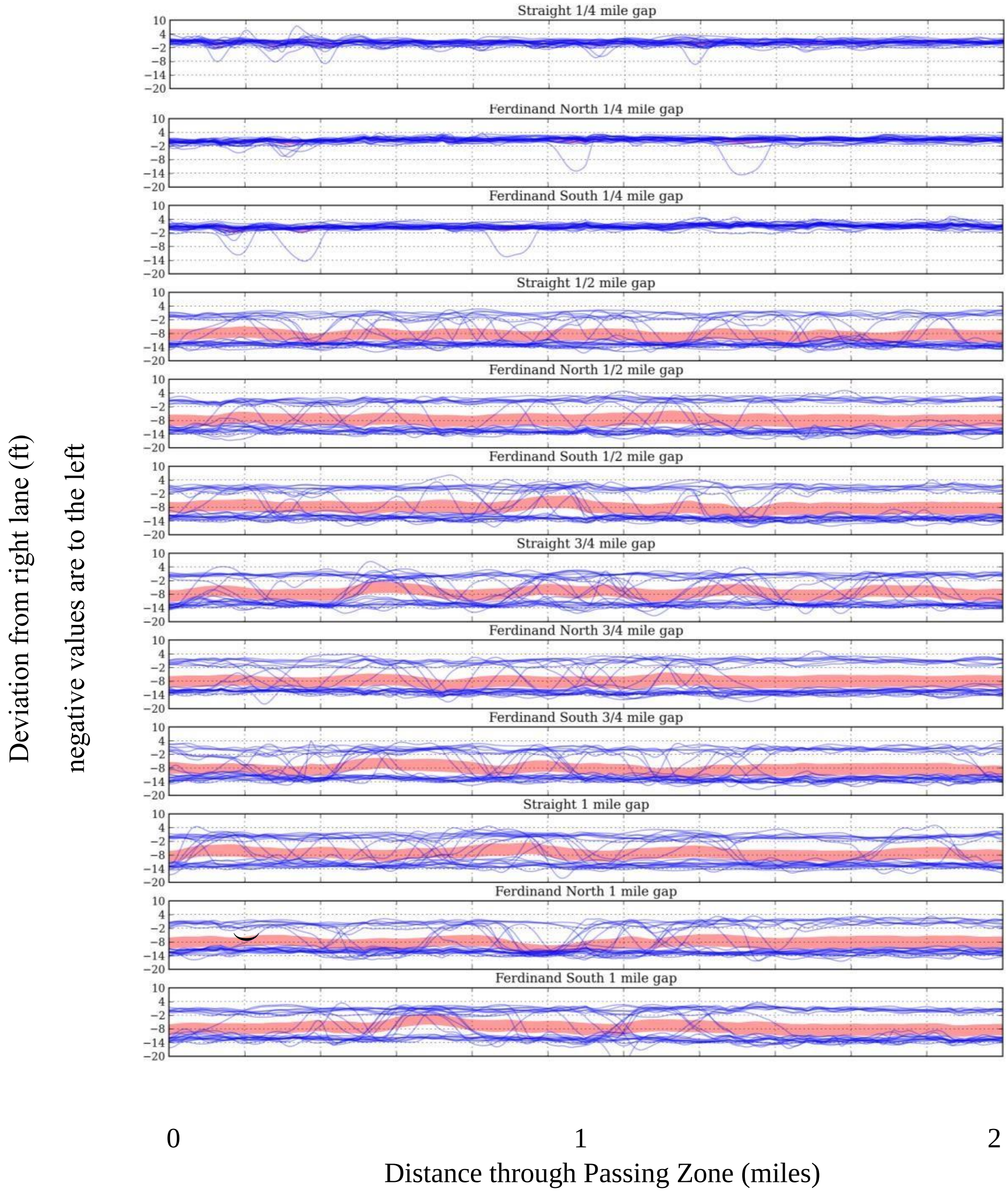

Figure 6.2 Ensemble plots of vehicle lane position by passing zone condition.

Table 6.1 Number of passes executed by each participant

Participant	Number of Passes (48 max)
1	35
2	2
3	3
4	9
5	0
6	1
7	0
8	26
9	6
10	16
11	1
12	36
13	4
14	1
15	10
16	27
17	2
19	11
20	16
21	5
22	2
23	0
24	0

Table 6.2 Number of passes executed by condition

High Traffic Density

Gap	Ferdinand N	Ferdinand S	Straight	Total
0.25		1		1
0.5	4	10	10	24
0.75	8	9	13	30
1	12	11	16	39
Total	**24**	**31**	**39**	**94**

LowTraffic Density

Gap	Ferdinand N	Ferdinand S	Straight	Total
0.25	1	1		2
0.5	7	8	16	31
0.75	7	14	19	40
1	14	13	19	46
Total	**29**	**36**	**54**	**119**

Table 6.2 shows the number of passes executed for each experimental condition. Drivers appear to have preferred passing on the straight and level section of roadway over the Ferdinand stretches that contained both vertical and horizontal curves, particularly at shorter gaps. In addition, drivers experiencing lower oncoming traffic density between passing zones passed roughly 20 percent more often than drivers experiencing higher traffic density.

Table 6.3 shows the maximum speeds obtained during passes for each condition. Road geometry again had an influence, with straight passing zones yielding slower maximum speeds.

Table 6.3 Maximum speeds (mph) during passes by condition

High Traffic Density

Gap	Ferdinand N	Ferdinand S	Straight	Total
0.25		89.89		89.89
0.5	103.19	80.57	86.00	84.60
0.75	82.99	88.05	83.71	84.92
1	91.53	84.96	79.68	84.33
Total	89.03	84.43	82.44	84.71

LowTraffic Density

Gap	Ferdinand N	Ferdinand S	Straight	Total
0.25	81.91	92.92		87.42
0.5	89.80	85.08	83.39	85.37
0.75	84.62	86.76	82.96	84.69
1	88.73	89.65	87.37	88.53
Total	87.39	87.48	84.49	86.34

Table 6.4 shows the TTC abreast during passes for each experimental condition. As one would expect, TTC was strongly related to gap distance. However, consistent with the data on number of passes presented in table 6.2, lower traffic density resulted in more passing at shorter gap distances, which lowered TTC averages. The field data and model simulations presented in Chapter 4 suggest that TTC abreast can be translated to TTC at passing decision by adding 4.2 sec.

Table 6.4 Time to collision abreast (TTCA, seconds) during passes by condition

High Traffic Density

Gap	Ferdinand N	Ferdinand S	Straight	Total
0.25		2.98		2.98
0.5	6.71	6.34	18.52	10.80
0.75	10.83	12.58	9.58	11.00
1	15.54	14.63	11.90	13.72
Total	12.46	10.53	13.05	11.88

LowTraffic Density

Gap	Ferdinand N	Ferdinand S	Straight	Total
0.25	2.99	2.75		2.87
0.5	7.36	5.78	5.24	5.88
0.75	11.62	11.15	11.79	11.52
1	15.71	15.34	12.93	14.68
Total	12.10	10.31	10.08	10.75

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Chapter 7 Discussion

The primary findings of this study are that both oncoming traffic density between passing zones and road geometry influence passing decisions in driving simulation. Higher traffic densities lower the number of passes made, particularly at shorter gap distances. This "calming" effect may be due to priming of the expectation of denser traffic when a driver enters a passing zone. Drivers experiencing lower oncoming traffic densities are more likely to make risky passing maneuvers with shorter TTC abreast.

The general behavior of participants in our simulation study appears to validly represent that found in previous studies, with minimum TTC at the decision point of roughly 7 seconds. However, the field study suggests that this TTC may be artificially low. Average TTC abreast in the field study was 18 sec, while in the simulation it was approximately 11 sec. This difference could result from drivers being willing to take more risks in a simulator, or could result from lower traffic density for the field data. Additional field data with higher traffic densities are needed to resolve this issue.

A major limitation of this study was the lack of inferential analysis due to empty cells in the factorial design. Larger sample sizes could help mitigate this limitation in future studies.

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Conclusions and Recommendations

The primary findings of this study are that both oncoming traffic density between passing zones and road geometry influence passing decisions in driving simulation.

Higher traffic densities lower the number of passes made, particularly at shorter gap distances. This “calming” effect may be due to priming of the expectation of denser traffic when a driver enters a passing zone. Drivers experiencing lower oncoming traffic densities are more likely to make risky passing maneuvers with shorter TTC. We recommend that such effects be included in macro-simulation models of highway capacity and quality of service.

Finally, straight and level road geometry also increases the likelihood of passing, even when horizontal and vertical curves do not produce sight obstructions. Furthermore, passing on straight stretches of highway is typically done at lower maximum speed. Taken together, these findings suggest that quality of service in passing zones is enhanced for straight and level road geometries.

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Appendix A Simulation Experiment Instructions

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 Idaho countryside. Your goal is to keep your vehicle centered in your lane and moving at an appropriate speed, just as you would in everyday driving. 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 50 minutes which will simulate a 50 mile drive on a rural highway, where you are returning from a weekend camping trip in rural Idaho. During this 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, road signs/markings, etc. and use normal driving etiquette (following speed limits, using turn signals, using passing lanes to pass slower moving vehicles, , etc.) just as you would if you were driving on a real rural highway, and in a ***hurry*** *to get home.*

From time to time, the other vehicles in the simulation will slow down and pull off on the shoulder. When this occurs, you should maintain a safe distance, stay in your lane, and accelerate back up to speed once the lane is clear.

Do you have any questions?

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

After approximately 25 miles, a message will appear on the screen asking you to pull over on to the shoulder 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 minute.

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?