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Investigation of driver behavior during crash and near-crash events using naturalistic driving data

by

Qiuqi Cai

A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Civil Engineering (Transportation Engineering)

Program of Study Committee:
Peter Savolainen, Major Professor
Jing Dong
Simon Laflamme

The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this thesis. The Graduate College will ensure this thesis is globally accessible and will not permit alterations after a degree is conferred.

Iowa State University

Ames, Iowa

2018

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DEDICATION

This thesis is dedicated to my family, especially my mother and father, for their endless support and devotion for my life. Without them, I would not have the chances to study aboard, see different world, and learn a lot of novel knowledge.

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NOMENCLATURE

AASHTO	American Association of State Highway and Transportation Officials
ABS	Anti-locking Brake System
ANOVA	Analysis of Variance
CTRE	Center for Transportation Research and Education
DAS	Data Acquisition System
TeleFOT	Field Operational Tests of Aftermarket and Nomadic Devices in Vehicles
GPS	Geographic Positioning System
ICC	Intelligent Cruise Control
ISU	Iowa State University
LOS	Level-of-Service
MUTCD	Manual on Uniform Traffic Control Device
NCHRP	National Cooperative Highway Research Program
NDS	Naturalistic Driving Study
OLS	Ordinal Least Square Linear Regression
PA	Pennsylvania
QA/QC	Quality Assurance and Quality Control
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users
SHRP2	The Second Strategic Highway Research Program
TRB	Transportation Research Board
VTTI	Virginia Technology Transportation Institute

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ACKNOWLEDGMENTS

I would like to express my greatest gratitude to my major professor, Dr. Peter Savolainen, for his endless support and guidance during my graduate life. Because of him, I have the opportunities to extensively explore the world of transportation.

I would also sincerely thank my committee members, Dr. Jing Dong, and Dr. Simon Laflamme, for their guidance and support throughout the course of this research and my undergraduate time at Iowa State University.

In addition, I would also like to thank my colleagues and friends, Raha Hamzeie, Trevor Kirsch, Megat Usamah Bin Megat Johari, Yu Tian, Chao Zhou, Jacob Warner, Hitesh Chawla, and Justin Cyr for providing constructive comments and extraordinary supports throughout the duration of the study and making my time at Iowa State University a wonderful experience. I want to also offer my appreciation to my friends who have always been there when I needed them.

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ABSTRACT

Various studies demonstrated that the human factors, driver performance, and the interactions among humans and other elements in the transportation systems significantly contributed to the traffic safety and highway design. Therefore, it is critical to understand driver behaviors to reduce the likelihood of crashes and enhance the design of the highway system. The major objective of this study is to investigate driver behavior, particularly during crash and near-crash events, as well as during the preceding time intervals. Of specific interest is how drivers' reaction times, deceleration rates, and speed selection vary under different roadway environments. The freeway non-crash and crash or near-crash events were obtained from the Second Strategic Highway Research Program Naturalistic Driving Study (SHRP 2 NDS) dataset and the associated Roadway Information Database (RID). Due to the unique features of the data, the random effect linear regression model with a participant-specific intercept term was utilized to perform the analyses.

The participants' reaction times of crash/near-crash events were determined to have a average value of 1.51 sec., standard deviation of 1.25 sec, and 85th percentile of 2.60 sec. The results of analysis showed that reaction time varied based upon the type of crash/near-crash event, the gender of driver, and whether the driver was distracted over the course of the driving event. The driver's deceleration rates of crash/near-crash events were also calculated in the study. The mean, standard deviation, and 85th percentile of deceleration rates were about 9.53 ft/s^2 (0.30 g), 4.99 ft/s^2 (0.15 g), and 14.27 ft/s^2 (0.44 g) respectively. The initial speed of braking, the grade of the roadway, and the type of incident presented significant influences on the deceleration rates of crash/near-crash events. Lastly, the mean and standard deviation of travel speed for non-crash and crash/near-crash events were investigate to

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explicitly understand the speed selection of drivers. On average, normal drivers showed higher driving speeds and less variability. Speed limits and traffic density had relatively consistent impacts on mean speed and speed variance under both baseline and crash/near-crash conditions. However, opposing effects of curves and work zones occurred on the standard deviation in travel speed between two groups. These effects suggested drivers were more likely to put themselves at risk for crashes by failing to reduce their speeds in response to these conditions. Other roadway and driver characteristics such as age, time of day, shoulder width, and weather conditions also somewhat showed influence on average speed and speed variance.

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CHAPTER 1. INTRODUCTION

1.1 Background

Each year, more than 6 million motor vehicle crashes occur across the United States, resulting in more than 30,000 fatalities (NHTSA, 2018). Traffic crashes represent a serious public health dilemma and are among the leading causes of death, particularly among people ages 16 through 25 (Liu, Singh, & Subramanian, 2015). Research has shown the critical reason for crashes is related to the driver in more than 90 percent of all cases (Singh, 2015), highlighting the importance of better understanding the factors that precipitate crash and near-crash events. To this end, human factors, or the interaction among humans and other elements of a system, is crucial to safe driving and a critical consideration in the highway design process.

The American Association of State Highway and Transportation Officials' (AASHTO) A Policy on Geometric Design of Highway and Streets ("the Green Book") notes that human factors and driver performance are important when considering the suitability of how a highway is designed (AASHTO, 2011). A properly designed highway should be compatible with the most drivers' capabilities and restrictions. The possibilities of human errors to occur increases during driving if the use of a highway is beyond a driver's abilities or if the driving environment introduces limitations to safe operation. This could result in inefficient highway operations or, of graver concern, traffic crashes, injuries, and fatalities. Overall, comprehension of driver behaviors could substantially assist with roadway design and reducing the odds of a crash occurring. To this end, there are several behavioral factors that are important to safe driving. Of particular interest are reaction time, deceleration rate, and speed selection.

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Reaction time can reflect various driver's responses to visual cues in the roadway environment under certain circumstances. For design purposes, reaction time is defined as "the period from the time the object or condition requiring a response becomes visible in the driver's field of view to the moment of initiation of the vehicle maneuver (e.g., first contact with the brake pedal)" (NCHRP, 2012). The AASHTO Green Book assumes reaction time to have an average value of 0.6 sec for expected events, which increases by 35 percent if the drivers encounter unexpected events (AASHTO, 2011). Longer reaction time are generally associated with greater possibilities of human errors. National Cooperative Highway Research Program (NCHRP) Report 600 (2012) indicates reaction time is one component of a critical design –factor, sight distance (i.e., the total distance traveled during the reaction time and the time required for a driver to complete an appropriate maneuver). Several factors affecting reaction time are summarized in Table 1.

Table 1: Factors Affect the Reaction Time (NCHRP, 2012)

Activity	**Factor**	**Explanation**
Seeing/Perceiving	Low contrast (e.g., night)	Drivers take longer to perceive low-contrast objects.
	Visual glare	Objects are perceived less quickly in the presence of glare.
	Older age	Older drivers are less sensitive to visual contrast and are more impaired by visual glare (e.g., oncoming headlights).
	Object size/height	Smaller objects/text require drivers to be closer to see them.
	Driver expectations	Drivers take substantially longer to perceive unexpected objects
	Visual complexity	Drivers take longer to perceive objects "buried" in visual clutter.
	Driver experience/familiarity	PRT to objects and situations will generally be faster with increased experience and/or familiarity.
Cognitive Elements	Older age	Older drivers require more time to make decisions.
	Complexity	Drivers require more time to comprehend complex information or situations and to initiate more complex or calibrated maneuvers.
Initiating Actions	Older age	Older Drivers require more time to make vehicle control movements and their range of motion may be limited.

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There are multiple circumstances under which a driver would be expected to recognize and react to expected or unexpected situations. For example, the driver could accelerate or change their lateral position to avoid conflict when they notice a car is proceeding to merge unexpectedly into their travel lane. Alternatively, the driver could take their foot off the gas pedal and begin to decelerate to avoid a potential traffic conflict.

In the latter case, understanding drivers' braking performance is also important to roadway design when attempting to reduce the potential for crashes to occur. Deceleration behavior is also the other important factor (in addition to reaction time) affecting the sight distance (NCHRP, 2012). The rate of deceleration reflects driver braking performance, specifically the rate at which a driver reduces their speed. NCHRP Report 600 (2012) suggests a value of 13.8 ft/s^2 (0.43 g) for average deceleration rate and 0.38 g for the 85th percentile deceleration rate under wet conditions with standard brakes. With anti-locking brake system (ABS), the average deceleration rate is 0.53 g, and the 85th percentile is around 0.45 g on the wet pavements. These typical values are based only on the underlying physics without any consideration of human factor (NCHRP, 2012). Although the deceleration rate or braking behavior is significantly affected by roadway surface conditions, driver characteristics also could have an impact to a certain extent (NCHRP, 2012). Due to the unique features of the braking rate, many dimensions of the roadway designs fundamentally depend on it such as intersections, freeway ramps, and turnout bays for buses, etc. (AASHTO, 2011).

A third behavioral concern related to highway design is driver speed selection, which can be quantified by average travel speed or the variation in travel speed during a driving event. As with reaction time and deceleration rate, speed is also an important contributing

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variable of sight distance. Driving speed affects if whether a vehicle can safely complete a maneuver (e.g., stopping) within the available time and distance. Many design guidelines (e.g., AASHTO) also utilize "design speed" to determine various design elements, including the required stopping sight distance, though NCHRP Report 600 (2012) indicates the actual operating speed should be used in calculation of sight distance instead of posted speed limit or design speed. Driving speed also has a significant correlation with the posted speed limit, which is the maximum statutory limit allowed for vehicles based on prevailing roadway conditions (FHWA, 2012).

Unfortunately, research as to the impacts of driver behavior and other in-vehicle factors on crash risk has been inhibited historically as such research has generally focused on the use of police-reported crash data. Examining issues such as reaction time, deceleration rate, and speed selection is challenging since crash data has significant limitations with respect to its accuracy and completeness, particularly with respect to these types of behavioral and in-vehicle factors.

Recently, naturalistic driving studies (NDS) have introduced a promising means for overcoming these limitations. NDS generally collect data by recording real-time information on vehicle kinematics, driver behavior, and roadway information through intricate data collection equipment (e.g., video cameras and radars). These data have the potential to provide excellent insight for researchers to better understand driver performance (Van Schagen, Welsh, Backer-Grøndahl, Hoedemaeker, Lotan, Morris, Sagberg, & Winkelbauer, 2011). Most prior research in this area has utilized traditional methods (e.g., driving simulator, field experiments, and survey) to study driver behaviors. However, these traditional methods may not able to ultimately reflect the real world traffic and driver

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performance. For example, the use of driving simulators may not accurately reflect how drivers would respond to real-world conditions and study participant behavior may vary due to their awareness of participating in a specific experiments (Van Schagen & Sagberg, 2012). NDS provide a robust method to examine these research questions as they allow for the unobtrusive collection of data on driver behavior under natural conditions.

1.2 Research Objectives

The primary objective of this study is to investigate driver behavior, particularly during crash and near-crash events, as well as during the preceding time intervals. Of specific interest is how drivers' reaction times, deceleration rates, and speed selection vary under different roadway environments. The Second Strategic Highway Research Program (SHRP 2) NDS dataset and the associated Roadway Information Database (RID) are used to conduct this research. These datasets provide specific information about driving behaviors, roadway characteristics, and geometrics, as well as corresponding traffic operations and environmental information. Unlike traditional data collection methods, the events from the SHRP 2 NDS and RID were recorded by advanced equipment such as video cameras and various sensors installed in the participants' vehicles over the course of the study duration. This study focuses on driving events on freeways, where design standards are relatively consistent across states and where traffic flow is relatively uninterrupted, reducing the amount of noise as a part of the investigation. In order to accomplish the goals of the study, the following tasks were completed:

1. Drivers' reaction times were examined during the time leading up to crash and near-crash events. Research using the NDS has traditionally utilized two methods to estimate reaction time: 1) the time difference between the coded timestamp for

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the "Event Start" field and the time at which drivers applied the brake pedal; and 2) the time difference between the coded timestamp for "Event Start" and the timestamp for the "Subject Start to React" field.

2. Drivers' average deceleration rates were examined over the course of these same crash and near-crash events. These deceleration rates were estimated based upon the changes in vehicle speed from the time immediately before drivers started to react to the time at which they reached their lowest speed.
3. Driver speed selection behavior was considered by examining how mean and standard deviation in speeds varied under crash and near-crash situations as compared to normal, baseline driving events.
4. In each case, the research examines those factors related to the driver, vehicle, and roadway that influence reaction time, deceleration rate, and speed selection. The results provide insights that are valuable for improving roadway design and other traffic safety policies and programs in consideration of driver behavior under these high-risk scenarios.

1.3 Thesis Structure

This thesis consists of six main chapters, which introduce the background of the research problem of interest, provide the review of existing research literature, describe the data and the methodology utilized, discuss the critical findings from the results concerning the objective of this study, and summarize the findings. Brief descriptions of each chapter are as follows:

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- Chapter 1: Introduction – This chapter includes the background of the study of driver behaviors. Notably, the importance of understanding the drivers' reaction time, deceleration rate, and speed selection are introduced part by part. The motivations and outline of the study are also presented.
- Chapter 2: Literature Review – This chapter is organized into three sections to summarize the extant literature review regarding the reaction time, deceleration rate, and speed selection behaviors. The first section provides the typical values of the reaction time determined by the previous research. The possible methods to determine reaction time and the factors affected it was also demonstrated in this section. The second sections specified the values and methodologies utilized for deceleration rate, as well as detailed the variables have impacts on the deceleration behaviors. The third section discussed the findings of the speed selection behaviors.
- Chapter 3: Data Description – This chapter provides an overview of the SHRP 2 program, NDS dataset, and the RID. The processes of data collection and integration are presented. In addition, the descriptive statistics for the final dataset are included in this chapter, including details of reaction time, deceleration rate, mean and standard deviation of travel speed, as well as the corresponding driver and roadway characteristics.
- Chapter 4: Methodology – This chapter describes the statistical methods utilized in this study, which include a series of random effects linear regression models. Technical details and motivation for the use of this analysis framework are presented.

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- Chapter 5: Results and Discussion – This chapter contains the results and discussions of the results of the statistical analyses. The chapter is structured into three sections, one for each variable of interest: reaction time, deceleration rate, and travel speed.
- Chapter 6: Conclusion – This chapter summarizes the key findings of the research. This includes a discussion of the practical implications, limitations, and recommendations for future research.

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CHAPTER 2. LITERATURE REVIEW

2.1 Drivers' Reaction Time

Drivers' reaction time is one of the critical component of determining the sight distances, including the stopping, decision, passing, and intersection sight distances (AASHTO, 2011). The AASHTO (2011) stated that several previous studies (MIT, 1935; Normann, 1953: Johansson & Rumar, 1971; Fambro, Fitzpatrick, & Koppa, 1997) showed that the reaction time of 2.5 sec. should be used to calculate stopping sight distance. However, as AASHTO indicated, the reaction time expects to be higher than 2.5 sec. for the most complex conditions encountered in actual driving such as driving at at-grade intersections and at ramp terminals, even though 2.5 sec. is adequate for the situations that are more complicated than simple situations used in road tests (AASHTO, 2011).

Early time, many studies estimated the reaction time by field experiments or driving simulators. For example, a study of reaction time by Johansson and Rumar (1971) performed two experiments among two groups to determine the reaction time. The first group included 321 drivers who expected to apply the brake. The reaction time of this group was individually measured under the normal highway driving conditions (experiment 1). The second group included five drivers who experienced repeated measurements under expected and unexpected conditions (experiment 2) to obtain the reaction times. The results of the first experiment stated the estimated reaction time was 0.9 sec. or longer in 50 percent of all unexpected situations, while 10 percent of them experienced 1.5 sec. or longer. In the second experiment, the 75^{th} percentile measurement was 0.9 sec. (Johansson & Rumar, 1971). Another study by Olson and Sivak (1986) also measured the reaction time by experimenting groups of drivers under a particular occasions. The drivers were divided into two groups: 49

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younger subjects (18 to 49 years old) and 15 older subjects (50 to 84 years old). At the end of the experiment, the 95th percentile of the reaction times was around 1.6 sec. for both age groups (Olson, & Sivak, 1986).

Additionally, various studies explored the factors that could potentially influence reaction time such as speed, age, gender, and whether drivers were distracted or not. For instance, a study from Sweden (Tornros, 1994) proposed the reaction time was smaller at a lower speed (i.e., 70 km/h or 43.5 mi/h) while comparing with the higher speed (i.e., 110 km/h or 68.4 mi/h). In addition, if the drivers were distracted, they were more likely to react slower than the regular drivers (Consiglio, Driscoll, Witte, & Berg, 2003; Welford, 1980; Broaadbent, 1971). The effects of the genders of motorists were examined by many studies as well. The findings revealed that males had shorter reaction time than females (Der & Deary, 2006; Dane & Erzurumluoglu, 2003).

A study from Minnesota also examined the impact of driver distraction on brake reaction time under the car-following situation (Gao & Davis, 2017). The data was obtained from the SHRP2 NDS dataset and collected based on various conditions. This study mainly focused on the freeway rear-end events including crash, near-crash, and crash-relevant incidents. By the end of data collection, 130 events were extracted from the NDS database. To understand the relationship between the driver distraction and reaction time, Gao and Davis calculated the reaction time and distraction duration. The reaction time was defined as "the time gap between the time point when leader vehicle's brake light first went on and that when the follower driver first swerves or braked, whichever came first, as the response to leader driver's brake." Specifically, the reaction time was determined based on the difference between the timestamp "Event Start" in the NDS dataset and the timestamp when drivers

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applied the brake pedal or reduce the speed. The basic statistics of reaction time in different driving groups is shown in Table 2. The distraction duration was the time difference between the timestamps “Secondary Task Start Time” and “Secondary Task End Time.” After conducting the causal model structure exploration regarding the drivers’ distraction impacts on the reaction times, the results showed there was a correlation between the reaction time and drivers’ distraction duration. Longer distraction duration related to longer reaction time. Besides, if the driver was on the secondary task when the leader braked, the reaction time was higher than the average driving condition (Gao & Davis, 2017).

Table 2: Basic Statistics of Reaction Time in Different Driving Group (Gao & Davis, 2017)

	Normal driving group (sec.)	Distracted driving group (sec.)
1st quantile	0.642	1.246
2nd quantile	1.162	1.836
3rd quantile	2.129	2.792
Mean	1.575	2.113
Standard deviation	1.255	1.364

Higgins, Avelar, and Chrysler (2017) also conducted a similar study regarding the influence of drivers’ distraction on driver’s reaction time. However, the driver’s distraction was primarily focused on the cell-phone use related distractions and categorized as baselines, manual-cognitive distractions, and visual-manual distractions. In addition to the distractions, the impacts of drivers’ age and roadway environment on reaction time were agin investigated in the study. Likewise, the data was obtained from the SHRP2 NDS dataset as well including the lead-vehicle or approaching-vehicle incidents, which included 249 events from 179 drivers. Different from the previous research, the reaction time in this study was defined as “the difference between the start of a precipitating event (e.g., a braking lead vehicle) and the start of the driver’s first recognizable reaction to the precipitating event as coded in NDS dataset.” It also referred to the time gap between the timestamps “Event Start” and “Subject

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Start to React" in the NDS dataset. A summary table of median reaction times across age, distraction type, and roadway location are shown in Table 3. A mixed-effect linear regression model was utilized to perform the reaction time analysis with a random effect per driver. The analysis showed that the median reaction time was 40.5 percent greater among drivers who were involved in visual-manual distractions; the median reaction time for crashes or near-crashes events occurred in urban area was 1.377 times longer than the events in highway or residential areas; the median reaction time for teenagers (16 to 19 years old) was 1.36 times larger than the older drivers (Higgins, Avelar, & Chrysler, 2017).

Table 3: Median Reaction times Across Age, Distraction Type, and Roadway Location (Higgins et al., 2017).

Age Group	Distraction Type	Crash (sec.)			No Crash (sec.)		
		Fwy	Residential	Urban	Fwy	Residential	Urban
Teens	None/Baseline	N.A.	1.924	N.A.	0.640	0.991	0.707
	Manual-Cognitive	N.A.	N.A.	2.226	0.833	N.A.	0.872
	Visual-Manual	N.A.	3.432	2.368	0.749	1.626	2.582
Older than 19	None/Baseline	1.950	0.620	1.961	1.471	1.506	1.480
	Manual-Cognitive	N.A.	N.A.	N.A.	2.031	1.756	2.047
	Visual-Manual	4.168	3.514	2.942	2.175	0.405	2.085
Overall	Minimum	0.018			Mean	2.142	
	1st Quantile	0.864			3rd Quantile	2.810	
	Median	1.790			Maximum	12.213	

Another study from Dozza (2012) investigated the variables that impacts the reaction time as well including drivers' distraction, roadway environment, crash types, and speed limit. This study utilized the 100-car and 8-truck naturalistic data from Virginia Technology Transportation Institute (VTTI). In order to determine the reaction time, Dozza (2012) analyzed the dataset by using the NatWare toolkit, which can "recognize different data structure from different naturalistic studies and adapts its look and features to the dataset." After determining the reaction time, a univariate analysis of variance (ANOVA) and Turkeys

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post hoc tests were used to perform the statistical analysis. The results showed that when the drivers' eyes were off the road, the reaction times for them were significantly greater than when the drivers look at the road. Additionally, the reaction times for the distracted drivers were higher than the attentive drivers. Younger drivers showed, on average, less reaction time. Speed also influenced the reaction time. Higher speed (25-45 mi/h) correlated with the smaller reaction time while comparing with the speeds under 25 mi/h. However, if the incident types were controlled, the speed limit did not significantly influence the reaction times. Additionally, drivers had quicker reaction times when they encountered road departures, and sideswipe crashes, or experienced darkness. Lastly, the response times for car drivers were significantly higher than the truck drivers (Dozza, 2012) .

2.2 Drivers' Deceleration Behaviors

After the drivers recognized and started to react to the unexpected events occurring on the roads, the drivers would either choose to apply the brake or swerve to other directions to avoid the severe incidents. According to the study from Fambro, Fitzaptrick, and Koppa (1997), if the drivers needed to stop for an emergency or unexpected events, or objects in their travel lanes, most of them had deceleration rates greater than 14.8 ft/s^2 (0.46 g). However, on wet surface, 90 percent of drivers decelerated at a rate about 11.2 ft/s^2 (0.35 g's) if they were capable of staying in their driving lane and maintaining steering control during the braking maneuver. Therefore, the deceleration rate of 11.2 ft/s^2 was the suggested deceleration threshold in the AASHTO (AASHTO, 2011).

The research conducted by the Wood and Zhang (2017) summarized the findings of the deceleration rate from the previous studies (Fambro, Fitzpatrick, & Koppa, 1997; Fitch, Blanco, Morgan, & Wharton, 2010; Paquette & Porter, 2014; Deligianni, Quddus, Morris, & Anvuur, 2016; Ariffin, Hamzah, Solah, paiman, Jawi, & Isa, 2017). The summary table is

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shown in Table 4. The top section of the table indicated that the range of average deceleration rate was from 0.27 g to 0.77 g regardless of other factors such as the driver and geometric characteristics. Additionally, curves were associated with the lower mean deceleration rates, while the tangents experienced the higher average deceleration rate. Thirdly, the drivers generally decelerated at a lower rate on the wet pavement when compared to the mean deceleration rate on dry pavement. Additionally, the deceleration rates had more variability on dry pavements and tangents. The following table also showed that most deceleration rates from the previous literature were larger than the recommended value in AASHTO (Wood & Zhang, 2017).

Table 4: Summary Table of Deceleration Rate from Previous Studies (Wood & Zhang, 2017)

Tangent/Curve	Pavement Condition	Drivers Ages	Mean Deceleration Rate (g)	Deceleration Standard Deviation (g)	References
Curve	Dry	Mixed	0.54	0.11	(Fambro et al., 1997)
Tangent			0.57	0.12	
Curve	Wet		0.51	0.09	
Tangent			0.55	0.08	
Tangent	Dry	18-25, 65+ Years	0.48	0.03	(Fitch et al., 2010)
		Not Specified	0.77	-	(Paquette & Porter, 2014)
		Not Specified	0.75	-	
		Not Specified	0.81	-	
		Not Specified	0.83	-	
		23-59 Years	0.27-0.67 (dependent on other variables)	-	(Deligianni et al., 2016)
		Not Specified	0.56	0.17	(Ariffin et al., 2017)

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Furthermore, Wood and Zhang (2017) utilized the SHRP2 NDS data to determine the deceleration rates as well. The deceleration rates were extracted from the NDS time series data by Java application. The effects of deceleration rate by event severity are given by Table 5 (Wood & Zhang, 2017).

Table 5: The Effects of Deceleration Rate by Event Severity (Wood & Zhang, 2017)

Event Level	Count	Declaration Rate (g)		
		Mean	Median	Std. Dev.
Crash	455	0.41	0.34	0.34
Near-Crash	2556	0.45	0.46	0.23
Total	3011	0.44	0.45	0.26

Except for the determination of specific deceleration rate, some research also investigated the relationship between braking performance and other features such as driver behaviors, drivers, and roadway characteristics. For instance, a study (Fitch, Blanco, Morgan, Wharton, 2010) shown in Table 4 asked 64 participants to drive two instrumented vehicles at an inflatable barricade at 45 mi/h to understand the correlations between deceleration behaviors and other variables. There was a strong correlation between deceleration rate and the gender, age, and vehicle driven in the analysis results. One of the studies included in Table 4 (Deligianni, Quddus, Morris, & Anvuur, 2016) also investigated the driver braking behaviors by utilizing the naturalistic driving data from the Pan-European TeleFOT project (Field Operational Tests of Aftermarket and Nomadic Devices in Vehicles). This project was more extensive collaborative European field experiments under seventh framework program. The tests were conducted by 16 drivers which included six males and ten females with an average age of 40 years (i.e., the range of 23 to 59 years old). They were asked to drive an instrumental vehicle on a road of 16.5 km (10.25 miles). After the data collection, the multilevel mixed-effects linear regression models were used to examine the impacts of factors on deceleration rate and duration of the event. The factors included trip duration, age,

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gender, miles driven per year, initial speed, traffic light, deceleration profile, reasons for braking, traffic density, and travel distance. The results revealed the most critical factors affecting the deceleration events were initial speed, distance, deceleration profile, and the reason for braking; the initial speed had the most significant influence. The deceleration rates decreased while the initial speed increased. None of the driver characteristics (i.e., age, gender, and miles driven per year) were statistically significant. This was probably due to the small sample size. Only 16 drivers were included in the trials.

Another study investigated the braking performance at the onset of a yellow-phase transition on high-speed approaches to a signalized intersection ((EI-Shawarby, Rakha, Inman, & Davis, 2007). Sixty drivers were asked to drive vehicles equipped with Global Positioning Systems (GPS) on a 2.2 mile two-lane road with a four-approached signalized intersection. The participants were divided into three age groups with an almost equal number of males and females: under 40 years old (16 drivers), 40 to 59 years old (12 drivers), and 60 years old or older (32 drivers). In addition, the tests were conducted under clear weather, daylight time, dry surface, and without any leading vehicles to eliminate any noises caused by other factors. The chi-square analysis and analysis of variance (ANOVA) were utilized to examine the data with five yellow phase trigger time (1.6 s, 2.7 s, 3.3 s, 4.4 s, and 5.6 s). As a result, the range of the driver deceleration rate was between 5 and 24.5 ft/s^2, and the average value was 10.7 ft/s^2. Furthermore, the results of analysis also indicated that the male participants decelerated at a slightly higher rate than female drivers. The driver under 40 years old and over 59 years old had higher deceleration rates while compared to the deceleration rates of the drivers in the age group of 40 to 59 years old. Loeb, Kandadai, McDonald, Winston (2015) also proved that age was an influential factor of the deceleration

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rate. They compared the braking behaviors between two age groups: novice teens (i.e., 16 – 17 years old) and experienced adults (i.e., 25 – 50 years old). The novice teens experienced deceleration rates that were on average 50 percent less than the deceleration rates of experienced adults (Loeb et al., 2015).

Similar research was finished by Haas, Inman, Dixson, and Warren (2004). However, unlike the study described before, the researchers not only investigated the deceleration behavior but also determined the acceleration behaviors. Initially, there were 108 drivers required to perform the experiment at stop-controlled intersections on rural highways without any leading vehicles. This data collection was a part of a 1996 Intelligent Cruise Control (ICC) Field Operational Test conducted in Michigan. The testing vehicles also were equipped by GPS to record the necessary information. After the data filtering and quality assurance, 299 deceleration events and 214 acceleration events with 24 drivers were selected. Based on the results from graphic plots and a novel mathematical model, the most significant factor affecting the deceleration rate was the initial speeds. Mainly, the lower rate of deceleration correlated with less initial speed. Even though the influences of other variables such as genders, ages, and day of the week were investigated, the statistical correlation was negligible.

Furthermore, Lindheimer, Avelar, Dastgiri, Brewer, and Dixon (2018). analyzed deceleration rates in urban corridors. The purpose of this research was to compare the braking behaviors of drivers involved increase or near-crash events with braking behaviors of normal drivers (baseline events) while controlling other factors. The data were obtained from the SHRP 2 InSight website and extracted based on multiple scenarios. The deceleration rates of each event were calculated according to the difference between the maximum and

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minimum speeds which occurred during the events. A total of 155 events was selected to estimate the deceleration rates, ranging from 1.84 ft/s^2 to 23.46 ft/s^2 with an average rate of 8.38 ft/s^2. The linear regression model was utilized to analyze the dataset. In addition to the variables that indicated crash involvement, the number of through lanes was discovered to affect the deceleration rate. Within the crash-related events, the deceleration rates increased as the number of through lanes increased. However, if any unexpected vehicles switched from other lanes, the deceleration rate increased (Lindheimer et al., 2018)

2.2 Drivers' Speed Selection Behaviors

Another essential component of highway design was travel speed. It could potentially affect the design of speed limit and roadway geometries. The travel speed was also associated with crash risk. A vehicle traveling with a higher speed typically had a higher likelihood to be involved in a crash. Because of this, understanding the interrelationship between travel speed and other factors would be critical for both design and safety perspectives. AASHTO stated five variables that are generally associated with the travel speed of a vehicle on a road or highway: the roadway geometric characteristics, the number of roadway obstacles, the weather, the presence of other vehicles, and the speed limitations (AASHTO, 2011). Additionally, Oxley (2015) discussed that the drivers' speed choices were affected by the drivers, vehicles, roadways, and traffic characteristics. Moreover, , Royal (2003) conducted surveys to prove that drivers believed weather conditions, perceptions of the "safe" speed, posted speed limit, traffic densities, and their past driving experiences were the most influential variables dictating the drivers' speed choice (Royal, 2003).

Some other literature supported the statement mentioned in AASHTO. For example, a study of travel speed from Canada utilized the data collected by Bluetooth sensors to

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investigate the effect of weather on speed selection behavior. The researchers primarily collected the drivers' travel speed on the urban arterial during the2013 to 2014 winter seasons. The ordinal least square (OLS) linear regression model was proposed to analyze the data. The results demonstrated that the operating speeds of drivers highly depend on the weather conditions such as rain and snow (Romancyshyn, Lesani, & Mirand-Moreno, 2016). Another study from Hokkaido University also proved that the adverse weather had negative impacts on driving speeds (Hong, Hagiwara, Takeuchi, & Lu, 2014).

Speed limits posted on the roads were highly related to the travel speed. Shirazinejad and Dissanayake (2018) analyzed the speeds before and after the speed limit change on the freeway to understand the relationship between speed selection behaviors and speed limit. They compared 85th percentile speeds with speed limit of 70 mi/h to 85th percentile speeds with speed limit of 75 mi/h by utilizing the t-test and F-test. As a result, the 85th percentile speed increased as the speed limit increased. The similar study conducted by Kloeden, McLean, Moore, and Ponte (2006) investigated the influence of increasing the speed limit on the driving speed and the correlated variability in the speed on high-speed roadways. The findings stated that even though the change of speed limits had an effect on the travel speed, the operating speeds and variability of speed were more significantly impacted by the roadway geometric characteristics (Kockelman et al., 2006).

Another study of the relationship between speed limit and speed selection behaviors was conducted by Hamize (2016) which also indicated that the travel speed depended on the speed limit. The researcher obtained the freeway data from SHRP2 NDS database and roadway information database (RID) including time preceding crashes, near crashes, and baseline (non-crashes) events. Moreover, the mean and standard deviation of speed for each

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event with various speed limits were calculated to examine the impacts of speed limits on the drivers' speed choice. The summary table for mean and standard deviation of travel speeds over events is given in Table 6.

Table 6: Mean and Standard Deviation of Speeds Over Events (Hamzeie, 2016)

Speed Limit (mi/h)	Average of Mean Speeds (mi/h)	Std. Dev. Of Mean Speeds (mi/h)	Average of Std. Dev. Speed (mi/h)
55	58.38	13.56	1.90
60	56.40	15.04	1.92
65	67.67	8.95	1.20
70	69.49	12.17	1.31

The random effect linear regression model was utilized to analyze the data to provide better understandings of the driver speed selection. The results demonstrated that the average speeds and variability of speed depends on various characteristics. First, the mean and standard deviation of travel speeds decreased as the traffic density increased and the speed limit decreased. Additionally, the drivers were more likely to drive slower on horizontal curves and along uphill roadways. The weather, driver, and roadway characteristics showed significant impacts on the driving speeds. The speeds of males among age 16 to 24 were higher than others. The speeds under raining or snowing weather were lower than the speeds under other weather conditions. If work zones were presented on the sites, the drivers had a higher likelihood to drive slower with more variabilities.

In summary, most of the previous literature somewhat discussed and explored the methods and variables that could be utilized to define and explain the reaction time, driver deceleration rate, and the speed selection behaviors. For example, the field experiments, driving simulators, and naturalistic driving tests were both able to assist the researchers in examining the reaction time, deceleration rate, and traveling speed. The typically ranges of

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these dependent variables were introduced in that literature as well, which provided general pictures for other researchers. In addition to the methodologies and typical values, the research above also estimated the factors that could affect those variables. The driver characteristics of age and gender, the driver behaviors such as distraction during driving, weather conditions, and the roadway characteristics of a number of lanes and speed limits were most common factors that the researchers investigated in the previous studies. However, there was a limited amount of literature that used naturalistic driving data to investigate the correlations between the roadway geometric characteristics and reaction time, decelerating behaviors, and operating speeds. Because of this, the research discussed in this paper will determine the reaction time, deceleration rate, and average and standard deviation of travel speeds; it also discussed the interrelationships between these factors and other variables such as driver and roadway geometric characteristics by utilizing the naturalistic driving data from SHRP2.

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CHAPTER 3. DATA DESCRIPTION

3.1 Data Background

The second Strategic Highway Research Program (SHRP 2) was the primary database for this study, which is currently being managed by the National Research Council's Transportation Research Board (TRB). The SHRP 2 program was created based on the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU). It aims to explore the strategic solutions to help transportation professionals to (1) improve highway safety, (2) reduce congestion, and (3) improve quality of life for rehabilitating the roads and bridges in the United States (TRB, 2001). As mentioned above, driver behavior is one of the significant factors that contribute to the highway design and likelihood of crashes. However, there were no adequate details and direct observations for the researchers to understand the relationship between driver behaviors and crashes. To achieve a better understanding of the relationship, a novel and comprehensive set of data including what happens in the vehicle before and during crashes and near-crash events was developed by the SHRP 2 program. The data was from two primary sources: NDS database and roadway information database (RID) (FHWA, n.d.).

3.1.1 Naturalistic Driving Study

The primary purpose of the NDS is to understand the interactions between the drivers and the vehicles, the traffic control devices, the roadway environment and characteristics, as well as other environmental factors. It is also used to determine the differences in collision risk associated with each of these features and their interactions (Campbell, 2012). The data of NDS was collected from six states: Florida, Indiana, New York, North Carolina, Pennsylvania, and Washington, including the naturalistic driving information from 3,400

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participant drivers between 2010 and 2013 (Hankey, Prez, & McClarfferty, 2016). These participants were recruited through (1) call centers operated by VTTI and Battelle and (2) advisements in the web-based Craigslist, flyers, presentations, mass mailings, and e-mails. The participant vehicles were requested to install the data acquisition system (DAS) to record the drivers' behaviors and other exposure characteristics continually. The DAS includes forward radar, four video cameras, accelerometers, Geographic Positioning System (GPS), onboard computer vision lane tracking, plus other computer vision algorithms, and data storage capability. A DAS schematic view is shown in Figure 1 (Campbell, 2012).

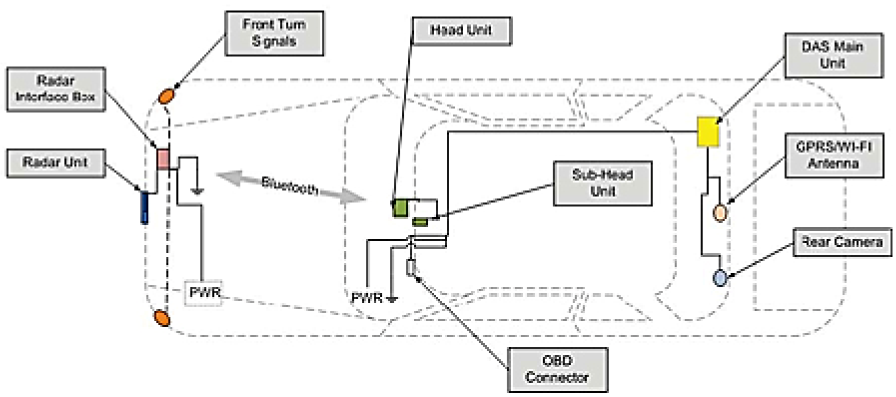

Figure 1: DAS Schematic View (Campbell, 2012)

Four fields of view can be recorded by the video cameras which are installed in the head unit, including (1) driver and left side view, (2) passenger snapshot view, (3) rear and right view, and (4) forward view. It captured the data on the drivers and roadways. Figure 2 includes a schema and example for the fields of view (Campbell, 2012). Besides, the vehicles' speed, acceleration, braking and other evasive maneuvers are also recorded by the DAS in every decisecond. All the collected data is being managed by VTTI and readable, but non-extractable in the InSight website. The actual datasets need to be requested from VTTI (FHWA, n.d.).

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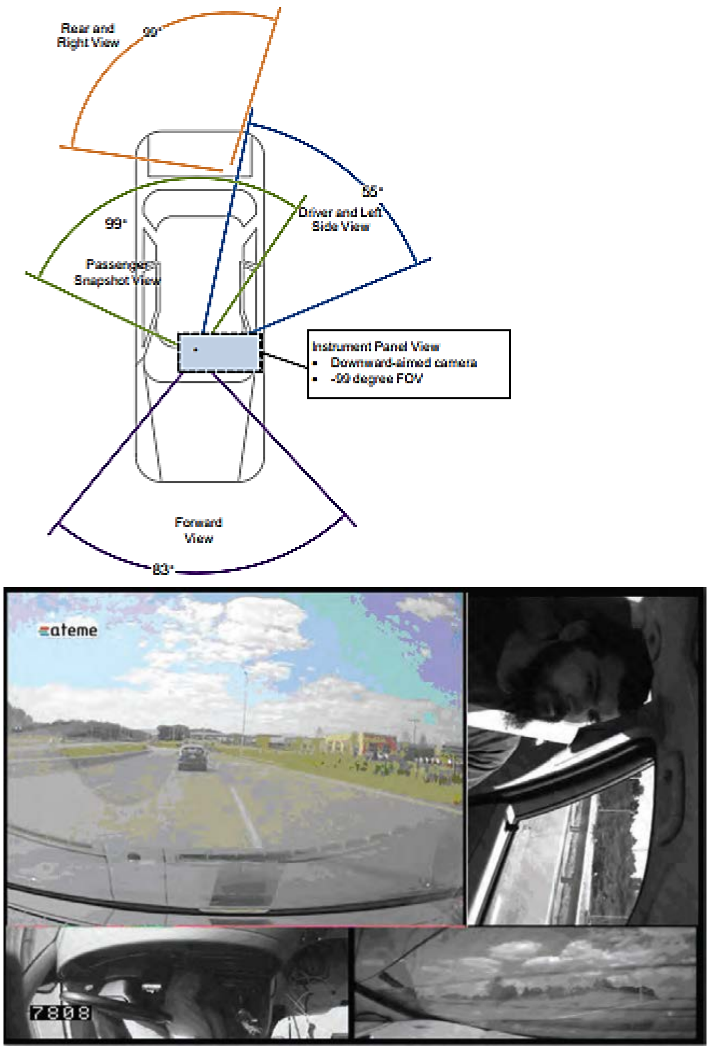

Figure 2: Schema and Example for Field of View for DAS (Campbell, 2012)

Overall, the NDS dataset includes (FHWA, n.d.):

- Videos – front, rear, driver face and hands
- Accelerometer data – 3 axis
- GPS location – latitude, longitude, elevation, time, velocity
- Forward radar – positions and velocities
- Vehicle network data – speed, accelerator, brake, gear position, steering wheel angle, turn signals, horn, seat belt use, air bag deployment, etc.
- Illuminance sensor

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- Cell phone call – beginning and end times
- Passive alcohol sensor
- Driver assessment data – vision, cognition, health, medication, driving knowledge and history

3.1.2 Roadway Information Database (RID)

Roadway information is critical to addressing the relationship between the driver's behavior and roadway characteristics. The RID was developed by the Center for Transportation Research and Education (CTRE) of Iowa State University (ISU) (Campbell, 2012). It is a geospatial database which includes roadway characteristics every second from 25,000 miles of roadway where the NDS was conducted among the six study states (Hamzeie, 2016). The CTRE collected the roadway information data by combing the existing roadway data from the state highway departments and other sources with data collected by Fugro Roadware-equipped vans. The routes were selected according to the GPS traces of the roads where the participant drivers traveled at NDS sites, which were prepared by VTTI. An example of the data collection by Fugro Roadware-equipped van is provided in Figure 3 (Campbell, 2012).

Overall, the RID includes (FHWA, n.d.):

- Number of lanes
- Lane type and width
- Grade
- Cross slope
- Horizontal curvature: curve start, end, direction, length, and radius
- Lighting

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- Rumble Strips
- Median type
- Shoulder width
- All Manual on Uniform Traffic Control Devices (MUTCD) signs
- Barriers
- Location of intersections, number of approaches, and traffic control type

Figure 3: An Example of Roadway Data collection by Fugro Roadware-equipped Vans (Campbell, 2012)

3.2 Data Collection

3.2.1 Reaction Time and Deceleration Rate

One of the objectives of the study is to evaluate the influences on drivers' behaviors, specifically, the driver and roadway characteristics on the reaction time. To achieve this objective, the reaction time and deceleration rate when the drivers encountered the unexpected events needed to be determined first. Because of this, the timestamps when the drivers noticed the unexpected events (e.g., leading vehicles braked, other vehicles suddenly shifted to the driving direction, unexpected objects occurred on the roads, etc.), the

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timestamps when the drivers started to react to these events, and the timestamps when the drivers stopped to brake needed to be accessible. Additionally, the instantaneous travel speeds and status of the brake pedal associated with every time interval were required to be approachable.

As mentioned previously in the data background section, the vehicles' speed, acceleration, braking and other evasive maneuvers were recorded in 0.1 sec intervals by the DAS installed in each participate vehicle for NDS data. To complete the scope of the study, the NDS time series freeway event data was requested from VTTI, which included all freeway trip events accomplished by the volunteering participants throughout the whole NDS data collection period. Every event was assigned a unique event identification. It could be used to link other data such as information about events, drivers and vehicles from NDS database and forward videos from the InSight website to each event. Since the data was constructed in 0.1 sec interval, multiple observations were recorded in a same freeway trip event duration. Specifically, the crashes, near crashes, and crash-relevant events included 300 observations (30 sec.) and the non-crash events (baseline) involved 210 observations (21 sec.).

As the literature review described, the drivers typically react within a couple of seconds. To ensure the accuracy and precision, data with a small interval was appropriate for the determination of the reaction time and deceleration rate. After compiling the NDS data of travel speed, the status of the brake pedal, event-related information and driver-related information together by using programming software such as Python, R and functions in Excel, data reduction, quality check, and quality assurance (QA/QC) needed to be completed based on several criteria. Firstly, because the reaction time and deceleration rate were

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required when the drivers were involved in the unpredicted events, the data was filtered to only include the crashes, near-crashes, and crash-relevant events based on "Event Severity" coded in the NDS dataset. Secondly, after the drivers reacted to the unexpected situations, they would have various evasive maneuvers to avoid the dangers. For example, they could start to brake to lower their speed, or they could accelerate to reduce the chance of conflict with other vehicles. However, the deceleration rate needed to be evaluated regarding the reduction of speed after drivers responded. Thus, the events should solely include the evasive maneuvers of braking that drivers performed after they were confronted with unexpected events. There was a variable of "Vehicle Evasive Maneuver" in NDS dataset. It described how the drivers responded to the events. Due to the reasons discussed before, the events were selected if the action of braking was present during the event period. Thirdly, events had higher traffic density (i.e., Level-of-service (LOS) F) were removed to eliminate possible biases caused by LOS F (e.g., deceleration rate and speed significantly varied on roadways with LOS F due to frequent, irregular stoppings and departures). Lastly, if an event included missing values for more than ten observations out of 300, the whole event was excluded from the dataset to ensure the accuracy of the data.

Next, the information such as the number of lanes, lane width, shoulder width, grade or any parameters related to the horizontal curves from RID was integrated to the NDS time series data. However, the RID recorded the roadway information every second. In other words, the crashes, near crashes, and crash-relevant events had 30 observations from RID (i.e., 30 sec.) rather than 300 observations (i.e., 30 sec.) from NDS time series data. To link the data from RID with 1 sec. interval to NDS time series event data with 0.1 sec. interval, the events containing more than five observations out of 30 were deleted. Then, one-second

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roadway information was assumed to apply to every decisecond NDS data within that one-second interval. Since the tenth of a second was a relatively short time interval, the features of the roadway did not change dramatically. As the results, there were 159 events with 126 participants involved in the final dataset of crash or near-crash events.

The following step was to determine the reaction time for each event. The reaction time was defined as the period between the time when the driver notices an unpredicted event and the time when driver starts to make a maneuver. At the beginning of the project, it was considered that the start point of reaction time could be identified by manually checking the videos including the facial expressions of drivers to determine when the drivers started to notice the unexpected events/objects. This approach was not pursued subsequently due to the subjectivity of determining facial expression and the lack of such visual data. Another consideration was to assume the time point when drivers noticed dangers was the timestamps "Event Start," which was identified and coded by VTTI. The description for timestamps "Event Start" from InSight website (SHRP2 NDS, 2013) was "the point in the video when the sequence of events defining the occurrence of the incident, near-crash, or crash begins, Defined as the point at which the Precipitating Event (i.e., the action by the subject vehicle, another vehicle, person, animal, or non-fixed object was critical to this vehicle becoming involved in the crash or near-crash.) begins." The drivers were assumed to be aware of the unexpected actions of other vehicles or objects immediately when the precipitating event started. The ending time point of reaction time was identified as the moment that the driver begins to make a maneuver. Therefore, it should be taken as the time when the driver applied the brake. As discussed above, the data set included the status of the brake pedal, which could be used to determine the ending time of the reaction. However, a variable "Subject

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Reaction Start" coded by VTTI was also reasonable to utilize to set up the ending time. According to the InSight website, the definition of the timestamps "Subject Reaction Start" was the moment when drivers begin to react after they observed the incidents occurring. It was manually identified from the facial videos and recorded by the VTTI data reductionist (SHRP2 NDS, 2013). After performing QA/QC, the time when the driver started to brake was not always identical with the timestamps of "Subject Start to React." The researcher decided to calculate the reaction time of drivers in terms of these two time points available in the dataset and compare the difference between them. The considerations were similar to the methods from other two researches described in the literature review chapter. They defined the reaction time as (1) the time gaps between the VTTI coded timestamps "Event Start" and the time point when the driver started to react (i.e., the drivers started to swerve or brake) (Gao, 2017) and (2) the time gaps between the VTTI coded timestamps "Event Start" and the timestamps "Subject Reaction Start" (Higgins et al., 2017). As the results, there were two methods to determine the reaction time (Equations 1 and 2):

Method 1:

$$r1 = T2 - T1 \tag{1}$$

r1 = Reaction Time 1, in seconds.

T2 = the time point when the driver applied brake, which can be identified by the status of the brake pedal and the travel speed from NDS time series data, in seconds.

T1 = the time point when the precipitating event start, which can be identified by the timestamps "Event Start" from NDS event data, in seconds.

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Method 2:

$$r2 = T3 - T1 \tag{2}$$

r2 = Reaction Time 2, in seconds.

T3 = the time point when the driver started to react, which can be identified by the timestamps "Subject Reaction Start" from NDS event data, in seconds.

After determining the reaction time, the deceleration rates needed to be calculated as well. The deceleration rate was defined as the rate of speed change from the driver started to react until the driver stopped decelerating. At the previous step, the time point of the reaction start was already identified. The most significant step for the determination of the deceleration rates was to find the time points when the drivers stopped decelerating. Unfortunately, there were no variables coded by the VTTI reductionists to indicate this specific timestamps. Because of this, the point when the driver stopped decelerating was assumed to be the point when the driver had the lowest travel speed after the driver began to respond to the unexpected events. This time point was manually recorded by going through the NDS time series data and forward videos on the InSight website. Once the time difference, initial and final speeds were confirmed, the deceleration rate could be calculated by the following equations (Equations 3 and 4):

$$d1 = \frac{1.47 \times (v_f - v_{i1})}{t_1} \tag{3}$$

d1 = Deceleration Rate 1, in ft/s^2.

v_{i1} = Initial travel speed when the driver applied the brake, in mi/h.

v_f = Final travel speed when the driver had the lowest travel speed after the reaction started, in mi/h.

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t_1 = Time difference between initial travel speed (v_{i1}) and final travel speed (v_f), in seconds.

$$d2 = \frac{1.47 \times (v_f - v_{i2})}{t_2} \tag{4}$$

d2 = Deceleration Rate 2, in ft/s^2.

v_{i2} = Initial travel speed at timestamps "Subject Reaction Start", in mi/h.

t_2 = Time difference between initial travel speed (v_{i2}) and final travel speed (v_f), in seconds.

Since each event is associated with a unique reaction time and deceleration rate, it was not necessary to utilize the time series data with 0.1 sec. resolution to perform the analysis. The data were aggregated to an event -level dataset. The descriptive statistics of the reaction time, deceleration rate, associated drivers, and roadway characteristics are shown in Table 7. More details will be introduced in the data summary section.

3.2.2 Mean and Standard Deviation of Travel Speed

Another aspect of the research was to examine and compare the factors that affect the mean and the standard deviation of speeds, particularly during non-crash and crash-involved situations, as well as during the preceding time intervals. The freeway NDS time series data and RID were also used for this objective. Unlike the previous section requiring the time series data with 0.1 sec. resolution, the data with 1 sec. interval was sufficient for calculating mean and standard deviation of travel speeds. As RID recorded the roadway information at 1 sec. interval, the links between RID and time series data would be more straightforward. Because of these, the freeway time series data in every decisecond was aggregated to data in every second.

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Despite the time interval of the data, the purpose of the study required data including both non-crash and crash/near-crash events. The crash or near-crash events with 0.1 sec. interval from the determinations of the reaction time and deceleration rate were aggregated into the time series data with 1 sec. interval. The non-crash (baseline) events were determined based on the "Event Severity" from the NDS event detail fields. The rules of data reduction and QA/QC for baseline events followed the rules for crash/near-crash events described previously. By the end of data collection and QA/QC, 1920 non-crash events with 1217 participants were selected to perform the analysis. After the data preparation, average travel speed (μ_s) and standard deviation (σ_s) in travel speed were calculated for only first 20 sec. of each event to minimize the downward bias in speeds for the crash or near-crash events (as vehicles may have reduced speeds immediately after they responded to the unexpected sisutaions). The period between the first sec. of each event and the time point driver started to decelerate was examined to ensure that 20 sec. interval was appriproate to utilize. The data was aggregated to an event-level dataset all. The data summary of non-crash events is given in Table 8 in the following section.

3.3 Data Summary

This section outlines the descriptive statistics of non-crash and crash-related events, including the calculated reaction time, deceleration rate, mean and standard deviation speeds. The summary of roadway and participants characteristics is also provided in the section. Table 7 depicted the data summary of crash or near-crash events.

As Table 7 shows, the table was structured into four parts: interested variables, event-related variables, driver-related variables, and roadway geometrics-related variables. First, the minimum, maximum, average values and standard deviation of calculated reaction time, deceleration rate, mean, and standard deviation for travel speed of crash/near-crash events

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were summarized. The minimum reaction time was 0 sec. with the maximum estimations of 5.80 and 5.55 sec. regarding the two methods of determinations, respectively. The average reaction time was about 1.51 sec. (1.57 sec. for r1 and 1.46 sec. for r2). Two deceleration rates had the similar mean which was about 9.53 ft/s^2 (0.30 g) (9.67 ft/s^2 for d1 and 9.40 ft/s^2 for d2). The mean of average travel speed was 53.00 mi/h with standard deviation of 3.15 mi/h.

The following part was event-related variables. It included the characteristics of the events. Most of them were obtained from the SHRP 2 NDS. For example, the initial speeds associated with each deceleration rate was given by the instant travel speed recorded in NDS. Since these events were integrated by the crash events, near-crash events, as well as the crash-relevant events from NDS events, there were three indicators variables created to specify the types of the events followed by initial speeds. The traffic density (i.e., LOS), presence of work zones and time of the day were other three event-related variables presented by the indicators variables. The roadway and weather information related to every event such as dry surface, clear, fog and rain weather conditions were also included with binary variables. The variable of “Fully Stopped Events” is another binary variable in the table. However, unlike other event-related variables, it was manually coded by the researcher by watching the videos and investigating the instant travel speed of events. It indicated whether the drivers completely stopped after they confronted the unexpected events. Lastly, three indicator variables were created to exhibit the types of crashes. Based on the SHRP2 NDS and the videos in InSight website, three types of crashes were recorded. The rear-end crashes or near-crashes meant the vehicle braked if there was a leading vehicle braked. If a conflict occurred because the participant vehicle attempted to switch to another travel lane or

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other vehicles shifted to the driving direction of the participant vehicle, the event was recorded as the sideswipe crash or near crash. Besides, if a volunteer driver braked because an unexpected object (e.g., a board or bucket) occurred on her/his driving way, it was coded as the variable “Encountered Unexpected Objects.”

Following the event-related variables, the variables correlated with the driver characteristics were outlined, which were entirely extracted from SHRP2 NDS dataset. The first binary variable was “Distracted.” It revealed if the driver was distracted or not during the event period. It was created according to a variable in NDS dataset named “Secondary Task 1”, which describes whether the driver involved in a secondary task and the type of the secondary task. If a narrative specified that the driver did not perform a secondary task during the event time, the driver was categorized as a non-distracted driver, otherwise coded as a distracted driver. The gender and ages of the drivers were demonstrated by the binary variables as well. The ages were subset to three levels: the age of 16 to 29, the age of 30 to 64, and the age of 65 to 94. Despite the age and gender of drivers, the number of violations and crashes the drivers had been involved in during the time preceding of study period was also included.

Following the event-related variables, the variables correlated with the driver characteristics were outlined, which were entirely extracted from SHRP2 NDS dataset. The first binary variable was “Distracted.” It revealed if the driver was distracted or not during the event period. It was created according to a variable in NDS dataset named “Secondary Task 1”, which describes whether the driver involved in a secondary task and the type of the secondary task. If a narrative specified that the driver did not perform a secondary task during the event time, the driver was categorized as a non-distracted driver, otherwise coded

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as a distracted driver. The gender and ages of the drivers were demonstrated by the binary variables as well. The ages were subset to three levels: the age of 16 to 29, the age of 30 to 64, and the age of 65 to 94. Despite the age and gender of drivers, the number of violations and crashes the drivers had previously been involved in was also included.

The roadway geometrics-related variables are displayed in the last section of Table 7, which were obtained from RID. Specifically, these variables involved the indicators variables for speed limit, average lane width, number of lanes, left and right shoulder widths, as well as the grade of the roadway corresponding with each event. All of them were calculated by averaging the dimensions of the roadways for the entire event time. Additionally, if the average grade was positive, the roadway was categorized as an upgrade, otherwise recorded as downgrade or tangent roadway. Furthermore, the indication of the horizontal curve and correlated average radius, as well as the degree of curvature were also summarized in the table by the minimum, maximum, average values and standard deviation.

Similar tables (Table 8) was produced to detail the event-related features, driver-related features, and roadway geometric-related features of non-crash and crash/near-crash events for mean and standard deviation of travel speeds. As noted, only fist 20 observations (i.e., 20 sec.) with five LOSs (i.e., LOS A, B, C, D, and E) were utilized to calculate the average value and standard deviation of speed. The rest of variables were determined by the similar process with the crash/near-crash events. Table 8 showed that the average values of mean and standard deviation of speeds were 63.57 mi/h and 1.48 mi/h for non-crash events.

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Table 7: Descriptive Statistics of Crash or Near-Crash Events

n = 159				
Description	Min	Max	Mean	Std. Dev
Reaction Time 1 (r1) (sec.)	0	5.800	1.565	1.217
Reaction Time 2 (r2) (sec.)	0	5.554	1.461	1.272
Deceleration Rate 1 (d1) (ft/s^2)	0.555	31.010	9.659	5.040
Deceleration Rate 2 (d2) (ft/s^2)	0.164	27.220	9.396	4.943
Average Travel Speed (μ_s) (mi/h)	7.329	107.245	52.993	18.793
Standard Deviation in Travel Speed (σ_s) (mi/h)	0.090	21.230	3.150	3.256
Event-Related Variables				
Initial Speed for d1 (mi/h)	10.020	105.708	50.627	18.616
Initial Speed for d2 (mi/h)	6.350	101.165	49.870	19.097
Fully Stopped Events (1 if the vehicle is fully stopped, 0 otherwise)	0	1	0.177	0.382
Presence of Work Zone (1 if yes, 0 otherwise)	0	1	0.113	0.318
Rear-End Crashes/Near Crashes (1 if yes, 0 otherwise)	0	1	0.591	0.493
Sideswipe Crashes/Near Crashes (1 if yes, 0 otherwise)	0	1	0.384	0.488
Encounter Unexpected Objects (1 if yes, 0 otherwise)	0	1	0.025	0.157
Crash Event (1 if yes, 0 otherwise)	0	1	0.006	0.079
Crash Relevant Event (1 if yes, 0 otherwise)	0	1	0.013	0.112
Near-Crash event (1 if yes, 0 otherwise)	0	1	0.981	0.137
Level-of-Service A (1 if yes, 0 otherwise)	0	1	0.132	0.340
Level-of-Service B (1 if yes, 0 otherwise)	0	1	0.371	0.485
Level-of-Service C (1 if yes, 0 otherwise)	0	1	0.233	0.424
Level-of-Service D (1 if yes, 0 otherwise)	0	1	0.182	0.387
Level-of-Service E (1 if yes, 0 otherwise)	0	1	0.082	0.275
Distracted (1 if driver is distracted, 0 otherwise)	0	1	0.213	0.410
Daylight (1 if yes, 0 otherwise)	0	1	0.792	0.407
Fog (1 if yes, 0 otherwise)	0	1	0.006	0.079
Mist/Light Rain (1 if yes, 0 otherwise)	0	1	0.063	0.244
Clear (1 if yes, 0 otherwise)	0	1	0.365	0.483
Rain and Fog (1 if yes, 0 otherwise)	0	1	0.006	0.079
Raining (1 if yes, 0 otherwise)	0	1	0.044	0.206
Dry Surface (1 if yes, 0 otherwise)	0	1	0.836	0.373

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Table 7 Continued

Driver-Related Variables				
Female (1 if yes, 0 otherwise)	0	1	0.579	0.495
Male (1 if yes, 0 otherwise)	0	1	0.421	0.495
Age 16 to 29 (1 if yes, 0 otherwise)	0	1	0.484	0.501
Age 30 to 64 (1 if yes, 0 otherwise)	0	1	0.428	0.496
Age 65 to 94 (1 if yes, 0 otherwise)	0	1	0.088	0.284
Zero Violation Before (1 if yes, 0 otherwise)	0	1	0.579	0.495
One Violation Before (1 if yes, 0 otherwise)	0	1	0.239	0.428
Two or More Violation Before (1 if yes, 0 otherwise)	0	1	0.182	0.387
Involved in Zero Crash Before (1 if yes, 0 otherwise)	0	1	0.679	0.468
Involved in One Crash Before (1 if yes, 0 otherwise)	0	1	0.245	0.432
Involved in Two or More Crash Before (1 if yes, 0 otherwise)	0	1	0.075	0.265
Roadway Geometrics-Related Variables				
55 mph Speed Limit	0	1	0.270	0.446
60 mph Speed Limit	0	1	0.453	0.499
65 mph Speed Limit	0	1	0.132	0.340
70 mph Speed Limit	0	1	0.138	0.346
Average Lane Width (ft.)	9.924	25.701	12.359	2.446
Average Number of Lanes	1.7	6	3.394	0.897
Average Left Shoulder Width (ft.)	0.199	20.970	7.255	3.300
Average Right Shoulder Width (ft.)	0.254	19.234	7.534	3.083
Average Radius (ft.)	0	14610	2006.024	2927.223
Average Degree of Curvature (Degree)	0	2.769	0.382	0.650
Curve (1 if yes, 0 otherwise)	0	1	0.627	0.487
Average Grade (%)	-4.405	2.92	-0.382	1.444
Upgrade (1 if yes, 0 otherwise)	0	1	0.537	0.502
Downgrade (1 if yes, 0 otherwise)	0	1	0.463	0.502

Table 8: Descriptive Statistics of Non-Crash Events

n = 1920				
Description	Min	Max	Mean	Std. Dev
Average Travel Speed (μ_s) (mi/h)	8.636	133.178	63.570	12.132
Standard Deviation in Travel Speed (σ_s) (mi/h)	0.023	17.482	1.475	1.485

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Table 8 Continued

Event-Related Variables				
Presence of Work Zone (1 if yes, 0 otherwise)	0	1	0.057	0.232
Level-of-Service A (1 if yes, 0 otherwise)	0	1	0.559	0.497
Level-of-Service B (1 if yes, 0 otherwise)	0	1	0.344	0.475
Level-of-Service C (1 if yes, 0 otherwise)	0	1	0.061	0.240
Level-of-Service D (1 if yes, 0 otherwise)	0	1	0.022	0.146
Level-of-Service E (1 if yes, 0 otherwise)	0	1	0.014	0.116
Distracted (1 if driver is distracted, 0 otherwise)	0	1	0.495	0.500
Daylight (1 if yes, 0 otherwise)	0	1	0.767	0.423
Fog (1 if yes, 0 otherwise)	0	1	0.006	0.075
Mist/Light Rain (1 if yes, 0 otherwise)	0	1	0.028	0.164
Clear (1 if yes, 0 otherwise)	0	1	0.913	0.283
Rain and Fog (1 if yes, 0 otherwise)	0	1	0.001	0.032
Raining (1 if yes, 0 otherwise)	0	1	0.052	0.222
Dry Surface (1 if yes, 0 otherwise)	0	1	0.877	0.328
Driver-Related Variables				
Female (1 if yes, 0 otherwise)	0	1	0.513	0.500
Male (1 if yes, 0 otherwise)	0	1	0.487	0.500
Age 16 to 29 (1 if yes, 0 otherwise)	0	1	0.501	0.500
Age 30 to 64 (1 if yes, 0 otherwise)	0	1	0.339	0.474
Age 65 to 94 (1 if yes, 0 otherwise)	0	1	0.160	0.367
Zero Violation Before (1 if yes, 0 otherwise)	0	1	0.635	0.481
One Violation Before (1 if yes, 0 otherwise)	0	1	0.240	0.427
Two or More Violation Before (1 if yes, 0 otherwise)	0	1	0.125	0.331
Involved in Zero Crash Before (1 if yes, 0 otherwise)	0	1	0.717	0.450
Involved in One Crash Before (1 if yes, 0 otherwise)	0	1	0.216	0.412
Involved in Two or More Crash Before (1 if yes, 0 otherwise)	0	1	0.067	0.250
Roadway Geometrics-Related Variables				
Description	Min	Max	Mean	Std. Dev
55 mph Speed Limit	0	1	0.259	0.438
60 mph Speed Limit	0	1	0.284	0.451
65 mph Speed Limit	0	1	0.276	0.447
70 mph Speed Limit	0	1	0.181	0.385
Average Lane Width (ft.)	8.287	26.513	11.875	1.594
Average Number of Lanes	1	6.524	2.910	0.914
Average Left Shoulder Width (ft.)	0.586	25.956	9.217	2.101
Average Right Shoulder Width (ft.)	0.085	18.458	5.783	2.737
Average Radius (ft.)	0	28815	2182.654	3312.774
Average Degree of Curvature (Degree)	0	7.133	0.518	0.681
Curve (1 if yes, 0 otherwise)	0	1	0.583	0.493
Average Grade (%)	-5.310	8.124	0.025	1.307
Upgrade (1 if yes, 0 otherwise)	0	1	0.500	0.500
Downgrade (1 if yes, 0 otherwise)	0	1	0.499	0.500

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CHAPTER 4. STATISTICAL METHODS

Using the data described in Chapter 3, a series of statistical analyses were conducted to examine various aspects of driver behavior leading up to, and during, crash and near-crash events. These analyses involved the estimation of multiple linear regression models for each of four variables of interest:

1. Reaction time (r1 and r2)
2. Deceleration rate (d1 and d2)
3. Average travel speed (μ_s)
4. Standard deviation in travel speed (σ_s)

The event-level data used for these analyses were aggregated from the NDS time series and RID data. Consequently, each observation (i.e., row in the dataset) was associated with one event. The reaction time and deceleration rate data were only obtained for those events that resulted in a crash or near-crash event. However, average travel speed and standard deviation of travel speed were examined for both crash/near-crash events, as well as normal baseline driving events. This allowed for an explicit comparison of differences in speed selection behavior between those drivers who were crash/near-crash involved and those who were not.

Each of the dependent variables noted above is essentially continuous in nature. To investigate the relationships between continuous variables and a series of independent variables of interest, ordinary least square (OLS) linear regression presents an appropriate modeling framework. The functional form (Equation 5) of the OLS linear regression model is (Washington, Karlaftis, & Mannering, 2011):

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$$Y_i = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_k X_k + \varepsilon \quad (5)$$

Y_i = Dependent variable (r1, r2, d1, d2, μ_s, or σ_s) for event i

β_0 = Constant term (i.e., y-intercept)

β_1 , β_2 ,…, β_k = Estimated regression coefficients for each independent variable

X_1 ~ X_k = Independent variables (e.g., driver characteristics, roadway geometry)

ε = Normally distributed error term with mean of zero and variance of σ^2

The error term is assumed to be independently and identically distributed across events. However, one concern that arises within the context of this study is that multiple events may be correlated since several drivers had a number of different trip events in the analysis dataset. For example, one driver was shown to have a reaction time of 3.3 sec. when involved in one event, but a 4.2 sec. reaction time when involved in a second event. Likewise, the same driver decelerated at 9.29 ft/s^2 during the first event and 19.56 ft/s^2 during the second event. It is assumed that this driver may tend to react or decelerate differently (faster or slower) than other drivers due to factors that are not observed in the dataset. This would result in correlation among events involving this same driver. For the perspective of the analysis, it was critical to account for this correlation to avoid any biased estimates for the influences of specific features (e.g., drivers' behavior and roadway characteristics) and underestimate the variability in the reaction times and deceleration rate (Hamzeie, 2016).

To address the concern discussed before, a participant-specific intercept term was added to the model. This intercept term was used to account for the unique characteristics of individual drivers (e.g., driving styles and performance, risk perception) which were not able to be reflected by the information from NDS and RID. This term allowed the coefficient for each participant in every event to remain the same, capturing the variability in reaction times

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and deceleration rates. The functional equation of the model after introducing the participant-specific intercept term is given by Equation 6:

$$Y_i = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_k X_k + \varepsilon + \delta \tag{6}$$

δ = A participant- specific intercept term, with a mean of zero and variance of σ^2

This model is also referred to as the random effect linear regression model. It assumes these events were a random sample from a broader driving population with the specific individual effects (Hamzeie, 2016). As in the case of reaction time and deceleration rate, a participant-specific intercept term was also included when examining the mean speed and standard deviation in speed for events involving the same driver.

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CHAPTER 5. RESULTS AND DISCUSSIONS

The primary goal of the study was to understand several driver behaviors by the naturalistic driving study. To do so, the freeway events from SHRP 2 NDS program and RID were analyzed by utilizing the random effect linear regression models to examine those factors related to the driver, vehicle, and roadway that influence reaction time, deceleration rate, and speed selection. The results provide insights that are valuable for improving roadway design and other traffic safety policies and programs in consideration of driver behavior under these high-risk scenarios.

This chapter consists of three sections. The first section discusses the results regarding the driver' reaction time in unexpected situations. The reaction time was determined with Equations 1 and 2. The second section includes the findings for the deceleration rate. The deceleration rate was calculated from the reaction time and the lowest speed presented in the period of the precipitating event. Additionally, the discussion of computed mean and standard deviation of travel speed for both non-crash and crash-involved events is in the following section.

5.1 Reaction Time

Due to the unique characteristics of the datasets, the reaction times were calculated in terms of two time periods. The first reaction time (r1) was determined depended on the time difference between the timestamp of "Event Start" and the time point when the driver applied the brake. The distribution of r1 is given in Figure 4. The minimum, maximum, and average values and standard deviation of r1 were 0 sec., 5.80 sec., 1.57 sec., and 1.22 sec., respectively. The extant literature determined similar results. For example, Dozza (2013) conducted a study that showed the mean of the reaction time was 1.45 sec. for both distracted

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and non-distracted drivers. Another study utilized the same method to identify the reaction time indicated that the average reaction time of normal drivers was 1.58 sec. and 2.11 sec. for the distracted drivers (Gao, 2017).

The second reaction time (r2) was calculated by directly subtracting the timestamps of “Event Start” from the timestamps of “Subject Start to React,” which were recorded by the VTTI reductionists. The distribution of r2 is also provided in Figure 4. It displays a trend that is similar to r1. The histograms for both reaction times displayed right-skewed distributions. Additionally, most reaction times fell in the range of 0 to 1 sec. Only a few drivers had reaction time greater than 3 sec. Despite the similar distributions, the minimum, maximum, average values and standard deviations of r2 were 0 sec., 5.55 sec., 1.46 sec., and 1.27 sec., respectively, which were similar to the statistics of r1 to a great extent.

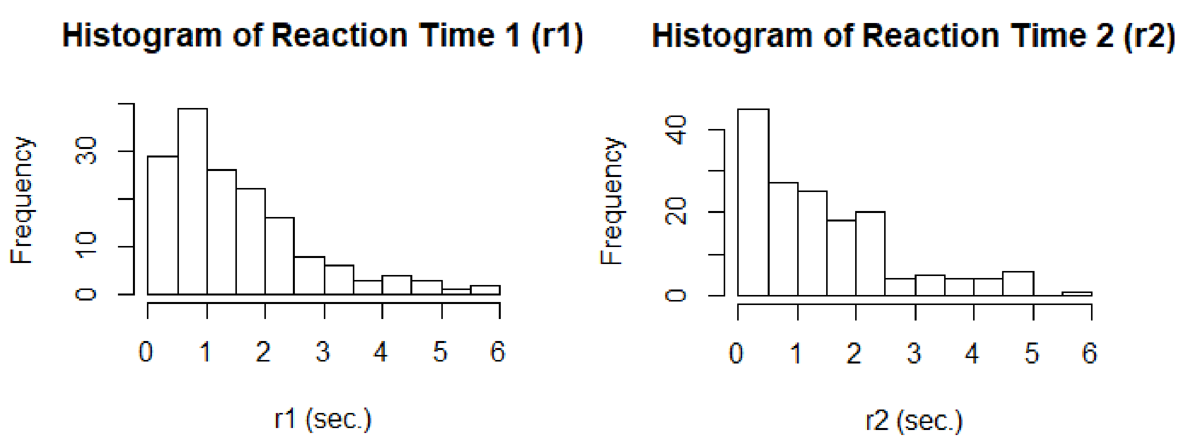

Figure 4: Distributions of Reaction Time

In addition to descriptive statistics and distributions, cumulative distribution plots and nth percentiles were utilized to compare r1 and r2 as well, which are presented in Table 9 and Figure 5. As expected, the nth percentile and trend of cumulative distributions of r1 and r2 were comparable. Moreover, Table 9 and Figure 5 showed that the 85th percentile reaction

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time was, on average, 2.60 sec. (2.70 sec. for r1, 2.51 sec. for r2), which were similar with the value of 2.50 sec. indicated in several previous studies (MIT, 1935; Normann, 1953: Johansson & Rumar, 1971; Fambro, Fitzpatrick, & Koppa, 1997). Under stoping sight situations, a 2.5 sec. reaction time reflects the capabilities of most motorists. If r1 and r2 were compared merely regarding data summary and distributions, there were no significant differences between r1 and r2. The following sections will examine and compare the factors affecting reaction time to provide an in-depth understanding of driver's reaction time.

Table 9. Percentiles of Reaction Time

Percentile	r1 (sec.)	r2 (sec.)
0%	0.000	0.000
5%	0.290	0.083
10%	0.400	0.137
15%	0.500	0.244
20%	0.600	0.395
25%	0.700	0.477
30%	0.740	0.538
35%	0.800	0.690
40%	1.000	0.776
45%	1.100	0.999
50%	1.200	1.140
55%	1.400	1.275
60%	1.600	1.411
65%	1.700	1.744
70%	1.900	1.914
75%	2.100	2.085
80%	2.400	2.273
85%	2.700	2.513
90%	3.300	3.459
95%	4.210	4.231
100%	5.800	5.554

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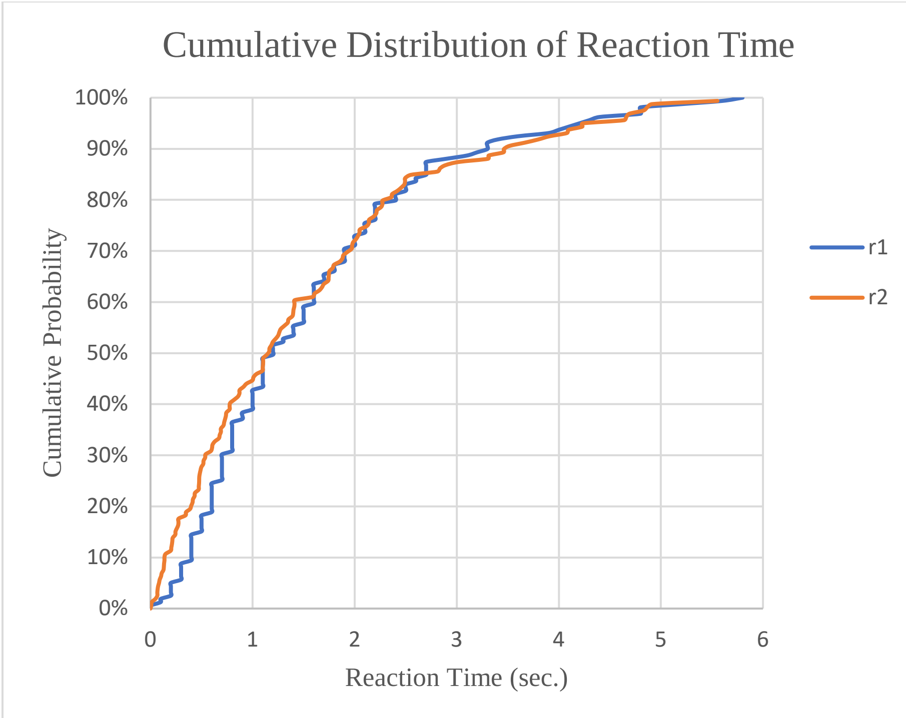

Figure 5. Cumulative Distribution of Reaction Time

The 159 crash-relevant events were analyzed by the statistical model with the dependent variable of reaction time and independent variables of event-related, driver-related, and roadway geometrics-related characteristics. The results of r1 and r2 are provided in Table 10.

The results from Table 10 show that the type of crash/near-crash driving event (i.e., rear-end, sideswipe, or reaction to an unexpected object in the roadway), gender of the driver, and whether the driver was distracted all exhibited a statistically significant relationship with reaction time. This was true for both definitions of reaction time (r1 and r2) that were considered as a part of the analysis. The roadway geometrics and other roadway characteristics did not show statistically significant correlation with the reaction time in this study. This may be reflective of several factors, including the relatively homogenous nature of freeway facilities or the consistency in driving behavior on such facilities.

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Table 10: Random Effect Linear Regression Model for the Reaction Time

	r1 (n = 159)			r2 (n =159)		
Description	Estimate	Std. Error	P-value	Estimate	Std. Error	P-value
(Intercept)	1.323	0.174	<0.001	1.388	0.174	<0.001
Rear-end Crashes/Near Crashes (1 if yes, 0 otherwise)	Baseline					
Sideswipe Crashes/Near Crashes (1 if yes, 0 otherwise)	-0.275	0.199	0.167	-0.588	0.205	0.005
Encounter Unexpected Objects (1 if yes, 0 otherwise)	-1.221	0.572	0.037	-1.046	0.598	0.082
Distracted Female (1 if the driver is distracted, 0 otherwise)	0.869	0.290	0.003	0.977	0.300	0.001
Distracted Male (1 if the driver is distracted, 0 otherwise)	0.939	0.356	0.009	0.574	0.364	0.117
Non-Distracted Female (1 if the driver is distracted, 0 otherwise)	Baseline					
Non-Distracted Male (1 if the driver is distracted, 0 otherwise)	0.458	0.218	0.037	0.387	0.218	0.078

Reaction times were lowest for crash/near-crash events where non-distracted female drivers encountered an unexpected object in the roadway. Reaction times varied with respect to both gender and distraction and the results varied within and across genders when considering the two different means by which reaction time was calculated.

The model result for r1 showed drivers reacted 0.27 sec. faster if they were engaged in a sideswipe conflict, which could include another vehicle changing lanes unexpectedly (compared to the reaction time of rear-end conflicts). Drivers reacted 1.22 sec. quicker (compared to rear-end events) when they were confronted by unexpected objects in the roadway. Drivers displayed the longest reaction times when they encountered rear-end conflicts where the leading vehicle began braking. This is likely due, in part, to the fact that drivers were able to pick up on other visual cues in advance of when the leading vehicle began its braking maneuver. For example, traffic congestion upstream may lead to drivers being generally more alert in these settings. In contrast, a vehicle or an object suddenly

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appearing in the driver's field of view was likely to be more surprising and prompt a more aggressive response from the driver. Most drivers assume other motorists would check carefully before they change to another lane and no object would suddenly occur on the road, especially on the freeways. However, the braking of a leading vehicle would happen more frequently due to the traffic jam or other possible situations.

Of particular concern, distracted drivers responded significantly more slowly than non-distracted drivers. Overall, distracted females and males showed nearly a one-second longer response time (0.87 sec. for distracted females and 0.94 sec. for distracted males) as compared to non-distracted females. The non-distracted males reacted 0.46 sec. slower than non-distracted females. In cases of distraction, the driver's attention is not completely focused driving and the roadway environment and it would be more difficult to notice behaviors of other motorists. These results substantiate findings from previous research. Interestingly, the reaction times were almost identical for distracted females and males. However, the females showed faster reaction time than males under non-distracted situations, even though the extant literature (Der & Deary, 2006; Dane & Erzurumluoglu, 2003) suggested males generally react more quickly than females.

The results for the second reaction time variable (r2) showed comparable findings with the first (r1). The drivers responded slower when they confronted the vehicle braking ahead, while the drivers had shorter reaction time in situations of sideswipe crashes or near crashes, as well as unexpected objects suddenly appearing on the roads. Furthermore, the results presented that distractions increased the drivers' reaction time, and non-distracted females reacted faster than non-distracted males. The only result different from r1 was that distracted males were related with shorter reaction times compared with distracted females.

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The reasons of the difference between model results of r1 and r2, as well as the difference between previous work and the current study might be due to the difference in how the reaction time is determined, the fact that females had shorter reaction times under non-distracted conditions in this particular study, or the small sample size of the study. Further investigation will be conducted in the future to explore this point.

5.2 Deceleration Rate

To understand the braking behaviors of drivers, an investigation focused on the deceleration rates when drivers started to respond to unexpected events in crash or near-crash scenarios. The deceleration rate was calculated from the onset of the braking maneuver to the point at which the lowest speed occurred over the course of the event. Two deceleration rates were calculated, with these rates calculated at the end of reaction time 1 (r1) and reaction time 2 (r2). These rates are referred to as d1 and d2, respectively. The distribution for d1 is shown in Figure 6. As the data summary shows, d1 had an average rate with standard deviation of 9.66 ft/s^2 (0.30 g) and 5.04 ft/s^2 (0.17 g), respectively. The calculated average values were marginally lower than the values reported in the previous literature. For instance, Wood and Zhang (2017) determined a mean deceleration rate of 14.17 ft/s^2 (0.44 g) with the standard deviation of 8.32 ft/s^2 (0.26 g) for the crash and near-crash events from SHRP 2 NDS dataset. These values were determined based on the data including all types of roadways and relatively higher sample size. Therefore, the deceleration rates in these studies varied from the rate of this study. Another study conducted by utilizing the SHRP 2 NDS dataset showed a lower deceleration rate compared to the current study. It showed an average deceleration rate of 8.38 ft/s^2 (0.26 g). This research only focused on near-crash events occurred on urban local roadways during daytime (Lindheimer et al., 2018), yet the current

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study focused on freeway crash and near-crash events during day and night time. Thus, the values were moderately different from d1.

For d2, the average rate and standard deviation of deceleration were 9.40 ft/s^2 (0.29 g) and 4.94 ft/s^2 (0.15 g) as summarized in Table 7, which similar to the values shown previously for d1. The distribution of d2 is depicted in Figure 5. The histograms of two rates were similar to each other. The graphs showed the trend of normal distributions with the most values on the range of 5 ft/s^2 to 15 ft/s^2.

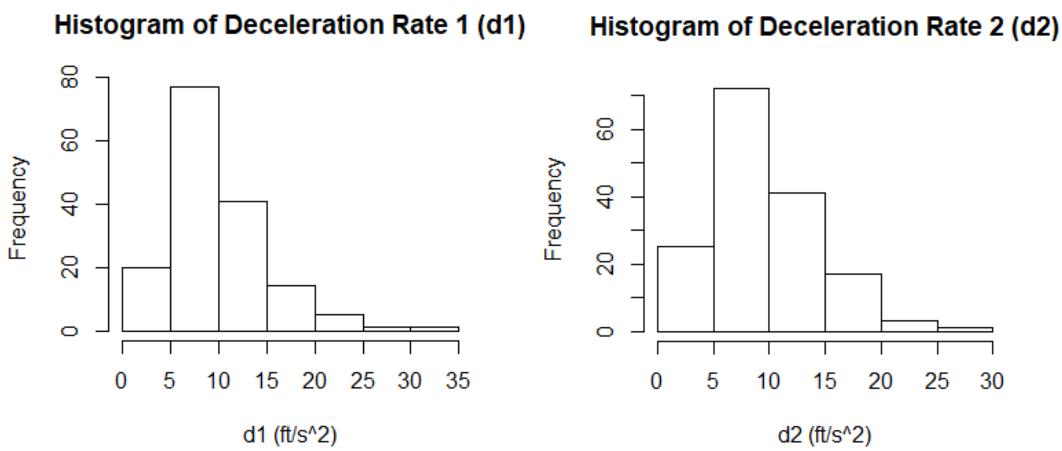

Figure 6: Distributions of Deceleration Rate

As with reaction time, nth percentiles and cumulative distributions were used to provide extensive comparison between d1 and d2, which are included in Figure Table 11 and Figure 7. The values associated with each percentile and trend of plots of d1 and d2 were similar with each other. Additionally, the finding of deceleration rate supported the finding from previous study. Specifically, 85th percentiles of d1 and d2 were comparable to the value of 14.80 ft/s^2 (0.46 g) in the study from Fambro et al (1971), which was the braking rate that most drivers had when they encounter situations requiring emergency stop. More investigation regarding the deceleration rate will be introduced in the following section.

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Table 11: Percentiles of Deceleration Rate

Percentile	d1 (ft/s^2)	d2 (ft/s^2)
0%	0.555	0.164
5%	2.591	2.369
10%	3.608	3.395
15%	5.248	4.612
20%	5.732	5.967
25%	7.048	6.655
30%	7.318	6.941
35%	7.673	7.311
40%	7.894	7.486
45%	8.320	8.004
50%	8.583	8.407
55%	9.352	9.103
60%	9.880	9.670
65%	10.641	10.676
70%	11.286	11.244
75%	11.962	12.094
80%	12.895	13.253
85%	14.502	14.187
90%	16.111	16.060
95%	18.993	18.118
100%	31.010	27.220

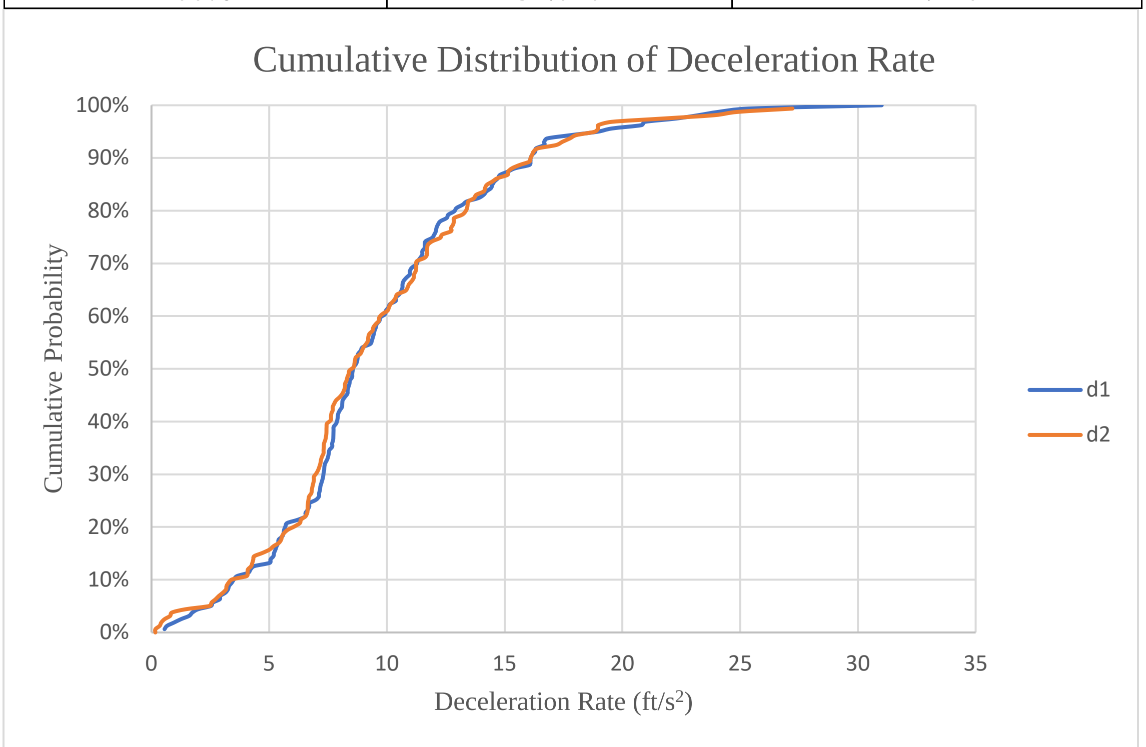

Figure 7. Cumulative Distribution of Deceleration Rate

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The deceleration rates were treated as the dependent variables and analyzed by the random effect linear regression model with predictors of event-related, driver-related, and roadway geometrics-related variables. Table 12 exhibits the model results of two deceleration rates.

Table 12: Random Effect Linear Regression Model For Deceleration Rate

	d1 (n = 159)			d2 (n = 159)		
Description	Estimate	Std. Error	P-value	Estimate	Std. Error	P-value
(Intercept)	12.060	1.165	<0.001	12.277	1.090	<0.001
Initial Speed (mi/h)	-0.047	0.021	0.027	-0.056	0.020	0.005
Downgrade or Tangent (1 if yes, 0 otherwise)	Baseline					
Upgrade (1 if yes,0 otherwise)	2.162	0.719	0.003	2.035	0.691	0.004
Rear-end Crashes/Near Crashes (1 if yes, 0 otherwise)	Baseline					
Sideswipe Crashes/Near Crashes (1 if yes, 0 otherwise)	-3.041	0.789	<0.001	-2.983	0.765	<0.001
Encounter Unexpected Objects (1 if yes, 0 otherwise)	-4.102	2.307	0.077	-4.589	2.216	0.040

In contrast to the reaction time analysis, the results for the two models for deceleration rate produced very consistent results. The same variables were found to be statistically significant. Furthermore, the magnitudes and signs of the estimated coefficients for each variable in the two models were close to each other, as well. The results indicated there was no correlation between deceleration rate and other event-related, driver-related, and roadway geometrics-related factors, except the initial speed of calculation of deceleration rate, whether the roadway was in an upgrade, and the types of crash or near crash (i.e., rear-end, sideswipe, or reaction to an unexpected object in the roadway). The initial speed was a continuous variable. As expected, vehicles with higher initial speed had a higher likelihood to decelerate slowly than vehicles with lower initial speed. This phenomenon might be caused by the natures of higher speeds and the associated driving behaviors. Specifically, the

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negative sign and estimated coefficient meant as the initial speed increased one mi/hr., the deceleration rate decreased 0.05 ft/s^2 (0.06 ft/s^2 for deceleration rate 2). The findings of the study supported the results of previous studies in the literature. For example, Deligianni et al. (2016) indicated that the drivers were more likely to brake at a greater rate if the initial speed was low,

Another statistically significant factor was the upgrade roadway. Unlike the initial speed, the binary variable was created to indicate if the roadway was an uphill road or not. The negative sign and the estimated coefficient demonstrated that the vehicle was more likely to decelerate at a rate 2.16 ft/s^2 greater on the upgraded roadway than a vehicle decoration rate on the downgrade or tangent roadway. The drivers generally apply brake while they are traveling on the downhill roadways for the safety purpose and accelerate on the uphill roadways to provide more tractions. Additionally, the gravity might be another significant cause of this situation. The motorists need to overcome the gravity while they traveling on an upgrade roadway. Therefore, when an unexpected event occurred and drivers traveled on an upgrade roadway, they required to brake at a higher rate.

The following factors in the Table 12 were indicator variables as well. The magnitudes and signs of estimated coefficients specified that vehicles encountering sideswipe conflicts with other vehicles or unexpected objects suddenly appearing on the roadway were associated with deceleration rates 3.04 ft/s^2 and 4.10 ft/s^2 more, when compared to vehicles observing the brake lights of leading vehicles. The drivers involved in the sideswipe crashes or near crashes were related to a lowest deceleration rate, while the drivers involved in the rear-end crashes or near-crashes had a higher likelihood to decelerate at a higher rate. This could be due to the vehicles need to fully stop to avoid the conflict with the leading vehicles

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in most cases, but only require slightly speed reduce to stay away from the sideswipe conflicts.

5.3 Mean and Standard Deviation of Travel Speed

The mean and standard deviation of travel speeds of non-crash and crash/near-crash events, as well as the factors related with the event, driver, and roadway geometric characteristics were examined to provide an understanding of driver speed selection behavior. The average of mean speeds for normal, baseline driving events was about 63.57 mi/h with a standard deviation of 12.13 mi/h, while the crash/near-crash events showed an average mean speed of 53 mi/h and standard deviation of 18.79 mi/h. As noted previously, the values of speeds were determined only for the first 20 sec. with four speed limits and five level of services (LOSs). If the study was to merely compare the average and standard deviation value of the mean speed, the vehicles not involved in the unexpected events experienced lower average travel speeds, but with more variabilities compared to vehicles that were traveling under normal conditions. However, there were many other factors could potentially affect the travel speed, and an in-depth investigation was conducted by utilizing the statistical model to analyze the 159 crash-related events and 1920 non-crash events. For the purpose of comparison, the variables included in the model were identical for non-crashes and crash-involved events. The model results are provided in Table 13.

As the results show, numerous variables were found to be associated with mean speeds during baseline events, including degree of curvature, shoulder width, speed limit, traffic density, presence of work zone, time of day, weather conditions, driver age, and the number of violations drivers had during the time preceding the study period.

As expected, there was a strong correlation between the speed limit and the selected speed. The model result showed drivers were more likely to drive slower on the roadways

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with lower speed limits (i.e., 55, 60, and 65 mi/h) when compared to the roadways with higher speed limit (i.e., 70 mi/h). The individuals had greater propensities to drive faster on roadways with higher speed limits. As the past studies described in literature review chapter, the travel speed was largely correlated to the posted speed limit. However, speeds tended to increase by smaller amounts at higher speed limits.

The next factor included in the model was degree of curvature, with large values of D associated with sharp curves (i.e. curves with smaller radii). For a one degree increase, speeds were reduced by 0.55 mi/h on average. This result is reasonable because people are more cautious while traveling on sharp curves. The widths of the left and right shoulders showed a positive influence on the driving speeds. Drivers were more likely to travel faster on the roadway with wider shoulders. On average, an increase of one foot in the left and right shoulder resulted in increased individual speeds of 0.20 mi/h. and 0.33 mi/h, respectively. The larger width of the right shoulder could provide a better driving experience and more space for an emergency stop.

Traffic density also had impact on the driver's running speed. Level-of-service (LOS) was a direct variable to visualize the traffic density. As compared to LOS A, speeds decreased at each successive LOS, with LOS E showing the largest decrease, results that are consistent with the general speed-density relationship. In addition, the presence of work zone tended to reduce speeds, as well, by 3.6 mph on average. The characteristics of the work zone restricted the driving speed. Furthermore, the participants were more likely to drive faster during the daytime and under better weather conditions. Adverse weather had negative influences on the driving speed. Specifically, the speed would be reduced most in rainy conditions according to the model results. Drivers between the ages of 65 and 94 had the

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slowest speed, while the drivers from the ages of 16 and 29 experienced the fastest speed. Therefore, the increasing age of drivers had negative effects on the travel speed. Lastly, the number of previous violations drivers had impacted their speeds as well. If the drivers had no previous violation, they had a higher likelihood to drive slower than others. These model results were similar with the findings from the existing literature.

Table 13: Random Effect Linear Regression Model for Mean of Travel Speed

	Non-Crash Events (n = 1920)			Crash/Near-Crash Events (n = 159)		
Description	Estimate	Std. Error	P-value	Estimate	Std. Error	P-value
(Intercept)	67.481	1.147	<0.001	59.433	5.882	<0.001
55 mi/h Speed Limit	-10.371	0.585	<0.001	-7.411	3.008	0.015
60 mi/h Speed Limit	-9.238	0.582	<0.001	-2.273	2.886	0.432
65 mi/h Speed Limit	-2.889	0.571	<0.001	8.393	3.450	0.016
70 mi/h Speed Limit	Baseline					
Average Degree of Curvature (Degree)	-0.553	0.268	0.039	0.653	1.157	0.573
Average Left Shoulder Width (ft.)	0.197	0.089	0.027	0.583	0.260	0.026
Average Right Shoulder Width (ft.)	0.328	0.068	<0.001	0.308	0.260	0.238
Level-of-Service A (1 if yes, 0 otherwise)	Baseline					
Level-of-Service B (1 if yes, 0 otherwise)	-2.030	0.398	<0.001	-3.761	2.495	0.135
Level-of-Service C (1 if yes, 0 otherwise)	-8.120	0.759	<0.001	-13.845	2.750	<0.001
Level-of-Service D (1 if yes, 0 otherwise)	-36.362	1.237	<0.001	-28.574	2.856	<0.001
Level-of-Service E (1 if yes, 0 otherwise)	-43.080	1.540	<0.001	-47.323	3.354	<0.001
Presence of Work Zone (1 if yes, 0 otherwise)	-3.569	0.777	<0.001	4.397	2.742	0.111
Daylight (1 if yes, 0 otherwise)	0.740	0.425	0.081	0.298	1.928	0.877
Mist/Light Rain (1 if yes, 0 otherwise)	-3.256	1.080	0.003	-8.150	3.301	0.015
Raining (1 if yes, 0 otherwise)	-2.881	0.794	<0.001	6.070	3.898	0.122
Age 16 to 29 (1 if yes, 0 otherwise)	2.935	0.586	<0.001	3.897	3.550	0.274
Age 30 to 64 (1 if yes, 0 otherwise)	1.727	0.614	0.005	1.860	3.410	0.586
Age 65 to 94 (1 if yes, 0 otherwise)	Baseline					
Zero Violation Before (1 if yes, 0 otherwise)	-1.354	0.436	0.002	-2.034	1.965	0.303

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Interestingly, the results showed some significant differences with respect to the effects of some of these factors on speed selection between baseline and crash or near-crash events. Some of this differences is attributable to the smaller sample size for crash/near-crash events as only a few variables were found to be statistically significant, including left shoulder width, speed limit, traffic density, as well as weather conditions. Interestingly, speeds were quite similar between baseline and crash/near-crash events at higher speed limits (65 and 70 mi/h). In contrast, speeds were significantly lower among crash/near-crash involved drivers where lower limits of 55 or 60 mi/h were in place. The left shoulder width had impacts on the speeds of crash and near-crash events, as well. The mean of travel speed increased 0.58 mi/h as the average left shoulder width increased one foot. This finding was similar to the findings from non-crash events which was that wider left shoulder correlated to higher speeds. Furthermore, the model result revealed that the drivers confronting the safety-critical events had higher likelihood of driving slower at higher traffic densities and adverse weather condition, which were comparable with the findings of normal driving events.

In addition, there were a few notable observations worthy of discussion. Beyond the differences with respect to speed limits as discussed previously, the degree of curvature was not shown to have a significant impact on speed selection among crash and near-crash events. While sharper curves resulted in lower driving speeds among baseline events, there was no significant association between degree of curvature and speed among the crash/near-crash events. In fact, speeds tended to increase as curves become sharper among drivers in the high-risk events. This may be reflective of such drivers either having greater risk tolerance or adapting their behavior to a lesser degree when encountering a curve as compared to those drivers in normal events, who tended to reduce their speeds accordingly.

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Similarly, the presence of a work zone did not reduce the traveling speeds of drivers who were involved in crashes or near crashes, nor did heavier rain conditions. Other roadway surface conditions, weather condition, time of the day, and driver characteristics showed a similar direction of effect with respect to speed selection behaviors under these incident-related situations, though several of these differences were not statistically significant.

Further insights as to speed selection behavior are provided by an analysis of the standard deviation of travel speeds within the 20-s driving events. The results show that the average standard deviations of the baseline and crash/near-crash events were 1.48 mi/hr. and 3.15 mi/hr., respectively. As the values showed, the variance of the speed under normal conditions was significantly smaller than that in incidents, but more investigation needs to be conducted to learn the speed selection behaviors in all aspects. The same dataset presented previously (for the analyses of average speed) was utilized to explore how these same factors relate to the variability in driving speeds over these 20-s intervals. The results for the baseline and crash/near-crash events are summarized in Table 14.

Within the model, although almost all the event-related, driver-related, and roadway geometrics-related features were examined, only speed limit, degree of curvature, number of lanes, traffic density, and presence of work zones were found to be statistically significant. The findings from non-crash events showed that the travel speeds of the normal drivers had less variability as the speed limit of roadway increased. Drivers tended to travel at more consistent speeds on roadways with higher speed limits. This phenomenon is likely reflective of the nature of these high-speed facilities, which tend to have lower traffic volumes, fewer on- and off-ramps, wider lanes and shoulders, and more accommodating design standards overall as compared to lower speed facilities. Speeds tended to be more variable when

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vehicles navigated horizontal curves, especially sharp curves. To ensure the driving safety on the horizontal curve, the driver would adjust their speeds to travel comfortably and safely. In addition, the results showed that traffic density was a crucial influential factors of speed. As traffic density increased, there was significantly more variability in driving speeds. Lastly, the travel speeds varied if a work zone presented on a roadway. The number of lanes did not reveal any correlation with the selected speed for non-crash events.

Table 14: Random Effect Linear Regression Model for Standard Deviation of Travel Speed

	Non-Crash Events (n = 1920)			Crash/Near-Crash Events (n = 159)		
Description	Estimate	Std. Error	P-value	Estimate	Std. Error	P-value
(Intercept)	0.827	0.115	<0.001	3.620	1.190	0.003
55 mi/h Speed Limit	0.405	0.079	<0.001	1.639	0.660	0.014
60 mi/h Speed Limit	0.303	0.084	<0.001	1.416	0.620	0.024
Average Degree of Curvature (Degree)	0.161	0.047	<0.001	-0.608	0.332	0.069
Average Number of Lanes	0.026	0.040	0.508	-0.821	0.297	0.006
Level-of-Service A (1 if yes, 0 otherwise)	Baseline					
Level-of-Service B (1 if yes, 0 otherwise)	0.383	0.071	<0.001	1.206	0.765	0.117
Level-of-Service C (1 if yes, 0 otherwise)	0.865	0.137	<0.001	1.902	0.824	0.022
Level-of-Service D (1 if yes, 0 otherwise)	2.043	0.219	<0.001	3.149	0.864	<0.001
Level-of-Service E (1 if yes, 0 otherwise)	2.603	0.276	<0.001	3.139	1.049	0.003
Presence of Work Zone (1 if yes, 0 otherwise)	0.590	0.136	<0.001	-1.495	0.779	0.057

The effects of speed limits and traffic density on the traveling speed for the drivers involved in crashes or near-crashes were similar with the speeds of normal drivers. The drivers had more likelihood of driving with consistent speeds on the roadways with higher speed limit and lower traffic density. However, unlike the non-crash events, the degree of curvature, number of lanes, and presence of work zone had negative impacts on the standard

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deviation of speeds. The results indicated the drivers were less likely to adjust speed while they were traveling on the curve, the roadways with more lanes and had work zone presented. These behaviors may suggest that drivers tend to put themselves at risk for crashes by failing to reduce their speeds in response to these conditions.

Overall, the variability of speed were significantly affected by the speed limit and traffic density regardless of the type of events. Despite that, the degree of curvature and presence of work zone had impacts on the speed of normal and crash-related drivers, even if the influences on the normal drivers were opposite from the drivers involved in the crashes or near-crashes. The number of lanes was significant for the speed of crash-related events, but not correlated to the speed of non-crash events. This suggests the drivers should maintain the similar speed regardless of the number of lanes.

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CHAPTER 6. CONCLUSIONS

This study provides important insights into driver behavior leading up to, and during the course of, crash and near-crash events. The investigations focused on understanding how reaction time, deceleration rate, and speed selection varied with respect to traffic conditions, roadway geometry, driver characteristics, and behavioral factors. Driver response and braking behaviors were examined under unexpected situations where braking was required. Speed selection performance was compared between normal baseline driving events and high-risk crash/near-crash events. The data were collected from the SHRP 2 naturalistic driving study (NDS) dataset and the associated Roadway Information Database (RID). The naturalistic driving data recorded the real-time driving speed, status of brake and gas pedals at 0.1 sec. intervals. In addition, the features related to each event (event start and end time, crash severity, incident type, weather information), drivers (presence of secondary task, age, gender, number of violation and crashes drivers had before), and roadway (surface conditions and presence of work zone) were documented in the dataset as well. The roadway geometrics such as the lane and shoulder width were involved in the RID. Due to the unique characteristics of the naturalistic driving study, this analysis method provided a greater opportunity to learning drivers' performance in contrast to traditional study methods. At the end, 159 crash-relevant events and 1,920 baseline events were extracted from the datasets and analyzed by estimating a series of random effect linear regression models.

The participants' reaction times were determined using two different methods. One method was based upon the time gap between the event start time (as coded by VTTI staff who reviewed the NDS video) and the time drivers applied the brakes. The other method evaluated the time difference between the event start time and the time when the subject

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starts to react (also as coded by data reductionists at VTTI). In general, there was no significant difference in the summary data (mean, standard deviation, etc.) and distributions for reaction time across the two methods. The average reaction time was about 1.51 sec., with a standard deviation of 1.25 sec. and 85th percentile of 2.60 sec., which supported the findings reported in the literature. The analysis results show that reaction time varied based upon the type of crash/near-crash event, the gender of driver, and whether the driver was distracted over the course of the driving event. Particularly, the drivers were slow to respond to the braking of leading vehicles. The reaction time was longer for distracted drivers and males. Other factors such as the age of the driver, weather conditions, and the road surface showed no correlation with the reaction time. While the research literature has shown those factors to be important determinants of reaction time, it is important to note that very small samples were available for many of these areas of concern (e.g., poor weather/surface conditions, various age groups).

A second significant factor, deceleration rate, was evaluated from the end of the response time (and the start of braking) by the driver involved in the crash or near-crash event. Likewise, two deceleration rates were calculated with two different approaches, and showed similar average values, shapes of distribution and variabilities. The means and standard deviations of deceleration rates were 9.53 ft/s^2 (0.30 g) and 4.99 ft/s^2 (0.15g) respectively. In addition, the 85th percentile of deceleration rate was about 14.27 ft/s^2. The rates identified in this study were comparable to the aforementioned literature values. According to the modeling results, the rate of braking was significantly affected by the initial speed of braking, the grade of the roadway, and the type of incident. The drivers had higher likelihood to brake at a greater rate if the initial speed was low, which further substantiated

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the reported results described in Chapter 2. On an upgrade roadway or when drivers were involved in rear-end crashes or near crashes, drivers tended to decelerate more rapidly.

Lastly, the average speed and variability of travel speeds was investigated between normal driving events and crash/near-crash events. The average value of mean and standard deviation of travel speed for baseline were 63.57 mi/h and 1.48 mi/h, and 53.00 mi/h and 3.15 mi/h for crash-related events, respectively. On average, crash-involved drivers showed lower driving speeds and greater variability. However, speeds tended to be relatively consistent between the two groups at higher speed limits (e.g., 65 and 70 mi/h). Speed limits and traffic density had relatively consistent impacts on mean speed and speed variance under both baseline and crash/near-crash conditions.

Older drivers and those without a history of traffic violations tended to drive more slowly. Speeds also tended to be lower on roads with narrow shoulders, during night time, or under adverse weather conditions. Interestingly, speeds were also lower along horizontal curves or near work zones, but this was only true for the baseline driving events. In the case of crash or near-crash events, speeds were actually marginally higher on curves and entering work zone environments. Similarly, speeds also tended to be less variable in these circumstances among crash/near-crash involved drivers (as compared to normal baseline driving events). These opposing effects may suggest that drivers tend to put themselves at risk for crashes by failing to reduce their speeds in response to these conditions, which provides important empirical support for prior research showing crashes to be overrepresented on curves and in work zone environments. Such insights present one of the principal advantages in analyzing detailed naturalistic driving data.

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The findings of this study provides extensive insights into the driver's reaction, braking behavior and speed selection under normal driving conditions, as well as in high-risk scenarios resulting in crash or near-crash events. These variables of interest are important from several perspectives. First, they provide insights that are useful for design practices, such as in the reliable estimation of the stopping sight distance. The results of this study help to inform the design of safer transportation systems. The results also demonstrate the negative impacts of driver distraction, particularly as it relates to delayed driver response during crash precipitating events.

Lastly, there are several limitations of this study that should be acknowledged. Foremost, the sample size of crash-relevant events was relatively small and limited by the number of such events in the NDS dataset. The study focused exclusively on freeway events and, in future work, additional insights may be gained by examining driver behavior on other types of roadway environments. The study can be broadened to include non-freeway events to investigate if and how the drivers' behaviors might change on different types of roadway, including local roads and intersections.

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