The interrelationships between speed limits, geometry, and driver behavior: A proof-of-concept study utilizing naturalistic driving data

by

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NOMENCLATURE

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
CSV	Comma-Separated Values
CTRE	Center for Transportation Research and Education
DAS	Data Acquisition System
DOT	Department of Transportation
ERB	Ethical Review Board
ESRI	Environmental System Research Institute
GPS	Global Positioning System
HHS	Health and Human Services
ID	Identifier
IEC	Independent Ethics Committee
IID	Independently and Identically Distributed
IRB	Institutional Review Board
ISU	Iowa State University
LOS	Level of Service
NDS	Naturalistic Driving Study
NMSL	National Maximum Speed Limit
OLS	Ordinary Least Squares
PDO	Property Damage Only
PII	Personal Identifying Information
QA/QC	Quality Assurance / Quality Control
REB	Research Ethics Board
RID	Roadway Information Database
SDE	Secure Data Enclave
SHRP2	Second Strategic Highway Research Program
Std. Dev	Standard Deviation
STURAA	Surface Transportation and Uniform Relocation Assistance Act
SUV	Sport Utility Vehicle
TRB	Transportation Research Board
VTTI	Virginia Tech Transportation Institute

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DISCLAIMER

The findings and conclusion of this study are those of the author and do not necessarily represent the views of the VTTI, the Transportation Research Board, or the National Academies.

ABSTRACT

Speed management has been an extensive focus of traffic safety research dating back to the 1960's. Research has generally shown crash risk to increase as the average speed of traffic increases and as the standard deviation of travel speeds increases within a traffic stream. However, research as to the effects of speed limits has been somewhat inconclusive.

This study investigates how speed limits affect driver speed selection, as well as the resultant crash risk, while controlling for various confounding factors such as traffic volumes and roadway geometry. Data are obtained at very high resolution from a Naturalistic Driving Study (NDS) conducted as a part of the second Strategic Highway Research Program (SHRP 2). These data are integrated with a Roadway Information Database (RID), which provides extensive details as to roadway characteristics in the six-state study area (Florida, Indiana, New York, North Carolina, Pennsylvania, and Washington.) These sources are used to examine how driver speed selection varies among freeways with different posted speed limits, and how the likelihood of crash/near-crash events change with respect to various speed metrics.

Regression models are estimated to assess three measures of interest: the average speed of vehicles during the time preceding crash, near-crash, and baseline (i.e., normal) driving events; the variation in travel speeds leading up to each event as quantified by the standard deviation in speeds over this period (i.e. the average acceleration/deceleration rate); and the probability of a specific event resulting in a crash or near-crash based on speed selection and other salient factors.

Significant correlation was observed with respect to speed selection behavior among the same individuals and particularly within a single driving event. Mean speeds are shown to increase with speed limits. However, these increases are less pronounced at higher speed limits. Drivers tend to reduce their travel speeds along horizontal or vertical curves, under adverse weather conditions, and particularly under heavy congestion. Increases in average travel speed and the variability in travel speeds are both found to increase crash risk. Crash risk also increases on vertical curves and ramp junctions, as well as among the youngest and oldest age groups of drivers.

Ultimately, this research provides an important demonstration of how naturalistic driving data may be leveraged to examine driver behavior and research questions of interest that are difficult or impractical through other empirical settings. The results also provide important insights that provide greater understanding of how drivers adapt their speed selection behavior in response to posted speed limits and other roadway characteristics.

CHAPTER 1: INTRODUCTION

1.1 Background

Speed management has been an extensive focus of traffic safety research dating back to seminal work from the 1960's that showed crash risk (i.e., the probability of being involved in a crash) to be higher among vehicles traveling at speeds either significantly above or below the average speed of traffic (Solomon, 1964; Cirillo, 1968). While the crash risks at lower speeds have been shown to be overstated (West and Dunn 1971).Various studies have shown that increases in average speed and speed variance each tend to be associated with increased crash or fatality rates (West and Dunn., 1971; Forester et al., 1984; and Fowles and Loeb, 1989). These results provide support for maximum statutory speed limits, which are posted to inform drivers of the highest speed that is considered safe and reasonable for ideal traffic, road, and weather conditions.

The existing research literature has consistently shown fatalities to increase with higher limits. A recent longitudinal study of fatality trends on rural interstates across the United States showed that states with 70-mph maximum limits experienced 31 percent more fatalities than states with 60-65 mph maximum limits and states with 75 mph limits experienced 54 percent more fatalities (Davis et al., 2015). Research suggests these negative safety impacts may be due to differences in mean speed and speed variance across roadways where different speed limits are in place.

Despite these findings, numerous states have recently increased statutory speed limits on their freeway networks to speeds as high as 85 mph. Table 1 provides a list of the states that have gone through some speed limit policy changes on their roadways networks from

2011 to 2016. Consequently, speed management has become an increasingly important area for researchers and other traffic safety stakeholders.

Table 1. Changes in speed limit policies by state, 2011-2016

State	Type of Roadway	Prior Limit	New Limit	Year
Kansas	Rural Freeways	70	75	2011
Louisiana	Select Rural Freeways	70	75	2011
Ohio	Ohio Turnpike	65	70	2011
Arkansas	Select Rural Highway	55	60; 65	2012
Indiana	Tollway	55	70	2012
Kentucky	Select US Highway	55	65	2012
Texas	Rural Freeways; Tollway	75; 80	80; 85	2012
Alaska	State Highway	55	65	2013
North Carolina	Select Rural Freeways	65	70	2013
Ohio	Select Rural Freeways	65	70	2013
Utah	Select Rural Freeways	75	80	2013
Georgia	Select Interstate	55	70	2014
Idaho	Rural Freeway	75	80	2014
Illinois	Tollway; Select Freeways	55; 65	70	2014
Maine	Select Interstates	55; 65	60; 70	2014
New Hampshire	Select Interstates	65	70	2014
Pennsylvania	Rural Freeways	65	70	2014
South Carolina	Select Interstates	55	60	2014
Wyoming	Select Interstates	75	80	2014
Delaware	Select Interstates	55	65	2015
Montana	Rural Interstates	75	80	2015
South Dakota	Select Interstates	75	80	2015
Wisconsin	Rural Interstates	65	70	2015
Maryland	Select Interstates	65	70	2015
Nevada	Select Freeways	75	80	2015
Kentucky	Select Rural Highways	55	65	2015
Oregon	Select Interstates	55;65c/55t	65c/60t;70c/65t	2016
Washington	Freeways	70c/60t	75c/60t	2016

NOTE: c = passenger car limit; t = truck limit

While research literature has generally shown that speed limit, driver speed selection behavior, roadway geometry, and crash risk are interrelated, distinguishing the nature of these relationships is often challenging. For example, it is often difficult to determine the exact time at which a crash occurred, as well as the associated speed characteristics of the traffic stream immediately preceding the crash event. While research has shown both mean speed and speed variance to be affected by posted speed limits, most prior studies have been limited to using aggregate data for specific road segments where detailed driver information was not available. As such, it is difficult to infer how the behaviors of individual drivers may vary in response to different speed limits, as well as how these behavioral changes may impact crash risk.

1.2 Research Objectives

In order to better understand the differences in driver behavior that may result from speed limit policies, a detailed assessment of the behavior of individual drivers is necessary. Such an assessment should consider how driver speed selection changes in response to the speed limit while controlling for important roadway, environmental, and driver characteristics. The second Strategic Highway Research Program (SHRP2) Safety Data provides unique resources to investigate the nature of these relationships. These data include information from the Naturalistic Driving Study (NDS), which resulted in real-time behavioral data from more than 5 million trips, as well as related information from the Roadway Information Database (RID), which is a geospatial database providing detailed information for 25,000 miles of roadway across the NDS study sites.

The goal of this study is to develop and demonstrate procedures for effectively leveraging the information from the NDS and RID in order to examine the interrelationships between driver, vehicle, and roadway factors with driver speed selection and crash risk. The integration of data from the NDS and RID allows for a detailed examination of these issues, which is generally impractical through alternative study designs. Two specific research questions addressed as part of this study are:

1. How does speed selection vary for specific drivers, as well as across different drivers?

2. How does the risk of traffic crash or near-crash events change with respect to speed?

This proof-of-concept study focuses primarily on freeways, where the design standards are higher and, thus, there is a higher range in operating speeds. The research begins with an analysis of general trends in driver speed selection and crash/near-crash risk as they relate to the posted speed limit. A series of statistical models are estimated to determine where significant differences in these measures exist with respect to posted speed limit, roadway geometry, and driver characteristics. Additional data are collected for the purpose of a more detailed comparison of vehicle dynamics and driver behavior during crash, near-crash, and baseline (i.e., control) driving events. Methods are developed and pilot tested to determine how the SHRP2 data may be used for the purposes of speed management, including the establishment of maximum speed limits and the identification of appropriate countermeasures for speeding-related crashes.

In order to examine the research questions, regression models are estimated to examine three primary metrics of interest:

1. the average speed of vehicles during the time preceding each crash, near-crash, and baseline event;
2. the variation in travel speeds for vehicles leading up to each event as quantified by the standard deviation of speeds over this period; and
3. the rate of crash or near-crash involvement among study participants included in the sample of events.

1.3 Thesis Structure

This thesis is organized into six main chapters, which detail the background of the research problem of interest, provide context with respect to the extant research literature, outline the study methods, and demonstrate findings in respect to the research questions of interest prior to presenting final conclusions and recommendations. A brief description of these chapters follows:

Chapter 1: Introduction **–** This chapter provides background on the role of speed management in transportation safety, as well as detailing recent speed limit policy changes that have occurred, and outlining the need for additional research in this area. The background section is followed by a presentation of the research hypotheses and objectives that have been outlined to address these questions.

Chapter 2: Literature Review – This chapter is structured into three sections to better summarize the extant literature regarding speed management, and speed selection behavior. First, an overview of speed management history and speed policies is provided. This is followed by a review of previous studies as they relate to the effect of speed limit on speed selection and crash risk. Lastly, a brief review of research focused on the effects of speed limits on operating speed is presented.

Chapter 3: Data Description – This chapter first provides a brief description of the Naturalistic Driving Study (NDS) conducted as a part of the second Strategic Highway Research Program (SHRP2). This includes details of the information obtained as a part of the NDS, as well as companion data collected during development of the Roadway Information Database (RID). The chapter concludes with a description of the data requested for the purpose of this study, along with a description of data integration methods and processes.

Chapter 4: Methodology – The statistical methods used for the purpose of this study are described in this chapter. General formulation of the statistical methods is provided, including a discussion as to why these methods are appropriate for the nature of the data that are analyzed.

Chapter 5: Results and Discussion – This chapter presents the results of a series of statistical regression models developed over the course of this study. These results are accompanied by a discussion as to the practical implications of the findings, as well as a discussion of potential drawbacks and limitations given the pilot nature of the study.

Chapter 6: Conclusion – Conclusions of this research study and a discussion on how these findings address the research questions are summarized in this chapter. This chapter also includes how these findings could apply to real-world problems, as well as outlining potential directions for future research.

CHAPTER 2: LITERATURE REVIEW

2.1 General Overview

Numerous studies have examined the relationship between posted speed limits and the frequency and severity of traffic crashes. Much of the research in this area was conducted following the passage of the Emergency Highway Energy Conservation Act in 1974 in which the 55-mph National Maximum Speed Limit (NMSL) was introduced. The motivation to establish a lower speed limit was to reduce the fuel consumption. However, one issue emerged by introducing the 55-mph statuary speed limit was that the drivers speed selection did not have compliance with the established speed limit policy. This was more pronounced on interstate highways where the design speed was significantly higher than the posted speed limit. Later in 1987, the Surface Transportation and Uniform Relocation Assistance Act (STURAA) was passed in which states were permitted to post speed limits as high as 65 mph on rural interstate highways which had populations less than 50,000. As a result, numerous studies were conducted to examine the effects of the enactment of the STURAA on the traffic crashes in response to the increase in the posted speed limits. While a series of research studies revealed an increase in traffic crashes following this policy change (Baum et al., 1989; Baum et al., 1992; Gallaher et al. 1989; Greenstone, 2002; Ledolter et al., 1989; McKnight and Klein, 1990; Wagenaar et al., 1990; Upchurch, 1989), some others were not able to identify any significant impact on the safety conditions of the roadway segments (Pant et al., 1992, 1992; Sidhu, 1990; Chang and Paniati, 1990). Surprisingly, a couple of evaluation studies concluded that increasing the posted speed limits was in fact associated with some safety improvements (Lave and Elias, 1994; McCarthy, 1999).

Research has also shown that the number of the crashes, as well as related injuries and fatalities increase when unreasonable speed limits are posted since drivers compliance would be reduced subsequently (Najjar et al., 2000). Moreover, Thornton and Lyles (1999) stated that when 85^{th} percentile speed is used as a basis for calculating the speed limit, speed variations would decrease resulting in more smooth traffic flow. A study by Garber and Gadiraju (1988) also provided additional support as to correlation of speed dispersion to traffic conflicts on rural non-limited-access highways.

Despite these findings, nineteen states have increased speed limits on rural freeways since 2010 and several additional states have considered such increases. In contrast to earlier increases, which were often implemented on a system-wide basis, many of the recent speed limit policy changes have affected specific road segments. In such instances, states have considered a range of factors in determining whether speed limit increases were appropriate at a given location. These factors include the existing mean and 85th percentile speeds, speed variance, and recent crash history. Following sections summarize the extant literature to provide a better understanding of what have been investigated to date, what methods have generally been proved to be useful, and what unresolved questions or controversial subjects need to be addressed furtherly. Section 2.2 focuses on the effect of speed limit on crash risk, as well as the crash frequency. Subsequent section includes a review of the literature regarding the effect of different geometric characteristics as well as speed limits on operating speed. The results of this study are compared to previous findings later in chapter 6.

2.2 Relationship between Speed, Speed Limit, and Crash Risk

The speed with which the traffic is moving plays a significant role in roadway safety. The risk of being involved in a crash as well as the severity of the outcome could dramatically be affected by the speed of the moving vehicle (Elvik et al., 2004). Traveling at higher speeds results in longer stopping distance as well as less maneuverability and also requires more prompt reaction to a certain change (Aarts and Van Schagen., 2006).

In earlier studies, vehicles travelling at lower speed than the modus speed were found to be more likely to experience a crash, however, many recent studies found limited evidence of such a relationship. (Evans, 2004).

In a 1964 study on 600 miles of rural highways, three-quarters of which were two-lane highways, Solomon reported that for speeds less than 50 mph, the involvement rate of vehicles (i.e. the number of vehicles involved in accidents per 100 million vehicle-miles travel) in crashes decreases as the speed increases (Solomon, 1964). Solomon proposed that the probability of getting involved in a crash per vehicle-miles travel as a function of vehicle speed follows a U-shaped curve. Later, while the Solomon’s curve was replicated in some other research studies (Cirillo, 1968; and Munden, 1967) with some modification, criticism arose in subsequent research for the use of estimated pre-crash speeds of the involved vehicle, which could bias the results (White and Nelson, 1970).

By passage of the Surface Transportation and Uniform Relocation Assistance Act (STURAA) in 1987, states were permitted to post speed limits as high as 65-mph on rural interstate highways. As a result, numerous research studies aimed at assessing the effect of this law change on crash risk and particularly fatalities.

One concern that arose while assessing the effect of 65-mph speed limit on crash rates was that these rates should not be examined solely on interstates in isolation from the rest of a network. In a study conducted in 1997, Lave and Elias proposed that the increase in the speed limit on interstates had resulted in reallocation of traffic and drivers. Consequently, they concluded that this reallocation in the system addresses the increased fatality rates on interstates. They also showed that imposing 65-mph speed limit on rural interstates resulted in a 3.4-5.1 percent reduction in the statewide fatality rates (Lave and Elias, 1994)

In 2002, a similar study was conducted to reexamine the findings of Lave and Elias (Greenstone, 2002). This study utilized similar data over a slightly shorter period of time from 1982 to 1990. This study also found evidence as to a modest decline in the statewide fatality rates. Although the findings showed a significant increase in the fatality rates on interstates, a large reduction in the same measure of interest was reported on urban non-interstates. In addition, unlike the previous study, the author found no evidence regarding the reallocation phenomenon on roadway networks (Greenstone, 2002).

Baum et al. (1989) used data available through Fatal Accident Reporting System (FARS) to compare the fatality rates between states that imposed higher speed limits versus those that retained the 55-mph speed limit. The data from 38 states with increased speed limit were aggregated across the months with higher speed limits in 1987, as well as the same months from 1982 to 1986. Figure 1 shows the number of fatalities on rural interstates which implies that fatalities are significantly higher after the enactment of STURAA as compared to prior 5-year data (Baum et al., 1989).

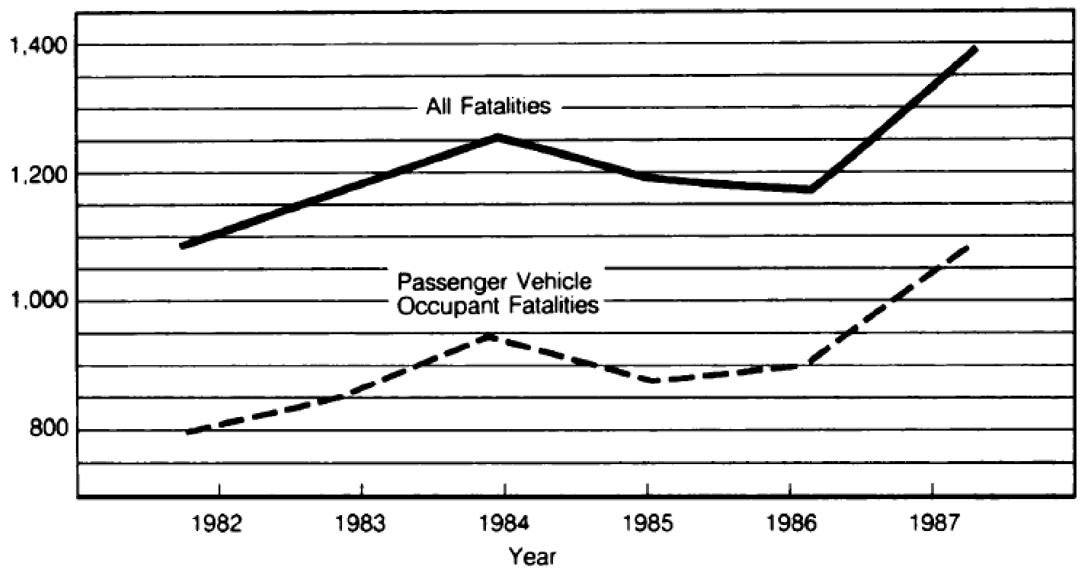


Figure 1. Fatalities on rural interstates during months of higher speed limits in 1987 and same months in 1982-1986 (Baum et al. 1989)

New Mexico was the first state to utilize 65-mph speed limits after the passage of legislations in April 1987. As a result, a before and after analysis was conducted by Gallaher et al. (1989) to compare the rate of casualties along these roadways. The results indicated that the rate of fatal crashes had increased by 2.9 per 100 million vehicle-miles traveled (VMT) during one year after period, while 1.5 per 100 million VMT increase was predicted using the same trend based on the data from preceding five years.

The speed limit on rural limited access highways in state of Michigan was raised to 65-mph effective January 1988. As a result, a study was conducted to examine the number of fatalities in response to this change. To this end, the number and rates of crashes, as well as injuries and fatalities were collected along the segments were the speed limit was raised, as well as those for which the limit was retained. The analyses revealed that roadways where the speed limit was raised were associated with 19.2 percent higher fatalities, while this increase jumped up to 39.8 percent for major injuries, as well as 25.4 percent for moderate injuries. Also, they noticed that fatalities increased even on roadways which maintained 55-mph speed limit, suggesting that imposing higher speed limit may also have spillover effects on other roadway segments (Wagenaar et al., 1990)

A similar study was designed to examine the effect of the introduction of 65-mph speed limit in state of Ohio. A before and after analysis was conducted using 36 months of data before and after the implementation. In contrast to prior literature, Pant et al. were not able to identify any significant difference in the number of fatalities between rural interstate highways posted at 65-mph as compared to those which retained a 55-mph posted limit. However, slight increases were reported with respect to the number of injury and property damage only (PDO) crashes on roadway stretches that had been posted at 65-mph. In addition, rural interstates posted at 55-mph were found to be associated with lower rates of injury and PDO crashes as compared to before implementation period. Consequently, no evidence was found as to the spillover effect which had been proposed by some other studies (Pant et al., 1992)

In November 1995, states were given the authority to determine interstate limits by the National Highway System Designation Act. Consequently, many states set higher posted speed limits on their roadway networks which provided the opportunity to evaluate driver behavior in response to these variable limits along similar highways. Collectively, some of the conducted studies found that lower speed limits result in safety benefits (Dart, 1977, Weckesser et al., 1977, and Deen and Godwin, 1985) which were attributed to lower average speeds and speed variance (Burritt et al., 1976).

The implementation of higher speed limits was thought to be associated with some economic benefits most important of which was travel time. However, the change in the number of fatal and injury crashes might not justify such a modification. In order to address this concern, speed and volume data, as well as crash data were obtained from Iowa Department of Transportation on four main roadway classes: 1) rural interstates; 2) rural primary roads; 3) rural secondary roads; and 4) urban interstates. However, the 65-mph speed limit was only imposed on rural interstates. This study found 38.2 percent increase in the number of fatal crashes on rural interstates, while the findings showed 15.6 percent reduction in major-injury crashes on the same roadway networks. However, significant reduction in both fatal and major-injury crashes was reported on rural primary roads, rural secondary roads, and urban interstates (Ledolter and Chan, 1996).

Farmer et al. compared the number of fatalities across 12 states which increased the posted speed limit to 70-mph in 1996 with the similar data from 1990 to 1995. Rural and urban interstates, as well as freeways were included in this study. As shown in Figure 2, states with higher posted speed limit were associated with 12 percent increase in the number of fatalities on interstates and freeways. However, on other types of roadways, this increase was mitigated to only three percent, while the overall increase on all types of roadways was 6-percent (Farmer et al., 1999).

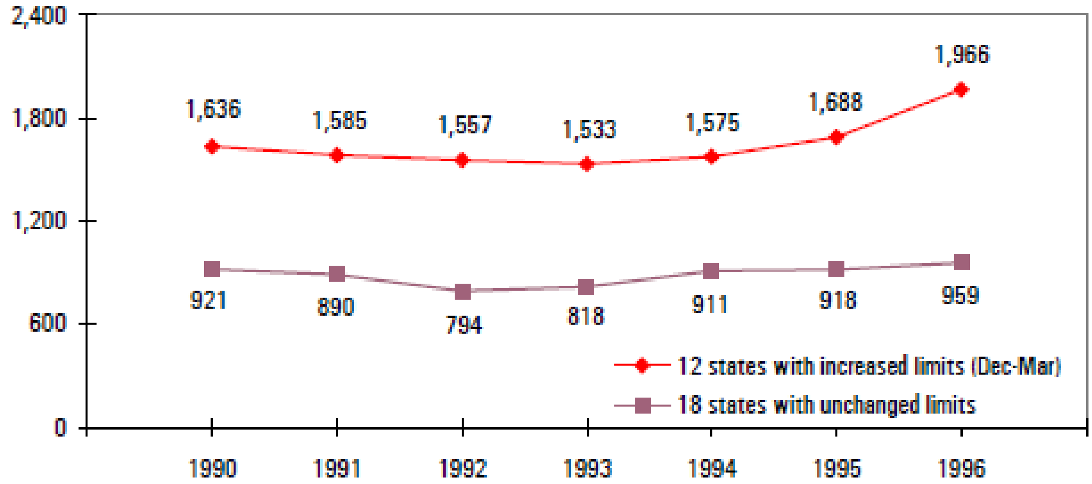


Figure 2. Number of occupant fatalities on interstates and freeways 1990-1996 (Farmer et al. 1999)

In 2005, Elvik conducted an extensive review of 460 studies about the speed and road safety associations and concluded that there is a robust relationship between them. It was also revealed that the effect of a 10 percent change in the mean speed of traffic on traffic fatalities is more pronounced as compared to a 10 percent change in traffic volume (Elvik, 2005). Subsequently, in an extensive review, Aarts et al. (2006) provided a thorough list of the studies that had been conducted to investigate the relation between crash risks and speed in general. They concluded that crash rates increase exponentially for individual vehicles that increase their speed and this increase is more pronounced in minor/urban roads as compared to major/rural highways.

The investigation of the effect of speed on crash risk, as well as the crash frequency was not limited to the United States. This high-interest area in traffic safety and operation has also been investigated by researchers all over the world.

Aljanahi et al. (1999) developed models to investigate how crash rates change with regard to various roadway and traffic characteristics including speed. The crash rates were explored on divided highways in two sets of locations, one in UK and the other one in Bahrain. They proposed that substantial safety improvement could be achieved either by mandating lower speed limits or reducing the spread of vehicle speeds. They also found that in UK sites which had lower crash rates, there is a strong statistical relationship between crash counts and the variability of traffic speed, while the results for Bahrain, which was associated with higher accident rates, indicated that mean speed of the traffic is a stronger predictor of crash rates (Aljanahi et al., 1999).

Fildes et al. (1991) conducted a self-report study in both rural and urban highways in Australia to investigate the effects of speed selection and speed spread on crash rates. The study was performed on two urban and two rural roads with speed limits of 60 km/h and 100 km/h respectively. Drivers who drove at a speed below V15 or above V85 were pulled over and asked about their crash history during last 5 years. Fast drivers had experienced more crashes recently and there was an exponential relationship both for urban and rural highways with a much steeper curve for urban roads (Fildes et al., 1991). In another similar study by Maycock et al. (1998), a 13.1 percent increase in crash liability was reported in response to a one percent increase in speed.

In July 2003, the speed limit on 1100 km of rural roads in South Australia was reduced from 110 km/h to 100 km/h. Using crash data from two years of before and two years of after speed limit reduction, Long et al. found only a 1.9 km/h reduction in the average speed of the vehicles and a 20 percent reduction in casualty crashes (Long et al., 2006). Also, a follow up report on the same roadway segments analyzed ten years of before and after speed reduction data and compared the results with control segments where the speed limit was still 110 km/h. It was revealed that the control segments, which still had the same speed limit, had also experienced a long-term trend of crash counts reduction. A pronounced drop in casualty crashes was still apparent.

The results of a study on a number of divided segments in Naples-Candela Italy, also showed that the absolute value of the operating speed difference in the tangent-to-curve transition is a significant predictor for total crash counts (Montella and Imbriani, 2015).

2.3 Relationship between Speed Limit and Operating Speed

The American Association of State Highway and Transportation Officials (AASHTO) notes that driving speeds are affected by the physical characteristics of the road, weather, other vehicles, and the speed limit (AASHTO, 2001). Among these, road design is a principal determinant of driving speeds. Geometric factors tend to have particularly pronounced impacts on crashes. Ultimately, many factors affect speed selection beyond just road geometry and posted limit as shown by prior research in this area (Emmerson, 1969; McLean, 1981; Glennon et al., 1985; Lamm and Choueiri, 1987; and Kanellaidis et al., 1990;) Research has generally shown that speed limit increases result in changes in the observed mean and 85^{th} percentile speeds that are less pronounced than the actual speed limit increases (Freedman and Esterlitz, 1990; Brown et al., 1991; Lynn and Jernigan, 1992; Parker, 1997; and Ossiander and Cummings, 2002).

Parker conducted an extensive evaluation study from 1985 to 1992 on non-limited access highways to evaluate the effect of changing the posted speed limit on driver behavior. The maximum posted speed limit on the select roadways was 55 mph at that time. However, during the course of study the speed limits were increased or decreased on a number of segments along these roadways. Subsequently, driver behavior data along with crash data were collected from 22 states to study any potential interrelationship. In order to properly evaluate any safety impact associated with changing speed limit, the data were collected along 100 sites where the speed limit was changed as well as 83 control segments where no change was made regarding speed limit policies. These changes in the speed limit included either increasing or decreasing the maximum permitted speed along the roadway segments. The limits were lowered by 5, 10, 15, or 20 mph or raised by 5, 10, or 15 mph all of which could have had particular impacts on traffic crashes. Surprisingly, less than 1.5 mph change in the speed was reported after the implementation of these changes. The study findings revealed that drivers generally tend to select their speeds on non-limited access highways based on the roadway geometry rather than solely the speed limit (Parker, 1997).

In a similar study, Kockelman et al. (2006) studied the impact of raising the speed limit on the operating speed as well as the associated variability in the speed on high-speed roadways. The findings demonstrated that the increases in the operating speed were, on average, less than half of the actual amount with which the speed limit had been raised. It was also noted that the average speed and the speed variability are more influenced by roadway geometry and cross-sectional characteristics as compared to posted speed limits. These findings are largely reflective of driver opinions on speed limits.

A survey of freeway users found that, on average, respondents drove 11 mph over the speed limit on roads posted 55 mph, 9 mph over the speed limit on roads posted at 65 mph, and 8 mph over the speed limit on roads posted at 70 mph (Mannering, 2007). Research also shows that drivers believe the most influential factors dictating their speed selection are weather conditions, their perception of what speeds are “safe”, the posted speed limit, traffic volume levels, and the amount of personal driving experience they have on a particular road (Royal, 2003).

In a report by the Federal Highway Administration the operating speed along horizontal and vertical curves, as well as tangent segments was predicted by developing regression equations. It was concluded that the best independent parameter to model the speed along horizontal curves is the inverse radius. Operating speeds along horizontal curves with radius greater than 800 m were found to be very similar to that of tangent segments. However, the operating speed decreases significantly on horizontal curves with radius less than 250 m. Figure 3 presents the developed equations to estimate the operating speed along horizontal curves on grades (FHWA, 2000).

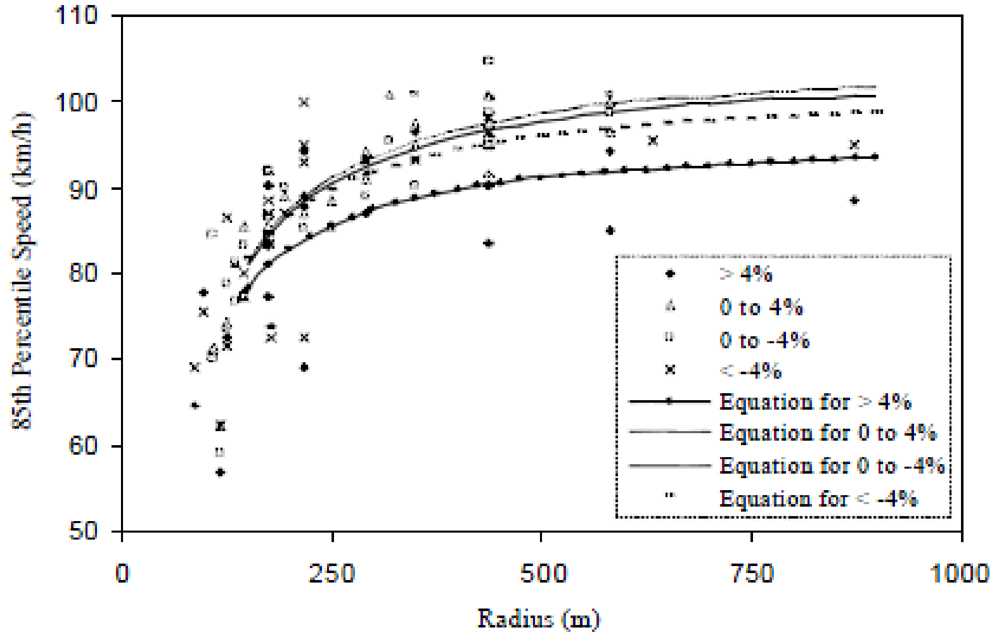


Figure 3. 85th percentile speed versus radius along horizontal curves on grades (FHWA, 2000)

Collectively, existing literature suggests that degree of curvature, length of curve, and deflection angle are salient factors to predict the operating speed along horizontal curves. Voigt et al. proposed an equation to estimate the 85th percentile speed along horizontal curves in which the degree of curvature, curve length, deflection angle, and superelevation were statistically significant. The proposed equation is given as:

$$V_{85} = 99.6 - 1.69D + 0.14L - 0.13\Delta + 71.82e \quad (1)$$

where

V_{85} = 85th percentile speed;

D = degree of curvature;

L = curve length;

Δ = deflection angle; and

e = superelevation along the segment.

Schurr et al. (2002) utilized the data from 40 different sites across the state of Nebraska to estimate the mean speed of the traffic. In addition to deflection angle and curve length, the posted speed limit was found to be a significant predictor for the mean speed. The mean speed regression equation is given in Equation 2.

$$V_{mean} = 67.4 - 0.112\Delta = 0.02243L + 0.27V_p \quad (2)$$

where

V_{mean} = the average speed of free-flow passenger car at the curve midpoint;

Δ=deflection angle (decimal degree);

L=arc length curve (m); and

V_p= posted speed limit (km/h)

In addition to the operating speed along horizontal curves, regression models were developed to identify the significant factors in determining the operating speed on tangent segments in advance of the curves and is presented in Equation 3.

$$V_{mean} = 51.7 + 0.508V_p \quad (3)$$

where

V_{mean} = the average speed (km/h); and

V_p = posted speed limit (km/h)

In summary, the research literature has been somewhat inconclusive as to the effect of speed limit on crash risk and crash frequency. While some studies concluded that raising speed limit results in higher number of crashes, some others found evidence on safety improvements as a result of increased speed limits.

In addition, while research has shown both mean speed and speed variance to be affected by posted speed limits, most prior studies were limited to specific road segments and detailed driver information was not available. As such, it is difficult to infer how the behaviors of individual drivers may vary in response to different speed limits, as well as how these behavioral changes may impact crash risk.

To this end, it is particularly important to gain a greater understanding of how driver speed selection changes in response to changes in the speed limit while controlling for various external (e.g., road geometry) or in-vehicle (e.g., driver distraction) factors.

In addition to the aforementioned issues, this research will also investigate important differences among drivers. Given the level of detail provided by data from the NDS and RID, speed selection behavior can be related back to individual driver characteristics.

CHAPTER 3: DATA DESCRIPTION

The second Strategic Highway Research Program (SHRP2) is aimed at identifying solutions to three major transportation challenges at the national level: improving transportation safety to save lives; reducing congestion; and improving methods for renewing roads and bridges which would ultimately result in improving the quality of life. Extensive data collection has been conducted for the purpose of various aspects of SHRP 2, providing a unique opportunity to address different research questions that were not possible to examine before. Within the context of traffic safety, this includes a large-scale data collection exercise across six different states, including Florida, Indiana, New York, North Carolina, Pennsylvania, and Washington. This section includes details of the background and data acquisition systems used to conduct this study of naturalistic driving behavior, as well as how these data sources were used for the purpose of this study.

3.1 Data Background

3.1.1 Naturalistic driving study

The naturalistic driving study (NDS) that has been done as part of SHRP2 is the largest NDS ever undertaken. More than 3,092 drivers from the six study sites volunteered to participate in this study in which their real-world driving behavior was recorded. Over the course of this extensive data collection, more than five million trips and 3,900 vehicles years were monitored. The drivers and study sites were selected such that they well represent a sample of driving behaviors, weather conditions, demographic distribution, and a variety of road types. The participants were recruited using different means such as emails, websites, cell phones, and flyers. Table 2 provides the number of participants at each site. The sample size varies largely between sites due to differences in the characteristics of the study areas, as well as the existing limitations. As a compensation for the participation, each driver was paid $300 per year.

Table 2. SHRP 2 NDS sites and participants counts

State	Site	Participant Count
Florida	Tampa	698
Indiana	Bloomington	239
New York	Buffalo	719
North Carolina	Durham	504
Pennsylvania	State College	256
Washington	Seattle	676
Total Number of Participants		3092

Data Acquisition System (DAS) was developed to keep records of all trips made during the study period. Consequently, four video cameras, front and rear radar, accelerometer, Global Positioning System (GPS), vehicle controller area network, lane-tracking system, alcohol sensor, incident button, and data storage system were installed on all registered vehicles. Figure 4 shows the schematic view of the data acquisition system used in the data collection process. The recorded trips were collected and maintained by Virginia Tech Transportation Institute (VTTI) resulting in more than four petabytes (four million gigabytes) of data.

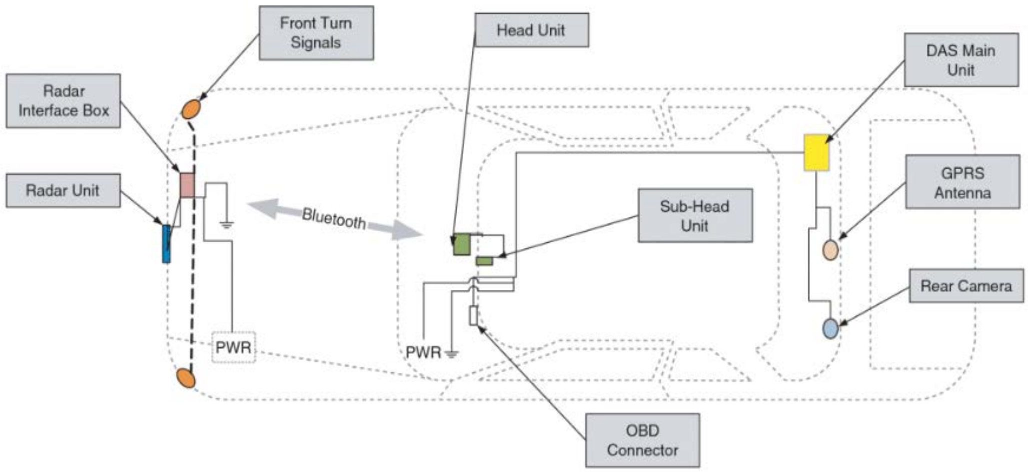


Figure 4. Data acquisition system schematic (Antin et al., 2011)

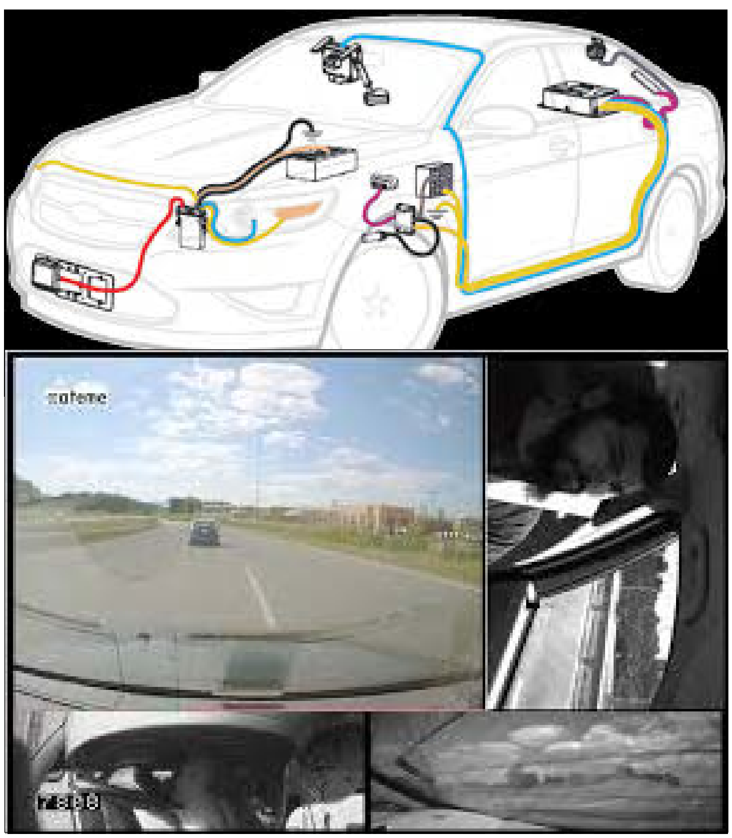


Figure 5. Composite snapshot of four continuous video camera views (Antin et al., 2011)

The vehicles were equipped with forward view, in-cabin driver face view, instrument panel view, and rear view cameras to record both the in-vehicle and out-of-vehicle environment in great details. Figure 4 and Figure 5 show a schematic view of where each of the cameras were installed, as well as the four different views that were being recorded.

The use of the SHRP2 NDS data is critical since it deals with human subjects. This requires further consideration and obligation to ensure the secure use of Personally Identifying Information (PII). PII is any sort of information that could potentially be used to identify human subjects in real world. This includes driver face video, GPS traces that might reveal the participant’s home, or work location, and etc. Therefore, all the NDS participants were promised that the confidentiality of this sort of data would be maintained. A certificate of confidentiality was issued by the department of Health and Human Services (HHS) to protect the participants. Also, secure data enclave (SDE) was developed to restrict data access and protect the PII accordingly. An SDE is a physically isolated environment where only qualified researchers could access the PII. Consequently, the data collected during this naturalistic driving study are divided into two main portions with regard to their nature: InSight; and InDepth. Following sections provide a brief description of what is included in each of these and how they can be accessed.

3.1.1.1 InSight

This subset of the NDS data includes the aggregated and summarized data which excludes any personally identifying type of information which is also publicly available through InSight website. Any registered user could view this type of data through InSight website online. A registered user is the one who successfully undertook the Institutional

Review Board (IRB) training, however, these data cannot be downloaded or accessed outside the working environment designed by VTTI. An IRB which is also regarded as an Independent Ethics Committee (IEC), Ethical Review Board (ERB), or Research Ethics Board (REB) is the board that has been basically formed to ensure secure conduct of any research study which involves human subjects. These data have been extracted and coded through manual review of the videos by VTTI trained interns and staff in the secured data enclave (SDE). These data have been directly captured by the DAS, or were collected through surveys either before or after that the study began.

The InSight data are basically divided into four major subsets, vehicles, trips summary, participant, and event some of which have their own subdivisions. The integration of all of these provide a comprehensive set of data elements for each unique event. Unique identifiers have been developed for each event, trip, driver, and vehicle to allow for an easy integration of the datasets. A single trip may be associated with more than one event, and some drivers might have had multiple trips and events associated with them.

3.1.1.2 InDepth

As mentioned previously, the second portion of the NDS data is referred to as InDepth. This subset of data includes any information which potentially may result in identifying the participants, including time series data, and video data. This information is not available online, and needs further investigation as to the eligibility of the involved researchers and research questions to access this sort of data. Any researcher who wants to request extract of data from this portion may submit required documents to the local Institutional Review Board (IRB) including research questions, details as to what variables will be required, how these data would help to better investigate the questions of interest, how the data will be maintained and secured, and etc. Consequently, authorized investigators with eligible research questions will be provided by the requested data under certain agreements and conditions.

3.1.2 Roadway Information Database

In conjunction with the NDS data, the roadway information database (RID) was developed as part of SHRP2 to better address the research questions. Roadway Information Database (RID) is a geospatial database that provides detailed data for 25,000 miles of roadway across the six study states (Florida, Indiana, New York, North Carolina, Pennsylvania, and Washington). The RID is comprised of road characteristics, which were collected through a combination of existing roadway data from public and private sources, as well as supplemental data collected by ISU using a mobile van.

The RID was collected and is being maintained by the Center for Transportation Research and Education (CTRE) at Iowa State University. The effort was to collect and combine data at sites where the NDS was conducted to the extent possible. However, due to the limited resources and complications associated with the data collection process, the roadways with higher trip densities and more interesting features for researchers to further investigate were collected through this project.

Multiple data sources were leveraged to gather a comprehensive roadway database. Existing data for over 200,000 miles of roadways though related departments of transportation (DOTs) and environmental systems research institute (ESRI) were integrated with the roadway asset inventory which was collected through the instrumented mobile van driving along designated roadway stretches. The colored links in Figure 6 shows the roadway stretches on which the mobile van was driven.

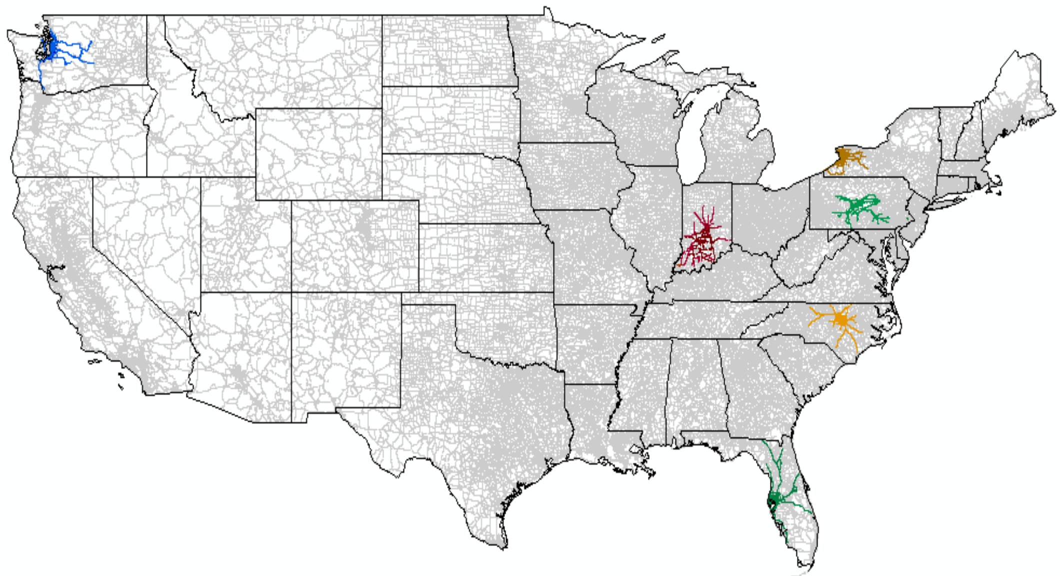


Figure 6. Collected links for SHRP 2 roadway information database

The primary purpose in RID development was to provide a database that could be linked directly to the data from the NDS. The integration of the NDS data with roadway information provides a great opportunity to expand the available data elements to be investigated, as well as to collect more detailed information by locating events if necessary through google earth. The RID is ultimately comprised of the following shapefiles:

Lighting	Rumble Strip Links	Location attributes
Lane	Intersections	Alignment
Median Strip	Signs	Section
Shoulder	Barrier	

These shapefiles could be linked to one another as needed using the tools available through GIS based on linear referencing system. Ultimately, a comprehensive database could be developed including a multitude of data elements across the six study sites.

3.2 Requested Data

As mentioned in chapter one, the purpose of this study is to investigate the interrelationship between speed limits, geometry, and driver behavior along freeways. Hence, the first step in the data request process was to query the data such that only freeway events be included. There is a locality field in the database, which designates the type of roadway on which the event occurred. Candidate events were identified where the locality field was "Interstate/Bypass/Divided Highway with no traffic signals". Upon identifying these candidates, data were obtained from the four tables noted above:

Event Detail Table: 6,023 unique events were identified (each event has a unique "anonymous event ID" field) and a total of 73 different fields were provided through a data sharing agreement with VTTI. The Event Detail Table includes details as to the general characteristics associated with each event (e.g., lighting condition, horizontal and vertical alignment, etc.).

Trip Summaries Table: 5,925 unique trip IDs were included among the 6,023 events. This table included 122 fields, which provide descriptive information about each trip (e.g., trip length, min/mean/max speed, time-of-day, etc.). These 5,925 trips comprise all 6,023 events as there were some instances where multiple events (i.e., crash, near-crash, and baseline) occurred as a part of the same trip.

Vehicle Detail Table: 2,323 records are detailed in this table, which includes 27 different fields. This table is considerably smaller than the Event Detail and Trip Summaries tables due to the fact that a number of vehicles were involved in multiple events. Unique records in this dataset were identified using a combination of the vehicle ID and participant ID fields as some vehicles were used by multiple study participants.

Vehicle and Driver Survey Table: 2,290 unique records were included in this table, which was comprised of 133 fields that describe the participant's behavior and demographic characteristics. Each record from this table corresponds to one participant from the Event Detail and Trip Summaries tables. As with the Vehicle Detail table, specific drivers/vehicles were involved in multiple events, which is why this dataset has fewer records.

At the onset of the study, the tables described above were aggregated into a comprehensive database that included details of each event, trip, driver, and vehicle. The full database included an in-depth inventory of 355 fields from these 6,023 unique events. This included 656 crash or near-crash events, as well as 5,367 baseline events, which were randomly selected from the same types of roadways.

Table 4 provide sample tables that summarize how the rate of crash/near-crash events varied with respect to weather conditions, level-of-service (i.e., traffic density), and violation rate of study participants over the preceding three-year period.

Table 3. Crash/Near-Crash risk by weather conditions

Weather Condition	Event Type		Total
	Baseline	Crash / Near-Crash	
Normal	4844 (89.4%)	573 (10.6%)	5417
Rain/Fog	501 (86.4%)	79 (13.6%)	580
Sleet/Snow	22 (84.6%)	4 (15.4%)	26
Total	5367 (89.1%)	656 (10.9%)	6023

Table 4. Crash/Near-Crash risk by number of traffic violations in prior 3 years

Values	Event Type		Total
	Baseline	Crash / Near-Crash	
(null)	59 (89.4%)	7 (10.6%)	66
0	3362 (90.5%)	353 (9.5%)	3715
1	1275 (89.2%)	154 (10.8%)	1429
2 or More	671 (82.5%)	142 (17.5%)	813
Total	5367 (89.1%)	656 (10.9%)	6023

Table 5. Crash/Near-Crash risk by estimate Level-of-Service

Level-of-Service	Event Type		Total
	Baseline	Crash / Near-Crash	
A	2987 (96.1%)	122 (3.9%)	3109
B	1785 (87.7%)	250 (12.3%)	2035
C	336 (72.1%)	130 (27.9%)	466
D	145 (56.9%)	110 (43.1%)	255
E	93 (70.5%)	39 (29.5%)	132
F	21 (80.8%)	5 (19.2%)	26
Total	5367	656	6023

Summary statistics are provided in for these 6,023 events in Table 6. These statistics are broadly representative of general travel characteristics across the six study areas where the NDS was conducted (Florida, Indiana, North Carolina, New York, Pennsylvania, and Washington). The primary exception is with respect to the driver age distribution as oversampling was conducted among the younger and oldest age groups as detailed in a recent SHRP2 report. It is also important to note that sample sizes were relatively small across several categories of interest (e.g., heavy congestion, wintry weather, and the oldest age group).

Table 6. Summary statistics for event data from NDS Insight database

Variable	Category	Count	Variable	Category	Count
Gender	Male	3020	State	Florida	1346
	Female	2965		Indiana	291
	Unknown	38		North Carolina	985
Age	16-19	645		New York	1238
	20-24	1637		Pennsylvania	348
	25-29	705		Washington	1815
	30-34	398	Relation to	Non-junction	3612
	35-39	233	Junction	Interchange/intersection	2023
	40-44	246		Entrance/exit ramp	384
	45-49	287		Other	4
	50-54	273	Alignment	Straight	4953
	55-59	277		Curve left	491
	60-64	223		Curve right	579
	65-69	308	Grade	Level	4989
	70-74	240		Grade down/dip	328
	75-79	238		Grade up/hillcrest	706
	80-84	180	Lighting	Daylight	4682
	85-94	46		Dawn/Dusk	375
	Unknown	87		Dark, lighted	566
Seatbelt	Proper use	5824		Dark, not lighted	500
Use	Improper or non-use	191	Weather	Clear	5417
	Unknown	8		Rain/Mist/Fog	580
Vehicle	Car	4305		Snow/Sleet	26
Type	SUV Crossover	1225	Surface	Dry	5176
	Pickup Truck	295	Condition	Wet	822
	Van/Minivan	198		Snowy/Icy	25
Prior	0	4221	Level-of-	LOS A: no lead	888
Crashes	1	1323	Service	LOS A: leading traffic	2221
	2 or more	404		LOS B	2035
	Unknown	75		LOS C	466
Prior	0	3715		LOS D	255
Violations	1	1429		LOS E	132
	2 or more	813		LOS F	26

Table 6. Continued

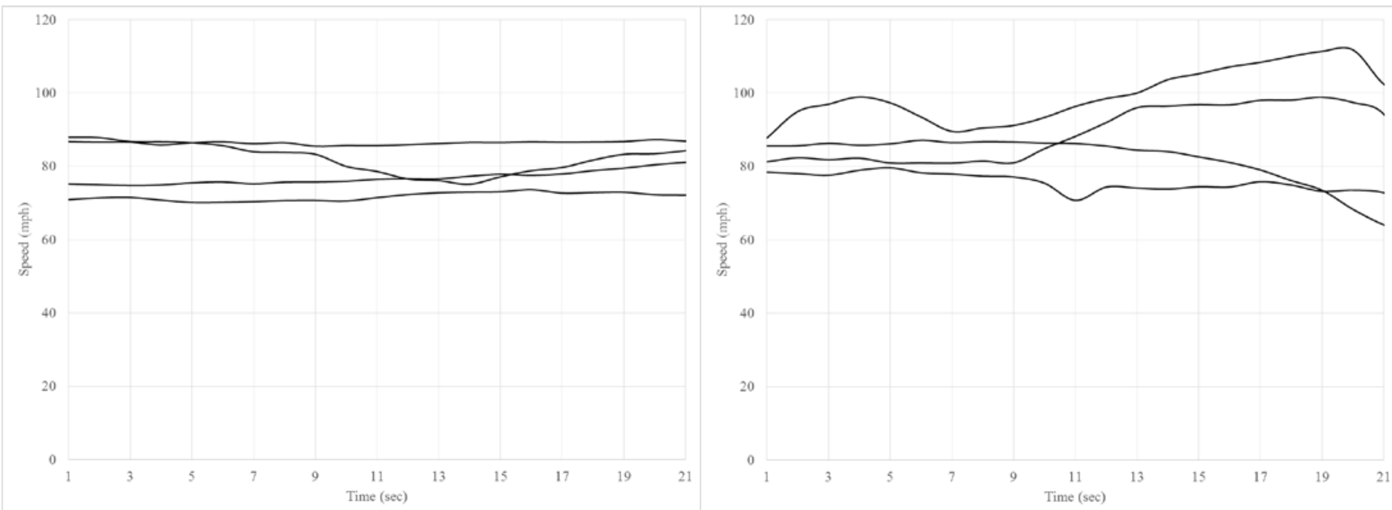
	Unknown	66	Work Zone	Not work zone-related	5599
Event Type	Crash/Near-Crash	656		Occurred in work zone	255
	Baseline	5367		Other work zone-related	169
TOTAL		6023	TOTAL		6023

Beyond the event-specific information provided through InSight, further data were obtained from the InDepth database. The InDepth data are of a time-series nature, providing details of the geographic location, speed, and acceleration of the study vehicles during each event. Among the 6,023 candidates, time-series data were obtained for 5,687 events. Data were unavailable for the remaining 336 events, which were primarily comprised of crashes where the associated GPS data could have potentially allowed for the identification of specific drivers and crash locations.

The InDepth data were comprised of a series of comma-separated values (CSV) files (one file for each event). Each file includes GPS location information at 1.0-s intervals, as well as speed and acceleration data at 0.1-s intervals. In either case, data were provided for the 20 seconds preceding each crash or near-crash, as well as for the 10 seconds immediately following each crash or near-crash. Similar data are provided for 20-second snapshots from the baseline driving events.

Preliminary analyses showed that one-second intervals were generally sufficient for speed and location data. Consequently, the data were aggregated and complete speed, acceleration, and latitude/longitude information was determined at one-second intervals. This resulted in a dataset with 90,961 records (reduced from more than 1 million records for 0.1-s intervals). The data from the InDepth database were combined with those from the

InSight database using the event ID field. As the data from InSight were of a general nature (i.e., the same information applied to each one-second interval), this information was copied to all intervals from the same events. Sample speed profiles for two drivers are provided inFigure 7 .



Driver 1 – Baseline Event Driver 2 – Near Crash Events

Figure 7. Speed profiles for baseline and near-crash events

The first driver was involved in four baseline events while the second driver was involved in four near-crash events. All events occurred on freeways with 70-mph posted speed limits and under low traffic volumes (level-of-service A or B as per the InSight database). Visual examination of these figures demonstrate significantly more variability in the speed profiles for the second driver, who was involved in the near-crash events. This driver is also shown to travel at excessively high speeds more frequently than the other driver.

Once the NDS datasets were assembled, geographic information system (GIS) software was used to plot the point data from the NDS databases on base maps for each of the study locations. There were a limited number of events that fell outside the boundaries of the six states (Florida, Indiana, New York, North Carolina, Pennsylvania, and Washington) where the NDS was conducted. These records were removed from the dataset since no roadway data were available from the RID.

The available geospatial data from the NDS (based on X and Y coordinates) were in point format and were conflated (i.e., linked) to the linear referencing system network upon which the RID is based. Once the event data were conflated to the appropriate shapefile for each state, the relevant roadway geometric information was assigned to each point datum. A dynamic segmentation process was utilized, where relevant attributes were queried from each shapefile based route ID and mile point. The dynamic segmentation process is briefly describes in the following steps:

1. The attribute table of the shapefile of interest was queried for those route identifiers in the event table.
2. The selected records were then exported as a new dBase table in ArcGIS.
3. To conflate the events to the shapefile of interest, the "Overlay Route Events" from linear referencing tools menu in ArcToolbox was used. Figure 8-Figure 10 shows the steps that need to be followed to extract the required information.

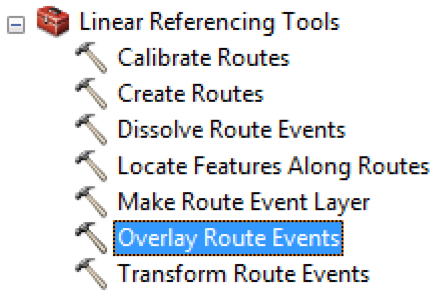


Figure 8. GIS tool to overlay the shapefiles

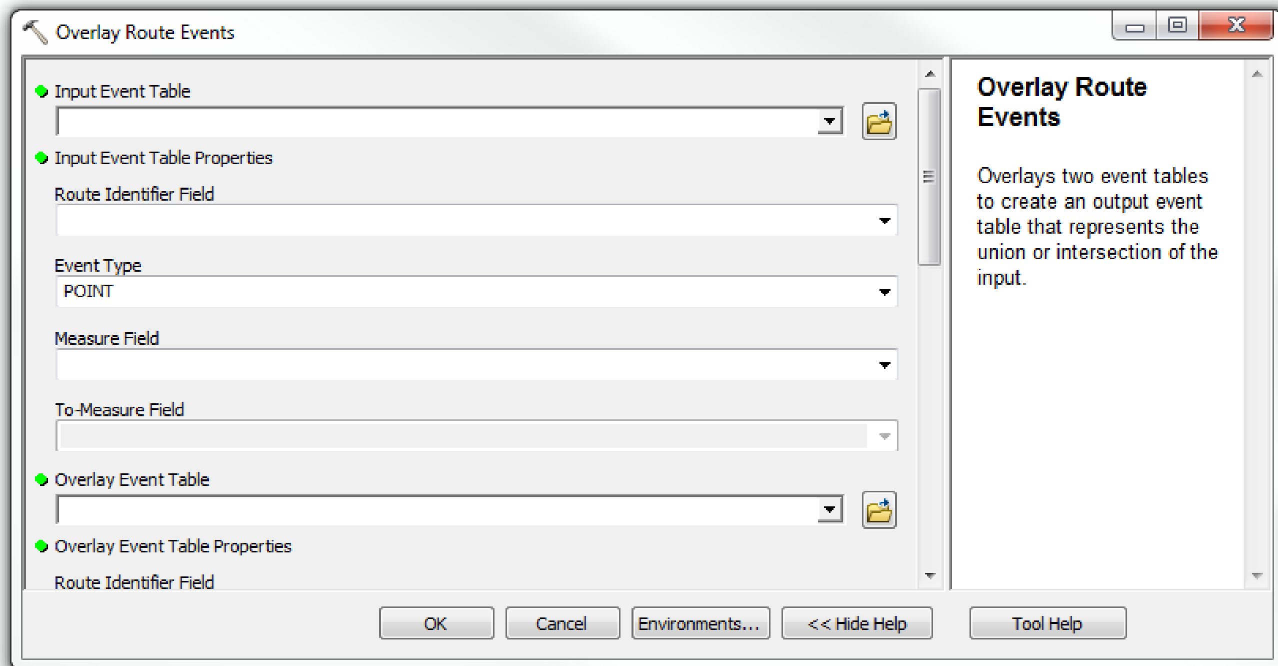


Figure 9. Steps to overlay route events

4. The event dataset should be selected as the input event table, and the measure field is “From Measure” (since the event type is “point”, “To-Measure” field is disabled).

5. The dBase of the shapefile from which the information needed to be extracted should be selected as the overlay event table.

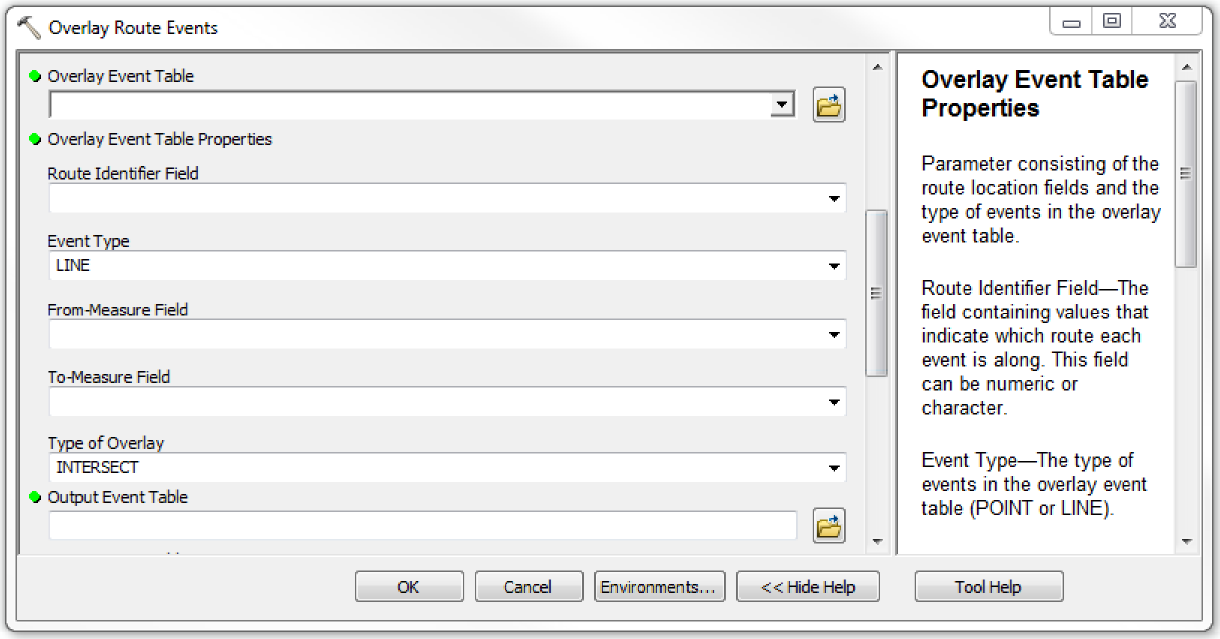


Figure 10. Steps to overlay route events – Continued

6. Unlike the input table which is in point form, the overlay tables of interest are all of a nature of lines. Hence, the event type must be changed to line to be able to define from and to measures.

7. Ultimately, the output should be saved and exported as a comma separated values (CSV) file.

This dynamic segmentation process was used to extract all segmented data including alignment, annual average daily traffic (AADT), barrier, lighting, grade, rumble strip, lane designation, shoulder, and median information. The information for each event point was extracted from the proper record which had the same Route ID, a "From Measure" smaller than the event's mile point, and an "End Measure" greater than the event's mile point. Blank fields were displayed if no record matched this condition.

In contrast to the other roadway geometric data from the RID, the speed limit information (and all other sign data) were in point format. In order to derive the information as to speed limit on each segment, a “signs” shapefile developed as a part of the RID was queried to identify those signs that included statutory speed limit information. The output from this query included location information (route ID and mile point), as well as the associated sign message (i.e., the posted speed limit). Speed limit was assumed consistent between consecutive signs, meaning that the begin mile-point for each sign was the end mile-point for the previous sign. Table 7 provides summary statistics for the data that were extracted from the RID for the purposes of this study. With the exception of degree of curvature and percent grade, the other variables are binary indicator variables based upon the range of values for the specific characteristics of interest.

Table 7. Summary statistics for data extract from Roadway Information Database

Variable	Minimum	Maximum	Mean	Std. Dev.
Lane width ≥12 ft	0	1	0.283	0.450
Lane width ≥11 ft, < 12 ft	0	1	0.478	0.500
Lane width <11 ft	0	1	0.239	0.427
Percent grade (upgrade)	0	5.7	0.591	0.959
Percent grade (downgrade)	0	5.9	0.595	0.995
Tangent segment	0	1	0.667	0.471
Curve to the left	0	1	0.170	0.376
Curve to the right	0	1	0.158	0.365
Degree of curve	0	5.9	0.473	0.854
Lighting present	0	1	0.399	0.490
55-mph speed limit	0	1	0.148	0.355
60-mph speed limit	0	1	0.375	0.484
65-mph speed limit	0	1	0.262	0.440
70-mph speed limit	0	1	0.215	0.411

While the dynamic segmentation process described previously provides a reasonably accurate means to extract the data, several issues were identified as a part of this process that needed to be addressed. The primary issue identified after linking the RID and NDS was a difficulty in identifying those events that actually occurred on a freeway segment. As noted previously, candidate events were first identified using the locality field from the InSight database. Events were retained where locality was equal to “Interstate/Bypass/Divided Highway with no traffic signals”. As the name of this field implies, these events may also include divided, non-limited access facilities. As there was not a specific field in the NDS or RID that directly indicates freeway segments, additional criteria were considered to screen the database. Ultimately, after assessing several candidates, the following criteria were found to be most effective in distinguishing between freeway and non-freeway segments:

- Two or more through lanes in the event direction;
- Presence of a median in the event direction; and
- No intersections along the segment where the event occurred or up to 5 miles upstream.

The first two criteria (number of lanes and median presence) restricted the dataset to freeways, expressways, and divided multilane highways. To eliminate the non-freeway segments, the boundaries of each event segment were first extended by five miles upstream of the first event data point. Once these new segments were created, the intersection shape files from the RID were overlaid on these extended segment data. Subsequently, any such extended segment that included an at-grade intersection was removed from the dataset.

One complication that arose as a part of this process was that the number of lanes and median presence attributes sometimes changed over the course of several extended segments. Hence, summary data were examined for all instances where these attributes changed. Segments were eliminated if these attributes varied over the extended event segment. After applying these QA/QC procedures, the final time series dataset included information for 2,963 unique events that covered 55,667 seconds (i.e., time series events). A manual review was subsequently conducted of each route ID using Google Earth in order to verify whether the segment was actually a freeway. Among the candidate events, 94.7 percent were verified to have occurred on freeways. Among the total sample, 1.8 percent of the events occurred on expressways and 3.4 percent occurred on other high-speed divided roadways that were neither freeways nor expressways. The subsequent analyses were conducted on those events that were verified to have occurred on freeways. After removing cases with missing data, the final sample included 1,969 freeway events.

CHAPTER 4: METHODOLGY

Collectively, available empirical data and information from drivers suggest that the posted speed limit is just one of several factors that play an important role in driver speed selection, as well as the related crash risk. This research leverages the data from the NDS and RID to provide a framework for better understanding the relationships between speed, crash risk, and other factors. For the purposes of this proof-of-concept, data are collected at two levels of detail. First, information was obtained as to the general characteristics associated with each event (crash, near-crash, or baseline) from the NDS InSight database. Subsequently, more detailed information are obtained from the NDS InDepth database (e.g., speed, acceleration, and GPS location information), as well as the RID (e.g., roadway geometry, traffic control, speed limit, etc.). These data were utilized to assess two primary questions of interest:

- How does driver speed selection vary among freeways with different posted speed limits? Speed data are available at 0.1-s intervals from the NDS, allowing for an investigation of differences in driver speed selection as a function of the posted speed limit while accounting for the effects of roadway geometry, traffic characteristics, and other factors associated with each driving event.

- How do rates of crashes/near-crashes vary among freeways with different speed limits? Prior research has demonstrated substantive differences in fatal crash rates with respect to maximum freeway speed limits. However, due to differences across states in reporting practices, research into the effects of speed limits on total crashes or surrogate events (e.g., near-crashes) has been more limited. As a part of this proof-of-concept, one of the primary initiatives was to compare the rate of crash/near-crash events as they relate to posted speed limits, as well as driver speed selection.

In order to examine these questions, regression models were estimated to examine three primary metrics of interest:

1. the average speed of vehicles during the time preceding each crash, near-crash, and baseline event;
2. the variation in travel speeds for vehicles leading up to each event as quantified by the standard deviation of speeds over this period; and
3. the rate of crash or near-crash involvement among study participants included in the sample of events.

Details of the statistical methods used to analyze these data are briefly described in the following section of the report.

4.1 Statistical Methods for Driver Speed Selection

The focus of the speed data analysis was to determine the effects of speed limit policies on the mean and standard deviation of travel speeds. To analyze these speed characteristics, separate multivariate linear regression models were estimated for both measures. These models were estimated using the NDS event and time series data, as well as the RID information.

For the purposes of this study, ordinary least squares (OLS) regression models were estimated using the NDS event and time series data, as well as the RID information. The OLS equations for each of these performances measure take the following form:

$$ms_i = \beta_i X + \varepsilon_i \quad (4)$$

$$sd_i = \beta_i X + \varepsilon_i \quad (5)$$

where: ms_i is the spot mean speed (in mi/h) during event i; sd_i is measured standard deviation of speeds during event i (in mi/h); X is a vector of speed limit, traffic, and roadway characteristics; β's are vectors of estimable parameters; and ε's are disturbance terms capturing unobserved characteristics

One concern that arises within the context of this study is the anticipated correlation in speed selection behavior among the same individuals and particularly within a single driving event. For example, Figure 11 demonstrates four speed profiles for two different drivers from the NDS. Each speed profile corresponds to an event that occurred on a freeway with a 70-mph posted speed limit under low traffic volumes (level-of-service A or B as per InSight database). Visual examination of these figures shows that driver 2 generally tends to drive at higher speeds (mean speed of 78.5 mph vs. 72.0 mph for driver 1). Driver 2 also tends to exhibit greater variability in travel speeds (standard deviation of 3.5 mph vs. 1.4 mph for driver 1). From an analytical standpoint, it is important to account for the fact that specific drivers may tend to driver faster (or slower) than others (i.e., their general travel speeds are correlated across events). Failing to account for such correlation would underestimate the variability in travel speeds and potentially lead to biased estimates for the impacts of specific factors, such as the speed limit or geometric characteristics.

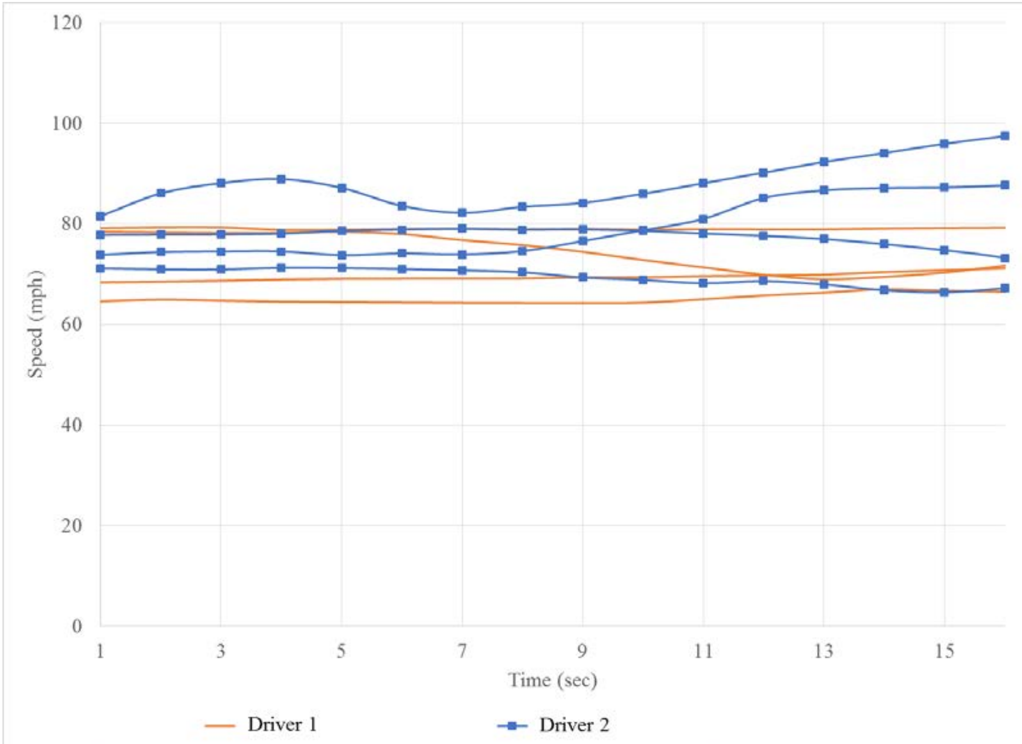


Figure 11. Speed profiles for baseline and near-crash events at 70-mph speed limit

For the purposes of these speed-related models, two additional parameters are added to each model:

- A participant-specific intercept term is introduced, to account for the fact that specific drivers may tend to drive faster (or slower) than others due to factors that are not captured by the information from the NDS or RID. These may include differences in driving styles, risk perception, or other factors that affect speed selection. This participant-specific term retains the same coefficient for each driver in every event (assuming the driver has multiple events in the database) and, thus, is able to capture general differences in speed selection behavior.

- An event-specific intercept term is also introduced, which is allowed to vary across events, but maintain the same value for each individual driving event. This parameter accounts for unobserved factors that are unique to each event. Continuing from the preceding discussion, individual drivers are likely to travel faster (or slower) during individual trips due to similarly unobserved factors.

These terms, each of which are assumed to be normally distributed with mean of zero and variance of σ^2, result in the following equations:

$$ms_i = \beta_i X + \varepsilon_i + \delta_j + \gamma_{ij} \quad (6)$$

$$sd_i = \beta_i X + \varepsilon_i + \delta_j + \gamma_{ij} \quad (7)$$

In essence, these terms capture the effects of important, unobserved variables that would otherwise lead to biased or inefficient parameter estimates. For example, some drivers may tend to drive faster (or slower) or their speeds may tend to vary more (or less) than other drivers due to factors that are not captured by the information from the NDS or RID. Consequently, δ_j is a parameter that retains the same coefficient for each driver in every event (assuming the driver has multiple events in the database) and, thus, is able to capture general differences in speed selection behavior. Likewise, γ_{ij} is a parameter that accounts for unobserved factors that are unique to each specific driving event. Adding these participant- and event-specific terms results in what is commonly referred to as a random effects model. While these effects are specific to each event or study participant, they are a random sample from the broader driving population (hence the random effects nomenclature).

4.2 Statistical Methods for Crash/Near-Crash Involvement

In addition to analyzing driver speed selection, a companion objective in this study is to assess those factors affecting crash risk. To this end, logistic regression models were estimated to examine trends in crash/near-crash involvement among study participants. Logistic regression presents an appropriate modeling framework since the dependent variable is dichotomous in nature (involvement versus non-involvement in a crash or near-crash). Under the logistic regression framework, the odds of a participant being involved in a crash or near-crash is related to a linear function of predictor variables as shown in Equation 8:

$$log\left(\frac{p_i}{1-p_i}\right) = \beta_0 + \beta_1 x_{1i} + \beta_2 x_{2i} + \cdots + \beta_k x_{ki} \text{ ,} \quad (8)$$

where pi is the probability of participant i being involved in a crash or near-crash event, the βi terms represent a vector of estimable parameters, the xi terms indicate a vector of explanatory variables associated with the event outcome (e.g., driver, vehicle, roadway, and temporal characteristics), and εi is an error term which follows the logistic distribution.

The logistic regression model assumes that the error terms (ε_i) are independently and identically distributed (IID), which is potentially problematic as there is expected to be potential correlation in the rate of crash/near-crash events among study participants, resulting in a violation of the IID assumption. This assumption can be relaxed by adding a participant-specific parameter vector that varies randomly across drivers, similar to the approach that was utilized in the speed models discussed previously. This vector allows the constant term to vary across participants, permitting the model to capture heterogeneity that is due to other unobserved factors. Under this setting, the probability of crash or near-crash involvement is then:

$$p_i = \int_x \frac{\text{EXP}(\beta x_i + \varepsilon_i)}{1 + \text{EXP}(\beta x_i + \varepsilon_i)} f(\beta|\varphi) d\beta \ , \tag{9}$$

where (β|φ) is the density function of β with φ referring to a vector of parameters of the density function (mean and variance), and all other terms as previously defined. This model structure is commonly referred to as a random effects (or random intercept) logistic regression model.

Similar to the linear regression models that are estimated for driver speed selection, the logistic regression model assumes that crash or near-crash involvement is independent (i.e., not correlated) across events. This is potentially problematic as there is the potential for correlation in the rate of crash/near-crash events among study participants. That is, some individuals may inherently be at higher or lower risk for crash-involvement due to unobserved factors such as driving skill, perception-reaction time, etc. To accommodate this concern, a participant-specific intercept term is added to the logistic regression model. This constant term is allowed to vary across participants to capture the effects of such factors (this is also a random effects model).

CHAPTER 5: RESULTS & DISCUSSION

After the data were assembled, three general questions of interest were investigated:

- How did speed limit and other roadway, driver, vehicle, and environmental factors affect the mean vehicle speed during each of the events?
- How did speed limit and other factors affect the standard deviation of speeds for drivers/vehicles during each event?
- How did speed limit, mean speed, and standard deviation in speeds affect the risk of crash/near-crash events while controlling for other pertinent factors?

First, an explanatory analysis of the data was conducted to ascertain general trends in driver speed selection. Table 8 provides data related to the mean speeds among the 1,969 unique events in the final dataset. Speed data were examined for only the first 15 seconds of each event. Subsequent data were excluded because of concerns as to downward bias in speeds for the crash and near-crash events (as vehicles may have slowed down immediately before these safety-critical events).

Table 8. Summary statistics for mean speed by posted speed limit

Speed Limit	Average of Mean Speeds (All Events)	Std. Dev. of Mean Speeds (All Events)	Average of Mean Speeds (LOS A Only)	Std. Dev. of Mean Speeds (LOS A Only)
55	58.38	13.56	63.28	6.93
60	56.40	15.04	63.62	7.25
65	67.67	8.95	69.11	5.66
70	69.49	12.17	71.48	8.41

The information in Table 8 provides details of the average value and the standard deviation of the mean speeds across the entire sample of events. To clarify, the mean speed over the first 15 seconds of each event was calculated. This table presents the averages and standard deviations of these mean speeds as it relates to the four posted speed limits that were considered. Separate summaries are provided for the full sample, as well as a restricted sample that includes only those events that occurred under level-of-service A according to the traffic density variable in the NDS data.

When examining these aggregate-level data, a few points stand out. First, the mean speeds tended to be relatively consistent among those roadways posted at 55 and 60 mph, as well as among those roads posted at 65 or 70 mph. These mean speeds are also not found to be monotonically increasing (e.g., the mean speed at 60 mph is greater than at 55 mph). There are several reasons for this result. First, these data summaries do not consider the effects of the various other factors that impact speed selection behavior and were included in the subsequent multivariate regression models that were estimated. Secondly, the samples are unbalanced with respect to the six site locations from the NDS. As prior research has shown significant differences across jurisdictions (Davis et al., 2015), this is likely to explain some of this difference. It is also interesting to note that the standard deviation among these speeds is relatively large compared to what is generally found at specific roadway locations. This is due to the fact that these summary statistics are calculated over all events and all roadway locations. Consequently, there is significantly higher variability because the speeds are not measured on the same road segments. However, this variance is reduced considerably when considering only LOS A conditions.

Table 9 provides similar summary statistics for the standard deviations in travel speeds over the duration of the 1,969 events. For each event, the standard deviation was calculated from the first 15 seconds of available speed data. Separate summaries are provided for both the total sample of events, as well as for free-flow (i.e., LOS A) conditions. In contrast to the overall variability in speeds presented in Table 8, the standard deviations for individual trips is much smaller. This is reflective of the fact that driver speeds tend to be quite consistent when considering 15-s snapshots. In general, speeds are shown to be more variable under lower speed limits, which is consistent with the broader empirical research literature in this area. The variability in speeds tends to be similar among freeways posted at 55 mph and 60 mph, as well as among those posted at 65 or 70 mph. As noted previously, it is important to recognize that some of this variability is due to the presence of other factors that are not accounted for in presentation of these raw data.

Table 9. Standard deviation of speeds over events

Speed Limit	Average Of Std. Dev. Data (All Events)	Average of Std. Dev. Data (LOS A Only)
55	1.90	1.17
60	1.92	1.22
65	1.20	0.97
70	1.31	1.07

To gain a better understanding as to driver speed selection, random effects linear regression models were estimated for both mean speed and standard deviation in speeds as described previously. Table 10 provides results of the random effects models for mean travel speed. Separate models are provided for the total sample, as well as for the subset of events that occurred under level-of-service A. This subset of data were examined exclusively to control for other unobserved factors that might influence the speed selection behavior by drivers under congestion. The level-of-service at the time when the event took place was provided through the InSight Data.

Starting with the entire sample, the results show that speeds were primarily affected by the level of traffic congestion that was present at the time of the event. Speeds were relatively stable across levels-of-service (LOS) A and B, within a range of 2.5 mph on average. Speeds began to drop significantly under LOS C and, particularly, in LOS D and E. Several driver and roadway characteristics were also found to affect speed selection behavior. Speeds were marginally lower (1.6 mph) on freeways posted at 65 mph versus 70 mph. In comparison, speeds were approximately 7.2 mph lower on facilities posted at 55 mph or 60 mph. Speeds were higher across events that occurred on a segment without a junction (i.e. an intersection point which could be a ramp or an interchange entrance or exit in case of freeways) along them. Speeds were also found to decrease on horizontal curves and along upgrades while speeds increased on downgrades (at similar rates to the speed reductions on upgrades). Speeds were higher among male drivers and particularly among those age 16-24. Drivers who aged between 25 and 59 also tended to drive at higher speed as compared to more senior drivers who age over 60. Adverse weather condition was found to affect the mean speed significantly, as well. Speeds were approximately 4 mph lower in presence of snow or sleet, while the reduction drops to roughly 2 mph in rainy weather. Work zones were also found to be associated with lower speeds.

The results are generally consistent for those events that occurred under free-flow conditions (i.e., LOS A), although a few notable differences were found. When considering only those events occurring during LOS A, significant differences are observed across all four speed limit categories. The difference between speeds on freeways posted at 55-mph versus 60-mph is more evident under free flow condition. While the coefficient for segments posted at 55-mph under LOS A is similar to that of the total sample, speeds are marginally higher on freeways posted at 60-mph under LOS A as compared to the estimated effect for the total sample. The difference in speeds between male and female drivers was not found to be statistically significant under LOS A. Also, downgrades were not found to have a significant effect on the speed selection behavior as compared to the base condition (i.e. flat train).

Table 10. Random effects linear regression model for mean speed

Variable	Total Sample			Level-of-Service A Only		
	Coeff.	Std. Err.	t-stat	Coeff.	Std. Err.	t-stat
Intercept	16.75	0.89	18.78	68.81	0.54	127.45
LOS A (no lead vehicle)	52.31	0.75	69.37	-	-	-
LOS A (lead vehicle)	53.26	0.74	72.22	-	-	-
LOS B	50.75	0.73	69.25	-	-	-
LOS C	40.20	0.75	53.85	-	-	-
LOS D	19.41	0.76	25.39	-	-	-
LOS E	11.64	0.78	14.86	-	-	-
Non-junction	1.20	0.12	10.16	0.72	0.11	6.50
Age 16 to 24	2.34	0.57	4.13	3.13	0.62	5.06
Age 25 to 59	1.70	0.58	2.93	2.43	0.64	3.79
Upgrade	-0.50	0.06	-8.81	-0.32	0.05	-6.19
Downgrade	0.63	0.06	11.26	-	-	-
Rain	-2.14	0.18	-11.69	-2.30	0.22	-10.65
Sleet or snow	-4.02	0.95	-4.24	-8.52	0.78	-10.93
Female	-0.86	0.44	-1.98	-	-	-
Work zone	-1.24	0.22	-5.59	-2.38	0.20	-11.84
55-mph limit	-7.22	0.24	-29.58	-7.53	0.23	-32.94
60-mph limit	-7.18	0.21	-34.86	-5.98	0.18	-33.58
65-mph limit	-1.61	0.24	-6.78	-2.62	0.19	-13.85
Degree of curve	-0.33	0.05	-6.14	-0.10	0.05	-2.06

Table 11 presents similar results from the random effects linear regression model that was estimated to examine the standard deviations in travel speeds that occurred during study events. As expected, the variability in travel speeds was predominantly affected by congestion. The standard deviation was lowest under LOS A and highest under LOS E. Speeds were also highly variable on the approach to work zone environments and particularly within the work zone itself. As shown by prior research in this area, speeds also tended to become more consistent (i.e., decreased variability) as the speed limit increased. This is a possible reflection of the more rural nature of the higher speed facilities and/or a tendency of drivers to travel significantly above the lower posted speed limits.

Table 11. Random effects linear regression model for standard deviation in speed

Model Term	Coeff.	Std.Err.	t-stat
Intercept	2.41	0.55	4.35
Non-junction	-0.36	0.08	-4.45
LOS A (no lead vehicle)	-1.36	0.56	-2.42
LOS A (lead vehicle)	-1.19	0.56	-2.14
LOS D	1.19	0.58	2.04
LOS E	1.42	0.61	2.35
Work Zone	0.82	0.18	4.60
Work Zone approach	0.63	0.23	2.71
55-mph limit	0.40	0.12	3.43
60-mph limit	0.30	0.09	3.45

After determining the relationships between travel speeds and various event characteristics, random effects logistic regression models were estimated to assess factors affecting crash/near-crash risk. Table 12 presents results of two random effects logistic regression model for crash/near-crash risk.

Table 12. Random effects logistic regression model for crash/near-crash risk

Model Term	Coeff.	Std.Err.	t-statistic	Odds Ratio
Intercept	-2.54	0.42	-5.99	N/A
Non-junction	-0.29	0.17	-1.77	0.75
Vertical curve	0.42	0.21	2.03	1.52
Age 35 to 74	-0.87	0.20	-4.39	0.42
LOS A	-2.22	0.26	-8.46	0.11
LOS B	-1.17	0.22	-5.21	0.31
LOS D	0.62	0.32	1.97	1.86
Mean Speed	0.02	0.01	3.25	1.02
Speed Std. Dev.	0.35	0.04	8.09	1.42

For each of the variables in the final model, the parameter estimate, standard error, and t-statistic are included, along with the odds ratio. A positive coefficient indicates the variable is associated with a higher risk of a crash/near-crash while negative coefficients are indicative of conditions that are associated with lower crash/near-crash risks. The magnitude of these impacts can be discerned by examining the odds ratios, which represent the average change in the odds of a crash or near-crash occurring as compared to the baseline condition to which these factors are compared.

As expected, the odds of getting involved in a crash or near-crash significantly varied across different traffic conditions. The odds ratio of a crash or near-crash taking place under free flow condition is 0.11, while this jumps up to 1.86 under LOS D. This indicates that a crash or near-crash is 89 percent less likely to occur under free flow condition as compared to the base condition. On the other hand, the likelihood of getting involved in a crash or near-crash increases by 86 percent under LOS D. The odds of a crash or near-crash occurring on a freeway were approximately 52 percent higher at locations where vertical curvature is present. Also, more senior drivers who age 35-74 are 58 percent less likely to be involved in a crash or near-crash.

In contrast to the factors discussed previously, mean speed and the speed standard deviation are the only continuous variables in this model. The results show that the risk of a crash or near-crash increased with both the average speed and the standard deviation in speeds over the course of each event. The odds of a crash/near-crash increased by approximately 2 percent for every 1-mph increase in speed and by 42 percent for a 1-mph increase in standard deviation. However, it is noteworthy that these findings are true within the neighborhood of average of these variables and cannot be generalized to a broad range of these values.

These findings are particularly noteworthy given the difficulty that is normally associated with relating crash outcomes with speed profile data. Most of the extant research literature has relied on traffic detector data, which is often difficult to link directly to the time a crash occurred due to time lags in these systems. These results provide compelling evidence that is based on speed profiles immediately preceding crash and near-crash events.

CHAPTER 6: CONCLUSION

This study demonstrated a proof-of-concept for how naturalistic driving data could be leveraged to answer important questions of interest as to how drivers adapt their behavior in response to posted speed limits and roadway characteristics and, in turn, how these behaviors affect the risk of a crash or near-crash event. The following is a summary of the salient findings from this proof-of-concept study.

Drivers were found to adapt their speeds based upon changes in the roadway environment. Turning to the primary factor of interest, higher speed limits were found to result in higher travel speeds. However, the increases in travel speeds tended to be less pronounced at higher posted limits, which is consistent with recent research in this area (Davis et al. 2015). Drivers tended to reduce their travel speeds along horizontal or vertical curves, under adverse weather conditions, and particularly under heavy congestion. The variability in travel speeds was also found to be influenced by several factors, including the posted speed limit, as well as the presence of congestion or work zone activities.

These differences in average speed and standard deviation of speed were both found to affect crash risk. As either the average or standard deviation increased, so too did the probability of a crash or near-crash event. Specifically, the odds of a crash or near-crash was 2 percent greater for every 1-mph increase in speed and 42 percent greater for every 1-mph increase in standard deviation of speed. It is important to note this standard deviation in speeds is essentially reflective of the average acceleration rate during the 15-second interval preceding each crash. This suggests that drivers who maintain constant speeds tend to exhibit lower crash/near-crash risk. It is unclear how reflective of this driver-specific variability is of the broader driving population on these specific road segments preceding each crash. This represents one important opportunity area for subsequent research.

Differences in crash risk were also observed with respect to traffic congestion, geometric characteristics, and driver age. As traffic became more congested, the risk of crash/near-crash events also increased. Limited sample sizes prohibited the ability to conduct detailed assessment at or near capacity conditions (i.e., LOS E/F). Turning to geometric characteristics, crashes and near-crashes were more likely to occur on a freeway section where vertical curvature is present. Crash risk also tended to be higher among younger drivers, a finding that is consistent with the broader research literature.

Of equal importance to the findings related to driver behavior, the study also demonstrates several important methodological contributions. The random effects models presented herein were found to provide significantly improved fit as compared to simpler model formulation (i.e., naïve or pooled regression models). In each case, the random effects model provided better fit at 99-percent confidence level. This result demonstrates that there are inherent differences in speed selection among drivers and also that some drivers tend to be more or less likely to be crash-involved than others. As some of these differences are due to unobserved factors, it is important that statistical methods are employed that are able to accommodate the correlation among the same drivers or events.

The findings of this study are generally consistent with the extant literature, particularly with those that have been conducted recently. A 13.1 percent increase in the crash liability was reported by Maycock (1998) in response to 1 percent increase in the traffic speed. This study concluded that 1 mph increase in the mean speed, increase the odds of a crash or near-crash occurrence by 2 percent.

In addition, the findings of the study conducted by Kockelman (2006) demonstrated that the increase in the operating speed were less than half of the actual amount with which the speed limit had been raised. In comparison, 1.5 to 3.5 mph increase in the mean speed was observed in response to 5 mph increase in the posted speed limit. However, while Kockelman noted that the speed in its associated variability are more influenced by roadway geometry and cross sectional characteristics rather than the speed limit, findings presented herein show significant correlation between mean speed and its standard deviation with speed limit. Previous literature showed that drivers believe that the speed is significantly dictated by weather condition (Royal 2003). As such, rainy weather, as well as presence of sleet or snow were proved to significantly influence the mean speed in this study.

Although this proof of concept study provides valuable insight as to the relationship between speed limit, operating speed, crash risk, and roadway geometry, more detailed examination of driver behavioral data to investigate how crash potential and driver speed selection are related to posted speed limit and other driver, traffic, and roadway characteristics is warranted. Future research will continue the exploration of freeway facilities and, in addition, the scope will be expanded to consider how these relationships vary across a broader range of high-speed roadways, including two-lane and multilane highways. Ultimately, the results of these analyses will lead to the identification of potential countermeasures, policies, and programs with the greatest potential to reduce traffic crashes and injuries on high-speed roadways. The research will also leverage state-maintained safety and operational data from each of the six study states, which will allow for a better understanding of how driver speed selection affects crash risks. Investigating these research questions will provide critical insights to the transportation community. Of particular interest are several of the potential practical countermeasures and policy issues that may be impacted through the proposed research:

- Setting of maximum speed limits - The 85th percentile speed is generally used as a primary factor in establishing maximum speed limits. However, research has suggested that roadway characteristics play a greater role than posted limit in affecting travel speeds. The SHRP2 data provide an excellent opportunity to address this issue, as the maximum freeway speed limits in the six states included in the study range from 55 mph to 70 mph. In addition, the speed limits also vary by state on the non-limited access system. As several states have recently increased speed limits selectively, it is critical that a soundly designed, quantitative analysis is able to inform agencies of the expected impacts of such policy decisions.

- Use of speed advisory signs - Limited right-of-way, frequent access points, and challenging geometry often require the use of speed advisory signs along segments that cannot be designed to satisfy the prevailing design speed. Prior research has shown that such areas are prone to increased crash rates. It is important to better understand driver response when approaching these locations (i.e., horizontal curves), particularly with respect to the location of advance warning signs.

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