Investigation of drivers speed selection behavior: A naturalistic driving approach

by

Raha Hamzeie

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Program of Study Committee:
Peter T. Savolainen, Major Professor
Omar Smadi
Anuj Sharma
Jennifer S. Shane
Farzad Sabzikar

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

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NOMENCLATURE

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway Officials
AIC	Akaike Information Criterion
BIC	Bayesian Information Criterion
DAS	Data Acquisition System
FDA	Functional Data Analysis
FHWA	Federal Highway Administration
GPS	Global Positioning System
IRB	Institutional Review Board
LOS	Level of Service
LRS	Linear Referencing System
MUTCD	Manual on Uniform Traffic Control Devices
NDS	Naturalistic Driving Study
NMSL	National Maximum Speed Limit
NMVCCS	National Motor Vehicle Crash Causation Survey
PC	Point of Curve
PII	Personally Identifying Information
PT	Point of Tangent
RID	Roadway Information Database
SCE	Safety Critical Event
SDE	Secure Data Enclave

SHRP 2	Second Strategic Highway Research Program
STURAA	Surface Transportation and Uniform Relocation Assistance Act
USDOT	United States Department of Transportation
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

Research studies have generally shown that increased travel speeds result in higher crash frequencies and greater traffic fatalities. On the other hand, road users generally favor higher posted speed limits due to the resulting increases in travel speeds and reductions in travel time. Therefore, the influence of speed limits, traffic characteristics, and roadway geometry on driver speed selection, as well as the interrelationship between speed and crash risk, continue to be critical areas of interest for transportation agencies across the United States. To better understand the differences in driver behavior that may result from speed limit policies, this study involved a detailed assessment of the behavior of individual drivers using data collected as a part of the second Strategic Highway Research Program (SHRP2) Naturalistic Driving Study (NDS). The SHRP2 Safety Data from the NDS includes very detailed data on individual driver behavior, as well similarly detailed information regarding the roadway environment from the related Roadway Information Database (RID). By leveraging these data, drivers' speed selection behavior was investigated under three different settings including: 1) Contiguous road segments with constant posted speed limit zones; 2) Transition areas where the speed limit increased or decreased; and 3) Horizontal curves, with particularly emphasis on those with advisory speed signs in place. Speed profiles of study participants under each setting were examined through the estimation of a series of mixed-effect linear regression models. For the first two settings, separate models were estimated for freeways and two-lane highways, whereas the latter analysis of horizontal curves was solely focused on two-lane highways. The impact of drivers' behaviors, as well as roadway geometry and other environmental conditions on crash risk were examined.

Drivers were generally found to vary their speeds with respect to changes in the roadway geometry and weather condition. On segments with constant speed limits, drivers were shown to

increase their speed based on the posted speed limit and on segments with limited access points (e.g., ramps, intersections, driveways). Conversely, reduced speeds were observed under traffic congestion, adverse weather conditions, and along horizontal curves. Younger drivers tended to travel faster, and, in addition, significant differences were observed between individual drivers, with some tending to drive consistently faster or slower than other similar drivers. A subsequent crash risk analysis showed that safety critical events (i.e., crashes and near-crashes) were more likely under increased traffic congestion, along horizontal curves, near access points, and through work zones.

Speed profiles demonstrated similar patterns across speed limit transition areas. Drivers were found to begin adjusting their travel speeds upstream of the new regulatory speed sign. More pronounced changes were seen where limit reductions were introduced as compared to more limited changes when limits were increased. In all cases, the changes in actual driving speed were significantly less pronounced than the magnitude of the speed limit change. Weather and traffic flow conditions demonstrated significant impacts on travel speeds, like the first analysis, and speeds also varied by driver age. The third series of analyses revealed more complicated patterns in drivers' behavior and how they negotiate curves. Generally, drivers were found to reduce their travel speeds across horizontal curves, especially when advisory speed signs were present. Increased reductions were observed when negotiating with sharper curves. However, as with the analyses of regulatory limits, the speed reductions tended to be much lower than what was suggested by the advisory speed signs. Individual locations were examined by deploying functional data analysis (FDA) methods, which showed much of the speed reduction occurred upstream of the sign, between the advisory sign and the point of curve (PC). Where smaller reductions were advised, drivers tended to begin accelerating back to baseline speed within the curve. In contrast, they maintained the reduced speed throughout the curve where greater speed reductions were suggested.

CHAPTER 1. INTRODUCTION

1.1 Problem Statement

The first gasoline-powered automobile was introduced to the public by Karl Friedrich Benz in 1885. This vehicle, which was the first to use an internal combustion engine, was able to go as fast as 13 mph. Later, more advanced vehicles with greater power and higher attainable speeds were manufactured and revealed to the market. The continuing advances in science and technology resulted in significant increases in the highest speed a vehicle could reach, making authorities to consider setting a limit on how fast vehicles can travel on roads. United Kingdom parliament is credited for setting the first numeric speed limit through a series of Locomotive Acts in late 1800s. Since then speed limits have been vastly used across majority of countries. However, jurisdictions follow different regulations and guidelines to set the maximum speed limits. Also, drivers have been found to not follow an exact predetermined behavior when selecting their travel speeds which further complicates the process of setting maximum speed limits (Royal 2004, Hurwitz and Knodler Jr 2007, Leandro 2012).

Since the introduction of maximum statutory speed limits, there has been significant debate as to how speed limits are most appropriately determined for specific locations. On one hand, research studies have generally shown that increasing speed limits result in higher crash frequencies and greater traffic fatalities (Baum, Lund and Wells 1989, Solomon 1964, Cirillo 1967, Munden 1967, Davis et al. 2015). On the other hand, road users generally favor higher posted speed limits due to the resulting increases in travel speeds and associated reductions in travel time. Therefore, statutory speed limits continue to be an important concern across jurisdictions. Despite the safety concerns associated with higher speed limits, in the United

States, which is the general focus of this dissertation, seven states have recently increased their maximum limits to 80 mph or above. Figure 1 demonstrates the maximum daytime posted speed limit across the 50 states and the District of Columbia as of May 2018. Texas is the only state that has implemented an 85-mph limit across some of its select segments.

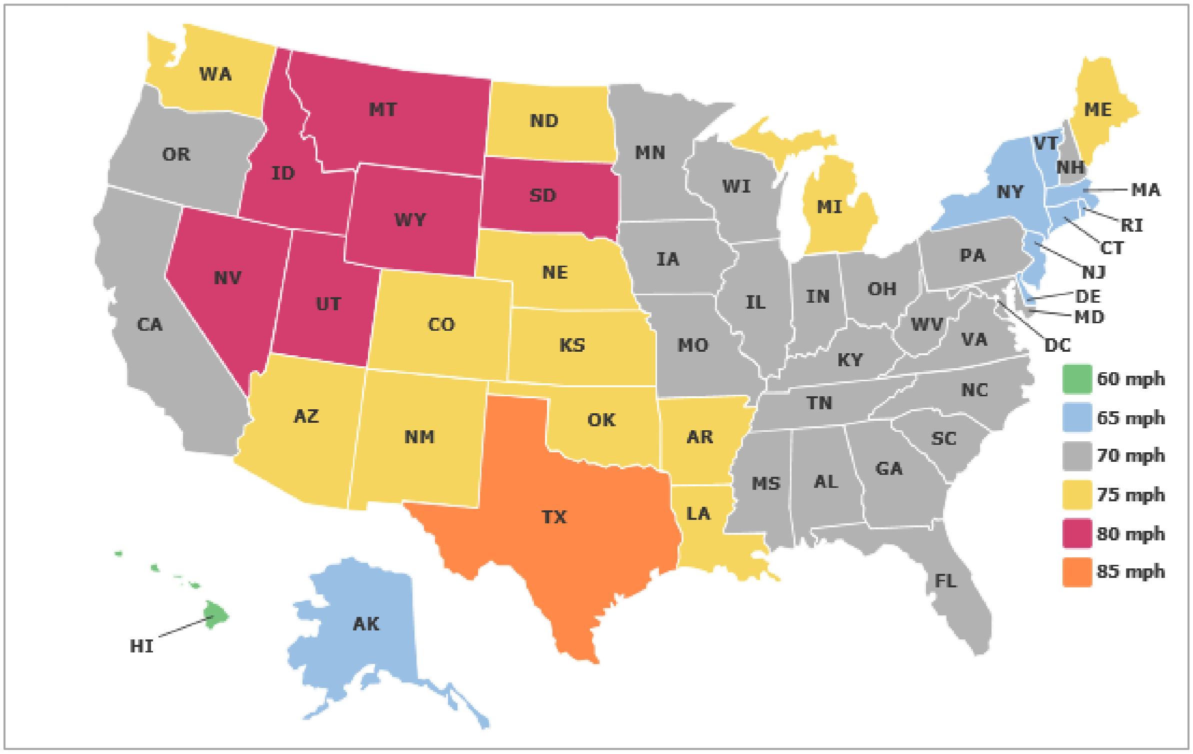

Figure 1. Maximum daytime posted speed limits on rural interstates

Maximum regulatory speed limits are mandated on roadways in consideration of roadway characteristics, traffic volumes, and environmental conditions to notify drivers of the highest speed one can travel under most conditions. In addition to regulatory speed limits, advisory speeds are introduced at certain locations to inform drivers of a lower recommended speed in conditions where the safe speed is below the posted speed limit. Such locations include sharp curves, highway ramps and roundabouts, as well as locations where the sight distance is limited. According to the Manual on Uniform Traffic Control Devices (MUTCD), the difference between the mandatory speed limit and the advisory speed typically ranges from 5 to 25 mph (FHWA 2010).

Table 1 outlines the criteria developed in the 2009 edition of the MUTCD for installing advisory speed signs. This includes conditions where advisory speed signs are required, recommended, or optional. However, it is imperative to note that advisory speeds do not mandate the driver to follow the recommended speed (i.e. citation cannot be issued by law enforcements). Several studies showed that advisory speeds are generally too low compared to what drivers perceive as comfortable (Bennett and Dunn 1994, Chowdhury, Warren and Bissel 1991).

Table 1. MUTCD 2009 Edition Criteria for the Selection of Horizontal Alignment Sign (FHWA 2010)

Type of Horizontal Alignment Sign	**Difference Between Speed Limit and Advisory Speed**				
	5 mph	10 mph	15 mph	20 mph	25 mph or more
Turn (W1-1), Curve (W1-2), Reverse Turn (W1-3), Reverse Curve (W1-4), Winding Road (W1-5), and Combination Horizontal Alignment / Intersection (W10-1) (See section 2C.07 to determine which sign to use)	Recommended	Required	Required	Required	Required
Advisory Speed Plaque (W13-1P)	Recommended	Required	Required	Required	Required
Chevrons (W1-8) and/or One Direction Large Arrow (W1-6)	Optional	Recommended	Required	Required	Required
Exit Speed (W13-2) and Ramp Speed (W13-3) on exit ramp	Optional	Optional	Recommended	Required	Required
Note: Required means that the sign and/or plaque shall be used, recommended means that the sign and/or plaque should be used, and optional means that the sign and/or plaque may be used.					

There are also inconsistencies in the installation of advisory speed signs between states, and even between locations within a single state (Ritchie 1972). Consequently, the efficacy of such signs is still under question and requires further investigation. Examination of drivers' behavior in response to such signs and how they adjust their speed considering the combination of regulatory and advisory speeds when negotiating horizontal curves can shed light on the actual effect of such signs and the levels of drivers' compliance.

Although speed limits and advisory speed signs provide drivers with clues as to what a reasonable travel speed on a roadway is, driver speed selection behavior has been shown to be more sophisticated and difficult to untangle as it is driven by a multitude of factors, speed limit being one of them (Hamzeie, Savolainen and Gates 2017). As a result, there continues to be a debate as to how drivers react to different posted speed limits, visual cues, and environmental conditions, and recent efforts have sought to quantify the relationship between posted speed limit, operating speed, and crash risk.

The intent of all these efforts to regulate travel speed is to lower crash frequencies and the associated level of injuries while allowing drivers to travel at a reasonably high speed. However, travel speed is not the sole contributing factor to safety critical (i.e. crash/near-crash) events. Traffic crashes may occur due to a combination of factors including poor roadway design, adverse environmental conditions, or inappropriate driver behavior. Researchers have long been trying to examine crashes to identify the contributing factors, suggest potential solutions to eliminate them, or mitigate the consequences (Aarts and Van Schagen 2006, Solomon 1964, Cirillo 1967, Munden 1967). However, these efforts were mostly limited to examination of crashes as outcomes of geometric attributes and traffic conditions and lacked thorough investigation of the impacts that driver behavior and their characteristics have on the resulting incident. However, according to the National Motor Vehicle Crash Causation Survey (NMVCCS), human error is the critical reason for 93% of crashes where critical reason is perceived as the last event in the crash causal chain (Administration 2008). Consequently, assessing driver behavior at time of safety critical events, as well as during normal driving events provide insights as to the factors that distinguish between such incidents. Identification of crash contributing factors including driver behavior and the associated characteristics, as well as the cross-sectional and geometric attributes will help to recommend appropriate countermeasures, improve existing design criteria, revise in-place legislations if necessary, and better target public education and outreach.

The investigation of these relationships is complicated due to significant heterogeneity in driver behavior and a limited understanding at a fundamental level of how vehicle operators react to changes in speed limits and roadway conditions. Much of the extant research literature in this area has relied on the examination of aggregate-level speed and crash data. Such an approach is unable to account for the more detailed, disaggregate-level characteristics impacting individual driver behavior. The second Strategic Highway Research Program (SHRP 2) Naturalistic Driving Study (NDS), which involved collection of detailed second-by-second data from more than 3,000 drivers, allows for an investigation of how drivers adapt their behavior in response to the speed limit and other changes in roadway geometry, traffic conditions, and environmental characteristics. These data also allow for close investigation of driver behavior preceding the occurrence of crash and near-crash events. The majority of research studies conducted to date have relied predominantly on police crash reports or post-crash surveys. Failing to properly account for precipitating events and driver behaviors that led to the incident may inhibit proper identification of contributing factors. This dissertation aims to address this gap and to improve our understanding of fundamental aspects of speed selection behavior using naturalistic driving data. The following section details the research objectives and questions that were examined as part of this dissertation.

1.2 Research Objectives

The objective of this dissertation was to investigate driver behavior with regard to speed selection in consideration of posted speed limits, traffic conditions, roadway geometry, and environmental attributes through analysis of data from the SHRP2 naturalistic driving study. Such relationships were examined separately on freeways and two-lane highways due to the inherent differences between these facilities. Drivers speed selection behavior was studied under three major scenarios and are elaborated on below.

The first set of analyses examined drivers' speed selection on freeways and two-lane highways where the speed limit remained constant over the duration of the driving event. Here, speed profiles were examined over a 20-second interval for baseline events (i.e. normal driving events), as well as the same duration preceding the occurrence of a safety critical event (i.e. crash or near-crash). In this case, mixed-effect linear regression models were estimated to identify the impacts of driver characteristics and different geometric and environmental factors, particularly posted speed limits, on the mean and standard deviation of travel speeds.

The second set of analyses focused on driver behavior across speed limit transition areas where the posted speed limits were either increased or decreased. Similarly, separate analyses were conducted for freeways and two-lane highways. Locations where posted speed limits change were selected, and speed profiles were examined upstream and downstream to discern how drivers adjust their travel speeds in response to changes in posted limits.

The third focus area of the speed analyses conducted as part of this study involved examination of speed profiles across horizontal curves. Particularly, this study focused on the role of advisory speed signs and aimed at discerning the impacts of such signs on drivers' choice of speed. These locations were sampled such that they cover a wide range of speed limit and advisory speed combinations.

The analysis method for the latter two scenarios were slightly different as the actual trends in the speed profiles were of interest. As a result, mixed effect linear regression models were estimated to investigate how drivers adjust their travel speeds in response to visual cues including regulatory and advisory speed signs. In addition, select groups of time-series data were analyzed using functional data analysis (FDA) techniques. First, the discrete time-series data were converted to continuous functions. Subsequently, the mean and confidence intervals were calculated to outline the average driver behavior when traversing such locations. Ultimately, the derivative information was calculated to ascertain how drivers alter their acceleration/deceleration with respect to the driving environment.

Ultimately, the last analysis assessed the likelihood of a crash or near-crash occurrence and how it varies in response to various roadway and environmental conditions, as well as driver behavior. For the purpose of this research question, logistic regression models were developed to identify those factors that distinguish between safety-critical (i.e. crash or near-crash) and baseline events.

1.3 Organization of Dissertation

This dissertation consists of seven chapters. The first chapter focused on defining the existing problems and the motivation to undertake this study. The second chapter summarizes the extant research literature on the proposed topic. Synopsis of select research studies are presented on various elements of this study including the factors impacting travel speed and crash risk. Chapter three extensively describes the data used in this study and the process followed to collect and integrate them. The fourth chapter examines the first research question and is focused on analyzing speed profiles under constant posted speed limits. Chapter five presents the analyses conducted at speed limit transition areas. Detailed explanation as to the datasets structure and the methodologies used is provided. Chapter six is dedicated to analysis of speed profiles on horizontal curve. This chapter includes information as to the additional data collected, as well as procedures followed to deploy the functional data analysis techniques. Chapter seven is focused on analyzing safety critical events and aims at identifying factors that impact the likelihood of occurrence of such incidents. Ultimately, chapter eight summarizes the findings of this study and presents the conclusions achieved. In addition, this chapter comments on limitations associated with this study and possible avenues for future work.

CHAPTER 2. LITERATURE REVIEW

Due to the broad scope of the dissertation presented herein, the existing research literature with regard to the outlined objectives are summarized into four different sections. The first section summarizes the results of previous research studies on the relationship between posted speed limit and vehicles' travel speed. Secondly, a summary of the past endeavors related to travel speeds on horizontal curves, particularly those focused on the role of advisory speed signs, and the associated level of drivers' compliance is presented. In the third section, the extant literature focused on the interrelationships between roadway geometry and travel speeds are summarized collectively. A multitude of research studies have found a variety of characteristics to be important determinants in drivers' speed selection behavior (Parker Jr and Parker 1997, Wilmot and Khanal 1999, Kockelman et al. 2006). In the final section, a synopsis of the existing research literature regarding to the safety component of this dissertation is presented. This includes investigation of the relationship between crash risk, geometric attributes, and driver behavior, as well as speed limit and travel speed.

2.1 Operating Speed and Speed Limit

Speed management has long been an extensive area of focus among researchers. Studies were generally aimed at evaluating the impacts of speed limits on mobility, safety, and operation. This section of this dissertation is focused on summarizing the extant literature on the impact of posted speed limits on vehicles' travel speed.

The endeavor to set a maximum speed limit in the United States dates back to 1974 following the passage of the Emergency Highway Energy Conservation Act when the 55-mph National Maximum Speed Limit (NMSL) was established. This limit was introduced to reduce the operating speed with an aim to lower fuel consumption; however, drivers' speed selection was found incompliant with posted limits particularly on interstates where the design speed was considerably greater than the introduced 55-mph limit. Given this issue, the Surface Transportation and Uniform Relocation Assistance Act (STURAA) was introduced later in 1987 which permitted a maximum limit of 65 mph on rural interstates in areas with populations below 50,000 people. Following implementing each of these speed limit policies, numerous studies examined the relationship between posted speed limits and the frequency and severity of traffic crashes. Ultimately, in 1995 the NMSL was repealed and states were given the entire authority to determine the posted speed limits in their jurisdictions. Since the dawn of maximum speed limit, numerous studies aimed at examining its impacts on travel speeds, synopses of some prominent ones are described below.

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 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. 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. Surprisingly, less than 1.5 mph change in the speed was reported after the implementation of these changes. This 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 Jr and Parker 1997).

A study conducted by Wilmot and Khanal, leveraged the results from numerous studies all over the world to ascertain the impact of speed limit on travel speeds. Similar to previous study, they concluded that drivers do not necessarily follow the speed limit to adjust their travel speed, but rather choose the speed they personally perceive as safe (Wilmot and Khanal 1999).

The United States Department of Transportation (USDOT) surveyed over 4,000 drivers in 2002 to collect information as to their general attitude regarding speed limit violations and other risky behaviors while driving. It was reported that most drivers believe they can travel approximately 7 to 8 mph over the posted limit before getting cited by law enforcements. Table 2 provides a summary of the respondents' general opinion regarding speeding. This study also found that drivers believe the most influential factors when selecting their speed are weather conditions, their perception of what speeds can be regarded as 'safe', the posted speed limit, traffic volume and level of congestion, and how experienced they feel they are on a particular road given previous travels (Ritchie 1972).

Table 2. Results of the USDOT National Survey on Speeding

Facility Type	Amount of speed limit violation perceived as comfortable before getting cited by law enforcement	What respondents believed they should be allowed before getting a ticket
Multilane interstate highways	7.8 mph	10 mph
Non-interstate multi-lane roads with limit of 40-55 mph	7.6 mph	8.9 mph
Two-lane roads with limit of 45 mph or above	6.7 mph	8.1 mph
City, town or neighborhood roads	7.0 mph	7.4 mph

Kockelman et al. (2006) studied the impact of raising speed limits on operating speeds, as well as the associated variability in speeds on high-speed roadways. The findings demonstrated that increases in the operating speed were, on average, less than half of the actual amount with which the speed limit had been raised. The authors 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 (Kockelman et al. 2006).

A survey of freeway users found that, on average, respondents drove 11 mph over the speed limit on interstates posted at 55 mph, 9 mph over the speed limit on interstates posted at 65 mph, and 8 mph over the speed limit on interstates posted at 70 mph (Mannering 2007). Also, male drivers were shown to drive at higher speeds as compared to females. Driver age was also found to be inversely correlated with speeding.

Utah is one of the states that experienced speed limit increases over the past years. In November 2010 and October 2013 speed limit was increased from 75 mph to 80 mph over approximately 300 miles of rural interstates in Utah. In a study conducted by Hu, travel speeds were investigated at 80 mph zones and nearby locations that experience spillover effects, as well as more distant segments that retained the 75 mph as control locations (Hu 2016). Log-linear regression models were estimated to evaluate the impact of increased speed limit on travel speeds. The author reported the mean travel speed to be 4.1% and 3.5% higher across 80 mph segments and nearby locations, respectively. In addition, the probability of exceeding 80, 85, or 90 mph was examined through estimating a series of logistic regression models. The results showed that increasing speed limits not only is associated with higher travel speeds, but also results in greater probability of exceeding the new speed limit.

In a similar study conducted by Johnson et al., speed data were collected and analyzed over 19 sites across rural interstate highways (Johnson and Murray 2010). These locations covered a variety of speed limits, uniform or differential, and were all flat and straight over two miles upstream of the study site. The analysis of operating speeds for those vehicles with no leading vehicle revealed that drivers tend to exceed the posted speed limit regardless of its magnitude. Aggregated speed data showed a compliance rate of only 7% on roadways posted at 55 mph, whereas this measure increased to 49% for locations posted at 75 mph.

2.2 Operating speed and Curve Advisory Speed

Horizontal curves and roundabouts, as well as exit and entrance ramps are integral components of highway design. While these roadway elements have long drawn significant amount of attention from researchers, crash statistics show that such locations still experience a disproportionate number of severe crashes. As a result, various methods and techniques have been employed to warn drivers as to potential hazards associated with driving across such locations. One of such methods is to install curve warning signs with or without advisory speeds. Given the focus of this dissertation, this section aims at summarizing the extant literature regarding installation methods, as well as effectiveness and drivers' perception of these signs.

Warning signs are generally installed to notify drivers with a change in alignment that may not be evident to the road user. Advisory speed signs often supplement warning signs to recommend drivers a lower speed with which the curve can be traversed comfortably. A comprehensive list of such signs is presented in the Manual on Uniform Traffic Control Devices (MUTCD) and is shown in Figure 2. According to the Federal Highway Administration (FHWA), curve advisory speeds can be determined using six different methods: (1) Direct Method (using field measurements of curve speeds), (2) Compass Method (through a single-pass survey technique using a digital compass), (3) Global Positioning System (GPS) Method (through a single-pass survey using a GPS and software to derive curve radius and deflection angle), (4) Design Method (using the curve radius and deflection angle from the as built plans), (5) Ball-Bank Indicator Method (record the ball-bank indicator through a collection of field driving tests), and (6) Accelerometer Method (record the maximum lateral gravitational force using an electronic accelerometer device and a GPS receiver through a collection of field driving tests). While this list included most of methods that are currently being used by agencies to determine the advisory speeds, some other methods have previously been used to designate the advisory speed most important of which is the American Association of State Highway Officials (AASHTO)'s method which simply derive the advisory speed using superelevation, side friction factor, and curve radius. Due to this variety in the methods and procedures to determine the advisory speeds, there is no consistency in determining advisory speed among different states, and even within a state at different locations. This has impacted the plausibility and effectiveness of such signs. Consequently, numerous studies tried to examine the influence of advisory speed signs on travel speed and how drivers adhere to such signs.

In one of the earlier studies, 50 drivers drove through 162 curves which can be grouped into three different categories: (1) curves with no warning signs, (2) curves with warning signs, and (3) curves where advisory speed sign was installed in conjunction with warning signs. The advisory speeds ranged between 15 to 50 mph, and the state speed limit was 60 mph at the time of study. Lateral acceleration, as well as travel speed data were collected. Interestingly, Ritchie reported that drivers travel at higher speeds on curves where a warning sign was installed as compared to those with no sign, and such behavior was more pronounced when an advisory speed sign was present in addition to curve warning sign. The participants were found to drive at higher speeds compared to what was recommended by the sign with an exception for advisory speeds of 45 and 50 mph where the subjects' speeds were roughly the same as the recommended speed which could be related to the posted speed limit of 60 mph at the time (Ritchie 1972).

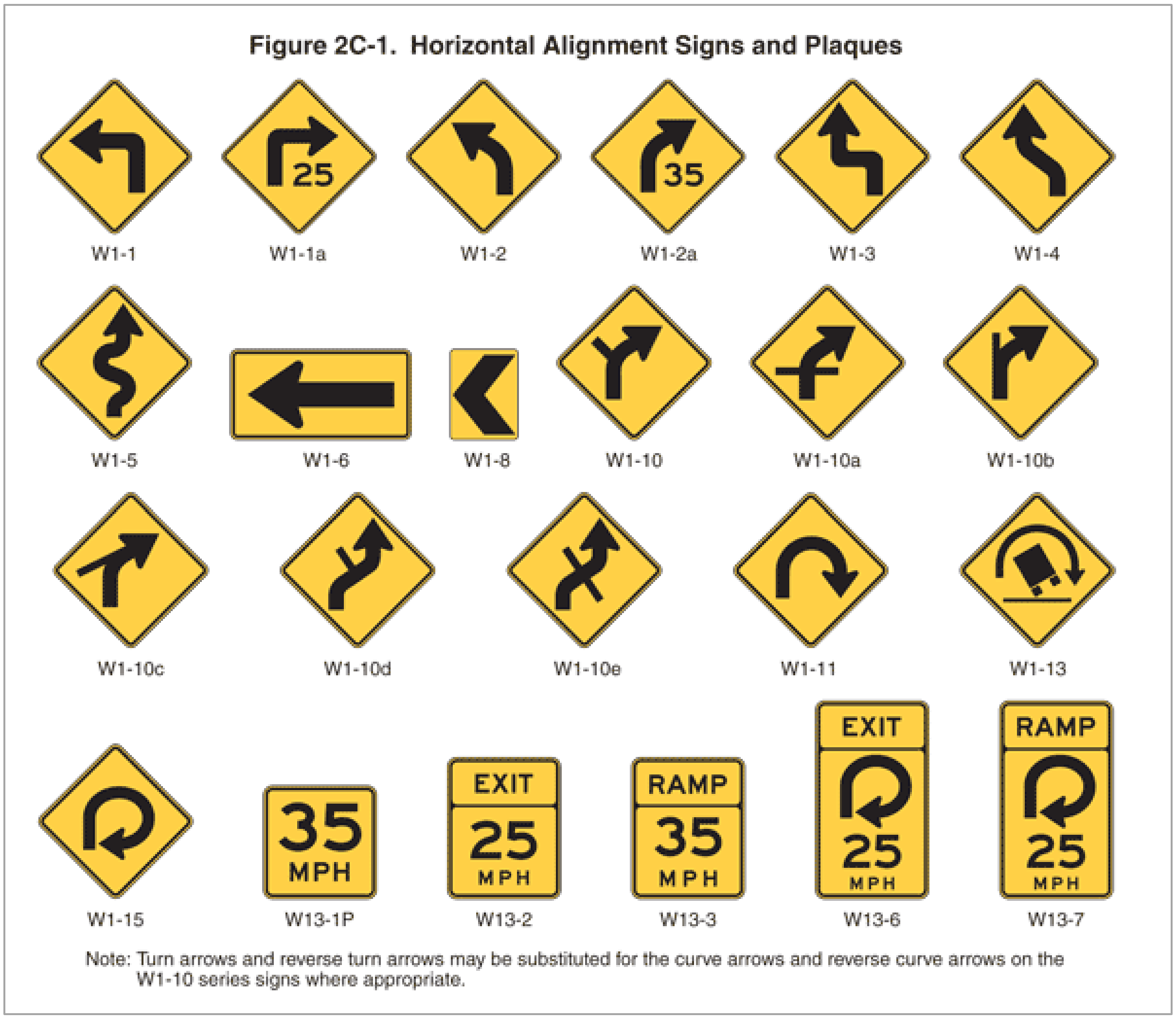

Figure 2. Horizontal Alignment Signs and Plaques Outlined in MUTCD (FHWA 2010)

In 1991, Chowdury collected speed data on 28 curves to investigate drivers' compliance with in-place advisory speeds. The results showed the level of compliance to vary between different advisory speeds, with zero percent complying with advisory speeds of 15-20 mph, and only 43 percent adhering to the 45-50 mph advisory speeds. They also reported that the actual observed drop in vehicles' speeds was less than half of what was suggested by the advisory speed sign, and is detailed in Table 3 (Chowdhury et al. 1991).

Table 3. Observed Average Speed Reduction Reported by Chowdury et al. 1991

State	Suggested Speed Drop (mph)	Actual Speed Drop (mph)
Virginia	15.8	4.6
Maryland	18.7	10.4
West Virginia	7.9	4.9
All Curves	15.1	6.1

In 1994, Bennet and Dunn evaluated drivers' speed selection behavior on 23 different curves in New Zeland and concluded that in only less than 39 percent of cases were the speeds below the design values. They further investigated those curves with advisory speeds in place and observed that the 85th percentile speeds were approximately 10-28 km/h (9 to 17 mph) greater than that of advisory speed sign (Bennett and Dunn 1994).

The effectiveness of advisory speeds was also examined using drivers' eye scanning and fixation duration. Zwahlen concluded that advisory speeds do not have significant impact on reducing travel speeds under dry weather conditions when compared to curve warning signs. However, it was noted that such signs may be of more beneficial impacts when considering heavy vehicles and motorcycles (Zwahlen 1987).

In general, previous research has shown lack of efficacy when installing advisory speed signs. Most critiques have attributed this relative ineffectiveness to the inconsistencies in methods utilized to determine the advisory speeds. The majority of research conducted to evaluate the impact of advisory speeds have shown travel speeds to be higher than what was recommended by the sign. This could be hazardous when drivers, on the other hand, assume consistencies between locations. For example, a driver who travels through a curve on a daily basis may realize that he could still travel comfortably and safely at speeds beyond the advisory speed. Following such perception, he may assume for same settings when travelling through an unfamiliar curve with similar sign where the design speed is lower than that of previous location. As such, further research as to the impact of advisory speed signs on travel speed and safety, as well as investigating how same individuals react to different conditions is warranted.

2.3 Operating Speed and Geometric Attributes

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, Neuman and Leisch 1983, Lamm and Choueiri 1987, Kanellaidis, Golias and Efstathiadis 1990).

In a report by the FHWA 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 (Fitzpatrick 2000).

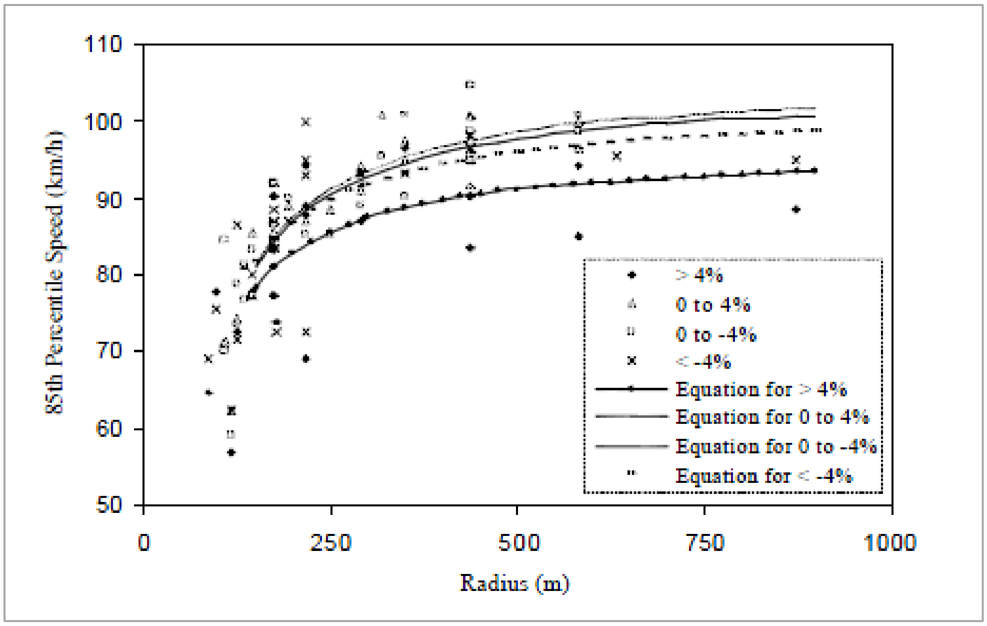

Figure 3. 85th percentile speed versus radius along horizontal curves on grades (Fitzpatrick 2000)

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 (Voigt 1996). The proposed equation is given as:

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

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. 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 (Schurr et al. 2002). The mean speed regression equation is given in Equation 2.

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

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:

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

where:

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

V_p = posted speed limit (km/h)

Consequently, the existing research literature suggests that the operating speed is not also affected by the posted speed limit, but also by the geometric characteristics when the geometric design deviates from base conditions (e.g. presence of horizontal curves).

Majority of studies that evaluated impacts of geometric attributes on travel speeds have been focused on curves since speeds on such segments are significantly influenced by a few known variables including curve radius and superelevation. Unlike these studies, in 2000, Polus et al. aimed at estimating travel speeds on tangent sections on two-lane rural highways. They grouped the study segments into four different gcategories based on the tangent length and the radii of the preceding and succeeding curves. They proposed numerical equations for speed estimation across each group by computing a geometric measure that was comprised of the tangent length, and the preceding and succeeding curves radii. However, they were unable to identify any association between travel speed and other geometric characteristics like presence of vertical curves (Polus, Fitzpatrick and Fambro 2000).

2.4 Operating Speed and Crash Risk

Traffic speeds play 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 2005). Traveling at higher speeds results in longer stopping distance, as well as less maneuverability, and requires more prompt reaction to a certain incident or change in the roadway (Aarts and Van Schagen 2006).

In a study conducted in 1964 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 in crashes (i.e. the number of vehicles involved in accidents per 100 million vehicle-miles travel) 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 1967, 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).

Baum et al. 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 (Baum et al. 1989). 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 4 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.

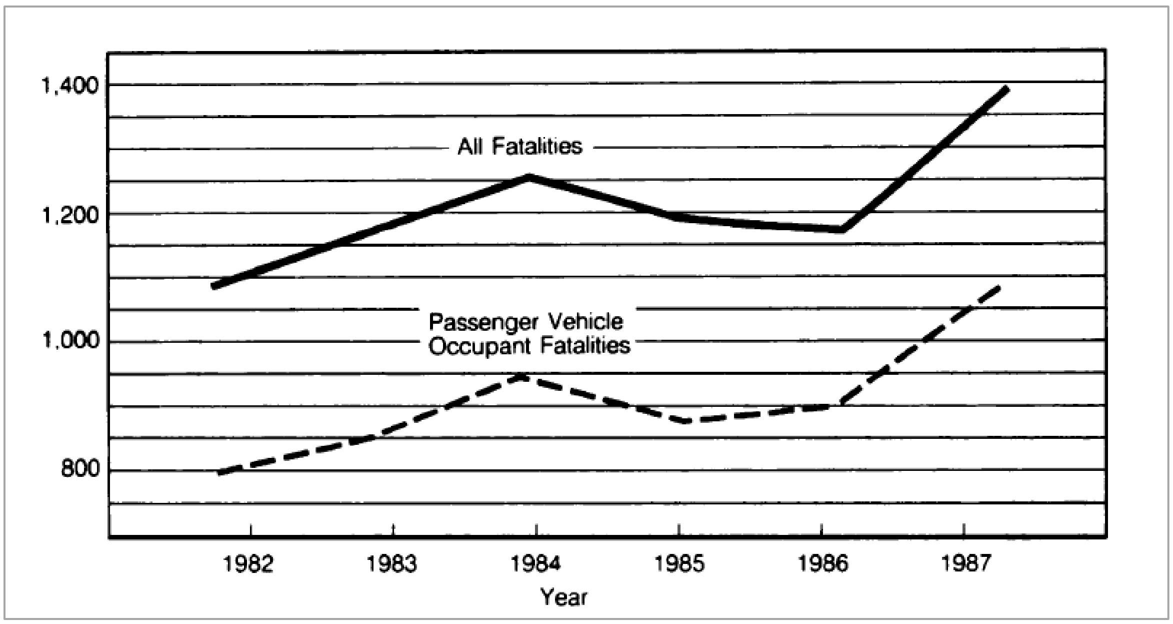

Figure 4. Fatalities on rural interstates during months of higher speed limits in 1987 and same months in 1982-1986 (Baum et al. 1989)

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. to compare the rate of casualties along these roadways (Gallaher et al. 1989). 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 resulting from this change (Wagenaar, Streff and Schultz 1990). To this end, the number and rates of crashes, as well as the 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.

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).

A similar study was designed to examine the effect of the introduction of 65-mph speed limit in state of Ohio (Pant, Adhami and Niehaus 1992). 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.

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, whereas a 15.6 percent reduction in major-injury crashes was observed on the same roadway segments. 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 5, 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 only three percent, while the overall increase on all types of roadways was 6 percent (Farmer, Retting and Lund 1999).

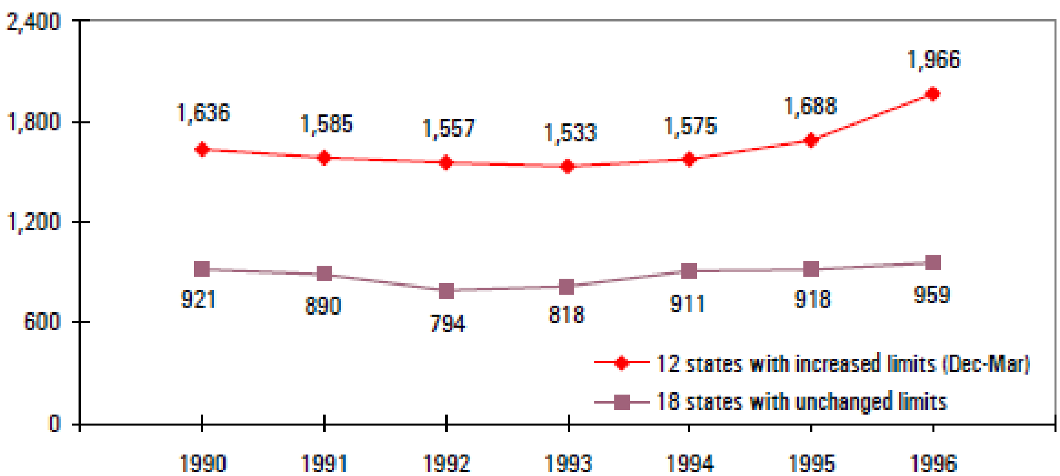

Figure 5. Number of occupant fatalities on interstates and freeways 1990-1996 (Farmer et al. 1999)

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. provided a thorough list of the studies that had been conducted to investigate the relation between crash risks and speed in general (Aarts and Van Schagen 2006). 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.

In a more recent study, Kockelman et al. investigated the safety impacts of raising speed limit from 55 to 65 mph and from 65 to 75 mph (Kockelman et al. 2006). Total and fatal crashes were shown to increase by 3 and 28 percent when raising speed limit from 55 to 65 mph. In addition, they estimated less pronounced increases by raising the posted limits to 75 mph. It was shown that a 10-mph increase from 65 mph to 75 mph would result in total and fatal crashes to go up by 0.6 and 13 percent, respectively.

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. developed models to investigate how crash rates change with regard to various roadway and traffic characteristics including speed (Aljanahi, Rhodes and Metcalfe 1999). 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.

Fildes et al. 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 (Fildes, Rumbold and Leening 1991). 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. In another similar study by Maycock et al., a 13.1 percent increase in crash liability was reported in response to a one percent increase in speed (Maycock, Brocklebank and Hall 1998).

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.

Also, the results of a study on a number of divided segments in Naples-Candela Italy, 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).

In summary, the existing research literature has been somewhat inconclusive as to the actual impact of posted speed limit on crash frequencies and severities. As such, speed limit policies and their consequences on traffic safety and mobility remained a controversial subject due to the difficulty associated with unraveling the impacts of numerous other confounding factors such as geometric characteristics, vehicle features, and driver behaviors. Naturalistic driving study data provide an opportunity to closely examine drivers' behavior, vehicle's operation, and the present geometry at the time of incidents. This allows to control for various confounding factors and identify the true impact of various factors on occurrence of SCEs and the associated probabilities to the extent possible.

CHAPTER 3. SHRP2 NATURALISTIC DRIVING DATA

The second Strategic Highway Research Program (SHRP2) was 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 the 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 utilized in this study.

3.1 Data Background

The naturalistic driving study (NDS) that has been conducted as part of the SHRP2 is the largest NDS ever undertaken. Approximately 3,400 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, between 2010 to 2013, more than 4,300 years of naturalistic driving data were monitored and recorded. The drivers and study sites were selected such that they well represent a sample of driving behavior population, weather conditions, demographic distribution, and a variety of road types. Despite all the cautions taken in the first place, there have been studies to compare the SHRP 2 NDS sample with the national data that will be furtherly discussed in the following sections.

The first initiative to recruit participants involved random cold calling which turned to have a very low response rate of approximately 2 percent. In addition, it was found that even a smaller proportion of the respondents owned vehicles eligible for the study. The other limitation associated with this approach was the fact that study design required oversampling among older and younger drivers. However, the random cold calling did not allow to target specific age groups. Once these issues were identified, a more efficient approach was followed in which the cold calling was limited only to those households who own qualified vehicles. Also, the study sites were given the authority to pursue their own means of recruiting including social media, local newspapers, web-based Craigslist, etc (Hankey, Perez and McClafferty 2016).

Ultimately, over 3,300 eligible vehicles were selected for inclusion in the study. A 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 6 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 two petabytes (four million gigabytes) of data. 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 with fine details. Figure 7 demonstrates the fields of view for each of the mounted cameras. Figure 8 shows where each of the cameras were installed, as well as the four different views that were being recorded.

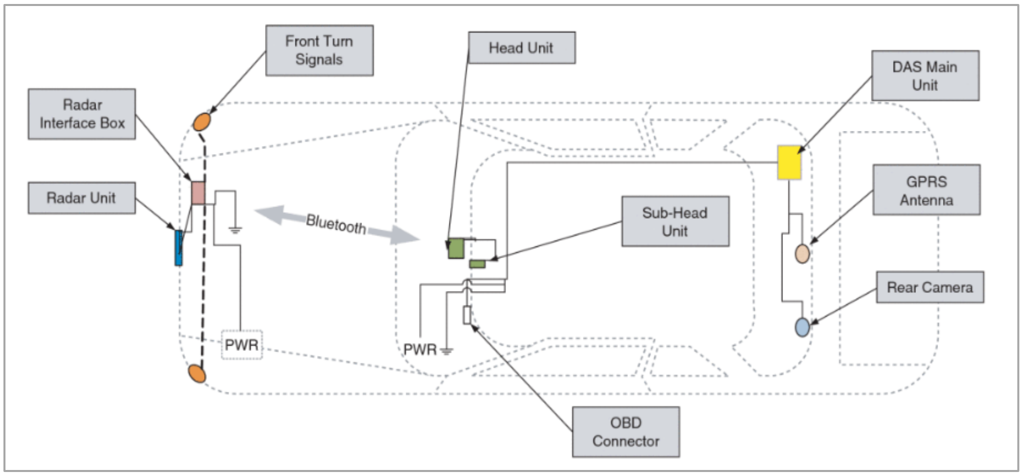

Figure 6. Data acquisition system schematic (Antin et al. 2015)

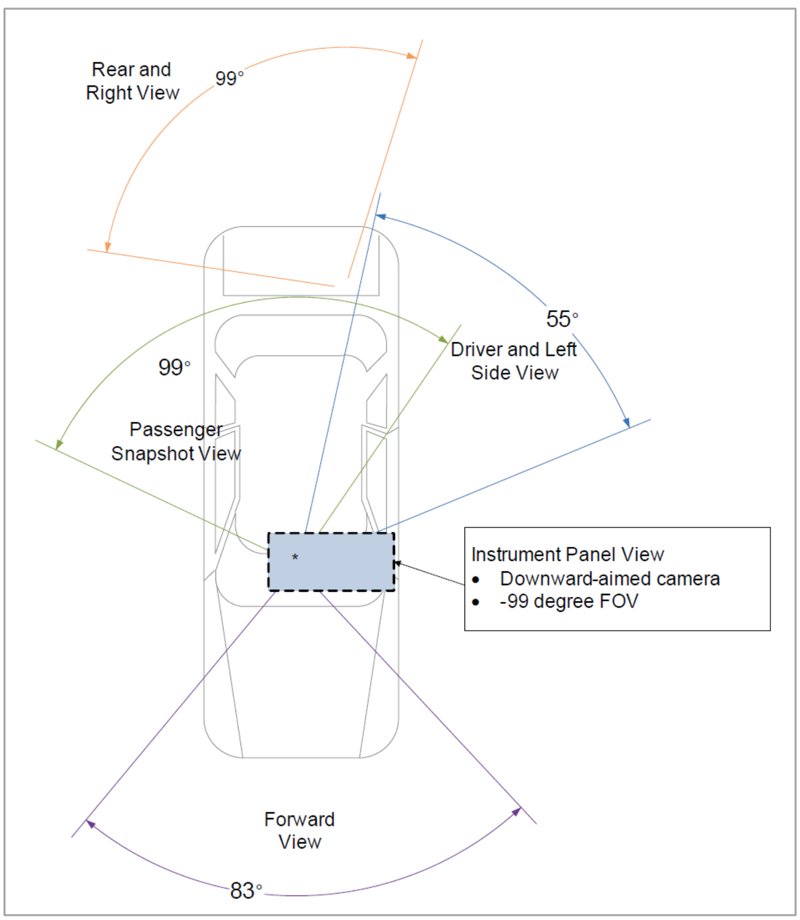

Figure 7. Fields of View for the DAS

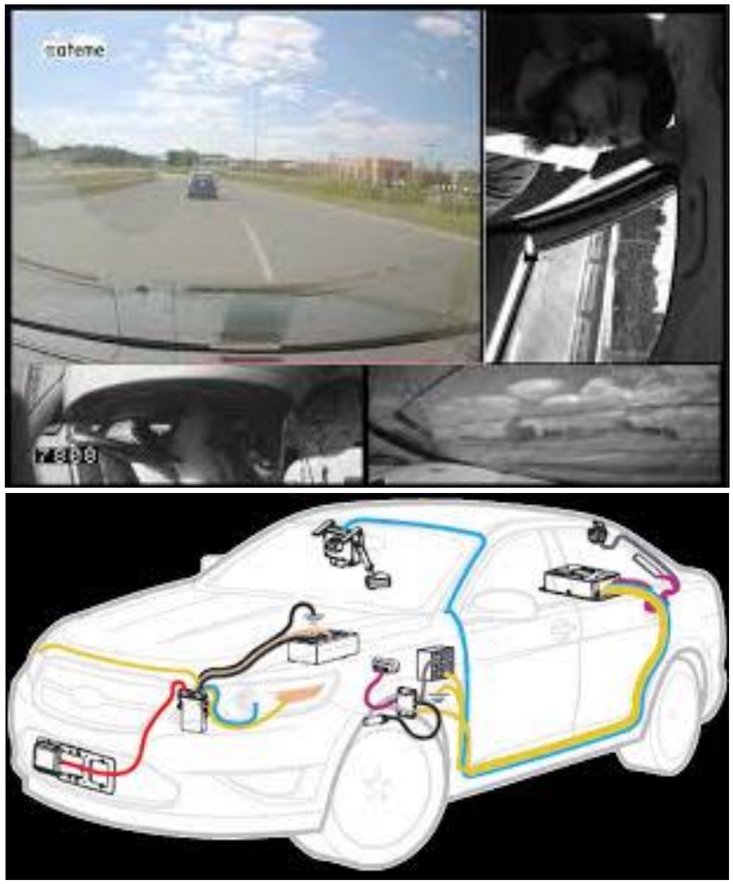

Figure 8. Composite snapshot of four continuous video camera views (Antin et al. 2015)

Initially, the study design involved equal number of participants across the six study sites. However, the contribution of each study site to the overall study sample turned to be different. The largest study areas were Seattle, Washington; Tampa, Florida; and Buffalo, New York with each providing roughly 20% of entire data. Following to these is Durham, North Carolina that involved collection of approximately 15% of the data, whereas State College, Pennsylvania; and Bloomington, Indiana each contributed for over 5% of the entire data (Hankey et al. 2016).

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, work location, etc. Therefore, all the NDS participants were promised that the confidentiality of this sort of data would be maintained (Hankey et al. 2016). A certificate of confidentiality was issued by the U.S. Department of Health and Human Services (HHS) to protect the participants. Prior to participation in the study, select drivers were asked to sign an informed consent per IRB obligation. As such, the data pertaining to only those drivers who signed an informed consent could be reduced for analysis purposes. Also, a 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.

Ultimately, 85% of the entire collected trip data were reduced and presented to researchers for analysis purposes. The remaining 15% were excluded from the database for various reasons. For example, a trip was excluded if it involved an unconsented driver, had missing or unusable video data, or was associated with more than one driver (Hankey et al. 2016).

The SHRP2 NDS data may be categorized into seven different groups as follows:

1. Participant Assessments:
    - Demographic Questionnaire
    - Driving History
    - Driving Knowledge
    - Medical Conditions and Meds

- ADHD Screening
- Risk Perception
- Frequency of Risky Behavior
- Sensation Seeking Behavior
- Sleep Habits
- Visual, Physical, and Cognitive Test Results
- Exit Interview

2. Vehicle Information:

    - Make, Model, Year, Body Style
    - Vehicle’s Condition (Tires, Battery, etc.)
    - Safety and Entertainment Systems

3. Continuous Data:

    - Face, Forward, Rear, and Instrument Panel Video
    - Vehicle Network Data
    - Accelerometers, Gyros, Forward RADAR, GPS
    - Additional Sensor Data

4. Trip Summary Data:

    - Characterization of Trip Content

- Start Time and Duration of Trip
- Min, Max, Mean Sensor Data
- Time and Distance Driven at Various Speeds, Headways
- Vehicle Systems Usage

5. Event Data:
    - Crash, Near-Crash, Baseline
    - 30-second Events with Classification
    - Post-Crash Interviews
6. Cellphone Records:
    - Subset of Participant Drivers
    - Call Time and Duration
    - Call Type (Call, Text, Picture, etc.)
7. Roadway Data:
    - Matching Trip GPS to Roadway Database
    - Roadway Classifications
    - Other Roadway Data

All the data that have been collected and reduced during this naturalistic driving study, as detailed above, are divided into two main parts considering their nature: InSight; and InDepth.

Following sections provide descriptions of what is included in each of these and how they may be accessed and analyzed.

3.1.1 SHRP2 InSight Data

This subset of the NDS data includes the aggregated and summarized data excluding any personally identifying type of information which is also publicly available through the InSight website. Any registered user may view this type of data through this website online. A registered user is the one who successfully undertook the IRB training. The InSight website may be used to conduct some preliminary analysis of aggregated data, or to get some preview and background on the data to plan subsequent steps of requesting and analyzing data; however, this website does not allow any sort of extraction or export of data.

IRB which is also referred to 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. The InSight 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 the study initiation.

The integration of all the collected and reduced data provide a comprehensive set of data elements for each trip included in the study sample. 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, a single vehicle may have been driven by multiple consented drivers, and some drivers might have had multiple trips and events associated with them. Further details on the statistics of the data used for each research question are provided in related chapters.

3.1.2 SHRP2 InDepth Data

As mentioned previously, the second portion of the NDS data is referred to as InDepth. This subset of data includes any information which may potentially result in identifying the participants, including time-series 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 be examined using these data. Any researcher who wants to request extract of data from this type may submit required documents to the local IRB including research questions, details as to what variables are required, how these data would help to better investigate the questions of interest, how the data will be maintained and secured, etc. Consequently, authorized investigators with eligible research questions may be provided by the requested data under certain agreements and conditions.

The time-series data are provided by specific key identifiers for events, trips, vehicles, and drivers that may be used to integrate and/or query data. However, these identifiers are designed and coded in a way that they cannot be used to identify the drivers, their vehicle, and/or their home, work or any other of their locations in real world. The VTTI privacy constraint code indicates that time-series data may not be provided for any traversal near the beginning and the end of a trip defined as a pre-determined distance from trip origin or destination. At such locations, GPS data contain a limited random noise to further anonymize the trip. However, the VTTI tries to minimize or if possible completely eliminate such traversals when providing time-series data. In addition, any sort of face video data and unaltered forward video of a crash are regarded as PII and may be viewed only in the SDE located in Blacksburg, Virginia. However, the forward video data, used as part of this dissertation, may be obtained and reviewed off-site when certain technical and IT supports are present.

3.1.3 Roadway Information Database

In conjunction with the NDS data, the roadway information database (RID) was developed as part of the SHRP2 to provide supplementary data regarding roadway geometry and traffic attributes. The 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 and combined using existing roadway data from public and private sources, as well as supplemental data collected by the ISU using a mobile van shown in Figure 9.

Figure 9. Mobile Van Used to Collect RID

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 and complement the driving data with roadway and geometry data 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 research purposes were selected for data collection purposes 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 10 shows the roadway stretches on which the mobile van was driven.

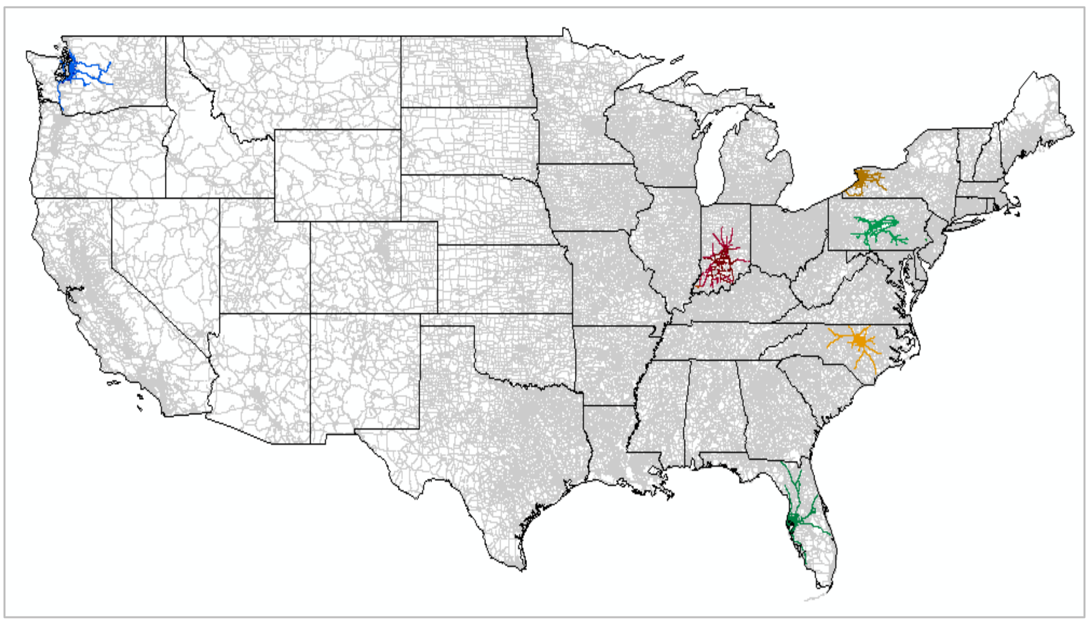

Figure 10. Collected links for SHRP 2 roadway information database

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 RID provides a great opportunity to expand the available data elements to be investigated, as well as to collect more detailed information by locating traces through google earth. The RID is comprised of several shapefiles for each state as follows:

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

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

3.2 Data Acquisition

Given the objectives of this extensive study, high resolution data were required from a wide range of facility types. Overall, the data utilized for this study consisted of four major categories of traces: (1) Under constant speed limit; (2) Across speed limit transition areas; (3) Along horizontal curves with speeds; and (4) Along curves without advisory speed signs as control sites. The first two included separate datasets for freeways and two-lane highways. However, the latter two were solely focused on two-lane facilities as the advisory speeds on freeways were limited to exit/entrance ramps and did not provide adequate samples of driving events for analysis purposes. The IRB approval memo for this study may be found in Appendix A of this dissertation. Since the data integration process was similar for all four datasets, the following section describe how the datasets were constructed by integrating information from different sources. There are additional differences between the datasets design and how they were structured for analysis that will be described in later chapters where related.

3.3 Data Integration

The research team was provided with individual comma-separated-value (i.e. csv) files for each of the requested traces. The first step was to combine all the individual csv files and create datasets to examine the research questions. To visualize the traces in ArcMap environment, and extract the geometric information from the RID, each timestamp in the time series data needed to have valid longitude and latitude information. This information was supposed to be provided at each one second interval; however, such information may be missing for some or, in some rare cases, all of the timestamps during a single trip. Consequently, only those instances with valid longitude and latitude information were retained in the dataset. This process resulted in losing parts or all of a number of trips and, as a result, subsequent analyses needed to be done by caution in such cases. Once the traces with valid geographic information were identified, they were visualized in ArcMap environment. Figure 11 displays how the obtained traces were scattered across states and were not necessarily within the boundaries of the six study areas (highlighted in aqua color). This further resulted in losing some traces as the RID only includes information across the prementioned six states. Subsequently, separate datasets were created for each state for conflation purposes as the RID is state-based.

The RID uses linear referencing system as its method of spatial referencing where the location of features is described in terms of measurements along a linear element, from a predetermined starting point. However, the obtained traces only included GPS outputs containing longitude and latitude. As a result, the first step was to convert the raw data to linear referencing system. A python script was developed to perform this task. Once the conversion was done, each point was assigned a route identifier and a measurement along that route that may be used to extract other geometric features from the RID.

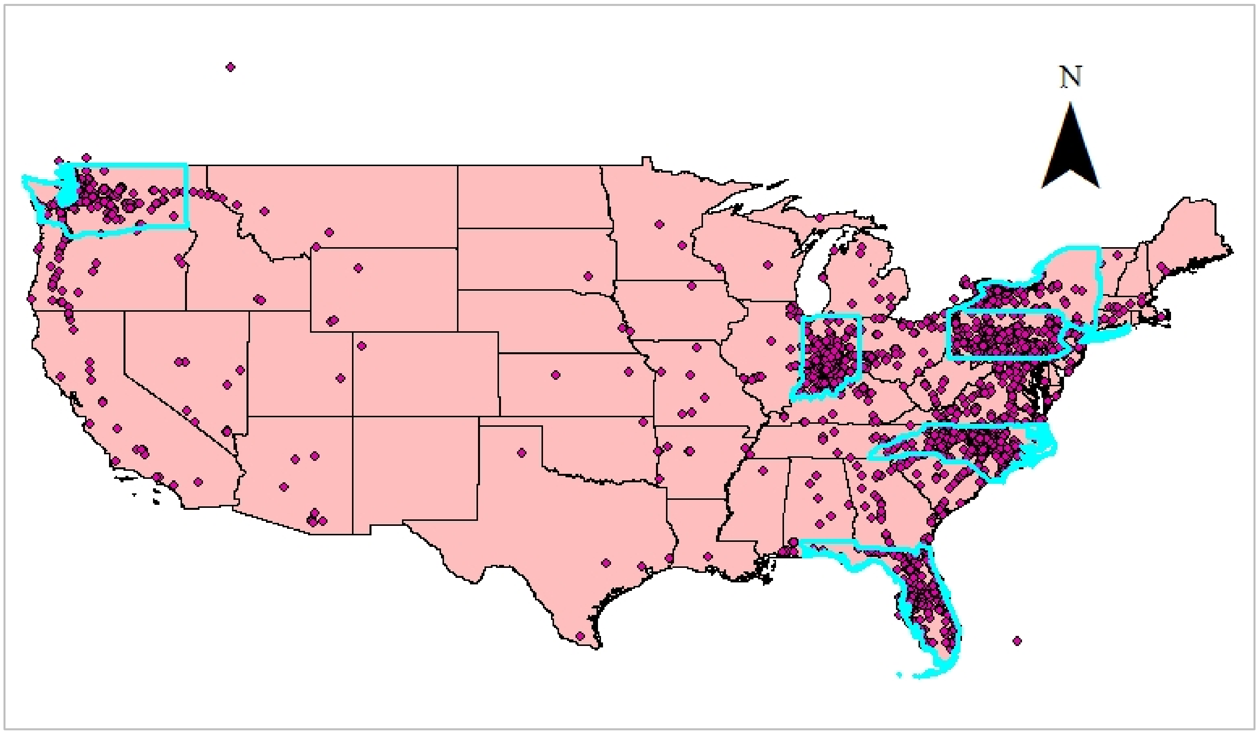

Figure 11. Map of the obtained traces

Once the time-series data were converted to the appropriate referencing system, geometric features were conflated (i.e. linked) to each datum using the ArcMap tool called “Overlay Route Events”. A dynamic segmentation process was utilized, where relevant attributes were queried from each shapefile based on the route identifier and the mile point. The dynamic segmentation process is briefly described in the following steps:

1. The attribute table of the shapefile of interest was queried for those RouteIDs in the time-series data and exported as a dBase file in ArcMap. This step reduced the amount of underlying data to be read and analyzed by a significant amount, resulting in noticeable reduction in the processing time.

2. To conflate the time-series data to the shapefile of interest, the “Overlay Route Events” from linear referencing tools menu in ArcToolbox was used. The time-series dataset needed to be selected as the “Input Event Table”. Since each row in the time-series data corresponded to one point along the trip trace, the “Event Type” must be selected as “POINT”. Subsequently, “FrMeasure” has to be selected as “Measure Field”. Due to the point nature of this table, the “To-Measure-Field” is disabled.

3. The dBase file exported in step 1 must be selected as the “Overlay Event Table”. Unlike the input table which was of a point type, all the tables that needed to be overlaid were in line format. Consequently, the “Event Type” must be selected as “LINE” for all these tables. In this case, both “From-Measure Filed” and “To-Measure Field” needed to be specified which corresponded to the start and end points of the layer that was being overlaid. Ultimately, the output were exported and saved as a comma separated values (CSV) file in the desired location. These steps are shown in Figure 12.

This dynamic segmentation process was used to extract desired features from various RID shapefiles.

Table 4 provides a list of shapefiles and the features extracted from the RID as part of this dissertation. The information for each point along the event traces was extracted from the proper record with identical Route ID, and a From- and To- Measure which made up a segment embracing the queried point. Blank fields were displayed if no record matched these conditions.

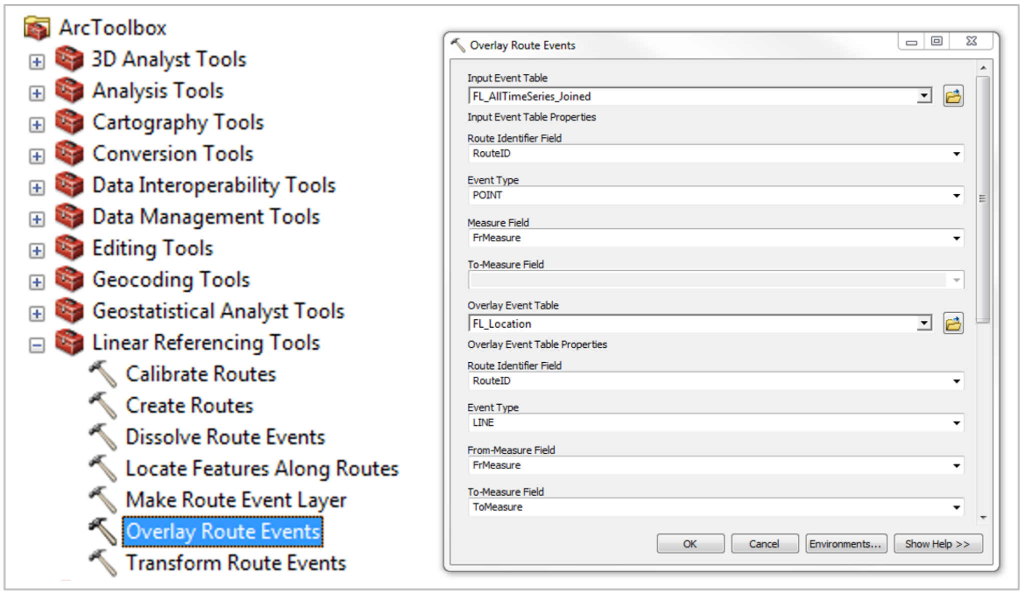

Figure 12. A snapshot of the conflation process

Table 4. RID Shapefiles and the Associated Extracted Information

Shape file	Information	Polynomial	Point
Alignment	Tangent vs. Curve - Curve Radius - Curve Direction - Super Elevation	x	
Location	Grade - Cross Slope	x	
Lane	Number of Lanes by Type – Lane Width	x	
Median	Median Type	x	
Shoulder	Shoulder Type – Shoulder Width	x	
Barrier	Barrier Type	x	
Rumble Strip	Location (Edge Line vs. Shoulder vs. Centerline)	x	
Sign	MUTCD Code- Message		x

In contrast to the other shapefiles in RID, the speed limit and advisory speed data (i.e. all sign-related information) were in point format. Since the time-series data were also in point format, it was not possible to follow similar procedure detailed above to extract this type of data from RID. To be able to do the conflation process, at least one of the two tables must be of line type. Therefore, to extract the speed limit data, polynomial shapefiles were developed from the sign inventory. To derive the information as to speed limit at each point, the "signs" shapefile from the RID was queried to identify those that represent the statutory speed limit information. According to the MUTCD the code R2-1 corresponds to the regulatory speed limit signs and was used to query the shapefile. The output from this query included location information (RouteID and mile point), as well as the associated sign message (i.e., the posted speed limit). Speed limits were assumed consistent between two consecutive signs, meaning that the begin mile-point for each sign was the end mile-point for the previous sign. Consequently, using this line-based dBase, speed limit information was extracted following the conflation process outlined previously.

While the outlined approach performed relatively well on conflating RID features to obtained trip traces, there were some issues that needed closer investigation and are detailed here:

- **Wrong Conflation:** Adjacency to other roadways may result in some conflation issues. During the data collection process by the mobile van, the collected data were assigned to the closest roadway, thus in some cases there may be multiple conflated information to a road segment.

- **Lack of Directional Data on Undivided Roadways:** In the RID, divided roadways (e.g. freeways in the context of this study) were assigned two different RouteIDs to account for each direction of travel lanes. However, this was not the case for undivided roadways, meaning that only one RouteID was specified for either of directions. Consequently, conflation of the attributes corresponding to the opposing direction was likely. This required further investigation of the resulting tables to match the coded attributes for the same side of the roadway centerline. *Figure 13* displays a flow chart for the logic used to eliminate the irrelevant features extracted in the conflation process.

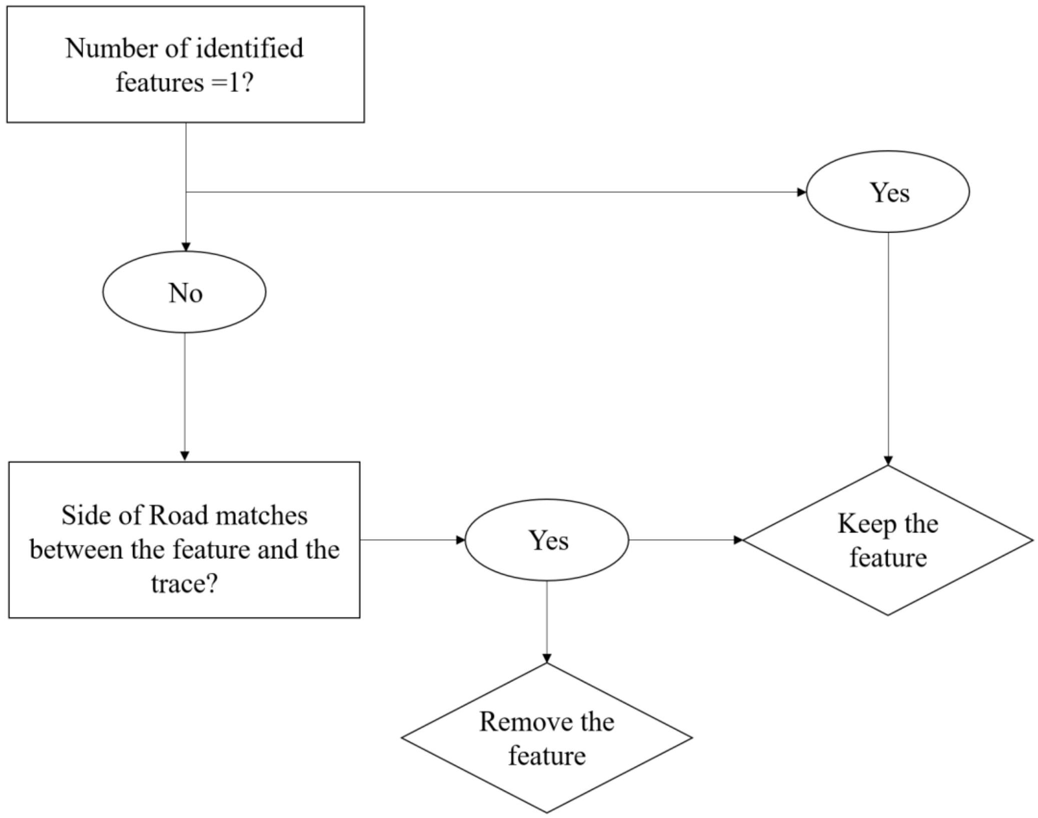

Figure 13. Flow chart of the logic used to resolve the conflation issues

Once these issues were resolved, comprehensive datasets including time-series data, geometric features from RID, and InSight supplementary data were created. Further details as to how the raw data were queried and requested, as well as dataset structures are discussed in the following chapters, separately.

CHAPTER 4. SPEED ANALYSIS UNDER CONSTANT POSTED SPEED LIMIT

The first research question investigated as part of this dissertation involved examining speed profiles under constant posted speed limit. While the segments over which the speed profiles were analyzed included a wide variety of geometric characteristics and environmental conditions, they were not associated with multiple speed limits or advisory speed signs. Due to essential differences in the nature of freeways and two-lane highways, the speed profiles were examined separately for each of these facilities. The SHRP 2 InSight data included an extensive inventory of driving traces across all six states. To provide researchers with an opportunity to be able to analyze various scenarios, these reduced data were comprised of baseline events (i.e. normal driving events), as well as crash, near-crash, and other types of conflicts. Speed profiles were analyzed for near-crash and baseline events to examine how drivers select their travel speed under various roadway and environmental conditions.

4.1 Data

Data were obtained for all crash, near-crash, and baseline events that had been reduced by the VTTI as of April 2016 for both freeways and two-lane highways across the six study states. The facility type was determined using the “Locality” field in the InSight event table. Events with locality type of “interstate/bypass/divided highway with no traffic signals” were selected as potential candidates for freeway-focused portion of this dissertation. On the other hand, events for which the locality field was marked as “bypass/divided highway with traffic signal” were identified as likely subjects to represent two-lane highways. Consequently, the InSight data including events, trips, participants, and vehicle tables, as well as the InDepth data including the location, speed, and lateral acceleration/deceleration data were obtained for every candidate event. This resulted in a total of 9,508 and 7,495 potential events for freeways and two-lane highways, respectively. However, as the locality field from InSight is not necessarily reflective of where the event occurred, an extensive quality control process was conducted for all events using the RID attributes and Google Earth. Different criteria including maximum speed limit, number of lanes, and presence of intersections along segments were used to categorize the data into potential freeways and two-lane segments. One other factor that resulted in losing traces was improper GPS information or missing RID attributes, specifically posted speed limit which was the main focus of this study. Consequently, these resulted in significant reduction in the sample size yet providing sufficient data to examine the proposed research questions. Ultimately, a total of 4,909 and 2,898 events were identified on freeways and two-lane highways, respectively.

The data used in this section were comprised of a series of 20-second snapshots of driving traces across all six study sites. The raw data provided by the VTTI included 20-second snapshots of trips for baseline events, whereas this extended to 30 seconds for safety critical events including 20 seconds preceding the crash/near-crash start and 10 seconds following that. However, since the focus of this chapter was to investigate general drivers' speed selection behavior, only the first 20 seconds of such incidents were included in the analysis. The author verified that these 20-second snapshots were in fact reflective of drivers' choice of speed and do not include the duration over which the speed was impacted by the incident. When involved in a crash or near-crash, there are myriads of other factors besides driver behavior that impact travel speed where abrupt breaking and marked speed variability occur. Unlike traditional data collection methods in which the exact start of the crash or near-crash event was not evident, naturalistic driving study data allowed for accurate identification of time and location of crash/near-crash incidence.

Figure 14 displays examples of one near-crash and one baseline incident across a segment posted at 70-mph. There is no sign of abrupt change over this duration of the near-crash. However, the speed profile displayed an evident sharp reduction later at around second 22, probably due to the driver reaction to the occurrence of the near-crash, which was not included in the analysis set. In all such cases, this pattern starts after the 20th second, and the speed seems stable prior. This was not only verified through visualization, but also by examining a field in the InSight data that indicated the timestamp the driver was believed to first notice the threat. As a result, these 20 second snapshots were selected as surrogates of drivers' choice of speed under constant speed limit across freeways and two-lane highways.

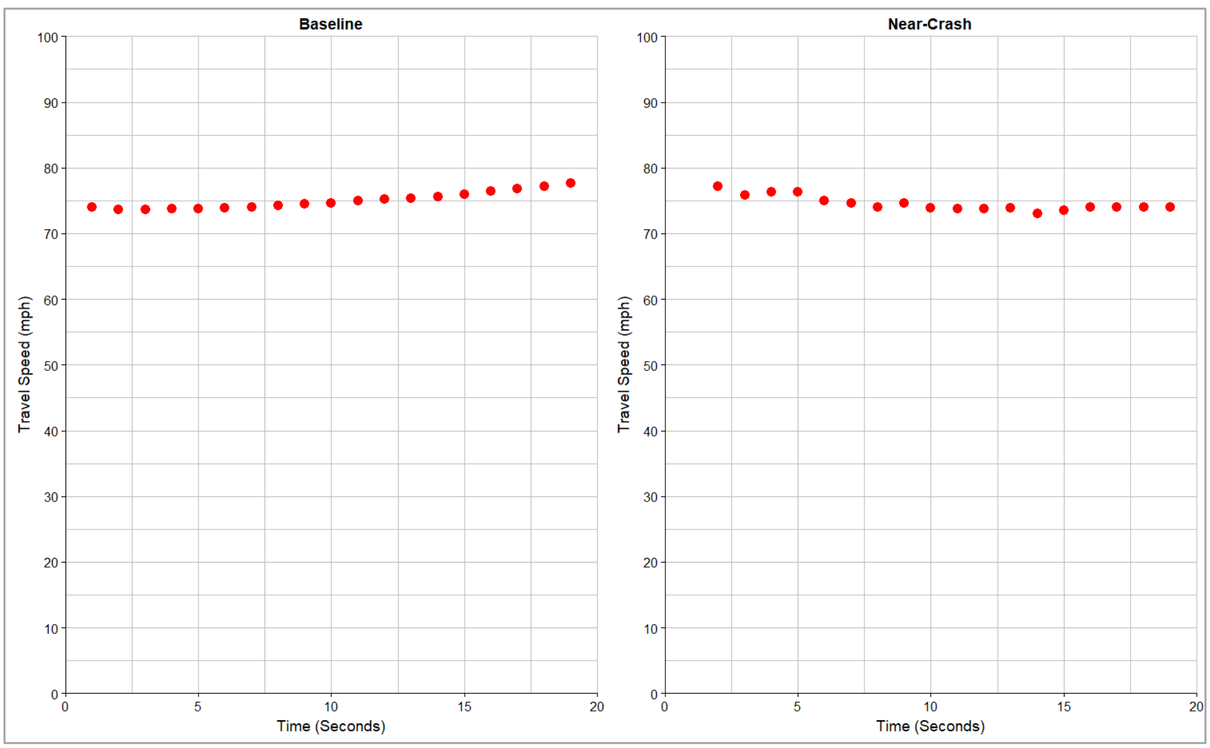

Figure 14. Example Speed Profiles of a Baseline and a Near-Crash Posted at 70 mph

Once all the data were integrated and reduced, a comprehensive dataset including a total of 4,375 driving traces at four different posted speed limits ranging from 55-mph to 70-mph was created for freeways. The mean speed, as well as the speed standard deviation were calculated over the 20-second duration of the travel for each trace. Figure 15 displays the boxplots for the mean travel speed at each speed limit. This indicates that as the posted speed limit increases so does the mean travel speed. However, such increases do not seem to emerge with a fixed stepped pattern as the mean speeds at 55- and 60-mph, as well as those at 65- and 70-mph fall closer to one another.

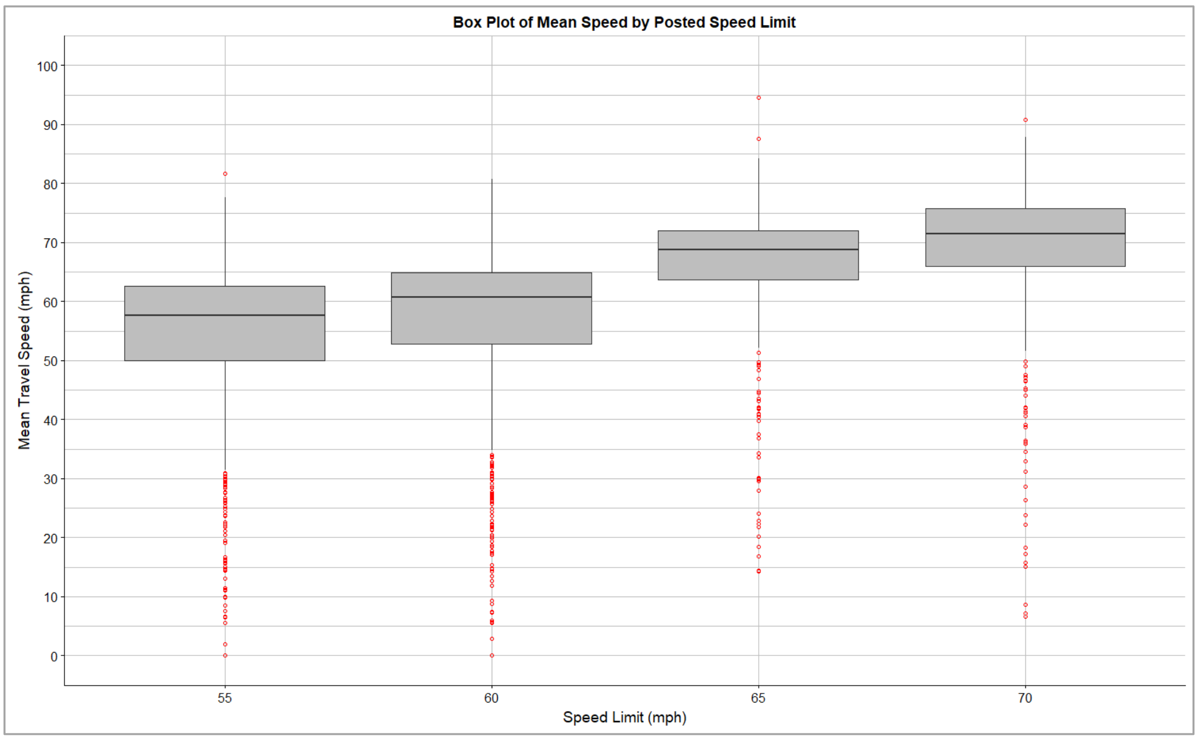

Figure 15. Box Plots of Mean Travel Speed by Posted Speed Limit on Freeways

In addition, research studies have generally shown the travel speed to be inversely impacted by traffic density (McLaughlin and Hankey 2015). The InSight data included a variable indicating the traffic density at time of travel and was used to investigate such impact in this study. This parameter defines the level of traffic congestion by reposting level of service (LOS) measure. According to Garber and Hoel (Garber and Hoel 2014), “level of service is a qualitative measure, ranging from A to F, that characterizes both operational conditions and within a traffic steam and highway user's perception". To visually assess the impact of traffic density on mean speeds, boxplots were generated at combinations of speed limit and level-of-service and are presented in Figure 16. As expected the travel speed was shown to be adversely impacted by poor LOS. However, the speeds were shown to be more stable at LOS A through C, while significant reductions are evident when reaching LOS D and beyond.

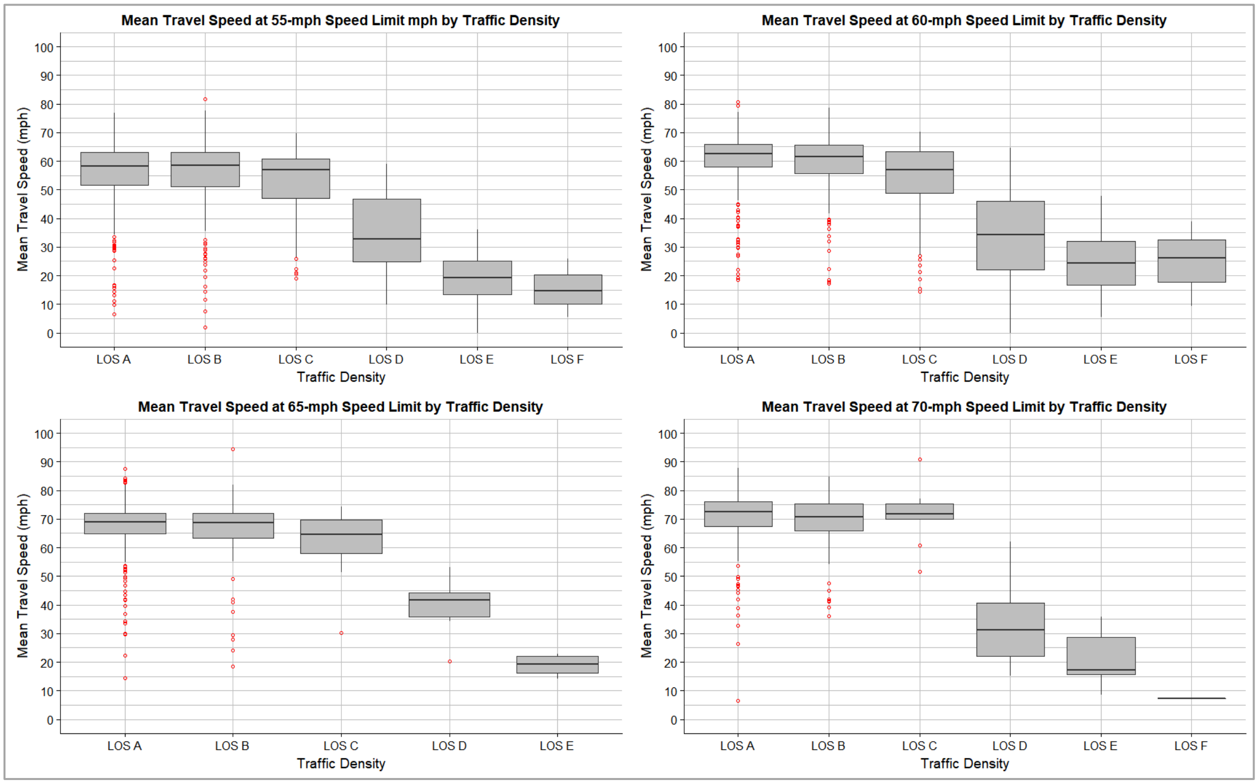

Figure 16. Boxplots of Mean Speed by Posted Speed Limit and Traffic Density on Freeways

As alluded to previously, a comprehensive dataset including variables describing roadway geometry, driver behavior, vehicle characteristics, and speed profiles was put together for each of the samples. To simplify the modeling steps and the subsequent discussion of results, a series of indicator variables were introduced for different categories of variables. Table 5 provides the summary statistics of the analyzed data where the mean value, as well as the standard deviation are presented for each variable. In case of binary indicators, the mean value is reflective of the percentage of sample possessing such characteristic.

The summary statistics indicate that the dataset was relatively balanced considering the posted speed limit with the majority of traces belonging to 55- and 60-mph segments. However, this was not the case with traffic density where less than one percent of traces occurred at LOS F. Also, the data included information as to driver's age and gender. The sample was balanced with respect to gender. On the other hand, the younger and older drivers were oversampled when recruiting participants for the naturalistic driving study (Antin et al. 2015) and such pattern was evident in this dataset, as well. Ultimately, these data were used to develop regression models to investigate driver's choice of speed under different conditions and are furtherly discussed in later sections.

Table 5. Summary Statistics of Freeway Traces Under Constant Speed Limit

Variable	**Minimum**	**Maximum**	**Mean**	**Std. Dev.**
55-mph Limit	0	1	0.33	0.47
60-mph Limit	0	1	0.32	0.47
65-mph Limit	0	1	0.21	0.41
70-mph Limit	0	1	0.14	0.35
LOS A	0	1	0.53	0.50
LOS B	0	1	0.34	0.47
LOS C	0	1	0.08	0.27
LOS D	0	1	0.04	0.18
LOS E	0	1	0.02	0.12
LOS F	0	1	<0.01	0.06
Clear Weather	0	1	0.91	0.28
Rain	0	1	0.08	0.28
Snow/Sleet	0	1	0.00	0.07
Non-Workzone	0	1	0.96	0.19
Workzone	0	1	0.04	0.19
Non-Junction	0	1	0.63	0.48
Junction	0	1	0.37	0.48
Upgrade	0	1	0.10	0.30
Downgrade	0	1	0.05	0.22
Female Driver	0	1	0.51	0.50
Male Driver	0	1	0.49	0.50
Driver Age: 16-24	0	1	0.38	0.49
Driver Age: 25-59	0	1	0.41	0.49
Driver Age:60 or above	0	1	0.21	0.41

A similar dataset was created including 2,901 traces occurred on two-lane highways under constant speed limit. This dataset included a variety of posted limits ranging from 25 mph to 60 mph depending on the state and area type (i.e. urban vs. rural). Figure 17 presents boxplots of the mean travel speed by posted speed limit. The pattern is similar to what was observed for freeways where the travel speed and posted speed limit were directly correlated. However, the interquartile ranges were found to be wider for two-lane highways which is indicative of more diverse speed choices on these facilities as compared to freeways. In addition, the difference in mean speeds between two consecutive limit seems to be decreasing when reaching higher posted limits.

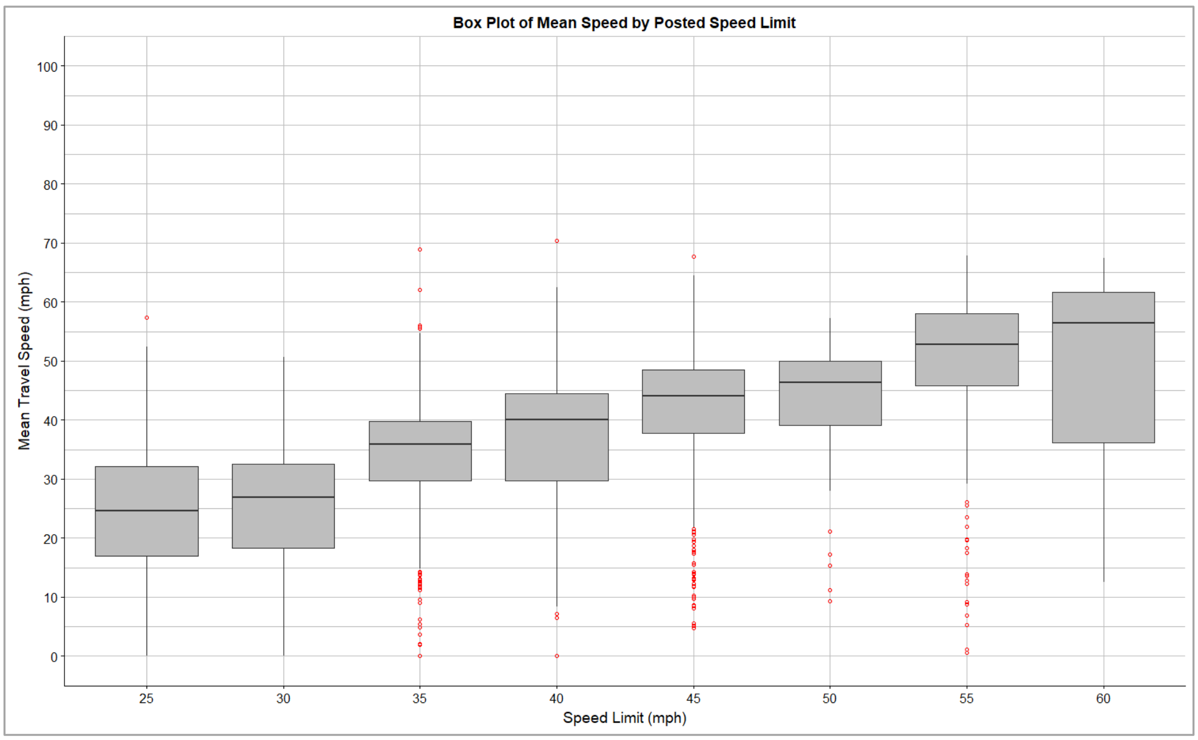

Figure 17. Box Plot of Mean Travel Speed by Posted Speed Limit on Two-Lane Highways

In addition, the impact of traffic density on mean speeds was investigated through boxplots presented in Figure 18. It is imperative to note that unlike freeways, these traces did not cover all LOSs due to lower AADTs and the fact that they occurred in less urban areas. Such pattern was more evident at higher speed limits. For example, the traces under the 60-mph limit corresponded to only LOS-A and LOS-B, whereas more variation in traffic density was observed at lower limits.

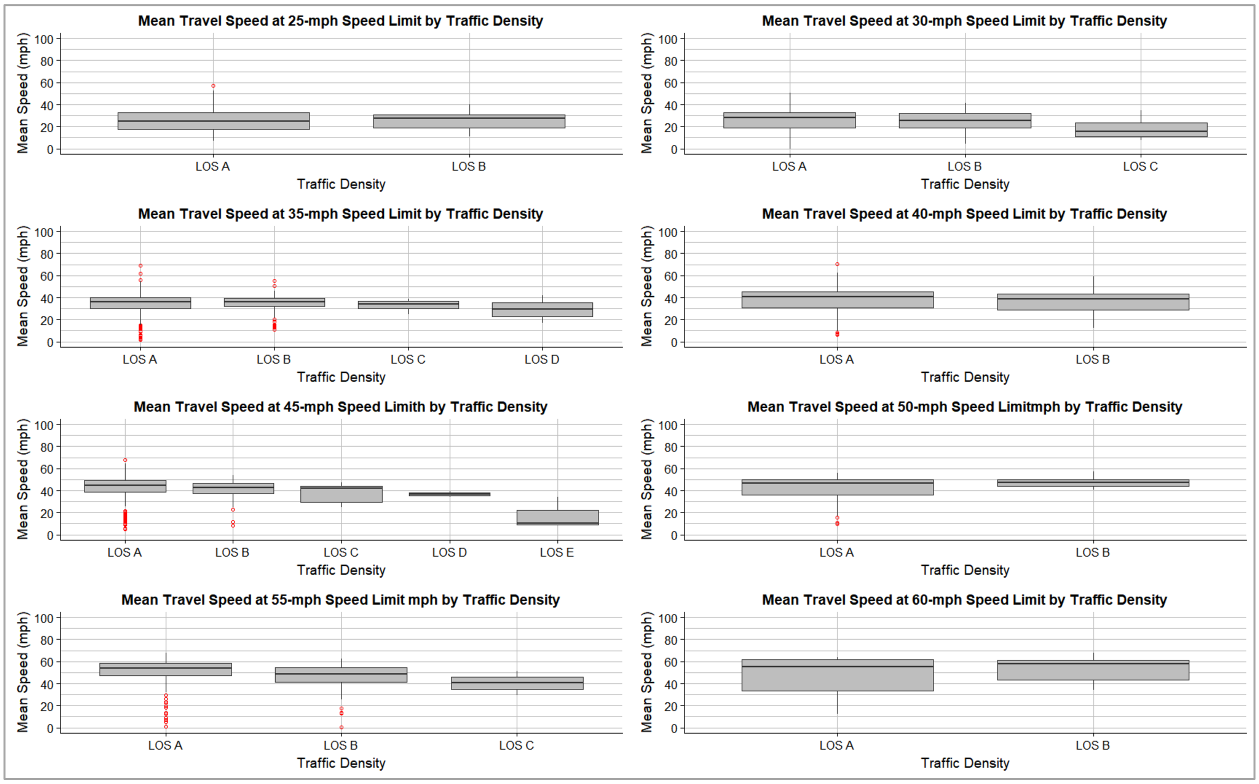

Figure 18. Boxplots of Mean Speed by Posted Speed Limit and Traffic Density on Two-Lane Highways

Like freeways, a series of binary indicators were introduced to represent various categories of variables included in the dataset. The descriptive statistics for a subset of variables is presented in Table 6. When looking at the speed limit indicators, one important point is the smaller percentages for 25-, 40-, 50-, and 60-mph limits compared to other limits. Also, the majority of traces occurred under LOS-A and LOS-B resulting in less than two percent of the sample having LOS-C or below. One other characteristic specific to two-lane highways is presence of various kinds of access points along segments. This includes, but is not limited to, intersections, driveways, and on-street parking; however, since all other types access points had very few frequencies, they were not included as separate categories in the analysis set.

Table 6. Summary Statistics of Two-Lane Traces Under Constant Speed Limit

Variable	Minimum	Maximum	Mean	Std. Dev.
25-mph Limit	0	1	0.05	0.22
30-mph Limit	0	1	0.19	0.39
35-mph Limit	0	1	0.21	0.41
40-mph Limit	0	1	0.09	0.29
45-mph Limit	0	1	0.23	0.42
50-mph Limit	0	1	0.03	0.16
55-mph Limit	0	1	0.18	0.38
60-mph Limit	0	1	0.02	0.14
LOS A	0	1	0.77	0.42
LOS B	0	1	0.21	0.41
LOS C	0	1	0.01	0.12
LOS D	0	1	<0.01	0.05
LOS E	0	1	<0.01	0.06
LOS F	0	1	<0.01	0.02
Clear Weather	0	1	0.92	0.27
Rain	0	1	0.07	0.26
Snow/Sleet	0	1	0.01	0.09
Non-Workzone	0	1	0.99	0.12
Workzone	0	1	0.01	0.12
Intersection	0	1	0.09	0.29
Driveway	0	1	0.16	0.37
Parking	0	1	0.08	0.27
Upgrade	0	1	0.10	0.30
Downgrade	0	1	0.05	0.21
Male	0	1	0.49	0.50
Female	0	1	0.51	0.50
age1624	0	1	0.36	0.48
age2559	0	1	0.36	0.48
age60above	0	1	0.28	0.45

4.2 Methodology

For the purpose of analysis, mixed-effect ordinary least squares (OLS) regression models were estimated. Mean speed and the standard deviation in speed over the first 20 seconds of each event was computed for the purpose of model estimation. The OLS equations for each of these performances measure take the following form:

$$ms_i = \boldsymbol{\beta_{i,ms}} \boldsymbol{X_{ms}} + \varepsilon_{i,ms} \qquad \text{(Equation 4)}$$

$$sd_i = \boldsymbol{\beta_{i,ms}} \boldsymbol{X_{sd}} + \varepsilon_{i,ms} \qquad \text{(Equation 5)}$$

where: ms_i is the mean speed (in mph) during event i; sd_i is the calculated standard deviation of speeds during event i (in mph); $\boldsymbol{X}$ is a vector of speed limit, traffic, and roadway characteristics; $\boldsymbol{\beta}$'s are vectors of estimable parameters; and ε's are disturbance terms capturing unobserved characteristics normally distributed with mean zero and variance of σ^2.

One concern that arises within the context of this study is the anticipated correlation in speed selection behavior among the same individuals. 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. Consequently, a participant-specific intercept term, δ_j, was introduced to account for the fact that specific drivers may tend to drive faster (or slower) than others due to factors that were 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 retained the same coefficient for each driver in every event (assuming the driver has multiple events in the database) and, thus, was able to capture general differences in speed selection behavior. This additional term was assumed to be normally distributed with mean of zero and variance of σ^2; Consequently, the previous equations take the following forms:

$$ms_{ij} = \boldsymbol{\beta_{i,ms}} \boldsymbol{X_{ms}} + \varepsilon_{i,ms} + \delta_{j,ms} \quad \text{(Equation 6)}$$

$$sd_{ij} = \boldsymbol{\beta_{i,sd}} \boldsymbol{X_{sd}} + \varepsilon_{i,sd} + \delta_{j,sd} \quad \text{(Equation 7)}$$

where δ_j is an intercept term specific to driver *j*; this is what is generally referred to as mixed-effect linear regression model. The following section provides the results of the models developed as part of this chapter and discusses the findings.

4.3 Results and Discussion

Table *7* and Table 8 provide results of the analyses for mean travel speed and standard deviation in travel speeds on freeways. For these facilities, a total of 4,375 events corresponding to 1,975 unique drivers were analyzed. To gain a better understanding as to driver speed selection, separate models are provided for the overall sample, as well as a subset of events that occurred under level-of-service A. The reason for that is the fact that under traffic congestion, some parameters other than roadway geometry and drivers' characteristics may influence drivers' choice of speed. This includes but is not limited to travel speed of those vehicles surrounding the subject vehicle.

Starting with the entire sample, the average speed on freeways with a 70-mph posted limit was found to be 69.3 mph. Speeds were approximately 3.3 mph lower on freeways posted at 65 mph (mean of 66.0 mph). More pronounced decreases occurred on the lower speed freeways as the mean speeds were 56.1 and 59.5 mph where speed limits were 55 and 60 mph, respectively. This is consistent with prior research showing that speed limit increases result in changes in the observed mean and 85th percentile speeds that are less pronounced than the actual speed limit increases (Lynn and Jernigan 1992, Ossiander and Cummings 2002, Freedman and

Esterlitz 1990, Parker Jr and Parker 1997, Kockelman et al. 2006), (Davis et al. 2015, Hu 2016, Johnson and Murray 2010).

Table 7. Mixed Effect Linear Regression Model for Mean Speed on Freeways

	Total Sample			LOS-A Only Sample		
Random Effects:						
Groups	**Variance**	**Std. Dev.**		**Variance**	**Std. Dev.**	
Participant ID	17.920	4.233		19.350	4.399	
Residual	82.050	9.058		60.270	7.763	
Fixed Effects:						
Model Term	**Coeff.**	**Std. Err.**	**t-stat**	**Coeff.**	**Std. Err.**	**t-stat**
Intercept	69.343	0.537	129.028	69.847	0.587	118.943
55-mph limit	-13.176	0.498	-26.443	-13.605	0.574	-23.708
60-mph limit	-9.766	0.518	-18.851	-9.163	0.612	-14.979
65-mph limit	-3.335	0.541	-6.168	-3.530	0.594	-5.939
70-mph limit		Baseline			Baseline	
LOS A		Baseline			-	
LOS B	-1.479	0.331	-4.473		-	
LOS C	-8.455	0.577	-14.644		-	
LOS D	-27.004	0.823	-32.826		-	
LOS E	-40.907	1.194	-34.275		-	
LOS F	-46.167	2.590	-17.823		-	
Non-junction		Baseline			Baseline	
Junction	-1.758	0.312	-5.637	-2.578	0.392	-6.578
Non-work zone		Baseline				
Work zone	-3.606	0.776	-4.648	-3.219	1.096	-2.937
Clear weather		Baseline			Baseline	
Rain	-2.222	0.536	-4.146	-2.403	0.696	-3.452
Snow or sleet	-12.336	2.205	-5.596	-13.094	2.439	-5.368
Age 16 to 24	3.795	0.465	8.162	3.589	0.528	6.804
Age 25 to 59	2.479	0.467	5.306	2.340	0.535	4.372
Age 60 or above		Baseline			Baseline	
Null Log-Likelihood			-17,760			-8,794
Log-Likelihood			-16,213			-8,333
Null AIC			35,416			17,592
AIC			32,460			16,690
Null BIC			35,429			17,603
BIC			32,568			16,759
Number of Observations: 4,375				Number of Observations: 2,320		
Number of Participants: 1,975				Number of Participants: 1,432		

Beyond speed limits, mean speeds were also largely affected by the level of traffic congestion present at the time of the event. Speeds were relatively stable across levels-of-service A and B, but began to drop significantly under LOS C and, particularly, at LOS D, E, and F. As shown by various prior studies (Emmerson 1969, McLean 1981, Glennon et al. 1983, Lamm and Choueiri 1987, Kanellaidis et al. 1990) speed selection was also highly dependent upon the roadway environment as speeds decreased significantly in work zones (3.6 mph) and under adverse weather conditions (2.2 mph in rainy and 12.3 mph in snowy weather).

As far as drivers' characteristics, travel speeds were shown to be considerably higher among younger and middle-aged drivers. The mean speeds were found to be approximately 3.8 mph greater for those age under 24, whereas this effect is reduced to 2.5 mph when considering drivers between 25 and 59, compared to elderly drivers. All parameters included in the model were statistically significant under a 95-percent confidence interval (i.e. t-value greater than 1.96).

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, slight differences were observed across all four speed limit categories. Mean speeds were roughly 0.5 mph greater across the four speed limits when considering those events under LOS A as compared to those of the entire sample. Also, the events under free flow condition were shown to be more impacted by presence of roadway junctions (i.e. interchanges) which is probably due to the unexpected interruptions resulting from weaving movements. The impact of adverse weather condition, as well as drivers' age were found to be consistent between the two models.

In addition, separate models were developed for each individual state in the study to investigate potential variability in these effects across the states. The results of these analyses may be found in Appendix B of this dissertation. While the trends and parameter estimates are generally similar, there are some slight differences between the models that may be due to the differences in geographic factors, speed enforcement methods, or general population driving behavior. For example, Florida and North Carolina did not have any event occurring under snowy weather condition. Also, two of the states in the study, New York and Pennsylvania, do not cover all four categories of speed limit as they have only 55- and 60-mph limits in place.

Table 8 includes the results of the random effect model developed for speed standard deviation across freeways. As shown by prior research in this area (Emmerson 1969), speeds tended to become more consistent (i.e., lower variability) as speed limits increased. The results indicated no statistically significant difference in speed variability between events under 70- and 65-mph limits. A recent Michigan study has shown similar results (Gates et al. 2015), with speeds being significantly more variable on 55-mph urban freeways, suggesting these findings are transferable across states.

As expected, the variability in travel speeds was predominantly affected by the level of congestion. The standard deviation was lowest under LOS A and highest under LOS E, where an approximate difference of 2 mph was observed. Speeds were also highly variable within work zone environments and across interchange areas.

Table 8. Mixed Effect Linear Regression Model for Speed Standard Deviation on Freeways

Random Effects:			
Groups	**Variance**	**Std. Dev.**	
Participant ID	0.274	0.523	
Residual	4.142	2.035	
Fixed Effects:			
Model Term	**Coeff.**	**Std. Err.**	**t-stat**
Intercept	0.987	0.063	15.775
55-mph limit	0.864	0.079	10.959
60-mph limit	0.364	0.084	4.345
65-mph limit		Baseline	
70-mph limit		Baseline	
LOS A		Baseline	
LOS B	0.412	0.071	5.823
LOS C	1.237	0.124	9.992
LOS D	2.183	0.177	12.349
LOS E	2.344	0.258	9.085
LOS F	1.173	0.561	2.090
Non-junction		Baseline	
Junction	0.484	0.067	7.254
Non-work zone		Baseline	
Work zone	0.360	0.166	2.175
Null Log-Likelihood		-9722	
Log-Likelihood		-9448	
Null AIC		19448	
AIC		18919	
Null BIC		19461	
BIC		18996	

Number of Observations: 4,375

Number of Participants: 1,975

Turning to two-lane highways, many of the same factors were found to influence driver speed selection. Table 9 and Table 10 provide results of similar analyses conducted on two-lane highways. On these facilities, mean speeds were generally near the posted limit under low-speed conditions, but tended to decrease below the posted limit at higher speeds. For example, the mean speed was around 26.2 mph and 34.6 mph at 25- and 35-mph limits, respectively. However, starting from 40-mph limit, travel speeds started to drop below the posted limit. No significant differences were observed between the segments posted at 55 and 60 mph where mean speeds turned out to be much lower than the posted limit (nearly 50 mph). This is largely reflective of the larger number of urban highways included in the NDS sample, where speeds are significantly lower as compared to more rural facilities.

As with freeways, traffic congestion was a primary determinant of travel speeds, reducing mean speeds by as much as 23.7 mph at LOS E. Similarly, speeds were shown to be relatively consistent across LOS A and B and began to drop markedly starting from LOS C. Unlike freeways, no event occurred under LOS F. Speeds were also significantly reduced in the vicinity of access points including driveways and intersections, as well as in presence of on-street parking. Among these, on-street parking had the highest impact with approximately 4.5 mph reduction in travel speeds. However, this effect is much lower near driveways and intersections where mean speeds dropped by 0.9 and 2.3 mph, respectively. Similarly, marked reductions were observed across workzones and under snowy weather condition. However, the results indicated no differences between clear and rainy weather condition which could be attributed to the general lower speeds on two-lane highways as compared to freeways.

One other difference between the two facilities was the significant impact of horizontal curvature on mean speeds across two-lane highways. This probably relates back to the lower design standards of these segments and the fact that much sharper curves are permitted to be built. The effect of horizontal alignment on travel speed is investigated at length in chapter six.

Table 9. Mixed Effect Linear Regression Model for Mean Speed on Two-Lane Highways

	Total Sample			LOS A Only		
Random Effects:						
Groups	**Variance**	**Std. Dev.**		**Variance**	**Std. Dev.**	
Participant ID	7.470	2.733		13.090	3.618	
Residual	80.380	8.966		78.030	8.833	
Fixed Effects:						
Model Term	**Coeff.**	**Std. Err.**	**t-stat**	**Coeff.**	**Std. Err.**	**t-stat**
Intercept	49.314	0.502	98.332	49.801	0.564	88.263
25-mph limit	-23.114	0.872	-26.516	-23.213	0.970	-23.937
30-mph limit	-21.551	0.585	-36.862	-21.514	0.676	-31.846
35-mph limit	-14.727	0.557	-26.454	-14.916	0.635	-23.488
40-mph limit	-11.242	0.705	-15.949	-11.538	0.795	-14.505
45-mph limit	-7.811	0.544	-14.367	-8.130	0.619	-13.127
50-mph limit	-4.864	1.133	-4.292	-5.769	1.375	-4.195
55/60-mph limit		Baseline			Baseline	
LOS A		Baseline			-	
LOS B	-1.362	0.434	-3.135		-	
LOS C	-6.245	1.450	-4.307		-	
LOS D	-11.307	3.322	-3.404		-	
LOS E	-23.639	3.135	-7.541		-	
LOS F		-			-	
No access points		Baseline			Baseline	
Driveway	-0.874	0.486	-1.798	-1.195	0.558	-2.141
Intersection	-2.339	0.616	-1.798	-1.728	0.736	-2.349
On-street parking	-4.413	0.616	-3.797	-5.032	0.731	-6.887
Non-work zone		Baseline			Baseline	
Work zone	-3.783	1.481	-2.555	-6.405	1.877	-3.412
Degree of Curvature	-0.013	0.005	-2.746	-0.011	0.005	-2.107
Clear/rainy weather		Baseline			Baseline	
Snow or Sleet	-7.588	2.006	-3.782	-8.771	2.302	-3.811
Age 16 to 24	1.924	0.469	4.107	1.418	0.544	2.608
Age 25 to 59	1.118	0.469	2.382	0.665	0.544	1.221
Age 60 or above		Baseline			Baseline	
Null Log-Likelihood			-11464			-8835
Log-Likelihood			-10600			-8196
Null AIC			22932			17673
AIC			21242			16425
Null BIC			22944			17685
BIC			21368			16552

Number of Observations: 2,901

Number of Participants: 1,593

Like freeways, younger drivers were shown to travel at higher speeds compared to middle aged and older drivers. However, this effect was found to be smaller on two-lane highways which is probably due to the inherent differences between the nature of these facilities and the fact that two-lane highways do not allow for speeding as much. The author also investigated separate models for individual states; however, there found to be significant variability among coverage of a lot of these factors by individual states, resulting in insufficient samples in most cases.

As for the variability in speed, speeds were generally shown to be less variables at higher speed limits; however, some noises were observed which could be due to the sample size variation mentioned previously in the data sections. Also, speeds were shown to have more fluctuations under LOS C and below, a pattern found with the freeway events, as well. No additional differences were identified in the variability in speeds at lower LOSs due to the limited number of events available under such conditions.

Generally, the mixed-effect models were shown to provide improved fit as compared to simple linear models which is reflective of differences in driving patterns between different individual drivers. Individual intercept terms were estimated for every model presented in this chapter. The select speeds were found to be variable among drivers as much as 4 mph on freeways, whereas this variability reduced to approximately 3 mph on two-lane highways.

Table 10. Mixed Effect Linear Regression Model for Speed Standard Deviation on Two-Lane Highways

Random Effects:			
Groups	**Variance**	**Std. Dev.**	
Participant ID	7.470	2.733	
Residual	80.380	8.966	
Fixed Effects:			
Model Term	**Coeff.**	**Std. Err.**	**t-stat**
Intercept	2.476	0.117	21.193
25-mph limit	1.061	0.267	3.969
30-mph limit	1.184	0.173	6.835
35-mph limit	0.809	0.167	4.855
40-mph limit	1.007	0.214	4.705
45-mph limit	0.51	0.163	3.127
50-mph limit		Baseline	
55/60-mph limit		Baseline	
LOS A		Baseline	
LOS B		Baseline	
LOS C or Below	0.894	0.382	2.342
No access points		Baseline	
Driveway		Baseline	
Intersection		Baseline	
On-street parking	0.474	0.199	2.381
Degree of Curvature	0.003	0.001	1.973

Number of Observations: 2,901

Number of Participants: 1,593

In addition to individual mixed-effect linear regression models for mean speeds and standard deviation in speeds, simultaneous modeling frameworks were deployed due to concerns as to potential correlations between the two measures. As a result, seemingly unrelated regression equations (SURE) models were estimated to determine if such correlations do exist and whether such modeling framework provide better fit. However, there found to be nearly no evidence as to such correlation and model results were shown to be nearly identical to individual models.

This chapter provided insights as to how drivers select their travel speed on freeways and two-lane highways. 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 (Burritt, Moghrabi and Matthias 1976). Drivers tended to reduce their travel speeds along horizontal 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.

CHAPTER 5. SPEED ANALYSIS ACROSS SPEED LIMIT TRANSITION AREAS

In addition to examining driver speed selection under constant speed limits, a related item of interest is how drivers adapt their speeds when speed limits increase or decrease. This issue has important practical value as transportation agencies are often tasked with trying to control traffic speeds in high-risk scenarios, such as in work zone environments or under adverse weather conditions. It is also of general interest to discern how drivers alter their travel speeds when speed limits change. This section summarizes outcomes of an investigation of driver speeds while traversing through transition areas, where speed limits are either increased or decreased.

5.1 Data

Data were obtained for speed limit transition areas along both freeways and two-lane highways to gain a better understanding as to how drivers adjust their speeds when posted limits are increased or decreased. According to the manual on uniform traffic control devices (MUTCD), each sign is associated with a code identifier. This is equal to 218 for regulatory speed limit signs. Using the RID sign shapefile, speed limit signs, the associated message, and the corresponding location were extracted across the six study sites. Consequently, a line shape file was developed using these point data with an assumption that speed limit remains constant between every two consecutive speed limit signs. Subsequently, by overlaying the link layer from RID -which consists of short roadway segments generated through the data collection process- with this speed limit layer, the links along which the speed limit changed were identified. Next, select links were manually investigated using the Google Earth add-in in ArcMap to confirm that the links do satisfy the required condition. In addition to the speed limit criterion, the research team ensured with the VTTI that at least 10 traces corresponding to unique drivers are available along each of the requested links. Ultimately, unique link IDs were identified for a total of 79 and 106 locations across freeways and two-lane highways, respectively. This resulted in acquisition of a total of 2,578 and 2,940 traces across each of these facilities.

When examining the select links, they were found to vary significantly in their lengths and in the relative location of the sign to the link's beginning/end. Consequently, the time-series data were obtained for the 30 seconds immediately upstream and downstream of each identified link to capture sufficient data while approaching and passing the speed limit sign. For the purpose of analysis, fixed segments of up to 1000 ft upstream and downstream of the sign were created. This helped to better capture the drivers' behavior across the transition areas. This included segments where the speeds were stable under the initial posted limit, when the driver first noticed the sign (approximately 400 ft upstream of the sign), and sufficient distance when they passed the sign until they reached a stable speed, again.

As mentioned previously, the location information was collected with a frequency of 1 Hz, while the speed information had higher resolution with frequency of 10 Hz. After some preliminary analysis, it was shown that using the time-series data with a 10-Hz frequency may provide finer and more accurate results in the analysis of these types of segments. As a result, first the obtained time-series were overlaid with the generated segments to extract the portions of trips that fell along these segments. Subsequently, the position of the vehicle during the intermediate time stamps were approximated using the travel speed calculated by the Equation 8-9:

$$x^{(t)} = x^{(t-0.1)} + v^{(t-0.1)} * 1.47 * 0.1 \qquad \text{(Equation 8)}$$

$$x^{(t)} = x^{(t+0.1)} - v^{(t)} * 1.47 * 0.1 \qquad \text{(Equation 9)}$$

where $x^{(t)}$ is the location of the vehicle at timestamp *t*; $v^{(t)}$ is the travel speed at timestamp *t* in mph; and 1.47 is the conversion factor between mph to ft/s as the locations were measured in feet rather than miles. This resulted in identification of the location of all points included in the analysis set and their relative distance to the sign. Figure 19 displays a randomly selected trace going through a 5-mph increase in the posted speed limit prior and following to location interpolation.

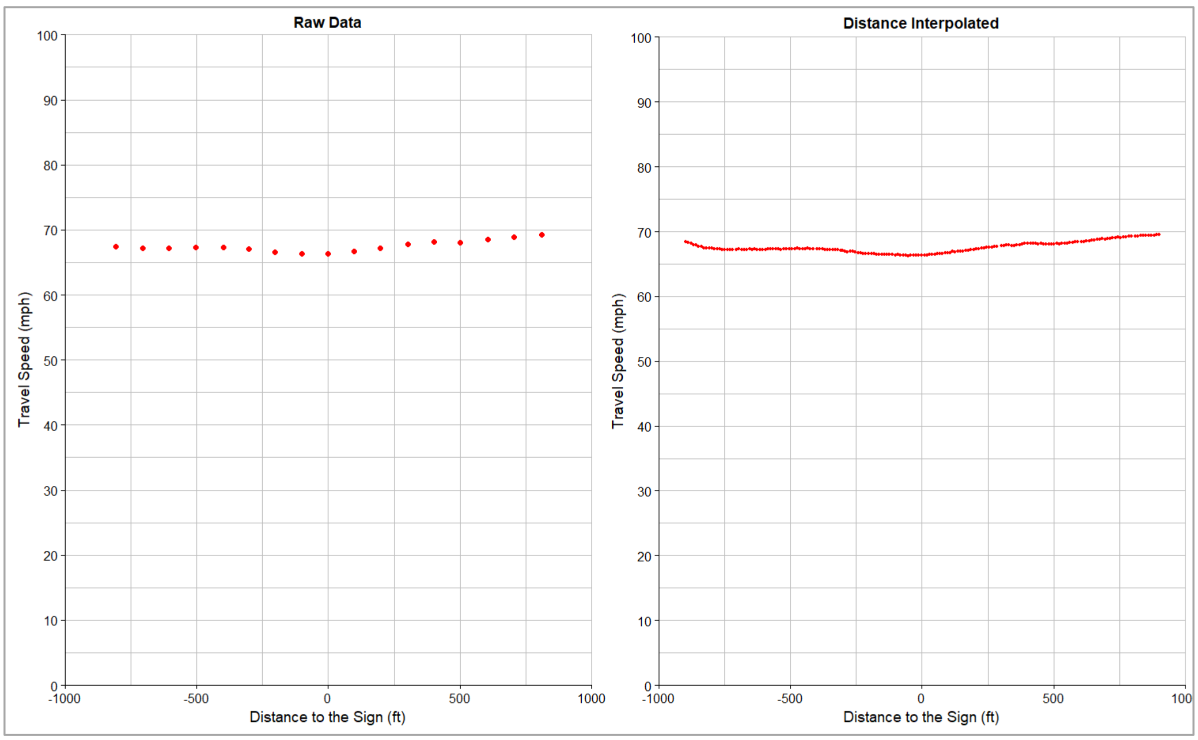

Figure 19. Example of a Trace with and without Location Interpolation

Utilizing the fixed segments as base layer for each of the identified signs also helped to resolve the issue of mixed directions on two-lane highways. While there were unique route identifiers for each direction of travel on divided roadways, single route identifier was assigned to both directions on undivided roadways that may occasionally result in the information of the opposing direction being conflated to the data in the direction of travel.

In addition to approximating the vehicle location using the above equations, the geometric attributes across the intermediate time stamps were filled using the fill-forward method first, and the fill-backward method next. In other words, the geometric attributes were assumed to remain constant until a second observation was recorded. In case of missing geometric data during the beginning of a trace, when no information has yet been recorded, the data were filled using the succeeding observations.

Candidate locations were selected with an aim to cover a wide range of speed limit and speed limit changes, as well as geometric characteristics across both freeways and two-lane highways. However, differences in sample size across speed limits were inevitable due to prevalence of certain limits and limit changes across states. Table 11 provides an overview of the frequency of trips obtained at each speed limit by size of speed limit change. For freeways, the 55- and 65- mph limits had the highest frequencies which was due to the fact that two states in the study (i.e. New York and Pennsylvania) have only 55- and 65-mph limits in place. Consequently, traces under 10-mph increase/reduction had the majority, as well.

Table 11. Number of Obtained Trips by Speed Limit and Size of Speed Limit Change on Freeways

Initial Speed Limit (mph)	**Size of Speed Limit Change (mph)**						
	-15	-10	-5	5	10	15	Total
55	-	-	-	-	584	213	797
60	-	-	-	62	197	-	259
65	-	735	75	228	-	-	1,038
70	190	198	155	-	-	-	543
Total	190	933	230	290	781	213	2,637

Table 12 provides similar information for the number of trips obtained across two-lane highways. In this case, traces covered a wider range of limits and limit changes. Traces under 35- and 45-mph accounted for approximately half of the sample, whereas the traces under 60-mph had the minimum frequency. As far as frequencies across various limit changes, traces under 10-mph reduction held the highest frequency with 813 trips. On the other hand, there were only 97 traces undergoing a 15-mph reduction in posted speed limit. A few cases with 25 mph reduction/increase were identified, as well; however, these trips had to be removed from the sample due to limited frequencies.

Table 12. Number of Obtained Traces by Speed Limit and Size of Speed Limit Change on Two-Lane Highways

Initial Speed Limit (mph)	**Size of Speed Limit Change (mph)**								
	-20	-15	-10	-5	5	10	15	20	Total
25	-	-	-	-	30	174	48	-	252
30	-	-	-	17	40	76	38	-	171
35	-	-	135	41	78	338	-	138	730
40	-	32	72	73	160	62	-	-	399
45	7	51	291	184	-	223	-	-	756
50	-	14	88	26	31	-	-	-	159
55	129	-	227	37	42	-	-	-	435
60	-	-	-	46	-	-	-	-	46
Total	136	97	813	424	381	873	86	138	2,948

Figure 20 and Figure 21 display boxplots of travel speeds at various limits and limit changes upstream of the regulatory speed sign for freeways and two-lane highways, respectively. These plots show the travel speed at each speed limit separated by the upcoming limit change. Any differences between plots within a single speed limit are indicative of variations in speed selection patterns upstream of speed limit signs.

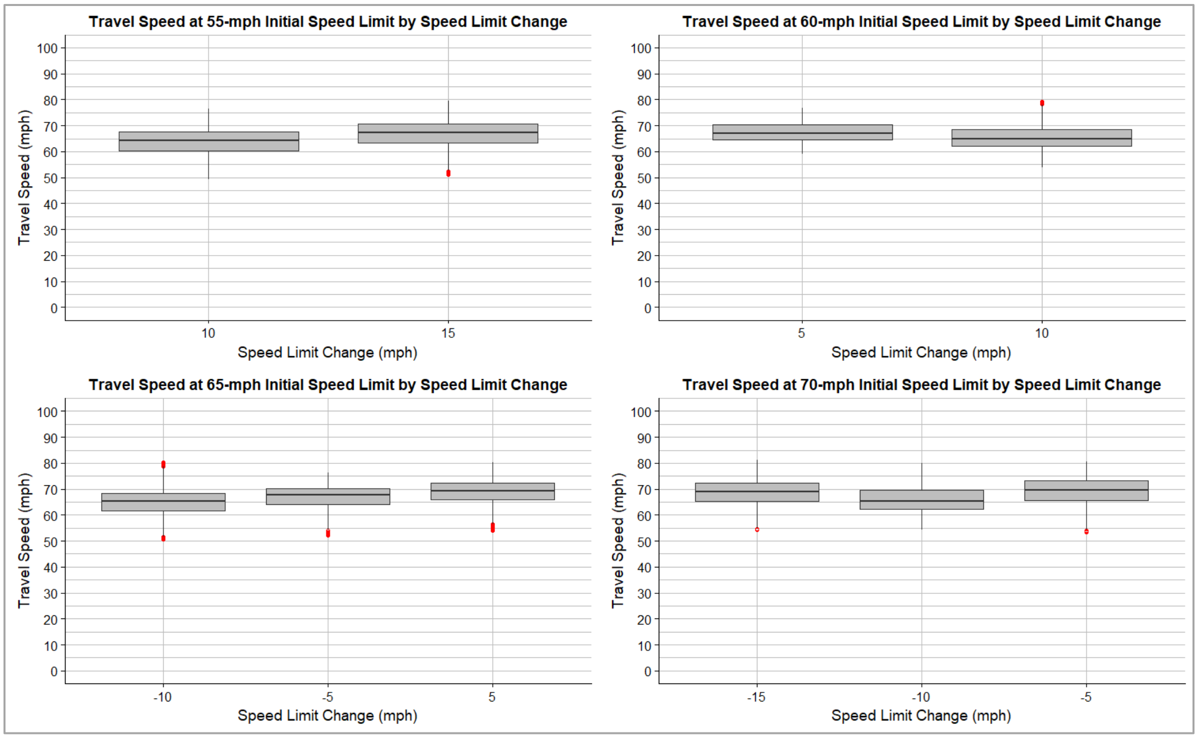

Figure 20. Upstream Travel Speeds by Posted Speed Limit and Size of Upcoming Speed Limit Change on Freeways

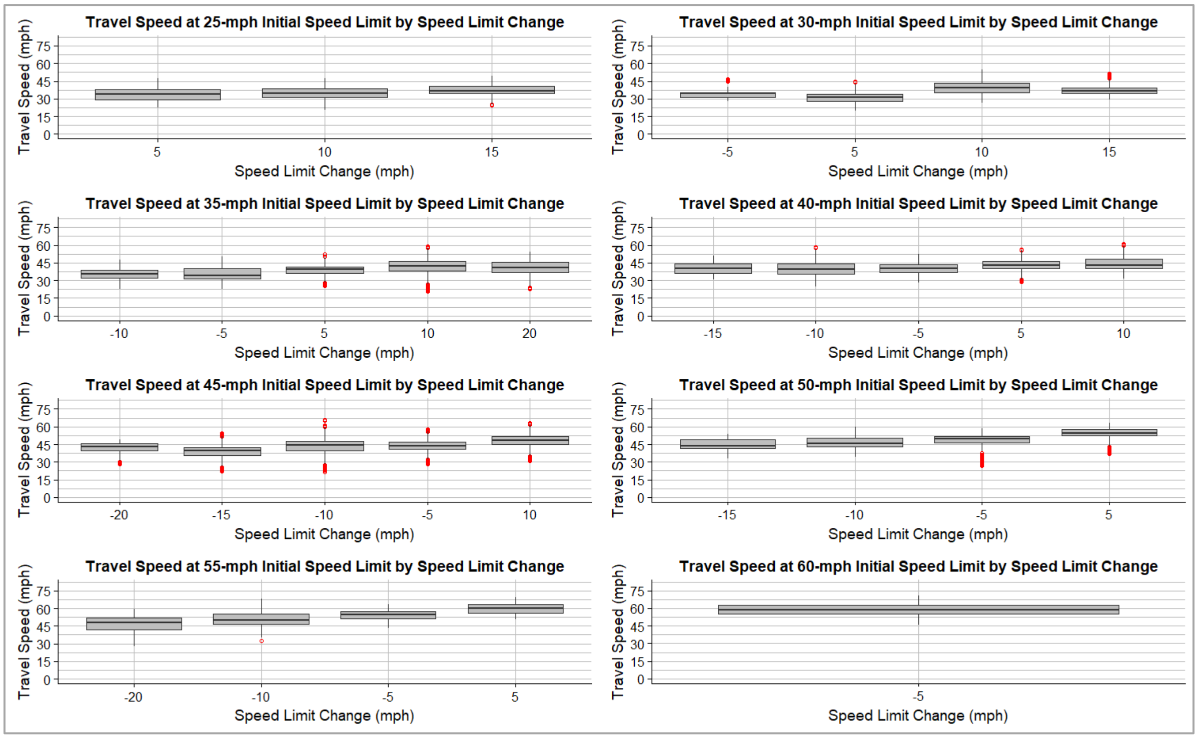

Figure 21. Upstream Travel Speed by Posted Speed Limit and Size of Upcoming Speed Limit Change on Two-lane Highways

One other important hinderance to properly assess the speed selection behavior was the lack of traffic congestion information along these segments as they were not necessarily among those events reduced by the VTTI. As such, no information was available to indicate whether the speed profiles are reflective of drivers' own choice of speed or they were essentially imposed from outside. To resolve this issue, forward video data for all the obtained trips were requested by the research team for review. In this process, video data were reviewed by team members with an aim to identify any incident, object, or condition that may potentially impact the select speed. Information was collected regarding presence of leading vehicles or pedestrians, weather condition, time of day (i.e. day versus night), and presence of workzones along the trip. This information was collected as a series of indicator variables that may simply be included in the models.

Figure 22 and Figure 23 display the information extracted from the video data for freeways and two-lane highways, respectively. These results indicate presence of leading vehicles in approximately 50 percent of the trips across both facilities. Also, while the majority of trips occurred under clear or cloudy weather conditions, nearly 6.5 percent of trips took place under snowy weather conditions. The attempt was to match the data elements between these datasets with those available from the InSight reduced data described in the previous section to the extent possible.

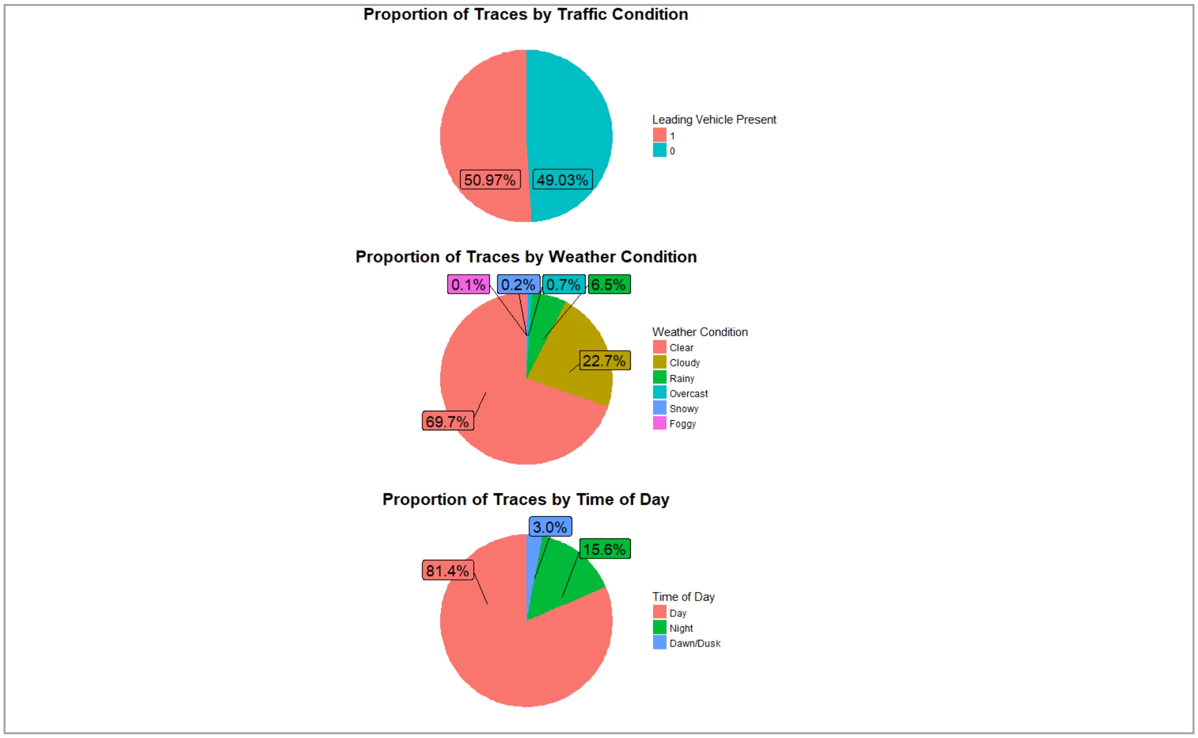

Figure 22. Overview of the Reduced Video Data for Trips across Freeways Transition Areas

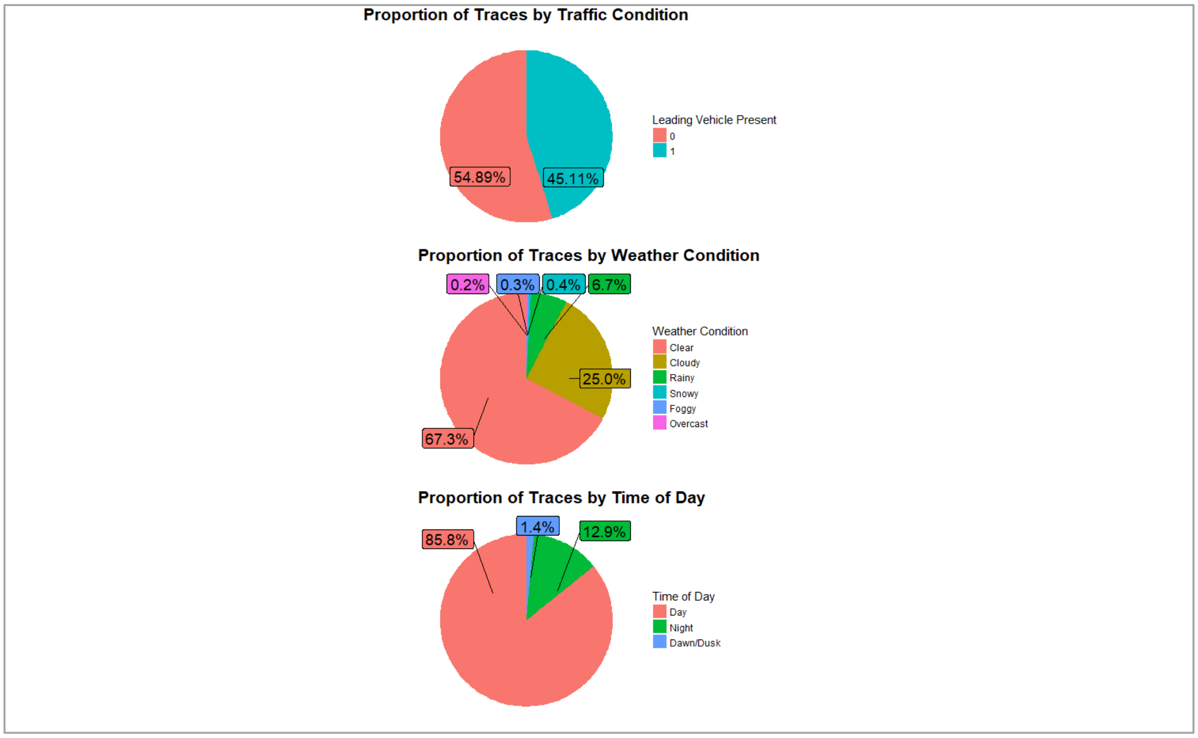

Figure 23. Overview of the Reduced Video Data for Trips across Two-Lane Highways Transition Areas

The reduced video data were integrated with the time-series data to account for other factors such as presence of a leading vehicle that could have potentially altered drivers' select speed. However, video files were missing in some cases due to the cameras' malfunction or other reasons resulting in losing some traces when using the video data.

5.2 Methodology

Like the previous section, speed analysis was conducted through estimation of mixed-effect OLS regression models. However, in this case speed profiles were included as time-series data instead of averaging the speed over the entire trip duration. This was imperative as the pattern in the speed profiles was of interest. Consequently, although the overall model utilized in this section was similar to that of chapter four, some minor tweaks were necessary. In addition to the participant specific term described in the previous section, two other intercept terms were introduced. The first one was trip-specific that may vary across trips but retained same value for each individual trip. This parameter accounts for unobserved factors that are unique to each event. The second term was location specific and was designed to capture the correlation between traces that took place at same locations. Ultimately, the travel speed at each point is estimated through OLS regression models using the following equation:

$$S_{ijk}{}^{(t)} = \boldsymbol{\beta_i}{}^{(\boldsymbol{t})}\boldsymbol{X_i}{}^{(\boldsymbol{t})} + \varepsilon_i{}^{(t)} + \delta_j + \gamma_i + \zeta_k \qquad \text{(Equation 10)}$$

where $S_{ijk}{}^{(t)}$ is the travel speed corresponding to trip i, driver j, and location k at timestamp t; $\boldsymbol{\beta_i}{}^{(\boldsymbol{t})}$ is the vector of estimable coefficients, $\boldsymbol{X_i}{}^{(\boldsymbol{t})}$ is a vector of roadway geometric features, traffic attributes, and driver behavior/characteristics at timestamp t; $\varepsilon_{\mathrm{i}}{}^{(\mathrm{t})}$ is an error term capturing unobserved heterogeneity; δ_j is the driver-specific term corresponding to driver j to account for potential correlations between different observations corresponding to same individuals; γ_i is an intercept term corresponding to event *i* to capture correlations between observations within a single trip; and ζ_k is the location specific intercept that controls for unobserved heterogeneity in events corresponding to same location k. These intercept terms are assumed to be normally distributed with mean of zero and variance of σ^2.

In essence, these terms captured 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). Consequently, δj is a parameter that retains the same coefficient for each driver in every trip (assuming the driver has multiple events in the database) and, thus, is able to capture general differences in speed selection behavior. Likewise, γ_i and ζ_k are parameters that account for unobserved factors that are unique to each specific trip and location, respectively. Adding these participant-, trip-, and location- specific terms results in what is commonly referred to as a random effects model. While these effects are specific to each trip or study participant, they are a random sample from the broader driving population.

5.3 Results and Discussion

For each facility type, random effects linear regression models were estimated, which detail how speeds change when a speed limit reduction or increase is introduced. In each case, the mean baseline (i.e., pre-speed limit change) speed is provided, along with estimates of the mean increase (or decrease) in speeds associated with speed limit changes of 5 to 15 mph for freeways and 5 to 20 mph for two-lane highways. Table 13 demonstrates the results of the mixed linear regression model estimated for freeway trips across transition areas.

Table 13. Mixed Effect Linear Regression Model for Travel Speed across Speed Limit Transition Areas on Freeways

	Total Sample			No Leading Vehicle Sample		
Random Effects:						
Groups	**Variance**	**Std. Dev.**		**Variance**	**Std. Dev.**	
Trip ID	17.238	4.152		15.979	3.997	
Location ID	3.930	1.982		5.195	2.279	
Participant ID	3.893	1.973		2.685	1.639	
Residual	2.247	1.499		1.924	1.387	
Fixed Effects:						
Model Term	**Coeff.**	**Std. Err.**	**t-stat**	**Coeff.**	**Std. Err.**	**t-stat**
Intercept	63.780	0.358	177.924	63.521	0.386	164.672
55-mph limit		Baseline			Baseline	
60-mph limit		Baseline			Baseline	
65-mph limit	0.934	0.281	3.326	0.863	0.269	3.206
70-mph limit	2.990	0.443	6.752	2.320	0.416	5.575
5-mph limit reduction	-0.341	0.018	-19.471	-0.891	0.024	-37.931
10-mph limit reduction	-1.012	0.010	-104.750	-0.768	0.012	-62.712
15-mph limit reduction	-1.422	0.026	-54.726	-1.429	0.028	-51.330
5-mph limit increase	0.745	0.015	51.123	0.686	0.018	38.402
10-mph limit increase	1.118	0.010	107.972	1.077	0.013	81.851
15-mph limit increase	1.515	0.021	70.882	1.371	0.026	53.488
No Leading Vehicle		Baseline			-	
Leading Vehicle Present	-0.448	0.242	-1.853		-	
Clear weather		Baseline			Baseline	
Rain	-1.079	0.469	-2.299		N/S	
Snow		N/S			N/S	
Age 16 to 24	2.080	0.335	6.204	2.501	0.439	5.702
Age 25 to 59	2.150	0.320	6.714	2.357	0.420	5.619
Age 60 or above		Baseline			Baseline	
Null Log-Likelihood			-1221717			-582588
Log-Likelihood			-562107			-297148
Null AIC			2443437			1165180
AIC			1124249			594325
Null BIC			2443459			1165200
BIC			1124429			594475
Number of Observations: 304,799				Number of Observations: 168,140		
Number of Events: 1,525				Number of Events: 829		
Number of Participants: 951				Number of Locations: 623		
Number of Locations: 262				Number of Participants: 218		

N/S: Not Significant

For such traces, it is interesting to note that speeds remained relatively stable, regardless of the posted limit. No differences were observed between mean speeds at 55- and 60-mph limits where the mean speeds were approximately 63.8 mph. The mean speeds increased by only 0.9 mph at 65 mph and approximately 3 mph at 70 mph (both values relative to the 55-/60-mph limits). This indicates that travel speeds are significantly above the posted limits upstream of the transition points at lower limits, whereas the opposite is true at 65- and 70-mph limits. This probably relates back to the distribution of the trips presented back in Table 11. It is imperative to keep in mind that all traces at 70-mph initial speed limit were upstream of a speed reduction zone, whereas the traces at 55-mph initial speed limits were all followed by speed limit increases of 10 or 15 mph. This could be another reason for the observed mild speed differences, meaning that drivers start to adjust their speeds upstream of the sign, before limit change occurrence. As shown by past literature, drivers tended to change their speeds by lesser amounts at higher posted limits (Parker Jr and Parker 1997, Kockelman et al. 2006, Mannering 2007).

When changes did occur, the actual speed changes were significantly less than the associated change in the posted limit. For example, increases of 5, 10, and 15 mph, result in increases of 0.7, 1.1, and 1.5 mph, respectively. When speed limits were reduced, similarly muted impacts occurred. When limits were reduced by 5 mph, travel speed decreased by only 0.3 mph; this reduction was slightly greater when limits were reduced by 10 and 15 mph; travel speeded reduced by 1.0 and 1.4 mph at each of these limit changes, respectively. It is important to note that while these reductions turned out to be much smaller than expected, they were all statistically significant at a 99 percent confidence interval; meaning that though minimal, some changes in travel speed did occur across transition areas.

Similar to the results presented in chapter 4, some other variables were also found to significantly impact travel speeds aside from posted limits. Presence of a leading vehicle was shown to reduce the mean speeds by approximately 0.5 mph. In addition, travel speeds were found to be lower under rainy weather condition; however, no significant effect associated with snowy weather was found which is probably due to the limited sample size available for such trips. Again, mean speeds were shown to be higher among younger and middle-aged drivers.

In addition, a separate model was estimated for those events that were not found to follow any leading vehicle. This was done with an aim to examine drivers' select speed under free-flow condition. Parameter estimates were found to be relatively stable between the two models. However, the coefficients for the two age categories slightly increased which is probably reflective of more opportunities for speeding when no leading vehicle was present. The slight reductions in speeds in absence of leading vehicles (compared to the total sample), as well as the increased estimates for driver age indicate that when other vehicles are present drivers tend to adjust their speeds with regard to the moving flow. When examining the goodness-of-fit measures, both models were shown to be relatively successful.

Turning to the results for the analysis of two-lane highway trips, presented in Table 14, speeds were comparable on highways posted at 25 or 30 mph where no statistically significant difference was observed. As in the analyses presented previously, travel speeds tended to increase by lesser amounts at higher posted speed limits with an exception for those at 60-mph limit. This could be due to the limited sample available for these traces as presented in Table 12, as well as the fact that only one type of limit change (i.e. 5-mph reduction) occurred at this limit. Also, travel speeds were shown to be markedly above the posted limit at lower speeds and below the posted limit at higher limits. This is a similar trend to that observed with freeway trips. The mean speeds were shown to be significantly above the posted limit at 25 and 30 mph (approximately 36 mph). It is essential to note that all trips at an initial speed limit of 25 mph were upstream of a speed limit increase zone with the majority undergoing a 10-mph increase. On the other hand, all trips under 60-mph limit and approximately 90 percent of those at 55-mph limit went through speed limit decreases.

Interestingly, the speed limit changes were associated with much greater impact on two-lane highways than on freeways. For example, speeds were shown to decrease by 3.6 and 2.6 mph where reductions of 15 and 10 mph occur. These values are roughly two times greater than what was observed for freeways. Much of this may be attributable to the nature of two-lane highways as speed changes generally occur in concert with changes in functional class, land use, access density, and in other ways that significantly alter the driving environment. Drivers were found to decrease their speeds by roughly 1.2 mph for every 5-mph reduction in the posted limit. Reductions of 10, 15, and 20 mph in posted limit decreased mean speeds by only 2.5, 3.6, and 6 mph. It is interesting that much larger changes occurred when the speed limit was decreased as opposed to increased, which may be reflective of concerns as to speed enforcement in addition to some of the other factors noted previously.

Although the speed changes seem to be much lower than what was expected, it is crucial to interpret the results considering both mean baseline speeds and the trip frequencies. For example, all trips at a 60-mph initial limit went through a 5-mph limit increase. For these traces, mean baseline speed was around 57.6 mph upstream and 56.5 mph downstream the sign. Likewise, upstream mean speed was found to be 48.5 mph where initial posted limit was 55 mph. When looking at the frequency distribution of trips in Table 12, nearly 50 percent of such trips went through a 10-mph limit reduction. Adding such reductions’ associated parameter estimate results in a downstream speed of 46 mph which is comparable to the downstream speed limit of 45 mph. These results indicate that drivers start adjusting their travel speeds upstream of the regulatory speed sign. This behavior probably starts as soon as drivers notice the sign. Such behavior is probably more pronounced on roadways with which the drivers are more familiar with and had experienced driving through.

Table 14. Mixed Effect Linear Regression Model for Travel Speed across Speed Limit Transition Areas on Two-Lane Highways

	Total Sample			No Leading Vehicle Sample		
Random Effects:						
Groups	**Variance**	**Std. Dev.**		**Variance**	**Std. Dev.**	
Trip ID	16.369	4.046		14.793	3.846	
Location ID	1.580	1.257		3.468	1.862	
Participant ID	13.554	3.682		11.550	3.399	
Residual:	5.572	2.360		4.816	2.195	
Fixed Effects:						
Model Term	**Coeff.**	**Std. Err.**	**t-stat**	**Coeff.**	**Std. Err.**	**t-stat**
Intercept	36.519	0.585	62.406	36.879	0.643	57.398
25-mph limit		Baseline			Baseline	
30-mph limit		Baseline			Baseline	
35-mph limit	2.798	0.663	4.222	2.938	0.722	4.068
40-mph limit	5.689	0.812	7.003	5.265	0.848	6.208
45-mph limit	7.007	0.675	10.378	6.886	0.718	9.589
50-mph limit	10.483	1.036	10.121	10.120	1.170	8.650
55-mph limit	11.896	0.775	15.355	11.897	0.830	14.334
60-mph limit	21.139	2.173	9.729	21.668	2.191	9.888
5-mph limit reduction	-1.198	0.023	-52.281	-1.183	0.028	-41.531
10-mph limit reduction	-2.579	0.016	-159.506	-2.634	0.020	-130.610
15-mph limit reduction	-3.622	0.053	-68.732	-3.147	0.072	-43.554
20-mph limit reduction	-6.032	0.064	-94.657	-6.308	0.083	-75.702
5-mph limit increase	1.479	0.024	62.140	1.352	0.027	49.241
10-mph limit increase	1.988	0.016	121.862	1.995	0.020	101.844
15-mph limit increase	1.937	0.070	27.538	1.344	0.092	14.592
20-mph limit increase	3.069	0.051	60.150	3.802	0.073	51.937
Degree of Curvature	-0.162	0.003	-53.339	-0.241	0.004	-53.652
No Leading Vehicle		Baseline			-	
Leading Vehicle Present	-1.210	0.240	-5.046		-	
Age 16 to 24	1.306	0.293	4.462	1.836	0.392	4.680
Age 25 to 59	0.878	0.293	2.993	0.951	0.393	2.419
Age 60 or above		Baseline			Baseline	

Table 14. (Continued)

Null Log-Likelihood	-1,299,120	-738,458
Log-Likelihood	-696,226	-386,818
Null AIC	2,598,245	1,476,919
AIC	1,392,498	773,681
Null BIC	2,598,267	1,476,940
BIC	1,392,743	773,902
Number of Observations: 303,230		Number of Observations: 173,892
Number of Events: 1,491		Number of Events: 864
Number of Participants: 1,046		Number of Locations: 666
Number of Locations: 410		Number of Participants: 351

Unlike freeways, mean speeds were shown to be notably reduced across horizontal curves. An impact that was found to be more pronounced when no leading vehicle was present. Due to the substantial impact of horizontal alignment on travel speeds, this impact was investigated more in-depth chapter six. As for driver age, younger and middle-aged drivers were found to be associated with higher travel speeds. However, such impacts were found to be less pronounced across transition areas as compared to areas with no limit change. This is reflective of stronger role of roadway condition rather than individuals' behavior when selecting speeds across transition areas. These models were all found to provide significantly improved fit when considering different goodness-of-fit measures including AIC, BIC, and log-likelihood.

These models all estimated the mean baseline speed as well as the mean increase or decrease across transition areas. One concern was the differences between drivers' speed selection behavior when same increases or decreases are introduced at different initial speed limits. As such, separate models were developed at each speed limit across both facilities to better capture such differences between drivers' behavior. The results of these analyses may be found in the Appendix C of this dissertation.

CHAPTER 6. SPEED ANALYSIS ON HORIZONTAL CURVES

The results from the past two chapters demonstrated significant impact of horizontal curvature on drivers' select speed, especially on two-lane highways. As a result, the third focus area of this study was to examine driver speed selection along horizontal curves on two-lane highways and evaluate the efficacy of advisory speed signs. Few studies have investigated the impact of advisory speed signs on mean speeds and drivers' level of compliance with them in the past and have generally shown minimal or no impact associated with installation of such signs. Also, majority of these studies investigated the drivers' compliance rate or the average speed changes across the curves and fail to account for changes in the speed profiles upstream and downstream of the curves. In addition, much of such studies date back to the 90's or earlier (Ritchie 1972, Chowdhury et al. 1991, Bennett and Dunn 1994)which necessitates revisiting this issue. This section investigates the general drivers' choice of speed on horizontal curves across two-lane highways and the impact of advisory speed signs on them.

6.1 Data

A procedure similar to that of speed limit transition areas was followed to identify links associated with advisory speed signs. Following the coding system provided by the MUTCD, depicted previously in Figure 2, a series of links associated with advisory speed signs were identified. Subsequently, these links and the identified signs were reviewed using the Google Earth add-in available in ArcMap to confirm that the select candidates are indeed curve advisory speed signs and do display the listed message. Also, like the previous dataset, the minimum 10 traces per link criterion was considered. Ultimately, a total of 135 links associated with curve advisory speed signs were identified. In addition, 29 links were identified corresponding to curves without advisory speed signs to be utilized as control segments. When selecting these links, curve radius and length, as well as posted speed limits were considered so that they match the ones in the other set to the extent possible. However, in most cases it was difficult to identify identical curves since if a collection of characteristics does satisfy the criteria for installation of curve advisory signs, it is somewhat unlikely to have them not being associated with an advisory sign. As with the speed limit transition areas, requested time-series data were extended for the 30 seconds immediately before and after each link where a sign was located. Ultimately, a total of 4,604 and 842 traces were obtained for curves with and without advisory speed signs, respectively. The frequency distribution of the obtained trips is provided in Table 15. The increase in the number of trips in this table compared to the previously mentioned values is the due to the fact that in a few cases extending the trips for 30 seconds upstream and downstream of the sign link resulted in capturing other advisory signs, and as a result the total number of trip segments used for analysis increased.

Table 15. Frequency Distribution of Obtained Trips by Posted Speed Limit and Suggested Speed Reduction

Posted Speed Limit (mph)	**Suggested Speed Reduction (mph)**						
	0	5	10	15	20	25	Total
30	191	278	220	5	-	-	694
35	50	693	250	114	211	23	1,341
40	127	60	103	81	-	-	371
45	213	658	949	177	8	178	2,183
50	65	14	48	60	22	-	209
55	87	56	564	201	27	9	944
Total	733	1759	2,134	638	268	210	5,742

One complication associated with preparation of this set of data related back to the point-based nature of the sign shapefiles. While regulatory speed limits were assumed consistent between consecutive signs, this assumption does not apply to advisory speed signs. Subsequently, a curve inventory dataset was created for the collection of curves for which the data were requested. For each location, information was collected as to the location of the curve beginning, referred to as point of curvature (PC), curve end, referred to as point on tangent (PT), and advisory speed sign. These segments were extended for 400 ft upstream of the sign to capture the patterns in travel speeds preceding to the sign, as well. Once this inventory was put together, these segments were overlaid by the obtained time-series data using the ArcMap's "Overlay Route Events" tool, described in chapter three, to integrate the obtained data with the curves and the associated characteristics.

Like speed limit transition areas, time-series data were used with 10-Hz frequency where travel speed information was recorded with a resolution of 10^{th} of a second. Similarly, the intermediate locations were interpolated using Equation 8 and Equation 9 discussed in the previous chapter. This was done to capture the changes in drivers' select speed both upstream and downstream of the curve.

Figure 24 displays the boxplots of the baseline mean travel speeds by posted limit and advisory speed. Some slight differences are evident between the baseline speeds based on the size of upcoming advisory speed. These plots indicate that upstream speeds were decreased as the difference between posted speed limit and advisory speed increased. This finding indicates that drivers begin adjusting their speeds far upstream of the curve PC, especially when larger reductions are suggested.

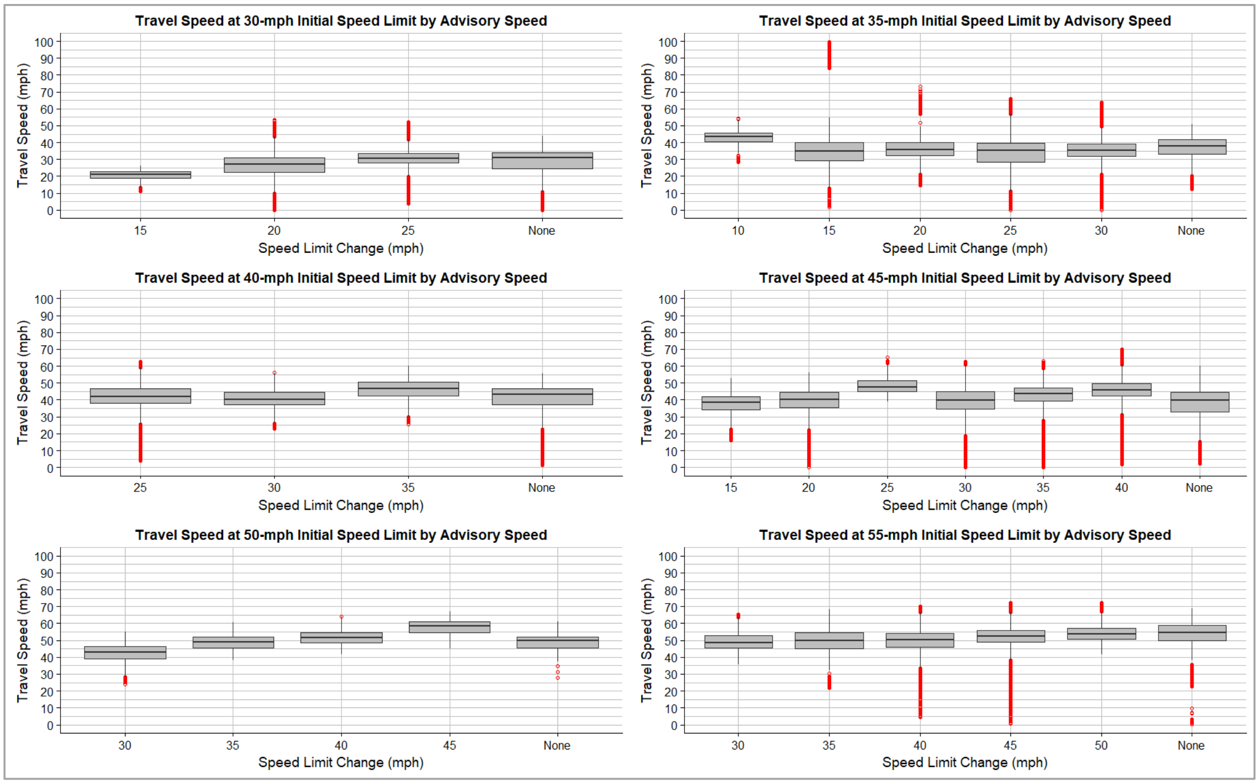

Figure 24. Upstream Travel Speed by Posted Speed Limit and Advisory Speed

In addition, video data were obtained and reviewed by the research team following similar process outlined in chapter five. Figure 25 presents a summary of the reduced video data. Nearly 45 percent of the subject vehicles were found to be following a leading vehicle which may potentially impact travel speeds. Although the majority of trips occurred under clear weather condition, 8.5 percent of them were found to occur under rainy weather, whereas less than 1 percent were associated with snowy weather condition.

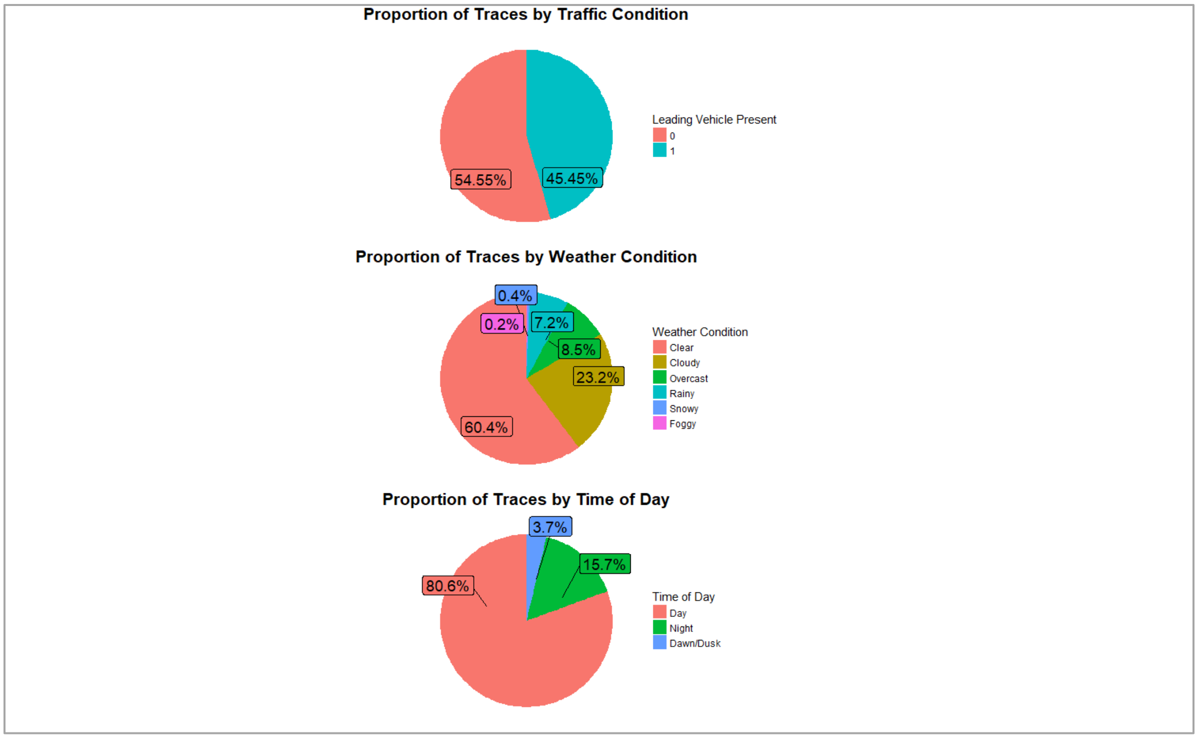

Figure 25. Overview of the Reduced Video Data for Curves

Next the integrated data were analyzed using two different methods. First, mixed effect linear regression models were estimated following the same process described in chapter five. In addition, time-series data were analyzed using Functional Data Analysis (FDA) methods at select locations to better investigate the patterns in drivers' speed selection behavior. Following section describes the underlying theory of FDA and discusses the steps performed to evaluate the patterns in the functional data.

6.2 Methodology

In addition to investigation of driver behavior with respect to speed selection across speed limit transition areas and horizontal curves, a more in-depth analysis of behavioral data was conducted through employing Functional Data Analysis (FDA) methods for select locations. This study used the procedures for FDA as outlined by Ramsay and Silverman in the book 'Functional Data Analysis' (Ramsay 2006). FDA is essentially employed by researchers (where possible) to demonstrate the existing data in a way that more prominent characteristics can be highlighted. Also, such analysis is broadly conducted to further examine the existing pattern and variations in the data, as well as to identify the sources resulting in such variations in the outcome or dependent variable. More importantly, what makes FDA a strong analysis candidate method is its ability to compare the variation and patterns between two or more sets of data. Such datasets may be made of different replicates of same function, or different functions built from same replicates.

In the context of FDA, functions are presented as linear combination of basis functions. Fourier and B-spline basis functions are broadly used for FDA purposes. Fourier basis functions are generally employed when some sort of periodicity and cyclic trends are present, whereas use of B-spline basis functions is suggested in absence of such repetitive patterns.

The basic assumption of FDA is that the observed discrete data values are basically snapshots of an underlying smooth function at any given time (or other continuous domain). In addition, the underlying function is assumed to be smooth to some degree, meaning that certain number of derivatives are defined and computable. While smoothness of the assigned function is one of the fundamental assumptions of FDA, the discrete observed vector $y = (y_1, y_2, y_3, \ldots, y_n)$ may not exhibit such property due to the presence of noise in the data, and is specified as:

$$y_j = x(t_j) + \varepsilon_j \qquad \text{(Equation 11)}$$

where y_j is the observed value at point j, $x(t_j)$ is the assigned function evaluated at point t_j, and ε_j is the error or disturbance term, normally distributed with mean zero and variance of σ^2. As alluded to previously, functional data are generated through a weighted sum of K basis functions φ_k as:

$x(t) = \sum_{k=1}^{K} c_k \varphi_k(t)$ (Equation12)

where c_k is the k^{th} element of the vector of coefficients denoting the weights, and φ_k is the k^{th} basis function. For speed analysis purposes conducted as part of this study, B-spline basis functions were used as they best fit data that are open-ended and do not exhibit any periodic patterns. The *Roughness Penalty* or *Regularization* approach was used to smooth the discrete functional data in this dissertation for it not only preserves the general properties of basis functions, but also generates better results particularly when considering derivatives.

The objective of an FDA was to fit the discrete measures y_j , $j = 1, 2, \dots, n$ a function $x(t)$ such that it minimizes the residuals sum of squares. In a standard model, such measure is defined as:

$SMSSE\ (\boldsymbol{y}|\boldsymbol{C}) = \sum_{j=1}^{n}[y_j - \sum_{k}^{K} c_k \varphi_k\ (t_j)]^2 = (\boldsymbol{y}\ - \boldsymbol{\Phi}c)'(\boldsymbol{y}\ - \boldsymbol{\Phi}c)$ (Equation 13)

However, an underlying assumption for this standard model is that the residuals (ε_j's) are independently and identically distributed (IID) with mean of zero and constant variance of σ^2 which is often violated with real world data. Consequently, to account for autocorrelated errors, Equation 13 is expanded to:

$SMSSE\ (\boldsymbol{y}|\boldsymbol{C}) = (\boldsymbol{y}\ - \boldsymbol{\Phi}c)\boldsymbol{W}'(\boldsymbol{y}\ - \boldsymbol{\Phi}c)$ (Equation 14)

Where **W** is the inverse variance-covariance matrix.

One other concern that arises when smoothing the functional data is the tradeoff between smoothness and bias. While the observed value of y_j is an unbiased estimator for $x(t_j)$, it may result in high variance curves which exhibit high frequency local fluctuations. As such, a new term is added to Equation 14 to penalize the sum of squared errors for excessive roughness. Consequently, Equation 14 is revised to:

$$PENSSE_{\lambda}(x|\boldsymbol{y}) = [\boldsymbol{y} - x(\boldsymbol{t})]'\boldsymbol{W}[\boldsymbol{y} - x(\boldsymbol{t})]^2 + \lambda\, PEN_2(x) \qquad \text{(Equation 15)}$$

where λ is a smoothing parameter, and PEN_2 is a measure of roughness calculated based on the second derivative of the introduced function (defined across the entire range of values), and is defined as:

$$PEN_2(x) = \int [D^2 x(s)]^2 ds \qquad \text{(Equation 16)}$$

By using the *penalized sum of squared errors* (PENSSE), the function goodness of fit, as well as its roughness are considered simultaneously to identify an appropriate smooth function. Larger values of λ results in marked penalty amounts for SSE, and in this way more emphasis must be given to function smoothness rather than goodness of fit. As such, when λ goes to infinity the smoothed function ($i.e. x(t)$) approaches the standard linear regression, whereas when λ goes to zero, there is nothing to penalize the SSE for, and as a result, $x(t)$ is just an interpolant to the data.

Subsequent step was to identify an appropriate smoothing parameter that refrains excessive roughness while still capturing the noticeable properties of the underlying function. This dissertation utilized the *generalized cross-validation* (*GCV*) (Golub, Heath and Wahba 1979) method to choose the tuning function whose specification is:

$$GCV(\lambda) = \left(\frac{n}{n - df(\lambda)}\right)\left(\frac{SSE}{n - df(\lambda)}\right) \qquad \text{(Equation17)}$$

Once the smoothed functions were developed, the mean and confidence interval of groups of functional data, as well as the first derivatives were calculated to further investigate driver behavior in speed across various horizontal curves. The mean of functional data is simply the point-wise average of the generated functional data as:

$$\bar{x}(t) = \frac{\sum_1^n x_i(t)}{n} \qquad \text{(Equation 18)}$$

Ultimately, given the variance-covariance matrix of the fitted functions as $Var(\hat{y}) = \mathbf{\Phi} C \sum C^T Q^T$, the confidence interval of the group of time-series data can be computed as:

$$CI = \hat{y}(t) \pm z_{\alpha/2}\sqrt{Var(\hat{y}(t))} \qquad \text{(Equation 19)}$$

In the context of this study, deriving the patterns in the first derivative of the speed profiles was also beneficial as they exhibit where drivers begin adjusting their acceleration. As a result, similar procedures were conducted to smooth and estimate the mean acceleration function at select locations. Following section, summarizes the findings from the regression analysis, as well as the outcomes of the FDA.

6.3 Results and Discussion

Initially, a series of mixed effect linear regression models was developed to examine drivers' select speed on horizontal curves using the time-series data. Various analysis strategies were investigated to identify the most proper informative model. Table 16 presents the result of the model where segments were split into only two chunks upstream and downstream of the curve PC. Parameter estimates are provided for mean baseline speed at each speed limit, as well as the associated reduction in travel speeds downstream of the PC. The impact of advisory speed signs was investigated by considering the difference between the posted speed limit and the advisory speed sign's message rather than the advisory message itself. Like previous analyses separate models were developed for the total sample, as well as a subset where no leading vehicle was present according to the forward video.

Table 16. Mixed Effect Linear Regression Model for Travel Speed across Horizontal Curves – No Distance Variable Included

	Total Sample			No Leading Vehicle Sample		
Random Effects:						
Groups	**Variance**	**Std. Dev.**		**Variance**	**Std. Dev.**	
Trip ID	20.340	4.509		13.230	3.637	
Participant ID	10.390	3.224		13.310	3.648	
Location ID	23.480	4.845		23.810	4.879	
Residual:	15.190	3.898		13.420	3.663	
Fixed Effects:						
Model Term	**Coeff.**	**Std. Err.**	**t-stat**	**Coeff.**	**Std. Err.**	**t-stat**
Intercept	48.977	0.663	73.872	48.675	0.673	72.347
30-mph limit	-21.178	1.187	-17.838	-21.615	1.215	-17.787
35-mph limit	-12.121	0.973	-12.457	-11.996	0.996	-12.048
40-mph limit	-5.991	1.156	-5.183	-6.343	1.196	-5.301
45-mph limit	-5.096	0.740	-6.887	-4.824	0.733	-6.585
50-mph limit		Baseline			Baseline	
55-mph limit		Baseline			Baseline	
Advisory Sign Suggested Reduction						
No reduction (control)		Baseline			Baseline	
5-mph reduction	-0.642	0.018	-36.482	-0.708	0.024	-29.422
10-mph reduction	-1.111	0.016	-71.248	-1.766	0.020	-87.314
15-mph reduction	-2.755	0.031	-89.846	-3.790	0.037	-102.230
20-mph reduction	-2.810	0.047	-60.137	-4.046	0.052	-78.237
25-mph reduction	-3.591	0.054	-66.860	-3.898	0.062	-62.777
Degree of Curvature	-0.133	0.001	-200.233	-0.103	0.001	-137.582
No Leading Vehicle		Baseline			-	
Leading Vehicle Present	-1.273	0.188	-6.773		-	
Clear weather		Baseline			Baseline	
Rain	-1.079	0.345	-3.125	-1.040	0.427	-2.436
Snow	-3.710	1.328	-2.795	-7.526	1.748	-4.306
Age 16 to 24	1.714	0.278	6.160	2.199	0.351	6.271
Age 25 to 59	1.319	0.277	4.762	1.795	0.344	5.221
Age 60 or above		Baseline			Baseline	
Null Log-Likelihood			-4018423			-2027043
Log-Likelihood			-2576071			-1298318
Null AIC			8036875			4054113
AIC			5152181			2596884
Null BIC			8036851			4054091
BIC			5152416			2596674
Number of Observations: 922,481				Number of Observations: 475,413		
Number of Events: 3,938				Number of Events: 2,066		
Number of Participants: 1,760				Number of Participants: 1,118		
Number of Locations: 259				Number of Locations: 252		

No significant difference was observed between the mean speeds at 55- and 50-mph posted limits where the mean speed was shown to be nearly 49 mph. Likewise, mean speeds were comparable between 40- and 45-mph limits where less than 1 mph difference was observed. Also, mean speeds were estimated approximately 36.5 and 28 mph at 35- and 30-mph limits, respectively.

Turning to the parameter of interest, interestingly, the associated reductions in travel speeds were found to be much lower than the suggested amount by the advisory speed sign. For example, speeds were reduced by 3.5 and 2.8 mph when reductions of 25 and 20 mph were introduced, respectively. The parameter estimates were found to be relatively similar between 20 and 15 mph reductions, as well as 10 and 5 mph reductions. These estimates are all relative to the curves where no advisory speeds were installed. Despite these comparably small estimates, it is essential to note that they were all found to be statistically significant at a 95-percent confidence interval.

In addition to both regulatory and advisory speeds, a few other variables were shown to impact drivers' select speed. Like past analyses, speeds were reduced where leading vehicles were present and under adverse weather condition. Travel speeds were reduced by approximately 1 and 3.7 mph under rainy and snowy weather, respectively. Speeds were found to be considerably different between younger and older drivers, a finding that was observed in previous chapters, as well.

Moreover, degree of curvature was still found to play a significant role in drivers' speed selection behavior. The associated parameter estimate was found to be lower than what was observed before which indicates that parts of such effect were captured by the variables introduced for advisory signs. However, the statistically significant impact of degree of curvature even in presence of those variables is reflective of considerable differences in the sharpness of curves with similar posted speed limit and advisory speed signs. These differences are furtherly discussed in the analysis of select location using FDA.

When comparing the two models, the total sample and the subset with no leading vehicle, a few differences stand out. First, although the mean speeds were nearly the same upstream the curve PC at each speed limit, the reductions were more pronounced when no leading vehicle was present. However, the degree of curvature parameter estimate was marginally reduced. This indicates that when no leading vehicle was present, drivers tended to adjust their speeds more based on the visual cues (i.e. curve warning and curve advisory speed signs). On the other hand, when leading vehicles were present, drivers rather moved with the flow and adjusted their speeds according to the curve sharpness as they traversed it. The parameter estimates for drivers' age and rainy weather condition remained relatively stable; however, the reductions in speeds were found to be more pronounced under snowy weather condition. This increased impact was partly because of the limited sample size available for trips under such condition.

While the previous model did provide some general insights as to how drivers adjust their speeds when traveling across horizontal curves, it did not yield into any finding as to where drivers start altering their speeds upstream of the curves and how these alterations emerge as they traverse the curves. As a result, another model was developed with an aim to gain a better understanding as to these patterns. Table 17 displays the results of this effort where the speed profiles were approximated by including a series of variables for intermediate segments upstream and downstream of the curve PC. The trips were split into smaller segments depending on their relative distance to the curve PC and PT. The parameter estimates for baseline speeds, far upstream of the curve PC, were found to be similar to that of Table 16. However, the results of the new model indicated that speed alteration begins approximately 200 ft upstream of the curve PC. In addition, it was shown that these changes do vary based on the magnitude of the suggested speed reduction. Consequently, separate variables were introduced for each individual suggested reduction. When looking at the general trends, drivers tended to reduce their speeds gradually as they approached the curve. This reduction continued as they entered the curve at higher reductions; however, drivers were found to start accelerating back to baseline speed within the curve where a 5-mph reduction was introduced. No marked changes were observed in the parameter estimates for other variables including drivers' age and weather condition.

Table 17. Mixed Effect Linear Regression Model for Travel Speed across Horizontal Curves – Step Function

	Total Sample			No Leading Vehicle Sample		
Random Effects:						
Groups	**Variance**	**Std. Dev.**		**Variance**	**Std. Dev.**	
Trip ID	20.22	4.50		13.19	3.63	
Participant ID	10.40	3.23		13.20	3.63	
Location ID	23.24	4.82		23.37	4.83	
Residual:	15.01	3.87		13.22	3.64	
Fixed Effects:						
Model Term	**Coeff.**	**Std. Err.**	**t-stat**	**Coeff.**	**Std. Err.**	**t-stat**
Intercept	49.135	0.660	74.437	48.807	0.668	73.060
30-mph limit	-21.188	1.182	-17.928	-21.623	1.206	-17.933
35-mph limit	-12.058	0.969	-12.449	-11.952	0.988	-12.097
40-mph limit	-5.990	1.151	-5.203	-6.344	1.189	-5.336
45-mph limit	-5.108	0.736	-6.937	-4.850	0.727	-6.670
50-mph limit		Baseline			Baseline	
55-mph limit		Baseline			Baseline	
5-mph suggested reduction						
100-200 ft upstream PC	-0.331	0.033	-10.066	-0.148	0.045	-3.263
0-100 ft upstream PC	-1.064	0.030	-35.962	-0.646	0.041	-15.623
0-30 percent through curve	-1.064	0.025	-42.431	-0.785	0.035	-22.447
30-60 percent through curve	-0.947	0.025	-37.428	-1.020	0.035	-28.978
60-90 percent through curve	-0.300	0.026	-11.593	-0.548	0.036	-15.371
10-mph suggested reduction						
100-200 ft upstream PC	-0.116	0.027	-4.283	0.048	0.036	1.363
0-100 ft upstream PC	-0.601	0.025	-23.638	-0.665	0.033	-20.022

Table 17. (Continued)

0-30 percent through curve	-0.440	0.022	-19.909	-1.003	0.029	-34.684
30-60 percent through curve	-1.204	0.023	-53.444	-1.720	0.029	-58.784
60-90 percent through curve	-1.213	0.023	-53.539	-1.796	0.029	-61.068
15-mph suggested reduction						
100-200 ft upstream PC	-1.113	0.049	-22.654	-1.326	0.059	-22.411
0-100 ft upstream PC	-3.577	0.047	-75.738	-4.427	0.056	-79.442
0-30 percent through curve	-3.094	0.045	-69.400	-4.248	0.054	-78.522
30-60 percent through curve	-3.655	0.046	-78.760	-4.963	0.056	-89.110
60-90 percent through curve	-2.854	0.048	-59.818	-4.002	0.058	-69.174
20-mph suggested reduction						
100-200 ft upstream PC		N/S			N/S	
0-100 ft upstream PC	-1.583	0.070	-22.529	-1.285	0.079	-16.233
0-30 percent through curve	-1.549	0.072	-21.526	-2.287	0.080	-28.626
30-60 percent through curve	-2.543	0.071	-35.838	-3.595	0.078	-46.118
60-90 percent through curve	-3.275	0.071	-46.231	-4.396	0.077	-57.112
25-mph suggested reduction						
100-200 ft upstream PC	-2.297	0.097	-23.624	-1.657	0.115	-14.386
0-100 ft upstream PC	-6.269	0.089	-70.378	-6.414	0.103	-62.358
0-30 percent through curve	-3.525	0.078	-44.926	-3.923	0.091	-43.283
30-60 percent through curve	-3.507	0.079	-44.153	-4.152	0.092	-45.351
60-90 percent through curve	-3.597	0.075	-48.262	-3.600	0.086	-41.705
Degree of Curvature	-0.145	0.001	-223.690	-0.117	0.001	-158.810
No Leading Vehicle		Baseline			-	
Leading Vehicle Present	-1.277	0.188	-6.807		-	
Clear weather		Baseline			Baseline	
Rain	-1.083	0.344	-3.146	-1.057	0.426	-2.481
Snow	-3.756	1.324	-2.836	-7.514	1.744	-4.308
Age 16 to 24	1.710	0.278	6.153	2.203	0.350	6.303
Age 25 to 59	1.322	0.277	4.778	1.803	0.343	5.259
Age 60 or above		Baseline			Baseline	
Null Log-Likelihood			-4018423			-2027043
Log-Likelihood			-2570426			-1294742
Null AIC			8036875			4054113
AIC			5140929			2589560
Null BIC			8036851			4054091
BIC			5141387			2589981

Number of Observations: 922,481
Number of Events: 3,938
Number of Participants: 1,760
Number of Locations: 259

Number of Observations: 475,413
Number of Events: 2,066
Number of Participants: 1,118
Number of Locations: 252

Comparing the parameter estimates between the overall model and the subset under free flow yielded to similar findings discussed previously. For example, more pronounced reductions were found when no leading vehicle was present, whereas the impact of degree of curvature was lessened. The goodness-of-fit measures presented in Table 17 exhibit marginal improvements when compared to those of Table 16 which indicate that speed changes did occur gradually and not abruptly.

Although this second model was able to marginally reduce the existing heterogeneity through estimation of a step function, it was not able to provide a smooth continuous replicate of the speed profiles. In addition, as indicated by the mixed-effect linear regression models presented before, the drivers' select speeds did vary between different locations even when parameters like speed limit, advisory speed, and curve sharpness were controlled for. These limitations may be relaxed by deploying the FDA method. The FDA method provides an appropriate framework to compare the existing patterns and variations in groups of time-series data. Using this method, speed profiles were estimated as a linear combination of a series of B-spline basis functions to better examine the actual patterns in speed profiles when traversing horizontal curves. Here the results of the FDA analysis are presented for a subset of locations. These locations were selected with an aim to estimate the average driver behavior across a wide range of speed limits, advisory speeds, curves radius, and curves length.

Starting with the minimum suggested reduction, speed profiles were approximated using the FDA method for a curve posted at 35 mph with an advisory speed sign of 30 mph. The curve's radius and curve length were 418 ft and 800 ft, respectively. First the speed profiles were examined visually. The drivers were shown to start reducing their speeds upstream of the sign with minimal deceleration. This deceleration starts to increase as they approach the curve, especially when they were approximately 200 ft upstream of the curve PC. The absolute deceleration magnitude was highest at curve PC. Once drivers entered the curve, the reduction continued with milder rates. Ultimately, they started to accelerate back to the baseline speed after traversing approximately 25 percent of the curve.

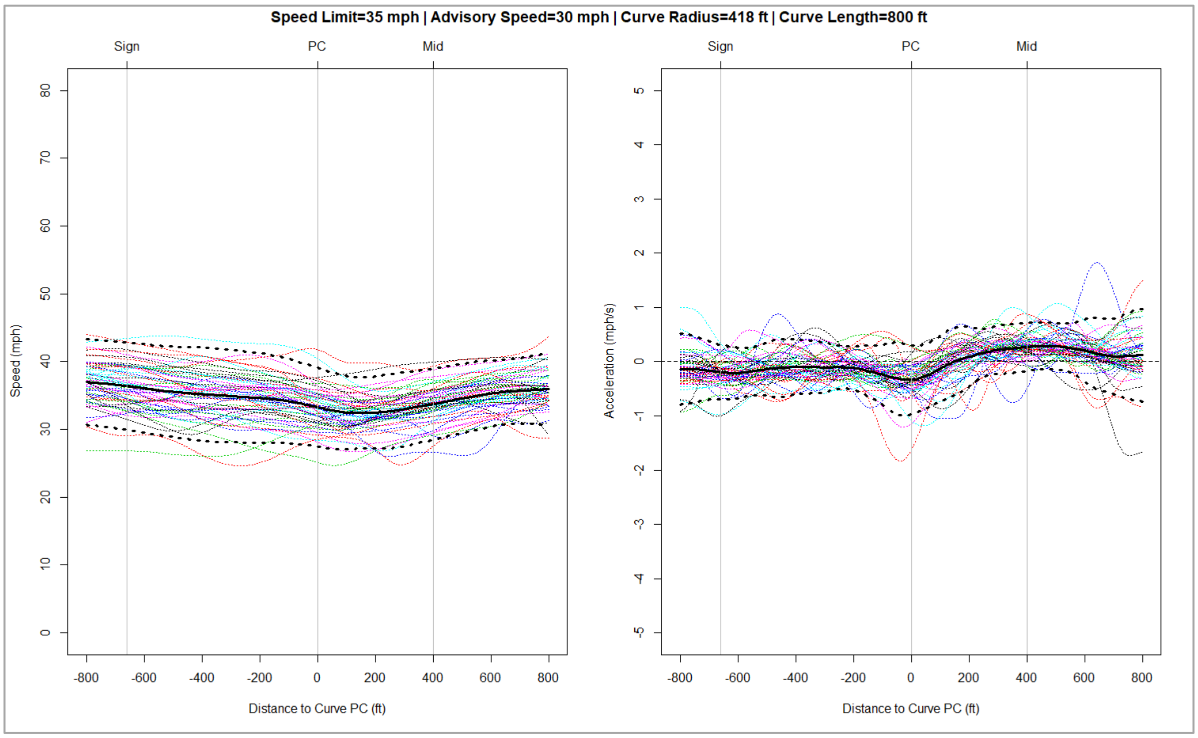

Figure 26. FDA Results for a Curve Posted at 35 mph and Advisory Sign of 30 mph

To quantify the visual patterns, travel speeds were evaluated at two points upstream of the curve including the baseline travel speed upstream of the sign and at advisory speed sign location, as well as the curve PC and eight equally distant points along the curve (100 ft steps). Next, paired two-sample t-test was conducted between the speeds of each two consecutive points to discern if the observed changes were statistically significant. These results did confirm the findings from the visual inspection and are presented in Table 18. The results indicate that though drivers started reducing their speeds as soon as seeing the sign, much of speed reductions occurred between the advisory sign and the curve PC (approximately 3 mph). This reduction continued for the first 100 ft of the curve where the speeds were lowest. Approximately, 200 ft through the curve drivers were shown to start increasing their speeds. All the pairwise comparisons were found to be statistically significant under a 95 percent confidence interval except for the speeds across the first and last 200 ft of the curve where they were shown to remain stable. The lowest mean speed evaluated across this curve was 32.5 mph indicating that drivers reduced their speeds by only half of what had been suggested by the advisory sign.

Table 18. Paired Two-Sample t-test Results for a Curve Posted at 35 mph and Advisory Sign of 30 mph

Distance to Curve PC (ft)	Mean Speed (mph)	Mean Differences (mph)	P-Value
-800	36.997	-	-
-660	36.405	-0.592	<0.001
0	33.285	-3.120	<0.001
100	32.503	-0.782	<0.001
200	32.494	-0.008	0.947
300	32.974	0.480	<0.001
400	33.715	0.741	<0.001
500	34.557	0.842	<0.001
600	35.289	0.732	<0.001
700	35.690	0.401	0.003
800	35.961	0.271	0.07

A similar process was conducted to examine the speed profiles across other select locations. Figure 27 exhibits the results of the FDA for a curve posted at 45 mph and an advisory speed of 35 mph. The curve had a radius of 582 ft and was 820 ft long. Figure 27 exhibits the result of the FDA for this curve. A total of 47 trips were used to approximate the average drivers' select speed at this location. Similarly, speeds were shown to be reduced downstream of the sign. Unlike previous example, the reduction continued even downstream of the curve PC. Speeds were shown to be lowest approximately 200 ft past the curve PC and remained relatively consistent after. The results of the paired two-sample t-test conducted to compare the mean differences, presented in Table 19, indicate that drivers reduced their travel speeds by nearly 2.6 mph between the point they first saw the advisory sign and the curve PC. Additional reduction was observed over the first 200 ft (25 percent) of the curve and stayed stable until curve PT. Over the entire length of the curve, the minimum observed mean travel speed was approximately 39.5 mph, nearly 5 mph over the advised speed which again demonstrates that speeds were reduced by only half of the difference between speed limit and the advisory speed.

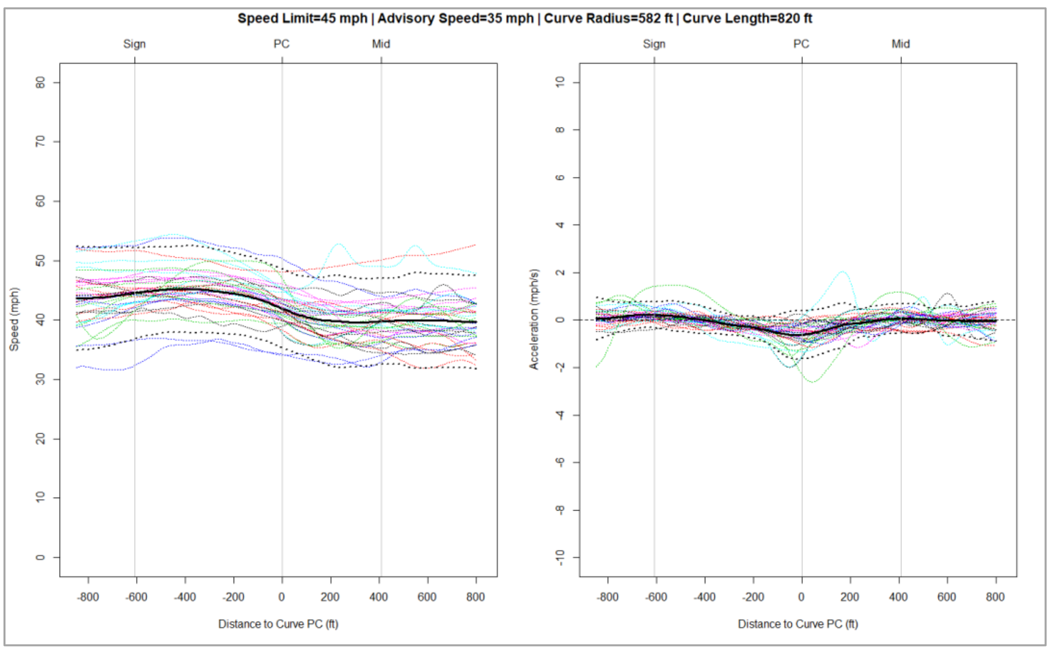

Figure 27. FDA Results for a Curve Posted at 45 mph and Advisory Sign of 35 mph

Table 19. Paired Two-Sample t-test Results for a Curve Posted at 45 mph and Advisory Sign of 35 mph

Distance to Curve PC (ft)	**Mean Speed(mph)**	**Mean Differences (mph)**	**P-Value**
-850	43.64		
-610	44.52	0.88	<0.01
0	41.93	-2.59	<0.01
100	40.50	-1.44	<0.01
200	39.88	-0.62	<0.01
300	39.59	-0.28	0.06
400	39.76	0.16	0.29
500	39.92	0.16	0.33
600	39.89	-0.03	0.78
700	39.83	-0.06	0.68
800	39.67	-0.16	0.37

As for 15 mph advised reduction, speed profiles were examined across a curve with a posted limit of 55 mph and an advisory speed sign of 40 mph. The curve associated radius and length were 828 ft and 600 ft, respectively. As shown in Figure 28, functional data were smoothed for a total of 73 trips at this location. Despite the large difference between the posted speed limit and the advisory speed message, no significant reduction is evident when visually examining the mean speed profile, a finding implied by the acceleration profile, as well. To statistically confirm this, two sampled t-test was conducted, and its results are presented in Table 20.

The baseline mean speed, upstream of the sign is approximately 53 mph at posted limit of 55 mph. The speeds were shown to be reduced by only 1.5 mph over 650 ft from the advisory sign location, and curve PC. The minimal reduction in speeds continued for the first half of the curve resulting in an average speed of 50 mph which is 10 mph over the advised speed. This minimal reduction may be attributed to the large curve radius and is reflective of inconsistencies in guidelines regarding advisory speed sign installation. Past literature has generally shown drivers' sensitivity to curves to decrease as the curve radius increases where no significant alteration occurs across curves with radii around 1000 ft (Schurr et al. 2002, Wang 2015).

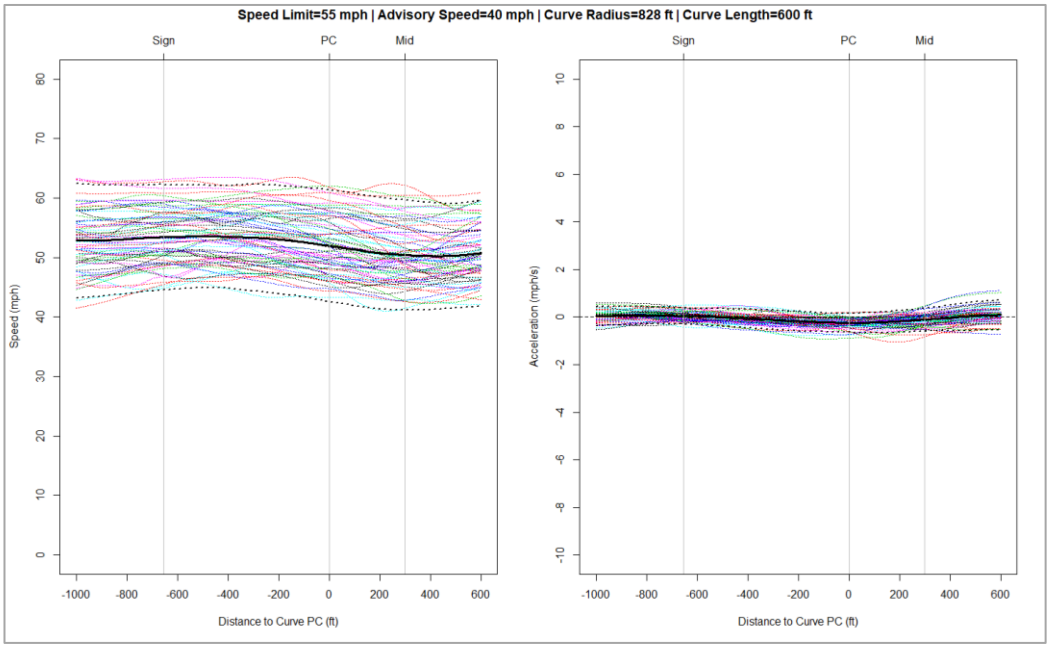

Figure 28. FDA Results for a Curve Posted at 55 mph and Advisory Sign of 40 mph

Table 20. Paired Two-Sample t-test Results for a Curve Posted at 55 mph and Advisory Sign of 40 mph

Distance to Curve PC (ft)	Mean Speed	Mean Differences	P-Value
-1000	52.83		
-650	53.43	0.60	<0.001
0	51.97	-1.45	<0.001
100	51.34	-0.63	<0.001
200	50.75	-0.59	<0.001
300	50.43	-0.32	<0.001
400	50.26	-0.17	0.055
500	50.33	0.07	0.465
600	50.77	0.44	<0.001

The last FDA conducted as part of this study corresponded to a curve with a 45-mph limit in place, and advised speed of 20 mph. The curve was associated with a radius of 555 ft and was 410 ft long. The time-series data were obtained for a total of 28 trips along this curve. Figure 29 presents the results of the FDA for these trips where a marked reduction in travel speeds is apparent. Drivers tended to sustain their initial travel speed beyond the sign and began to reduce their speeds approximately 200 ft upstream of the curve PC. Travel speeds continued to decrease with an average deceleration of 1.5 mph/s all the way to 100 ft downstream of the curve PC. Subsequently, drivers began to accelerate and reached a stable speed around curve midpoint.

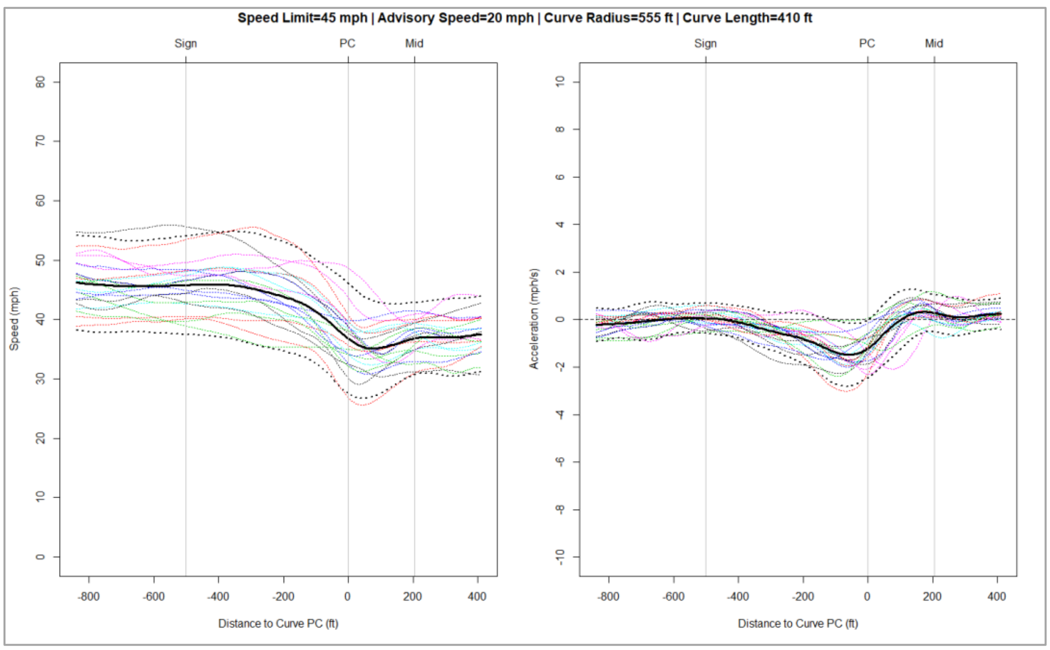

Figure 29. FDA Results for a Curve Posted at 45 mph and Advisory Sign of 20 mph

To quantify the visual findings, mean speed function was evaluated at seven points ranging from 1000 ft upstream of the PC to curve PT. The baseline mean speed at this location was around 46 mph which is comparable to the posted speed limit. No speed reduction occurred upstream of the sign; however, drivers reduced their speeds by about 9 mph between the sign’s location and the curve PC. This reduction continued for 100 ft within the curves. After this point drivers started to increase their speeds. The notable finding here is a total reduction of 12 mph over nearly 1000 ft resulting in mean speed of 35 mph within the curve which is 10 mph over the advised speed. This again confirms the previous finding that the overall reduction in travel speeds is about half of the advised reduction.

Table 21. Paired Two-Sample t-test Results for a Curve Posted at 45 mph and Advisory Sign of 20 mph

Distance to Curve PC (ft)	Mean Speed (mph)	Mean Differences (mph)	P-Value
-1000	46.22	-	-
-650	45.80	-0.41	0.369
0	36.83	-8.97	<0.001
100	35.23	-1.60	<0.001
200	36.75	1.52	<0.001
300	36.97	0.23	0.47
400	37.46	0.49	0.029

Comparing the results for these four examples indicated that drivers tended to adjust their speeds based on the associated sharpness of curves rather than the advised speed. For example, the radii for the second and the fourth curves are comparable (582 ft versus 555 ft). However, the advised speed for the first one was found to be 35 mph, whereas the second curve was associated with a 20-mph advisory speed. Despite the 15-mph difference between the two advised speeds, drivers were found to negotiate the curve similarly with nearly same travel speed across the curve.

In general, this chapter provided some insights as to drivers' speed selection when traversing horizontal curves. Drivers were shown to reduce their speeds based on curve radius and in presence of advisory speeds. However, the results indicated that the advisory speeds are generally too conservative considering roadway conditions and, generally, drivers tend to drive significantly above the recommended speed.

CHAPTER 7. ANALYSIS OF SAFETY CRITICAL EVENTS

As mentioned in Chapter 3, one of the key contributions of the SHRP2 NDS data to the realm of traffic safety research is its inclusion of crash, near-crash, and baseline events. Prior naturalistic driving studies have shown evidence as to importance of including such incidents as they can provide researchers with unique opportunities to investigate critical factors and behaviors pertaining to traffic safety (Dingus et al. 2006). The risk and prevalence of safety critical events including crash and near-crash incidents may be examined in consideration of drivers' behavior and attributes, environmental conditions, and roadway geometry. This can help to identify contributing factors and, subsequently, introduce solutions and potential countermeasures. Also, as the connected/autonomous vehicles (CAVs) become more popular among the public and receive greater attention from researchers, it becomes of a greater importance to know how human drivers generally behave at time of incidents to identify and plan appropriate strategies especially when mixture of conventional and CAVs are present on the road.

This chapter of the dissertation presented herein aims at identifying the contributing factors to safety critical events. A variety of factors including driver behaviors, roadway geometry, and environmental conditions were considered. While several previous studies have focused on addressing this question, this study is unique in-that it used a naturalistic driving data rather than relying on police crash reports or post-crash.

7.1 Data

This section of the study used the event data from the SHRP2 NDS described in chapter four. Three types of events were initially requested for analysis including crash, near-crash, and baseline events. The VTTI provided definition of crash and near-crash incidents as follows:

Crash: ″Any contact that the subject vehicle has with an object, either moving or fixed, at any speed in which kinetic energy is measurably transferred or dissipated is considered a crash. This also includes non-premeditated departures of the roadway where at least one tire leaves the paved or intended travel surface of the road, as well as instances where the subject vehicle strikes another vehicle, roadside barrier, pedestrian, cyclist, animal, or object on or off the roadway.″(Hankey et al. 2016)

Near-Crash: ″Any circumstance that requires a rapid evasive maneuver by the subject vehicle, or any other vehicle, pedestrian, cyclist, or animal, to avoid a crash is considered a near-crash. A rapid evasive maneuver is defined as steering, braking, accelerating, or any combination of control inputs.″(Hankey et al. 2016)

The time-series data provided by the VTTI did not include the geographic information for crashes due to confidentiality concerns. Consequently, it was not possible to extract the RID features for such events. Ultimately, the event data used in this study were comprised of only near-crash and baseline events. The summary statistics of the freeways and two-lane highways event datasets may be found in Table 5 and Table 6, respectively. Among freeway events, there were a total of 448 and 3,927 near-crash and baseline events, respectively. For two-lane highways there found to be 242 near-crash and 2,659 baseline events. A variety factors including driver behavior and roadway characteristics were examined to identify those factors influencing the likelihood of involvement in near-crash events.

7.2 Methodology

In addition to analyzing driver speed selection, a companion objective in this study was 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 on both freeways and two-lane highways. 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). As describes before, near-crash incidents were used as surrogates for crashes in this study. Under the logistic regression framework, the odds of a participant being involved in a near-crash is related to a linear function of predictor variables as shown in Equation 18:

$$log\left(\frac{p_i}{1-p_i}\right) = \boldsymbol{\beta_i X_i} + \varepsilon_i \qquad \text{(Equation20)}$$

where p_i is the probability of participant *i* being involved in a crash or near-crash event, $\boldsymbol{\beta_i}$ is a vector of estimable parameters, and $\boldsymbol{X_i}$ indicates a vector of explanatory variables associated with the event outcome (e.g., driver, vehicle, roadway, and temporal characteristics), and ε_i 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:

$$p_i = \int \frac{EXP(\beta x_i + \varepsilon_i)}{1 + EXP(\beta x_i + \varepsilon_i)} f(\beta|\varphi) d\beta \quad \text{(Equation 21)}$$

where $(\beta|\varphi)$ 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 random effects (or random intercept) logistic regression model. Following section provides the results of the logistic regression models developed for SCE analysis on freeways and two-lane highways.

7.3 Results and Discussion

Mixed-effect logistic regression models were estimated to assess factors affecting near-crash involvement on freeways and two-lane highways. Table 22 presents results of the analysis for freeway events, where positive coefficients indicate a variable is associated with a higher risk of a near-crash while negative coefficients are indicative of conditions that are associated with lower risks.

The results show that the risk of a crash or near-crash increased significantly with increases in the standard deviation of speeds over the course of each event. The odds of a near-crash increased by approximately 19.2 percent for a 1-mph increase in standard deviation. These results provide compelling evidence that further supports the importance of minimizing variability in travel speeds to reduce crash potential. Interestingly, mean speed and speed limit were not shown to impact crash risk directly. However, speed limit was shown to have an indirect effect through the standard deviation variable.

Turning to the other factors of interest, crash risks were highest under heavy congestion (LOS D) and particularly within work zone environments. The results indicate that presence of a workzone increase the likelihood of involvement in a near-crash by approximately 63 percent.

Likewise, near-crashes were found to be more like at junctions (i.e. interchanges) where the probability of involvement in such incidents was increased by 88 percent. Conversely, such risks were lower among drivers aged 35 to 74.

Table 22. Random Effect Logistic Regression Model for Crash/Near-Crash Risk, Freeways

Model Term	**Coeff.**	**Std. Err.**	**z-stat**	**Pr(>|z|)**	**Odds Ratio**
Intercept	-4.599	0.231	-19.865	<0.001	-
Speed std. dev.	0.176	0.024	7.39	<0.001	1.192
LOS A		Baseline			-
LOS B	1.418	0.156	9.074	<0.001	4.129
LOS C	2.29	0.208	10.984	<0.001	9.875
LOS D	3.24	0.272	11.921	<0.001	25.534
LOS E/F	2.134	0.349	6.119	<0.001	8.449
Non-junction		Baseline			-
Junction	0.63	0.129	4.896	<0.001	1.878
Non-work zone		Baseline			-
Work zone	0.487	0.277	1.76	0.078	1.627
Age 34 or less		Baseline			-
Age 35 to 74	-0.349	0.158	-2.214	0.027	0.705
Age 75 plus		Baseline			
Null Log-Likelihood	-1445				
Log-Likelihood	-1162				
Null AIC	2892				
AIC	2345				
Null BIC	2898				
BIC	2408				

Number of Observations: 4,375

Number of Participants: 1,975

Table 23 provides the results of the similar analysis conducted using the two-lane highways event data. Crash/near-crash risk was found to be highest under moderate congestion, peaking under LOS C. This may be reflective of the fact that speeds generally decrease in a linear fashion as volumes increase on two-lane highways. Consequently, as traffic conditions approach capacity, speeds are significantly lower. This provides an explanation as to why crash risks were not significantly different between free-flow conditions (LOS A) and LOS D through F.

Table 23. Random Effects Logistic Regression Model for Crash/Near-Crash Risk, Two-Lane Highways

Model Term	Coeff.	Std. Err.	z-stat	Pr(>|z|)	Odds Ratio
Intercept	-8.967	0.492	-18.231	<0.001	-
Speed std. dev.	0.145	0.04	3.574	<0.001	1.156
LOS A		Baseline			-
LOS B	1.703	0.292	5.836	<0.001	5.490
LOS C	2.574	0.727	3.542	<0.001	13.118
LOS D/E/F		Baseline			-
No access points		Baseline			-
Intersection		Baseline			-
On-street parking	-1.67	0.574	-2.909	0.003	0.188
Driveway	-0.809	0.428	-1.892	0.058	0.445
Null Log-Likelihood	-833				
Log-Likelihood	-728				
Null AIC	1667				
AIC	1470				
Null BIC	1673				
BIC	1512				

Number of Observations: 2,901

Number of Participants: 1,593

Interestingly, crash risks were lower where on-street parking or driveways were present and highest at intersections and on segments with no access points. Parking may serve as a proxy for the level of development, so this finding may also be an indication of lower speeds due to increased congestion and activity levels in more urban environments. Intersections were found to be higher risk and, interestingly, so were segments with no access points. In the latter case, it is important to note that access density is lower on higher functional class roads. Consequently, this finding could relate to other characteristics of higher class roads.

Like freeways, mean speeds and speed limits were not shown to be directly correlated with crash/near-crash involvement. However, speed standard deviation over the duration of trips was found to have a significant impact on the likelihood of near-crash occurrence. The probability of involving in a near-crash was shown to increase by nearly 16 percent for each 1 mph increase in the speed standard deviation. This impact is marginally lower than what was observed with freeways which is probably related to the lower speed limits on two-lane highways.

The analyses presented in this chapter helped to identify the factors that significantly impact the likelihood of near-crash involvement. The results demonstrated the importance of speeds variability in traffic safety and how fluctuations in travel speed can result in occurrence of safety critical events. Likewise, near-crash involvement was shown to be directly influenced by the level of congestion. Near-crashes were more likely under moderate to severe congestion, as well as in presence of junctions and intersections.

CHAPTER 8. SUMMARY AND CONCLUSIONS

This study provides important insights into how drivers adapt their behavior by examining travel speeds under various roadway and environmental conditions. Time-series data from the SHRP 2 NDS were leveraged to examine how drivers adapt their speeds: 1) under constant speed limits; 2) across speed limit transition areas; and 3) along horizontal curves. The substantial number of data elements available through the NDS for crash, near-crash, and baseline driving events provide a unique opportunity to identify salient factors impacting traffic safety at the level of individual drivers. The findings from this study are largely supportive of the extant research literature and identified several important considerations for transportation agencies in considering policies, programs, and countermeasures to address speed-related concerns. The following sections briefly summarize key findings of this study and discuss the resulting implications, as well as the associated limitations and potential avenues for future research.

8.1 Assessment of Travel Speeds under Constant Speed Limit

Drivers' speed selection behavior under constant speed limit was investigated for freeways and two-lane highways through the estimation of a series of regression models for each facility type. Unsurprisingly, 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. Drivers are generally shown to drive above the posted limited on the lower range of posted speed limits and, as limits are increased, mean speeds tend to revert nearer to the posted limit. The maximum limits at NDS sites is 70 mph, inhibiting the ability to analyze how this behavior may vary at higher limits.

In addition to responding to changes in speed limits, drivers were found to adapt their speeds based upon changes in the roadway environment, such as the introduction of horizontal curves. As noted by AASHTO (Aashto 2001), travel speeds were also found to be affected by other roadway and environmental characteristics. Drivers tended to significantly reduce their speeds under congested conditions, when adverse weather conditions were present, and when encountering work zone environments. As for drivers' characteristics, it was shown that those who are under 24 tend to travel at higher speeds, whereas this impact is less pronounced for drivers between 25 and 59 (both compared to drivers who age over 60).

Beyond changes to mean speeds, the impacts of speed limits and other characteristic on the variability of travel speeds is also of particular interest. Within the context of this study, the standard deviation of speeds within individual 20-s event intervals was examined. Consequently, this measure of variability is reflective of how drivers adapt their speeds over space and time. This variability is reflective of changes in traffic conditions, geometry, and differences in the behaviors of individual drivers.

On freeways, speeds tended to be more variable at lower posted limits, particularly at 55 and 60 mph, which is likely reflective of several factors beyond just the posted limit, such as the more urban nature of these lower speed facilities. These areas tend to have more frequent interchanges, increased levels of congestion, and may exhibit general differences in driving behavior as compared to more rural areas. The variability in travel speeds was also found to increase in the presence of congestion or work zone activities.

Likewise, speed fluctuations were generally higher at lower speed limits on two-lane highways, as well. Speed standard deviation was increased under traffic congestion, along horizontal curves, and in presence of on-street parking which all probably relates back to changes in roadway environment, and especially are indicative of more urban areas.

8.2 Assessment of Travel Speeds across Speed Limit Transition Areas

In addition to examining travel speeds under constant speed limits, another related item of interest was how drivers adapt their speed when the speed limit increases or decreases. As such, speed profiles were examined under a variety of transition areas, where speed limit increases and decreases occurred on both freeways and two-lane highways. Time-series data were examined from segments with 5, 10, or 15 mph increases or decreases in posted speed limits on freeways. Two-lane highways included a wider range of speed limit changes, including increases or decreases from 5 to 20 mph. Collectively, these analyses suggest that speed changes are very gradual in the areas immediately upstream and downstream of where the posted limit changes.

For freeways, speeds were shown to marginally increase at higher speed limits. The differences between mean speeds upstream of the new regulatory speed limit were found to be much lower compared to those under constant speed limit, which is indicative of speed alterations beginning upstream of the new speed limit introduction. Speed profiles were examined for up to 1000 ft upstream of the regulatory speed sign location; however, the distance at which drivers started to alter their speeds varied significantly between locations depending on posted limit, size of limit change, and other roadway and environmental characteristics. Speeds were shown to decrease downstream of the regulatory speed sign by only 0.3 to 1.5 mph where limit reductions were introduced. Likewise, muted increases ranging from 0.7 to 1.5 mph were observed when speed limits were increased. This is true regardless of whether the magnitude of the increase or decrease in limits was 5, 10, or 15 mph. This suggests drivers are: (a) exhibiting different behaviors near these transition areas than on similar segments with constant speed limits; and (b) the actual posted limit is having minimal impact as compared to other features, such as roadway geometry and traffic density.

Similar phenomena were observed on two-lane highways. At lower speed limits, mean travel speeds were found to be significantly above the posted limit upstream of the new regulatory speed limit sign. Conversely, mean speeds over the segments upstream of the sign were shown to be markedly below the posted limit at higher limits. When speed limits increased, so did the travel speeds. Such increases ranged between 1.5 to 3 mph depending on the size of introduced limit increase. Again, the largest increases in mean speed were very small in comparison to the actual magnitude of the speed limit increases, which were as large as 20-mph in some cases. More pronounced changes were observed where limit reductions were introduced, though these decreases in mean speeds were still relatively small in consideration of the magnitude of the change in limits. For example, speeds were reduced by as much as 6 mph where reductions of 20 mph were in place. The relatively higher magnitude of reductions in mean speeds may be reflective of concerns as to speed enforcement that may occur in concurrence with these reductions, as well as more pronounced changes in roadway design. Speeds were found to be lower in presence of leading vehicles, as well as under adverse weather condition. Also, speeds were shown to reduce markedly along horizontal curves, an impact that was subsequently investigated in greater detail.

8.3 Assessment of Travel Speeds along Horizontal Curves

Given the impacts of horizontal alignment on travel speeds and the historical overrepresentation of crashes on horizontal curves, the final speed analyses conducted as a part of this study were focused on examining drivers’ speed selection along horizontal curves, particularly those with an advisory speed signs in place. Drivers were found to reduce their speeds on curves, particularly on sharper (i.e., smaller radius) curves. These speed reductions were greater in magnitude when advisory speed signs were present. Further, the reductions were also larger in magnitude when the differences between the posted limit and the advisory speed were larger, as well. However, the reductions were found to be markedly smaller than (approximately half of) the recommended advisory speed. This reinforces prior research literature, which has shown advisory speeds to be conservative (i.e., lower) compared to what drivers perceive as comfortable (Chowdhury et al. 1991, Bennett and Dunn 1994). Like speed limit transition areas, drivers were shown to begin reducing their speeds upstream of the indicated changepoint. The results demonstrated that much of the speed reduction occur between the advisory speed sign and the point of curve (PC).

Further analysis revealed that drivers tend to start accelerating back to baseline speed while within the curve when smaller differences between the posted speed limit and the advisory speed was present. Ultimately, drivers were found to adjust their speeds more based on the roadway geometry and curve radius rather than the visual cues. In addition, this study found some evidence as to inconsistencies in advisory speed sign installations across different locations, a finding supported by the past literature, as well (Ritchie 1972).

8.4 Assessment of Safety Critical Events

Beyond establishing the relationships between various factors and driver speed selection behavior, the overarching goal is to understand how these behaviors influence the risk of a driver being involved in a crash. To this end, a series of logistic regression models were estimated to identify how speed metrics and various other factors influence crash risk. The results of this study showed that increases in the standard deviation of speeds among individual drivers significantly increases the risk of crash/near-crash events. This research showed that increases in the variability of speeds among individual drivers over time and space during 20-s event intervals led to increases in the risk of crash- or near-crash events. This is in contrast to historical research in this domain that has examined how speeds vary at individual roadway locations across different drivers over short time periods. This variability in speeds may be reflective of several factors, such as traffic congestion or differences in individual driving behaviors, which collectively contribute to an increased risk of rear-end or side-swipe collisions. Variability in speeds has also been demonstrated to increase the likelihood of severe crashes (Yu and Abdel-Aty 2014).

The risk of a safety-critical event was not found to vary significantly across similar highways with different posted speed limits. However, posted speed limits were found to have an indirect influence on crash risk, both on freeways and two-lane highways. For example, speed limits were shown to affect the variability in travel speeds, which in turn influenced crash risks. In addition, several other factors that are directly related to speed also impacted crash risk, including level-of-service and highway alignment. Increased crash risk was observed at junctions and intersection across freeways and two-lane highways, respectively. However, the likelihood of near-crash involvement was found to reduce in presence of driveways and on-street parking which probably relates back to lower speeds and greater level of development at such locations.

From an analysis standpoint, the random effects framework showed significant variability in speed selection and crash risk across drivers and locations. This is supported by a meta-analysis of research from Europe and the US which concludes that drivers ultimately choose their speeds based on perception of safety rather than posted speed limits (Wilmot and Khanal 1999). These findings are largely reflective of driver opinions on speed limits, which suggests speed selection is based upon individual perceptions of what speeds are “safe”, traffic volume levels, and driving experience.

8.5 Practical Applications

As demonstrated by the findings of this study, drivers select their speeds in consideration of a combination of various factors including speed limit, roadway geometry, environmental conditions, and driver behavior. The impacts of speed limits were shown to be highly variable depending upon these other factors, particularly the context of the driving environment. These findings can be used to help support policy decisions such as the establishment of maximum limits, as well as the determination as to when and where advisory speeds may be appropriate. The results also suggest contexts in which the identification of countermeasures and appropriate strategies for speed management are most needed. For example, this study demonstrated increased crash risk under variable travel speeds. As such, introducing countermeasures including speed display trailers and dynamic speed feedback signs to reduce such fluctuations may be beneficial. In addition, this study provided some evidence as to incompliance of drivers with advisory speed signs in most cases. Consequently, revisiting the criterion for installation of such signs, as well as developing uniform guidance are warranted.

In addition, the outcomes of this study have some important implications in the area of connected and autonomous vehicles. These findings can be directly utilized in the learning stages of developing CAVs. Further, traffic engineers can benefit from the results of this study to develop traffic management strategies to overcome challenges introduced when a mixture of autonomous and conventional vehicles is present on the roads.

8.6 Limitations and Future Work

Although this study demonstrated some important insights as to drivers' speed selection under various conditions, there were some limitations associated with this study that needs to be mentioned. The obtained time-series data included some missing speed and location information that resulted in losing some trips. This elimination of traces impacted the associated coverage of various roadway and environmental conditions. In addition, insufficient number of trips under some of the conditions of interest resulted in the study not being able to discern the actual impact of some parameters of interest including level of service and adverse weather condition. Also, one other factor that can potentially impact travel speeds is the level of drivers' familiarity with the roadway. Failing to account for this factor may result in biased estimates especially when examining speed profiles across curves and speed transition areas. Further, no information was available as to the level and means of speed enforcements across the study locations. Another shortcoming in the SHRP 2 NDS data is the lack of information for heavy vehicles and how interactions between those and passenger cars impact travel speeds at both macro and micro level. In addition, speed selection behavior was examined and compared across different roadway segments which may potentially have some inherent differences.

Future research is warranted to examine speed selection behavior across same roadway segments prior and after limit changes. This study assessed driver behavior using data from different individuals and locations with similar characteristics. However, as shown by the random effects models, there might be some unobserved heterogeneity specific to locations that inhibits identifying the actual impact of different roadway and environmental characteristics on travel speeds. Consequently, examining speed profiles across same roadway segments under different conditions is suggested.

Further, the findings from this study demonstrated significant differences in speed selection behavior between different individuals. Aside from driver age, other individuals' characteristics including risk perception, mental and physical health history, driving experience and level of driving exposure need to be investigated for potential impact on speed selection behavior.

Another item of interest is to examine speed profiles where differential speed limits are in place. Currently, only seven states have a differential speed limit along their roadways; however, the findings of such analysis have broader impacts as a lot of trucking companies utilize speed control devices resulting in de facto differential speeds regardless of the in-place speed limit policies. Additional research is also warranted to investigate drivers' speed selection behavior in presence of mixed traffic, and particularly heavy vehicles, and how the presence of such vehicles alters drivers' speed profiles, specifically on two-lane highways.

Also, as the transportation industry is expected to undergo significant changes in near future due to the fast-ongoing advances in automobile industry, examining drivers' behavior in consideration of their use of different levels of automation including cruise control, advanced breaking systems, and more advanced technologies might be of interest. This is of great importance particularly for the transition period when a mixture of conventional and autonomous vehicles is present on the road.

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APPENDIX A – IRB APPROVAL MEMO

IOWA STATE UNIVERSITY
OF SCIENCE AND TECHNOLOGY

Institutional Review Board
Office for Responsible Research
Vice President for Research
2420 Lincoln Way, Suite 202
Ames, Iowa 50014
515 294-4566

Date: 3/30/2017

To: Dr. Peter T Savolainen
482A Town Engr

From: Office for Responsible Research

Title: The Interrelationships between Speed Limits, Geometry, and Driver Behavior

IRB ID: 15-050

Study Review Date: 3/30/2017

The project referenced above has been declared exempt from the requirements of the human subject protections regulations as described in 45 CFR 46.101(b) because it meets the following federal requirements for exemption:

- (4) Research involving the collection or study of existing data, documents, records, pathological specimens, or diagnostic specimens if these sources are publicly available or if the information is recorded by the investigator in such a manner that subjects cannot be identified directly or through identifiers linked to the subjects.

The determination of exemption means that:

- **You do not need to submit an application for annual continuing review.**
- **You must carry out the research as described in the IRB application.** Review by IRB staff is required prior to implementing modifications that may change the exempt status of the research. In general, review is required for any modifications to the research procedures (e.g., method of data collection, nature or scope of information to be collected, changes in confidentiality measures, etc.), modifications that result in the inclusion of participants from vulnerable populations, and/or any change that may increase the risk or discomfort to participants. Changes to key personnel must also be approved. The purpose of review is to determine if the project still meets the federal criteria for exemption.

  Non-exempt research is subject to many regulatory requirements that must be addressed prior to implementation of the study. Conducting non-exempt research without IRB review and approval may constitute non-compliance with federal regulations and/or academic misconduct according to ISU policy.

  Detailed information about requirements for submission of modifications can be found on the Exempt Study Modification Form. A Personnel Change Form may be submitted when the only modification involves changes in study staff. If it is determined that exemption is no longer warranted, then an Application for Approval of Research Involving Humans Form will need to be submitted and approved before proceeding with data collection.

Please note that you must submit all research involving human participants for review. **Only the IRB or designees may make the determination of exemption**, even if you conduct a study in the future that is exactly like this study.

Please be aware that **approval from other entities may also be needed.** For example, access to data from private records (e.g. student, medical, or employment records, etc.) that are protected by FERPA, HIPAA, or other confidentiality policies requires permission from the holders of those records. Similarly, for research conducted in institutions other than ISU (e.g., schools, other colleges or universities, medical facilities, companies, etc.), investigators must obtain permission from the institution(s) as required by their policies. **An IRB determination of exemption in no way implies or guarantees that permission from these other entities will be granted.**

Please don't hesitate to contact us if you have questions or concerns at 515-294-4566 or IRB@iastate.edu.

APPENDIX B – STATE SPECIFIC MODELS UNDER CONSTANT SPEED LIMIT

Table 24. Mean Speed Model for Florida Freeways Under Constant Speed Limit

	Total Sample			LOS-A Only		
Random Effects:						
Groups	**Variance**	**Std. Dev.**		**Variance**	**Std. Dev.**	
Participant ID:	14.8	3.847		11.310	3.363	
Residual:	97.62	9.88		78.380	8.853	
Fixed Effects:						
Model Term	**Coeff.**	**Std. Err.**	**t-stat**	**Coeff.**	**Std. Err.**	**t-stat**
Intercept	69.414	0.923	75.243	70.594	0.988	71.432
55-mph limit	-13.404	0.83	-16.16	-16.251	1.036	-15.685
60-mph limit	-8.062	1.055	-7.645	-7.255	1.274	-5.694
65-mph limit	-5.214	1.168	-4.463	-3.939	1.422	-2.770
70-mph limit		Baseline			Baseline	
LOS A		Baseline			-	
LOS B	-1.405	0.748	-1.879		-	
LOS C	-9.718	1.314	-7.397		-	
LOS D	-29.636	2.001	-14.812		-	
LOS E	-40.382	2.241	-18.022		-	
LOS F	-53.453	5.234	-10.212		-	
Non-junction		Baseline			Baseline	
Junction	-1.431	0.729	-1.962	-2.559	0.936	-2.733
Non-work zone		Baseline			Baseline	
Work zone	-4.867	1.264	-3.852	-5.425	1.719	-3.156
Clear weather		Baseline			Baseline	
Rain	-2.755	1.609	-1.712	-3.400	2.055	-1.655
Snow or sleet	-12.336	2.205	-5.596		-	
Age 16 to 24	3.673	0.971	3.784	3.762	1.090	3.452
Age 25 to 59	2.066	1.079	1.916	1.660	1.228	1.352
Age 60 or above		Baseline			Baseline	
Null Log-Likelihood			-4036			-2027
Log-Likelihood			-3678			-1905
Null AIC			8075			4057
AIC			7387			3831
Null BIC			8085			4066
BIC			7465			3878
Number of Observations: 975				Number of Observations: 520		
Number of Participants: 465				Number of Participants: 327		

Table 25. Mean Speed Model for Indiana Freeways Under Constant Speed Limit

	Total Sample			LOS-A Only		
Random Effects:						
Groups	**Variance**	**Std. Dev.**		**Variance**	**Std. Dev.**	
Participant ID:	18.87	4.344		52.26	7.229	
Residual:	64.46	8.029		28.57	5.345	
Fixed Effects:						
Model Term	**Coeff.**	**Std. Err.**	**t-stat**			
Intercept	70.289	1.483	47.408	69.082	1.372	50.333
55-mph limit	-14.981	1.572	-9.529	-11.897	1.523	-7.813
60-mph limit	-7.959	1.643	-4.843	-6.329	1.478	-4.283
65-mph limit		Baseline			Baseline	
70-mph limit		Baseline			Baseline	
LOS A		Baseline			-	
LOS B	-2.498	1.355	-1.844		-	
LOS C	-7.253	2.589	-2.801		-	
LOS D	-23.546	8.933	-2.636		-	
LOS E		N/S			-	
LOS F		N/S			-	
Age 16 to 24	2.226	1.335	1.667		N/S	
Age 25 or above		Baseline			N/S	
Null Log-Likelihood			-1040			-714
Log-Likelihood			-978			-674
Null AIC			2084			1432
AIC			1974			1358
Null BIC			2091			1439
BIC			2007			1374

Number of Observations: 271 — Number of Observations: 194

Number of Participants: 134 — Number of Participants: 109

N/S: Not Significant

Table 26. Mean Speed Model for North Carolina Freeways Under Constant Speed Limit

	Total Sample			LOS-A Only		
Random Effects:						
Groups	Variance	Std. Dev.		Variance	Std. Dev.	
Participant ID:	55.560	7.454		38.380	6.195	
Residual:	75.700	8.701		72.940	8.540	
Fixed Effects:						
Model Term	**Coeff.**	**Std. Err.**	**t-stat**	**Coeff.**	**Std. Err.**	**t-stat**
Intercept	70.565	1.596	44.227	69.540	1.688	41.207
55-mph limit	-15.638	1.445	-10.820	-14.186	1.649	-8.602
60-mph limit	-11.931	1.870	-6.379	-9.719	2.216	-4.386
65-mph limit	-4.809	1.395	-3.447	-3.787	1.573	-2.407
70-mph limit		Baseline			Baseline	
LOS A		Baseline			Baseline	
LOS B	-1.171	0.795	-1.474		-	
LOS C	-7.406	1.642	-4.510		-	
LOS D	-24.623	2.985	-8.250		-	
LOS E	-44.626	3.919	-11.387		-	
LOS F		-			-	
Non-junction		Baseline			Baseline	
Junction	-1.817	0.746	-2.437	-2.041	0.959	-2.129
Clear weather		Baseline			Baseline	
Rain	-7.609	1.582	-4.808	-6.387	2.111	-3.026
Snow or sleet		-			-	
Age 16 to 24	5.729	1.424	4.023	5.304	1.460	3.632
Age 25 to 59	4.185	1.350	3.100	3.962	1.397	2.838
Age 60 or above		Baseline			Baseline	
Null Log-Likelihood			-3232			-1868
Log-Likelihood			-3010			-1785
Null AIC			6469			3740
AIC			6047			3590
Null BIC			6478			3748
BIC			6113			3632
Number of Observations: 796				Number of Observations: 477		
Number of Participants: 355				Number of Participants: 286		

Table 27. Mean Speed Model for New York Freeways Under Constant Speed Limit

	Total Sample			LOS-A Only		
Random Effects:						
Groups	**Variance**	**Std. Dev.**		**Variance**	**Std. Dev.**	
Participant ID:	5.140	2.267		8.182	2.860	
Residual:	72.790	8.532		53.402	7.308	
Fixed Effects:						
Model Term	**Coeff.**	**Std. Err.**	**t-stat**	**Coeff.**	**Std. Err.**	**t-stat**
Intercept	65.733	0.902	72.890	66.076	0.971	68.045
55-mph limit	-9.265	0.710	-13.058	-9.102	0.769	-11.832
60-mph limit		-			-	
65-mph limit		Baseline			Baseline	
70-mph limit		-			-	
LOS A		Baseline			-	
LOS B		Baseline			-	
LOS C	-5.411	1.126	-4.804		-	
LOS D	-23.656	1.830	-12.928		-	
LOS E	-42.103	3.948	-10.665		-	
LOS F	-42.219	5.088	-8.298		-	
Non-junction		Baseline			Baseline	
Junction	-2.485	0.643	-3.865	-4.243	0.788	-5.383
Non-work zone		-			-	
Work zone	-3.618	1.565	-2.312		N/S	
Clear weather		Baseline			Baseline	
Snow or sleet	-11.237	2.806	-4.004	-12.599	3.203	-3.933
Age 16 to 24	2.688	0.909	2.957	2.727	1.041	2.619
Age 25 to 59	1.665	0.914	1.822	1.895	1.035	1.832
Age 60 or above		Baseline			Baseline	
Null Log-Likelihood			-3232			-1868
Log-Likelihood			-3113			-1703
Null AIC			6469			3740
AIC			6252			3421
Null BIC			6478			3748
BIC			6314			3455
Number of Observations: 866				Number of Observations: 490		
Number of Participants: 405				Number of Participants: 303		

N/S: Not Significant

Table 28. Mean Speed Model for Pennsylvania Freeways Under Constant Speed Limit

	Total Sample			LOS-A Only		
Random Effects:						
Groups	**Variance**	**Std. Dev.**		**Variance**	**Std. Dev.**	
Participant ID:	12.990	3.605		22.680	4.763	
Residual:	39.590	6.292		20.640	4.543	
Fixed Effects:						
Model Term	**Coeff.**	**Std. Err.**	**t-stat**	**Coeff.**	**Std. Err.**	**t-stat**
Intercept	66.016	1.159	56.955	65.273	1.161	56.242
55-mph limit	-5.428	0.974	-5.574	-5.847	0.917	-6.373
60-mph limit		-			-	
65-mph limit		Baseline			Baseline	
70-mph limit		-			-	
LOS A		Baseline			-	
LOS B	-1.978	1.142	-1.732		-	
LOS C	-21.578	5.030	-4.290		-	
LOS D	-18.964	8.172	-2.321		-	
LOS E		-			-	
LOS F		-			-	
Non-junction		Baseline			Baseline	
Junction	-5.406	1.110	-4.871	-3.128	1.022	-3.059
Non-work zone		Baseline			Baseline	
Work zone	-5.135	3.573	-1.437		N/S	
Clear weather		Baseline			Baseline	
Snow or sleet	-19.110	3.594	-5.316	-10.355	3.463	-2.990
Age 16 to 24	3.801	1.364	2.787	4.037	1.429	2.824
Age 25 to 59	3.668	1.288	2.847	3.558	1.343	2.650
Age 60 or above		Baseline			Baseline	
Null Log-Likelihood			-921			-700
Log-Likelihood			-853			-653
Null AIC			1847			1405
AIC			1731			1323
Null BIC			1854			1411
BIC			1773			1349
Number of Observations: 252				Number of Observations: 201		
Number of Participants: 169				Number of Participants: 142		

Table 29. Mean Speed Model for Washington Freeways Under Constant Speed Limit

	Total Sample			LOS-A Only		
Random Effects:						
Groups	**Variance**	**Std. Dev.**		**Variance**	**Std. Dev.**	
Participant ID:	4.577	2.139		12.480	3.532	
Residual:	85.541	9.249		50.690	7.120	
Fixed Effects:						
Model Term	**Coeff.**	**Std. Err.**	**t-stat**	**Coeff.**	**Std. Err.**	**t-stat**
Intercept	69.633	1.162	59.946	69.924	1.136	61.537
55-mph limit	-16.980	1.843	-9.215	-14.814	1.934	-7.658
60-mph limit	-10.202	1.089	-9.366	-8.997	1.159	-7.763
65-mph limit		Baseline			Baseline	
70-mph limit		Baseline			Baseline	
LOS A		Baseline			-	
LOS B	-1.762	0.627	-2.810		-	
LOS C	-8.636	0.943	-9.161		-	
LOS D	-27.533	1.131	-24.336		-	
LOS E	-40.255	1.716	-23.463		-	
LOS F	-43.097	3.615	-11.921		-	
Non-junction		Baseline			Baseline	
Junction	-1.490	0.559	-2.665	-2.184	0.787	-2.776
Non-work zone		Baseline			Baseline	
Work zone	-2.911	1.614	-1.804	-4.469	2.542	-1.758
Clear weather		Baseline			Baseline	
Snow or sleet	-13.000	4.269	-3.045	-22.629	4.594	-4.926
Age 16 to 24	3.381	0.790	4.280	2.041	0.857	2.381
Age 25 to 59	1.551	0.761	2.039		N/S	
Age 60 or above		Baseline			Baseline	
Null Log-Likelihood			-4943			-1587
Log-Likelihood			-4460			-1529
Null AIC			9891			3178
AIC			8949			3076
Null BIC			9901			3186
BIC			9026			3112
Number of Observations: 1216				Number of Observations: 439		
Number of Participants: 494				Number of Participants: 291		

N/S: Not Significant

APPENDIX C – SPEED LIMIT SPECIFIC MODELS ACROSS SPEED LIMIT TRANSITION AREAS

Table 30. Mixed Effect Linear Regression Model for Travel Speeds across Speed Limit Transition Areas on Freeways – Initial 55-mph Limit

Random Effects:			
Groups	**Variance**	**Std. Dev.**	
Trip ID	15.100	3.886	
Participant ID	6.892	2.625	
Location ID	3.111	1.764	
Residual	2.490	1.578	
Fixed Effects:			
Parameter	**Estimate**	**Std. Error**	**t-Value**
Intercept	64.741	0.307	210.690
Increase of 5 mph	0.414	0.152	2.719
Increase of 10 mph	1.046	0.011	94.393
Increase of 15 mph	1.447	0.021	67.750

Number of Observations: 114,710

Number of Traces: 611

Number of Participants: 516

Number of Locations: 124

Table 31. Mixed Effect Linear Regression Model for Travel Speeds across Speed Limit Transition Areas on Freeways – Initial 60-mph Limit

Random Effects:			
Groups	**Variance**	**Std. Dev.**	
Trip ID	14.291	3.780	
Participant ID	3.732	1.932	
Location ID	1.023	1.011	
Residual	1.868	1.367	
Fixed Effects:			
Parameter	**Estimate**	**Std. Error**	**t-Value**
Intercept	65.550	0.406	161.653
Reduction of 5 mph	-0.186	0.110	-1.692
Increase of 5 mph	0.337	0.028	11.871
Increase of 10 mph	1.166	0.015	79.707

Number of Observations: 45,287

Number of Traces: 253

Number of Participants: 222
Number of Locations: 23

Table 32. Mixed Effect Linear Regression Model for Travel Speeds across Speed Limit Transition Areas on Freeways – Initial 65-mph Limit

Random Effects:			
Groups	**Variance**	**Std. Dev.**	
Trip ID	17.138	4.140	
Participant ID	5.109	2.260	
Location ID	4.358	2.088	
Residual	2.043	1.429	
Fixed Effects:			
Parameter	**Estimate**	**Std. Error**	**t-Value**
Intercept	65.859	0.317	207.870
Reduction of 5 mph	-0.856	0.026	-32.700
Reduction of 10 mph	-0.994	0.009	-111.190
Increase of 5 mph	0.751	0.015	51.240

Number of Observations: 159,353

Number of Traces: 847

Number of Participants: 671

Number of Locations: 130

Table 33. Mixed Effect Linear Regression Model for Travel Speeds across Speed Limit Transition Areas on Freeways – Initial 70-mph Limit

Random Effects:			
Groups	**Variance**	**Std. Dev.**	
Trip ID	11.337	3.367	
Participant ID	11.473	3.387	
Location ID	2.892	1.701	
Residual	2.406	1.551	
Fixed Effects:			
Parameter	**Estimate**	**Std. Error**	**t-Value**
Intercept	68.07446	0.39647	171.701
Reduction of 5 mph	-0.02943	0.02172	-1.355
Reduction of 10 mph	-1.02147	0.01657	-61.628
Reduction of 15 mph	-1.54111	0.02544	-60.583

Number of Observations: 75,884

Number of Traces: 394

Number of Participants: 353

Number of Locations: 53

Table 34. Mixed Effect Linear Regression Model for Travel Speeds across Speed Limit Transition Areas on Two-Lane Highways – Initial 25-mph Limit

Random Effects:			
Groups	**Variance**	**Std. Dev.**	
Trip ID	15.118	3.888	
Participant ID	0	0	
Location ID	15.119	3.888	
Residual	4.839	2.2	
Fixed Effects:			
Parameter	**Estimate**	**Std. Error**	**t-Value**
Intercept	36.499	0.785	46.487
5-mph increase	1.393	0.06	23.056
10-mph increase	1.453	0.03	49.06
15-mph increase	0.362	0.072	5.007

Number of Observations: 32,835

Number of Traces: 197

Number of Participants: 185

Number of Locations: 36

Table 35. Mixed Effect Linear Regression Model for Travel Speeds across Speed Limit Transition Areas on Two-Lane Highways – Initial 30-mph Limit

Random Effects:			
Groups	**Variance**	**Std. Dev.**	
Trip ID	4.675	2.162	
Participant ID	9.109	3.018	
Location ID	16.914	4.113	
Residual	3.899	1.975	
Fixed Effects:			
Parameter	**Estimate**	**Std. Error**	**t-Value**
Intercept	36.577	0.908	40.271
5-mph reduction	-0.512	0.072	-7.105
5-mph increase	4.079	0.057	71.122
10-mph increase	2.061	0.042	48.668
15-mph increase	4.541	0.088	51.87

Number of Observations: 20,314

Number of Traces: 119

Number of Participants: 118

Number of Locations: 28

Table 36. Mixed Effect Linear Regression Model for Travel Speeds across Speed Limit Transition Areas on Two-Lane Highways – Initial 35-mph Limit

Random Effects:			
Groups	**Variance**	**Std. Dev.**	
Trip ID	12.545	3.542	
Participant ID	5.379	2.319	
Location ID	13.146	3.626	
Residual	5.640	2.375	
Fixed Effects:			
Parameter	**Estimate**	**Std. Error**	**t-Value**
Intercept	39.115	0.420	93.135
5-mph reduction	-1.658	0.077	-21.446
10-mph reduction	-2.536	0.034	-74.445
5-mph increase	-0.325	0.060	-5.417
10-mph increase	1.737	0.024	72.207
15-mph increase	3.139	0.047	66.468

Number of Observations: 86,573

Number of Traces: 518

Number of Participants: 485

Number of Locations: 119

Table 37. Mixed Effect Linear Regression Model for Travel Speeds across Speed Limit Transition Areas on Two-Lane Highways – Initial 40-mph Limit

Random Effects:			
Groups	**Variance**	**Std. Dev.**	
Trip ID	15.567	3.945	
Participant ID	2.589	1.609	
Location ID	7.620	2.760	
Residual	3.416	1.848	
Fixed Effects:			
Parameter	**Estimate**	**Std. Error**	**t-Value**
Intercept	41.882	0.505	82.898
5-mph reduction	0.029	0.045	0.648
10-mph reduction	-2.856	0.037	-77.300
15-mph reduction	-0.723	0.071	-10.120
5-mph increase	1.784	0.024	73.363
10-mph increase	2.442	0.041	59.377

Number of Observations: 54,879

Number of Traces: 337

Number of Participants: 134

Number of Locations: 46

Table 38. Mixed Effect Linear Regression Model for Travel Speeds across Speed Limit Transition Areas on Two-Lane Highways – Initial 45-mph Limit

Random Effects:			
Groups	**Variance**	**Std. Dev.**	
Trip ID	21.145	4.598	
Participant ID	0.000	0.000	
Location ID	16.366	4.045	
Residual	4.559	2.135	
Fixed Effects:			
Parameter	**Estimate**	**Std. Error**	**t-Value**
Intercept	44.172	0.468	94.450
5-mph reduction	-1.067	0.028	-38.540
10-mph reduction	-2.172	0.023	-96.410
15-mph reduction	-4.302	0.062	-69.730
20-mph reduction	-4.828	0.131	-36.970
10-mph increase	2.593	0.026	98.000

Number of Observations: 98,528

Number of Traces: 562

Number of Participants: 471

Number of Locations: 113

Table 39. Mixed Effect Linear Regression Model for Travel Speeds across Speed Limit Transition Areas on Two-Lane Highways – Initial 50-mph Limit

Random Effects:			
Groups	**Variance**	**Std. Dev.**	
Trip ID	19.488	4.415	
Participant ID	0.000	0.000	
Location ID	21.094	4.593	
Residual	5.924	2.434	
Fixed Effects:			
Parameter	**Estimate**	**Std. Error**	**t-Value**
Intercept	48.058	1.008	47.680
5-mph reduction	-3.680	0.102	-35.940
10-mph reduction	-3.586	0.052	-69.080
15-mph reduction	-5.752	0.127	-45.450
5-mph increase	1.984	0.072	27.440

Number of Observations: 18,621

Number of Traces: 102

Number of Participants: 88

Number of Locations: 29

Table 40. Mixed Effect Linear Regression Model for Travel Speeds across Speed Limit Transition Areas on Two-Lane Highways – Initial 55-mph Limit

Random Effects:			
Groups	**Variance**	**Std. Dev.**	
Trip ID	22.944	4.790	
Participant ID	0.000	0.000	
Location ID	26.935	5.190	
Residual	5.423	2.329	
Fixed Effects:			
Parameter	**Estimate**	**Std. Error**	**t-Value**
Intercept	49.622	0.770	64.470
5-mph reduction	-2.849	0.064	-44.270
10-mph reduction	-2.660	0.028	-94.900
20-mph reduction	-5.335	0.058	-92.230
5-mph increase	0.859	0.056	15.350

Number of Observations: 52,650

Number of Traces: 308

Number of Participants: 293

Number of Locations: 65

Table 41. Mixed Effect Linear Regression Model for Travel Speeds across Speed Limit Transition Areas on Two-Lane Highways – Initial 60-mph Limit

Random Effects:			
Groups	**Variance**	**Std. Dev.**	
Trip ID	0.841	0.917	
Participant ID	24.847	4.985	
Location ID	2.066	1.438	
Residual	2.647	1.627	
Fixed Effects:			
Parameter	**Estimate**	**Std. Error**	**t-Value**
Intercept	58.137	1.220	47.640
5-mph reduction	-1.222	0.043	-28.280

Number of Observations: 20,314

Number of Traces: 119

Number of Participants: 118

Number of Locations: 28

APPENDIX D – SPEED LIMIT SPECIFIC MODELS FOR CURVES WITH ADVISORY SPEED SIGNS IN PLACE

Table 42. Mixed Effect Linear Regression Model for Travel Speeds across along Horizontal Curves – Initial 55-mph Limit

Random Effects:			
Groups	**Variance**	**Std. Dev.**	
Trip ID	17.489	4.182	
Participant ID	14.657	3.828	
Location ID	29.858	5.464	
Residual	6.866	2.620	
Fixed Effects:			
Parameter	**Estimate**	**Std. Error**	**t-Value**
Intercept	51.240	0.859	59.640
5-mph reduction	-1.098	0.049	-22.340
10-mph reduction	-0.711	0.022	-31.930
15-mph reduction	-0.692	0.038	-18.240
20-mph reduction	-5.645	0.102	-55.350
25-mph reduction	-9.732	0.160	-60.990
Degree of Curvature	-0.118	0.003	-39.660

Number of Observations: 179,109

Number of Traces: 718

Number of Participants: 463
Number of Locations: 60

Table 43. Mixed Effect Linear Regression Model for Travel Speeds across along Horizontal Curves – Initial 50-mph Limit

Random Effects:			
Groups	**Variance**	**Std. Dev.**	
Trip ID	5.360	2.315	
Participant ID	11.879	3.447	
Location ID	7.996	2.828	
Residual	6.415	2.533	
Fixed Effects:			
Parameter	**Estimate**	**Std. Error**	**t-Value**
Intercept	49.647	0.863	57.496
5-mph reduction	0.410	0.085	4.833
10-mph reduction	-1.743	0.064	-27.372
15-mph reduction	-2.087	0.070	-29.755
20-mph reduction	-0.577	0.122	-4.736
Degree of Curvature	-0.284	0.005	-57.347

Number of Observations: 42,455

Number of Traces: 174

Number of Participants: 132

Number of Locations: 18

Table 44. Mixed Effect Linear Regression Model for Travel Speeds across along Horizontal Curves – Initial 45-mph Limit

Random Effects:			
Groups	**Variance**	**Std. Dev.**	
Trip ID	21.650	4.653	
Participant ID	11.980	3.461	
Location ID	27.750	5.268	
Residual	17.420	4.174	
Fixed Effects:			
Parameter	**Estimate**	**Std. Error**	**t-Value**
Intercept	43.313	0.622	69.590
5-mph reduction	-0.653	0.029	-22.170
10-mph reduction	-2.101	0.024	-88.900
15-mph reduction	-2.305	0.054	-43.070
20-mph reduction	-6.334	0.270	-23.450
25-mph reduction	-3.344	0.060	-56.080
30-mph reduction	-3.405	0.104	-32.710
Degree of Curvature	-0.096	0.001	-97.170

Number of Observations: 368,219

Number of Traces: 1663

Number of Participants: 974

Number of Locations: 93

Table 45. Mixed Effect Linear Regression Model for Travel Speeds across along Horizontal Curves – Initial 40-mph Limit

Random Effects:			
Groups	**Variance**	**Std. Dev.**	
Trip ID	13.334	3.652	
Participant ID	7.191	2.682	
Location ID	28.004	5.292	
Residual	7.984	2.826	
Fixed Effects:			
Parameter	**Estimate**	**Std. Error**	**t-Value**
Intercept	43.449	1.263	34.410
5-mph reduction	-1.163	0.064	-18.070
10-mph reduction	-1.067	0.049	-21.900
15-mph reduction	-6.915	0.067	-103.500
Degree of Curvature	-0.218	0.003	-80.020

Number of Observations: 68,950

Number of Traces: 338

Number of Participants: 254

Number of Locations: 21

Table 46. Mixed Effect Linear Regression Model for Travel Speeds across along Horizontal Curves – Initial 35-mph Limit

Random Effects:			
Groups	**Variance**	**Std. Dev.**	
Trip ID	15.900	3.988	
Participant ID	12.730	3.568	
Location ID	23.760	4.874	
Residual	13.360	3.656	
Fixed Effects:			
Parameter	**Estimate**	**Std. Error**	**t-Value**
Intercept	36.844	0.717	51.404
5-mph reduction	-0.740	0.027	-27.673
10-mph reduction	0.243	0.049	4.994
15-mph reduction	-6.510	0.074	-87.440
20-mph reduction	-3.961	0.052	-76.283
25-mph reduction	-3.148	0.150	-21.036
Degree of Curvature	-0.056	0.001	-39.044

Number of Observations: 208,701

Number of Traces: 910

Number of Participants: 531

Number of Locations: 61

Table 47. Mixed Effect Linear Regression Model for Travel Speeds across along Horizontal Curves – Initial 55-mph Limit

Random Effects:			
Groups	**Variance**	**Std. Dev.**	
Trip ID	16.760	4.094	
Participant ID	26.300	5.129	
Location ID	23.070	4.803	
Residual	26.420	5.140	
Fixed Effects:			
Parameter	**Estimate**	**Std. Error**	**t-Value**
Intercept	28.769	0.985	29.215
5-mph reduction		N/S	
10-mph reduction	3.588	0.079	45.288
15-mph reduction	0.519	0.399	1.300
Degree of Curvature	-0.259	0.002	-135.204

Number of Observations: 143,940

Number of Traces: 626

Number of Participants: 451

Number of Locations: 31