THE SPEED AND SAFETY EFFECTS OF REPLACING DIFFERENTIAL WITH UNIFORM SPEED LIMITS ON RURAL FREEWAYS

by

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To my wife, Laura
I am blessed to walk this path with you.

To my children, Victoria and Nicolas
You bring joy to my world.

To my mom, Aura
You are my hero.

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LIST OF ABBREVIATIONS

AADT:	Annual Average Daily Traffic.
AIC:	Akaike Information Criterion.
DSL:	Differential Speed Limit.
EIA:	Energy Information Administration.
FHWA:	Federal Highway Administration.
GIS:	Geographical Information System.
HEEM:	Highway Economic Evaluation Model.
HPMS:	Highway Performance Monitoring System.
HSIS:	Highway Safety Information System.
INDOT:	Indiana Department of Transportation.
IRI:	International Roughness Index.
LRI:	Likelihood Ratio Index.
LRT:	Likelihood Ratio Test.
NHTSA:	National Highway and Traffic Safety Administration.
NMSL:	National Maximum Speed Law.
NOAA:	National Oceanic and Atmospheric Administration.
NPMRDS:	National Performance Management Research Data Set.
PDO:	Property Damage Only.
PSL:	Posted Speed Limit.
STEAM:	Surface Transportation Efficiency Model.
TCDS:	Traffic Count Database System.
USL:	Uniform Speed Limit.
USD:	United States Dollars.
VMT:	Vehicle miles traveled.

ABSTRACT

After the repeal of the National Maximum Speed Law in 1995, state governments were allowed to set speed limits on their interstate freeways. Several states adopted uniform speed limits (USLs) while others implemented differential speed limits (DSLs), namely lower speed limits for heavy vehicles and higher posted speeds for light vehicles. Indiana's current speed limit law for rural freeways allows passenger cars to travel up to 70 mph and restricts large vehicles' speed with a gross weight of 26,000 pounds to 65 mph.

Previous studies comparing the safety performance of USLs and DSLs have yielded inconclusive results. This dissertation developed a new methodology to estimate the mobility and safety effects of changes in statewide speed limits and applied it in a case study for rural interstate freeways in Indiana. Unlike previous studies on speed limits, the effects of the speed limits were estimated hourly. Typically, a speed limit's effects are assessed under low-density conditions close to free flow, but the proposed methodology calculates a speed limit's effect on speed and safety under various congestion levels. Additionally, recognizing that there are differences in driving behavior, the speed limit's effect can be estimated separately for passenger cars and heavy trucks. The proposed hourly analysis in this methodology also considers previously omitted factors such as travel speed characteristics, weather conditions, lighting, and other seasonal variables.

Advanced statistical models were used in this dissertation to connect the speed limit with the operating travel speed, probability of crash, and probability of injury or death given crash occurrence. The effects of speed limits on travel speeds were estimated using multiple linear regression, while the effects on crash risk and severity were estimated using logistic regression with random parameters that accounted for unobserved variability. These models were then used in a statistical simulation to calculate the effects of alternative statutory speed limit scenarios, namely USLs. These scenarios were subsequently compared to the current speed limit policy in terms of their impacts on travel time, vehicle operating costs, and safety outcomes.

This dissertation found that speed limits affected mobility and safety, mostly under non-congested traffic conditions, but no statistically significant effects of the speed limits were found under congested traffic conditions. A marginal detrimental effect of DSLs on crash injury severity was detected under intermediate traffic conditions. These results suggest that replacing the current

DSL, i.e., 70 mph for passenger cars and 65 mph for heavy trucks, on Indiana rural interstate freeways with a USL of 70 mph may yield benefits in terms of safety and mobility.

1. INTRODUCTION

1.1 Motivation

Speed is one of the primary factors that affect traffic safety. Increasing a vehicle's operating speed is known to reduce the reaction time and increases the braking distance needed to avoid a collision. In 2017, there were 9,717 people killed in crashes in the United States, for which speeding was listed as the primary crash cause (NHTSA, 2019). This number accounts for more than a quarter of all traffic fatalities in 2017.

In addition to its connection with safety, speed is an important factor for traffic engineers and researchers as it serves as a measure of performance for road operations and directly affects economic competitiveness. Consequently, transportation officials have traditionally used various traffic control devices to encourage safe vehicle operation while maintaining acceptable performance levels; speed limits are among the most common tools to promote prudent speed behavior among drivers.

Traffic engineers set posted speed limits (PSLs) to ensure prudent operating speeds for road users. PSLs are periodically revisited based on operating speed distribution and traffic safety performance; locations with many speed-related crashes are usually candidates for lowering their PSL. A recent survey (K. Fitzpatrick et al., 2019) summarized the attitudes among practitioners about defining PSLs. Their results showed that operating speed distribution statistics, such as the median and 85th percentile, play an essential role in selecting PSLs on high-speed roads such as rural interstate freeways. Additionally, the limited use of technical tools, such as USLIMITS2, to support the setting of PSLs was reported.

While PSLs are set based on the speed distribution and crash history, among other factors; statutory speed limits generally are selected based on political demands and economic repercussions. To fulfill this task, some states conduct statewide analyses of the effects of modifying their policies (Iowa Highway Safety Management System, 2002; Monsere et al., 2004; Savolainen et al., 2014; Skszek, 2004) before making final decisions. Such an analysis must also include the often-used PSLs placed locally where drivers' behavior and the crash history depart from the areawide speed limit. Even though this practice of setting speed limits targets the operational speeds and local conditions, drivers frequently exceed the speed limit based on their risk perception, desired speed, and speed enforcement consciousness (Tarko, 2009).

Some researchers have opposed the setting of speed limits based solely on operating speed characteristics. They argued that drivers' speed choices are not "objectively rational" and thus demand regulatory strategies such as speed limits (Elvik, 2010). This claim was confirmed by studying the effect of PSLs on drivers' speed choices (Anastasopoulos & Mannering, 2016). Several factors were found to alter drivers' speed choices in the presence of speed limits, including age, gender, marital status, number of children, level of education, household income, age when first licensed, and opinions about pavement quality. The previous findings imply a lack of objectivity in drivers' speed choices.

All in all, the relationship between speed, traffic safety, and the speed limit is complicated (see Figure 1). An increase in speed is usually related to an increase in crash frequency and severity (Elvik, 2009, 2013; Elvik et al., 2004). Changes in speed limit also have been connected to crash frequency and severity changes (Farmer, 2016; Farmer et al., 1999). Using regression analysis, the speed limit also has been connected to the operating speed and therefore is one of the factors that drivers consider when selecting their operating speed (Bassani et al., 2014; Eluru et al., 2013; K. Fitzpatrick et al., 2005; Parker, 1997). Tarko and Medina (2006) also found that drivers adapt their operating speed based on their perception of crash risk and enforcement.

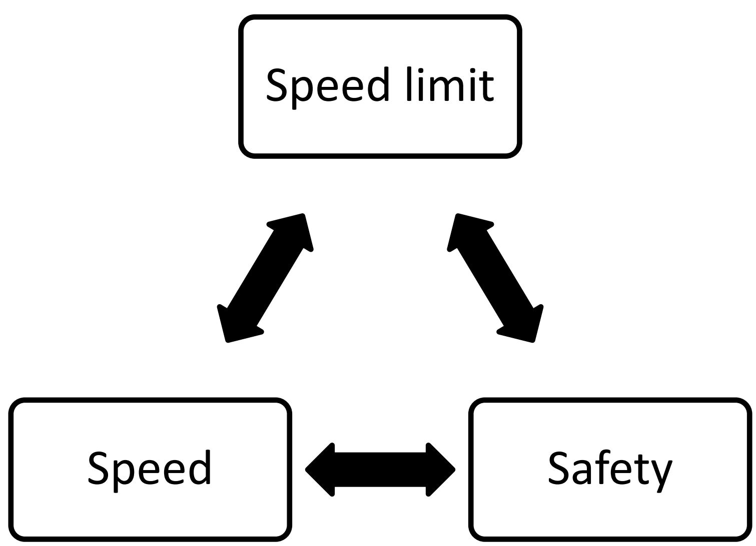

Figure 1. The triangular relationship between speed limit, operating speed, and traffic safety.

1.2 Statutory Speed Limits

Unlike the process of setting PSLs, elected officials usually set statutory speed limits based on system-wide economic effects and political demands. In January 1974, the U.S. Congress passed the Emergency Highway Energy Conservation Act. One of its provisions, the National Maximum Speed Law (NMSL), set the maximum speed limit on U.S. highways to 55 mph, where speed limits before 1974 were as high as 75 mph in some midwestern states such as Kansas. In April 1987, Congress passed the Surface Transportation and Uniform Relocation Assistance Act, which allowed the states to raise their speed limits to 65 mph on rural interstates and other non-interstate roads designed and built to freeway standards. California, Florida, Illinois, Iowa, Kansas, Kentucky, and Oklahoma raised their speed limits without much delay, and others followed. Eventually, the repeal of the NMSL in December 1995 transferred the setting of freeway speed limits back to the state governments; and most of the states immediately readopted their pre-1974 speed limit policies.

The repeal of the NMSL encouraged diversity in statutory speed limits, particularly on rural interstate freeways. Simultaneously, some states adopted USLs while others implemented DSLs, i.e., lower PSLs for heavy vehicles and higher PSLs for lighter vehicles. Other speed restrictions on interstate freeways included minimum speed limits, time-dependent speed limits (e.g., day/night), season-dependent speed limits (e.g., winter), and most recently, variable speed limits. The thought process behind the setting of statutory speed limits was addressed by Albalate and Bel (2012), who performed an econometric analysis of the determinants of speed limit policies and state reactions after the repeal of the NMSL. The authors concluded that geography (size and population) and political ideology were two of the main factors influencing statutory speed limits. Figure 2, which shows the current maximum speed limit allowed in each state, clearly indicates that higher speed limits are generally implemented in states with lower population densities.

There are currently eight states with active DSL policies: Arkansas, California, Idaho, Indiana, Michigan, Montana, Oregon, and Washington (see Figure 3). The largest speed differential between passenger cars and heavy trucks is 15 mph in California. Also, minimum speed limits can be found in 19 states, for which 40 mph is the selected posted speed in most cases. There are nighttime speed limits in only seven states: Arizona, Colorado, Florida, Montana, Rhode Island, Tennessee, and Washington. To facilitate this differential, retroreflective paint is used for the daytime speed limits, so only the nighttime speed limits signs are visible at night.

After the NMSL's repeal, Indiana adopted a 65/60 mph DSL on rural interstates. In 2005, the speed limits were upgraded to 70 mph for cars and 65 mph for trucks with a gross vehicular weight of 26,000 pounds or greater (Malyshkina et al., 2007). The 2005 upgrade also allowed urban freeway speed limits to range from 50 to 65 mph. The current maximum allowed speed on rural interstate freeways is 70 mph for passenger cars and 65 mph for trucks with a gross vehicular weight of 26,000 pounds or greater. Most of Indiana's neighboring states implemented a 70-mph USL policy, except Michigan with a 75/65 mph DSL policy. For urban interstate freeways, as established by Indiana Code I.C. 9-21-5-2, the statutory maximum speed limit is 55 mph for all vehicles. Neighboring states' urban speed limits range between 45 mph in Illinois and 70 mph in Michigan.

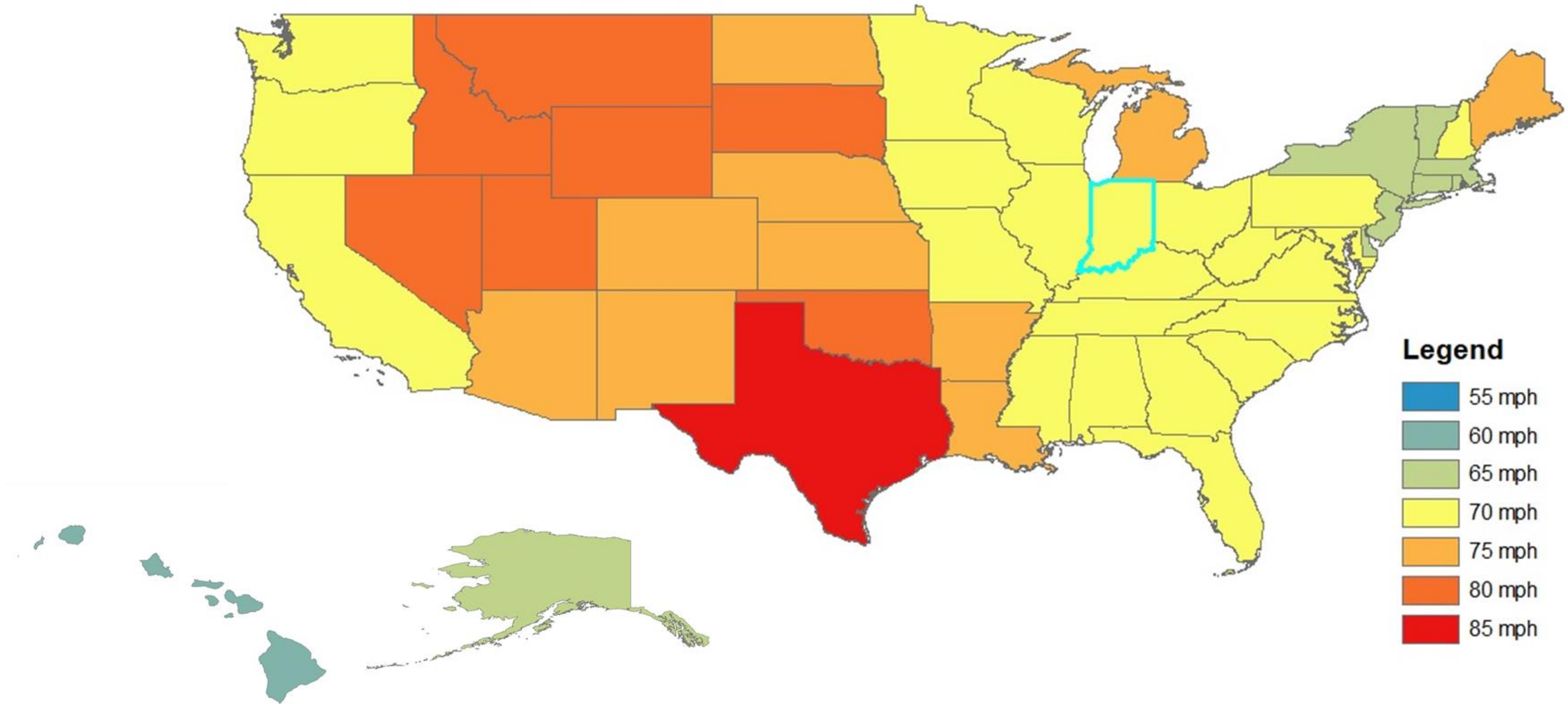

Figure 2. Maximum speed limits in the United States.

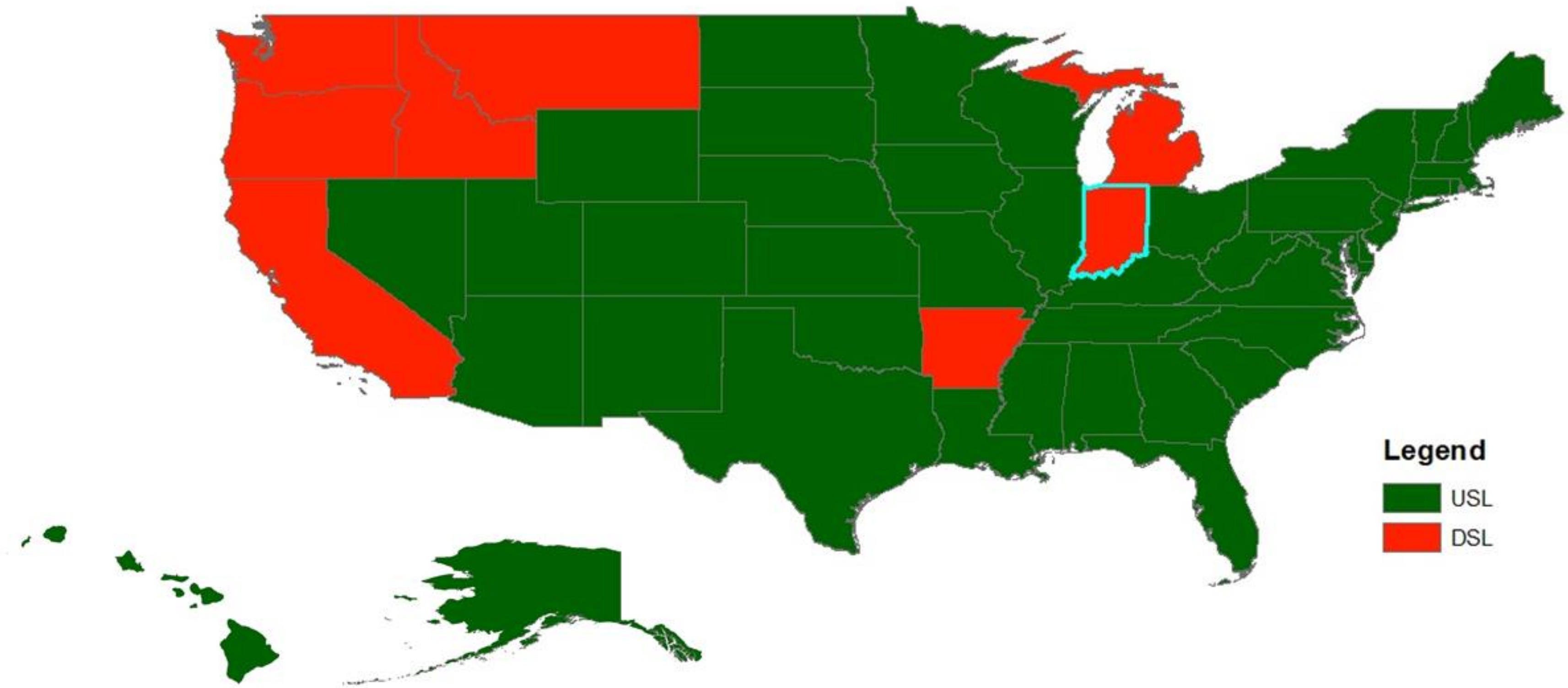

Figure 3. States with uniform and differential speed limits.

1.3 Research Objectives

This dissertation expands the current knowledge by addressing the following objectives:

- Introduce a methodology to estimate a comprehensive travel cost of statutory speed limits changes according to a formulated disaggregated analysis of the effects of speed limits on operating speed and crash risk and severity.
- Investigate the speed and safety effects of speed limits under various traffic conditions. This dissertation evaluated the speed limit effects under non-congested traffic conditions close to free-flow and checked the validity of the assumption that there is no significant effect expected under congested traffic congestions understood as stopped or moving traffic queues.
- Apply the proposed methodology in a case study for Indiana's rural interstate freeways. Indiana's current DSL policy was compared to alternative scenarios based on their effects on travel time, vehicle operating costs, and crash frequency and severity.
- Estimate the comprehensive travel cost effect on Indiana's interstate network of alternative speed limit policies via statistical simulation.

Since 1974, there has been a tendency towards continuously increasing the speed limits on freeways. However, before making any significant change in speed limit policies, the mobility and safety effects of these changes need to be considered. Specifically, it is necessary to evaluate the possible implications of changing the Indiana speed limit policy according to different scenarios. This dissertation focused on freeway roads categorized as interstates. Other restricted-access highways were not included in the analysis.

1.4 Dissertation Organization

The remainder of this dissertation is organized in the following chapters and appendices:

- *Chapter 2, Literature Review* summarizes the relevant literature pertaining to the relationship between speed limits, operating speed, and traffic safety. The research gap that justifies the present study is discussed.

- *Chapter 3, Empirical Setting* describes the current statutory speed limit policy in Indiana and its bordering states.
- *Chapter 4, Research Approach* presents the proposed new methodology to estimate the mobility and safety effects of statutory speed limits. The underlying assumptions and statistical analysis tools also are described.
- *Chapter 5, Data* illustrates the available data for further analysis. The data preparation tasks and final linking structure are briefly described. The descriptive statistics of the sample also are presented.
- *Chapter 6, Estimated Speed Effect* presents the resulting estimated effects on the travel speeds of cars and trucks under several congestion levels.
- *Chapter 7, Estimated Safety Effect* presents the resulting estimated effects on the probability of a crash and the severity of injuries. Significant random-parameter effects also are discussed.
- *Chapter 8, Evaluation of Statutory Speed Limit Alternatives* summarizes the expected costs related to alternative speed limit settings, segregated by the value of time, vehicle operating costs, and safety outcomes.
- *Chapter 9, Closure* summarizes this dissertation, including its importance by presenting the methodological and empirical implications as well as the transferability of the results, study limitations, and future research directions.
- *Appendix* There are three appendices: 1) the AADT hourly adjustment factors needed to simulate alternative speed limit scenarios, 2) the SAS/ETS® code of the estimated models for speed and safety, and 3) the models used to define the thresholds for classifying observations by congestion level.

2. LITERATURE REVIEW

This chapter presents a summary of the relevant literature pertaining to the relationship between speed limits, operating speed, and traffic safety. The main findings from past studies that aimed to compare the safety performance of differential and uniform speed limit policies first are presented. Recent publications on drivers' perspectives towards PSLs and the economic evaluation elements of statutory speed limits are discussed. Finally, the research gap that justified this dissertation is clearly stated.

2.1 Operating Speed and Safety

Increasing the speed of motor vehicles reduces a driver’s available time to react to an emergency stop and increases the required braking distance. Following this logic, various researchers have observed that the average speed has a significant effect on the crash frequency and severity (Elvik, 2009, 2013; Elvik et al., 2004; Hauer, 2009; Nilsson, 1981). Other authors who focused on studying the speed variation of interacting motor vehicles also found a connection between crash risk and speed variance (Aarts & van Schagen, 2006; Garber & Gadiraju, 1989; Johnson & Pawar, 2007; Solomon, 1964; Taylor et al., 2000). The general conclusion from the above authors was that the total effect of operating speed on traffic safety results from a combination of several operating speed characteristics.

2.1.1 Average speed and safety

Various models that relate the average operating speed with traffic safety have been proposed and validated. Some of the most remarkable are the exponential and power models (Hauer, 2009; Nilsson, 1981).

In 1981, Nilsson proposed a power-like relationship between operating speed changes and traffic safety outcomes (Nilsson, 1981). The power model is shown in Equation 1 and Equation 2 for the number of crashes and fatalities.

$$Y_1 = \left(\frac{V_1}{V_0}\right)^{\alpha} Y_0 \qquad \text{Equation 1}$$

where, Y_1 is the number of crashes at a certain injury severity level after the speed change, V_1 is the average operating speed after the change, Y_0 is the number of crashes at a specific injury severity level before the change, V_0 is the average operating speed before the change, and α is the power coefficient of the relation between the speed change ratio and the number of crashes before the change.

$$Z_1 = \left(\frac{V_1}{V_0}\right)^{\alpha_1} Y_0 + \left(\frac{V_1}{V_0}\right)^{\alpha_2} (Z_0 - Y_0) \qquad \text{Equation 2}$$

where, Z_1 is the number of fatalities after the speed change, Z_0 is the number of fatalities before the change, V_1 is the average operating speed after the change, V_0 is the average operating speed before the change, α_1 is the power coefficient of the relation between speed change ratio and the number of fatalities before the change, and α_2 is the power coefficient of the relation between the speed change ratio and the number of fatalities minus the total number of crashes before the change. The best current estimates of the power model's exponent are 5.5 for fatalities and 3.9 for injury crashes (Elvik et al., 2019).

Notably, Elvik et al. (2004, 2009, 2013), using meta-analysis to evaluate Nilsson's power model and, based on a sample of 526 studies, confirmed the power relationship between the average speed and safety outcomes.

In addition to the power model, an exponential-like model was proposed in (Hauer, 2009). Hauer's exponential model has been widely used to study changes in the average operating speed and their effects on safety. A simplified version of the exponential model is presented in Equation 3.

$$\left(\frac{Y_1}{Y_0}\right) = e^{\beta[V_1 - V_0]} \qquad \text{Equation 3}$$

where Y_0, Y_1 are the number of crashes at a certain injury severity level before and after the speed change, and β is the exponential coefficient of the relationship between the operating speed change and the crash ratio. The best current estimates of the exponential model's speed coefficient are 0.08 for fatalities and 0.06 for injury accidents (Elvik et al., 2019).

2.1.2 Speed variance and safety

Many studies have found a connection between speed variance and traffic safety outcomes (Aarts & van Schagen, 2006; Johnson & Pawar, 2007; Solomon, 1964; Taylor et al., 2000). These authors argued that not only the magnitude of the operating speed, but the interaction of motor vehicles, are reflected in the speed variance, affect traffic safety.

Solomon's seminal work in 1964 proposed a U-shaped relationship between the crash involvement rate and the degree of deviation from the average speed (Solomon, 1964). The crash rates at multiple injury severity levels were found highest at very low operating speeds, lowest at the approximate average operating speed, and intermediate at high operating speeds, particularly at night. Solomon concluded that the greater a vehicle's variation in speed from the average operating speed of all the traffic, the greater its chance of being involved in a crash. The proposed U-shaped pattern was confirmed for vehicles moving above the average operating speed but is still under debate for vehicles moving below the average operating speed (Aarts & van Schagen, 2006). Other studies confirmed that driving close to the average traffic speed reduces the crash risk (Johnson & Pawar, 2007). In conclusion, drivers who "go with the flow," i.e., travel at speeds closer to the average, have a lower chance of being involved in a crash.

While the average operating speed and speed variance may influence safety, they should not be considered separately as some researchers have found a strong connection between them. Taylor et al. (2000) observed that the speed variance increased with the average operating speed.

In this dissertation, the effect of speed on safety is represented using several speed characteristics, including the average operating speed, speed variance, and, notably, rapid operating speed decreases.

2.2 Speed Limits and Speed

The relationship between speed limits and speed has been a matter of study for decades. Multiple authors have addressed this relationship using a variety of approaches, including before-and-after studies related to changes in the speed (El-Basyouny et al., 2014; Hu, 2017; Iowa Highway Safety Management System, 2002; Islam et al., 2014; Monsere et al., 2004; Taylor et al., 2000); cross-sectional analyses looking for a correlation between speed limits and operational speed characteristics (Bassani et al., 2014; Eluru et al., 2013; K. Fitzpatrick et al., 2005; Parker, 1997; Tarko, 2009); and, lately, human behavior survey-based studies that focused on the driver's perception of speed enforcement and how drivers respond to PSLs (The Gallup Organization, 2003).

From before-and-after studies, some authors have agreed that the observed change in operating speed characteristics, such as the average speed and the 85th percentile, was steadily lower than the change in the PSL (El-Basyouny et al., 2014; Hu, 2017). Islam et al. (2014) studied vehicle speeds in residential zones where the speed limit was lowered from 50 to 40 km/h (31.1 to 24.9 mph). The authors noted that the mean free-flow speed decreased by 3.9 km/h (2.4 mph) and 4.9 km/h (3.0 mph) three and six months, respectively, after the speed limit change was implemented; and a statistically significant reduction in speed variance also was reported. Interestingly, when looking at the treatment effect over time, the PSL change's effectiveness increased. Lastly, heavy vehicles experienced a more considerable reduction in operating speed compared to light vehicles.

In 2002, the statewide changes in Iowa's speed limits were studied by observing changes in the distribution of speed and crash patterns (Iowa Highway Safety Management System, 2002), which found that in terms of mobility, a 10-mph rise in speed limit resulted in an 8.2-mph increase in the 85th percentile of speed distribution. In 2004, Oregon authorities suggested that a 5-mph rise in interstate speed limits was likely to produce a 2- to 4-mph increase in the 85th percentile of speed distribution (Monsere et al., 2004; Taylor et al., 2000).

Another aspect considered by researchers is the alteration in drivers' compliance to the PSL after a speed limit change. Hu (2017) investigated the effects of raising the speed limit on Utah's rural interstates from 75 to 80 mph on the operating speed characteristics and the probability of exceeding the PSL and found that the mean speed of passenger cars increased by 3.1 mph after the change in the PSL and the operating speed for heavy trucks also increased by 1.7 mph. Most importantly, the author found that increasing the speed limit had a significant positive effect on a driver's probability of exceeding the PSL.

Modeling the speed characteristics as dependent variables of many predictors, including the speed limit, some authors found a strong correlation between the two. Parker (1997) studied the effects of speed limit changes on speed and found that drivers responded to changes in the speed limits; however, this change was not very large and may not be of practical significance. A 5-mph change in PSL has been connected to a 1.5 mph change in operating speed. Fitzpatrick et al. (2005) studied the relationship between design speed, operating speed, and PSLs and found that the last two presented a higher correlation. The author's analysis was based on free-flow conditions at 79 sites in six states. A 1-mph change in speed limits was associated with a 0.963-mph change in speed. More recent studies (Bassani et al., 2014; Eluru et al., 2013) also found that speed limits changes affected the operating speed. However, the magnitude of the effect decreased significantly after including other attributes, such as temporal indicators, light conditions, geometry, and pavement characteristics.

Tarko (2009) proposed modeling driver-preferred speeds as a trade-off behavior between safety, travel time, and enforcement. Using free-flow speed measurements (headways of 5 s or greater), a 0.485 mph increase in speed was linked to a 1-mph change in PSL after including roadway characteristics, surrounding environmental conditions, and time indicators. Another interesting finding by Tarko was that speed limits seem to encourage slow drivers to drive faster and fast drivers to drive slower.

Survey-based studies provide the driver's perception of speed limits. The results from the *National Survey of Speeding and Unsafety Driving Attitudes and Behaviors* suggested that drivers believe they can drive 7 to 8 mph above the speed limit before getting a ticket. Other interesting findings included that younger and male drivers are more likely to speed. Most drivers seem to believe that speed limits appropriately reflect road capacity, but 35% of the surveyed drivers said that interstate roads' speed limits were too low. Alarmingly, four out of 10 drivers will still drive above the speed limit even though it was increased by 10 mph on freeways (The Gallup Organization, 2003).

2.2.1 The endogeneity issue

There exists a two-way relationship between speed limits and operating speeds. First, PSLs are set based, among other factors, on the operating speed distribution (K. Fitzpatrick et al., 2019). On the other hand, individual drivers adjust their speeds, keeping in mind the PSL, their perceived crash risk, and the speed enforcement level (Tarko, 2009). This endogenous relationship between speed limits and operating speeds, where one influences the other simultaneously, was tested by Himes et al. (2013). They recommended using speed limit as an exogenous variable when modeling operating speed characteristics (e.g., mean speed and 85th percentile).

2.3 Speed Limits and Safety

In addition to studying changes in operating speed, researchers often examine changes in safety outcomes, such as the number of crashes or the fatality rate, due to speed limits changes. The literature on the safety effect of speed limit changes has been updated. The main findings from selected relevant studies are presented in this section. Special attention has been placed on studies pertaining to interstate freeway roads.

2.3.1 Posted speed limits and safety

Single-vehicle crashes were analyzed by Renski et al. (1999) after increasing the PSL on some interstate highways in North Carolina. Raising the PSL from 55 to 60 or 65 mph was found to increase the probability of a minor or non-incapacitating crash. Nevertheless, increasing the PSL from 65 to 70 mph did not have a significant effect on safety.

Ossiander and Cummings (2002) investigated the connection between PSL increases and traffic safety on Washington's rural interstate freeways. In road segments where the PSL was raised from 55 to 65 mph, the number of fatal crashes was 2.1 times larger than the expected value. However, no significant effect was detected on overall crash rates. Contrary to Ossiander and Cummings, Kweon and Kockelman (2005) found that interstate segments with a PSL of 55 mph or below had lower overall crash rates; and the effect of the PSL on fatal crash rates was found not significant.

Malyshkina et al. (2007) evaluated speed limits in Indiana and their effects on crash frequency and severity by examining crash records. The authors found that higher speed limits on freeways had no statistically significant effect on the probability of "unsafe speed" being listed as the leading cause of a crash, nor was it shown that the speed limit had any influence on crash severity. However, for some non-freeway highways, they found that higher speed limits significantly raised the likelihood of an "unsafe speed" assessment; and in contrast, on other low-hierarchy roads, higher speed limits decreased the likelihood of unsafe speeds. Lastly, higher crash severity levels were associated with higher speed limits on some non-freeway highways.

Before and after studies also have been conducted to examine the relationship between the speed limit and traffic safety. Using data from 1993 to 2013, Farmer (2016) found that a 5-mph increase in the posted maximum speed limit was linked to an 8% rise in accident rates. Parker

(1997) analyzed the safety effects of speed limit changes on selected roadway sections, and the evidence the author collected led to conclude that the crash frequency changed when PSLs were lowered or raised.

2.3.2 Statutory speed limits and safety

Several authors have studied the safety effects of changes in statutory speed limits (Farmer et al., 1999; Grabowski & Morrisey, 2007; Lave & Elias, 1994; Vernon et al., 2004; Warner et al., 2019). Lave and Elias (1994) quantified the safety effects of the Surface Transportation and Uniform Relocation Assistance Act of 1987, which allowed states to increase the maximum speed limit from 55 to 65 mph, and they surprisingly found that the increase was associated with a 3.4 to 5.1% reduction in statewide fatal crash rates.

After the complete repeal of the NMSL in 1995, several states were prompted to increase their maximum speed limits. Multiple studies investigated the changes in fatal crashes (Farmer et al., 1999; Grabowski & Morrisey, 2007; Vernon et al., 2004). Farmer et al. (1999) found that the number of fatal crashes on interstates increased by 15% in 24 states where speed limits were raised while fatal crash rates increased by 17%, and the fatalities on roads unaffected by the repeal were unchanged. Grabowski and Morrisey (2007) presumed that the increase in the number of fatal crashes on interstate roads was accompanied by an improvement in the safety performance on non-interstate roads; however, their evidence failed to confirm any significant decrease in vehicle miles traveled (VMT) or the number of fatal crashes on non-interstate roads after the repeal of the NMSL.

More recently, Warner et al. (2019) investigated the effects on traffic safety of recent increases in maximum statutory speed limits in several states. Their results showed that increasing the mileage of rural interstates with PSLs at 70, 75, and 80 mph by 1% increased by 0.2%, 0.5%, and 0.6%, respectively, the number of fatalities.

The reported discrepancies when assessing the speed limit effect on safety using the number of crashes and crash rates were analyzed by Castillo-Manzano et al. (2019). Using a meta-analysis with 17 publications that studied the relationship between increases in speed limits and their effects on traffic fatalities, the authors found that the frequency of traffic fatalities increases on rural interstates after speed limits were raised, but in other cases, it was reported that the statewide fatal crash rates were marginally improved by raising the legal speed limits. The latter finding could be linked to the setting of speed limits based on a location's safety performance, where lower speed limits may have been associated with higher historical crash rates. Intuitively, an increment in the PSL is associated with a detriment in safety performance; however, speed limits are frequently revised based on crash history, and lower posted speeds can be found sporadically on unsafe road segments. This bidirectional relationship between speed limits and safety adds complexity to the studied phenomenon.

2.4 Differential Speed Limits

2.4.1 Differential speed limits and speed

Several authors found that a DSL policy increased the actual difference in the average operating speed between passenger cars and heavy trucks (Dixon, Abdel-Rahim, & Elbassuoni, 2012; Garber & Gadiraju, 1991; Hall & Dickinson, 1974; Harkey & Mera, 1994; Johnson & Murray, 2010). While intuitive, the observed speed difference was not found to be as large as the difference between PSLs. For example, Garber and Gadiraju (1991) found that the average speed differences were about 1 to 4 mph in response to a 10-mph speed limit differential.

In contrast, other authors reported similar speed characteristics in states with USLs and DSL policies. In 1992, Freedman and Williams (1992) analyzed speed data from 11 northeastern states to determine the effect of DSLs on the mean and 85th percentile of speed and found that for passenger cars, the speed characteristics in states with a DSL policy were not significantly different from those in states with USLs. Similarly, Harkey and Mera (1994) found no significant differences for heavy trucks and non-trucks' mean speeds when comparing DSLs and USLs.

A more recent analysis in 2015 by Russo et al. (2015) examined operating speed characteristics in three states (Indiana, Michigan, and Ohio) with USL and DSL policies on freeways. They found that passenger cars had consistent speeds in the three states with a 70-mph PSL regardless of the statutory speed limit. More remarkably, the speed variance was highest in states with DSLs, followed by urban freeways with a 55-mph USL for all vehicles. Differences in speed behavior also were found among the states; specifically, the speeds were 3 to 4 mph lower in Ohio than in Indiana and Michigan. Also, truck speeds were 1 mph higher in Indiana compared to Michigan. These differences led to the conclusion that the operating speeds reflected the prevalent variability in the local driving culture across the states.

Finally, researchers who compared USLs vs. DSLs consistently reported that, regardless of the speed limit setting, trucks and non-truck vehicles exhibited different speed behavior (Johnson & Murray, 2010). Inspection of their different speed distributions has revealed that trucks tend to travel at considerably lower speeds than passenger cars, which could be attributed to the truck driving culture, company driving policies, and the presence of in-vehicle speed limiters.

2.4.2 Differential speed limits and safety

The traffic safety effects of implementing vehicle-specific statutory speed limits, including USLs and DSLs, have been estimated. However, past research studies have led to inconclusive or, in some cases, conflicting results. A compilation of some of the most relevant studies is presented below.

Some studies linked the implementation of DSLs with traffic safety improvements. Decreased crash rates were observed by Dixon et al. (2012) after implementing DSLs on Idaho rural interstate freeways. In their study, the crash data were divided into three analysis periods with a 65-mph USL, 75-mph USL, and 75/65-mph DSL, correspondingly. The authors found that the overall and truck-involved crash rates were lowest when the DSL was implemented; however, this effect was attributed to the significant reduction in truck operating speeds rather than speed limit policy changes.

Korkut et al. (2010) used regression analysis to determine the combined effect of DSLs and truck right-lane restrictions at the I-10 Atchafalaya Basin Bridge in southern Louisiana. In their study, hourly crash rates were modeled as a linear function of several traffic characteristics, including traffic volume by the vehicle type, proportion of heavy vehicles by lane, speed variance for each type of vehicle, and lane occupancy. They determined that while there was a beneficial effect of the combined policies on the overall safety, the individual effect of DSLs was not significant.

Recently, Davis et al. (2015) conducted a longitudinal analysis to explore the relationship between traffic fatalities and speed limit policies on rural interstates. Using a random parameter negative binomial regression model, the authors found that states with DSLs tended to have a 3.3% lower fatal crash rate than states with USLs. Examining the truck-involved crashes, they found a significant 24.6% reduction in the frequency of fatal crashes in states with a DSL policy. Moreover, truck-related crashes were lower in states with DSLs.

Contrary to the above studies, other authors found that the implementation of DSLs produced safety drawbacks or that the results were inconclusive. Hall and Dickinson (1974) investigated crash data from 83 sites in Maryland to study the connection between truck speed and safety and concluded that having different speed limits for trucks and non-trucks contributed to increased lane-changing maneuvers and rear-end crashes.

Some studies were unable to provide significant or consistent results of changes in the speed limit policies. For example, Pfefer et al. (1991) conducted a time series analysis to estimate the safety effect of DSLs in Illinois after the speed limit on rural interstate roads was changed from 55 mph to 65/55 mph. Monthly crash counts and VMT were gathered from January 1983 to July 1988. The authors found that although the frequency of total crashes rose by 14.2% after the speed limit change, there was no statistically significant increase in the frequency of fatal and injury crashes. Furthermore, no change was detected in the total crash rate; however, an 18.5% increase in the fatal and injury crash rate was observed. They also found a significant 27.3% reduction in the car-into-truck fatal and injury crash rate, but there was no conclusive change in the car-into-truck total crash rate when all crashes were considered.

Garber et al. (2003) studied safety performance in nine states with various speed limit policies (Arizona, Iowa, North Carolina, Illinois, Indiana, Washington, Arkansas, Idaho, and Virginia). The states were classified depending on their initial speed limit policy and whether it was changed. After considering variations in exposure, no significant difference in safety performance between states with DSLs and USLs was detected.

Similar to Garber et al., Neeley and Richardson (2009) modeled the safety effect of changes in speed limit using data from several states. They too found that a higher speed limit for trucks was associated with higher fatality rates; however, they found that the difference in speed limits between cars and trucks had no significant effect on safety.

Johnson and Pawar (2007) analyzed the discrepancies between their findings regarding the safety effects of DSLs. They attributed the inconsistencies to two opposing factors: on the one hand, the positive effect results from the improved vehicle dynamics (braking and maneuvering) for trucks moving at lower speeds, and on the other hand, the negative effect subsequent to an increase in the number of overall traffic interactions from the increased speed variation. They suggested that these two effects of DSLs might counteract each other, ultimately resulting in no consistently observable crash data effects. Additionally, they concluded that four methodological issues contributed to the inconclusive results: (1) the use of fatal crashes and crash rates, to the contrary; (2) differences in the results due to using frequencies or rates; (3) various lengths of the analysis period, which has been shown to produce differing results; and (4) driver use of speed limiters, or governors, that may limit drivers' responses to PSLs.

2.5 Drivers Perspectives

Regardless of the PSL, there exist certain drivers who will operate at excessive speeds. Mannering (2009) conducted a survey of a sample of Indiana drivers showed that drivers' perceptions of the extent to which they could drive above the speed limit without receiving a speeding ticket was a critical determinant of their idea of a safe speed. Of the surveyed drivers, 21% said that driving 5 mph over the PSL was safe, 44% indicated 10 mph, and 35% felt as much as 20 mph was safe. Other significant variables affecting the "safe speed" value included driver age, gender, being previously stopped for speeding, and ethnicity.

With regard to professional truck drivers, Johnson and Pawar (2005) surveyed truck drivers on their opinion of DSLs vs. USLs. Most drivers stated that DSLs increased interactions among vehicles and increased the probability of rear-end, sideswipe, and on-ramp collisions. Three scenarios concerned the drivers: (1) trucks being trapped in the right lane and continuously needing to yield to merging traffic from entrance ramps; (2) trucks not being able to reach traffic speed when merging into traffic; and (3) congestion, clustering of traffic, and bottleneck situations on freeways as the result of lower truck speeds. The preferred speed limit for the surveyed truck drivers was a 70-mph USL policy on rural freeways.

2.6 Economic Analysis Elements of Speed Limit Changes

Multicriteria analyses of alternative speed limits usually assess their effects on travel time, vehicle operating costs, crashes, infrastructure modifications, and environmental quality (Sinha & Labi, 2007) while the effect of truck speeds on pavement deterioration is typically overlooked (Cebon, 1999). Indeed, multiple authors have found that higher truck speeds may accelerate the failure process of already rough pavement (Hao et al., 2020; Shi & Cai, 2009) . Based on the past studies, optimal speed limits can be proposed from different viewpoints, including societal perspective, road user perspective, taxpayer perspective, and residential perspective. The road user and taxpayer perspectives tend to result in higher speed limits, while the societal and residential perspectives produce lower values (Elvik, 2002).

Examples of multicriteria analyses include a study by van Benthem (2015), who estimated the optimal speed limit on interstate freeways in California, Oregon, and Washington. Among the most important findings, a 10-mph speed limit increase was linked to a 3- to 4-mph increase in travel speed, a 9 to 15% increase in the total number of crashes, and a 34 to 60% increase in the number of fatal crashes. Overall, the social costs, especially those related to traffic safety, were two to seven times larger than the social benefits. An optimal speed limit of 55 mph was suggested in the three states.

More recently, Monsere et al. (2017) revisited the DSL effects in Oregon and determined that, except for travel time savings and economic development benefits, all the other issues (e.g., crashes, enforcement, health, and environment) would be negatively affected by the proposed modification of the DSLs from 65/55 to 70/65 mph.

Multicriteria analysis also may be used to distinguish between different road users since the effects of speed limits may be distinct depending on the target vehicle. Following this rationale, Gates and Savolainen (2016) carried out an economic analysis of speed limit policies on Michigan's interstate freeways. They considered the costs related to infrastructure modifications, fuel consumption, travel time, and fatal crash occurrence differentiated by light and heavy vehicles. Their results indicated that raising the speed limit for heavy vehicles from 60 mph to 65 or 70 mph might be cost-effective; however, increasing the speed limit for light vehicles from 70 mph to 75 or 80 mph could have a negative overall economic effect.

2.7 Statement of Research Need

The foregoing literature review shows that the evaluation of statutory speed limits is a challenging task. Previous studies have estimated the effects of changes in statutory speed limits on operating speed and traffic safety using aggregate performance measures such as the average speed, 85th percentile, number of crashes by injury severity level, and crash rates, which are commonly used due to their availability. While helpful, these measures may not be suitable for multifaceted effects such as those reported for DSLs. Moreover, several time-dependent factors, including weather, traffic congestion, and temporal variation, are omitted using such an approach.

This dissertation adds to the existing knowledge by proposing a methodology to assess the mobility and safety effects of statutory speed limit changes, which subsequently was implemented in a cross-sectional analysis of DSLs on rural freeways in Indiana. The proposed method departs from previous research by considering the short-term effects of speed limits. Additionally, the effects of speed limits on cars and trucks are estimated separately, and the speed limit effect of safety is evaluated both for the probability and injury severity of vehicle occupants.

Additionally, a generally accepted assumption in past research is that the speed limit's effect is maximum during free-flow conditions while it is null during complete congestion. However, there is no formal confirmation of such an assumption. Studying the effect of speed limits at multiple congestion levels is vital to estimate key elements of its economic effect. This dissertation fills this knowledge gap by estimating the speed limit speed and safety under three congestion states: congested, non-congested, and intermediate.

Lastly, the resulting models permit simulation of the comprehensive travel cost of changes in statutory speed limits on Indiana's rural freeways. The effects on travel time, crashes, and vehicle operating costs are estimated for one year; and a distinction is made between passenger cars and heavy trucks. It is assumed that external time-dependent factors such as weather, traffic, and seasonal variation remain constant during the simulation period, which helps simplify the computational efforts while focusing on the relationships of interest.

3. EMPIRICAL SETTING

3.1 Indiana's Speed Limit Policy

In Indiana, the maximum speed limit before the NMSL was enacted was 70 mph (Khan et al., 2000). After the NMSL's repeal in 1995, Indiana adopted a DSL on rural interstates of 65 mph for light vehicles and 60 mph for heavy vehicles. In 2005, the speed limits on rural freeways were raised to 70 mph for light vehicles and 65 mph for trucks with a gross vehicular weight of 26,000 pounds or greater (Malyshkina et al., 2007). Additionally, the speed limits on urban freeways were set to range from 50 to 65 mph according to IC-9-21-5-2. Since the 2005 change, some efforts have been made to remove the DSL on rural freeways, but the state continues to maintain its DSL policy to date.

3.2 Statutory Speed Limits in the Neighboring States

Table 1 is a summary of the current speed limits in Indiana and its neighboring states. Indiana and Michigan are the only states in the region that currently maintain DSLs on rural freeways. Michigan uses a 10-mph gap between cars and trucks, while Indiana uses a 5-mph speed differential. On urban freeways, USLs are predominant. Urban PSLs range from 45 mph on some freeway segments in Chicago to 70 mph on most interstate segments in Michigan's urban areas.

Table 1. Speed limits on freeways at states proximal to Indiana.

State	**Rural**		**Urban**
	Non-Trucks	**Trucks**	
Illinois[1]	70	70	45 – 70
Indiana	70	65	50 – 65
Kentucky	70	70	55 – 65
Michigan	70 –75	60 – 65	55 – 70
Ohio	70	70	50 – 65

[1] 45-mph minimum speed limit.

There have been significant changes to the speed limit policies of Indiana's bordering states in recent years. Effective January 2014, Illinois increased the maximum allowed speed limit on rural freeways from 65 mph to 70 mph, and urban interstate speed limits were set to range from 45 up to 70 mph. Ohio reformed its interstate speed limits in July 2013 with selected rural freeways permitted to increase speed limits from 65 to 70 mph. Over the last several years, Ohio has made several attempts to raise speed limits to 75 mph (Bischoff, 2016). Ohio has also adopted other speed limit strategies, such as seasonal speed limits and variable speed limits that are revised in real-time based on congestion, weather, and crash occurrence. In May 2017, Michigan raised its freeway speed limits, maintaining the 10-mph speed differential on rural freeways and increasing the speed limit by 5 mph on selected freeway sections with adequate geometric characteristics. The current speed limit in Michigan is 65 mph for trucks and 75 mph for non-trucks on rural freeways, and 55 to 70 mph on urban freeways, with 70 mph being the predominant posted speed limit.

4. RESEARCH APPROACH

4.1 General Considerations

The underlying objective of this dissertation was to identify a way to estimate the mobility and safety effects of the speed limit on selected road segments during a particular analysis period and to apply the developed estimated models to simulate performance during one year under two distinct speed limit policies, i.e., DSLs and USLs.

Following this chosen research strategy, rural freeway segments and hourly intervals were randomly selected to form a sample, with the hourly intervals grouped by traffic conditions based on the observed travel speed values. Next, the effects of the speed limits on mobility and safety were estimated using regression analysis. Then, the obtained models were used to assess the speed and safety performance of multiple statutory speed limit scenarios. Although the actual crash data were available for the existing DSL setting, the model-based simulation of USLs was then repeated for this sample to preserve the comparison consistency. The previous case provides an enormous advantage to the simulation of alternative speed limits since it would eliminate the prediction of time-dependent confounding factors such as weather. This what-if approach considerably increases the correctness of the work and thus allows the results to properly reflect the mix of various conditions affecting mobility and safety, including speed limits. Even though the analysis is performed in a recent period, the aggregation level allows being optimistic that the results, particularly the comparative ones, would reflect future years within a reasonably long period. Finally, the results were aggregated and expanded to the entire network of rural freeways in Indiana.

The methodology for evaluating alternative statewide statutory speed limits on Indiana interstate roads was devised to follow the proposed overall approach. The general methodology, applied in three consecutive steps, is depicted in Figure 4. First, the traffic conditions were classified based on the Congestion Index. Second, the mobility and safety effects of the speed limit were estimated with regression models. Third, the alternative scenarios and corresponding comprehensive travel costs were evaluated by statistical simulation of speed and safety in the analysis year. Each step is described in detail in the following subsections.

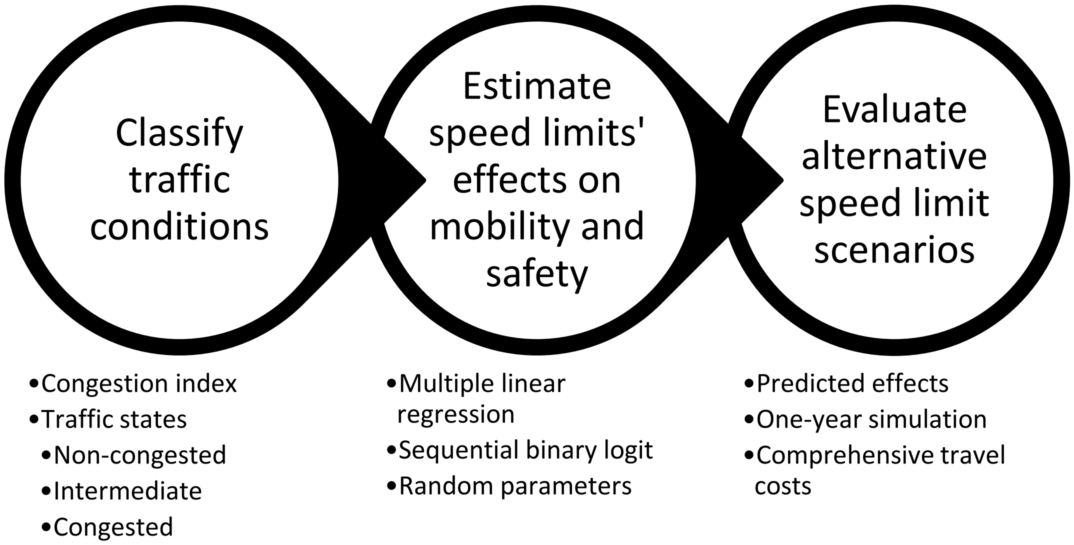

Figure 4. Overview of the proposed approach.

4.2 Classification of Traffic Conditions

A driver's speed selection in uncongested traffic is affected by many factors not yet entirely understood. For example, freeways are used by both local and intercity drivers who may have different speed preferences and attitudes towards speed limit enforcement. In addition, the presence of trucks may cause more frequent interactions between vehicles because truck drivers are more likely to comply with the PSL (Islam et al., 2014). It is also plausible that the speed limit's effect on speed selection diminishes in the presence of congestion as drivers are heavily influenced by other drivers and traffic flow dynamics dominate individual speed choices.

Herman and Prigogine (1979) proposed a two-state fluid model describing urban traffic, which addresses two distinct situations: 1) vehicles move relatively freely on uncongested roads and change lanes to pass slower vehicles, and 2) vehicles are slowed down considerably in congested traffic and lack the possibility of passing slower vehicles. In most cases, traffic conditions are a mix of these two states, which leads to an intermediate level of congestion. Mobility performance is defined by the proportion of the two distinct states. This perspective on traffic, sometimes called two-fluid flow, has been successfully tested in urban scenarios by several researchers (Chakraborty & Srinivasan, 2016; Dixit, 2013; Dixit et al., 2011; Mahmassani et al., 1984, 1990).

The traffic performance concept may be applied to estimating the speed limit effects, i.e., the maximum effect is observed under the non-congested conditions while there is no effect under congestion. However, the original concept seems to be successful for a rather coarse evaluation of traffic in large road networks.

1. **Non-congested:**

   Drivers operate at speeds close to their preferred speed. The range of traffic flow in this state is wide since drivers try to maintain their preferred speeds as long as passing slower-moving vehicles is possible. Occasional blocking somewhat reduces the speed.

2. **Congested:**

   All vehicles move collectively at speeds determined by the road geometry, road capacity, and drivers' spacing selections. This state is characterized by high traffic density and low travel speeds. For rural freeways, congested periods are typically linked to adverse weather or sporadic traffic events such as crashes. In order to limit the effect of congestion due to crashes, speed characteristics one hour before the crash were assigned to each crash observation. Additionally, records that follow crashes up to three hours after each collision were removed.

3. **Intermediate:**

   The coexistence of non-congested and congested conditions, this state is common in long freeway segments that may have single or multiple bottlenecks. The extended duration of this state is particularly likely on urban freeways.

The relative reduction of speed below free-flow speed, known as the Congestion Index, is used to measure the extent of free-flow operation remaining in each hourly interval (Equation 4).

$$CI_i = \begin{cases} \dfrac{v_f - v_i}{v_f} \times 100, & if\ v_i \leq v_f \\ 0, & otherwise \end{cases}$$ Equation 4

where CI_i is the Congestion Index for the i^{th} hourly interval, v_i is the hourly speed observed during the i^{th} hourly interval, and v_f is the segment-specific free-flow speed defined as the 90^{th} percentile of speed for one day.

Although drivers attempt to maintain their preferred speeds, the average free-flow speed is not affected by vehicle interactions due to the freedom of passing slower vehicles as desired. This scenario occurs under low traffic density. The absence of traffic volume data does not permit the estimation of traffic density, posing a challenge. A reliable alternative of determining the free-flow speed was employed in this dissertation. The 90^{th} percentile of hourly travel speeds on individual road segments on a given date was selected to represent the free-flow speed. As expected, the free-flow speeds varied across segments and dates to a limited extent. These variations may reflect differences in road geometry, day of the week (general travel purpose), heavy trucks, and weather conditions.

The thresholds that separate the three traffic states are defined based on the distribution of the Congestion Index and the effect of traffic volume on operating speed. Speed data collected on rural freeway segments indicate a slight speed reduction (approximately 10% of the free-flow speed) when traffic volumes and density increase to the point when passing other vehicles is not always immediately available. Nevertheless, the traffic still moves at high speed and may be considered non-congested. Beyond that point, the traffic becomes unstable, and the speed may drop dramatically. The previous findings are supported by a set of multiple linear regression models of hourly average speed for all vehicles (see Appendix C). Under non-congested conditions, there is a significant positive effect of traffic volume on travel speed, which can be explained as fast-moving vehicles overtaking slower vehicles to maintain a preferred speed. Under intermediate traffic conditions, a large negative effect of traffic volume on travel speed was found. This finding is intuitive as a vehicle has limited maneuvering space. Lastly, the effect of traffic volume on travel speed was found not significant under congested conditions as other factors, such as driver's spacing and bottleneck capacity, play a more significant role.

Figure 5 presents a histogram of the Congestion Index distribution for the final sample for the three traffic states. Observations with the Congestion Index that equaled 0 accounted for 12.8% of the total number of records. Most of the hourly intervals had values equal to or lower than 0.1, which corresponds to non-congested observations greater than or equal to 90% of the daily free-flow speed.

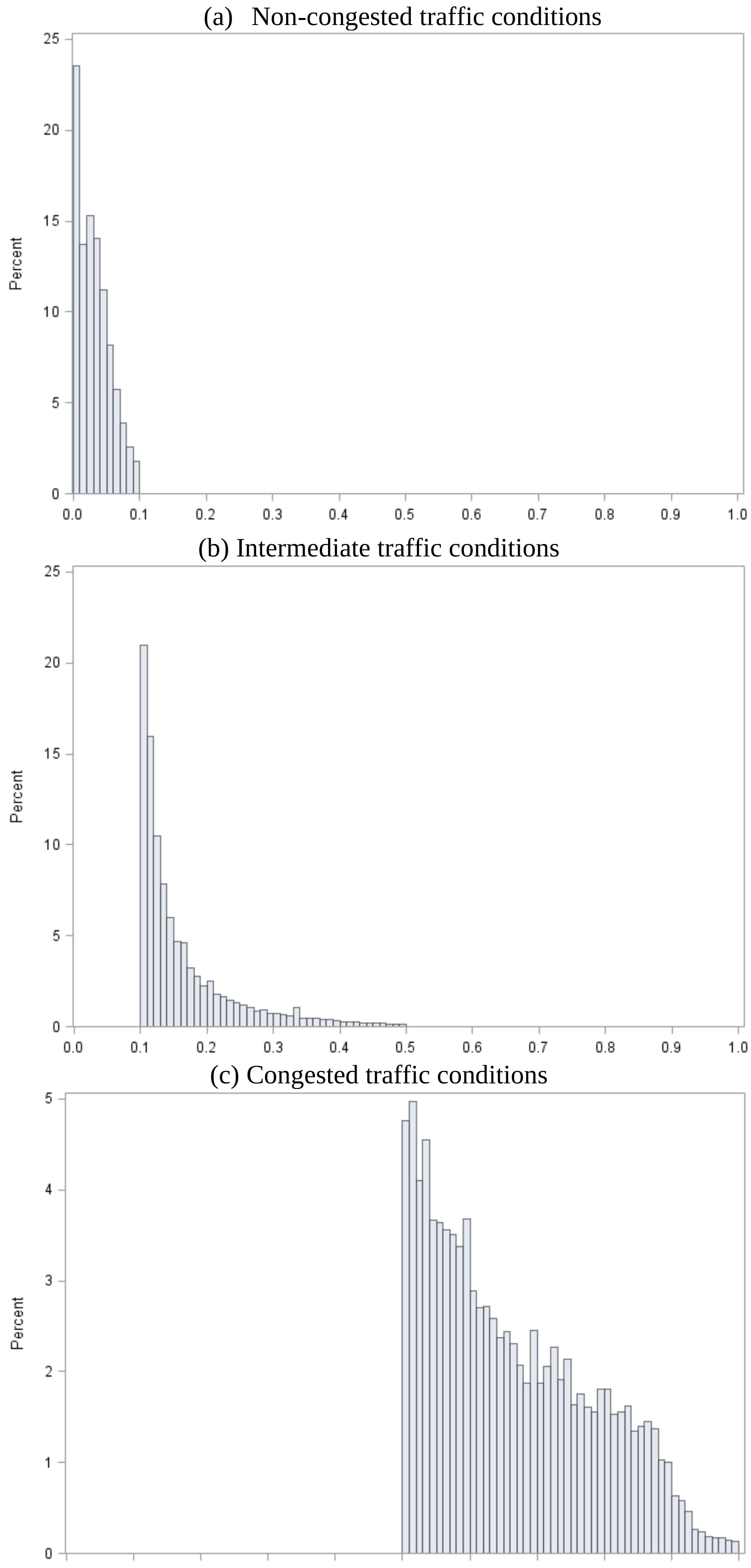

Figure 5 Distribution of congestion index.

Table 2 summarizes the results of the traffic condition classification. It provides additional insight into the distribution of crashes. While 94% of the hourly intervals were classified as non-congested, only 69.9% of crashes occurred during such traffic conditions. Congestion accounted for 0.2% of the total hourly intervals and 4.7% of the total crashes. Although intermediate traffic conditions persisted in 5.5% of the segment-hours, as many as 25.4% of crashes took place during these hours. Non-congested and intermediate traffic conditions are of particular interest for traffic safety. These findings justify analyzing safety in each traffic state separately.

The risk index in Table 2 helps visualize the importance of evaluating safety under multiple traffic conditions. The risk index is the ratio between the percent of crashes and the percent of records for a given traffic condition. It is evident that congested and intermediate traffic conditions are a key safety component since their risk index is approximately 7 and 50 times larger, respectively, than the ones observed under intermediate and non-congested traffic.

Table 2. Distribution of crashes under each traffic state.

Traffic condition	**Observations (%)**	**PDO[1] crashes (%)**	**Injury crashes (%)**	**Fatal crashes (%)**	**Risk Index**
Non-congested	94.40	69.90	52.62	42.37	0.71
Intermediate	5.45	25.45	39.32	45.76	5.14
Congested	0.15	4.65	8.06	11.86	35.26
Numb. of obs.	5,040,220	7,219	1,526	59	N.A.
[1] Property Damage Only					

4.3 Estimation of Speed Limit Effects

To establish the effects of changes in speed limits on travel speed and traffic safety, several assumptions and considerations were made regarding road environment, traffic conditions, and types of vehicles.

First, rural and urban roads should be considered separately because of differences in the speed limit settings, driving behavior, nature of the trip, and potentially different speed limit enforcement levels. Many rural interstates have DSL policies, while urban freeways typically have USL policies. Drivers on urban freeways tend to be daily commuters familiar with the roads and are likely to be more aggressive when changing lanes to maintain preferred speeds. The higher presence of police enforcement in urban areas may lead to greater visibility and thus influence drivers' speeds.

Second, speed limits are assumed to have their primary effect on low-density traffic conditions when operating speeds are close to free-flow speeds. In high-density traffic conditions, the speed limit effect diminishes, as it does in congested conditions when speeds are low. Thus, the speed limit's effect in this dissertation was estimated consistent with the two-fluid model proposed by Herman and Prigogine (1979). Long freeway segments may experience a mix of congested and non-congested conditions, and average speeds along these segments reflect the conditions by taking intermediate values.

Third, passenger cars and trucks are considered separately for several reasons. First, trucks tend to move more slowly than passenger cars regardless of the speed limit policy (Hanowski et al., 2012; Johnson & Pawar, 2007). This tendency can be linked to the different dynamic capabilities of trucks, the use of speed limiters in trucks, and oversight from truck companies. Second, drivers of trucks and cars might respond to the PSL differently because of their different perceptions of enforcement, i.e., truck drivers are at higher risk if they are ticketed for speeding. Finally, the value of time and fuel economy differs for the two types of vehicles. For instance, the average cost of one hour of truck operation is 1.3 times that of a car after accounting for the vehicles' occupancy (Sinha & Labi, 2007).

4.3.1 Estimation of speed limit effect on speed

The estimation of speed limits' effect on the actual speed was obtained by fitting multiple linear regression models. The estimated models' form is described in Equation 5.

$$v_i = \beta_0 + \beta_1 X_{1i} + \cdots + \beta_m X_{mi} + \varepsilon_i \qquad \text{Equation 5}$$

where v_i is the expected speed estimate in the i^{th} hourly observation, β_j is the estimated coefficient corresponding to variable j, X_{ji} is the value of explanatory variables in segment-hour i, and ε_i is the normally distributed error term with zero mean and standard deviation σ. Significant variables j $(j = 1, \ldots, m)$ are significant speed factors (e.g., roadway characteristics, weather conditions, seasonal indicators, and speed limit policy), while β_j values express the strength of these factors.

The models were calibrated using the GLM procedure in SAS/ETS version 9.4 (SAS Institute Inc., 2014)(SAS Institute Inc, 2013). The code for obtaining the final models is presented in Appendix B. The GLM procedure uses ordinary least-squares to estimate the unknown parameters. The goodness of fit of the calibrated models was assessed using the F statistic combined with the adjusted R-square. The F-statistic, which tests the null hypothesis of at least one of the predictors, has a significant effect on the response in the form of Equation 6.

$$F = \frac{\sum_m (\overline{V_{i\cdot}} - \bar{V})^2 \,/\, (m-1)}{\sum_m \sum_{j=1} \left(\overline{V_{ij}} - \overline{V_{i\cdot}}\right)^2 \,/\, (N-m)} \qquad \text{Equation 6}$$

where N is the total number of observations used to calibrate the model and m is the number of independent predictors. Finally, the adjusted R-squared is calculated as described in Equation 7.

$$R_{adj}^2 = 1 - \left[\frac{(1-R^2)(N-1)}{N-K-1}\right] \qquad \text{Equation 7}$$

Variables were retained in the models based on both the statistical and practical significance of the coefficients. Their statistical significance was demonstrated by low p-values, while their practical significance was demonstrated by the considerable marginal effects. Separate models for passenger cars and trucks were calibrated for rural and urban roads under non-congested and congested traffic conditions.

4.3.2 Estimation of speed limit effect on safety

A sequential binary logit model was selected for the safety analysis. The model consists of two consecutive logistic regression models. First, using a binary indicator variable for crash occurrence, the hourly probability of a crash was estimated. Second, all non-crash observations were removed, and a binary indicator variable for the presence of injury or fatal outcomes was used to estimate the conditional probability of a severe crash. The described approach was applied to each traffic state.

Let be $\eta_i = X_i'\boldsymbol{\beta}$ a linear combination of independent variables where $i = (1, \dots, n)$ are individual observations. The probability of an event of interest is assumed to follow the logit form shown in Equation 8. The logit link function maps from the scale of the linear prediction η_i to the scale of the mean.

$$P_n(i) = \frac{\exp\{X_i'\boldsymbol{\beta}\}}{1 + \exp\{X_i'\boldsymbol{\beta}\}} = \frac{\exp\{\eta_i\}}{1 + \exp\{\eta_i\}} \qquad \text{Equation 8}$$

A commonly used approach to estimate the unknown coefficients $\boldsymbol{\beta}$ consists of maximizing the log-likelihood. The log-likelihood function for the ith binary observation can be described as in Equation 9.

$$l(P_n(i); y_i) = y_i \log\{P_n(i)\} + (1 - y_i) \log\{1 - P_n(i)\} \qquad \text{Equation 9}$$

where $P_n(i)$ is the probability of an event of interest, and the variable y_i takes on the value 1 for an event (crash/injury or fatal crash) and the value 0 for a non-event (no crash/PDO crash).

Since two consecutive logistic regression are fitted, additional miscellaneous calculations are required to obtain the actual probability for each crash injury severity. For instance, assuming we are interested in the PDO, and injury or fatal crash (KABC), let A be the event of being involved in a crash, B the event of being involved in a KABC crash. The Sequential Binary Logit model provides the probabilities $P(A)$ and $P(B|A)$. The remaining probabilities are calculated as in Equation 10.

$$\begin{gathered} P(KABC) = P(B|A) \times P(A) \\ P(PDO) = P(A) - P(B|A) \times P(A) \end{gathered} \qquad \text{Equation 10}$$

The models were calibrated using the MDC procedure in SAS/ETS Version 9.4 (SAS Institute Inc., 2014). The code for obtaining the final models is presented in Appendix B. The MDC procedure uses the maximum likelihood method with quasi-Newton optimization to estimate the unknown parameters.

To evaluate the overall significance of the model, the likelihood ratio test (LRT) was used. This test statistic is defined as follows:

$$LRT = -2\ [LL(\beta_R) - LL(\beta_U)] \qquad \text{Equation 11}$$

where $LL(\beta_R)$ is the log-likelihood of the restricted model at convergence and $LL(\beta_U)$ is the log-likelihood of the unrestricted model at convergence. This test statistic is χ^2 distributed with degrees of freedom equals the difference between the two models.

Additionally, to compare the goodness of fit of multiple models, the Akaike Information Criterion (AIC) was used. Lower values of AIC are preferred as they represent a better fit. The AIC is given in Equation 12.

$$AIC = 2K - 2\ [LL(\beta)] \qquad \text{Equation 12}$$

where k is the number of parameters estimated and $LL(\beta)$ is the log-likelihood of the resulting model at convergence.

4.3.3 Accounting for unobserved heterogeneity

Fixed-parameters models assume a constant effect of explanatory variables across observations or individuals. Conversely, random-parameters models test this assumption by estimating additional coefficients representing an assumed distribution for a given effect. Then, random-parameters models help to account for unobserved heterogeneity across observations or individuals (Washington et al., 2010).

The mixed logit model is a generalization of the traditional logit model. The following expression is derived from McFadden and Train’s (2000).

$$P_n^m(i) = \int_X \ P_n(i)\, f(\boldsymbol{\beta}|\boldsymbol{\varphi}) d\boldsymbol{\beta} \qquad \text{Equation 13}$$

where $f(\beta|\varphi)$ is the density function of β with φ referring to a vector of parameters of that density function (mean and variance) and all other terms as previously defined.

Substituting this equation into the standard logit equation gives the mixed logit model:

$$P_n^m(i) = \int_X \frac{\exp(\boldsymbol{X}_i'\boldsymbol{\beta})}{1 + \exp(\boldsymbol{X}_i'\boldsymbol{\beta})} f(\boldsymbol{\beta}|\boldsymbol{\varphi}) d\boldsymbol{\beta} \qquad \text{Equation 14}$$

The mixed logit probabilities $P_n^m(i)$ are simply the weighted average of the standard logit probabilities $P_n(i)$ determined by the density function $f(\boldsymbol{\beta}|\boldsymbol{\varphi})$.

4.4 Evaluation of Alternative Speed Limit Settings

Two speed limit scenarios were considered as potential alternatives to the current 70/65-mph DSL policy. First, a 70-mph USL policy increases the trucks' speed limit by 5 mph. Second, a 65-mph USL policy reduces the passenger cars' posted speeds by 5 mph.

4.4.1 Statistical simulation concept

To effectively estimate the effects of the speed limit on speed and safety, it is important to isolate it from other confounding factors. This task is particularly challenging in cross-sectional analyses where temporal and spatial attributes vary across study locations. Evaluation of the overall effects of the speed limit policy on the road network must consider the variability of the traffic, weather, and light conditions on the roads during the entire year with the seasonal, weekly, and daily variability of the temporal conditions adequately reflected. Instead of predicting all these conditions for future years, this dissertation adopted a "what if" evaluation strategy by building disaggregated mobility and safety performance models and simulating studied speed limit scenarios under the real conditions observed during a selected recent year.

For this purpose, simulations of speed, crash frequency, and severity were conducted for each hour of the entire year 2014 on 198 randomly selected rural freeway segments in Indiana. The obtained speeds for these segments were converted to travel times and were combined according to the speed limits. Similarly, the number of crashes at two severity levels, namely property damage only and injury, were estimated separately and then combined. All 198 segments, including those with traffic conditions not sensitive to changes in the speed limit, contributed to the cumulative numbers of observed speeds and crashes. These cumulative numbers were expanded by a factor of 3 from the random sample to the actual number of Indiana interstate segments operating in 2014 under the corresponding speed limits. The total travel times and the total number of crashes were then used to estimate the cost components: the value of time, the vehicle operation costs, the economic losses caused by crashes, and the comprehensive costs of the crashes. The differences between the cost components for the existing and assumed speed limits were calculated. The following subsections present the methodology details.

4.4.2 Value of time

The value of time represents the amount of money that a user could earn by working instead of traveling (Sinha & Labi, 2007). It includes both in-vehicle and out-of-vehicle travel time (e.g., walking to the parking facility, waiting for a bus to arrive, etc.) and also can include the cost of delays in the traffic due to speed restricted by the PSL. After estimating the average speed under the studied speed limit, the travel time and corresponding value of time for passenger cars and trucks were calculated. The travel time was obtained using the predicted speed and the segment length as $t = s/v$, where t is the travel time in hours, s is the length of the freeway segment, and v is the predicted average hourly speed along the segment.

Since travel time represents the average condition during one hour for cars and trucks, the value must be multiplied by the number of vehicles in the traffic flow to obtain the total travel time in the hour. However, the traffic volume associated with the observed speed was not available in the original speed dataset. This limitation was overcome by using the car and truck annual average daily traffic (AADT) with hourly adjustment factors. Using the speed and volume data available from the Indiana Department of Transportation's Traffic Count Database System (TCDS), hourly adjustment factors for rural and urban freeways were developed. The detectors used included 70 permanent non-ramp freeway speed and volume detectors available during 2014 and are presented in Figure 6.

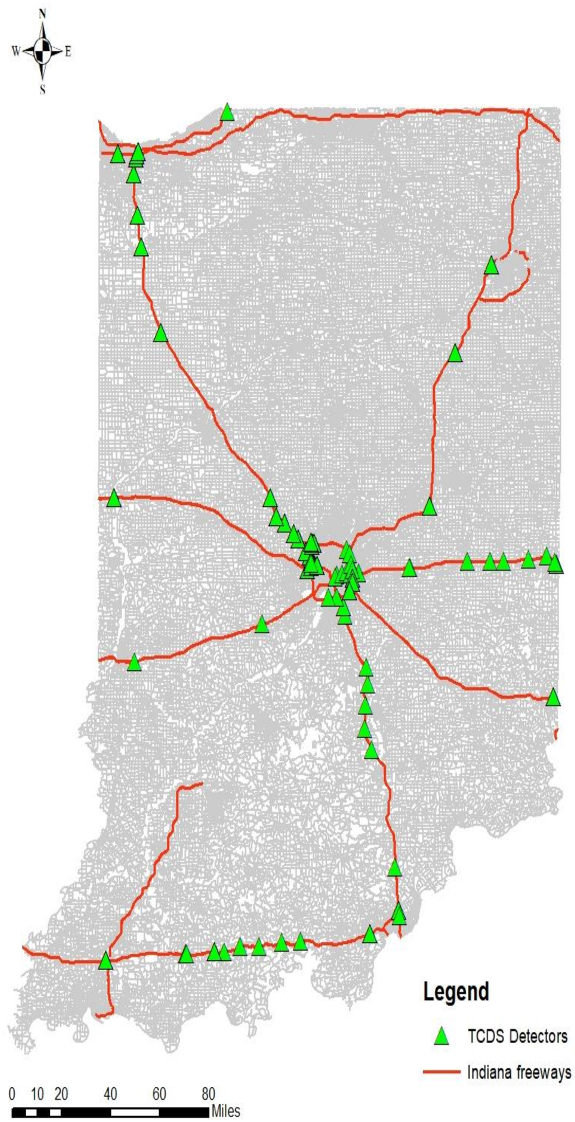

Figure 6. TCDS detector locations.

The adjustment factors for rural freeways were calculated for each day of the week and month of the year, which represent the average proportion of the AADT for each type of road and time. A total of 2,016 hourly traffic volume adjustment factors were calculated (see Appendix A). Figure 7 and Figure 8 display rural freeway profiles using the hourly adjustment factors for a sample weekday and weekend during November 2014.

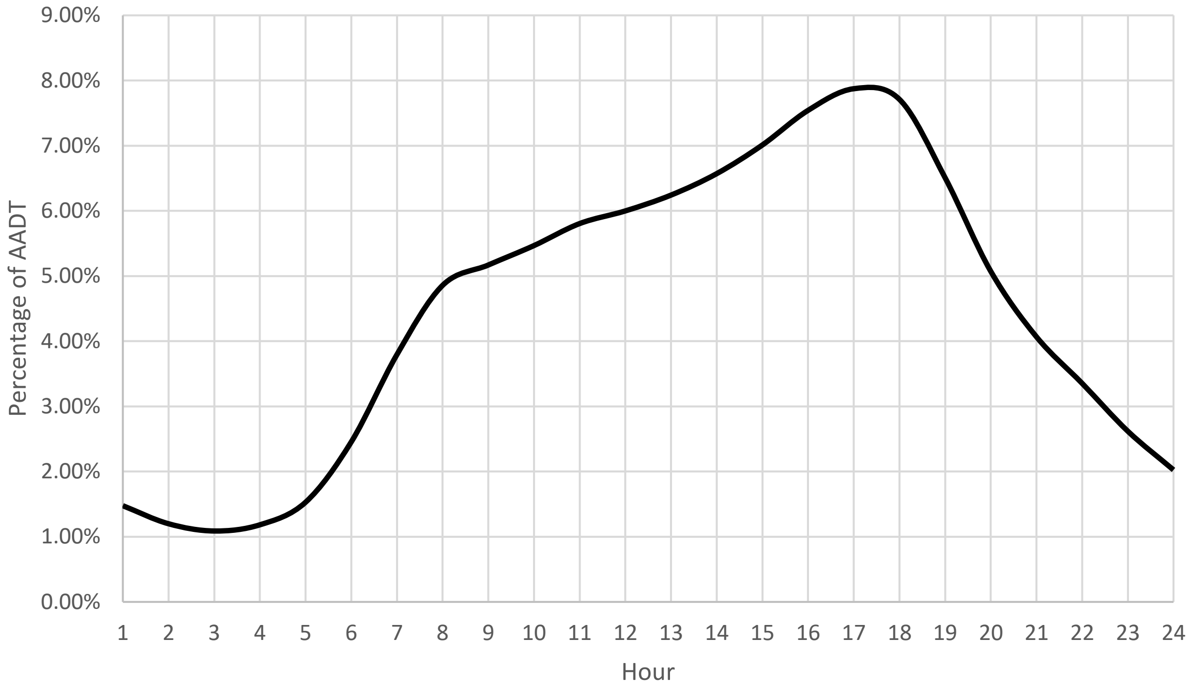

Figure 7. Example AADT hourly adjustment factors on a weekday (Monday to Friday).

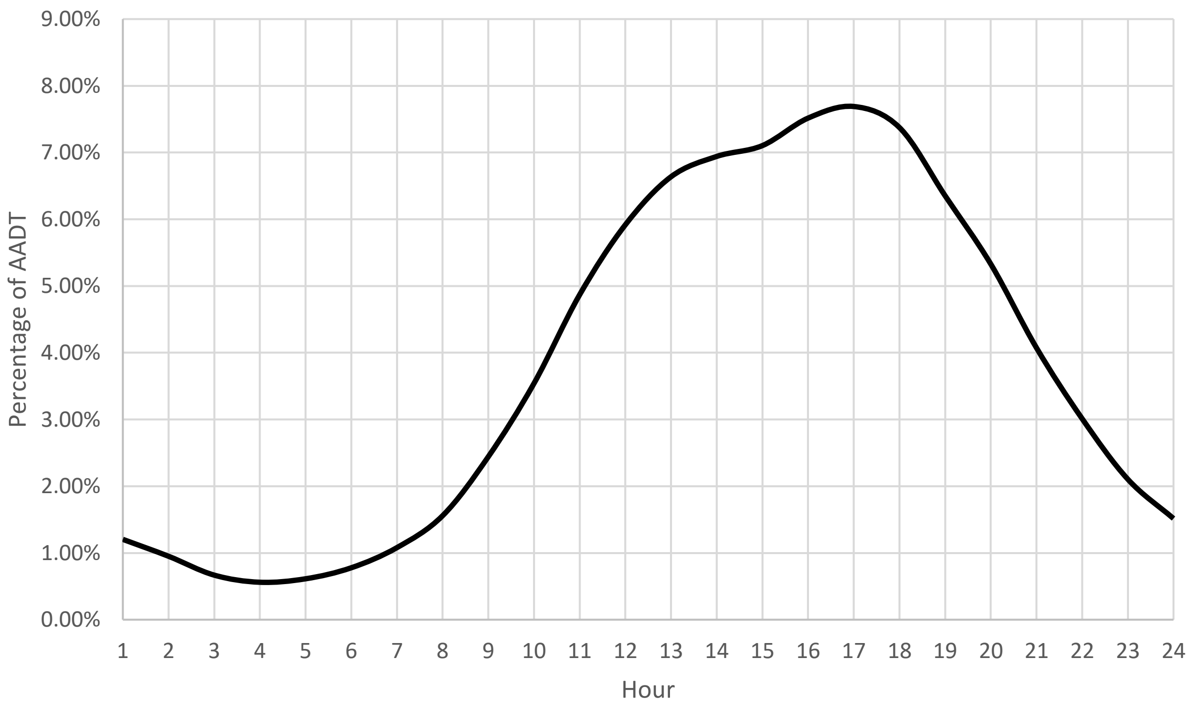

Figure 8. Example AADT adjustment factors on a weekend (Saturday and Sunday).

The total estimated hourly volume was divided into car and truck volumes using the proportion of the AADT that corresponds to heavy vehicles (u_t). This is shown in Equation 7 below:

$$T_{c_i} = t_{ci} \cdot q_i \cdot (1 - u_t)$$
$$T_{t_i} = t_{ti} \cdot q_i \cdot (u_t) \qquad \text{Equation 15}$$

where T_{c_i} is the total travel time for passenger cars during the i^{th} hour, T_{t_i} is the total travel time for heavy trucks during the *i*th hour, $t_{c_i}$is the average travel time of cars during the *i*th hour, t_{t_i} is the average time of trucks during the *i*th hour, q_i is the hourly volume calculated from the product of AADT and the adjustment factors, and u_t is the proportion of trucks in the segment's traffic.

The hourly travel time costs for passenger cars and trucks were obtained from (Sinha & Labi, 2007) (Table 5.3), and the values were converted to 2014 dollars using the change in the Consumer Price Index. The hourly 2014 travel time cost for passenger cars was $21.31 per occupant. An average vehicle occupancy of 1.7 was assumed based on the values provided by the Federal Highway Administration (2018). The average hourly travel time cost for trucks was $46.10, which does not require adjustment by the number of occupants.

4.4.3 Vehicle operating costs

Vehicle operating costs include fuel-related costs, which depend on the vehicle's fuel consumption and operating speed, and other costs, including oil, tires, maintenance, and depreciation. The fuel consumption costs for passenger cars and trucks as a function of speed were based on data from the California Department of Transportation, which is used in the Highway Economic Evaluation Model (HEEM). Two polynomial curves were fit to the data, and their equations are presented in Figure 9. These equations helped in the evaluation of the changes in the fuel-related costs that are due to speed changes. Trucks were found to have minimum fuel consumption at 30.3 mph, while the optimal speed of passenger cars was 50.7 mph. Any speed higher than 50.7 mph produced an increase in the fuel needed to operate the vehicle.

The average fuel cost for regular gasoline and diesel was obtained from the U.S. Energy Information Administration (EIA). In 2014, the average cost of one gallon of regular gasoline in the Midwest was $3.303. The average cost of a gallon of diesel was $3.806. These costs were used along with fuel consumption to obtain the fuel-related vehicle operating costs.

Other operating costs (oil, tires, etc.) are usually presented as a function of miles traveled. The average other operating costs per mile were obtained from the Surface Transportation Efficiency Model (STEAM). The 2014 costs for passenger cars and trucks were $0.227/mile and $0.392/mile, respectively.

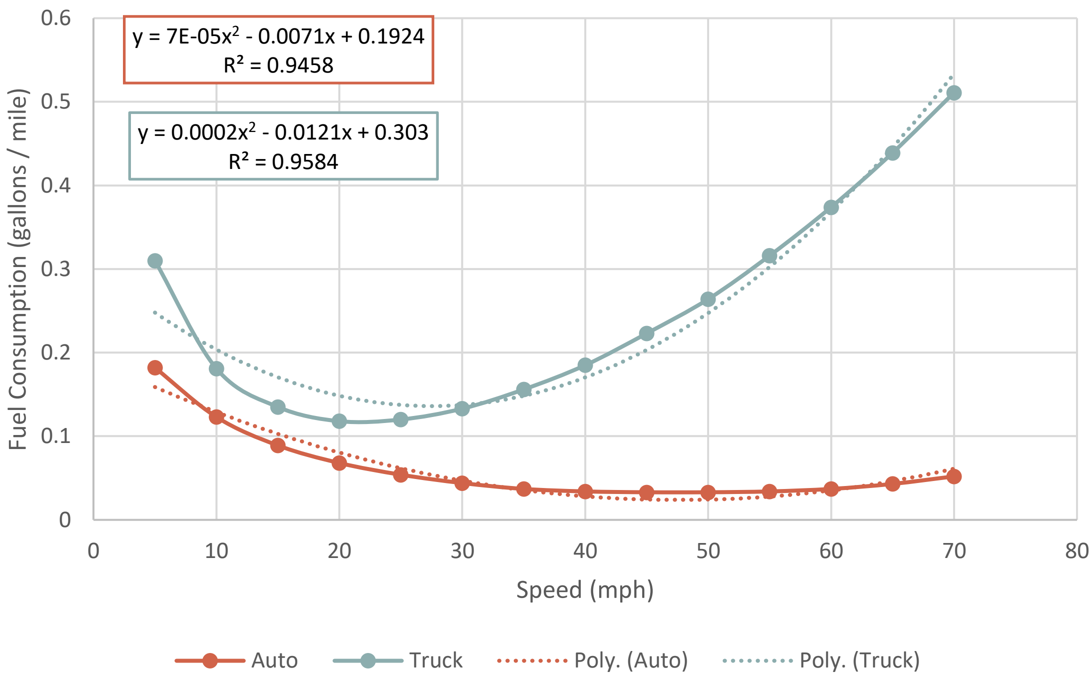

Figure 9. Fuel consumption for cars and trucks.

4.4.4 Cost of safety

The average crash costs for Indiana were estimated based on the 2014 Indiana crash database and the unit crash cost estimates from (National Safety Council, 2015). The number of vehicles involved and the number of people injured were used to estimate the individual crash costs. The costs were obtained separately for each crash severity level. The average economic and comprehensive costs for a single crash in Indiana in 2014 are presented in Table 3. The comprehensive values were much higher than the economic losses since they reflect what people are willing to pay to avoid a crash. The amounts were converted to 2014 dollars using the change in the Consumer Price Index.

Table 3. Average cost of a crash (2014 USD).

Cost Type	Crash Severity		
	PDO	**Injury**	**Fatal**
Economic	$ 5,726	$ 65,110	$ 1,586,886
Comprehensive	$ 29,381	$ 632,653	$ 10,555,870

5. DATA

5.1 Available Data Sources

One of the objectives of this dissertation was to isolate the effects of different speed limit policies using a cross-sectional approach. Thus, as many confounding factors as possible were included in the statistical models, these factors affect the travel speed and safety performance on rural freeways and include driver demographics, type of vehicle, roadway characteristics such as speed limit, weather conditions, seasonal factors, and spatial indicators. These elements were gathered from multiple data sources.

5.1.1 Smartphone-based speeds

Travel time data were obtained from the National Performance Management Research Data Set (NPMRDS). Travel times were measured along segments as defined by the data provider. On rural freeways, these segments are usually defined between two consecutive entering ramps. For each road segment, of which the average length is 2.5 miles, the average travel times for all vehicles, passenger cars, and trucks, are reported in five-minute intervals. Currently, NPMRDS does not provide information about the number of vehicles used to calculate the average travel time, which is the primary constraint of this data source. For this analysis, travel times were aggregated every hour for each segment.

5.1.2 Crash records

Crash records from the states of Illinois, Indiana, and Ohio were obtained from the Illinois DOT, the Purdue University Center for Road Safety, and the Ohio Department of Public Safety, respectively. The location, manner of collision, injury severity, number of vehicles involved, and number of people injured at each severity level were connected to each crash.

5.1.3 Inventory of roadway characteristics

The geometry and other roadway characteristics were extracted from the Highway Performance Monitoring System (HPMS), which provides a comprehensive set of variables reported by state agencies on an annual basis and includes the cross-sectional elements, pavement condition PSL, and the AADT by vehicle type. The HPMS road sections are smaller than the NPMRDS segments, with an average length of 0.1 miles. The HPMS data were linked to the NPMRDS, and continuous variables such as AADT were combined by calculating the weighted average, while discrete variables were aggregated using the mode.

5.1.4 Weather conditions

Daily weather conditions were obtained from the National Oceanic and Atmospheric Administration's server. The available data, which is aggregated at the county level, included precipitation intensity and snow accumulation. Other variables, such as wind speed and temperature, were only available for urban areas and therefore were not included in the final analysis.

5.2 Data Preparation

The various data sources needed to be combined into a single observation unit; and in our case, hourly observations at each NPMRDS segment were preferred, which is the minimum analysis period that can be obtained because of the considerable average length of the segments. Geographical Information System (GIS) and data analysis tools, ArcGIS version 10.7 (Environmental Systems Research Institute, 2019) and SAS/ETS version 9.4 (SAS Institute Inc., 2014), were used.

A description of the data structure and connection between the available datasets is presented in Figure 10. To assign crashes, a preliminary evaluation of the travel direction of vehicles involved was made. Then, the linking was done by location (latitude and longitude) and roadway characteristics (functional classification).

In terms of weather conditions, the nearest daily weather station with at least 90% of its data available was used. Multiple weather stations were linked to a single speed segment to avoid missing values. If the nearest station did not have any available data, the second nearest was used. This process was repeated until all the segments and dates were covered. The distance to the nearest weather station was recorded.

Geometric characteristics were gathered from the HPMS dataset. The convenient scope of our project, i.e., rural freeways, facilitated the availability of the full extent and sample data. The sample data provided information on selected roadway features such as speed limit for ~10% of the road segment. If multiple HPMS segments were linked to the same NPMRDS speed segment, the weighted average of the values or mode was used depending on the type of variable. Numerical variables such as AADT or IRI were the weighted average, while discrete variables such as the number of lanes or the presence of median barrier were aggregated using their mode.

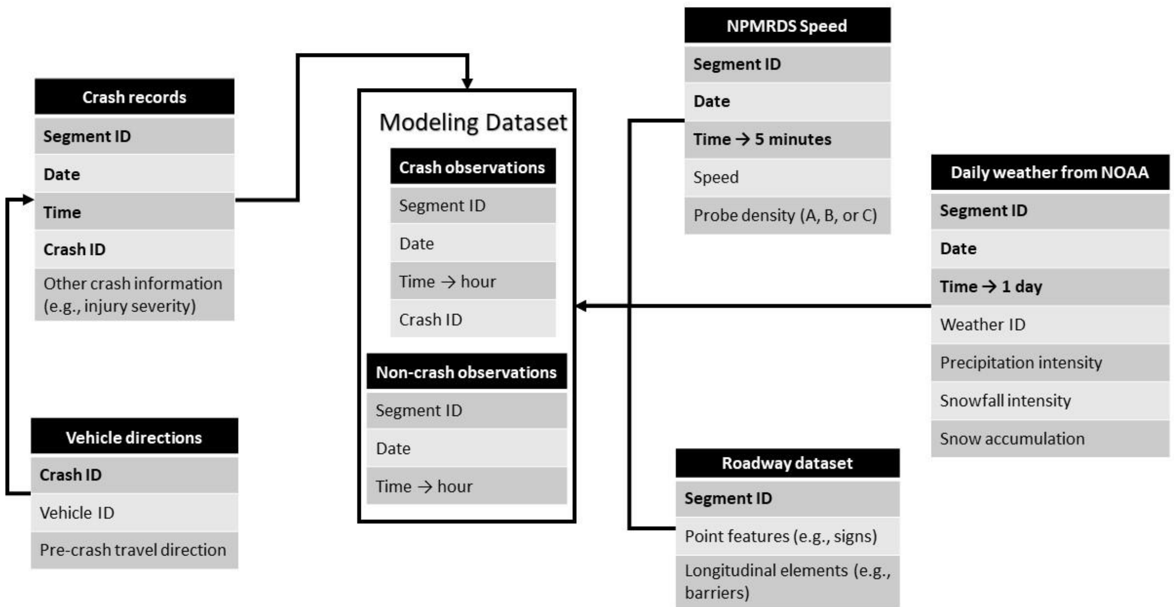

Figure 10. Data linking structure.

5.3 Data Limitations

To the best knowledge of the author, there is no data source with hourly traffic volume available at the system level. These data are needed to account for exposure, i.e., the amount of traffic exposed to potential crashes. Additionally, the fundamental connection between speed, volume, and traffic density allows establishing clear thresholds for the congestion level, improving the classification of traffic conditions. To address this limitation, the AADT and segment length were used in combination with estimated seasonal adjustment factors.

The operating travel speed is observed in large speed segments. While this way of observing speed is best suited for system-wide analysis compared to single point speed observations, there is a marginal drawback in precision. Some authors compared the quality of continuous speed data collection methods with traditional spot speed observations in terms of speed limit settings and safety effects (C. D. Fitzpatrick et al., 2016). These authors studied a 1.75-mile rural two-lane road in Amherst, Massachusetts, and found that the continuous speed data matched the speed distribution characteristics, such as the 85^{th} percentile, from spot speed observations. In conclusion, continuous speed data collection can be a cost-effective alternative to monitoring operating speeds.

5.4 Sampling

Data from 2014 to 2016 were compiled for Illinois, Indiana, and Ohio, and data validation and cleaning procedures were performed. Due to the vast amount of data, a random sample of 200 rural freeway segments was performed. Figure 11 displays the selected segments included in the random sample in green, while all other rural freeway segments are presented in red. The final sample included 77 road segments with a 70-mph USL policy (398.5 miles), 36 road segments with a 65-mph USL policy (185.1 miles), and 87 freeway sections with a 70/65-mph DSL policy (495.8 miles). Indiana is the only state that currently implements 70/65 mph speed limits. USLs, both 65 mph and 70 mph, are available in both Illinois and Ohio. However, Ohio offers a balanced distribution of the two rural speed limits while Illinois' 65-mph segments include a handful of suburban road segments.

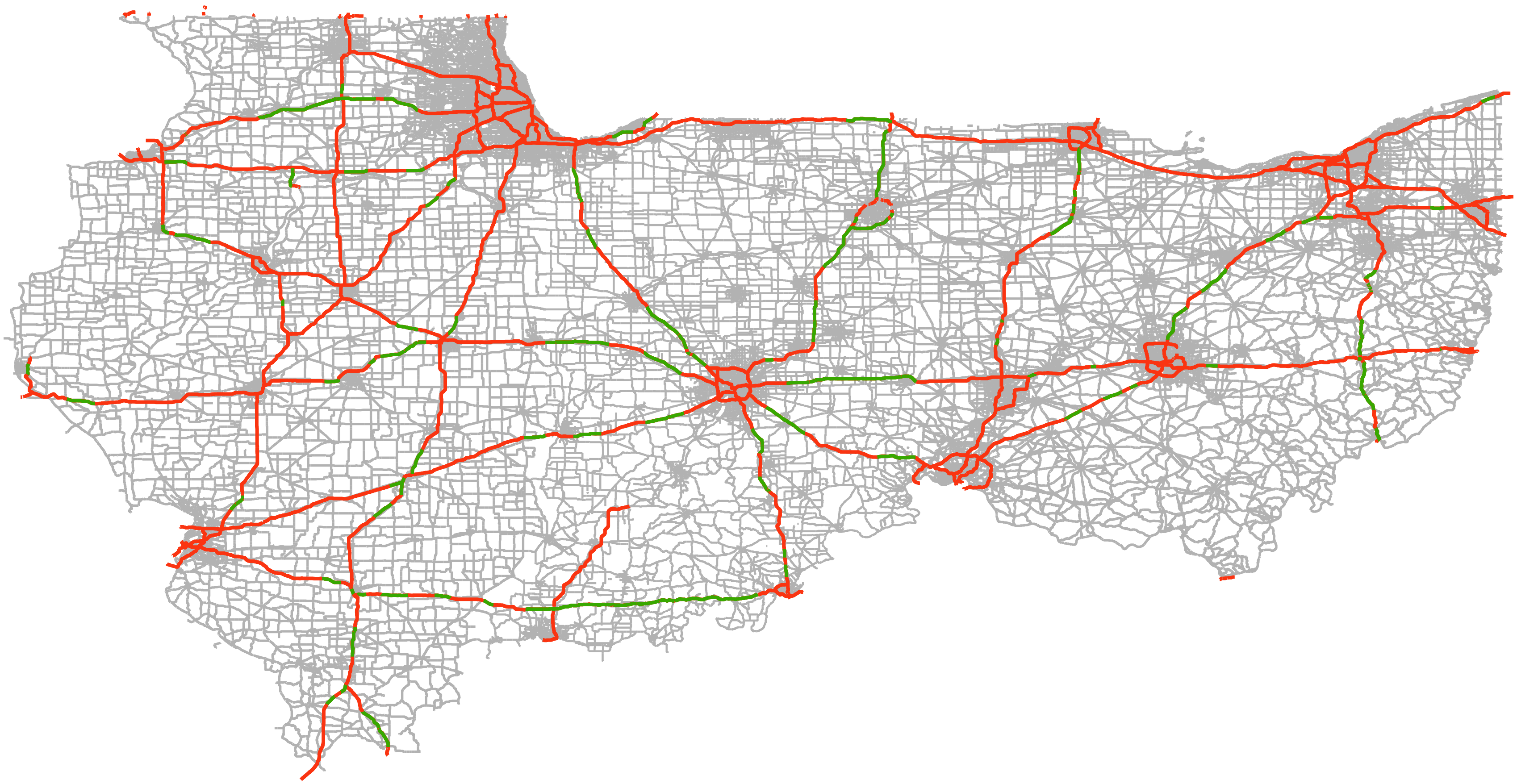

Figure 11. Freeway segments included in the random sample.

Since this dissertation uses hourly observations, the ratio of the crash to non-crash observations is very low, reflecting the small probability of a crash. There were approximately 570 non-crash hours for each hour with crashes. This unbalanced data could decrease the magnitude of the coefficients of the factors affecting the crash frequency; therefore, to mitigate this problem, the 1:30 crash to non-crash ratio was adjusted by selecting all crash observations and 30 times the number of crash observations of randomly selected non-crash observations. This distortion was later eliminated by adjusting the estimated intercept properly (Washington et al., 2010). The second model's parameters did not require adjustments.

5.5 Descriptive Statistics

Two hundred rural interstate freeway segments were randomly selected for further mobility and safety analysis. The distribution of road segments by state and speed limit policy is shown in Table 4. There were two segments with a 65/60-mph DSL policy in the sample, which were located outside of the I-465 loop in Indianapolis. This speed limit setting is not common on Indiana freeways and is only used at selected transition zones from rural to urban areas. INDOT is carrying out an ongoing evaluation of the effectiveness of intermediate speed limits in transition zones on freeways. Since it is not clear whether these speed limits will remain valid, the two segments with a 65/60-mph speed limit were not included in the scope of this dissertation.

Table 4. Speed limit settings of selected freeway segments.

State	Speed Limit (mph)	Number of Segments
Illinois	65	2
Illinois	70	58
Indiana	65/60	2
Indiana	70/65	87
Ohio	65	32
Ohio	70	19

The following descriptive statistics of the selected road segments are presented in Table 5: the roadway features, aggregated speed characteristics, spatial attributes, and safety performance measures.

The average segment length was 5.4 miles, and the maximum length was 22 miles. The longitude of the segments restricted the level of detail of the temporal attributes. One-hour intervals were selected for further mobility and safety analysis. It was assumed that this period was sufficient for vehicles to travel the entire length of a given segment. Under non-congested conditions, an example vehicle traveling at 65 mph would spend approximately 20 minutes in the longest segment.

The key roadway features were as follows. There were 51 segments (37%) with a right shoulder less than 9 feet. Most segments had two lanes for each travel direction, while only 10% had an additional third lane. The average number of ramps was 1.9. The previous value was expected since speed segments are typically defined between two consecutive entering ramps. The average proportion of truck traffic was 30%. Lastly, 76% of the segments were not protected by the presence of a roadside median barrier.

From the aggregated speed characteristics, it can be seen that the travel speed was surprisingly low considering the available PSLs. The average hourly travel speed for all vehicles was 63.6 mph. The presence of congestion may have reduced this value. A broader range of operating travel speeds was observed for cars compared to trucks. Passenger cars traveled 4.6 mph faster than trucks.

Only 26% of the segments were categorized as passing through small towns (< 50,000 habitants). On average, the nearest city (>50,000 habitants) was located 13 miles away, which was expected since the sample consisted of rural freeways. There were a few suburban segments within city limits, but they were labeled as rural due to their geometric characteristics and PSL.

The final section of Table 5 presents the aggregated safety performance measures. On average, there were 13.7 property damage only (PDO) crashes, 2.8 injury crashes, and 0.1 fatal crashes per segment-year. In terms of crash rates, there were 26.19 crashes per 100 million VMT and 4.5 injury or fatal crashes per 100 million VMT. Crash rates should be considered an objective comparison tool since they account for traffic volume and segment length.

Table 5. Descriptive statistics of sampled segments (N=200).

Variable	Mean	Std Dev	Minimum	Maximum
Roadway Features				
AADT (1,000 veh/day)	30.36	15.76	2.49	86.38
AADT per lane (1,000 veh/day)	14.19	6.47	1.24	38.14
Car AADT (1,000 veh/day)	21.46	12.16	1.60	71.93
Directional factor	53.95	3.68	50.00	65.00
IRI (in/mi)	67.10	43.77	25.00	295.00
Median width (ft)	59.70	20.93	3.00	99.00
Shoulder width <= 9 feet	0.37	0.48	0.00	1.00
Number of lanes	2.11	0.31	2.00	3.00
Number of ramps	1.91	1.03	0.00	7.00
Posted speed limit (mph)	69.10	1.93	65.00	70.00
Proportion of trucks	0.30	0.08	0.09	0.51
Ramp frequency (#/mi)	0.52	0.49	0.00	3.68
Segment length (mi)	5.40	3.56	0.04	22.04
Shoulder width (ft)	9.33	3.96	3.00	18.00
Truck AADT (1,000 veh/day)	8.90	4.68	0.89	23.58
Unprotected median indicator	0.76	0.43	0.00	1.00
Aggregated speed characteristics				
Average speed (mph)	63.60	1.70	57.36	72.51
Speed range (mph)	11.50	2.20	5.68	21.39
Average cars speed (mph)	66.17	2.17	58.99	75.80
Car speed range (mph)	12.27	2.58	2.02	20.83
Average trucks speed (mph)	61.61	1.47	51.34	63.80
Truck speed range (mph)	7.84	2.45	0.07	17.80
Spatial attributes				
Passing small town indicator	0.26	0.44	0.00	1.00
Distance to big city (mi)	13.02	13.77	0.00	77.61
Illinois	0.30	0.46	0.00	1.00
Indiana	0.44	0.50	0.00	1.00
Ohio	0.26	0.44	0.00	1.00
Safety performance measures				
Total number of crashes	49.75	56.92	0.00	302.00
Number of PDO crashes	41.13	47.32	0.00	252.00
Number of injury crashes	8.31	10.26	0.00	59.00
Number of fatal crashes	0.32	0.60	0.00	3.00
Crash rate (crashes per 100 million VMT)	26.19	17.81	0.00	78.00
Severe crash rate (crashes per 100 million VMT)	4.50	4.10	0.00	33.83

A total of 8,746 primary crashes and 1,139 secondary crashes were observed during the analysis period. There were about 570 non-crash observations for each crash observation. In terms of speed limits, 61% of the total crashes occurred under DSLs of 70/65 mph, 27% under USLs of 70 mph, and 11% under USLs of 65 mph.

The number of crashes for each combination of the speed limit is presented by severity level in Table 6. Crash records were available for all combinations at all severities except fatal crashes on Illinois' rural freeways with a 65-mph PSL. The crash injury severity levels were ultimately recategorized into two: 1) property damage only and 2) injury or fatal.

Table 6. Distribution of crashes by injury severity level, state, and speed limit.

State	Speed Limit (mph)	Crash Severity	Number of Crashes	Number of Miles
Illinois	65	Property damage only	17	4.59
Illinois	65	Injury	1	4.59
Illinois	65	Fatal	0	4.59
Illinois	70	Property damage only	414	328.10
Illinois	70	Injury	72	328.10
Illinois	70	Fatal	4	328.10
Indiana	65/60	Property damage only	50	6.45
Indiana	65/60	Injury	14	6.45
Indiana	65/60	Fatal	1	6.45
Indiana	70/65	Property damage only	5,158	495.85
Indiana	70/65	Injury	877	495.85
Indiana	70/65	Fatal	36	495.85
Ohio	65	Property damage only	2,072	174.07
Ohio	65	Injury	571	174.07
Ohio	65	Fatal	20	174.07
Ohio	70	Property damage only	514	70.37
Ohio	70	Injury	127	70.37
Ohio	70	Fatal	2	70.37

Table 7 presents the summary statistics for the 8,746 segment-hours with crashes, including roadway features, hourly traffic characteristics, spatial attributes, weather conditions, temporal indicators, and crash injury severity.

Comparing the summary statistics of crash observations from Table 7 with the sample segments characteristics presented in Table 5, it was noticed that crashes occur on longer segments with higher AADT per lane. The two trends were expected since these characteristics are related to traffic exposure. Interestingly, more crashes occurred at locations with good pavement conditions (lower IRI values). A relatively higher number of crashes were located on road sections with the presence of a median barrier. The barrier, in combination with a narrow shoulder (shoulder width <= 9 feet), may increase the collision risk. Crashes also occurred on segments with a much lower proportion of trucks. The average proportion of trucks was 9% for crash-segments and 30% for the population.

With regard to travel speed characteristics, a consistently lower average speed was observed for all vehicles when there was a crash. This effect might be due to the mere existence of a vehicle collision obstructing the road or the presence of congestion. To isolate the effects of crashes on mobility, four hours, including the time of the crash, were removed, which was assumed to be a sufficient period for the road to be cleared from obstructing vehicles. A higher speed range was observed on segments with crashes. The presence of queues also is a critical factor for safety analysis, and it was noticed that 53% of the hours with crashes presented a strong downstream speed trend (a reduction of 5 mph or more for one hour). Finally, the traffic conditions for hours with crashes were significantly different from those for the entire population as follows: 67% of the crash observations occurred during non-congested traffic conditions, 28% under intermediate, and 5% under congested. For non-crash observations, these values were 94%, 5%, and 0.1% respectively.

With regard to spatial factors, a lower proportion of the segments were located on the outskirts of small towns, and crash segments tended to be closer to large cities. These two findings may account for additional exposure or the presence of a mixed driving culture of long-distance and local drivers.

The weather characteristics of the crash observations were as follows: 43% of the crashes occurred under rainy weather, 16% under snowy weather, and 20% with accumulated snow. Lighting conditions also were different as 58% of crashes occurred during daylight hours.

Table 7. Descriptive statistics for safety dataset (N=8,746).

Variable	Mean	Std Dev	Minimum	Maximum
Roadway Features				
AADT (1,000 veh/day)	39.19	16.28	0.33	86.38
Car AADT (1,000 veh/day)	28.55	13.80	0.25	71.93
AADT per lane (1,000 veh/day)	17.61	6.13	0.16	38.14
Truck AADT (1,000 veh/day)	10.63	4.41	0.07	23.58
Directional factor	54.95	3.74	50.00	65.00
IRI (in/mi)	62.09	34.76	24.00	321.00
Unprotected median	0.72	0.45	0.00	1.00
Median width (ft)	59.06	17.70	3.00	99.00
Number of lanes	2.21	0.40	2.00	3.00
Number of ramps	2.18	1.13	0.00	7.00
Ramp frequency (#/mi)	0.48	0.00	3.68	3.68
Segment length (mi)	7.26	3.63	0.04	22.04
Shoulder width (ft)	3.77	3.00	18.00	18.00
Narrow shoulder (shoulder width <= 9 feet)	0.48	0.00	1.00	1.00
Proportion of trucks	0.09	0.07	0.58	0.58
Speed limit = 70/65 mph	0.60	0.49	0.00	1.00
Speed limit = 65 mph	0.28	0.45	0.00	1.00
Speed limit = 70 mph	0.12	0.33	0.00	1.00
Number of lanes >= 3	0.21	0.40	0.00	1.00
Hourly traffic characteristics				
Average speed (mph)	57.40	11.71	4.42	77.24
Speed range (mph)	17.81	13.67	0.00	74.87
Speed trend	-0.37	1.33	-9.73	7.29
Downstream speed trend	0.53	0.50	0.00	1.00
Congestion Index	0.13	0.17	0.00	0.93
Traffic state = non-congested	0.67	0.47	0.00	1.00
Traffic state = intermediate	0.28	0.45	0.00	1.00
Traffic state = congested	0.05	0.22	0.00	1.00
Average cars speed (mph)	59.28	12.47	3.74	81.56
Car speed range (mph)	20.48	15.70	0.00	79.77
Car speed trend	-0.34	1.29	-8.78	6.69
Downstream car speed trend	0.49	0.00	1.00	1.00
Average trucks speed (mph)	55.68	11.15	1.86	70.52
Truck speed range (mph)	14.44	13.46	0.00	67.81
Truck speed trend	-0.34	1.20	-8.75	6.37
Downstream truck speed trend	0.48	0.00	1.00	1.00
Cars-trucks speed difference (mph)	3.64	4.26	-34.09	56.08

Table 7 continued

Variable	Mean	Std Dev	Minimum	Maximum
Spatial attributes				
Passing small town	0.14	0.35	0.00	1.00
Distance to big city (mi)	8.57	10.21	0.00	73.94
State = Illinois	0.06	0.23	0.00	1.00
State = Indiana	0.60	0.49	0.00	1.00
State = Ohio	0.35	0.48	0.00	1.00
Weather conditions				
Daily precipitation (in)	0.37	0.89	0.00	12.70
Rain	0.43	0.50	0.00	1.00
Light rain	0.40	0.49	0.00	1.00
Moderate rain	0.03	0.18	0.00	1.00
Heavy rain	0.001	0.02	0.00	1.00
Daily snowfall (in)	0.83	2.88	0.00	40.60
Snowfall	0.16	0.36	0.00	1.00
Light snowfall	0.05	0.22	0.00	1.00
Moderate snowfall	0.08	0.27	0.00	1.00
Heavy snowfall	0.02	0.15	0.00	1.00
Snow accumulation	0.20	0.40	0.00	1.00
Temporal indicators				
Year	2014.88	0.84	2014.00	2016.00
Month (1-January, …, 12-December)	6.34	3.58	1.00	12.00
Winter	0.28	0.45	0.00	1.00
Spring	0.23	0.42	0.00	1.00
Summer	0.23	0.42	0.00	1.00
Fall	0.26	0.44	0.00	1.00
Day of week (1-Sunday, …, 7-Saturday)	4.04	2.09	1.00	7.00
Weekend	0.33	0.47	0.00	1.00
Hour (0-0:00 to 0:59, …, 23-23:00 to 23:59)	12.34	6.31	0.00	23.00
Daylight	0.58	0.48	0.00	1.00
Crash characteristics				
PDO crash	0.82	0.38	0.00	1.00
Injury crash	0.17	0.38	0.00	1.00
Fatal crash	0.01	0.08	0.00	1.00

Table 8 presents the summary statistics of 4,989,038 segment hours and includes information about the roadway features, hourly traffic characteristics, spatial attributes, weather conditions, and temporal indicators. Each variable's mean, standard deviation, and maximum and minimum values are provided for all valid observations.

Table 8. Descriptive statistics of mobility dataset (N=4,989,038).

Variable	Mean	Std Dev	Minimum	Maximum
Roadway Features				
AADT (1,000 veh/day)	29.38	14.84	0.33	86.38
AADT per lane (1,000 veh/day)	13.85	6.23	0.16	38.14
Car AADT (1,000 veh/day)	20.98	11.68	0.25	71.93
Directional factor	54.13	3.60	50.00	65.00
IRI (in/mi)	66.75	40.94	24.00	321.00
Median width (ft)	59.99	20.43	3.00	99.00
Narrow shoulder (shoulder width <= 9 feet)	0.37	0.48	0.00	1.00
Number of lanes	2.10	0.29	2.00	3.00
Number of ramps	1.91	1.03	0.00	7.00
Proportion of trucks	0.29	0.09	0.07	0.58
Ramp frequency (#/mi)	0.51	0.48	0.00	3.68
Segment length (mi)	5.46	3.57	0.04	22.04
Shoulder width (ft)	9.12	3.77	3.00	18.00
Speed limit = 65 mph	0.17	0.38	0.00	1.00
Speed limit = 70 mph	0.38	0.49	0.00	1.00
Speed limit = 70/65 mph	0.44	0.50	0.00	1.00
Truck AADT (1,000 veh/day)	8.40	4.41	0.07	23.58
Unprotected median	0.77	0.42	0.00	1.00
Hourly traffic characteristics				
Average speed (mph)	63.60	4.08	0.59	80.00
Speed range (mph)	11.54	6.75	0.00	79.16
Speed trend	0.003	0.79	-70.91	78.58
Downstream speed trend	0.40	0.49	0.00	1.00
Congestion Index	0.04	0.05	0.00	0.99
Traffic state = non-congested	0.94	0.23	0.00	1.00
Traffic state = intermediate	0.05	0.23	0.00	1.00
Traffic state = congested	0.001	0.04	0.00	1.00
Average cars speed (mph)	66.15	5.06	0.61	84.95
Car speed range (mph)	12.46	8.33	0.00	84.33
Car speed trend	0.00	0.58	-70.91	64.78
Downstream car speed trend	0.38	0.49	0.00	1.00
Average trucks speed (mph)	61.66	3.47	0.59	74.92
Truck speed range (mph)	7.93	5.99	0.00	73.26
Truck speed trend	0.00	0.49	-57.13	58.48
Downstream truck speed trend	0.34	0.48	0.00	1.00
Cars-trucks speed difference (mph)	4.46	3.79	-66.36	75.31

Table 8 continued

Variable	Mean	Std Dev	Minimum	Maximum
Spatial attributes				
Passing small town	0.25	0.43	0.00	1.00
Distance to big city (mi)	12.91	13.40	0.00	77.61
State = Illinois	0.30	0.46	0.00	1.00
State = Indiana	0.44	0.50	0.00	1.00
State = Ohio	0.26	0.44	0.00	1.00
Weather conditions				
Daily precipitation (in)	0.31	0.83	0.00	18.67
Rain	0.35	0.48	0.00	1.00
Light rain	0.32	0.47	0.00	1.00
Moderate rain	0.03	0.17	0.00	1.00
Heavy rain	0.00	0.02	0.00	1.00
Daily snowfall (in)	0.19	1.31	0.00	40.60
Snowfall	0.05	0.22	0.00	1.00
Light snowfall	0.02	0.15	0.00	1.00
Moderate snowfall	0.02	0.14	0.00	1.00
Heavy snowfall	0.00	0.07	0.00	1.00
Snow accumulation	0.10	0.29	0.00	1.00
Temporal indicators				
Year	2015.00	0.83	2014.00	2016.00
Month (1-January, …, 12-December)	6.69	3.36	1.00	12.00
Summer	0.26	0.44	0.00	1.00
Fall	0.26	0.44	0.00	1.00
Winter	0.22	0.42	0.00	1.00
Spring	0.26	0.44	0.00	1.00
Day of week (1-Sunday, …, 7-Saturday)	4.00	1.99	1.00	7.00
Weekend	0.28	0.45	0.00	1.00
Hour (0-0:00 to 0:59, …, 23-23:00 to 23:59)	11.52	6.90	0.00	23.00
Daylight	0.52	0.49	0.00	1.00

The distributions of speed for passenger cars and trucks are presented in the boxplots in Figure 12 and Figure 13, respectively. These plots show the distribution under non-congested traffic conditions of a random sample of 1,000 segment-hours for each category.

In terms of the magnitude of speeds, passenger cars were found to travel at similar rates under 65-mph USLs and 70/65-mph DSLs. A slightly higher, yet not significantly different, travel speed was reported for 70-mph USLs. Trucks exhibited similar behavior; and while there were no significant differences between the two USLs and the 70/65-mph DSL, the speeds were higher under a 70-mph USL.

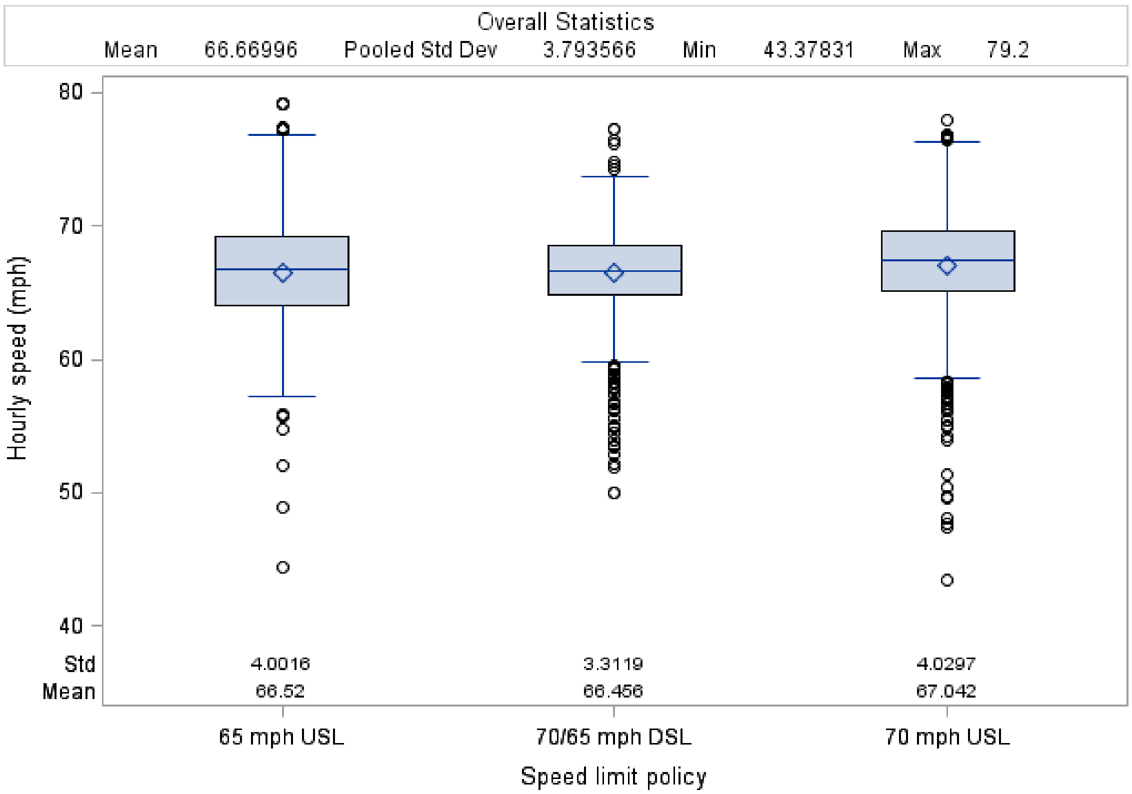

Figure 12. Distribution of passenger car hourly travel speeds by speed limit policy (N=1,000).

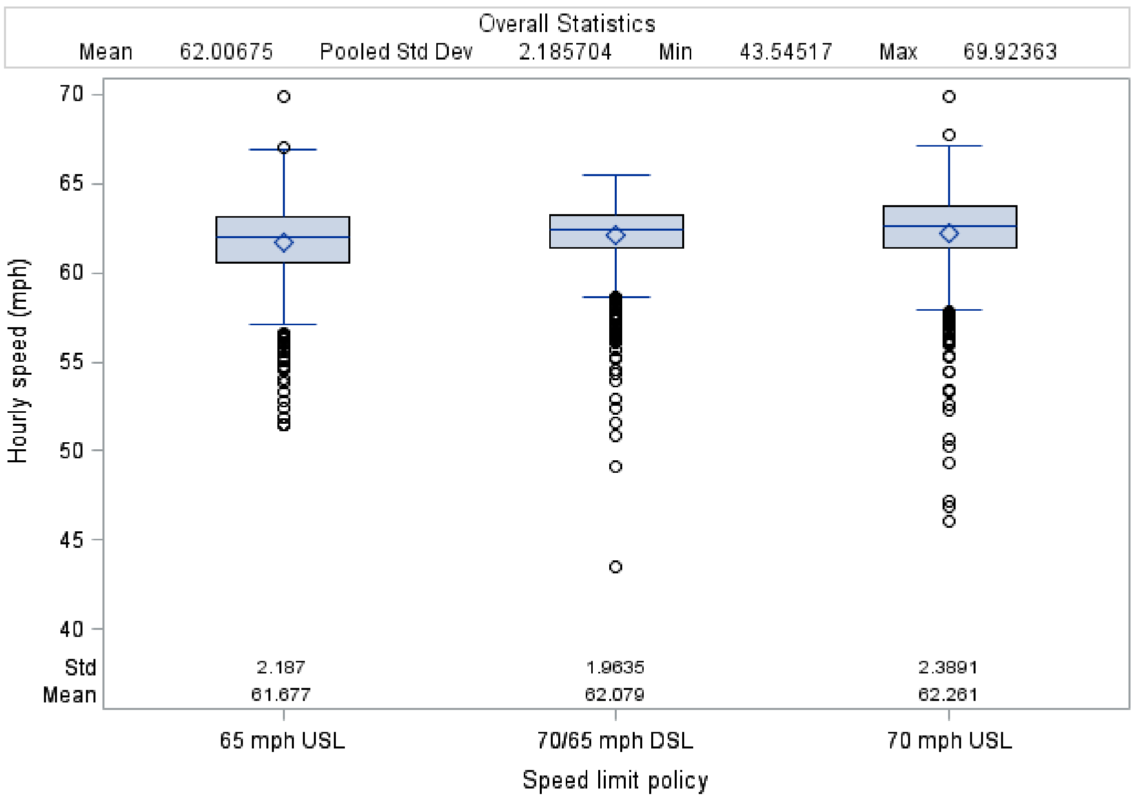

Figure 13. Distribution of heavy trucks hourly travel speeds by speed limit policy (N=1,000).

6. ESTIMATED SPEED EFFECT

The effects of several factors, including the speed limit policy, on the hourly travel speeds were estimated with multiple linear regression models. Separate models were fitted to specific vehicle types and congestion levels. The complete set of tables (see Table 10 to Table 13) with the resulting parameter estimates are presented and discussed in this chapter.

6.1 Goodness of Fit

The adjusted R-square values and F statistics for the speed models are summarized in Table 9. The adjusted R-square values suggest that passenger car speed models obtained under non-congested conditions performed better than the models for congested conditions, as the non-congested models unsurprisingly explained a larger portion of the variability in travel speed. Vehicles under congested traffic are affected by complex and unstable factors, such as bottleneck capacity and traffic flow on ramps, which are challenging to include due to data limitations. Large values of F-statistic support the conclusion that at least one predictor significantly affects travel speed. The seemingly low R-square values could be due to some of the data limitations, namely aggregation over time and space of speed measurements, lack of hourly volume data, and omitted variables such as speed enforcement.

Table 9. Goodness of fit measures for speed models.

Vehicle Type	Traffic Conditions	Adjusted R-square	F-statistic
Passenger cars	Non-congested	0.1610	17,670
Heavy trucks	Non-congested	0.1105	11,793
Passenger cars	Congested	0.0518	11.14
Heavy trucks	Congested	0.1362	32.11

6.2 Estimated Effects

A summary of the estimated effects on travel speed under non-congested traffic conditions is presented in this section. The discussion centers on the estimated effects for passenger cars and trucks under non-congested traffic conditions (see Table 10 to Table 12). Due to the large sample size, most of the predictors were found statistically significant with 99% confidence. Therefore, variables were selected based on their practical influence on travel speed, revealing whether their effects are large enough to be of interest.

Most of the findings were intuitive. Although the following explanation of the results is phrased in terms of causal effects, it should be kept in mind that the estimates reflect statistical association and may not fully reflect causality.

Changing the 70/65-mph DSL to a 70-mph USL on rural interstate freeways was associated with an increase of 0.48 mph in the travel speed of passenger cars and a marginal increase of 0.11 mph in the travel speed of trucks. On the other hand, replacing the existing DSL with a 65-mph USL was found to marginally reduce the travel speed of passenger cars by 0.06 mph and the travel speed of trucks by 0.28 mph. These values represent changes in the travel speed along freeway segments under non-congested traffic conditions. More considerable changes are anticipated on individual operating speeds. Under congested traffic, the effects of the speed limit on travel speed were not found to be significant.

Other variables also affected the average speed and were included in the models to help isolate the effects of the speed limit from confounding factors. An increase in the AADT per number of lanes was found to reduce the hourly travel speed of passenger cars and trucks on rural freeways. The previous effect was marginal in the latter vehicle type. The proportion of trucks, that is, the AADT corresponding to heavy trucks, was found to reduce the travel speed of passenger cars and to increase the travel speed of heavy trucks. This finding can be attributed to drivers adjusting their operating speed to overtake slow-moving trucks. In terms of pavement condition, a high value on the International Roughness Index (IRI), which is an indicator of pavement roughness, was found to reduce the speed of passenger cars and trucks. This reduction was larger for the former type of vehicles. The presence of wide unprotected medians largely favored the travel speed of passenger cars and trucks. The presence of narrow shoulders (shoulder width 9 feet or less) was connected to a reduction in the travel speed of passenger cars, while no practical effect was found on trucks. The travel speed of passenger cars and trucks increased when an extra passing lane was added. Ramp frequency, or the number of ramps per mile, was found to reduce the average speed of all vehicle types on rural freeways. However, this effect was higher on passenger cars than trucks.

Spatial attributes that reflect the nearby urban centers were tested in the models. The presence of a small town, which is an urban area with a population of 50,000 people or less, had a negative effect on the travel speed of cars and trucks. Additionally, the distance to a large city, which is an urban area with more than 50,000 habitants, was found to marginally reduce the travel speed of passenger cars and trucks. This effect had no practical relevance.

The estimated effects of weather-related conditions on travel speed are largely intuitive. The precipitation intensity and presence of snow were found to reduce the average travel speed of both passenger cars and trucks on rural interstates, although a more considerable reduction was observed for passenger cars. This result could be explained by the fact that truck drivers are usually exposed to multiple driving environments while passenger car drivers tend to operate locally, making them more prone to more extensive speed adjustments under adverse weather.

Temporal factors that reflect seasonal variations were found to be significant. Compared to 2014, during 2015 and 2016 higher travel speeds were observed. Compared to the autumn months, lower speeds were observed during the spring and summertime months, while higher travel speeds were found during the winter months. The seasonality effect was more prominent for trucks than passenger cars. Weekends were connected to a reduction in travel speed for trucks while the travel speed of passenger cars was the highest on the weekends compared to weekdays. Finally, the presence of daylight was associated with higher travel speeds for passenger cars and trucks and was significantly larger on the former vehicle type. Hourly indicator variables representing each hour of the day were included to account for daily traffic volume variation. Their significance was confirmed; however, no formal interpretation of these effects was provided due to their instrumental nature.

For congested traffic conditions, a smaller number of effects was found statistically significant. Most importantly, the effect of the speed limit was not significant. The estimated parameters were difficult to interpret, yet it was necessary to perform statistical simulation of alternative speed limit scenarios. It should be noted that rural freeways usually do not experience congested traffic, but it is a common phenomenon on urban freeways with the presence of a bottleneck downstream. Observations classified as congested may represent sporadic seasonal events, crashes, or extreme weather conditions.

Table 10. Multiple linear regression model for passenger cars' average hourly travel speed under non-congested traffic conditions.

Effect	Estimate	Std. Error	t Value	Pr. > |t|
Intercept	66.3329	0.0137	4,846.33	<.0001
Roadway Features				
Speed limit 65 mph	-0.0573	0.0066	-8.62	<.0001
Speed limit 70 mph	0.4781	0.0059	81.01	<.0001
AADT per lane (1,000 veh/day)	-0.0253	0.0003	-79.23	<.0001
Proportion of trucks	-2.6673	0.0210	-127.08	<.0001
IRI (in/mi)	-0.0116	0.0000	-260.76	<.0001
Unprotected median	1.5193	0.0046	331.32	<.0001
Narrow shoulder (shoulder width <= 9 feet)	-0.1598	0.0055	-29.22	<.0001
Number of lanes >= 3	0.5518	0.0062	89.62	<.0001
Ramp frequency (#/mi)	-0.5348	0.0041	-129.85	<.0001
Spatial attributes				
Passing small town	-0.5531	0.0047	-117.36	<.0001
Distance to big city (mi)	-0.0048	0.0002	-30.78	<.0001
Weather conditions				
Light rain	-0.1676	0.0037	-45.72	<.0001
Moderate rain	-0.3835	0.0100	-38.20	<.0001
Heavy rain	-0.9711	0.0827	-11.75	<.0001
Light snowfall	-0.3416	0.0119	-28.68	<.0001
Moderate snowfall	-0.8792	0.0145	-60.59	<.0001
Heavy snowfall	-2.8141	0.0320	-87.82	<.0001
Snow accumulation	-0.6496	0.0073	-89.09	<.0001
Temporal indicators				
Year 2015	0.4337	0.0041	105.51	<.0001
Year 2016	0.4487	0.0040	111.63	<.0001
Spring	-0.2168	0.0046	-46.66	<.0001
Summer	-0.0261	0.0047	-5.52	<.0001
Winter	0.0974	0.0052	18.77	<.0001
Friday	0.5529	0.0048	114.32	<.0001
Saturday	0.8930	0.0049	181.75	<.0001
Sunday	1.0604	0.0050	210.78	<.0001
Daylight	0.6517	0.0088	74.00	<.0001
00:00 - 00:59	-0.2135	0.0117	-18.18	<.0001
01:00 - 01:59	-0.3860	0.0118	-32.68	<.0001
02:00 - 02:59	-0.4313	0.0119	-36.36	<.0001
03:00 - 03:59	-0.3640	0.0118	-30.78	<.0001
04:00 - 04:59	-0.0931	0.0118	-7.92	<.0001
05:00 - 05:59	0.4331	0.0116	37.22	<.0001

Table 10 continued

Effect	Estimate	Std. Error	t Value	Pr. > |t|
06:00 - 06:59	0.8076	0.0118	68.40	<.0001
07:00 - 07:59	0.6423	0.0131	48.88	<.0001
08:00 - 08:59	0.6123	0.0144	42.48	<.0001
09:00 - 09:59	0.6251	0.0144	43.33	<.0001
10:00 - 10:59	0.6972	0.0144	48.34	<.0001
11:00 - 11:59	0.8212	0.0144	56.94	<.0001
12:00 - 12:59	0.8901	0.0144	61.74	<.0001
13:00 - 13:59	0.9723	0.0144	67.46	<.0001
14:00 - 14:59	1.1426	0.0144	79.31	<.0001
15:00 - 15:59	1.3390	0.0144	92.93	<.0001
16:00 - 16:59	1.4319	0.0143	100.30	<.0001
17:00 - 17:59	1.3805	0.0136	101.60	<.0001
18:00 - 18:59	1.2252	0.0129	95.14	<.0001
19:00 - 19:59	0.9518	0.0123	77.28	<.0001
20:00 - 20:59	0.6397	0.0117	54.65	<.0001
21:00 - 21:59	0.3565	0.0115	30.89	<.0001
22:00 - 22:59	0.1858	0.0116	16.04	<.0001

Table 11. Multiple linear regression model for passenger cars' average hourly travel speed under congested traffic conditions.

Effect	**Estimate**	**Std. Error**	**t Value**	**Pr. > |t|**
Intercept	28.8662	0.6826	42.29	<.0001
Roadway Features				
AADT per lane (1,000 veh/day)	-0.2675	0.0213	-12.56	<.0001
Proportion of trucks	-3.3087	1.2982	-2.55	0.0108
IRI (in/mi)	-0.0137	0.0026	-5.30	<.0001
Number of lanes >= 3	1.0903	0.3154	3.46	0.0006
Ramp frequency (#/mi)	-0.5844	0.2126	-2.75	0.0060
Spatial attributes				
Distance to big city (mi)	-0.0619	0.0105	-5.91	<.0001
Weather conditions				
Light rain	0.9312	0.2205	4.22	<.0001
Moderate rain	1.3400	0.6257	2.14	0.0323
Heavy rain	11.7820	6.1251	1.92	0.0544
Light snowfall	-1.2835	0.5547	-2.31	0.0207
Snow accumulation	1.6069	0.3169	5.07	<.0001
Temporal indicators				
Year 2015	1.1739	0.2723	4.31	<.0001
Year 2016	0.8976	0.2537	3.54	0.0004
Daylight	-0.9863	0.2350	-4.20	<.0001
05:00 - 05:59	2.2861	1.0326	2.21	0.0269
07:00 - 07:59	1.5041	0.7095	2.12	0.0340
10:00 - 10:59	1.1925	0.5479	2.18	0.0296
19:00 - 19:59	0.8409	0.4355	1.93	0.0535

Table 12. Multiple linear regression model for heavy trucks' average hourly travel speed under non-congested traffic conditions.

Effect	Estimate	Std. Error	t Value	Pr. > |t|
Intercept	61.9648	0.0070	8,907.02	<.0001
Roadway Features				
Speed limit 65 mph	-0.2821	0.0033	-86.32	<.0001
Speed limit 70 mph	0.1059	0.0025	42.67	<.0001
AADT per lane (1,000 veh/day)	-0.0084	0.0002	-44.82	<.0001
Proportion of trucks	0.7211	0.0125	57.77	<.0001
IRI (in/mi)	-0.0060	0.0000	-228.06	<.0001
Unprotected median	0.8446	0.0026	321.69	<.0001
Number of lanes >= 3	0.2293	0.0037	62.39	<.0001
Ramp frequency (#/mi)	-0.1469	0.0024	-60.16	<.0001
Spatial attributes				
Passing small town	-0.4004	0.0028	-143.16	<.0001
Distance to big city (mi)	-0.0015	0.0001	-15.81	<.0001
Weather conditions				
Light rain	-0.0978	0.0022	-44.70	<.0001
Moderate rain	-0.2701	0.0060	-45.13	<.0001
Heavy rain	-0.6976	0.0490	-14.24	<.0001
Light snowfall	-0.2029	0.0071	-28.60	<.0001
Moderate snowfall	-0.5063	0.0087	-58.50	<.0001
Heavy snowfall	-1.6338	0.0193	-84.74	<.0001
Snow accumulation	-0.1837	0.0043	-42.24	<.0001
Temporal indicators				
Year 2015	0.1341	0.0024	54.75	<.0001
Year 2016	0.7483	0.0024	312.28	<.0001
Spring	-0.2117	0.0028	-76.47	<.0001
Summer	-0.2404	0.0028	-85.05	<.0001
Winter	0.1829	0.0031	59.11	<.0001
Friday	0.0215	0.0029	7.44	<.0001
Saturday	-0.0807	0.0029	-27.56	<.0001
Sunday	-0.0867	0.0030	-29.09	<.0001
Daylight	0.1841	0.0053	34.93	<.0001
00:00 - 00:59	-0.0158	0.0057	-2.77	0.0057
02:00 - 02:59	0.0221	0.0057	3.85	0.0001
03:00 - 03:59	0.0513	0.0057	8.98	<.0001
05:00 - 05:59	-0.1628	0.0056	-28.82	<.0001
06:00 - 06:59	-0.3409	0.0058	-58.80	<.0001
07:00 - 07:59	-0.4533	0.0068	-67.08	<.0001
08:00 - 08:59	-0.5109	0.0076	-66.92	<.0001

Table 12 continued

Effect	Estimate	Std. Error	t Value	Pr. > |t|
09:00 - 09:59	-0.5380	0.0076	-70.36	<.0001
10:00 - 10:59	-0.5243	0.0076	-68.63	<.0001
11:00 - 11:59	-0.5089	0.0076	-66.64	<.0001
12:00 - 12:59	-0.4957	0.0076	-64.92	<.0001
13:00 - 13:59	-0.4904	0.0076	-64.23	<.0001
14:00 - 14:59	-0.4819	0.0076	-63.14	<.0001
15:00 - 15:59	-0.4684	0.0076	-61.37	<.0001
16:00 - 16:59	-0.4356	0.0075	-57.74	<.0001
17:00 - 17:59	-0.4113	0.0071	-58.19	<.0001
18:00 - 18:59	-0.3315	0.0066	-50.40	<.0001
19:00 - 19:59	-0.2748	0.0062	-44.50	<.0001
20:00 - 20:59	-0.2560	0.0057	-44.66	<.0001
21:00 - 21:59	-0.1474	0.0056	-26.29	<.0001
22:00 - 22:59	-0.0302	0.0056	-5.36	<.0001

Table 13. Multiple linear regression model for heavy trucks' average hourly travel speed under congested traffic conditions.

Effect	Estimate	Std. Error	t Value	Pr. > |t|
Intercept	31.2858	0.7130	43.88	<.0001
Roadway Features				
AADT per lane (1,000 veh/day)	-0.2839	0.0218	-13.00	<.0001
Proportion of trucks	-5.4697	1.3043	-4.19	<.0001
IRI (in/mi)	-0.0120	0.0026	-4.55	<.0001
Unprotected median	-1.5975	0.2325	-6.87	<.0001
Narrow shoulder (shoulder width <= 9 feet)	-0.8730	0.2344	-3.72	0.0002
Number of lanes >= 3	-0.9620	0.3397	-2.83	0.0046
Ramp frequency (#/mi)	-1.0467	0.2233	-4.69	<.0001
Spatial attributes				
Distance to big city (mi)	-0.0725	0.0105	-6.91	<.0001
Weather conditions				
Light rain	0.5709	0.2209	2.58	0.0098
Light snowfall	-1.3808	0.5676	-2.43	0.0150
Snow accumulation	2.5260	0.3116	8.11	<.0001
Temporal indicators				
Saturday	0.8619	0.2884	2.99	0.0028
Sunday	1.2031	0.2781	4.33	<.0001
Daylight	-1.3000	0.2580	-5.04	<.0001
00:00 - 00:59	4.7559	0.7001	6.79	<.0001
01:00 - 01:59	5.0828	0.7746	6.56	<.0001
02:00 - 02:59	3.3422	0.8685	3.85	0.0001
03:00 - 03:59	4.6515	0.8232	5.65	<.0001
04:00 - 04:59	4.0470	0.9031	4.48	<.0001
05:00 - 05:59	4.9954	0.9841	5.08	<.0001
06:00 - 06:59	3.9672	0.8787	4.51	<.0001
07:00 - 07:59	2.1774	0.7271	2.99	0.0028

6.3 Connection with Previous Studies

Several authors of past research found that the actual effects of changes in speed limits on the operating speed characteristics were lower than expected (K. Fitzpatrick et al., 2005; Hu, 2017; Islam et al., 2014; Monsere et al., 2004; Parker, 1997). Similarly, in this study, the estimated change in travel speed was found to be significantly lower than the proposed speed limit change. This could be attributed to the way speeds are measured. In previous studies, spot speeds of vehicles traveling at free-flow conditions were the source of speed data. In this case, the travel speed on long freeway segments was used. The effects of speed limit on travel speed might be reduced due to the aggregation of multiple vehicles over time and space. Nonetheless, this type of speed data is ideal for estimating the comprehensive travel cost at the system level as it is not limited to a specific point.

The effects of speed limits on the travel speeds of passenger cars also have been estimated in the past; and multiple authors agree that, regardless of the speed limit policy, the observed passenger car speeds remained unchanged (Freedman & Williams, 1992; Harkey & Mera, 1994; Russo et al., 2015). This conclusion may be consistent with our findings where there is a marginal reduction in travel speed when the passenger car's speed limit is reduced to 65 mph. However, a significant increase in speed was detected when the truck speed limit was increased. The previous result could be attributed to a portion of passenger cars that want to overtake fast-moving trucks.

Finally, the estimated effect of speed limit changes on truck speeds was found to be lower compared to passenger cars (Hu, 2017; Johnson & Murray, 2010). This result may reflect a combination of factors, including truck driver propensity to travel at lower speeds, private truck company policy, and the presence of in-vehicle speed limiters.

7. ESTIMATED SAFETY EFFECT

Fixed and random parameter logistic models were fitted to a sample of 8,269 crashes on rural interstate freeways. Their estimated safety effects are summarized in this chapter.

Due to the lower number of fatal crashes, crash severity was restricted to two levels:1) severe outcomes including fatalities and incapacitating, non-incapacitating, and possible injuries and 2) property damage only crashes. The two severity levels under three traffic conditions theoretically could produce six models for rural freeways. However, the actual number of models in this dissertation was smaller because the safety effect of the speed limit was not always present, particularly in congested conditions. In total, eight models were fitted (see Table 15 to Table 21).

7.1 Goodness of Fit

The goodness of fit measures for the resulting safety models are presented in Table 14. Looking at McFadden's likelihood ratio index (LRI) values, it is noticeable that the probability of crash models offered a better fit compared to the probability of severe outcome (injury or death) models. The Akaike Information Criterion (AIC) values for the fixed and random parameter models are similar. Since the likelihood ratio test (LRT) statistics were lower than 3.841 ($\chi^2_{1,0.05}$), we failed to reject the null hypothesis and concluded that there was no significant difference between the two types of models. The simpler fixed-parameter models were used to evaluate alternative speed limit scenarios further as they do not require the simulation of parameter variances.

Table 14. Goodness of fit measures for safety models.

Modeled probability	**Traffic conditions**	**McFadden's LRI**	**Fixed AIC**	**Random AIC**	**LRT**
Crash	Non-congested	0.8101	46,129	46,111	0.9996
Severe crash	Non-congested	0.4295	4,583	N/A	N/A
Crash	Intermediate	0.8142	15,438	15,440	1.0000
Severe crash	Intermediate	0.2455	2,522	2,523	1.0000

7.2 Estimated Effects

The effects of speed limits and other confounding factors on the hourly probability of crash and severe outcome were estimated. The resulting parameter estimates are presented in Table 15 to Table 21.

The effects of the speed limits on safety were detected under non-congested and intermediate traffic conditions. A significant reduction in the probability of crash was found when changing the current DSL policy with a USL policy. The improvement was largest when implementing a 70-mph USL. The average reduction in crash probability for replacing the 70/65-mph DSL with a 70-mph USL was 3%, with extreme decreases up to 25%. The average reduction in the crash probability of implementing a 65-mph USL was 0.3%. Slightly larger effects were noted under intermediate conditions compared to non-congested traffic. The previous results may be associated with a reduction in the number of vehicle interactions, particularly between passenger cars and heavy trucks.

On the other hand, a detrimental effect of USLs on the probability of severe safety outcomes (injury or death) given crash occurrence was observed. For non-congested traffic conditions, there was no statistically significant difference between the current 70/65-mph DSL policy and a 70-mph USL policy. Nevertheless, a 65-mph speed limit policy was expected to increase the proportion of severe crashes by 3%. For intermediate traffic conditions, both the 70-mph and 65-mph USLs were shown to be detrimental to safety, i.e., they increased the proportion of severe crashes. The average increase in the proportion of severe crashes of replacing the 70/65-mph DSL with a 70-mph USL was 7%, with extreme values as high as 10% for specific conditions. The previous findings can be explained since under a 70-mph USL, when a crash occurs, the trucks would be traveling at a higher speed, making a collision possibly more severe.

Other effects considered in the proposed safety models included roadway geometry, hourly speed characteristics, spatial attributes, weather conditions, and temporal variability. The exposure variables, including the AADT and segment length, were reflected in the roadway features. Most of these additional effects were intuitive. Additional factors associated with safety are used to improve the estimation of the speed limits effect for the same population of road segments. Therefore, counterintuitive yet significant results that provide an improvement in the overall goodness of fit were kept.

Higher AADT values are associated with higher crash risk. This result was observed under both non-congested and intermediate traffic conditions. The AADT, along with the hourly indicators, were assumed to provide a reasonable representation of the traffic volume effect. A 1% increase in the proportion of truck traffic was connected to a 3% higher risk of crash under intermediate conditions, while a 2% reduction in crash probability was observed under non-congested traffic conditions. The pavement roughness was found to marginally reduce the risk of crashes under non-congested and intermediate traffic conditions.

Narrow right shoulders (shoulder width of 9 feet or less) marginally increased the crash risk under non-congested and intermediate traffic conditions. The presence of an extra lane was associated with a 2% increase in the crash risk under non-congested and intermediate traffic conditions. The previous finding may reflect unobserved exposure due to the natural correlation between the traffic volume and the number of lanes.

Although the coefficients for some of the other factors in the safety models are challenging to interpret (e.g., higher ramp frequency is associated with a reduction in the probability of crash), they were kept in the model to improve the estimation of the most important parameters – the ones associated with the studied speed limits. Besides, the models were applied to the same population from which the sample was drawn to estimate the effects of alternative scenarios. Thus, any potential bias in these coefficients caused by any omitted variables was expected to be removed when comparing the safety effects of the studied speed limit scenarios.

A number of speed characteristics have been found associated with counterintuitive effects. Roshandel et al. (2015) did a systematic review and meta-analysis of the effect of real-time traffic characteristics on freeway crash occurrence. Among their findings, a one-unit increase in speed variation was linked to a 22.6% increase in crash occurrence, while a one-unit increase in average speed was linked to a 4.8% reduction in crash occurrence. Similar effects were reported in this dissertation when studying the probability of crash. Nevertheless, a marginal increase in the proportion of severe crashes was found due to an increase in the average travel speed.

In terms of speed variance, represented by the travel speed range, an increase in crash probability and severe outcomes was found under non-congested and intermediate traffic conditions. Additional to the magnitude and variation of travel speed, this dissertation evaluated the significance of a rapid speed reduction over time (5 mph for one hour). The downtrend speed indicator was found highly significant, especially for crash severity. A 6% increase in the proportion of severe outcomes was detected under rapid speed reduction conditions under both non-congested and intermediate traffic.

Weather-related factors were found to affect the probability of crash. Under non-congested traffic conditions, light precipitation was found to marginally increase the crash probability. A 1% increase in crash probability was connected to light snow, while a 2% increase in crash probability was linked to moderate and heavy snow. The presence of accumulated snow was found to marginally affect crash probability under intermediate conditions.

In terms of spatial attributes, the presence of a small town (population of 50,000 people or less) was found to marginally reduce the risk of crash under non-congested and intermediate traffic conditions. Additionally, a 4% reduction in the probability of severe injury given crash occurrence was linked to the presence of a small town under non-congested traffic. These findings can be attributed to the potential presence of local drivers who are familiar with the road.

The normally-distributed random parameters were tested for all four models: probability of crash under non-congested and intermediate traffic conditions and the conditional probability of injury or fatal given crash under non-congested and intermediate traffic conditions. Three random parameters were found significant. A description of these effects follows.

Interestingly, a significant normally distributed AADT effect was found under intermediate traffic conditions. For 95.2% of the observations, an incremental effect of AADT on crash risk was observed, while for 4.8% of the observations, a negative (safer) effect of AADT on crash risk was reported. The previous finding may be due to traffic approaching the intermediate condition.

The estimated effect of ramp frequency was found randomly distributed. For 97.9% of the observations, an increase in the number of ramps per mile produced a reduction in the crash risk under non-congested conditions. However, for 2.1% of the observations, the opposite was noted. This could be explained that under non-congested conditions, the presence of ramps may not produce issues with vehicle interactions. A small portion of intermediate traffic conditions may produce an increase in crash risk.

Finally, the estimated effect of travel speed range on the probability of severe outcomes was found to be normally-distributed under intermediate traffic conditions. For 85.1% of the observations, high values of speed variability were associated with an increment in severe crash risk due to more vehicle interactions. On the other hand, for 14.9% of observations, high values of speed variability were linked to a lower probability of severe outcomes.

Table 15. Binary logit model for probability of crash under non-congested traffic conditions.

Effect	Estimate	Std. Error	t Value	Pr. > |t|
Intercept	2.7577	0.3135	8.80	<.0001
Roadway features				
Speed limit 65 mph	-0.0991	0.0444	-2.23	0.0257
Speed limit 70 mph	-0.9885	0.0514	-19.23	<.0001
AADT per lane (1,000 veh/day)	0.0534	0.0026	20.77	<.0001
Proportion of trucks	-0.7770	0.1885	-4.12	<.0001
IRI (in/mi)	-0.0022	0.0004	-5.41	<.0001
Narrow shoulder (shoulder width <= 9 feet)	0.1670	0.0390	4.28	<.0001
Number of lanes >= 3	0.7693	0.0424	18.14	<.0001
Ramp frequency (#/mi)	-1.1068	0.0535	-20.70	<.0001
Hourly traffic characteristics				
Average speed (mph)	-0.1067	0.0047	-22.71	<.0001
Speed range (mph)	0.0280	0.0022	12.91	<.0001
Downstream speed trend	0.3064	0.0275	11.16	<.0001
Spatial attributes				
Passing small town	-0.3115	0.0482	-6.46	<.0001
Distance to big city (mi)	0.0057	0.0016	3.43	0.0006
Weather conditions				
Light rain	0.0971	0.0295	3.29	0.0010
Light snowfall	0.3094	0.0816	3.79	0.0001
Moderate snowfall	0.7171	0.0781	9.19	<.0001
Heavy snowfall	0.8597	0.1576	5.45	<.0001
Temporal indicators				
Year 2015	-0.1845	0.0334	-5.52	<.0001
Year 2016	-0.2277	0.0332	-6.86	<.0001
Spring	-0.1721	0.0381	-4.52	<.0001
Summer	-0.0987	0.0390	-2.53	0.0113
Winter	-0.2756	0.0415	-6.65	<.0001
Friday	0.1838	0.0392	4.69	<.0001
Saturday	0.1065	0.0405	2.63	0.0085
Sunday	0.1426	0.0403	3.53	0.0004
Daylight	-0.3074	0.0702	-4.38	<.0001
04:00 - 04:59	0.1907	0.0831	2.30	0.0217
05:00 - 05:59	0.2100	0.0824	2.55	0.0108
06:00 - 06:59	0.6654	0.0724	9.19	<.0001
07:00 - 07:59	0.8185	0.0835	9.81	<.0001
08:00 - 08:59	0.8082	0.1014	7.97	<.0001
09:00 - 09:59	0.6267	0.1054	5.95	<.0001
10:00 - 10:59	0.6585	0.1056	6.24	<.0001

Table 15 continued

Effect	Estimate	Std. Error	t Value	Pr. > |t|
11:00 - 11:59	0.7200	0.1035	6.95	<.0001
12:00 - 12:59	0.7995	0.1016	7.87	<.0001
13:00 - 13:59	0.8747	0.1006	8.70	<.0001
14:00 - 14:59	0.9015	0.1002	9.00	<.0001
15:00 - 15:59	0.9436	0.1001	9.43	<.0001
16:00 - 16:59	1.0389	0.0978	10.62	<.0001
17:00 - 17:59	0.9158	0.0916	10.00	<.0001
18:00 - 18:59	0.9215	0.0826	11.16	<.0001
19:00 - 19:59	0.5932	0.0824	7.20	<.0001
20:00 - 20:59	0.5996	0.0748	8.02	<.0001
21:00 - 21:59	0.4134	0.0747	5.53	<.0001
22:00 - 22:59	0.3566	0.0765	4.66	<.0001

Table 16. Binary logit model for probability of severe outcome given crash occurrence under non-congested traffic conditions.

Effect	Estimate	Std. Error	t Value	Pr. > |t|
Roadway features				
Speed limit 65 mph	0.2783	0.0971	2.87	0.0041
Number of lanes >= 3	0.2581	0.1038	2.49	0.0129
Hourly traffic characteristics				
Average speed (mph)	-0.0400	0.0014	-28.90	<.0001
Speed range (mph)	0.0283	0.0051	5.60	<.0001
Downstream speed trend	0.4999	0.0789	6.34	<.0001
Spatial attributes				
Passing small town	-0.3317	0.1207	-2.75	0.0060

Table 17. Binary logit model for probability of crash under intermediate traffic conditions.

Effect	Estimate	Std. Error	t Value	Pr. > |t|
Intercept	-2.7706	0.2440	-11.35	<.0001
Roadway features				
Speed limit 65 mph	-0.1696	0.0682	-2.49	0.0128
Speed limit 70 mph	-1.1956	0.0857	-13.94	<.0001
AADT per lane (1,000 veh/day)	0.0697	0.0040	17.38	<.0001
Proportion of trucks	1.1837	0.2878	4.11	<.0001
IRI (in/mi)	-0.0023	0.0006	-3.84	0.0001
Narrow shoulder (shoulder width <= 9 feet)	0.1313	0.0606	2.17	0.0301
Number of lanes >= 3	0.9160	0.0678	13.51	<.0001
Ramp frequency (#/mi)	-0.8246	0.0759	-10.87	<.0001
Hourly traffic characteristics				
Average speed (mph)	-0.0528	0.0028	-18.90	<.0001
Speed range (mph)	0.0277	0.0014	19.83	<.0001
Downstream speed trend	0.6564	0.0459	14.31	<.0001
Spatial attributes				
Passing small town	-0.2674	0.0704	-3.80	0.0001
Weather conditions				
Light snowfall	0.7734	0.0897	8.62	<.0001
Moderate snowfall	0.5596	0.0783	7.14	<.0001
Snow accumulation	0.2443	0.0676	3.61	0.0003
Temporal indicators				
Year 2015	-0.1758	0.0547	-3.21	0.0013
Year 2016	-0.1475	0.0567	-2.60	0.0093
Saturday	0.1713	0.0587	2.92	0.0035
Sunday	-0.1263	0.0601	-2.10	0.0356
01:00 - 01:59	-0.4947	0.1636	-3.02	0.0025
02:00 - 02:59	-0.4244	0.1529	-2.78	0.0055
03:00 - 03:59	-0.4857	0.1603	-3.03	0.0025
04:00 - 04:59	-0.3440	0.1558	-2.21	0.0272
06:00 - 06:59	0.3839	0.1295	2.97	0.0030
07:00 - 07:59	0.9021	0.1140	7.91	<.0001
08:00 - 08:59	0.8929	0.1207	7.40	<.0001
09:00 - 09:59	1.2009	0.1159	10.36	<.0001
10:00 - 10:59	1.1129	0.1240	8.98	<.0001
11:00 - 11:59	1.0533	0.1296	8.13	<.0001
12:00 - 12:59	0.9913	0.1343	7.38	<.0001
13:00 - 13:59	0.9472	0.1358	6.97	<.0001
14:00 - 14:59	1.1971	0.1279	9.36	<.0001
15:00 - 15:59	0.9985	0.1259	7.93	<.0001

Table 17 continued

Effect	Estimate	Std. Error	t Value	Pr. > |t|
16:00 - 16:59	1.1053	0.1201	9.21	<.0001
17:00 - 17:59	1.1051	0.1199	9.21	<.0001
18:00 - 18:59	0.7800	0.1342	5.81	<.0001
19:00 - 19:59	0.6833	0.1367	5.00	<.0001
20:00 - 20:59	0.4494	0.1383	3.25	0.0012
21:00 - 21:59	0.4723	0.1312	3.60	0.0003
22:00 - 22:59	0.3983	0.1355	2.94	0.0033

Table 18. Binary logit model for probability of severe outcome given crash occurrence under intermediate traffic conditions.

Effect	Estimate	Std. Error	t Value	Pr. > |t|
Intercept	-3.0414	0.4443	-6.85	<.0001
Roadway features				
Speed limit 65 mph	0.5734	0.1071	5.35	<.0001
Speed limit 70 mph	0.4244	0.1639	2.59	0.0096
Hourly traffic characteristics				
Average speed (mph)	0.0196	0.00716	2.73	0.0063
Speed range (mph)	0.0246	0.003526	6.99	<.0001
Downstream speed trend	0.3717	0.1108	3.35	0.0008
Weather conditions				
Moderate rain	-0.9249	0.3289	-2.81	0.0049
Moderate snowfall	-0.5053	0.1791	-2.82	0.0048
Heavy snowfall	-1.0126	0.3552	-2.85	0.0044
Snow accumulation	-0.2937	0.1387	-2.12	0.0343

Table 19. Mixed logit model for probability of crash under non-congested traffic conditions.

Effect	Estimate	Std. Error	t Value	Pr. > |t|
Intercept	2.7970	0.3350	8.35	<.0001
Roadway features				
Speed limit 65 mph	-0.1229	0.0462	-2.66	0.0078
Speed limit 70 mph	-0.9971	0.0537	-18.58	<.0001
AADT per lane (1,000 veh/day)	0.0543	0.0027	20.24	<.0001
Proportion of trucks	-0.8186	0.1873	-4.37	<.0001
IRI (in/mi)	-0.0021	0.0004	-5.00	<.0001
Narrow shoulder (shoulder width <= 9 feet)	0.1798	0.0397	4.53	<.0001
Number of lanes >= 3	0.7837	0.0451	17.39	<.0001
Ramp frequency (#/mi) – Mean	-1.4812	0.1203	-12.31	<.0001
Ramp frequency (#/mi) – StdDev	-0.7280	0.1013	-7.18	<.0001
Hourly traffic characteristics				
Average speed (mph)	-0.1064	0.0050	-21.40	<.0001
Speed range (mph)	0.0287	0.0023	12.73	<.0001
Downstream speed trend	0.3067	0.0280	10.94	<.0001
Spatial attributes				
Passing small town	-0.2948	0.0519	-5.68	<.0001
Distance to big city (mi)	0.0058	0.0017	3.41	0.0007
Weather conditions				
Light rain	0.0966	0.0298	3.24	0.0012
Light snowfall	0.3157	0.0830	3.80	0.0001
Moderate snowfall	0.7257	0.0792	9.16	<.0001
Heavy snowfall	0.8605	0.1632	5.27	<.0001
Temporal indicators				
Year 2015	-0.1858	0.0343	-5.41	<.0001
Year 2016	-0.2297	0.0344	-6.68	<.0001
Spring	-0.1705	0.0388	-4.39	<.0001
Summer	-0.0958	0.0399	-2.40	0.0163
Winter	-0.2780	0.0424	-6.56	<.0001
Friday	0.1850	0.0397	4.66	<.0001
Saturday	0.1062	0.0409	2.60	0.0093
Sunday	0.1438	0.0410	3.51	0.0005
Daylight	-0.3267	0.0695	-4.70	<.0001
04:00 - 04:59	0.1999	0.0831	2.40	0.0162
05:00 - 05:59	0.2182	0.0827	2.64	0.0083
06:00 - 06:59	0.6766	0.0725	9.33	<.0001
07:00 - 07:59	0.8349	0.0839	9.96	<.0001
08:00 - 08:59	0.8347	0.1018	8.20	<.0001
09:00 - 09:59	0.6533	0.1061	6.16	<.0001

Table 19 continued

Effect	Estimate	Std. Error	t Value	Pr. > |t|
10:00 - 10:59	0.6837	0.1064	6.42	<.0001
11:00 - 11:59	0.7449	0.1034	7.21	<.0001
12:00 - 12:59	0.8265	0.1018	8.12	<.0001
13:00 - 13:59	0.9012	0.1004	8.98	<.0001
14:00 - 14:59	0.9274	0.1001	9.27	<.0001
15:00 - 15:59	0.9686	0.1000	9.69	<.0001
16:00 - 16:59	1.0637	0.0981	10.84	<.0001
17:00 - 17:59	0.9370	0.0911	10.28	<.0001
18:00 - 18:59	0.9411	0.0824	11.42	<.0001
19:00 - 19:59	0.6098	0.0833	7.32	<.0001
20:00 - 20:59	0.6133	0.0753	8.14	<.0001
21:00 - 21:59	0.4208	0.0751	5.60	<.0001
22:00 - 22:59	0.3647	0.0765	4.77	<.0001

Table 20. Mixed logit model for probability of severe outcome given crash occurrence under intermediate traffic conditions.

Effect	Estimate	Std. Error	t Value	Pr. > |t|
Intercept	-2.6010	0.2661	-9.77	<.0001
Roadway features				
Speed limit 65 mph	-0.1773	0.0707	-2.51	0.0121
Speed limit 70 mph	-1.2295	0.0921	-13.35	<.0001
AADT per lane (1,000 veh/day) – Mean	0.0589	0.0076	7.72	<.0001
AADT per lane (1,000 veh/day) – StdDev	-0.0354	0.0102	-3.48	0.0005
Proportion of trucks	1.1611	0.3055	3.80	0.0001
IRI (in/mi)	-0.0024	0.0007	-3.39	0.0007
Narrow shoulder (shoulder width <= 9 feet)	0.1325	0.0641	2.07	0.0386
Number of lanes >= 3	0.9558	0.0747	12.79	<.0001
Ramp frequency (#/mi)	-0.8590	0.0824	-10.43	<.0001
Hourly traffic characteristics				
Average speed (mph)	-0.0560	0.0037	-15.23	<.0001
Speed range (mph)	0.0288	0.0020	14.38	<.0001
Downstream speed trend	0.6785	0.0519	13.08	<.0001
Spatial attributes				
Passing small town	-0.2835	0.0774	-3.66	0.0002
Weather conditions				
Light snowfall	0.8105	0.0912	8.89	<.0001
Moderate snowfall	0.5871	0.0793	7.41	<.0001
Snow accumulation	0.2426	0.0674	3.60	0.0003
Temporal indicators				
Year 2015	-0.1959	0.0608	-3.22	0.0013
Year 2016	-0.1580	0.0616	-2.57	0.0102
Saturday	0.1826	0.0617	2.96	0.0031
Sunday	-0.1340	0.0629	-2.13	0.0333
01:00 - 01:59	-0.4936	0.1657	-2.98	0.0029
02:00 - 02:59	-0.4359	0.1573	-2.77	0.0056
03:00 - 03:59	-0.4906	0.1633	-3.00	0.0027
04:00 - 04:59	-0.3456	0.1569	-2.20	0.0276
06:00 - 06:59	0.4065	0.1329	3.06	0.0022
07:00 - 07:59	0.9361	0.1246	7.52	<.0001
08:00 - 08:59	0.9347	0.1290	7.25	<.0001
09:00 - 09:59	1.2563	0.1251	10.04	<.0001
10:00 - 10:59	1.1554	0.1349	8.57	<.0001
11:00 - 11:59	1.0997	0.1400	7.86	<.0001
12:00 - 12:59	1.0242	0.1485	6.90	<.0001
13:00 - 13:59	1.0040	0.1411	7.12	<.0001

Table 20 continued

Effect	Estimate	Std. Error	t Value	Pr. > |t|
14:00 - 14:59	1.2550	0.1370	9.16	<.0001
15:00 - 15:59	1.0480	0.1368	7.66	<.0001
16:00 - 16:59	1.1753	0.1288	9.13	<.0001
17:00 - 17:59	1.1698	0.1288	9.08	<.0001
18:00 - 18:59	0.8256	0.1346	6.13	<.0001
19:00 - 19:59	0.7212	0.1375	5.25	<.0001
20:00 - 20:59	0.4767	0.1424	3.35	0.0008
21:00 - 21:59	0.4939	0.1329	3.72	0.0002
22:00 - 22:59	0.4263	0.1369	3.11	0.0018

Table 21. Mixed logit model for probability of severe outcome given crash occurrence under intermediate traffic conditions.

Effect	Estimate	Std. Error	t Value	Pr. > |t|
Intercept	-3.3201	0.5506	-6.03	<.0001
Roadway features				
Speed limit 65 mph	0.6289	0.1367	4.6	<.0001
Speed limit 70 mph	0.4846	0.1887	2.57	0.0102
Hourly traffic characteristics				
Average speed (mph)	0.0238	0.008765	2.72	0.0065
Speed range (mph) – Mean	0.024	0.004597	5.21	<.0001
Speed range (mph) – StdDev	0.0231	0.0151	1.53	0.1265
Downstream speed trend	0.3691	0.1263	2.92	0.0035
Weather conditions				
Moderate rain	-1.0753	0.4105	-2.62	0.0088
Moderate snowfall	-0.5254	0.202	-2.6	0.0093
Heavy snowfall	-1.0498	0.3696	-2.84	0.0045
Snow accumulation	-0.3137	0.1547	-2.03	0.0426

7.3 Connection with Previous Studies

Previous studies on the safety effect of implementing DSLs have led to inconclusive or, in some cases, conflicting results. This dissertation addressed this complex relationship by analyzing the short-term effect of the speed limit on safety performance under multiple congestion levels.

Conclusive results indicate that a USL policy reduced the probability of crash under non-congested and intermediate traffic, which supports previous research that attributed the safety benefits of USLs to fewer lane-changing maneuvers and rear-end crashes (Hall & Dickinson, 1974; Pfefer et al., 1991).

On the other hand, an increase in the probability of severe outcomes given a crash was observed on roads with a USL policy under intermediate traffic conditions, but such conditions account for less than 5% of the total observations for rural freeways. Previous research has reported a significant reduction in the car-into-truck fatal and injury crash rate when changing from USL to DSL, especially for truck-related crashes (Davis et al., 2015; Pfefer et al., 1991). While not significant, some authors who compared states with DSLs and USLs reported higher fatality rates in those with the USL policy (Garber et al., 2003; Neeley & Richardson, 2009). Specifically for Indiana, Khan et al. (2000) found that the total number of crashes and the crash rate increased after adopting a DSL policy. There were no significant effects observed on the crash severity.

The discrepancies between the findings regarding the safety effects of a DSL policy were analyzed by Johnson and Pawar (2007). They attributed the inconsistencies to two opposing factors. On the one hand, there was a positive effect resulting from improved vehicle dynamics for trucks moving at lower speeds; but on the other hand, there was a negative effect subsequent to an increase in the number of traffic interactions from increased speed variations. This dissertation complements this discussion with a conclusive overall safety improvement of repealing the existing DSL.

Lastly, previous studies have compared the safety performance on non-interstate roads before and after increases in the interstate speed limits (Farmer et al., 1999; Grabowski & Morrisey, 2007). They found that while the number and severity of crashes increased on interstates, the safety performance measures on roads unaffected by the speed limit change remained unaltered. This finding strengthens the results of this dissertation since it permits assuming that the largest safety effect of changes in the interstate speed limit is expected on rural interstate freeways.

8. EVALUATION OF ALTERNATIVE SPEED LIMITS

The effects of changing the statutory speed limit on rural interstate freeways in Indiana were assessed. The assessment included estimations for current and alternative speed limit scenarios, travel time value, vehicle operating costs, and crash-related costs. These elements are components of the overall economic impact and reflect the comprehensive travel cost. Table 22 presents the annual financial effect of changing the current DSL policy with a USL policy for rural interstate freeways. Two alternatives were evaluated. First, increasing the speed limit for trucks by 5 mph to create a 70-mph USL. Second, reduce the speed limit for passenger cars from 70 mph to 65 mph to establish a 65-mph USL.

Replacing the 70/65-mph DSL with a 70-mph USL would reduce travel time and the total number of crashes. Nevertheless, the proportion of severe crashes can be expected to increase marginally. Overall, a safety benefit was concluded. However, these gains come at the expense of increased vehicle operating costs. The annual cost difference could be expected to be slightly negative unless the comprehensive cost of crashes was considered.

On the other hand, changing the 70/65-mph DSL with a 65-mph USL was found to increase the travel time and safety costs paid by road users. A reduction in vehicle operating costs was observed for both passenger cars and trucks. Using the crashes' economic cost, a slight annual benefit was noted due to savings in vehicle operating costs. However, when the comprehensive cost of crashes was used, the safety and travel time extra costs outweighed the savings in vehicle operating costs. The previous result was due to an increase in the proportion of severe crashes. Therefore, it was concluded that the 65-mph USL is not a recommended setting.

Changing the interstate speed limit also could produce a spillover effect when drivers find more attractive routes. However, this effect was marginal for rural roads since interstates would continue being the fastest route for intercity travel. In terms of safety, previous authors have found that the crash frequency and severity on non-interstates remained unchanged after a speed limit change on interstates (Malyshkina & Mannering, 2008).

In addition to the mobility and safety effects, a complete evaluation of speed limit policies should include economic productivity impacts. Other economic analysis elements should include environmental and infrastructure improvements costs as well. Notably, Khan et al. (2000) estimated the impact of speed limit changes on the truck industry's productivity. Using a fixed-effects time series cross-section model for output per employee, it was concluded that the truck industry's productivity is improved when speed limits are raised. While not statistically significant, a marginal negative effect for a DSL on the truck industry's productivity was reported.

Table 22. Estimated annual comprehensive travel effects of changing the statutory speed limit on Indiana rural interstates from a 70/65-mph DSL to a 65-mph or 70-mph USL (2014 US dollars).

Item	**70/65 mph**	**65 mph**	**70 mph**
Value of time			
Predicted travel time for passenger cars (Hours)	93,917,132	93,997,590	93,253,462
Predicted travel time for heavy trucks (Hours)	26,371,648	26,484,468	26,328,236
Cost of travel time for passenger cars	$2,001,374,084	$2,003,088,642	$1,987,231,285
Cost of travel time for heavy trucks	$1,215,732,970	$1,220,933,976	$1,213,731,694
Total cost of travel time - Sample	$3,217,107,054	$3,224,022,618	$3,200,962,979
Total cost of travel time - Indiana	$8,911,386,541	$8,930,542,651	$8,866,667,452
Difference in cost from base scenario	$0	$19,156,110	-$44,719,089
Vehicle operating costs			
Predicted fuel consumption for passenger cars (gallons)	108,496,495	108,066,320	112,152,154
Predicted fuel consumption for heavy trucks (gallons)	495,274,085	489,927,383	497,300,773
Fuel related costs for passenger cars	358,363,923	356,943,056	370,438,564
Fuel related costs for heavy trucks	$1,885,013,169	$1,864,663,618	$1,892,726,742
Non-fuel related costs for passenger cars	$807,942,169	$807,942,169	$807,942,169
Non-fuel related costs for heavy trucks	$618,654,788	$618,654,788	$618,654,788
Total vehicle operating costs - Sample	$3,669,974,049	$3,648,203,631	$3,689,762,263
Total vehicle operating costs - Indiana	$10,165,828,116	$10,105,524,058	$10,220,641,469
Difference in cost from base scenario	$0	-$60,304,058	$54,813,353
Traffic safety – Economic cost			
Predicted PDO crashes	4,137	4,075	3,990
Predicted injury and fatal crashes	752	793	749
Cost of PDO crashes	$24,892,667	$24,515,387	$24,008,495
Cost of injury and fatal crashes	$111,875,839	$117,979,800	$111,483,413
Total cost of crashes - Sample	$136,768,506	$142,495,187	$135,491,908
Total cost of crashes - Indiana	$378,848,762	$394,711,669	$375,312,584
Difference in cost from base scenario	$0	$15,862,906	-$3,536,178
Traffic safety – Comprehensive cost			
Predicted PDO crashes	4,137	4,075	3,990
Predicted injury and fatal crashes	752	793	749
Cost of PDO crashes	$271,131,537	$267,022,193	$261,501,115
Cost of injury and fatal crashes	$939,201,811	$990,444,790	$935,907,376
Total cost of crashes - Sample	$1,210,333,349	$1,257,466,983	$1,197,408,490
Total cost of crashes - Indiana	$3,352,623,376	$3,483,183,544	$3,316,821,519
Difference in cost from base scenario	$0	$130,560,168	-$35,801,857
Total annual costs			
Total difference using safety economic cost	$0	-$25,285,042	$6,558,086
Total difference using safety comprehensive cost	$0	$89,412,220	-$25,707,593

9. CLOSURE

9.1 Dissertation Summary

This dissertation proposed a new methodology to assess the safety and mobility effects of changes in the statutory speed limits that introduces new approaches to an old problem. First of all, in contrast to previous research in this area, the effects of the speed limit were estimated hourly in this dissertation. In addition, the effects of speed limits on travel speed and crash probability were investigated under various congestion levels, which is a departure from the previous research approach of assessing speed under low-density conditions close to free flow. Furthermore, perceiving a difference in driving behavior and perception of speed enforcement, the speed limit's effect on travel speed was estimated separately for passenger cars and trucks. The proposed methodology also considers previously omitted time-varying factors such as travel speed characteristics, weather conditions, lighting, and other seasonal variables.

Advanced statistical models were used to connect the speed limit with travel speed, probability of crash, and probability of severe outcome (injury or death) given crash occurrence. The effects of speed limits on travel speed also were estimated using multiple linear regression; and the speed limit's effects on crash risk and injury severity were estimated using logistic regression with random parameters to accommodate for unobserved heterogeneity among observations.

The proposed models subsequently were used to estimate the annual effect of replacing Indiana's DSL policy with a USL policy on rural interstates. A comparison of the comprehensive travel costs among alternative speed limit scenarios was performed with criteria that included the differences in the value of time, vehicle operating costs, and the cost of crashes.

The various speed limits were found to affect mobility and safety in different ways, mainly under non-congested traffic conditions; and no statistically significant effects of speed limits were found under congested traffic conditions. The results indicate that replacing the 70-mph DSL policy on Indiana rural interstate freeways with a 70-mph USL policy may benefit both safety and mobility. A marginal increment in the proportion of severe crashes under a USL was detected for intermediate traffic conditions, which is the congestion level that accounts for approximately 5% of the total segment-hours. An overall safety improvement may be expected from the replacement of Indiana's 70-mph DSL policy with a 70-mph USL policy. The here results presented may be associated with two counteracting effects. On the one hand, a reduction in vehicle interactions, particularly between passenger cars and heavy trucks, could improve safety. On the other hand, trucks traveling at higher speeds might produce more severe injuries to people involved in crashes.

9.2 Methodological Contribution

This dissertation considered previously omitted factors from aggregate speed and safety analyses and used a short-term cross-sectional approach. Granular spatial and temporal predictors were used to estimate the safety and mobility effects; and the spatial characteristics related to the speed limit, road geometry, pavement condition, and presence of ramps were considered. Time-dependent factors such as speed characteristics, weather conditions, and seasonal factors also were included in the analysis. Considering these factors as predictors in statistical analysis improved the accuracy of estimating the speed limit's effects on travel speed and safety.

Two standard methodological good practices identified from the literature review were implemented in this dissertation. On the one hand, the effects of the speed limit on the travel speed of passenger cars and trucks were considered separately. The previous aspect was key since the two types of vehicles differ in their driving culture, vehicle dynamics, perception of speed limit enforcement, value of time, and vehicle operating costs. On the other hand, short-term safety performance was evaluated for two severity levels. This sequential approach was believed to better reflect the reality of crash events when there are contributing factors to crash occurrence and a second subset of factors that may affect the injury severity of vehicle occupants.

Most notably, this study tested the assumption that the speed limit has its maximum effect under non-congested traffic conditions close to free flow. A Congestion Index was defined as the relative difference between an observed hourly speed and the segment-specific daily free-flow speed. Multiple congestion levels were defined by looking at the effect of the traffic volume on the travel speed. The complete set of hourly observations was divided into three traffic states: non-congestion, intermediate, and congestion. It was confirmed that the effects of speed limit on travel speed and safety diminish as the traffic approaches congestion. Speed limits were found to affect mobility and safety mostly in non-congested traffic conditions, while no significant effects were found in congested conditions. A limited effect was detected under intermediate traffic conditions.

Observations of the past conditions of travel speed, roadway geometry, and weather were available for this dissertation. It can be assumed that their observed influence on speed and safety and their effect on the estimates of the effects of the speed limit can be applied to the same population from which they were derived. An optimum policy selected from the alternatives based on an analysis such as this could remain desirable for future years without the need to continually predict future temporal conditions such as traffic and weather, a challenging task by itself.

9.3 Empirical Contribution

Two alternative speed limit policies to replace the current DSL policy on rural interstate freeways in Indiana were evaluated. The comparison includes comprehensive travel costs related to travel time, vehicle operating costs, and crash outcomes. The safety costs are presented as the economic loss and the comprehensive cost. These results are intended to be among the essential elements of discussion for changes in the current speed limits on Indiana freeways.

The effects of replacing the existing 70/65-mph DSL policy on rural freeways with a 65-mph USL was estimated and the expected effects are as follows:

- Reduce passenger car travel speeds by 0.1 mph and truck travel speeds by 0.3 mph.
- Reduce crash frequency by approximately 1%, predominantly for property damage only crashes.
- Increase the proportion of severe crashes by 6%. While this effect was detected under non-congested and intermediate traffic conditions, a significantly larger increase in the proportion of severe crashes was noticed under intermediate traffic.
- Produce a benefit of $25.29 million per year, primarily due to lower vehicle operating costs.
- Result in an $89.41 million annual loss if the comprehensive cost of crashes is considered, primarily due to an increase in the proportion of severe crashes.

Alternatively, converting to a 70-mph USL policy could be expected to do the following:

- Increase passenger car speeds by 0.5 mph and increase truck speeds by 0.1 mph.
- Reduce crash frequency by approximately 3%, PDO crashes.
- Increase the proportion of severe crashes by 3%. This increase is exclusive of intermediate traffic conditions.

- Produce a loss of $6.56 million per year, primarily due to higher vehicle operating costs.
- Result in a $25.71 million annual net benefit if the comprehensive cost of crashes is considered.

9.4 Transferability of the Results

The use of data from the states of Illinois, Indiana, and Ohio raised questions about the transferability of the estimated speed limit effects between the three states. Differences in driving culture and level of speed limit enforcement may alter the results. Attaining reliable transferability is imperative for rural freeways where the speed limits are different.

The speed and safety differences between the states are presumably greater on urban than rural freeways due to the different nature of the travel, i.e., urban freeways are used for a combination of short and long-distance trips while rural freeways are predominantly used for long-distance trips. However, urban freeways data are more transferable between states because the roads more frequently have speed limits in common. Thus, urban roads offer a valuable opportunity to compare the relationships between the speed limit, travel speed, and safety while isolating the state driving culture effect.

Relative safety effects should be easier to transfer between states than speed effects. This observation is particularly plausible for rural interstate roads thanks to the predominantly long-distance traffic, which increases the commonality of drivers' behavior in neighboring states. On the other hand, urban freeways in and around large cities are used by a considerable number of local drivers. Thus, transferability of a speed limit policy's safety effects from out-of-state urban freeways to Indiana's urban freeways would be a strong indicator of the transferability of similar effects between rural freeways in multiple states.

Fortunately, the neighboring states of Illinois and Indiana have a large number of urban freeways operating under the same speed limits. However, it should be kept in mind that all the studied DSL segments are in Indiana, and all the USL segments are in Illinois. Due to possible differences in crash reporting and safety performance records between Indiana and Illinois, the "state" effect may be included in the estimated speed limit effect.

Remarkably, Tarko et al. (2019) calibrated a set of safety models on urban interstate freeways in Indiana and Illinois. Although the intercept term needed adjustment to account for differences between safety in the two states, all the other variables, including the speed limit variable, did not require any adjustments of their coefficients. All the attempted interactions between the state binary indicators and these variables turned out to be statically insignificant and negligible. This result has an important implication since it allows applying the adjustment for the USLs to the Indiana speed and safety estimated effects.

9.5 Study Limitations

The National Performance Management Research Data Set (NPRMDS) offered a comprehensive view of speed on all the freeway sections in Indiana. However, the NPMRDS estimates of the effects of the speed limit on actual speed may be larger than those estimated in the models. Previous authors found that the travel speeds detected from probes, such as NPRMDS data, are systematically lower than spot speed measurements (C. D. Fitzpatrick et al., 2016). The NPMRDS estimates are sustained using the average travel times of multiple vehicles over large freeway segments (2.5 miles on average) and over a considerable period. Use of this dataset is warranted, nonetheless, by its principal benefit, which is its coverage.

To the best knowledge of the author, there is no data source with hourly traffic volume available at the system level. These data are needed to account for exposure, i.e., the amount of traffic exposed to potential crashes. Additionally, the fundamental connection between speed, volume, and traffic density allows establishing clear thresholds for the congestion level, therefore improving the classification of traffic conditions. To address this limitation, the AADT and segment length were used in combination with the estimated seasonal adjustment factors.

The lack of system-wide speed enforcement limited this dissertation. Various authors have highlighted the importance of accounting for the level of speed enforcement when analyzing operating speeds (Malyshkina et al., 2007; Tarko, 2009). Drivers comply with the PSLs when they perceive an increase in the risk of getting a speeding ticket. Additionally, the level of speed enforcement has been found to affect safety. Khan et al. (2000) found that an increase in speed enforcement produced a reduction in the number of non-injury crashes.

9.6 Future Research Directions

Due to the large sample size, some of the implemented statistical analysis methods and assumptions need to be utilized carefully. The use of stochastic gradient descent or batch-gradient descent helps to test the validity of the assumptions when performing large-sample regression (Gardner, 1984). Generally, this approach consists of evaluating multiple subsets of the total data with a similar number of observations until reaching convergence in the estimated coefficients.

The use of cross-sectional analyses has been limited when studying the effect of the speed limit on safety for two possible reasons. First, the difficulty of gathering enough information to adequately represent the distinct characteristics of selected road sections. Second, the possible sample selection bias of poor safety performance roads. Future research tasks include providing a methodology that accounts for sample selection bias in cross-sectional studies that examine the effect of the speed limit on crash frequency and severity. Notably, Tarko and Azam (2011)used a bivariate ordered probit model to account for sample selection bias when looking at pedestrian injuries in police-hospital matched data. In their case, the two latent variables represented the binary outcome of the matched record and the multinomial outcome of crash injury severity. A similar approach can be applied to study the effect of the speed limit on safety. It consists of two latent variables that represent the speed limit and crash injury severity.

Finally, the probable combination of DSLs and USLs with other policies such as lane restrictions and truck platooning may be expected. While significant safety benefits of combined application of DSLs and truck lane restrictions have been reported in the literature (Korkut et al., 2010; Sun et al., 2009), truck platooning presents an opportunity for future research. Truck platooning occurs when two or more trucks adjust their speeds and headways to reduce drag, therefore increasing fuel efficiency (Tsugawa et al., 2016). Truck platooning has been proven beneficial to safety as it reduces the cut-ins and cut-offs done by lighter vehicles (Alam et al., 2015). Recent multi-state initiatives for autonomous trucks' platooning offers the opportunity to evaluate the combined effect of DSLs/USLs and truck platooning. Notably, the partnership between the states of Michigan (DSLs), Ohio (USLs), and Pennsylvania (USLs) is a clear example (Stedke, 2020).

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APPENDIX A. HOURLY VOLUME ADJUSTMENT FACTORS

The hourly volume adjustment factors represent the percentage of Annual Average Daily Traffic (AADT) for a specific month, day of the week, and hour. The following coding is used in Table 23:

- M: Month
  1 – January, 2 – February, …, 12 – December.

- D: Day of the week
  1 – Sunday, 2 – Monday, …, 7 – Saturday.

- H: Hour
  H0 – 0:00 to 0:59, H1 – 1:00 to 1:59, …, H23 – 23:00 to 23:59.

Table 23. AADT Hourly Volume Adjustment Factors for Rural Freeways in Indiana.

M	D	H0	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10	H11	H12	H13	H14	H15	H16	H17	H18	H19	H20	H21	H22	H23
1	1	0.84	0.57	0.45	0.38	0.43	0.56	0.79	1.11	1.64	2.38	3.28	4.04	4.68	4.93	5.07	5.22	5.22	5.17	4.52	3.68	3.04	2.27	1.67	1.19
1	2	0.86	0.67	0.62	0.67	1.00	1.90	2.84	3.79	3.88	4.17	4.43	4.56	4.75	4.91	5.15	5.61	5.91	5.80	4.61	3.41	2.77	2.34	1.87	1.46
1	3	1.06	0.90	0.84	0.87	1.22	2.09	2.96	3.81	3.83	3.95	4.10	4.20	4.30	4.58	4.92	5.40	5.63	5.49	4.25	3.19	2.50	2.21	1.79	1.42
1	4	0.98	0.88	0.78	0.79	1.07	1.77	2.62	3.43	3.58	3.87	4.12	4.33	4.64	4.88	5.17	5.57	5.71	5.51	4.35	3.28	2.61	2.35	1.85	1.45
1	5	1.16	0.98	0.87	0.90	1.25	2.07	2.98	3.90	3.95	4.00	4.08	4.30	4.51	4.98	5.18	5.57	5.90	5.79	4.52	3.44	2.94	2.52	2.02	1.62
1	6	1.23	1.05	0.96	0.99	1.31	2.20	3.09	3.93	4.11	4.41	4.77	5.07	5.44	5.99	6.43	6.95	7.34	7.25	6.01	4.62	3.44	2.92	2.26	1.67
1	7	1.24	0.98	0.83	0.77	0.89	1.27	1.64	2.15	2.88	3.80	4.61	5.06	5.07	5.04	5.03	4.91	4.77	4.42	3.77	3.09	2.62	2.22	1.89	1.39
2	1	0.85	0.60	0.46	0.40	0.40	0.55	0.75	1.07	1.68	2.47	3.43	4.11	4.78	5.08	5.44	5.73	5.76	5.48	4.63	3.67	2.88	2.22	1.65	1.20
2	2	0.84	0.67	0.64	0.69	1.04	2.05	3.12	4.18	4.16	4.40	4.57	4.62	4.80	4.95	5.10	5.50	5.75	5.66	4.43	3.31	2.61	2.25	1.83	1.42
2	3	1.11	0.98	0.90	0.98	1.33	2.28	3.31	4.31	4.40	4.50	4.63	4.62	4.74	4.99	5.21	5.55	5.66	5.46	3.99	3.00	2.42	2.09	1.69	1.31
2	4	0.97	0.84	0.78	0.80	1.15	1.99	2.90	3.87	3.91	3.95	4.06	4.07	4.23	4.43	4.85	5.29	5.66	5.59	4.43	3.32	2.69	2.34	1.91	1.48
2	5	1.18	0.96	0.89	0.98	1.32	2.40	3.57	4.68	4.68	4.71	4.82	4.89	5.06	5.37	5.72	6.26	6.69	6.57	5.10	3.74	3.08	2.62	2.18	1.68
2	6	1.24	1.05	0.97	1.00	1.39	2.42	3.51	4.58	4.62	4.90	5.17	5.43	5.77	6.06	6.63	7.30	7.81	7.83	6.48	5.03	3.78	3.12	2.51	1.88
2	7	1.34	0.98	0.79	0.76	0.94	1.31	1.65	2.29	3.10	3.91	4.59	4.91	4.88	4.79	4.67	4.75	4.74	4.47	3.90	3.21	2.63	2.21	1.76	1.26
3	1	1.30	0.86	0.65	0.59	0.62	0.72	1.05	1.48	2.20	3.23	4.41	5.48	6.07	6.30	6.59	6.68	6.53	6.31	5.57	4.89	3.88	2.95	2.00	1.38
3	2	1.01	0.80	0.70	0.74	1.06	2.02	3.06	3.99	4.05	4.45	4.71	4.90	4.96	5.15	5.39	5.84	6.05	5.98	4.84	3.70	2.97	2.57	2.12	1.63
3	3	1.22	1.04	0.94	0.97	1.32	2.33	3.53	4.54	4.60	4.80	4.87	4.96	5.16	5.37	5.70	6.20	6.46	6.34	5.05	3.86	3.20	2.68	2.16	1.68
3	4	1.29	1.09	1.00	0.99	1.36	2.24	3.31	4.27	4.43	4.69	4.79	4.94	5.19	5.47	5.94	6.32	6.57	6.33	5.05	3.94	3.22	2.74	2.13	1.70
3	5	1.31	1.07	1.02	1.07	1.43	2.38	3.58	4.64	4.93	5.32	5.48	5.68	5.80	6.07	6.49	6.96	7.32	7.25	5.94	4.69	3.73	3.17	2.55	1.95
3	6	1.53	1.25	1.12	1.12	1.52	2.48	3.61	4.68	5.06	5.72	6.11	6.50	6.81	7.27	7.99	8.59	9.01	9.05	7.96	6.33	4.92	4.05	3.06	2.27
3	7	1.60	1.23	1.00	0.94	1.06	1.51	2.12	3.05	4.21	5.26	6.14	6.45	6.25	6.07	6.06	6.12	6.14	5.83	5.19	4.32	3.62	3.03	2.47	1.81
4	1	1.26	1.01	0.68	0.61	0.59	0.74	1.11	1.69	2.60	3.82	5.04	6.27	6.68	6.88	7.22	7.75	8.15	8.24	7.52	6.29	4.94	3.76	2.53	1.70
4	2	1.22	0.95	0.80	0.83	1.21	2.26	3.44	4.52	4.61	5.06	5.43	5.45	5.77	5.81	5.96	6.19	6.19	5.95	4.72	3.90	3.06	2.67	2.16	1.76
4	3	1.32	1.15	1.06	1.14	1.46	2.41	3.56	4.58	4.70	4.93	4.97	4.06	3.73	3.85	4.16	4.65	5.33	5.74	5.51	4.79	4.15	3.57	3.05	3.02
4	4	2.79	2.83	2.87	3.22	3.40	3.64	3.74	4.23	4.07	4.12	4.03	3.98	4.00	4.16	4.49	5.00	5.74	5.98	5.78	5.02	4.15	3.70	3.27	2.91
4	5	3.10	3.15	3.29	3.57	3.75	3.83	4.02	4.20	4.18	4.31	4.06	4.94	5.89	6.39	6.89	7.46	7.74	7.38	6.12	5.02	4.17	3.52	2.77	2.02
4	6	1.51	1.28	1.13	1.19	1.53	2.35	3.52	4.67	5.09	5.83	6.30	6.74	7.00	7.65	8.11	8.70	8.92	8.81	7.60	6.24	4.95	4.01	3.20	2.33
4	7	1.64	1.26	1.00	0.91	1.07	1.54	2.16	3.12	4.38	5.44	6.28	6.40	6.12	5.99	5.97	5.98	5.95	5.66	5.08	4.31	3.75	3.15	2.53	1.91

Table 23 continued

M	D	H0	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10	H11	H12	H13	H14	H15	H16	H17	H18	H19	H20	H21	H22	H23
5	1	1.22	0.83	0.61	0.51	0.54	0.73	1.24	1.88	2.96	4.25	5.51	6.41	6.73	6.94	7.18	7.44	7.75	7.74	6.90	6.06	4.82	3.60	2.59	1.82
5	2	1.26	0.97	0.78	0.78	1.04	1.85	2.86	3.91	4.30	4.84	5.48	5.30	5.50	5.74	5.84	5.52	5.79	5.81	4.97	4.21	3.99	3.88	3.60	2.85
5	3	2.66	2.74	2.92	2.50	2.73	3.44	4.30	5.11	4.83	4.68	4.47	4.48	4.32	4.45	4.74	5.15	5.62	5.74	4.82	3.94	3.79	3.81	3.47	2.94
5	4	2.97	3.03	3.08	2.69	2.91	3.46	4.61	5.16	4.83	4.94	4.87	4.94	4.58	4.78	4.94	5.79	6.02	5.87	5.48	4.82	4.15	3.65	3.05	2.50
5	5	1.96	1.82	1.69	1.69	2.04	2.95	4.15	5.09	5.17	5.49	5.59	5.52	5.70	5.97	6.43	7.08	7.39	7.24	6.46	5.54	4.45	3.80	3.02	2.30
5	6	1.77	1.57	1.40	1.48	1.86	2.79	3.81	4.83	5.16	5.81	6.30	6.67	7.42	7.98	8.47	8.91	9.27	9.15	8.10	6.69	5.33	4.36	3.38	2.52
5	7	1.72	1.26	1.02	0.97	1.09	1.56	2.27	3.35	4.71	6.03	6.93	6.98	6.74	6.59	6.41	6.28	6.09	5.71	5.03	4.41	3.87	3.26	2.57	1.88
6	1	1.47	0.99	0.74	0.62	0.61	0.81	1.25	1.99	3.16	4.75	6.39	7.37	7.83	8.04	8.12	8.30	8.28	8.12	7.38	6.45	5.28	4.07	2.83	1.96
6	2	1.36	1.03	0.88	0.93	1.27	2.47	3.87	4.95	5.13	5.78	6.39	6.19	6.19	6.29	6.38	6.74	6.88	6.63	5.58	4.49	3.73	3.29	2.59	2.09
6	3	1.61	1.48	1.28	1.39	1.66	2.74	4.11	5.01	5.14	5.07	5.25	5.03	4.90	5.11	5.55	6.32	6.50	6.51	5.69	4.66	3.99	3.64	3.19	2.80
6	4	2.35	2.29	2.14	2.12	2.25	2.91	4.09	4.83	4.80	5.10	5.38	5.35	5.37	5.62	5.92	6.75	6.92	6.89	5.94	5.01	4.19	3.89	3.45	2.88
6	5	2.46	2.31	2.12	1.99	2.20	3.16	4.16	4.88	5.25	5.93	6.40	6.32	6.80	7.03	7.40	7.93	8.08	7.74	6.48	5.23	4.32	3.75	3.12	2.42
6	6	1.98	1.54	1.40	1.45	1.79	2.78	4.05	5.19	5.68	6.52	7.29	7.70	8.02	8.65	9.23	9.53	9.66	9.38	8.09	6.56	5.40	4.50	3.56	2.66
6	7	1.91	1.39	1.10	1.02	1.15	1.69	2.46	3.56	4.99	6.48	7.58	7.55	7.35	7.13	6.97	6.70	6.61	6.10	5.35	4.66	4.04	3.50	2.94	2.24
7	1	1.54	1.07	0.77	0.64	0.64	0.83	1.34	2.11	3.31	4.99	6.88	8.09	8.57	8.93	9.24	9.47	9.44	9.06	8.43	7.14	5.57	4.30	3.09	2.16
7	2	1.52	1.11	0.97	0.98	1.38	2.53	3.85	4.87	5.18	5.89	6.46	6.42	6.05	6.14	6.34	6.54	6.77	6.27	5.06	4.20	3.59	3.31	3.08	2.86
7	3	2.41	2.34	2.25	2.44	2.83	3.48	4.40	5.15	5.28	5.03	5.25	4.66	3.99	4.06	4.24	4.59	5.08	5.28	5.14	4.78	4.40	4.39	4.11	4.12
7	4	4.08	4.02	3.96	4.33	4.45	4.62	4.97	5.00	4.73	4.87	4.80	4.51	4.26	4.29	4.67	5.12	5.45	6.06	5.74	5.39	4.95	4.76	4.50	4.18
7	5	4.48	4.39	4.26	4.30	4.29	4.77	4.84	4.92	4.66	5.21	5.14	5.28	6.09	6.22	6.99	7.75	8.19	8.35	7.36	6.11	5.19	4.49	3.70	3.02
7	6	2.37	2.11	2.06	2.16	2.39	2.94	3.75	4.58	5.18	6.47	7.28	7.86	8.08	8.38	8.65	8.65	8.70	8.26	7.09	5.86	4.81	3.83	3.18	2.56
7	7	1.75	1.21	0.94	0.85	1.03	1.49	2.17	3.21	4.63	6.31	7.55	7.63	7.32	7.08	7.00	6.90	6.70	6.19	5.39	4.81	4.16	3.54	2.93	2.24
8	1	1.27	1.08	0.71	0.57	0.64	0.75	1.40	1.98	3.12	5.38	6.37	7.51	7.93	7.78	8.15	8.59	8.30	8.38	7.06	6.28	5.11	3.39	2.75	1.88
8	2	1.15	1.03	0.81	0.99	1.40	2.53	4.45	5.11	5.25	6.03	6.19	6.30	6.42	6.44	6.80	7.30	7.35	7.11	5.08	4.38	3.50	2.69	2.41	1.74
8	3	1.21	1.19	1.01	1.19	1.58	2.72	4.58	5.26	5.31	5.71	5.84	5.45	5.67	5.04	5.85	6.84	6.35	6.73	5.05	4.67	3.94	2.96	3.07	2.30
8	4	1.62	2.14	1.88	1.75	2.83	3.32	4.74	4.94	5.12	5.70	5.22	5.51	5.95	5.32	6.21	7.14	6.67	7.27	5.50	5.22	4.18	3.23	3.12	2.46
8	5	1.74	2.38	1.98	1.82	3.04	3.34	4.82	5.03	5.27	5.80	5.35	6.01	6.83	6.92	7.48	8.27	8.08	7.98	5.90	5.10	4.37	3.26	2.90	2.09
8	6	1.48	1.38	1.21	1.36	1.72	2.77	4.55	5.24	5.72	6.89	7.19	7.73	8.37	8.40	9.14	10.0	9.73	10.1	8.13	6.81	5.64	4.19	3.60	2.60
8	7	1.64	1.42	1.08	1.01	1.19	1.59	2.69	3.54	5.08	7.22	7.78	7.99	7.43	7.12	7.11	6.98	6.75	6.25	5.04	4.65	3.97	3.04	2.77	2.07

Table 23 continued

M	D	H0	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10	H11	H12	H13	H14	H15	H16	H17	H18	H19	H20	H21	H22	H23
9	1	1.13	0.93	0.60	0.51	0.60	0.72	1.32	1.86	2.82	4.84	5.85	6.93	7.20	7.12	7.43	7.93	7.78	7.82	6.67	5.92	4.64	2.91	2.34	1.52
9	2	0.98	0.90	0.71	0.84	1.17	2.12	3.68	4.31	4.49	5.15	5.42	5.40	5.40	4.63	5.37	6.29	5.44	6.13	5.12	4.80	4.05	3.06	3.33	2.54
9	3	1.96	2.73	2.21	1.99	3.25	3.35	4.38	4.58	4.55	4.69	4.09	4.32	4.57	3.96	4.60	5.56	4.90	5.62	4.62	4.38	3.95	3.05	3.31	2.72
9	4	2.34	3.48	2.88	2.72	3.90	3.77	4.46	4.58	4.43	4.53	3.86	4.29	5.16	4.92	5.51	6.48	6.06	6.18	4.74	4.09	3.50	2.85	2.87	2.31
9	5	1.65	2.06	1.84	1.78	2.59	3.21	4.51	5.04	5.03	5.36	5.17	5.29	6.13	6.12	6.92	7.71	7.64	7.40	5.42	4.74	3.89	2.89	2.60	1.82
9	6	1.30	1.26	1.07	1.28	1.67	2.71	4.31	4.93	5.15	5.90	6.18	6.63	7.48	7.65	8.48	9.47	9.18	9.27	7.39	6.16	4.81	3.55	3.15	2.23
9	7	1.34	1.18	0.94	0.97	1.18	1.61	2.65	3.50	4.75	6.20	6.67	6.86	6.53	6.38	6.40	6.32	6.17	5.77	4.84	4.45	3.60	2.81	2.48	1.75
10	1	1.26	0.91	0.64	0.57	0.58	0.77	1.13	1.74	2.80	4.30	5.83	6.96	7.46	7.68	7.96	8.27	8.46	8.50	7.63	6.23	4.75	3.50	2.38	1.72
10	2	1.23	0.95	0.85	0.88	1.27	2.41	3.71	4.64	4.82	5.34	5.64	5.83	5.93	6.15	6.37	6.68	6.98	6.70	5.20	4.01	3.29	2.78	2.27	1.72
10	3	1.31	1.10	1.07	1.11	1.50	2.57	3.78	4.80	4.89	5.21	5.41	5.38	5.58	5.94	6.28	6.80	7.10	6.75	5.41	4.13	3.44	2.90	2.39	1.78
10	4	1.39	1.18	1.07	1.18	1.57	2.65	3.94	4.90	5.03	5.46	5.68	5.66	5.74	6.08	6.50	7.04	7.28	6.88	5.49	4.31	3.49	3.04	2.46	1.90
10	5	1.42	1.21	1.14	1.20	1.62	2.73	3.97	4.95	5.20	5.58	5.77	5.93	6.14	6.54	6.98	7.59	7.85	7.42	6.23	4.93	3.91	3.32	2.75	2.04
10	6	1.57	1.26	1.16	1.25	1.65	2.68	3.79	4.79	5.11	5.78	6.44	6.78	7.28	7.89	8.43	9.07	9.45	9.20	7.94	6.17	4.80	3.96	3.18	2.33
10	7	1.57	1.20	0.99	0.97	1.16	1.66	2.20	3.15	4.41	5.79	6.70	7.06	6.87	6.61	6.55	6.52	6.31	5.92	5.26	4.43	3.95	3.35	2.59	1.91
11	1	1.20	0.95	0.67	0.56	0.61	0.78	1.08	1.56	2.44	3.54	4.87	5.92	6.64	6.94	7.10	7.52	7.69	7.37	6.35	5.33	4.07	3.01	2.11	1.52
11	2	1.09	0.90	0.80	0.82	1.17	2.14	3.42	4.44	4.67	4.83	5.12	5.15	5.30	5.45	5.71	6.02	6.41	6.30	5.20	3.93	3.07	2.61	2.16	1.68
11	3	1.28	1.10	1.02	1.07	1.44	2.37	3.63	4.64	4.99	5.10	5.19	5.18	5.42	5.73	6.11	6.56	6.93	6.76	5.56	4.28	3.43	2.97	2.43	1.92
11	4	1.48	1.20	1.09	1.18	1.53	2.45	3.79	4.86	5.17	5.47	5.80	6.00	6.24	6.57	7.01	7.54	7.87	7.71	6.51	5.07	4.07	3.35	2.62	2.02
11	5	1.53	1.22	1.10	1.13	1.42	2.15	3.16	4.15	4.65	5.44	5.95	6.36	6.18	5.93	5.87	6.22	6.76	6.51	5.44	4.48	3.69	3.09	2.45	1.84
11	6	1.37	1.09	1.00	1.01	1.33	2.14	3.22	4.12	4.61	5.21	5.67	6.16	6.65	7.13	7.69	8.15	8.41	8.35	7.26	5.69	4.49	3.60	2.86	2.26
11	7	1.40	1.06	0.87	0.87	1.07	1.54	2.01	2.79	3.93	5.13	6.22	6.68	6.74	6.60	6.51	6.47	6.45	6.12	5.37	4.40	3.70	3.05	2.38	1.74
12	1	1.24	0.90	0.69	0.61	0.64	0.81	1.18	1.59	2.42	3.72	5.15	6.15	6.59	6.71	6.92	7.02	6.98	6.83	6.10	4.92	3.93	3.04	2.16	1.54
12	2	1.17	0.94	0.82	0.85	1.18	2.10	3.37	4.24	4.53	4.93	5.32	5.63	5.80	6.04	6.20	6.51	6.76	6.44	5.28	4.04	3.28	2.85	2.34	1.82
12	3	1.38	1.20	1.09	1.10	1.41	2.30	3.51	4.40	4.67	4.99	5.29	5.72	5.89	6.08	6.36	6.77	7.07	6.71	5.63	4.39	3.51	3.02	2.50	1.89
12	4	1.43	1.17	1.06	1.10	1.35	2.10	3.10	3.96	4.16	4.64	5.12	5.51	5.71	6.09	6.39	6.56	6.62	6.07	5.02	3.87	3.06	2.60	2.10	1.63
12	5	1.32	1.04	0.95	0.95	1.20	1.96	2.94	3.68	4.09	4.44	4.97	5.30	5.47	5.68	5.87	6.23	6.43	6.16	5.22	4.18	3.44	3.00	2.35	1.82
12	6	1.33	1.10	1.03	1.04	1.31	2.15	3.18	3.99	4.46	5.18	5.90	6.44	6.77	7.13	7.58	7.91	8.14	7.86	6.83	5.30	4.29	3.57	2.86	2.15
12	7	1.49	1.15	0.96	0.91	1.05	1.49	1.98	2.64	3.65	5.04	6.28	7.01	6.94	6.76	6.65	6.66	6.49	6.12	5.23	4.27	3.58	3.12	2.48	1.75

APPENDIX B. SAS/ETS® CODE

Multiple Linear Regression for Travel Speed

```
* Non-congested | Cars;
proc glm data=rural_noncongested;
class State(ref='Indiana') year(ref='2014') season(ref='fall')
DayofWeek(ref='3') hour(ref='23') SpeedPolicy(ref='7065');
model speed_mean_cars = SpeedPolicy year season Friday Saturday Sunday hour
daylight SmallTown DistanceCity AADTperLane TruckProp iri UnprotectedMedian
NarrowShoulder Lanes3more RampFreq light_rain moderate_rain heavy_rain
light_snow moderate_snow heavy_snow snowaccum / solution;
run; quit;

* Non-congested | Trucks;
proc glm data=rural_noncongested;
class State(ref='Indiana') year(ref='2014') season(ref='fall')
DayofWeek(ref='3') hour(ref='23') SpeedPolicy(ref='7065');
model speed_mean_trucks = SpeedPolicy year season Friday Saturday Sunday hour
daylight SmallTown DistanceCity AADTperLane TruckProp iri UnprotectedMedian
Lanes3more RampFreq light_rain moderate_rain heavy_rain light_snow
moderate_snow heavy_snow snowaccum / solution;
run; quit;

* Congested | Cars;
proc glm data=rural_congested;
class State(ref='Indiana') year(ref='2014') season(ref='fall')
DayofWeek(ref='3') hour(ref='23') SpeedPolicy(ref='7065');
model speed_mean_cars = year hour daylight SmallTown DistanceCity AADTperLane
TruckProp iri UnprotectedMedian Lanes3more RampFreq light_rain moderate_rain
heavy_rain light_snow snowaccum / solution;
run; quit;

* Congested | Trucks;
proc glm data=rural_congested;
class State(ref='Indiana') year(ref='2014') season(ref='fall')
DayofWeek(ref='3') hour(ref='23') SpeedPolicy(ref='7065');
model speed_mean_trucks = Saturday Sunday hour DistanceCity AADTperLane
TruckProp iri UnprotectedMedian NarrowShoulder Lanes3more RampFreq light_rain
heavy_rain light_snow snowaccum / solution;
run; quit;
```

Fixed-Parameters Logistic Regression for Short-Term Safety

```
* Probability of crash under non-congested conditions;
proc mdc data=probability_noncongested_1 type=clogit;
model decision = choice2 Slim6565 Slim7070 speed_mean_all speed_range_all
downstream_all year015 year016 spring summer winter Friday Saturday Sunday
hour_4 hour_5 hour_6 hour_7 hour_8 hour_9 hour_10 hour_11 hour_12 hour_13
hour_14 hour_15 hour_16 hour_17 hour_18 hour_19 hour_20 hour_21 hour_22
daylight SmallTown DistanceCity AADTperLane TruckProp iri NarrowShoulder
Lanes3more RampFreq light_rain light_snow moderate_snow heavy_snow
/ nchoice=2;
id id;
run;

* Probability of injury or death given crash under non-congested conditions;
proc mdc data=severity_noncongested_1 type=clogit;
model decision = Slim6565 speed_mean_all speed_range_all downstream_all
SmallTown Lanes3more
/ nchoice=2;
id id;
run;

* Probability of crash under intermediate conditions;
proc mdc data=probability_intermediate_1 type=clogit;
model decision = choice2 Slim6565 Slim7070 speed_mean_all speed_range_all
downstream_all year_2015 year_2016 Saturday Sunday hour_1 hour_2 hour_3
hour_4 hour_6 hour_7 hour_8 hour_9 hour_10 hour_11 hour_12 hour_13 hour_14
hour_15 hour_16 hour_17 hour_18 hour_19 hour_20 hour_21 hour_22_2
SmallTown AADTperLane TruckProp iri NarrowShoulder Lanes3more RampFreq
light_snow moderate_snow snowaccum
/ nchoice=2;
id id;
run;

* Probability of injury or death given crash under intermediate conditions;
proc mdc data=severity_intermediate_1 type=clogit;
model decision = choice2 Slim6565 Slim7070 speed_mean_all speed_range_all
downstream_all moderate_rain moderate_snow heavy_snow snowaccum
/ nchoice=2;
id id;
run;
```

Random-parameters Logistic Regression for Short-Term Safety

```
* Probability of crash under non-congested conditions;
proc mdc data=probability_noncongested_1 type=mxl;
model decision = choice2 Slim6565 Slim7070 speed_mean_all speed_range_all
downstream_all year015 year016 spring summer winter Friday Saturday Sunday
hour_4 hour_5 hour_6 hour_7 hour_8 hour_9 hour_10 hour_11 hour_12 hour_13
hour_14 hour_15 hour_16 hour_17 hour_18 hour_19 hour_20 hour_21 hour_22
daylight SmallTown DistanceCity AADTperLane TruckProp iri NarrowShoulder
Lanes3more RampFreq light_rain light_snow moderate_snow heavy_snow
/ nchoice=2 mixed=(normalparam = RampFreq);
id id;
run;

* Probability of crash under intermediate conditions;
proc mdc data=probability_intermediate_1 type=mxl;
model decision = choice2 Slim6565 Slim7070 speed_mean_all speed_range_all
downstream_all year_2015 year_2016 Saturday Sunday hour_1 hour_2 hour_3
hour_4 hour_6 hour_7 hour_8 hour_9 hour_10 hour_11 hour_12 hour_13 hour_14
hour_15 hour_16 hour_17 hour_18 hour_19 hour_20 hour_21 hour_22_2
SmallTown AADTperLane TruckProp iri NarrowShoulder Lanes3more RampFreq
light_snow moderate_snow snowaccum
/ nchoice=2 mixed=(normalparam = AADTperLane);
id id;
run;

* Probability of injury or death given crash under intermediate conditions;
proc mdc data=severity_intermediate_1 type=mxl;
model decision = choice2 Slim6565 Slim7070 speed_mean_all speed_range_all
downstream_all moderate_rain moderate_snow heavy_snow snowaccum
/ nchoice=2 mixed=(normalparam = speed_range_all;
id id;
run;
```

APPENDIX C. CONGESTION INDEX THRESHOLDS ANALYSIS

Table 24. Multiple linear regression model for average hourly travel speed under non-congested traffic conditions.

Effect	Estimate	Std. Error	t Value	Pr. > |t|
Intercept	60.9325	0.0722	843.61	<.0001
Roadway Features				
Traffic volume (1,000 veh/h)	1.3313	0.0220	60.59	<.0001
Proportion of trucks	6.0383	0.2336	25.85	<.0001
Unprotected median	0.8035	0.0340	23.66	<.0001
Spatial attributes				
TMC 107N05613	-0.3585	0.0225	-15.93	<.0001
TMC 107P05344	-1.0554	0.0255	-41.37	<.0001
TMC 107P05708	0.1509	0.0322	4.68	<.0001
TMC 107P05750	1.0745	0.0191	56.38	<.0001
Weather conditions				
Rain	-0.0692	0.0112	-6.16	<.0001
Snowfall	-0.6718	0.0341	-19.71	<.0001
Snow accumulation	-0.2833	0.0243	-11.65	<.0001
Temporal indicators				
Year 2014	-0.5654	0.0136	-41.51	<.0001
Winter	-0.1893	0.0154	-12.33	<.0001
Spring	-0.3927	0.0132	-29.79	<.0001
Friday	0.2984	0.0157	19.06	<.0001
Saturday	0.3440	0.0156	22.12	<.0001
Sunday	0.3408	0.0158	21.53	<.0001
Daylight	0.2055	0.0194	10.61	<.0001
05:00 - 05:59	-0.1204	0.0278	-4.33	<.0001
06:00 - 06:59	-0.1418	0.0274	-5.18	<.0001
07:00 - 07:59	-0.2367	0.0267	-8.87	<.0001
10:00 - 10:59	-0.1289	0.0269	-4.78	<.0001
11:00 - 11:59	-0.1058	0.0269	-3.93	<.0001
18:00 - 18:59	0.1377	0.0267	5.15	<.0001
19:00 - 19:59	0.3163	0.0265	11.92	<.0001
20:00 - 20:59	0.2376	0.0267	8.89	<.0001
21:00 - 21:59	0.2135	0.0279	7.65	<.0001
22:00 - 22:59	0.2346	0.0279	8.41	<.0001
23:00 - 23:59	0.2891	0.0278	10.41	<.0001

Table 25. Multiple linear regression model for average hourly travel speed under intermediate traffic conditions.

Effect	Estimate	Std. Error	t Value	Pr. > |t|
Intercept	59.1902	0.3393	174.47	<.0001
Roadway Features				
Traffic volume (1,000 veh/h)	-3.9195	0.3185	-12.31	<.0001
Spatial attributes				
Distance to big city (mi)	0.1188	0.0254	4.67	<.0001
Weather conditions				
Snowfall	-1.6575	0.3746	-4.43	<.0001
Snow accumulation	-4.9552	0.4131	-11.99	<.0001
Temporal indicators				
Year 2014	-1.7091	0.2806	-6.09	<.0001
Winter	-1.6906	0.3606	-4.69	<.0001
Spring	-1.4171	0.4041	-3.51	0.0005
Friday	1.4759	0.4220	3.50	0.0005

Table 26. Multiple linear regression model for average hourly travel speed under congested traffic conditions.

Effect	Estimate	Std. Error	t Value	Pr. > |t|
Intercept	21.3961	0.8114	26.37	<.0001
Weather conditions				
Snow accumulation	6.7859	1.7887	3.79	0.0002
Temporal indicators				
Sunday	-3.1427	1.3574	-2.32	0.0223
16:00 - 16:59	-5.2459	2.1395	-2.45	0.0157

VITA

Raul Andres Pineda Mendez was born in Bogota, Colombia in 1993. He holds a Bachelor of Science in Civil Engineering from the National University of Colombia (UNAL), Bogota D.C., Colombia; a Master of Science in Civil Engineering with an emphasis on Intelligent Transportation Systems from Purdue University; and a graduate certificate in Applied Statistics from Purdue University.

Raul has extensive research experience in traffic safety. His work has centered on safety management, roadway design, traffic control devices, transportation in developing countries, and short-term safety analysis with big data. He is a co-author of national and international journal articles and conference proceedings. He is a member of several professional societies and an active peer reviewer in top journals and has received honors and awards for his work.

During his stay at Purdue, he was elected President of the Institute of Transportation Engineers student chapter. He also served in the Student Academic Council (CEGSAC) and the Colombian Student Association at Purdue (CSAP) board. Raul developed an interest in statistics, and most of his graduate coursework was in this area. He also volunteered in the Purdue Statistical Consulting Service, where he advised researchers from various disciplines.

Raul has a strong interest in teaching, which he cultivated at Purdue by working as a graduate teaching assistant in advanced transportation classes, volunteering as a faculty apprentice of multidisciplinary statistics, taking graduate-level courses in Purdue’s School of Engineering Education, and mentoring several undergraduate engineering students from Colombia.