ASSESSMENT OF OPERATIONAL AND SAFETY IMPACTS OF SPEED LIMIT INCREASES IN MICHIGAN

By

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ABSTRACT

The state of Michigan increased the passenger car speed limits on 614 miles of limited-access roadways from 70 mph to 75 mph following enactment of Michigan Public Acts 445 and 447 of 2016. This same legislation also increased the speed limits on 943 miles of trunk line non-freeways from 55 mph to 65 mph. Speed limits for trucks were also increased to 65 mph on all state trunk lines where passenger car speed limits were 65 mph or higher. This study investigates the impacts of these speed limit increases on travel speeds and traffic safety on both freeways and non-freeways.

To assess the impacts of these increases on vehicle speeds, data were compared between those sites where the speed limits were increased and similar control sites that retained the lower speed limits. Speed data were collected from various sources and compared. The 5-mph increase in speed limits on the freeway network was associated with an increase of 1.1 mph to 2.8 mph in free-flow speeds. Aggregate speeds increased on average by 1.4 mph to 3.2 mph. The standard deviation in speeds was also shown to increase by significant amount. Turning to the non-freeway network, spot-speed data were collected from free-flow vehicles using LIDAR and high-definition video cameras. The 10-mph speed limit increases corresponded with increases of 2.8 to 4.8 mph among various speed metrics for passenger cars and heavy vehicles. Across both types of roadways, speeds at the control sites remained relatively consistent. For the speed limit increase locations, the magnitude of the increases in speeds was found to be the highest among the highest-speed drivers, while the lowest speed drivers tended to increase their speeds by lesser amounts. The magnitude of the changes in speeds also varied based on roadway characteristics, including traffic volume, presence of horizontal curves, and roadway cross-sectional characteristics.

Safety impacts were examined using empirical Bayes (EB) evaluations. Safety performance functions (i.e., crash prediction models) were also developed for total crashes, for non-animal related crashes, and for various injury severity levels, among other subsets. On the limited access freeway network, total crashes increased by 9 percent. For fatal and incapacitating injuries, the increases ranged from 25 to 33 percent. Increases were also experienced among non-incapacitating injury and property-damage-only crashes. Additional regression analysis to relate crash frequency with speed metrics on the freeway network showed consistent increases in crashes across all severity levels after controlling for mean speed, variability in speeds and other site-specific variables. On the non-freeway system, total crashes and serious injury crashes increased by 11 percent and 1.7 to 4.7 percent, respectively.

Ultimately, the effects of speed limit increases were largely consistent with results from the extant research literature. The results have also shown that speed selection varies significantly both within and across locations. Changes in the characteristics of the roadway driving environment also affect speeds differently and, thus, careful consideration should be given in considering any subsequent speed limit increases. This is particularly true since the sites where speed limits were increased tended to be the safest when considering historical crash data. As a result, speed limit increases on other segments may be expected to experience larger increases in crashes as compared to these lower risk sites. In addition to crash history, other factors, such as the variability in speeds, roadway context, and geometric characteristics should be considered in determining speed limits.

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1. INTRODUCTION

1.1 Background

Posted speed limits are a means of indicating the driver of the maximum permissible safe speed on the highway under ideal roadway, traffic and weather conditions (Forbes et al., 2012). The issue of setting the speed limits on highways has been under scrutiny for a long time. Setting the limits too low, may increase non-compliance rates and setting them too high may lead to inefficient operations and increased number of crashes (N. Garber & Gadiraju, 1991; Harkey & Mera, 1994). Speed limits also provide a basis for the enforcement of unreasonably high travel speeds. Speed limits are generally applicable for a particular class of highways with specific design, functional, jurisdictional, or location characteristics (Federal Highway Administration (FHWA), 2012). These limits are typically established in consideration of the design speed of the road, which influences various geometric design features such as minimum stopping sight distance, minimum horizontal curve radius, and maximum grade (American Association of State Highway and Transportation Officials (AASHTO), 2018). The American Association of State Highway and Transportation Officials (AASHTO) recommends using above-minimum criteria where practical (American Association of State Highway and Transportation Officials (AASHTO), 2018) and, ideally, the statutory speed limit should be set at or below the highway's prevailing design speed.

Three major legislative decisions have influenced the speed limit policies in the United States. The National Maximum Speed Limit (NMSL) in the USA was first established as a part of the Emergency Highway Energy Conservation Act of 1974 in response to the 1973 oil crisis. This created a universal speed limit of 55 miles per hour (mph) in the country. All states were required to adhere to this limit in order to receive federal funding for highway construction and repairs. A detailed study conducted by the National Research Council (NRC) in 1984 found that the universal speed limit of 55 mph saved nearly 3,000-5,000 lives in 1974 and about 2,000-4,000 each year after that (Transportation Research Board & National Academies of Sciences Engineering and Medicine, 1984). Thereafter in 1987, the NMSL law was relaxed allowing states to increase their speed limits to a maximum of 65 mph on rural interstate highways (*Surface Transportation and Uniform Relocation Assistance Act of 1987*, 1987). In 1995, the NMSL was fully repealed, which gave the states complete freedom to set their own speed limits. As a result, most of the states increased their speed limits from 55 (or 65) mph to 70 mph on interstate highways including Michigan (MI) (Savolainen et al., 2014).

The state of Michigan (MI) has long debated the proposal to increase the maximum speed limits on freeways and non-freeways. Michigan increased their posted speed limit to 70 mph on freeways as a result of the repeal of NMSL. For trucks, the speed limit was 55 mph and the minimum speed was 45 mph. In 2016, the MI Public Act of 445 and 447 were passed, which led to the increase in posted speed limits once again in 2017. The speed limit was increased from 70 mph to 75 mph on approximately 614 miles of freeways. This same legislation resulted in increases from 55 mph to 65 mph on about 943 miles of trunk line non-freeways. Speed limits for trucks were also increased to 65 mph on all state trunklines where passenger car speed limits were 65 mph or higher. This follows national trends as at least 18 states increased their regulatory speed limits on selected rural interstate highways to 75 mph or more as of 2018 (Warner et al., 2019a). Figure 1.1 shows the comparison between the speed limits on rural interstates in 2001 and 2018 across all US states (Warner et al., 2019b).

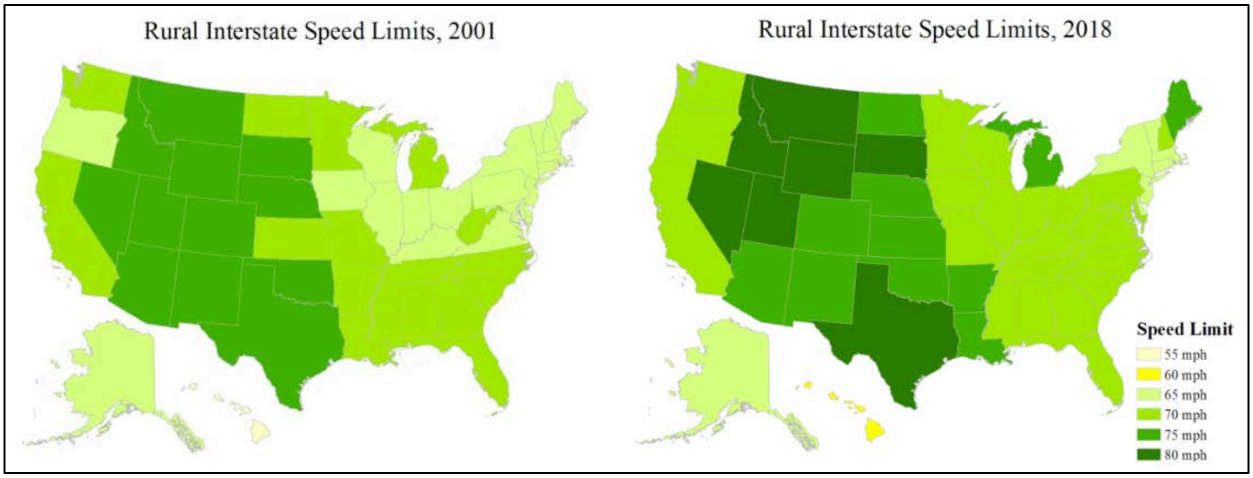

Figure 1.1 Speed Limits on Rural Interstate Highways in 2001 and 2018 (Warner et al., 2019b)

1.2 Problem Statement and Study Objectives

Various research studies have been conducted to assess the impact of changes in the speed limits on traffic operations and traffic safety. Literature has shown that the traffic operations, crashes, injuries and fatalities are affected by the mean speeds (and 85th percentile speeds) and variance in speeds. The recent increase in the speed limits in the state of MI has affected these speed characteristics which has resulted in operating speeds that are higher than the design speeds on some of these roadways. Figure 1.2 shows the annual rural interstate fatalities by maximum statutory speed limit (Davis et al., 2015).

The impacts of speed limits on traffic operations and safety have undergone extensive research, however, a strong consensus is yet to be achieved on the relationship between speed and safety. The speed limits in conjunction with other factors such as road, traffic and weather conditions, largely affect the driver speed selection on any typical roadway. A study showed that driver demographic factors such as driver age, gender, marital status, number of children, driver education level, household income, age when the driver was first licensed, and opinions about pavement quality, influence the choice of speed in the presence of speed limits (Anastasopoulos

& Mannering, 2016). Most of the studies in literature focuses on limited access facilities. Driver speed selection on non-limited access facilities is not only affected by the posted speed limits, but also by roadway and roadside characteristics, and traffic volume (Dixon et al., 1999; Figueroa-Medina & Tarko, 2004; Gates et al., 2015b; Russo et al., 2015; Savolainen et al., 2018a). Design speed, weather condition, pavement condition are some additional factors that affect driver speed selection on a typical highway (Savolainen et al., 2018a; Wali et al., 2018). Thus, research is needed to better understand the relationship between these characteristics and vehicular speeds, traffic crashes, injuries and fatalities.

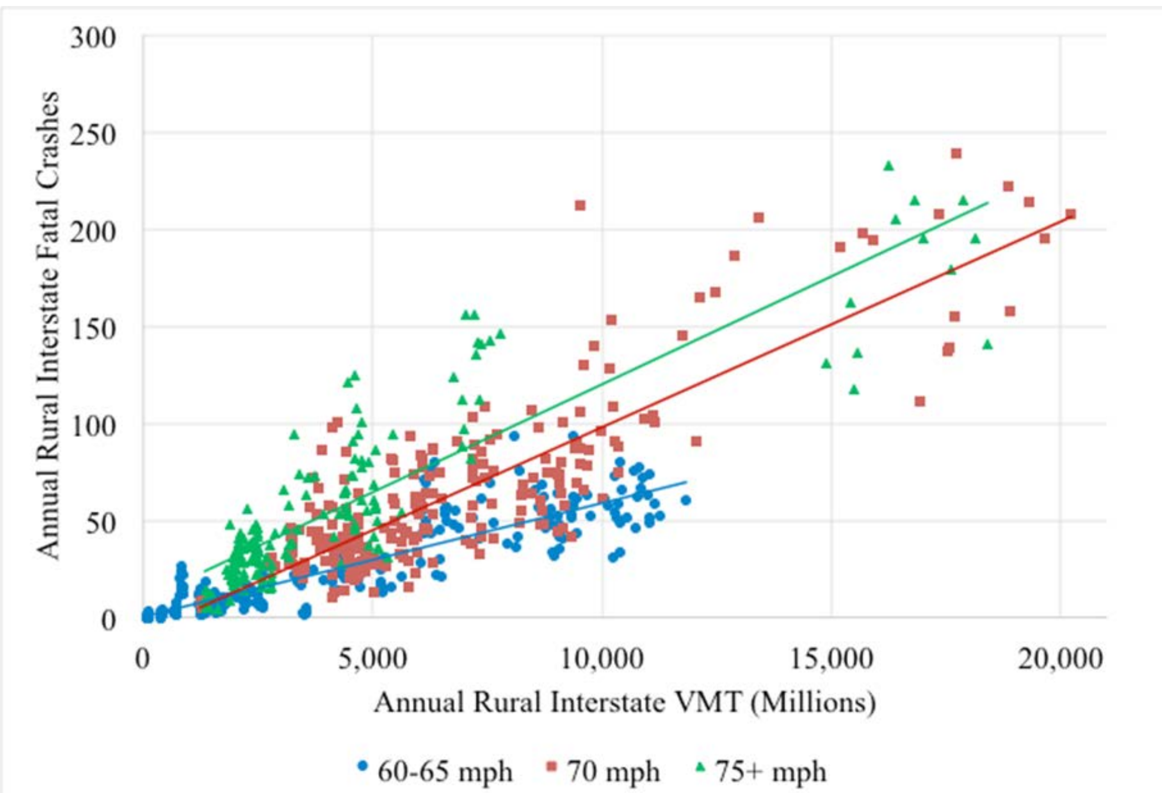

Figure 1.2 Annual Rural Interstate Fatalities by Maximum Statutory Speed Limit (A. Davis et al., 2015b)

The purpose of this research is to determine the potential impacts of the recent increases in the posted speed limits on both freeways and non-freeways. To this end, a careful and extensive analysis is required of a broad range of traffic safety, and operational performance measures, which include mean speeds, operating speeds, variability in speeds, traffic crashes and crash severity, etc. The following objectives have been established as a part of this dissertation:

1.3 Objective 1: Operational impacts of the 2017 speed limit increase that occurred along 600 miles of the freeway network.

As a part of this objective, the effect of 2017 speed limit increases on Michigan freeways was examined on traffic speed characteristics using speed data from three different sources. Free-flow speed data were collected from spot-speed studies using light detection and ranging (LIDAR) devices whereas aggregate-level traffic speed data were obtained from both permanent traffic recorder (PTR) stations, as well as from probe vehicle data. The impacts of the speed limit changes were evaluated using seemingly unrelated regression equations, which provide insights into how these increases affected the 15th, 50th, and 85th percentile speeds, as well as the standard deviation in speeds.

1.4 Objective 2: Assess the operational impacts of the 2017 speed limit increase that occurred along 900 miles of the non-freeway network.

This task aimed to investigate trends in free-flow travel speeds following 2017 legislation that increased the posted speed limit from 55 to 65 mph on 943 mi of rural highways in Michigan. Speed data were collected for over 46,000 drivers across 95 locations before and during each of the two successive years following the speed limit increases. Analyses were conducted using quantile regression separately for passenger cars and heavy vehicle.

1.5 Objective 3: Assess the safety impacts of the 2017 speed limit increase that occurred along 600 miles of the freeway network and 900 miles of the non-freeway network.

This task involved assessing the impacts of speed limit increases on Michigan freeways on traffic safety. Crash data along with roadway geometric data were collected for Michigan trunkline system for the period before speed limit increases went into effect (2014-2016), and two years after speed limits were increased (2018-2019). Safety analyses were conducted at various levels of sophistication. First, comparisons were made between the raw frequency and rate of crashes before and after the increases were introduced. Next, a series of simple before-after comparisons were made. This includes consideration of changes in traffic volumes, as well as contemporaneous trends at control sites. Lastly, empirical Bayes (EB) evaluations were conducted to account for the regression-to-the-mean effect, as well as changes in other factors, such as weather patterns and economic conditions.

1.6 Dissertation Structure

This research provides holistic investigation of the effect of speed limit increases on traffic speeds and safety. The rest of dissertation is divided into five chapters as described below:

Chapter 2 presents a comprehensive literature review on the effects of speed limit increases. Chapter 3, 4, and 5 explain the data collection, preparation, data summary, methodology, and results for each of the objectives presented above, respectively. Finally, Chapter 6 presents the conclusions, and limitations of the research.

Chapter 1 Introduction: The introduction provides background of speed limit policies in the United States. The changes in speed limit policies in the state of Michigan are also discussed which form the basis of the problem statement of this research. The chapter also provides study motivation and the objectives of this research.

Chapter 2 Literature Review: This chapter provides a comprehensive review of literature pertaining to the effects of historic changes in speed limit policies in the United States and around the globe on traffic operations and safety. Separate review is carried out for studies on freeways and non-freeways. Lastly, a brief summary of the extant literature is provided.

Chapter 3 Effect of Freeway Speed Limit Increase on Traffic Operations: This chapter demonstrates the operational impacts of speed limit increases on the freeway network in Michigan. The chapter discusses the data collection methods, followed by summary of data, and statistical methods used to analyse the data. Lastly, the results of the analysis are presented along with a discussion of results.

Chapter 4 Effect of Non-Freeway Speed Limit Increase on Traffic Operations: This chapter explains the data preparation, summary, methodology, and discussion of results related to the effects of speed limit increases on traffic operations on the rural two-lane roadway network in Michigan.

Chapter 5 Effect of Speed Limit Increase on Traffic Safety: This chapter explains the data collection, and methodology adopted to investigate the safety impacts of speed limit increases on traffic safety in Michigan. The chapter presents the results of the analysis separately for freeways and non-freeways. The results of additional analysis related to the relationship between speed and safety on the freeway network are also presented.

Chapter 6 Conclusions: This chapter presents the conclusions of the study in terms of how the speed limit increases in Michigan impacted traffic operations and safety on Michigan roadways. Lastly, limitations of the study and directions for future research are presented.

2. LITERATURE REVIEW

The following sections provide a comprehensive review of summary of studies and research that studied the effects of speed limits on actual speeds and safety. Most of the research efforts on the effect of speed limits in the United States was motivated by the passage of NMSL in 1974. The issue was then revisited in 1987 with the passage of Surface Transportation and Uniform Relocation Assistance Act (STRUAA) that relaxed the NMSL allowing states to increase speed limits to 65 mph on interstate highways in rural areas. The repeal of NMSL in 1995 provided another opportunity to researchers to observe the same highways under different speed limits and determine user response to these limits. This led to a series of additional studies which are discussed in this chapter. The primary purpose of this review is to critically assess the research carried out to date and summarize the findings. First, a general review of the relationship between speed and safety is provided. This is followed by the research carried out in the United States towards understanding the said relationship along limited access facilities and non-limited access facilities separately.

2.1 Relationship between Speed and Safety

Speed management has long been a concern of transportation agencies across the globe, dating back to research as early as the 1960's which showed that vehicles traveling excessively below or above the speed limit are overrepresented in crashes on rural highways and interstates (Cirillo, 1968; Solomon, 1964). A study conducted in Australia based on the interviews of drivers who provided self-reported information regarding their crash involvement during the preceding five-year period on two urban roadways with posted speed limit of 60 kilometers per hour (kph) (37 mph) and 100 kph (62 mph), showed that the drivers who were traveling at higher speeds tended to experience more crashes (Fildes et al., 1991). Two subsequent studies from the United

Kingdom (Maycock et al., 1999; Quimby et al., 1999) also used a similar self-reporting survey method and concluded that the crashes increase consistently with driver speed. Finch et al. (Finch et al., 1994) conducted a study in Switzerland which showed that decreasing speed limits to 120 kph (81 mph) from 130 kph (75 mph) reduces fatal crashes by 12 per cent. The study also showed similar trends between speed and safety as the other research around the world. Crash rates were found to consistently increase with speed when examining data from Denmark, Finland, Switzerland and the United States. A separate study carried out on several different roadway classes in the United Kingdom also showed similar relationship between speed and safety. As speed increased, the crashes also increased for all roadway types. Further, these increases in crashes were most pronounced in the more urbanized areas, where higher level of congestion were found (Taylor et al., 2000).

Aljanahi et al. (Aljanahi et al., 1999) studied the relationship between speed limits and speed and safety using two groups of sites, one in UK (Tyne and Wear county) and one in Bahrain. Keeping the speed distribution constant, the crash rate was found to decrease if the percentage of heavy vehicles increases, in both the groups (UK and Bahrain). In terms of speed distributions, statistically significant association between mean speed and crash crate was found for the Bahrain group. For the UK group, strong relationship between crash and speed variance was found. Pei et al. (Pei et al., 2012) evaluated the relationship between speed and crash risk with respect to distance and time exposure, using disaggregated crash and speed data collected from 112 road segments in Hong Kong. The study found no evidence that the standard deviation of speed is significantly associated with the likelihood of crash occurrence or crash severity. The correlation between speed and crash risk was found to be positive when distance exposure is considered, but negative when time exposure is used. However, in both the cases, speed was positively associated with the injury severity.

The research in the United States has also revealed similar trends in the relationship between speed and safety. The earliest work is that of Solomon (Solomon, 1964) and Cirillo (Cirillo, 1968), both of which showed that crash risk is high at very low and at very high speeds. However, the lowest crash rates were at about 6 mph and 12 mph above the average speeds in the two studies respectively. Figure 2.1 shows the crash involvement rate (per 100 million vehicle-miles traveled) with respect to travel speed and with respect to variation from the average speed of traffic under similar conditions (Solomon, 1964). The two figures suggest that the crash risk is greatest at very low as well as at very high speeds. Subsequent study conducted in 1970s conducted an analysis of crashes excluding crashes involving low speed maneuvers and demonstrated that crash risks were much less pronounced at low speeds in comparison to previous research (Research Triangle Institute, 1970). Subsequently, West and Dunn (West & Dunn, 1971) showed that removing turning vehicles substantially mitigates the apparent risk at lower speeds. Involvement rate per million vehicle-miles was found to be higher for the slow deviation vehicles than for the fast deviation vehicles. Crash involvement rate was found to be the same for high and low speed deviations after deletion of crashes involving turning vehicles. A study conducted at the road segment level by Garber and Gadiraju (N. Garber & Gadiraju, 1989) showed that roads with larger speed variance exhibited higher crash rates than roads with lower variance. The study found that the relationship between speed limit and design speed was a key determinant of safety trends. Both crash rates and speed variance were lowest when speed limits were 5-10 mph below the design speed of the road. Additional research has shown that crash fatality rates increase as the average speed and the variance in speeds increases (Forester et al., 1984; Fowles & Loeb, 1989; N. Garber & Ehrhart, 2000; Levy & Asch, 1989; Solomon, 1964; Zlatoper, 1991).

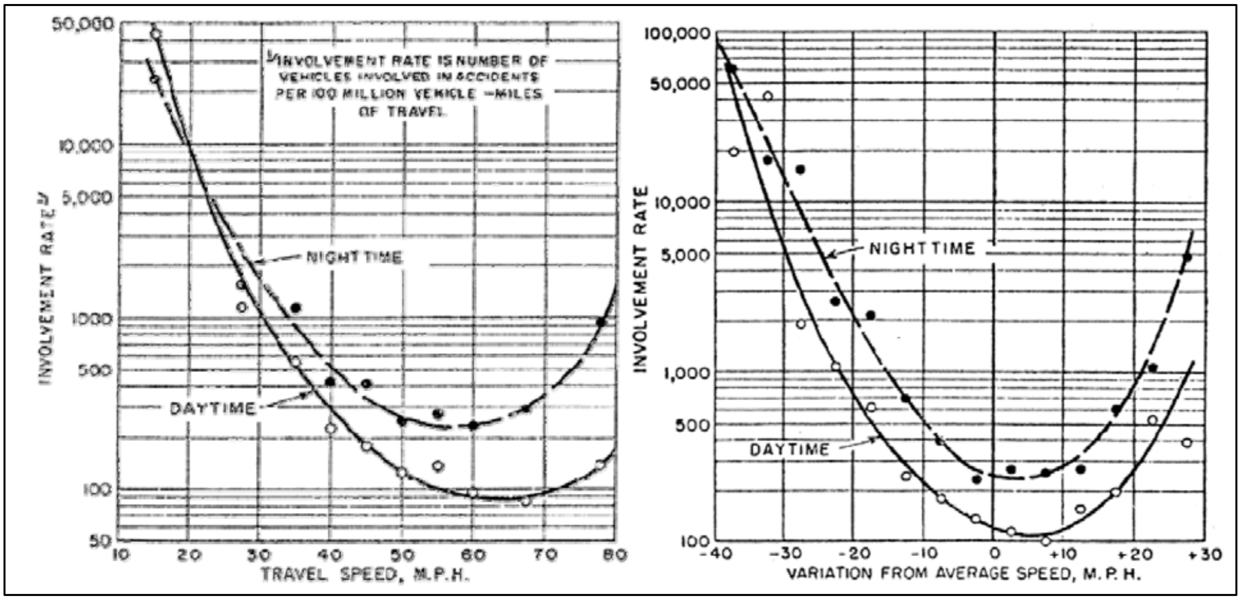

Figure 2.1 Crash Rates by Travel Speed and Variation from Average Speed (Solomon, 1964)

Nilsson (Nilsson, 2004) developed a ‘Power Model’ to demonstrate the relationship between the number of people injured in a crash and speed as well as number of people fatally injured in a crash and speed. The model takes the following general form as shown in equation (1). In this basic form, the exponent reflects the rate at which crashes change with respect to a relative change in speed.

$$Crashes_{after} = Crashes_{before} \cdot \left(\frac{Speed_{after}}{Speed_{before}}\right)^{exponent} \qquad (1)$$

Elvik (Elvik, 2005) in a meta-analysis study, showed that the speed is likely to be the single most important determinant of the number of traffic fatalities. As such, a 10% change in traffic mean speed is likely to have a greater impact on traffic fatalities than a 10% change in any other factor, such as traffic volume. A separate meta-analysis study which included data from 115 studies, which included 526 estimates of the relationship between changes in mean speed and the number of crashes or crash-involved injuries, showed crash risk to consistently increase as speed increases (Elvik, 2013). Empirical results utilizing the power model suggest that a one-percent increase in average speed increases the average frequencies of injury, severe injury, and fatal injury crashes by 2 percent, 3 percent, and 4 percent, respectively (International Transport Forum (ITF), n.d.). In subsequent research, an exponential function has also been shown to provide a better fit, as compared to the power model, to the relationship between speed and safety (Castillo-Manzano et al., 2019; Elvik et al., 2019). Figure 2.2 shows the relationship between speed and injury crashes using both the power model and the exponential model. It is clear from figure 4 that the exponential function is steeper at high speeds and flatter at low speeds than the power function. Analytical results from a separate study showed that a 5% increase in the average speed can lead to a 10% and 20% increase in the total amount of injury crashes and number of fatal crashes respectively (Transport Research Centre, 2006).

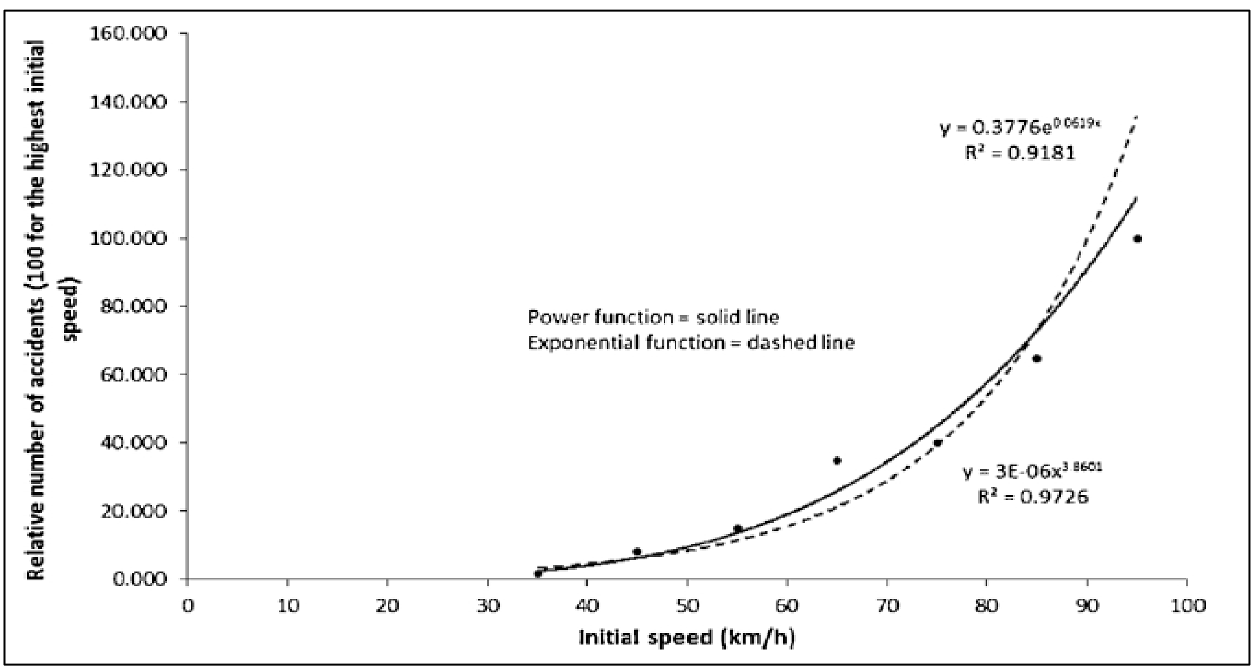

Figure 2.2 Relationship between Speed and Injury Crashes (Elvik et al., 2019)

2.2 Effect of Posted Speed Limits on Travel Speeds and Safety along Limited Access Facilities

In the United States, considerable research has been carried out that explores the relationship between posted speed limit and travel speeds and safety along the limited access roadway facilities. Much of this research began in 1974 due to the initiation of the NMSL. The initial reason for the change was to reduce the fuel consumption in response to the Mid-East Oil Embargo. However, the NMSL was extended, in part, due to reduction in traffic fatalities that occurred during this same time period. One issue with the introduction of the NMSL was that the observed driving speeds did not necessarily reflect the new lower speed limits. This was especially true on interstate highways where posted speeds were significantly lower than the design speeds of these highways. Subsequent changes in the speed limit policies were then introduced in 1987, and again in 1995 as stated before. Subsequent to the enactment of these laws, speed limits were predominantly increased on limited-access rural freeways, which are the types of roads with the highest speed limits and are also the safest when considering crash risks per distance traveled (National Highway Traffic Safety Administration, n.d.) given their higher design standards. The research literature shows that fatalities on rural interstates are consistently higher among those states with higher maximum statutory speed limits (Davis et al., 2015). The following sub-sections details the research that initiated as a result of the three major speed limit policy changes that occurred in the United States followed by discussion of more recent studies.

2.2.1 <u>Introduction of NMSL</u>

The introduction of NMSL in 1974, which mandated a national speed limit of 55 mph on interstate highways, led to nationwide research focusing on the effects of changes in posted speed limits on driving speeds and safety. Forester et al. (Forester et al., 1984) did an empirical analysis of speed limit on fatalities along with cost-benefit analysis of speed limit policy. It was found that nearly 7,466 fatalities per year were reduced due to reduced speed limits. However, the cost-benefit analysis concluded that maintaining the 55-mph limit has no benefits over the cost it incurs. The study suggested to impose a minimum speed limit rather than the maximum speed limit. Clotfelter et al. (Clotfelter & Hahn, 1978) also evaluated the desirability of the new speed limit using cost-benefit analysis and found similar results. He concluded that the benefits of the 55mph limit far exceeds the costs. The two most important benefits were fuel savings and increased safety.

Burritt (Burritt et al., 1976) established a causal relationship between the new speed limits and the crashes in the state of Arizona. The study found that the driver and vehicle characteristics had no effect on 1974 reduction in fatal crashes. The study attributed crash reduction to lower speeds and greater speed uniformity in the traffic stream. There was an almost 50% reduction in study area fatal crashes between 1973 and 1974. On interstate highways, fatal crash rate per 100 million vehicle miles dropped from 3.27 to 2.14. On other highways in the study area, it dropped from 5.74 to 3.64. This indicates fatal crash reduction in 1974 cannot be attributed to travel reduction only. Crashes reduced on all types of highways but 92% of the decline was on the high-speed roads. Considerable and significant changes in the driving speeds were also noticed. On Interstate highways, mean speed reduced from 110.6 km/h (69 mph) to 97.1 km/h (60 mph) and standard deviation (SD) from 13.82 km/h (8.6 mph) to 9.31 km/h (5.8 mph) from 1973 to 1974. On US highways, the mean speed reduced from 100.8 km/h (62.6 mph) to 91.5 km/h (57 mph) and SD from 12.99 km/h (8 mph) to 10.24 km/h (6.4 mph) from 1973 to 1974.

Dart (Dart Jr, 1977) utilized data from 3 states, North Carolina, Louisiana and Mississippi to study the role of enforcement to make speed limits effective using time series plots. It was found that the NMSL led to more uniform speeds (lower SD and higher pace group percentage). Average speeds were reduced in early 1974 by as much as 16 km/h (10 mph), but gradual increases have occurred ever since. The percentage of vehicles exceeding 105 km/h (65 mph) was less than 10, and speed variability was also significantly less. In North Carolina, all speed characteristics were reduced in 1975, with the average speeds on all classes of roads down about 3.2 km/h (2 mph). However, 1976 reports show increases in average speeds of up to 5 km/h (3 mph) over 1975 levels. In Mississippi, speeds initially decreased in the early 1974, but then increased somewhat but not at pre-crisis level. In Mississippi, death rate reduced from 7/mile in 1972 to 4.3/mile in 1975 as travel increased by 8%. Data from Louisiana showed large reductions in percentages of rural crashes for which excessive speed was cited as a contributing factor. Increased enforcement from 1974-1976 were responsible for maintaining uniform and safer speeds.

Tofany (Tofany, 1981) studied the effect of 55 mph universal speed limit on safety in all the 50 states. Of 50 states, 41 states showed average speed exceeding 55mph (FHWA data). Connecticut had the highest average speed (59.3mph) and Virginia had the lowest (50.6mph). The 85th percentile speeds ranged from 55.3-66.4 mph in all the states. The NMSL also led to reduced number of crashes. There were nearly 9,000 less fatalities in 1974 than in 1973, and 9,600 less fatalities in 1975 than in 1973. 40,000 lives were saved during 1973-1979, one-third to one-half of which can be attributed to reduced speeds. For every state except Washington, the mileage death rate decreased or remained same as the pre-energy crisis rate of 1973.

Deen and Godwin (Deen & Godwin, 1985) also studied the effects of reduced speed limits. They concluded that very high-speed driving patterns have reduced considerably with drivers exceeding 65 mph dropping down from 50% to 9%. The average speeds on interstates reduced from 65 mph in 1973 to 57 mph post NMSL. Safety also improved as a result of reduced speed limits. There was a 17% and 13% reduction in fatalities on primary and secondary highways respectively. On interstate highways, the reduction in fatalities was 32% while the fatality rates on local roads and streets showed no change (35mph or below speed limit).

Labrum (Labrum, 1976) determined statistically, whether 55 mph speed limit is the primary factor for traffic fatality reductions from 1974-1975. He found that the 55-mph limit and other factors existing in 1974 caused a significant reduction in fatalities.

Betty et al. (Chu & Nunn, 1976) estimated fatality trends in California under non-energy crisis conditions. It was found that 2,302 fatalities would have occurred during the first half of 1974 under normal conditions, whereas actual number was 1,726. 39% of this fatality reduction is attributed to reduced driving speeds due to lower limits. The remaining were attributed to reduced travel (29%) and permanent daylight-saving time (8%). Remaining 24% is due to other factors like reduced average occupancy, changes in day-night travel, changes in types of roads used, etc.

Kemper and Byington (Kemper & Byington, 1977) evaluated the effects of 55 mph limits on highway safety on a national level. It was found that the speed reduction prevented 4,700 fatalities and 81,000 injuries in 1974. Fatality rates reduced on all highway systems with major reduction on the interstates. Injury rates however, did not reduce much on all highway types except interstates.

Johnson et al. (Johnson et al., 1978) analyzed the effects of reduced limits on fatalities in Texas using time-series analysis. They concluded that the fatal crashes reduced more sharply on high speed roads (29%) than on the low speed roads (15%). Statistical analysis revealed that the reduced limit resulted in 19.8 less fatal crashes per month. The effects on driving behavior was also studied. There was nearly 7.4 mph reduction in average speeds on rural interstates whereas the average speed on all rural roads reduced by 8.3% or 5 mph accompanied by 28% reduction in speed variability. Minor changes were recorded on the urban roads. In another similar study conducted at the national level (Johnson et al., n.d.), the authors found that the mean and the 85th percentile speeds declined in 1974-1976 but started to increase in 1977. The average speeds dropped by 5% and 85th percentile speeds by 2% in 1974 from 1973 levels. Between 1976-1978, the average speed and 85th percentile speeds increased in 32 states and 27 states respectively. In terms of safety, total and interstate fatalities reduced in 1974-1975 but began to increase in 1976. Total fatalities, interstate fatality, interstate injury rate, fatality rate and interstate fatality rate showed substantial drop (>10%) in 1974 than 1973 levels. It was estimated that the 55-mph speed limit reduced fatalities by roughly 7500 annually in the early years of its implementation. The authors of this study concluded that the 55-mph reduced speed limit is one of the most effective countermeasures to have been used in reducing fatalities. The effect of the 55 mph NMSL on fatalities depends heavily upon the compliance level present on the nation's roads.

A report by Transportation Research Board (TRB) (Transportation Research Board & National Academies of Sciences Engineering and Medicine, 1984), presents comprehensive examination of NMSL mandated 55 mph limit. The report concludes that the lower speed limits did contribute to a reduction in average speeds and in a more uniform pace of travel (indicating less speed dispersion). The study estimated that the 55-mph speed limit accounted for 3,000 to 5,000 fewer traffic fatalities in its first year, 1974. The study further estimated that on an average, for the 1974-1984 period the lower speed limit saved 2,000 to 4,000 lives per year.

Borg (Borg, 1975) determined the effects of the 55 mph speed limit on typical measures of speed, compliance of the public to posted limits, crash rates, and anticipated relative gasoline savings on rural primary highways in Indiana. They study found that the speeds in 1974 were, on an average, 5-10 mph lower than their 1973 values. Observed speeds were also found to be statistically lower in 1974 for passenger cars and heavy trucks on all but one class of rural highways (heavy trucks on 2-lane). In terms of safety also, positive benefits were observed. The rate for the total number of crashes for each class of highway significantly decreased in the first six months of 1974. Fatality rate reduced by 67%, however the effect of reduced limit on this reduction was not estimated.

In a study conducted by the Michigan Department of Transportation (MDOT) (Enustun et al., n.d.) to study the effect of 55 mph speed limit on speed and safety in MI using multiple linear regression (MLR), it was found that the 85th percentile freeway speeds steadily decreased from 73 mph (just prior to the oil embargo) to 63 mph. For 2-lane high speed highways, 85th percentile speed decreased from 66 mph to 59 mph. For 4-lane divided highways, the corresponding reduction was from 70 mph to 62 mph. For freeways, travel decreased by 6.3 percent with total, injury, and fatal crashes decreasing by 19.7, 19.6, and 17.0 percent, respectively. In another study conducted in the state of MI (O'Day et al., 1975), it was found that the average speed went down by 10 mph on limited access routes and by 5 mph on other US routes and trunk lines, and by 3 mph on county roads. In terms of safety benefits, the effects of speed limit in reducing fatal crashes were apparent in the second half of 1974. In the first half of 1974, crash involvement declined by 5% and fatal crashes by 29% when compared with similar period of 1973. In the second half, fatal crashes were down by 7%.

A study by National Highway Traffic Safety Administration (NHTSA) (Cerrelli, 1977) correlated historic trends in fatality rates, reduced travel and speed limit. The study concluded that one-third of the variation in the fatality rate correlated with historic trend and reduced travel. Two-thirds was attributed to speed limit which suggested that nearly 6,000 lives saved annually could be due to slower and more uniform speeds. A separate study (Heckard et al., 1976) attributed the 55 mph speed limit to be the primary factor for reduced fatalities.

Pudinski (Pudinski, 1974) studied all highways in California where the speed limits were reduced to 55 mph and found a 46% decline in fatalities. This reduction was attributed to reduced average speed and speed variance. Similar study conducted in the state of Maryland (Dawson Jr, 1979) found that the reduced speed limits led to a 21-24% reduction in fatalities.

Klein (Klein, 1980) employed time series models to compare all highways with reduced speed limits with unaffected highways in the state of Illinois and found that the fatal crashes in 1974, when compared with 1971-1973 average, reduced by 60%. Similar study was conducted in Texas (Johnson et al., 1978) which also utilized time series models to determine the effect of reduced speed limits on crashes and found similar results.

Agent et al. (K R Agent et al., 1976) studied all highways in Kentucky using pre-post comparison to study the effects of NMSL. Crashes were found to be reduced significantly which were attributed to reduced speed limits. A separate but similar study (Council et al., 1975) conducted in the state of North Carolina also utilized pre-post comparison methodology and concluded that the reduction in fatal crashes cannot be explained by travel decline. Speed limit was considered to be an important factor in reducing speed variance but its effect was not estimated on crashes.

2.2.2 Relaxation of NMSL

After the NMSL was relaxed in 1987 allowing the states to increase the speed limits on their rural interstates to 65 mph, a second wave of research was initiated to study the effects of speed limit changes on driving speeds and safety. Ledolter and Chan (Ledolter & Chan, 1996) undertook a study in order to find a significant change in fatal and major injury crash rates following the implementation of the higher speed limit. The study concluded that the number of state-wide fatal crashes increased by 20% which was attributed to the speed limit change. Fatal crashes on rural interstates increased by 57% which was the largest increase recorded among all crash severity levels. No impact of speed limit change on major injury crashes was found.

Baum et al. (Baum et al., 1989) analyzed the fatalities on highways with increased speed limits for the 38 states that raised limits in 1987. It was concluded that there were 19% more fatalities on rural interstates in 1987 than the average for the previous 5 years, while there were only 4% more fatalities on other rural roads. In the 38 states that set higher speed limits in 1987, fatalities on rural interstates were estimated to be 15% greater than they would have been if the states had retained the 55-mph limit on these roads. Among states that retained the 55-mph limit, fatalities on rural interstates were 6% lower than expected. The authors extended their study to 48 states in 1991 (Baum et al., 1991) which included 40 states with increased speed limits. They found that among 40 states that increased the limit, fatalities were 29% higher than expected. Among the 8 states that retained the 55-mph limit, observed fatalities were 12% lower than expected (not statistically significant). Risk of fatality in an event of a crash increased by 19% in states with increased limits.

McKnight et al. (McKnight & Klein, 1990) utilized 5 years of before and 1 year of after period crash data to estimate the effect of raised speed limits on safety and driving speeds. In states that raised the limits, fatal crashes increased by 27% over projections based on previous trends. In the states that retained the 55mph limit, fatal crashes increased by 10% on both rural interstates and other highways. It was also found that speeding increased by 48% in states that raised the speed limits.

Wagenaar et al. (Wagenaar et al., 1990) examined the effects of the raised limit on injury morbidity and mortality in MI using time series models. The study reported a 19.2% increase in fatalities and a 40% and 25% increase in serious and moderate injuries respectively, on roads where speed limits were increased. The study also reported spillover effects which may have concurrently increased fatalities on 55mph road segments by 38%.

Gallaher et al. (Gallaher et al., 1989) compared the rates of fatal crashes before and after the speed limit change in the state of New Mexico and found that the rate of fatal crashes in the 1 year after the speed limit was increased was 2.9 per 100 million vehicle-miles traveled, compared with a predicted rate of 1.5 per 100 million vehicle-miles based on the trend of the 5 previous years. This increase in fatal crashes was attributed to an increase in fatal single-vehicle crashes.

Upchurch (Upchurch, 1989) in a separate study conducted in Arizona presented the facts on changes in driver behavior and actual numbers of crashes. No causal relationship was defined in this study. The study found no trends in the speed observed in the before period. Following the speed limit increase, vehicle speeds increased by only about 3 mph or less during the four quarters. Slightly more dispersion in vehicle speeds in the after period was also noted. Safety effects were also observed. A downward trend of crash rate on urban interstates and no change in crashes on rural interstates from 1984-86 was observed. The crashes however, increased in the 1 year after period (vehicle travel miles also increased). Fatal crash rate generally increased from 1983 to April 1988, with no change in injury crash rate in the after period. The limitation of this study was that it did not prove or disprove a cause and effect relationship between actual speeds driven and crash experience. Many other factors such as seat belt use, alcohol involvement, and weather conditions may have an influence on crashes.

Hoskin (Hoskin, 1987) studied the effect of raised speed limits on fatalities using two different methods, namely, National Safety Council (NSC) Method and the Transportation Research Board (TRB) Method. The NSC Method concluded that the fatalities were expected to increase by 200-700 per year, nationally, on rural interstates depending upon the speed limit increase. The TRB Method concluded that an increase of 300-450 deaths per year would be expected if each state returned to pre-1974 limits.

Lynn and Jernigan (Jernigan et al., 1994; Lynn & Jernigan, 1992) studied the effects of 65mph speed in Virginia after 30 months of its implementation. They found that the average speed increased by 5.9 mph and 3.8 mph on rural and urban interstates respectively. The 85th percentile speeds increased by 6.9 mph and 4.2 mph on rural and urban interstates respectively. The speed variance for passenger cars decreased by 4.1 mph on rural interstates, but increased by 2.0 mph for trucks. Between 1986 and 1989, fatalities on rural interstates increased by 42.2%. On urban interstates, the increase was 8.9%. Fatal crashes on rural interstates increased by 23.2/year to 66.5 post 65 mph limit and fatalities increased from 26.8/year to 76.5. Fatal crashes on Virginia's urban interstates increased by 1.8/year to 39.5, and fatalities increased by 2/year to 44.

Ossiander and Cummings (Ossiander & Cummings, 2002) undertook a study to determine if the 1987 speed limit increase on Washington State's rural freeways affected the safety on rural freeways, or affected average vehicle speeds or speed variance. They found that the average vehicle speed increased by 5.5 mph and 85th percentile speed increased by 6.4 mph. Speed variance was not affected by the speed limit increase. The speed limit increases also affected safety. The incidence of fatal crashes more than doubled after 1987, compared with what would have been expected if there had been no speed limit increase. This resulted in an excess of 26.4 deaths per year on rural freeways in Washington State.

Garber and Graham (S. Garber & Graham, 1990) examined the effects of the new 65 mph speed limit on U.S. rural highway fatality counts in 40 states that adopted the new 65 mph speed limits by mid-1988. For rural interstate and non-rural interstate fatalities, median estimates (among the 40 states) indicated 15% and 5% more fatalities respectively due to increased speed limits.

A nationwide study carried out by NHTSA (National Highway Traffic Safety Administration, 1989a) that included 38 states with increased limits and 10 states that retained their previous limits found that the percent of traffic traveling at very high speeds increased from 6% in the fall of 1986 to 16% in the fall of 1988 (for vehicles traveling faster than 70 mph). The standard deviation of vehicle travel speeds was 6.0 mph in 1986 and 6.7 mph in 1988. Rural interstate fatalities increased by 16% in 1987 compared to 1986. The increase was 10% after accounting for travel increment. Fatalities increased 31% in 1988 compared to 1986 (21% after accounting for travel changes). An update of this study published in 1990 (National Highway Traffic Safety Administration, 1989b) found 13% increase in rural interstate fatalities for the 1987-1988 period and a 2% decrease for 1988-1989. Rural interstates in the 55-mph states experienced a 12% decrease in fatalities between 1986 and 1989. On urban interstates, fatalities in the 65-mph states increased by 7% for the 1987-1988 period, and decreased by 7% for 1988-1989. Urban interstate fatalities in the 55-mph states increased by 13% during 1986-1989.

Brown et al. (Brown et al., 1990) studied the safety impacts of speed limit increases in Alabama and found that the crash frequency increased by 19% on rural interstates, although no significant change in crash severity was found.

Freedman et al. (Mark Freedman & Esterlitz, 1990a) studied the impact of raised speed limits on speed distributions in 3 states, namely, New Mexico, Virginia and Maryland. In Virginia, two weeks after the 65-mph speed limit was implemented, mean and 85th-percentile speeds of passenger cars were higher by almost 3 mph, whereas the speed of tractor-trailers (still limited to 55 mph) was unchanged. The proportion of cars exceeding 70 mph nearly doubled. A longer-term trend of increasing speed was also found. In Maryland on the other hand, speeds of cars and trucks (with 55-mph speed limit) did not increase during the same 2 weeks. Passenger car speeds showed no upward trend, but tractor-trailer speeds have increased to the same level as in Virginia. The data from New Mexico showed that average speeds of passenger cars and light trucks on rural highways increased nearly 3 mph within 9 months of the 65-mph law and have since continued to increase. The proportion exceeding 70 mph increased by five and two times for cars and heavy trucks respectively.

Pant et al. (Pant et al., 1992) studied the effects of the 65-mph speed limit on traffic crashes on rural interstate highways posted at 65 or 55 mph and rural non-interstate highways posted at 55 mph in Ohio. The study found that the mean fatal crash rate on rural interstate highways posted at 65 mph has not adversely changed after the implementation of the 65-mph speed limit. Some increase in injury and PDO crashes were observed in the after period. On rural interstates posted at 55 mph, mean fatal crash rates increased in the "after" period. However, when categorized based on weather, no significant change was found.

McCarthy (McCarthy, 1993) investigated the effect of the speed limit change on a subset of crashes in Indiana i.e., alcohol-related crashes using a time series cross section (regression-fixed effects) model, while controlling for exposure, age distribution, population, economy, alcohol availability and enforcement. On a statewide level, total, fatal, injury and property damage only crashes increased after the change in speed limits. Alcohol-related crashes underwent a redistribution from higher-speed to lower speed roads after the change in speed limit.

Houston (Houston, 1999a) developed separate models for state fatality rates on various categories of roads and found that the fatalities increased on rural interstates, but decreased on rural non-interstates.

Mace et al. (Mace & Heckard, 1991) studied speeds trends at 51 rural interstates sites using before-after study and found that there was 3.9 mph, 4.3 mph and 0.65 mph increase in average speeds, 85th percentile speeds and speed dispersion, respectively. Little local spillover effect was observed and there was no evidence of spillover onto urban interstates.

Freedman and Williams (M Freedman & Williams, 1992) studied the speed and crash data of 11 northeastern states to analyze the effect of speed limit increase. The study reported an increase in speeds on rural interstates in 65-mph states but speeds on rural interstates in 55-mph states were unchanged. Drivers generally traveled slower on the connecting roads but on 5 out of 6 sites, drivers coming out of higher-speed roads had speeds 1.8 to 4.7 percent higher than those coming from lower-speed roads. No statistical tests were conducted in the study.

Khorashdi (Khorashdi, 1994) studied the safety-speed limit relationship for California after the change in speed limit to 65 mph using before-and-after approach. ANOVA models were estimated to compare crash data for 65 mph rural interstates, 65 mph rural non-interstates and 55 mph rural interstates. The study reported an increase in the fatal crashes on 65 mph highways, both rural interstates and rural non-interstates. Crashes on 55-mph highways were compared with those on 65-mph highways and it was found that while the trend for total, fatal, and injury crashes was declining on the 55-mph highways, it was going up for the 65-mph highways.

Several studies have utilized Autoregressive Integrated Moving Average methods (ARIMA and ARIMAX) to analyze crash data. Streff and Schultz (Streff & Schultz, 1990) utilized ARIMA models to analyze monthly crash data for MI. It was found that the fatalities increased by 28 percent and serious injuries by 39 percent. These results were consistent with the findings of Wagenaar et al. (Wagenaar et al., 1990) with one difference. Unlike Wagenaar et al., who did find a significant increase in fatalities on 55 mph highways (urban interstate in particular) and attributed it to the "spillover" effect, Streff and Schultz found no significant impact on urban interstate fatalities. Pfefer et al. (Pfefer et al., 1991) also used an ARIMA intervention analysis methodology to analyze the impact of the change in speed limits in Illinois. The authors concluded that speed limit change had no significant effect on passenger car crash rates on the rural interstates but the fatal-injury car-truck crash rate decreased after the change in the speed limit. McCarthy (McCarthy, 1993) also employed ARIMA on monthly crash data from 1982-1988 for the state of Indiana. The study found that the total and injury interstate crashes increased but no change was found in fatal crashes. Chang et al. (Gang Len Chang et al., 1993) used ARIMA intervention models on monthly fatalities at aggregate level and then by various groups of states to study the effect of raised speed limits. Significant impact of raised speed limit was observed on fatalities at national level. Effects however, decayed after 1 year. Some large states like Illinois, California, Texas were insensitive to the speed limit increase. Small states, on the other hand, have experienced significantly larger increase in fatalities. The impacts were highly dependent upon the intervention function and hence were deemed indeterminate. Rock (Rock, 1995) studied the effects of 65mph limit on crashes, injury and deaths in Illinois using ARIMA. The study found that there were nearly 300 additional crashes/month in rural Illinois. Increases were also observed on 55mph roads indicating spillover effects.

Some studies have also reported safety improvement as a result of increased speed limits. Greenstone (Greenstone, 2002) in his study was unable to find claims by other studies that speed limit increase caused a statewide fatality rate decline. He found that the fatality rates increased by 30% on rural interstates and fell by 17% on urban non-interstates nationwide.

Chang and Paniati (G L Chang & Paniati, 1990) analyzed crash data for 32 states that raised speed limit prior to June 30, 1987 and found that in the short term, increased limits have no significant effect on fatalities on rural interstates by various measures. In 14 out of 15 months the fatalities were higher but not statistically significant. This is one of the few studies that found no statistical changes in safety. This may be due to limited after period data, thus making it difficult to accurately assess the long-term safety impacts of the new speed limit.

Sidhu (Sidhu, 1990) carried out trend analysis on five before-years of fatal, injury, and property damage crashes. Comparison of projected versus actual numbers in the year after 65 mph was carried out for rural interstates, urban interstates and other roadways. The study found no statistically significant change in fatal and injury crashes on rural interstates, urban interstates, or other primary roadways. Also, no change in severity of crashes was reported. A 6.6% statistically significant increase in PDO crashes on rural interstates was observed, which could be due to increased travel. On all other highways, statistically significant decreases in PDO crashes were found.

A nationwide study by Lave and Elias (C Lave & Elias, 1997; Charles Lave & Elias, 1994) analyzed the statewide consequences of raising the speed limit, treating highways and enforcement as a total system. The analysis at aggregate level found that the fatal crash rates improved by 3.6% for states who changed limit as compared to those that didn't. Regression analysis was also done which also showed that the fatal crash rates fell by 3.4-5.1% following the speed limit increase. This decrease in fatalities was maybe due to shift in police resources from speed enforcement to other activities. Godwin (Houston, 1999b) reported an overall system-wide decrease in fatalities in his study conducted in 38 states with 65mph limit and 8 states with 55 mph limit. Such a system-wide fatality decrease may have resulted from an unreasonably high VMT shift from non-interstate rural roads to rural interstates.

Penfield et al. (Penfield & Maleck, n.d.) in their study did not find any significant change in the fatality crash trend. The authors also found out that the impact of the 55-mph speed limit was more prominent on urban highways. Wright et al. (Wright & Sarasua, 1991) in their study reported no significant increase in fatalities, but a significant increase in injuries was observed. Jernigan (Lynn & Jernigan, 1992) also reported a decrease in system-wide fatalities but an increase in fatalities for the rural interstates.

2.2.3 The Repeal of NMSL

The 1995 repeal of NMSL gave the transportation researchers another opportunity to study the effects of speed limit increases on traffic speeds and safety. Binkowski et al. (Binkowski et al., 1998) studied the impact of raised 70 mph speed limits in MI on traffic speeds and safety and found that the crashes increased by 16.4% on test sites (sites where speed limit increase occurred). However, the safety results were inconclusive due to limited crash data available at the time of the study. In terms of traffic operations, no changes were observed on control sites (sites where speed limits remained same). However, 50th and 85th percentile speeds on test sites increased by 1 and 0.5 mph respectively. The truck speeds were nearly 8 mph higher than the car speeds. The changes in speed limit did not affect difference between day and nighttime speeds. The weekday and weekend speeds were also unaffected by the speed limit increase. The study reported no spillover effects on the freeways. In a follow-up study (W. C. Taylor, 2000), it was found that the fatal crashes increased by 4.5%, and the severe crashes resulting in incapacitating injury decreased by 9.3% as the result of speed limit increase. Truck involved fatal crashes decreased by 14.5%. A separate before-after study conducted in MI reported an increase of 1 mph in average speed and 0.5 mph in 85th percentile speed after the increase in the speed limit to 70 mph. The authors reported no meaningful change at the control sites and there was no spillover effect for sites located in proximity of test sites.

Retting and Green (Retting & Greene, 1997) studied the effects of repeal of NMSL on traffic speeds in five different states which included California, Montana, Nevada, New Mexico, and Texas. It was found that within three months of new speed limits, average and 85th percentile car speeds increased by 2mph. After 6 months, mean car speeds declined by 1 mph from the 3-months after period and the 85th percentile speeds were unchanged. After 1 year, mean and 85th percentile speeds were unchanged from the 3-month after speeds. The study was then refined by studying long-term speed trends (Retting & Teoh, 2008). On rural interstates without speed limit changes, travel speeds increased for both passenger vehicles and large trucks, and the proportion of passenger vehicles exceeding 80 mph tripled. On rural interstates in Montana where speed limits were lowered for passenger vehicles, travel speeds decreased, even for large trucks whose speed limits had not changed. On urban freeways where speed limits did not change, travel speeds declined for both passenger vehicles and large trucks. On urban freeways in Texas where speed limits declined for passenger vehicles, travel speeds decreased, even for large trucks whose speed limits actually had increased. The study showed that the travel speeds are still increasing, even after 10 years of NMSL repeal. It was also concluded that the traffic speeds can be curbed or even reversed, in some cases, by lowering the speed limits.

Renski et al. (Renski et al., 1999) studied the effect of speed limit increases on the most severe occupant injury in single vehicle crashes using ordered probit model and by using single-pair analysis. Various before-after speed limits were taken into consideration. The probability of sustaining minor and non-incapacitating injuries increased when the speed limits were increased from 55 mph to 60 mph and from 55 mph to 65 mph. However, when the speed limits were increased from 65 mph to 70 mph, no significant effect on the crash severity was found. There were too few fatal crashes to draw conclusive results for this category of injury severity. Road segments with good safety records were chosen in this study which may give findings that are too conservative.

A before-after study, utilized five years of before data and nine months of after speed and crash data (Pezoldt et al., 1997) to study the effects of new 70 mph speed limits on speed and safety in Texas. Separate analysis was conducted for urban and rural interstates. On rural interstates, the average vehicle speed increased from 64.0 mph to 66.0 mph while the 85th percentile speed increased from 72.3 mph to 74.0 mph. Average number of serious crashes per month increased from 162.8 to 176.1. Serious crashes per 100 million vehicles miles traveled (mvmt) increased from 13.5 to 14.2. On the urban interstates, the average vehicle speed increased from 57.9 mph to 60.6 mph, and the 85th percentile speed increased from 64.2 mph to 67.8 mph. The average number of serious crashes per month increased from 35.6 to 51.5 (44.7 percent), while the serious crashes per 100 mvmt increased from 13.6 to 18.8 (38.5 percent).

Several studies have utilized fatality data from Fatality Analysis and Reporting System (FARS) to study the fatality trends following the repeal of NMSL. Farmer et al. (Farmer et al., 1999) used fatality data from January 1990 to December 1997 to estimate the effects of repeal of NMSL on fatalities. The study included 24 states that raised their speed limits and 7 states that didn't. The study reported a 15% increase in fatalities in states that raised the speed limits (17% after accounting for travel miles increase). Friedman et al. (Friedman et al., 2009) examined the long term effects of the 1995 NMSL repeal on road fatalities and injuries in fatal crashes. The study reported a 3.2% increase in road fatalities attributable to the raised speed limits on all road types. On rural and urban interstates, the fatalities increased by 9.1% and 4% respectively, due to the raised speed limits.

A nationwide study (Balkin & Ord, 2001) utilized fatality data for each month from January 1975 to December 1998 for each state separated by rural and urban interstates from FARS to investigate the relationship between speed-limit increases and increases in the number of fatal crashes on U.S. rural and urban interstates. 19 of the 40 states experienced a significant increase in fatal crashes along with the speed-limit increases on rural interstates around 1987. 10 of 36 states experienced a significant increase in fatal crashes along with speed-limit increases on rural interstates around 1996. 6 of 31 states experienced a significant increase in fatal crashes along with the speed-limit increases on urban interstates.

Another study (Dee & Sela, 2003) used fatality data on state by year basis from FARS to investigate the relationship between speed limit and fatalities. Various models developed in the study indicated that the speed limit increase above 65 mph after the repeal of NMSL had positive and significant effect on fatality rates. Few models also suggested that the estimated effect of 70 mph or higher speed limits remains uniformly positive. The effect of gender and age on fatalities was the prime focus of the study. The study found that the fatality rates among females increased by 9.9% while no significant effect was reported on men.

Patterson (Patterson et al., 2002) modeled rural interstate fatalities between 1992 and 1999 against the size of the new speed limit (no change, 70 mph, and 75 mph), the period before and after the speed limit change (1992 to 1995 vs. 1996 to 1999), and their interaction. Fatalities in the groups of states that raised their speed limits to 75 mph and 70 mph were 38% and 35%, respectively, higher than anticipated based on fatalities in the states that did not change their speed limits. Moreover, the states that increased their speed limits to 75 mph had a higher rural interstate fatality rate before the speed limit was changed than the other groups of states.

Shafi et al. (Shafi & Gentilello, 2007) calculated the traffic fatality rates for all the states adjusted for state differences in vehicle miles traveled and several other potential confounding factors, and compared between states with speed limits less than or equal to 65 mph versus greater than 65 mph, using negative binomial regression. In 29 states with speed limits greater than 65 mph, there was a 13% increase in the risk of traffic fatalities. Grabowski et al. (Grabowski & Morrisey, 2007) analyzed nationwide crash data from 1982 to 2002 and found that the repeal of the NMSL resulted in an increase in rural interstate fatalities of 36–37%

The state of New Jersey did not increase their speed limits after the relaxation of NMSL. However, after NMSL was repealed, the speed limits were increased from 55 mph to 65 mph. The New Jersey DOT carried out research (Weinstein, 2001) to study the effect of the raised limits on traffic speeds and safety. The study reported nominal changes in travel speeds during the 36-month study period. However, after 18-month period, actual travel speeds increased on average, by only 1 mph with the exception of NJ Turnpike where travel speeds increased by 3-4 mph on average. The fatalities decreased by 10% and fatal crashes by 8% in the 65-mph zone over a similar 18-month period prior to the study. Crashes on 65 mph roads increased by 27% during the 36-month study period, also increased by 30% on 55 mph zones.

Few studies have also reported conflicting or no significant changes in the safety related trends following the speed limit increase. Vernon et al. (Vernon et al., 2004) analyzed effects of the increased speed limit on Utah highways on crash rates, fatality crash rates, and injury crash rates using ARIMA intervention time series analysis techniques. The study found significant increases in the total crash rates in urban interstate segments where the posted speed limits were increased from 60 mph to 65 mph. However, the total crash rate, fatality crash rate, and injury crash rates on rural interstate segments, and fatality and injury crash rates on urban interstate segments were unaffected.

Another study (Haselton et al., 2002) used simple regression, ANOVA and before-after observational study to determine whether there has been a statistically significant change in the traffic collisions following the speed limit increases in California. Both collisions count and rates were studied for early 1996 speed limit increases from 55 mph to 65 mph, and from 65 mph to 70 mph. Simple regression showed no statistically significant increases in any type of crash or fatalities. However, ANOVA showed significant decrease in fatal collision rates on highways with no speed limit increase. Fatal collision rates increased on treatment group (considering 3 years before and 3 years after data). The results from the observational study showed significant increase in fatal crashes on all highways where limit increased from 55 mph to 65 mph or from 65 mph to 70 mph.

Agent et al. (Kenneth R. Agent et al., 1998) compared the crash rates on adjacent sections of interstates in Kentucky where the speed limit was 88.6 km/h (55 mph) and 104.7 km/h (65 mph) and did not find a substantial difference in the total, injury, or fatal crash rates. Malyshkina et al. (Malyshkina et al., 2007) did not found any statistically significant relationship between speed limits and the severity of crashes on interstate highways. Yowell (Yowell, 2005) analyzed statewide fatality data from 27 states using regression to examine the relationship between speed limit increases and fatality rate. The study reported that the repeal of NMSL had little effect on statewide fatality rate. The change was found to be statistically significant only in Texas (in the positive direction), and in Michigan, and Colorado (in the negative). The study found no widespread positive relationship between raising the speed limit and statewide fatality rate.

2.2.4 Recent Studies

Several changes in the speed limit policy in various states across the nation have occurred even after several years of NMSL being repealed in 1995. Malyshkina et al. (Malyshkina & Mannering, 2008) studied the impact of increasing the speed limit on crash injury severities using multinomial logit model in Indiana. The speed limit increase occurred in 2005 and the study utilized one year of before, and one year of after data. 34 different injury severity models were estimated based on various combinations of roadway type, roadway location and the number and types of vehicles involved in the crash. It was found that speed limits did not significantly affect crash-injury severities on interstate highways. However, for other highway types, increases in speed limits significantly increase the likelihood of a fatal or injury crash.

The speed limits in Iowa were raised to 70 mph on rural interstates in 2005. Souleyrette et al. (Souleyrette et al., 2009) studied the effects of newly raised speed limits on traffic speed and safety. It was found that although the speeding reduced on the affected sections, the mean and 85th percentile speeds increased by 2 mph. Simple descriptive statistics revealed increases in all crash severity categories for the 2½ year period following the speed limit increase when compared to 2½-year period prior to the increase. However, when compared to longer term trends, the increases were less pronounced in some severity levels and types, and for a few severity levels the average crash frequencies were observed to decrease. A generalized regression model was fit to the time series data. The model found that none of the results were significant at the 95% confidence level.

The state of Texas raised the speed limits on I-10 and I-20 rural interstates from 75 mph to 80 mph in 2006. Retting et al. (Retting & Cheung, 2008) examined the effects of the new 80 mph speed limits on travel speeds considering 3, 12, and 16 months of after period speed data. During 16-months after period, mean speeds of passenger vehicles on I-20 increased by 9 mph relative to the comparison road, where no speed limit change occurred. On I-10, mean speeds increased by 4 mph relative to the comparison road. The study reported smaller speed increases on I-10, which was attributed to its close proximity to Mexico border.

The state of Pennsylvania raised the speed limits on rural freeways from 65 mph to 70 mph between July and August 2014. A before-after study conducted to study the effects of new limits on travel speeds found that the mean and 85th percentile speeds increased (by less than 5 mph). Due to insufficient data, a framework for safety analysis was developed (Donnell et al., 2016).

Between 2005 and 2010, the state of MI raised the speed limits on some of their freeways from 55mph to 65mph, from 55 mph to 70 mph, and from 65mph to 70 mph. Kwigizile et al. (Kwigizile et al., 2017) found that the 85th percentile speeds increased by 1.8-4.7 mph when the speed limit was increased by 5 mph. The increase in the 85th percentile speed was 3.5-4.2 mph when the speed limit was increased by 10 mph. In both the cases, a significant increase in the variability in speeds was observed. The cross-sectional analysis from this study found that the difference in the 85th percentile speeds between the test site (speed limit increased from 55 mph to 70 mph) and the control site (speed limit of 55 mph) was 4.5 to 8 mph, and 1 to 4.6 for passenger cars and trucks respectively. Mixed effects negative binomial model was utilized to study safety trends (Kwayu et al., 2018; Kwigizile et al., 2017). Results showed that the total crashes increased by 8.1% (CMF of 1.081). The effect was more pronounced on curved segments which had a 24.7% increase (CMF of 1.247) compared to straight segments which had a 5.8% increase (CMF of 1.058). Roadway departure crashes increased by 13.2 percent (CMF of 1.132). On curved segments, however, a 21 percent increase (CMF of 1.21) in roadway departure crashes was estimated. Raising the speed limit increased fatal (K), incapacitating injury (A), and non-incapacitating injury (B) crashes (combined) by 10.2 percent (CMF of 1.102).

A Utah study (Hu, 2017) found that the mean speeds of passenger cars increased by 4.1% (3.1 mph) when the speed limit was increased by 5 mph (from 75 mph to 80 mph). For trucks, the mean speeds increased by 2.5% (1.7 mph). However, no significant increase in the speed variance was observed in the study. Log-linear regression models were used in the study to estimate the percentage changes.

A study conducted in Montana (Gayah et al., 2018) also found similar results where a 5 mph increase in speed limit resulted in a significant increase in mean and 85th percentile speeds. Linear regression and quantile regression models were used to estimate mean and 85th percentile speeds respectively, as a function of various roadway characteristics. The safety analysis found a statistically significant reduction in total, fatal+injury, and property damage only (PDO) crash frequency at locations with posted speed limits set 5 mph lower than engineering recommendations. Locations with posted speed limits set 10 mph lower than engineering recommendations experienced a decrease in total and PDO crash frequency, but an increase in fatal+injury crash frequency. Due to smaller sample size, no clear conclusion for the safety effects of setting speed limits 15 to 25 mph lower than engineering recommendations were drawn. Overall, it was recommended to set the speed limits 5 mph lower than the engineering recommended limits for better safety and compliance.

These findings were supported by a study conducted in Kansas (R. S. Shirazinejad & Dissanayake, 2018a), where the speed limit increased from 70 mph to 75 mph in 2011. The 85th percentile speed increased by approximately 5 mph as a result of the speed limit increase. It was found that the 85th percentile speeds were different statistically during the before and after periods, but it was statistically different for both treated as well as non-treated sections. A separate study in Kansas (Dissanayake & Shirazenijad, 2018) used t-tests and showed that the 5-mph increase in the speed limit caused a statistically significant increase in 85th percentile speed for the sections affected by speed limit change. However, there was also an increase in control sections, but this was due to large sample sizes of speed data in the before-and-after period. The K-S test results also showed that the speed distribution of treated sites during the after period was different from the before period. For safety analysis, two different methodologies were used. Empirical Bayes

(EB) before-after study (R. S. Shirazinejad & Dissanayake, 2018b) showed a 16% increase in the total crashes, whereas, before-after with control group analysis (R. Shirazinejad et al., 2018) resulted in a 27% increase in the total crashes. Fatal and injury crashes increased by 35% based on the before-and-after with the control group method, but no significant change was found based on the EB method. Cross-sectional study results showed the speed limit increase had a significant effect on total crashes (increase of 25%). It was also significant for fatal and injury crashes, with those increasing by 62% (Dissanayake & Shirazenijad, 2018).

Himes et al. (Himes et al., 2018) used EB before-after study to analyze the effects of newly raised speed limits on Virginia rural interstates. The study found that the injury crashes and run-off-road crashes decreased by 8.2 percent and 5.9 percent respectively for the base freeway segments after the posted speed limit was increased from 65 mph to 70 mph. For interchange segments, total crashes, run-off-road crashes, and truck-related crashes increased by 23.7 percent, 15.8 percent, and 54.4 percent respectively.

Few studies have utilized nationwide crash data to study the effects of speed limit increases on traffic safety. Davis et al. (Davis et al., 2015) did a longitudinal comparison of state-level rural Interstate fatalities in the United States from 1999 through 2011. Total fatalities were found to consistently increase with the maximum statutory speed limit. States with 70-mph speed limits experienced 22.2% more fatal crashes than states with 60-mph or 65-mph limits. The 75-mph or higher speed limit group showed substantial variability in effects from state to state, with fatalities increasing from 51.5% to 124.7% (as compared with states with speed limits of 60 or 65 mph). States with 70-mph speed limits experienced 31.7% more truck and bus fatal crashes than states with lower limits. Fatality rates were generally higher among states with speed limits of 75 mph or above, although this result was highly variable from state to state.

Warner et al. (Warner et al., 2019b) examined changes in rural interstate fatalities from 2001 to 2016 using random parameter negative binomial models to control for unobserved heterogeneity, as well as time-invariant effects unique to each state. The results showed that the fatalities increased by 0.2%, 0.5%, and 0.6%, when the rural interstate mileage is increased by 1% on interstates with posted speed limits of 70 mph, 75 mph, or 80 mph, respectively.

Farmer (Farmer, 2017) studied the safety effects of increases in U.S. state maximum speed limits during the period 1993–2013. To model the annual traffic fatality rates per mile, Poisson regression model was used while considering several other factors such as time, the unemployment rate, the percentage of the driving age population that was younger than 25, per capita alcohol consumption, and the maximum posted speed limit. Separate analyses were conducted for all roads, interstates and freeways, and all other roads. The study reported an 8% and 4% increase in fatality rates on interstates and freeways, and on other roads respectively. 33,000 crash related deaths could have been prevented during 1995-2013, if the speed limits had not been increased.

Farmer (Farmer, 2019) analyzed the fatality rates per mile of travel from 1993-2017, on a state-by-state basis considering the effects of time, the unemployment rate, the percentage of the driving age population that was younger than 25, the safety belt use rate, and the maximum posted speed limit and found that a 5 mph increase in the maximum state speed limit was associated with an 8.5% increase in fatality rates on interstates/freeways and a 2.8% increase on other roads. Nearly 36,760 fatalities (13,638 on interstates/freeways and 23,122 on other roads) could have been prevented during the 25-year study period if the maximum speed limits had not increased.

2.3 Speed Limit Polices on Non-Freeways

The previous discussion has primarily focused on the speed limits and its relationship with travel speed and safety along freeways which are also categorized as limited access facilities.

Freeways generally have the highest speed limits and also the highest traffic volumes. Higher speeds are generally more appropriate along freeways than non-freeways as they are designed to a higher standard for opposing traffic separated by a median. Grade separated interchanges are provided as opposed to at-grade intersections. These differences virtually eliminate certain types of crashes, including head-on and angle collisions. Hence, freeways are considered safer when considering crash risks per distance traveled (National Highway Traffic Safety Administration (NHTSA), n.d.). Non-freeways, also categorized as non-limited access facilities which include two-lane highways, usually experience a disproportionate number of head-on collisions, as well as run-off-road crashes into roadside areas with hazardous fixed objects such as trees, utility poles, etc. As such, safety and speed limits on such highways is obviously also of great importance. The majority of US states operate with 55 mph (89 km/h) or 65 mph (105 km/h) maximum speed limits on two-lane highways, though several states post limits as high as 70 or 75 mph (113 or 121 km/h) (Gates et al., 2015a).

The relationship between speed limit, operating speeds, and safety is complex, especially on non-freeways as the driver speed selection is affected not only by the posted speed limits, but also by roadway, roadside, and traffic related factors. The following sub-section discusses the effects of changes in speed limits on driver speed selection and safety performance on non-freeways. Thereafter, factors affecting operating speeds and safety performance on these roadways are discussed.

2.3.1 Effect of Speed Limit Changes on Operating Speeds and Safety

On any highway, all segments may not be acceptable candidates for increasing the speed limits. Segments with extensive horizontal or vertical curvature, sight distance limitations, or other extreme features that do not comply with design standards may be unsuitable for speed limit increases. Generally, any changes in the posted speed limits, especially on non-limited access facilities are done selectively based upon traffic engineering, speed, and safety related studies (Gates et al., 2015a). For example, the road segments where the speed limits increased recently in MI, were selected carefully after considering comparatively lower safety risks and lower cost geometric upgrades (Kay et al., 2017). 12 factors were shortlisted to identify potential segments where limits could be increased. These include segment length, total crash rate, injury crash rate, severe (fatal and A-injuries) crash rate, horizontal curvature, speed reduction zones, no-passing zones, schools (kindergarten through eighth grade), driveway density, lane width, paved shoulder width, and signalized intersections.

The literature that explores how the changes in posted speed limits affect driver speed selection and the safety performance on non-freeways is scarce. Considerable variation in the design characteristics of two-lane highways is found, where speeds can range from 25 to 75 mph (40 to 121 km/h). This makes it difficult to assess the magnitude of large-scale speed limit increases across states as has been done frequently in the case of freeways (A. Davis et al., 2015a). Nevertheless, few studies have attempted to understand how the speed metrics and the safety performance is affected by lowering or increasing the posted speed limits along non-freeways.

After the NMSL was abolished, the speed limits on several multilane-highways in Georgia increased from 55 mph to 65 mph. As a result, the observed mean speed increased by 3.2 mph. Similar increases were also recorded in space-mean speed and the 85th-percentile speed (Dixon et al., 1999). However, an increase of 3.2 mph in mean speeds is relatively small when compared to a 10 mph increase in the posted speed limits. Another study (Parker, 1997) reported similar findings, wherein the change in mean, 85th percentile, and standard deviation of speeds was less than 2 mph, when the change in posted speed limits was between 5-20 mph (lowered at few sites and increased at others). The study deemed the 2 mph increase in the speed metrics as statistically significant but not practically significant. Ulman et al. (Ullman & Dudek, 1987) found little to no effect on the mean speed, 85th percentile speed, and skewness in the speed distribution due to lowering of speed limits from 55 mph to 45 mph at 6 sub-urban highway sites in Texas.

In terms of safety performance, crash rate has been found to increase with an increase in the posted speed limit (Gates et al., 2015b). Higher speed limits are also found to significantly increase the likelihood of unsafe speed being listed as the primary cause of the crash, and also with higher crash severity (Malyshkina et al., 2007). Analysis of crash data from Utah (Vernon et al., 2004) showed that the fatal crash rates on high-speed rural non-interstates increased significantly after the raised speed limits post NMSL repeal. However, total and injury crash rates were unaffected by the increase in the posted speed limits. Farmer et al. (Farmer et al., 1999) also reported similar findings and concluded that the effects of the NMSL repeal on non-interstate fatalities are close to zero and not statistically significant. Another study (Najjar et al., 2002) also reported no statistically significant increases in crash, fatal crash and fatality rates on two-lane rural highway network in Kansas as of 1998. Raising speed limits on freeways may also lead to some spillover effects on nearby non-freeways. Spillover effect refers to the inclination of drivers to maintain the same high speeds even after exiting a road with high speeds. This leads to higher vehicle speeds on roads adjacent to freeways (such as arterials).

A Michigan study reported (Alhomaidat et al., 2020) that an increase of 5 mph in the posted speed limits on a freeway could lead to a 13.9% increase in the likelihood of increasing crash frequency on adjacent arterial roads. Increased speed limit on freeways, the distance between road segments and the freeway, traffic volume, segment length, number of lanes, land use, ramp type, median type, and time have a significant association with crash occurrences on road segments adjacent to the freeway.

2.3.2 Factors Affecting Operating Speed

The previous sub-section talks about the explicit relationship between posted speed limits, speed metrics, and safety on non-freeways. However, there are several roadway, roadside, traffic, and weather related factors beside the posted speed limits that significantly affect the driver speed selection, and hence the safety on non-freeways. Several studies have shown that horizontal alignment is one of the main factors that affect the operating speeds on non-freeways, particularly on two-lane highways. Drivers tend to reduce their speed based upon the degree of curvature (Al-Masaeid et al., 1999; Banihashemi et al., 2011; Donnell et al., 2001; Figueroa-Medina & Tarko, 2004; Fitzpatrick, Elefteriadou, et al., 2000; Gong & Stamatiadis, 2008; Krammes et al., 1995; McFadden et al., 2001; McFadden & Elefteriadou, 2000; Misaghi & Hassan, 2005; Savolainen et al., 2018b; Voigt & Krammes, 1998). On horizontal curves, operating speeds generally differ on the inside and the outside lanes (Gong & Stamatiadis, 2008). For the inside lane, the significant factors that affect the operating speeds include shoulder type, median type, pavement type, approaching section grade, and horizontal curve length. For the outside lane, the factors include shoulder type, median type, approaching section grade, presence of approaching curve, and curve radius and length. Super-elevation rate has also been found to affect the speeds on horizontal curves, with speeds at curve midpoint increasing with increasing super-elevation rate (Voigt & Krammes, 1998). Apart from the degree of curvature, rainfall intensity, and nighttime conditions also have been found to affect the speed reduction between the tangent and the following curve on two-lane rural highways (Al-Masaeid et al., 1999). Fitzpatrick et al. (Fitzpatrick, Carlson, et al., 2000) in their study showed that the posted speed limit, access density, and deflection angle affect speeds on curves. When the effect of posted speed limits was not considered, the impact of median presence was also found to be significant, along with roadside development. The presence of curve advisory speed limit signs, and the magnitude of difference between posted speed limit and the advisory speed limit also significantly affect the speeds on curves (Savolainen et al., 2018b). However, Collins et al. (Collins et al., 1999) found no differences in speed measures (mean speed, 85^{th} percentile speeds, and standard deviation of speeds) for tangents, horizontal curves, and vertical curves, with one exception; for curves with radius less than 100 m, the standard deviation of speeds was found to be smaller.

Vertical alignment also has a significant relationship with operating speeds along tangent sections, however, this effect was significant for crest vertical curves with limited sight distance only (Dixon et al., 1999; Jessen et al., 2001). On crest vertical curves, the operating speeds were found to have a significant relationship with approach grade, posted speed limit, and traffic volume (Jessen et al., 2001).

Along tangent sections, posted speed limit has been shown to affect the operating speeds as well as the free-flow speeds, with higher speed limits resulting in higher speeds (Al-Masaeid et al., 1999; Figueroa-Medina & Tarko, 2004; Fitzpatrick, Carlson, et al., 2000; Hamzeie et al., 2017; Savolainen et al., 2018b; Ye et al., 2001). A study reported an increase of 3 mph in the operating speeds when the speed limits were increased from 55 mph to 65 mph (Mannering, 2007), while a separate study reported an average increase of 6 mph when the speed limits increased from 55 mph (car)/55 mph (truck) to 65 mph/60 mph on arterial roads during daytime (Ye et al., 2001). During nighttime, the increase in operating speeds of trucks was only 1.23 mph. On short tangent sections, the speeds are also influenced by the geometry of preceding and succeeding curve sections. However, on long tangents, the speed is primarily influenced by speed limits, level of enforcement, roadway cross-section, and longitudinal slope (Abishai Polus et al., 2000). Najjar et al. (Najjar et al., 2000) developed an artificial neural network model to model the relationship between 85th percentile speeds and roadway characteristics on two-lane highways in Kansas, and found that the shoulder width, shoulder type (pavement/combination or turf/gravel), traffic volume, percentage of no-passing zones significantly affect the 85th percentile speeds.

Access point density and signal density have also been shown to affect the operating speeds on non-freeways (Gluck et al., 1999; Torbic et al., 2012). Each traffic signal per mile added to a roadway reduces speed by about 2 to 3 mph, whereas, a reduction of 0.25 mph in the speeds is estimated for every access point up to a 10-mph reduction for 40 access points per mile. Multilane highways with two-way left turn lanes or median barriers have also been shown to exhibit lower operating speeds (Torbic et al., 2012).

Few studies have also studied the effects of adverse weather conditions on operating speeds. Generally, the drivers are more likely to driver slower during snowy conditions, as compared to other adverse weather conditions such as rain, fog, or sleet (Ghasemzadeh et al., 2018; Hamzeie et al., 2017). Speeds were shown to be 2.5 mph lower in rainy weather and 11 mph lower during snow or sleet, as compared to normal weather conditions (Hamzeie et al., 2017). Several driver demographic characteristics such as age, gender, marital status, driving frequency, income, education level, age when driver got license, drivers' assessment of pavement quality and vehicle also affect the driver speed selection (Anastasopoulos & Mannering, 2016; Mannering, 2007; Sadia et al., 2018).

2.3.3 Factors Affecting Safety Performance

This section briefly discusses the various factors that affect safety performance of non-freeways. Engineering-related factors which impact safety along two-lane highway segments have been shown to include traffic volume, horizontal and vertical alignment, lane/shoulder/median width, and the presence of roadside features and traffic control devices, among other (American Association of State Highway and Transportation Officials (AASHTO), 2010).

The safety literature generally suggests that increasing the non-freeway speed limit would likely result in an increase in the overall crash rate and would also shift the severity distribution toward more severe crashes due to the increase in the energy dissipated during crashes due to vehicles traveling at higher speeds (Kockelman, 2006). Increasing the non-freeway speed limit from 55 mph to 65 mph would increase the total crash rate by 3.3 percent, and the probability of a fatality (assuming a crash had occurred) would increase by 24 percent. The injury crash risk was also expected to increase with increasing speed limits (Kockelman, 2006). Garber et al. (N. Garber & Gadiraju, 1988) modeled the relationship between crash rate and speed dispersion, while considering various other factors including the posted speed limits. The study found that when the difference between design speed and posted speed limit is less than 10 mph, the speed dispersion was minimum resulting in better safety performance.

As seen before, the horizontal curvature reduces the operating speeds along non-freeways. Similarly, the horizontal alignment has also been shown to negatively impact the safety performance of these highways (Glavic et al., 2016; Harwood et al., 2000, 2014; Labi, 2006; Miaou & Lum, 1993; A. Polus, 1980; C. V. Zegeer et al., 1991; C. V Zegeer et al., 1987). More specifically, the following traffic, roadway, and geometric features have been found to affect the safety on horizontal curves (C. V. Zegeer et al., 1991; C. V Zegeer et al., 1987):

- Traffic volume on the curve and truck percentage
- Curve features (degree of curve, curve length, super-elevation, presence of transition curves)

- Cross sectional curve element (lane-width, shoulder width, shoulder type, shoulder slope)
- Curve section roadside hazard features (such as clear slope, rigidity, and types of obstacles)
- Stopping sight distance on curve
- Vertical alignment on horizontal curve
- Distance to adjacent curves
- Distance of curve to nearest intersection, driveway, etc.
- Pavement friction
- Presence and type of traffic control devices (signs and delineation).

Similar to horizontal alignment, vertical alignment has also been shown to impact the safety performance of non-freeways. Prior research has shown that steeper vertical curves are associated with increased crash rates (Kockelman, 2006; A. Polus, 1980). However, a Kockelman study (Kockelman, 2006) showed that injuries tend to be less severe on steeper vertical grades. The presence of hidden horizontal curves, intersections, or driveways along a crest vertical curve tend to increase crash frequency (Harwood et al., 2000).

Signal spacing and access point density also affect safety along non-freeways. As the number of intersections, and/or driveways per mile of highway increases, the crash frequency also increases (American Association of State Highway and Transportation Officials (AASHTO), 2010; Gluck et al., 1999; Michigan Department of Transportation, 2001). This is because the presence of an access point makes the driver more vulnerable to driving errors which may result in rear-end and/or sideswipe type crash (American Association of State Highway and Transportation Officials (AASHTO), 2010). An increase from 2 to 4 signals per mile can increase crash rate by 40% (in Georgia) to 150% (in Florida). In urban and suburban areas, each access point added would increase the annual crash rate by 0.11 to 0.18 on undivided highways (Gluck et al., 1999).

Several other roadway and roadside characteristics such as number of lanes, presence of medians, lane width, shoulder width, side slopes, and presence of passing zones significantly affect safety along non-freeways. Kockelman showed in his study (Kockelman, 2006) that roadways with four or five travel lanes tend to have higher crash rates than those facilities with two or three lanes. Addition of a median can reduce crash rates by nearly 9%, assuming all other factors remain constant (Kockelman, 2006). Wider lane widths have been associated with reduced run-off-the-road, sideswipe, head-on crashes (American Association of State Highway and Transportation Officials (AASHTO), 2010). The effect of lane width on safety performance is reduced for multilane highways as compared to two-lane highways. The safety performance impact is equal to approximately 75 percent and 50 percent to that of two-lane highways for undivided and divided multilane highways, respectively (Michigan Department of Transportation, 2013).

The shoulder width affects the crash frequency in a similar manner. Crash frequency tends to increase as paved shoulder widths are reduced below 6 ft. Although this effect is related to the traffic volume on the non-freeway being considered (American Association of State Highway and Transportation Officials (AASHTO), 2010). However, a separate study (N. Garber & Ehrhart, 2000) reported that the lane width and shoulder width have no effect on the crash rate along two-lane highways. Side slopes have also been shown to affect the safety performance along non-freeways (V. et al., 1988). Flatter side slopes of 3:1 to 7:1 were found to be related to lower rates of single-vehicle crashes. General roadside improvements can lead to a 19%-52% reduction in crashes. The Highway Safety Manual (HSM) (American Association of State Highway and

Transportation Officials (AASHTO), 2010) also mentions that the presence, length, and location of passing zones within two-lane highways may affect the safety along these highways.

2.4 Literature Summary

The literature indicates that raising the speed limits usually leads to reduced safety and higher operating speeds. However, the changes in the mean, and 85th percentile speeds are less pronounced as the changes in the speed limit itself. For example, Musicant et al. (Musicant et al., 2016) in a meta-analysis study showed that when speed limits were increased, mean speeds increased, but to a lesser degree than the actual increase in limits. When speed limits were reduced, the reduction in mean speeds also tended to be inelastic as compared to the change in limits. Additionally, it has also been noted that the speed increases with speed limit increase, with average vehicle speed increasing by less than half the amount of speed limit increase (Kockelman, 2006).

In terms of safety on limited access rural freeways and interstates, the collective literature shows that the fatalities are consistently higher among those states with higher maximum statutory speed limits (Davis et al., 2015; Farmer, 2017; Warner et al., 2019b). However, research has also shown the safety performance of these facilities to have improved over time regardless of the maximum limit. **Error! Reference source not found.** shows the fatality rate trends from 1999 to 2011 with respect to maximum statutory speed limits (Davis et al., 2015). A meta-analysis study reported the average impacts on traffic crashes and injuries were shown to be nearly proportional to the change in speed limits (Musicant et al., 2016). A positive relationship between speed limits and traffic fatality count is generally found considering both statewide roads, and just a subset of road network, such as, rural interstates (Castillo-Manzano et al., 2019).

On non-limited access freeways, speeds, speed limits, and safety are equally important. The literature generally suggests that increasing speed limits on non-freeways result in an increase in overall crash rate and fatality rate. Additionally, higher speed limits lead to higher proportion of more severe crashes due to the increase in the energy dissipated during crashes due to vehicles traveling at higher speeds. Thus, careful considerations should be made while raising speed limits, especially on rural two-lane highways as they have a disproportionate number of head-on collisions, as well as run-off-road crashes into roadside areas with hazardous fixed objects. Additional research is warranted to fully understand the nature of the relationships between operating speed, posted speed limits, and safety.

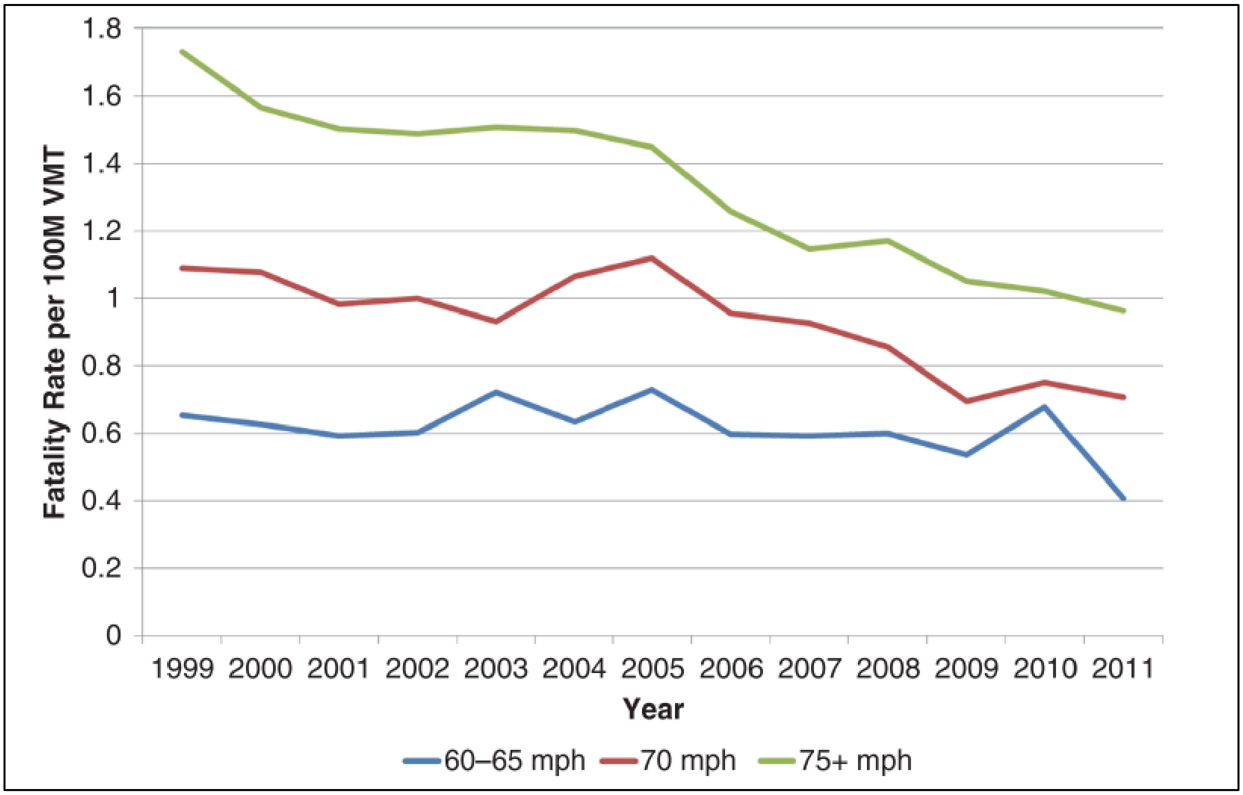

Figure 2.3 Annual Rural Interstate Fatality Rates by Maximum Speed Limit (A. Davis et al., 2015b)

3. EFFECT OF FREEWAY SPEED LIMIT INCREASE ON TRAFFIC OPERATIONS

Following the 2017 Michigan legislation, the posted speed limits were raised from 70 mph to 75 mph (60 mph to 65 mph for trucks) on 614 miles of freeways. These increases in the speed limits have affected the speed trends on the Michigan limited-access roadway network. More specifically, the speed limit increases have affected the speed distributions (15th percentile, 50th percentile, 85th percentile), mean speed, as well as variance of speed. This chapter presents a comprehensive analysis of the changes in speed trends as a result of speed limit increases on freeways.

3.1 Data Collection

The study required collection of extensive speed data from multiple freeway locations, spread over the sites where the speed limit increase has occurred as well as similar sites where speed limits did not increase. The speed data were obtained from multiple sources wherever available including hand-held LIDAR, data from permanent traffic recorder (PTR) stations, and probe vehicle data from Regional Integrated Transportation Information System (RITIS). The speed data were then integrated with other relevant information such as traffic volume and roadway geometric characteristics. Following sub-sections details the relevant data used, data collection and integration procedures.

3.1.1 Free-Flow Speed Data Collection by LIDAR

Hand-held LIDAR (Light Detection and Ranging) guns were used to collect free-flow speeds on freeways. Collecting speed data using video cameras posed a challenge on freeways due to high speeds prevalent on the limited-access facilities. Therefore, LIDAR method was utilized where an unmarked vehicle was parked as far as possible from the mainline traffic and the spot speed data were recorded. For collecting data using LIDAR, a total of 79 freeway locations were identified which were spread across 5 different MDOT regions, namely, Bay Region, Superior Region, Grand Region, North Region, and the University Region. The 79 total sites were segregated into two groups, 20 control sites (sites where speed limit did not increase) and 59 increase sites (sites where speed limit increased). The control sites were selected in such a way that the road and traffic characteristics were reflective of increase sites. The spot speed data using LIDAR was collected manually at each of these sites starting in 2017. The data were collected for two different time periods, before-period (prior to speed limit increase), and after-period (post speed limit increase). The before-period data were collected in the late spring and summer of 2017, and the after-period data were collected for 4 years from 2017 to 2020 under normal weather conditions. All the data were collected on weekdays during daylight hours under dry pavement conditions. Further, 8 sites out of 79 total sites were located along a horizontal curvature while the rest were on tangent sections. Figure 3.1 shows the locations of the selected sites.

While collecting the data in the field, the vehicles were selected randomly for speed measurement. At each of the sites, the data were collected until either 100 passenger car observations were recorded, or one hour had elapsed, whichever occurred first. Separate observations for heavy vehicles, which included trucks, single units, and buses were also recorded. Since the objective here was to observe vehicles under free-flow conditions, the speeds of vehicles having at least 4 seconds of time headway were recorded. Several other relevant characteristics were also recorded at the time of speed measurements including passenger car volume, heavy vehicle volume, lane position of the vehicle for which the speed is being measured, freeway number and the nearest cross-road, direction of traffic, and date and time of the observation.

For analysis purposes, the data from 2017 to 2019 are utilized, while the data collected in 2020 are analyzed separately to separate out the effects of the COVID-19 pandemic. During 2017-2019, a total of 27,334-speed observations for passenger cars and 4,604-speed observations for heavy vehicles were recorded across all sites.

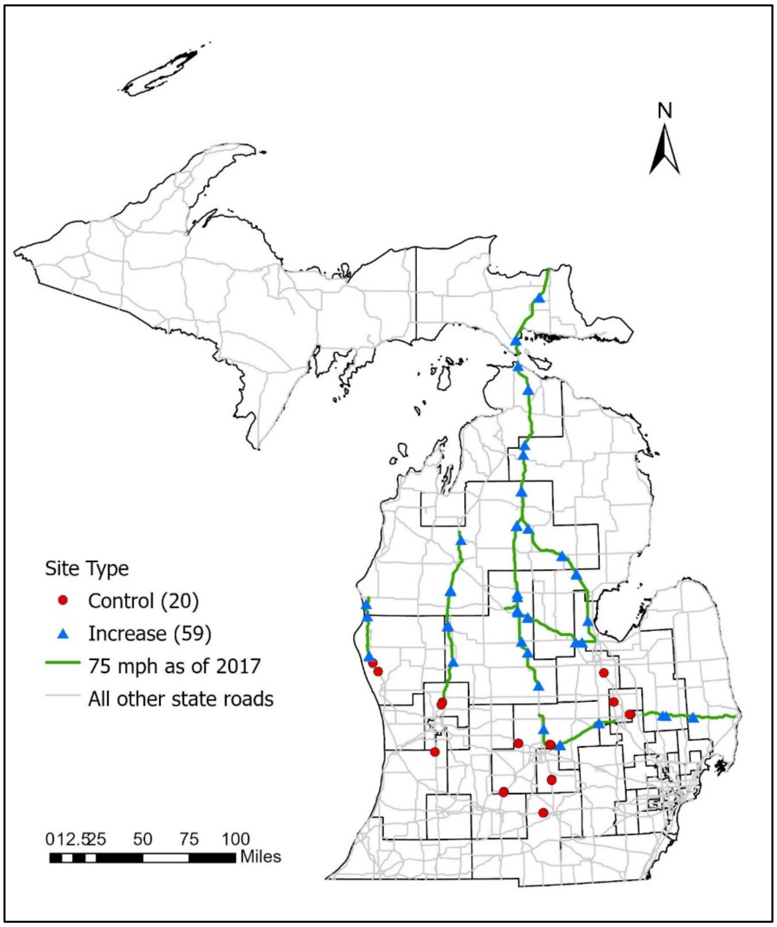

Figure 3.1 Location of LIDAR Data Collection Sites

3.1.2 <u>Speed Data Collection from PTR Stations</u>

PTR stations continuously record the directional count of vehicles, as well their speeds, using electronic sensors installed in the pavement. The data are generally aggregated on an hourly basis each day. For the purposes of this study, 12 PTR stations located on highway segments where the speed limits were increased, and 23 PTR stations on highway segments where no speed limit change occurred were identified as increase sites and control sites, respectively. It was ensured that the control sites had similar roadway and traffic characteristics as the increase sites. Thus, PTR stations in urban areas were avoided. Figure 3.2 shows the location of the control and increase PTR stations included in the study.

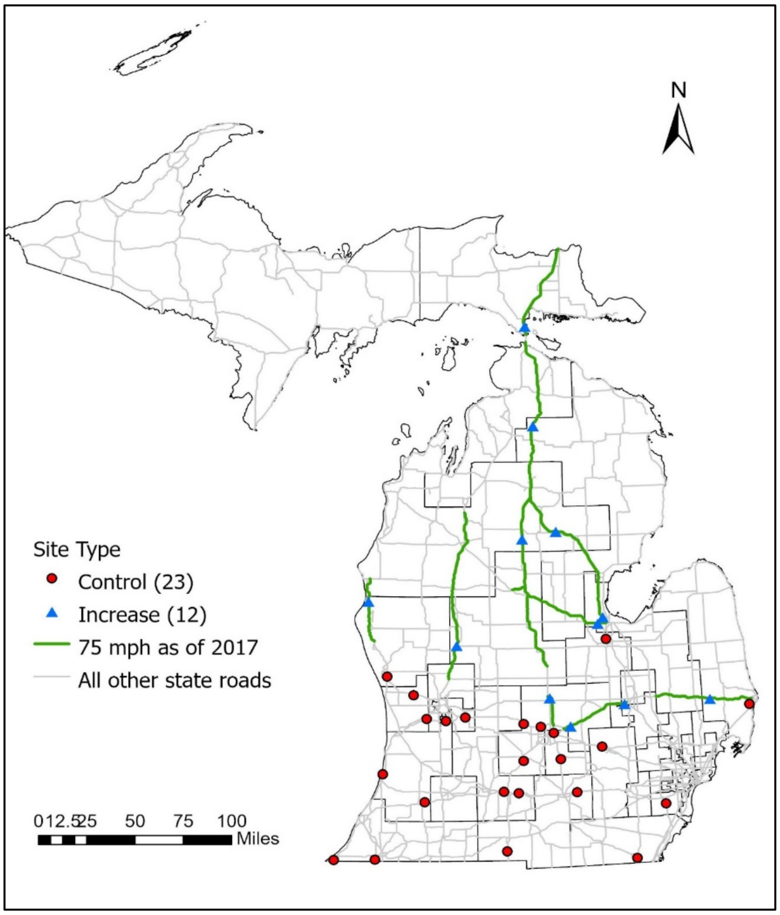

Figure 3.2 Location of Increase and Control Sites for PTR Data

Hourly aggregated speed data, which included speeds at different percentiles, mean speed, and standard deviation of speeds were obtained from these 35 PTR stations from MDOT starting from 2014 to 2019 excepting 2017. The period from 2014 to 2016 was considered as the before period and 2018 to 2019 was considered as the after period. The speed limit changes across various segments occurred during different months of late 2017, therefore, speed data from 2017 was not included in the PTR data analysis. As vehicle speeds can vary based on weather conditions, the year was divided into the four seasons as they present in Michigan: fall (October to November), winter (December to March), spring (April to June), and summer (July to September). To account for time of day variations, the day was divided into four periods: morning (6 to 11 a.m.), afternoon (11 a.m. to 4 p.m.), nighttime (7 to 11 p.m.), and midnight (11 p.m. to 6 a.m.). The data were subjected to manual quality assurance checks. To account for the volume of heavy vehicles, additional traffic volume data were obtained through MDOT open geographic information system data and integrated with the PTR dataset. These volume data were used to determine the percentage of commercial annual average daily traffic at each of the PTR stations.

3.1.3 Speed Data Collection from Probe Vehicles

Probe vehicle data are collected from global positioning systems (GPS) that are installed in a wide variety of vehicles and cell phones. The GPS devices send and receive signals from earth-orbiting satellites, which are converted to display real-time location and speed data for the probe vehicle. The probe vehicle data were provided by MDOT dating back to January 1, 2016, and include real-time speed information at various time intervals (e.g., 1, 5, 10, and 15 min, and 1 h). Initially, this study aimed to compare speed trends between 2016 (before period) and 2018 to 2019 (after period). However, a quality control review of the data showed a significant inflection point where speeds increased significantly in June 2019. This was the result of changes in the fleet from which the probe vehicle data were collected. Because of a significant reduction in the proportion of heavy vehicles in the fleet, increases of 5 mph or more were shown across locations in the speed data. Consequently, the before–after comparisons considering probe vehicle data focused only on data from calendar years 2016 and 2018.

Probe vehicle speed data were ultimately obtained for the entire Michigan freeway network. The segments were divided into control- and increase segments based on their speed limits in the after period. Figure 3.3 shows the control and increase segments considered in the probe vehicle data analysis. The speed data were obtained in 15-min intervals and were subsequently aggregated at a 24-h analysis level for each segment. The speed data were merged with traffic volume information and site-specific geometric data, which were obtained from MDOT. Similar to the case of the PTR dataset, the data were divided into four subsets to account for seasonal variations.

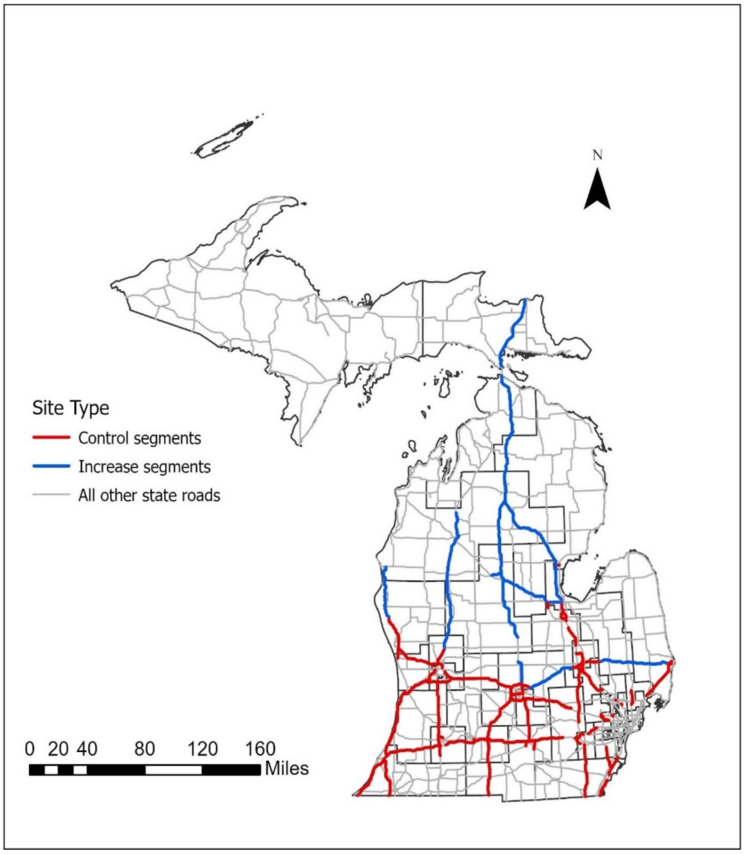

Figure 3.3 Control and Increase Segments for Probe Vehicle Data

3.1.4 Traffic Volume and Roadway Geometry Data

Details about Michigan roadway geometry data were also obtained from MDOT. The database had detailed information about the geometry of each individual segment. This included information about number of lanes, lane width, type of median and median width, width of left and right shoulders, speed limit, presence of signals, passing lanes, turn lanes, sight restrictions, horizontal curves among others.

Traffic volume information were also obtained from MDOT. MDOT provides annual average daily traffic (AADT) volume data for the entire MDOT maintained road network on a yearly basis in the form of GIS shapefiles. The AADT data can be integrated with the sufficiency file using spatial join in GIS. However, upon manual review of the AADT data, it was found that there was considerable year-to-year variability in the AADT values, especially beginning 2017. Hence, it was decided to review the AADT volume data in greater detail. Each segment was reviewed manually to identify scenarios where the shapefile data varied considerably from year to year. The AADT data on these segments were compared to raw count data which is published online on the MDOT Transportation Data Management System (TDMS). Upon review, AADT data were replaced with segments via manual process to ensure volumes were consistent throughout the study period (2017-2019).

3.2 Data Summary

The aggregated and integrated data were prepared for each of the cases: free-flow speed data, aggregated PTR speed data, and probe vehicle data. In each of the cases, the site type (control, increase) and period of data (before, after) were combined to form four binary indicator variables: before–control (period= before, site type= control), before–increase (period= before, site type= increase), after–control (period= after, site type= control), and after–increase (period= after, site type= increase). This helped to directly assess the impacts of speed limit increase on the control and increase sites. Table 3.1 presents the descriptive statistics of each variable included in each of the analysis datasets.

Table 3.1 Descriptive Statistics of Pertinent Variables

Parameter	LIDAR Data (255 site-hours)		PTR Data (2,551,528 site-hours)		Probe Vehicle Data (3,771,114 site-days)	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Period and Site Type						
Before-control sites (1 if yes; 0 if no)	0.08	0.27	0.39	0.49	0.31	0.46
Before-increase sites (1 if yes; 0 if no)	0.23	0.42	0.21	0.41	0.19	0.39
After-control sites (1 if yes; 0 if no)	0.19	0.39	0.26	0.44	0.31	0.46
After-increase sites (1 if yes; 0 if no)	0.50	0.50	0.14	0.35	0.19	0.39
Traffic Characteristics						
Traffic volume (veh/hr)	730.68	455.23	719.74	944.21	675.95	374.20
Percent trucks	12.33	6.70	12.73	6.50	12.49	6.78
Road Geometry Characteristics						
Curve geometry (1 if yes; 0 if no)	0.09	0.29	N/A	N/A	0.19	0.39
Median width 90+ ft (1 if yes; 0 if no)	0.52	0.50	0.46	0.50	0.36	0.48
Right shoulder 11+ ft (1 if yes; 0 if no)	0.15	0.36	0.30	0.46	0.27	0.45
Temporal Variables						
Winter season	N/A	N/A	0.28	0.45	0.33	0.47
Spring season	N/A	N/A	0.25	0.43	0.25	0.43
Summer season	N/A	N/A	0.28	0.45	0.25	0.43
Fall season	N/A	N/A	0.19	0.39	0.17	0.37
Morning (6am-11am)	N/A	N/A	0.21	0.41	N/A	N/A
Afternoon (11am-4pm)	N/A	N/A	0.21	0.41	N/A	N/A
Evening (4pm-7pm)	N/A	N/A	0.12	0.33	N/A	N/A
Night (7pm-11pm)	N/A	N/A	0.17	0.37	N/A	N/A
Midnight (11pm-6am)	N/A	N/A	0.29	0.46	N/A	N/A
Speed Metrics (mph)						
15^{th} percentile speed	67.07	2.62	62.72	11.08	62.67	3.38
50^{th} percentile speed	74.42	1.92	70.88	8.27	65.30	2.67
85^{th} percentile speed	79.04	1.69	77.13	6.14	69.07	3.08
Standard deviation of speed	5.68	0.56	8.30	4.25	3.58	1.58

As noted previously, the PTR and LIDAR data were both aggregated at a level of fidelity of 1 h. In contrast, the probe vehicle data were aggregated at a daily level over the entire year.

Consequently, the sample sizes were different between the sources, particularly in the case of LIDAR. For the LIDAR data, each row corresponds to 1 site-h (79 sites 3 4 years, with 61 missing site-years), each row in the PTR data corresponds to 1 site-h in one direction (35 sites 3 5 years 3 365 days 3 24 h, with some missing site-h), and each row in the probe vehicle data corresponds to 1 site-day (5,166 sites 3 2 years 3 365 days, with some missing site-days). Therefore, the sample size for the LIDAR dataset was much smaller than the other two data sources.

Figure 3.4 presents the aggregated summary of the three basic speed characteristics: mean, 85th percentile, and standard deviation of speeds for the increase sites. The results are presented for the free-flow speeds from the LIDAR data, and the aggregated speed data from PTR stations, and probe vehicle data. Spot-speed data collected at individual sites by LIDAR are generally representative of prevailing free-flow speeds. However, this analysis considered only LIDAR data for passenger cars. This was done for several reasons. First, the number of trucks in the LIDAR dataset was consistently sampled at a ratio of 5:1 (i.e., 100 speed observations for passenger cars and 20 for heavy vehicles). Traffic count data showed the study sites served approximately 12% heavy vehicles on average. Furthermore, since heavy vehicle speeds were generally much lower than passenger vehicle speeds, combining the data resulted in speed metrics that were actually lower than the PTR data.

The aggregated results from the LIDAR data showed that the mean speeds increased by 2.6 mph, on average, after the speed limit increases were introduced. The corresponding increase in the 85th percentile speed was 2.8 mph. Some small increases were observed in the 2 years after the speed limit increases occurred, though these increases were marginal (up to 0.5 mph). The standard deviation in after-period free-flow speeds, on the other hand, showed no practical increase after the speed limits were increased.

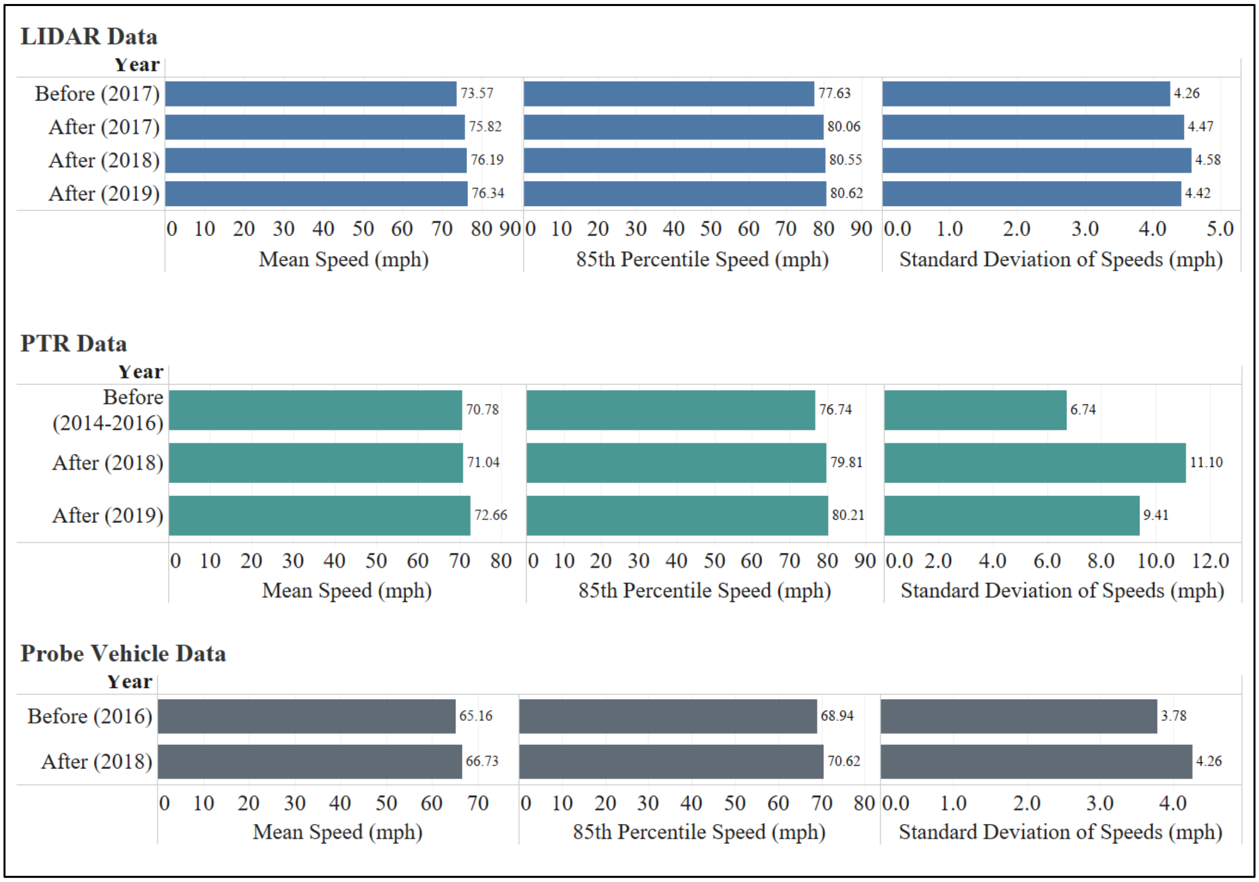

Figure 3.4 Aggregated Speed Trends on Increase Sites Based on Data Source

Turning to the aggregated speed data from PTR stations, the mean and 85th percentile speeds increased by 1.1 and 3.3 mph, respectively, after the speed limit increase. The increases in the standard deviation of speeds were 4.4 mph after 1 year and 2.7 mph after 2 years of speed limit increases. There are at least two reasons for the higher variability in speeds in the PTR data as compared to the other data sources. First, the PTR data include the speeds of both passenger cars and heavy vehicles. As such, higher variability in speeds was expected compared with the LIDAR data, which included only speeds from free-flowing passenger vehicles. Second, the method used to calculate the standard deviation in each of the datasets was different. In the case of LIDAR data, the variability in speed at a particular site was calculated based on individual vehicle speeds. In contrast, the PTR speed data were aggregated into 5- mph bins. Therefore, there was a loss of information as speeds within each bin were assumed to be equal to the bin midpoint when calculating the standard deviation. These two factors introduced additional variability when speeds were compared between the two sources. Additionally, the variation in PTR speeds after the speed limits were increased was much higher than in the before period. This suggests that different groups of drivers increased their speeds by different magnitudes. However, the reduction in the standard deviation of speeds in 2019 compared with 2018 suggests that the changes in travel speeds among drivers might become more stable with time.

Finally, the probe data showed that mean speeds increased by nearly 1.6 mph, whereas the 85th percentile speeds increased by 1.7 mph. The standard deviation of speed increased by about 0.5 mph. It should be noted that the probe vehicle data reflected the average speed of the traffic stream at any given time over extended freeway segments as compared to the point measurements obtained from the LIDAR and PTR data sources. Furthermore, there were substantial differences in the magnitude of the speed metrics for the probe vehicles as compared to the LIDAR and PTR data. These differences ranged from 5 to 10 mph for specific cases. This is largely a byproduct of the sampling scheme for the probe vehicle data, which included a disproportionate number of heavy vehicles that tend to introduce a downward bias as compared to the distribution of all vehicle speeds. Further, as raw speed data were not directly available, nor were data characterizing the distribution of probe vehicles in the sample, some caution should be exercised when comparing probe vehicle speeds with other data sources. Nonetheless, there are several prospective advantages to the use of such data that indicate vehicles provide an appealing source for the evaluation of speed trends at a large scale.

3.3 Statistical Analysis

To assess the impacts of speed limit increases on driver speed selection, statistical models are developed for four variables: 15th percentile speed, 50th percentile speed, 85th percentile speed, and standard deviation of speed as shown in equation 2.

$$\begin{aligned} s_{15,i} &= \beta_1 X_i + \varepsilon_{1i} \\ s_{50,i} &= \beta_2 X_i + \varepsilon_{2i} \\ s_{85,i} &= \beta_3 X_i + \varepsilon_{3i} \\ sd_i &= \beta_4 X_i + \varepsilon_{4i} \end{aligned} \qquad (2)$$

Where, $s_{15,i}$, $s_{50,i}$, $s_{85,i}$, and sd_i are the 15th, 50th, 85th percentile speeds, and standard deviation of speeds, respectively at site *i*. X_i is a vector of explanatory variables, β are vectors of parameters to be estimated, and ε are error terms.

The ordinary least squares (OLS) regression technique can be utilized to develop individual regression equations for each of the four dependent variables. For unbiased parameter estimates, OLS assumes that the model accounts for all the information relating to the regression variables (S. Washington et al., 2011). However, it is impractical to account for all possible information in a regression equation. This missing information is accounted for by the error term in the model. In a model with multiple equations, such as the one proposed in this study, it is reasonable to assume that the error term of one equation is correlated with the error term in another equation. This is because the unobserved variables that affect the driver speed selection will affect each of the three percentiles as well as the speed variance. In estimating such models with contemporaneous cross-equation error correlation, seemingly unrelated regression equations (SURE) provide higher efficiency compared to OLS and are able to account for correlations between the error terms (Zellner, 1962).

Parameter estimation in the SURE model is achieved using generalized least squares (GLS). Under OLS estimation, the estimated parameters are given as shown in equation 3, where n is the number of observations, p is the number of parameters, $\hat{\beta}$ is $p \times 1$ column vector of estimated parameters, X is an $n \times p$ matrix of data, and Y is an $n \times 1$ column vector.

$$\hat{\beta} = (X^T X)^{-1} X^T Y \quad (3)$$

GLS generalizes equation 2 by using a matrix that considers correlation among error terms of different equations (Ω) as shown in equation 4. The matrix Ω is estimated from initial OLS estimates of individual equations (S. Washington et al., 2011).

$$\hat{\beta} = (X^T \Omega^{-1} X)^{-1} X^T \Omega^{-1} Y \quad (4)$$

The SURE models were estimated using R-studio. Several variables that characterized the site conditions were included in the model. This included binary indicator variables for type of site (control or increase) and period of study (before or after), traffic volume, width of the shoulder, shoulder type, and width of the median.

3.4 Results and Discussion

The changes in travel speeds, as shown in the aggregated speed trends in Figure 3.4, cannot be solely attributed to speed limit increases. Other site-related factors, such as changes in traffic volume and site geometric characteristics, may have influenced the change in speed as well. Thus, the effect of these factors was accounted for in the statistical models as shown in Table 3.2, Table 3.3, Table 3.4 for LIDAR, PTR-, and probe vehicle data, respectively. The standard error for each of the estimates is provided in parenthesis and the statistically significant parameter estimates at a 95% confidence level are marked by an asterisk. The same set of predictors were used in both models, as much as possible, to investigate the effect of the same variables on free-flow speed distributions as well as aggregated speed distributions.

As discussed previously, the SURE modeling technique was used to model the different speed metrics for the free-flow speed as well as the aggregated PTR- and probe vehicle speeds separately. Furthermore, since the truck percentage at each of the sites was relatively low, the modeling for LIDAR data was undertaken only for passenger cars. This ensured the comparison between LIDAR- and aggregated speed data would be reasonable, for the reasons mentioned previously.

Table 3.2 SURE Model Parameter Estimates for LIDAR Data

	Estimate (Std. Error)			
Parameter	15^{th} Percentile Speed	50^{th} Percentile Speed	85^{th} Percentile Speed	Standard Deviation
Intercept	69.76 (0.38)*	74.34 (0.29)*	78.91 (0.29)*	4.54 (0.11)*
Period and Site Type				
Before-control		Baseline		
Before-increase	0.62 (0.44)	-0.82 (0.33)*	-1.31 (0.31)*	-0.28 (0.13)*
After-control	0.36 (0.44)	0.49 (0.33)	0.47 (0.32)	0.05 (0.13)
After-increase	1.68 (0.41)*	1.86 (0.31)*	1.45 (0.29)*	-0.04 (0.12)
Percent Trucks	-	-	-0.01 (0.01)*	-
Road Geometry				
Tangent		Baseline		
Curve	-1.78 (0.37)*	-0.89 (0.28)*	-0.57 (0.27)*	0.33 (0.10)*
Median Width(ft)				
< 90		Baseline		
>= 90	0.48 (0.19)*	0.33 (0.16)*	0.42 (0.16)*	-

3.4.1 Effect of Speed Limit Increases

The model results showed that the increase in speed limit significantly affected both free-flow speeds, as well as the aggregated PTR speed and probe vehicle speed distributions on freeways as indicated by the period and site type variables. However, it is interesting to note that the increases were more pronounced in aggregate PTR speeds as compared to free-flow- and probe vehicle speeds. Before the speed limit increases, the sites where such increases went into effect had marginally lower free-flow speeds compared with the control sites. This was true for 50th, and 85th percentile speeds, but not for 15th percentile speeds. The aggregated PTR speeds showed similar results in which the 15th percentile speeds were higher by 0.9 mph, but the 50th, and 85th percentile speeds were lower by 0.6 and 0.4 mph, respectively, where the increases eventually occurred. The probe vehicle speed data also showed that the 15th and 50th percentile speeds on such sites were 0.7 and 0.4 mph higher than on the control sites. However, the 85th percentile speeds were lower by 0.4 mph.

Table 3.3 SURE Model Parameter Estimates for PTR Data

	Estimate (Std. Error)			
Parameter	15th Percentile Speed	50th Percentile Speed	85th Percentile Speed	Standard Deviation
Intercept	63.10 (0.03)*	70.93 (0.02)*	75.95 (0.01)*	6.53 (0.01)*
Period, and Site Type				
Before-control		Baseline		
Before-increase	0.90 (0.02)*	-0.57 (0.01)*	-0.26 (0.01)*	-0.64 (0.01)*
After-control	-1.77 (0.02)*	-0.47 (0.01)*	0.51 (0.01)*	2.73 (0.01)*
After-increase	0.55 (0.02)*	2.06 (0.02)*	2.92 (0.01)*	2.88 (0.01)*
Percent Trucks	-0.16 (0.001)*	-0.15 (0.001)*	-0.06 (0.001)*	0.05 (0.001)*
Season				
Winter		Baseline		
Spring	1.87 (0.02)*	2.06 (0.01)*	1.60 (0.01)*	0.10 (0.01)*
Summer	3.25 (0.02)*	2.71 (0.01)*	1.82 (0.01)*	-0.38 (0.01)*
Fall	2.98 (0.02)*	2.44 (0.01)*	1.60 (0.01)*	-0.66 (0.01)*
Time of Day				
6am-11am		Baseline		
11am-4pm	0.60 (0.02)*	0.50 (0.02)*	0.31 (0.01)*	-0.11 (0.01)*
4pm-7pm	1.40 (0.02)*	0.97 (0.02)*	0.66 (0.01)*	-0.27 (0.01)*
7pm-11pm	0.16 (0.02)*	-0.32 (0.01)*	-0.22 (0.01)*	-0.15 (0.01)*
11pm-6am	-2.23 (0.02)*	-3.05 (0.01)*	-1.91 (0.01)*	0.32 (0.01)*
Median Width(ft)				
< 90		Baseline		
>= 90	-	1.06 (0.01)*	1.03 (0.01)*	0.73 (0.004)*
Right Shoulder Width (ft)				
< 11		Baseline		
>= 11	0.78 (0.02)*	0.56 (0.01)*	0.65 (0.01)*	0.10 (0.01)*

During the after period, speeds generally increased at both the control and increase sites. The free-flow speeds increased by only 0.4 to 0.5 mph at the control sites and this change was not statistically significant at a 95% confidence level. In contrast, free-flow speeds increased by 1.1 to 2.8 mph where the increases went into effect. The increases were at maximum in the 85th percentile speeds and lowest in the 15th percentile speeds. This indicated that faster-moving drivers increased their speed by the maximum amount after the speed limit was increased.

Table 3.4 SURE Model Parameter Estimates for Probe Vehicle Data

	Estimate (Std. Error)			
Parameter	15^{th} Percentile Speed	50^{th} Percentile Speed	85^{th} Percentile Speed	Standard Deviation
Intercept	60.11 (0.005)*	63.97 (0.004)*	68.32 (0.005)*	4.31 (0.003)*
Period, and Site Type				
Before-control	Baseline			
Before-increase	0.71 (0.005)*	0.37 (0.004)*	-0.40 (0.004)*	-0.50 (0.002)*
After-control	1.66 (0.004)*	1.48 (0.003)*	1.05 (0.004)*	0.01 (0.002)*
After-increase	2.08 (0.005)*	1.86 (0.004)*	1.38 (0.004)*	-0.10 (0.002)*
Percent Trucks	0.05 (0.001)*	-0.03 (0.001)*	-0.07 (0.001)*	-0.05 (0.001)*
Road Geometry				
Tangent	Baseline			
Curve	-0.79 (0.004)*	-0.68 (0.003)*	-0.71 (0.004)*	0.06 (0.002)*
Season				
Winter	Baseline			
Spring	1.37 (0.004)*	1.26 (0.003)*	1.39 (0.004)*	-0.10 (0.002)*
Summer	1.57 (0.004)*	1.71 (0.003)*	2.28 (0.004)*	0.13 (0.002)*
Fall	1.05 (0.005)*	0.94 (0.004)*	1.05 (0.004)*	-0.11 (0.002)*
Median Width(ft)				
< 90	Baseline			
>= 90	0.17 (0.002)*	N/A	N/A	-0.04 (0.002)*
Right Shoulder Width (ft)				
< 11	Baseline			
>= 11	0.33 (0.004)*	0.25 (0.003)*	0.41 (0.003)*	0.01 (0.002)*

Interestingly, when considering the aggregated PTR traffic speeds, the 15th and 50th percentile speeds actually reduced by 1.8 and 0.5 mph, respectively, whereas the 85th percentile speed increased by 0.5 mph at the control sites after the speed limits were increased. At the increase sites, the 50th and 85th percentile speeds increased by 2.6 and 3.2 mph, respectively, however, the 15th percentile speeds marginally reduced by 0.4 mph. The data suggested that at the increase sites, the magnitude of the speed increases was greatest among the highest-speed vehicles. This indicated that the drivers in the upper portion of the speed distribution increased their speeds more than other drivers, which was also true for free-flow speeds.

Looking into the probe vehicle data, the 15th, 50th, and 85th percentile speeds on the control sites increased by 1.7, 1.5, and 1.1 mph, respectively after the speed limits were increased. On the increase sites, the magnitude of increases was 1.4, 1.5, and 1.8 mph for the 15th, 50th, and 85th percentile speeds, respectively. As with the other data sources, these results provided further evidence that the increases in speeds were greatest among vehicles traveling at the highest speeds.

The effect of speed limit increases on the standard deviation of speeds was more pronounced when considering the aggregated- as compared to free-flow speeds. This suggests that the speed limit increase did not significantly affect the variability in free-flow speeds, as drivers tended to adjust their speeds by similar amounts under low speed conditions. However, the variability in aggregated PTR traffic speeds and the probe vehicle speed increased significantly after the speed limits were increased. The standard deviation of speed for the PTR data increased by 2.7 and 3.5 mph at the control and increase sites, respectively. The reason for such increased speed variance in the case of the PTR data was that the data included speeds of both heavy vehicles and passenger cars, which introduced variability in speed owing to the different speed limits for each vehicle type. The increase in the standard deviation of speeds at increase sites suggested that different groups of drivers (i.e., high- versus low-speed) increased their speeds by different amounts. Since the speed limit for trucks was increased to 65 mph across all sites (control and increase), we also observed an increase in speed variance at the control sites in the after period. When considering the probe vehicle data, the standard deviation of speeds increased by 0.4 mph at the speed limit increase sites, whereas no change was observed at the control sites. It is important to distinguish that the standard deviation of speed among the probe vehicle data was essentially a measure of the variation in daily speeds on a specific segment over a 1-year period. That is why the scale for this metric is significantly different from those of the other data sources, though the same general trend was observed.

Finally, Figure 3.5 provides a summary of how the primary speed metrics of interest varied by study period (before versus after) and site type (increase versus control) for the LIDAR, PTR, and probe vehicle data. The figure provides a summary of the mean change in each metric, along with the associated 95% confidence interval. The size of these confidence intervals varied considerably and was a function of both the variability in vehicle speeds and the level of aggregation within each data source (e.g., individual vehicle speeds as compared to daily average segment speeds). In any case, the increases in the magnitude of speeds, as well as the variability in speeds, raised potential concerns from a traffic safety perspective.

3.4.2 Effect of Site Characteristics

Considering site and traffic characteristics, the proportion of trucks in the traffic stream also significantly affected the speed distributions. As the proportion of trucks increased in the traffic stream, the free-flow speeds, as well as the aggregated PTR speeds and speeds from the probe vehicles reduced across most of the percentiles. In the case of aggregated PTR speeds, the reduction in speed was highest among the lowest percentile, indicating the slower-moving traffic reduced their speeds even further in the presence of heavy vehicles. The effect of truck proportion on speed variance was also positive for aggregated PTR speeds, whereas no significant effect was found on free-flow speeds. As the proportion of trucks increased, the standard deviation of aggregated PTR speeds also increased. A greater proportion of heavy vehicles is likely to further introduce variation in speed, which was also reflected in the model. However, for the probe vehicle data, opposite trends were observed by which the standard deviation in speeds reduced as the proportion of heavy vehicles increased in the traffic stream.

Considering other road geometric variables, the presence of horizontal curves was associated with various speed metrics, as were median widths and shoulder widths. In the presence of curves, the 15th, 50th, and 85th percentile free-flow speeds were reduced by 1.8, 0.9, and 0.6 mph, respectively. The aggregated speeds from the probe vehicle data also showed similar trends for which the corresponding speed reductions were 0.8, 0.7, and 0.7 mph, respectively. Curves can limit driver visibility, thereby increasing uncertainty, which leads to reduced speeds (47). The standard deviation of free-flow speeds was 0.3 mph higher on curves than on tangent road sections, whereas for the aggregated speeds from probe vehicles, a marginal increase of less than 0.1 mph was observed when navigating curves. Heavy vehicle speeds may be reduced considerably at curved sections to prevent toppling over, which increases speed variability. Both aggregated travel speeds (PTR and probe vehicle), as well as free-flow speeds, were consistently higher as the median width exceeded 90 ft. These larger median widths provide further separation from oncoming traffic, which may explain the higher speeds. Also, the increases in speeds were highest among the drivers at the lowest percentile for free-flow-, aggregated PTR-, and probe vehicle speeds indicating that the slowest moving group of drivers felt more comfortable driving at higher speeds on segments with wider medians. The width of the right shoulder had a similar effect on aggregated PTR- and probe vehicle speeds. As shoulder widths increased, the driving speeds also increased. Again, the effect was more pronounced among the lowest speed (i.e., 15th percentile) group of drivers, whose speeds increased by 0.8 mph as the right shoulder width exceeded 11 ft for PTR speeds, and by 0.3 mph when considering probe vehicle speeds. The speeds of the faster-moving drivers increased by 0.7 and 0.4 mph based on PTR speed data and probe vehicle speed data, respectively. The effect of shoulder width on free-flow speeds was found to be insignificant across all percentiles; therefore, this is not included in the final model. Collectively, the median-and shoulder widths tended to affect the slowest moving drivers the most. Faster-moving drivers tended to maintain their speeds regardless of changes in the roadway geometry.

The median- and shoulder widths were positively related to the standard deviation of aggregated PTR speeds. As stated before, higher median- and shoulder widths affected the groups of drivers differently, with each group changing their speeds by different magnitudes, which increased speed variability. Furthermore, this effect may be more pronounced on passenger vehicles than on heavy vehicles which could further increase speed variance. However, in the case of probe vehicle speed data, the opposite trend was observed for median width: the standard deviation of speeds reduced marginally by less than 0.1 mph as the median width increased. This might be because of the method by which the data were collected. As stated, unlike PTR data, the probe vehicle data did not include individual vehicle speeds but the average speed of the traffic stream. For the aforementioned reasons, wider shoulder- and/or median widths led to higher speeds, particularly for drivers traveling at otherwise lower speeds, leading to a more uniform traffic flow.

Since the PTR data as well as the probe vehicle data were collected year-round, the effects of seasonal variations were also accounted for in the model. As expected, the speeds were significantly higher during the spring, summer, and fall seasons as compared to the winter season for both cases. The extreme snowy conditions during the Michigan winter months caused a reduction in speed across all percentiles. However, again, the drivers in the lowest percentile of the speed distribution were affected the most. This again indicated that the faster-moving drivers tended to maintain their faster speeds during the winter season. However, the effect of winter may be more pronounced on heavy vehicles than on passenger vehicles, with the heavy vehicles reducing their speed by a significantly greater margin than the passenger vehicles. This will increase variability in speeds, which was reflected in the model, as the standard deviation of speeds was generally higher during the winter season.

In the case of PTR speed data, speed was also found to be affected by the time of day. The afternoon (11 a.m. to 4 p.m.) and nighttime speeds (7 to 11 p.m.) were only marginally different from the morning (6 to 11 a.m.) speeds indicating that the drivers tended to maintain their speeds for most of the duration of the day. The evening time (4 to 7 p.m.) speeds were higher than the morning time speeds. However, speeds were reduced by 1.9 to 3.1 mph from 11 p.m. to 6 a.m. This may have been the result of one or more of the following: poor visibility, increased risk of animals crossing the highways during the nighttime, and very large headways that enabled cautious driving. The standard deviation of speeds was also higher during this time period, possibly owing to greater truck volumes.

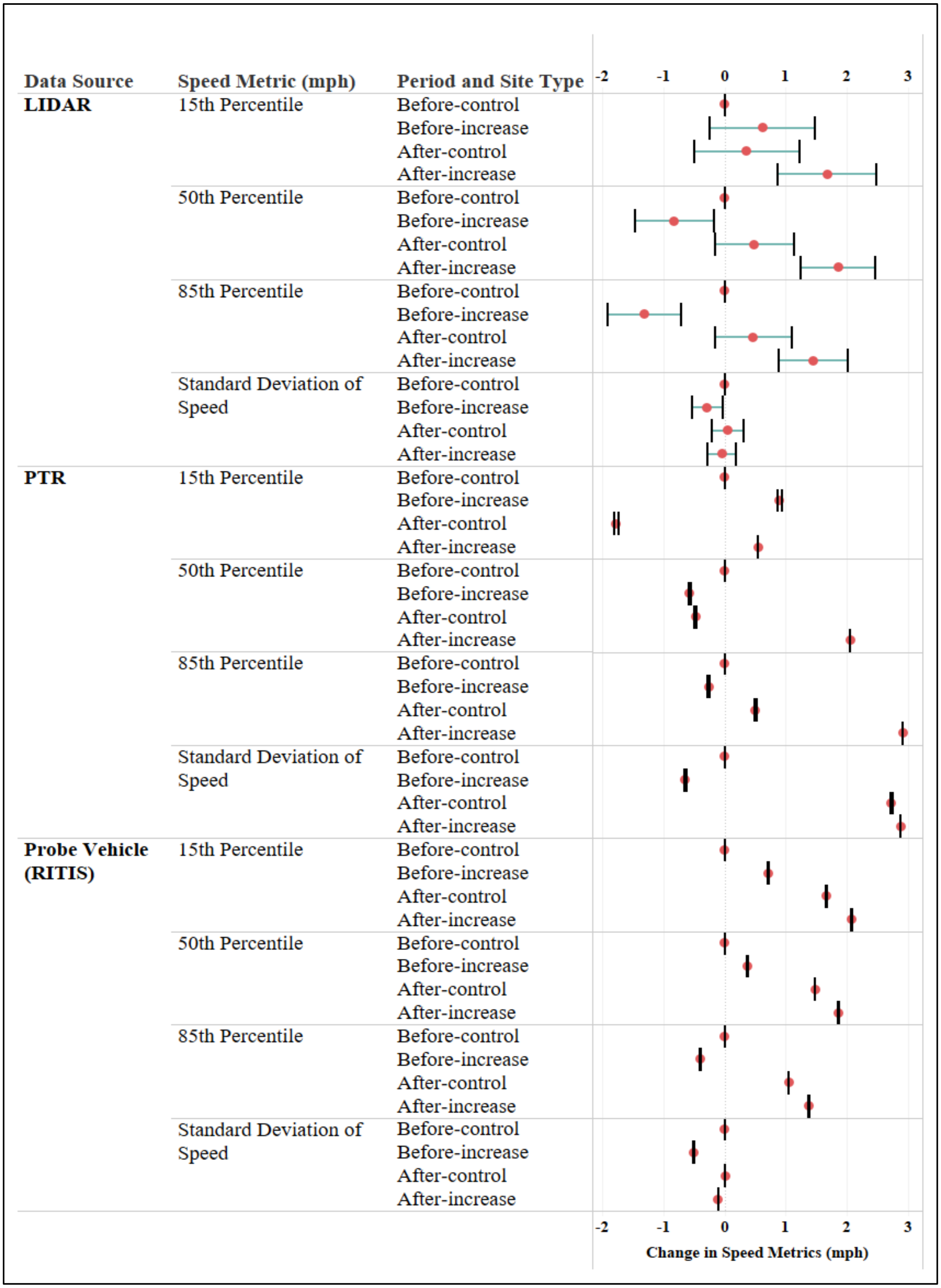

Figure 3.5 Mean Effects and 95% Confidence Intervals for Various Speed Metrics based on Period and Site Type

4. EFFECT OF NON-FREEWAY SPEED LIMIT INCREASE ON TRAFFIC OPERATIONS

As stated above, the speed limits on nearly 943 miles of non-freeways, which primarily included rural two-lane highways were increased from 55 mph to 65 mph. The following sections describe the data collection procedure, data analysis methodology, followed by results and discussion of the analysis carried out for the non-freeway network.

4.1 Site Selection

Before the speed limit increases in mid-2017, the research team identified locations on the MDOT rural two-lane highway network where periodic spot-speed data collection would be performed before and after implementation of the increased speed limit. This included a sample of locations where the speed limit was set to be increased to 65 mph, along with a comparison sample of similar highways where the 55-mph limit would be retained. As the speed limit increases mostly occurred in MDOT's most rural Superior and North regions, the majority of both the speed limit increase and control sites were selected from those areas. Additional control sites were selected from central and southern Michigan to provide representation among other regions where the 55-mph speed limit was retained.

The new speed limit signs were installed at various stages over the summer and fall of 2017. In addition to the speed limit signs, advisory speeds were introduced at various locations, including at speed limit reduction zones entering small towns and at horizonal curves where the speed limit exceeded the prevailing design speed of the facility.

The data collection setup at most locations occurred along straight, flat (i.e., grades less than 2%) sections of highway. However, a select group of horizontal curves with advisory speeds below 55 mph were also included, as such locations have been shown to exhibit disproportionately high numbers of speed-related crashes. Generally, no more than one site was selected per county along a specific highway route. Figure 4.1 provides a map of the routes where speed limits were increased to 65 mph, in addition to identifying locations where data were collected for both the speed limit increase and control sites.

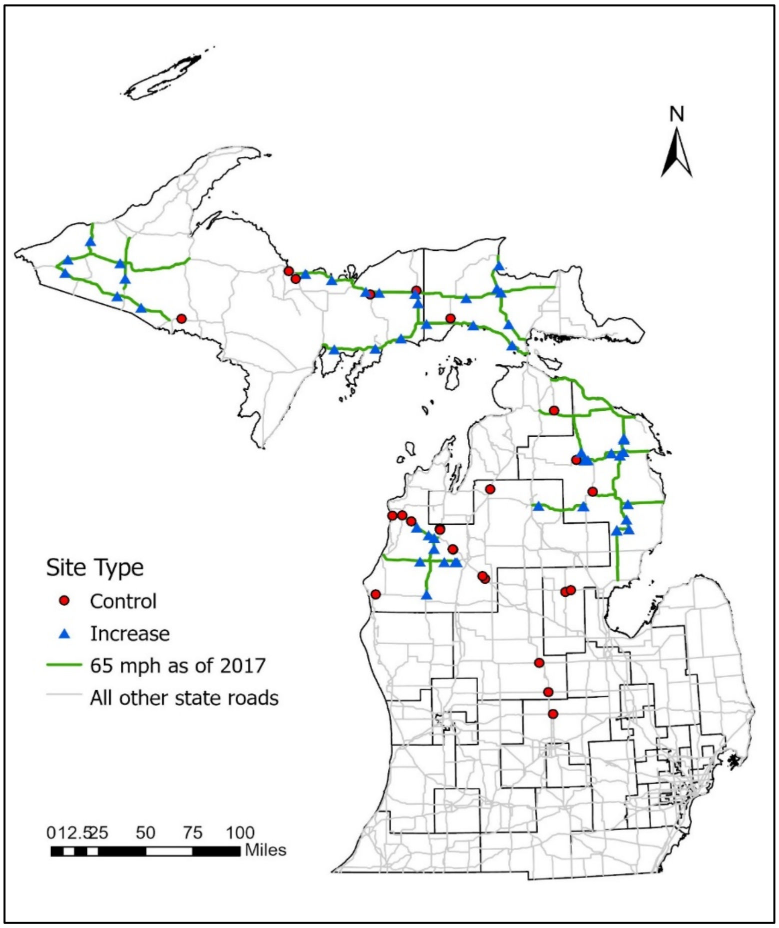

Figure 4.1 Location of Speed Limit Increase and Control Sites for Speed Data Collection on Non-Freeways

Data were collected from a total of 95 sites. At each location, spot-speed data were obtained from covert roadside locations using either elevated high-definition video cameras or handheld light detection and ranging (LiDAR) speed guns. The sites include 67 locations (30 camera sites and 37 LiDAR sites) at which the speed limits were increased, as well as 28 control sites (18 camera sites and 10 LiDAR sites) where the 55-mph limit remained in place. Supplementary site-specific information was also collected using aerial photography, including details such as lane width, shoulder widths, horizontal curvature, and the presence of no-passing zones or passing relief lanes.

4.2 Data Collection

Three waves of speed data collection were performed as a part of this study. The initial wave occurred during the late spring and summer of 2017 before the speed limit increases. Data for the periods after the speed limit increases were collected during late spring and summer of 2018 and 2019. Data were collected between 8:30 a.m. and 6:30 p.m. on weekdays under clear weather and dry pavement conditions.

For the LiDAR data collection, measurements were obtained from an unmarked vehicle parked on a side street, driveway, or parking area that was not readily visible to motorists on the subject highway segment. Specific attention was given to being covert so as not to affect the speed of approaching drivers. At each site, the targets were to collect 100 speed measurements for passenger vehicles and at least 10 for heavy vehicles in each direction of travel. During data collection, only vehicles with a headway of at least 4.0 s were considered to reduce potential impacts of platooning. Owing to the rural nature of these highways, free-flow conditions were typically present during data collection.

For data collection with high-definition video cameras, the cameras were temporarily installed on a telescoping pole at covert roadside locations. After completion of the field video recordings, a team of trained reviewers manually performed a frame-by-frame review of the videos to assess the time required for each vehicle to traverse a fixed distance between known reference markers. Vehicle classification, headway, and hourly volume in the direction of speed data collection during each study period were also recorded. Vehicles were classified as passenger vehicle, passenger vehicle with trailer, truck, single unit, tractor-trailer, motorcycle, farm equipment, or all-terrain vehicle. As the camera dataset included all the vehicles during the observation time, the dataset was filtered to include only vehicle observations with a minimum headway of 4.0 s. Other relevant roadway geometry information was obtained from MDOT as discussed previously in the case of freeway analysis.

The collected and calculated data were tabulated and coded into a single data file for subsequent analyses. The initial dataset included complete records for 62,939 vehicle observations collected across the three data collection periods from the 95 sites. Before the analyses, the dataset was filtered to exclude motorcycles, all-terrain vehicles, farm equipment, passenger vehicles with trailers, and any other observations where free-flow condition could have been compromised (e.g., bicyclist or pedestrian on the shoulder, turning vehicles, passing vehicles, vehicles with brake lights on).

4.3 Data summary

For all analysis purposes, the LIDAR and camera speed data were combined. Figure 4.2 provides a visualized summary of aggregate level changes in the average speed, 85th percentile speed, and speed standard deviation for both passenger cars and heavy vehicles at locations where the speed limit increases occurred. This figure provides details for the periods immediately before, 1 year after, and 2 years after the speed limit increases went into effect and only for the tangent segments (as speeds were significantly different during all periods at the horizontal curve locations).

These aggregate-level results show the average speeds of passenger cars were 3.8 mph higher after 1 year and 4.1 mph higher after 2 years compared with the pre-increase period. For heavy vehicles, these increases were 4.1and 4.5 mph, respectively. The 85th percentile speeds increased by 4.0 mph after 1 year and 5.0 mph after 2 years for both vehicle types. Importantly, the speed standard deviation (averaged across all sites) also increased following the speed limit increase. This suggests there was significant variability in the magnitude of increases across the distribution of drivers.

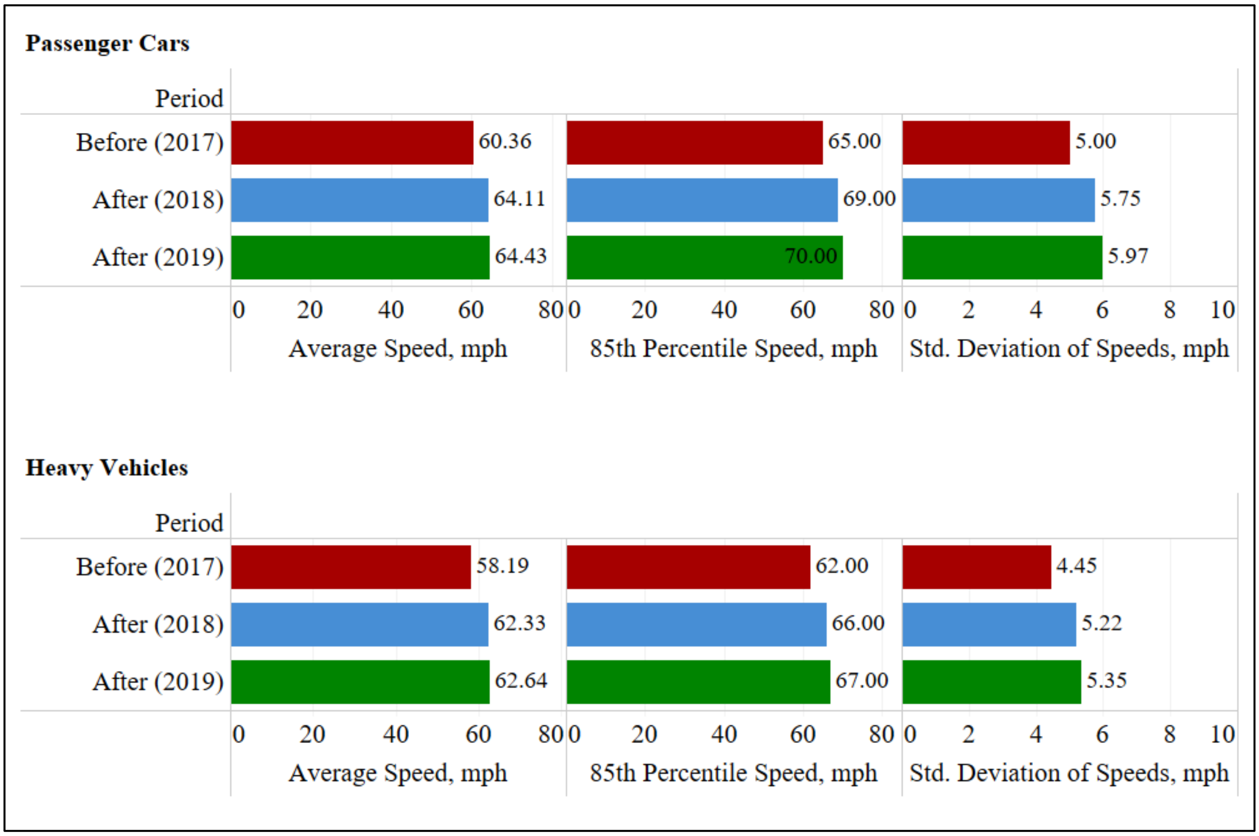

Figure 4.2 Aggregated Speed Trends on Increase Sites by Vehicle Type

Table 4.1 presents the descriptive statistics for each variable included in the final dataset, which included 46,162 free-flowing vehicles. Site types (increase or control) and data collection period (before or after the speed limit increase) were combined and categorized into four groups to test the impact of speed limit change on increase and control segments. Observed vehicles were categorized into passenger cars and heavy vehicles allowing separate analysis for each vehicle types. Sites were also categorized based on the passing permission or presence of passing relief lane in both directions. Roadway geometric characteristics such as lane width and degree of curvature were also used to categorize the collected data. Furthermore, location of the data collection sites in different MDOT regions were also used to categorize collected data.

Table 4.1 Descriptive Statistics of Parameters Considered in Analysis (n = 46,162)

Parameters	Mean	Std. Dev.
Traffic volume (veh/hr)	280.00	247.84
Before-control sites (1 if yes; 0 if no)	0.13	0.33
Before-increase sites (1 if yes; 0 if no)	0.21	0.41
After-control sites (1 if yes; 0 if no)	0.24	0.43
After-increase sites (1 if yes; 0 if no)	0.42	0.49
Passenger vehicle (1 if yes; 0 if no)	0.89	0.31
Heavy vehicle (1 if yes; 0 if no)	0.11	0.31
Normal section or one-way passing lane (1 if yes; 0 if no)	0.90	0.31
Two-way passing lanes (1 if yes; 0 if no)	0.10	0.31
Passing permitted (1 if yes; 0 if no)	0.80	0.40
Passing restricted (1 if yes; 0 if no)	0.20	0.40
Lane width =12 feet (1 if yes; 0 if no)	0.74	0.44
Lane width =11 feet (1 if yes; 0 if no)	0.26	0.44
Degree of curvature =0 (1 if yes; 0 if no)	0.86	0.35
Degree of curvature <5 (1 if yes; 0 if no)	0.08	0.27
Degree of curvature =5-10 (1 if yes; 0 if no)	0.04	0.20
Degree of curvature >10 (1 if yes; 0 if no)	0.02	0.14
MDOT region =Superior (1 if yes; 0 if no)	0.43	0.50
MDOT region =Bay (1 if yes; 0 if no)	0.06	0.24
MDOT region =North (1 if yes; 0 if no)	0.46	0.50
MDOT region =Grand (1 if yes; 0 if no)	0.04	0.19
MDOT region =University (1 if yes; 0 if no)	0.01	0.11

4.4 Statistical Methods

It is important to note that the aggregate data provide results at an aggregate level and do not consider the effects of traffic volume and geometric characteristics. These factors were considered in the regression analysis, along with similar data for the control locations.

Most of the prior studies evaluating impact of speed limit increase utilized aggregated data and compared before-after speed metrics using ordinary least squares (OLS) regression techniques (Enustun et al., n.d.; Gates et al., 2015b; Gayah et al., 2018; Hu, 2017; Retting & Cheung, 2008), ANOVA, and t-tests (Borg, 1975; Dissanayake & Shirazenijad, 2018; R. S. Shirazinejad & Dissanayake, 2018a). Although, these methods have been successful in proving significant changes in speed following the speed limit increases, they lack the ability to provide further details on driver speed selection behavior. While ordinary least squares (OLS) has been the most widely applied method for the analysis of speed data in a regression setting, there are several important limitations to OLS considering the study context. First, speed data tend to be skewed and, as such, the estimates for the conditional mean are not necessarily reflective of the entire speed distribution. Secondly, there is particular interest in the higher and lower quantiles. For example, the 85th percentile is still widely used as a metric for establishing speed limits and, as such, changes in this metric are of particular interest. There is also a potential concern as to drivers who are uncomfortable traveling at the highest speeds, which may result in platooning and high-risk passing by other motorists. Quantile regression is an appealing alternative to OLS as this allows for estimation of the entire conditional distribution rather than just the conditional mean. A few prior studies have successfully utilized quantile regression approach to analyze speed data (Bel et al., 2015; Hewson, 2008). To the best of our knowledge, this is one of the first studies using this technique to evaluate impact of speed limit policy change. For the purposes of this study, the analysis focuses on the 15th, 50th, and 85th percentile speeds. In addition, separate models are estimated for passenger cars and heavy vehicles to determine how speed selection within both groups were impacted by the speed limit increase. Quantile models are similar to OLS linear regression models as they also assume an additive relationship between the dependent variable and the independent variables. However, unlike OLS, quantile regression does not make any assumptions about the distribution of the dependent variable and is more resilient to the influence of outliers (Das et al., 2019).

The general form of the quantile regression model is similar to that of a linear regression model. Quantile levels are denoted by τ, which represents the value of the dependent variable below which the proportion of the conditional response population is τ. Within the context of this study, the quantile regression model takes the form shown in equation 5:

$$Q_\tau(y_i) = \beta_0(\tau) + \beta_1(\tau)x_{i1} + \beta_2(\tau)x_{i2} + \cdots + \beta_p(\tau)x_{ip} + \varepsilon_i \tag{5}$$

where $Q_\tau(y_i)$ is the τth quantile of the speed distribution, x_{ij} are observed independent variables associated with observation i, and ε_i is a random error term with mean equal to zero. The beta coefficients $\beta_j(\tau)$ are now the functions of quantile level τ. The $\beta_j(\tau)$ parameters are estimated by solving the minimization problem:

$$\min_{\beta_0(\tau),\cdots,\beta_k(\tau)} \sum_{i=1}^{n} \rho_\tau \left(y_i - \beta_0(\tau) - \sum_{j=1}^{p} x_{ij}\beta_j(\tau)\right) \tag{6}$$

where $\rho_\tau(r) = \tau \max(r, 0) + (1 - \tau) \max(-r, 0)$. The function $\rho_\tau(r)$ is referred to as the check loss which gives asymmetric weights to each of the individual error r for each data point, depending on the quantile and the sign of the error. The function max () returns the maximum value in the parenthesis. Thus, for positive errors, the check function multiplies the error by τ, and by $(1 - \tau)$ if the error is negative. Minimizing equation 6 results in minimum median absolute deviation for the quantile model. For each quantile level τ, the solution to this minimization problem yields a distinct set of regression coefficients (Koenker, 2005). The quantile regression was conducted using R-Studio in order to estimate a model for the 15th, 50th, and 85th percentile speeds.

The same set of predictor variables were included in each model. This included binary indicator variables for the study period (before vs. after) and site type (increase vs. control), hourly volume during the observation period, lane width, degree of curve, MDOT region, and presence of passing lanes or passing restrictions. Although the dataset included several other variables, including shoulder width and type, terrain, pavement type, and time-of-day, these variables were not found to be statistically significant.

4.5 Results and Discussion

Results of the quantile regression models are provided in Table 4.2 and Table 4.3 for passenger cars (PC) and heavy vehicles (HV), respectively. For each quantile model, parameter estimates are provided, along with standard errors and the p-value that corresponds to the t-statistic used to evaluate whether each of these parameters was significantly different than zero. For each quantile, a separate model and the model equation can be written using the parameter estimates shown in Table 4.2 and Table 4.3. This allows for an interpretation of how speeds at each quantile change with respect to each parameter of interest. It is also important to note that these models have been calibrated such that the baseline conditions correspond to a control site (where the speed limit was not increased) during the period before the increases had occurred. The period and site type variables allow for an assessment of the differences in speeds between the increase and control sites, as well as between the two study periods. For example, the 15th percentile (i.e., $\tau = 0.15$) passenger vehicle speeds where limits increased were 4.8 mph higher (after the speed limit increases) compared with the control sites during the period before the increases were introduced. The effects of the speed limit increases can be discerned by comparing the parameter estimates between the ‘‘before-increase sites’’ and ‘‘after-increase sites’’ indicator variables. In this case, the increase in 15th percentile passenger vehicle speeds is 2.35 mph (4.79-2.44 mph= 2.35 mph). Similarly, the increases at the 50th and 85th percentiles are 4.02 and 4.65 mph, respectively.

For comparison purposes, Figure 4.3 and Figure 4.4 provide graphical comparisons of the parameter estimates for each quantile, along with the same estimates for an OLS model of mean speeds for both vehicle types. When examining these plots, the OLS parameter estimates are reflected by a horizontal line, along with the associated 95 percent confidence intervals for each of the OLS parameters. If the quantile regression parameters fall outside of these bounds, it is reflective of differences that are statistically significant at this same confidence level. It is clear from these respective tables and figures that quantile regression is able to identify relationships in the data that would not be possible under the more typical OLS framework. The following section presents a more comprehensive discussion on the model results.

4.5.1 Effect of Speed Limit Increases

First, it should be noted that the sites where the speed limits were increased tended to have higher speeds than the control sites. Although the control sites were matched by traffic volume, geometric characteristics, and proximity to the sites where limits were increased, these results were expected, as the prior operating speeds were one of the factors considered in the selection of the segments where speed limits were changed (39). The 15th, 50th, and 85th percentile speeds were 58.1, 62.7, and 69.4 mph, respectively, when the 55-mph limit was in place (with other parameters set to zero). Before the speed limit change, speeds ranged from 0.9 to 2.4 mph higher among passenger cars and 0.9 to 2.3 mph higher among heavy vehicles at the sites where the increases would subsequently occur.

It is interesting to note that these differences were largest for the lowest quantile and smallest for the highest quantile. This suggests that drivers who tend to travel the fastest also tend to maintain these higher speeds without considering other roadway conditions when the speed limit is the same. In contrast, drivers who travel at lower speeds tend to increase their speeds when conditions are more favorable, as they tended to be at the sites where speed limits were increased. Although it is not possible to determine directly from the available data, this may help to explain why crash risks tend to be exacerbated at higher speeds as this subset of drivers seems less apt to reduce their speeds based on contextual factors. This point will arise during subsequent portions of the discussion, as well.

Table 4.2 Linear Quantile Regression Model for Passenger Vehicle Speeds

Dependent Variable = Speed of PC (n = 41,223)						
	τ = 0.15		τ = 0.50		τ = 0.85	
Parameters	Estimate (Std. Error)	P-value	Estimate (Std. Error)	P-value	Estimate (Std. Error)	P-value
Intercept	58.05 (0.48)	<0.01	62.65 (0.34)	<0.01	69.37 (0.45)	<0.01
Ln(Hourly Total Volume)	-1.15 (0.07)	<0.01	-0.93 (0.05)	<0.01	-1.16 (0.07)	<0.01
Period and Site Type						
Before-control sites			*Base Condition*			
Before-increase sites	2.44 (0.16)	<0.01	1.74 (0.11)	<0.01	0.88 (0.17)	<0.01
After-control sites	-0.42 (0.16)	<0.01	-0.10 (0.11)	0.36	0.02 (0.16)	0.90
After-increase sites	4.79 (0.17)	<0.01	5.76 (0.10)	<0.01	5.53 (0.17)	<0.01
Cross-section						
Normal/one-way passing			*Base Condition*			
Two-way passing	0.92 (0.13)	<0.01	0.63 (0.11)	<0.01	1.89 (0.12)	<0.01
Lane Width						
12 feet			*Base Condition*			
11 feet	-0.61 (0.12)	<0.01	-0.98 (0.06)	<0.01	-1.10 (0.11)	0.07
Passing						
Restricted			*Base Condition*			
Permitted	2.08 (0.17)	<0.01	1.38 (0.08)	<0.01	0.98 (0.08)	<0.01
Degree of Curvature						
0			*Base Condition*			
<5	-4.90 (0.31)	<0.01	-1.95 (0.13)	<0.01	-0.49 (0.21)	0.02
5-10	-11.86 (0.15)	<0.01	-11.23 (0.23)	<0.01	-8.87 (0.31)	<0.01
>10	-25.52 (0.29)	<0.01	-27.04 (0.21)	<0.01	-15.28 (0.91)	<0.01

Following the speed limit increases, significant increases were experienced across the entire speed distribution at sites where the limits were increased. Among passenger vehicles, these increases were 2.8, 4.1, and 4.6 mph for the 15th, 50th, and 85th percentiles, respectively. The corresponding speed increases for heavy vehicles were 3.0, 4.8, and 4.1 mph for these same percentiles. The increase in speeds was again higher in the upper portion of the distribution (i.e., the 50th and 85th percentiles), suggesting that the most aggressive group of drivers tended to increase their speeds by a greater margin.

Table 4.3 Linear Quantile Regression Model for Heavy Vehicle Speeds

Dependent Variable = Speed of HV (n = 4,939)						
	τ =0.15		τ =0.50		τ =0.85	
Parameters	Estimate (Std. Error)	P-value	Estimate (Std. Error)	P-value	Estimate (Std. Error)	P-value
Intercept	54.69 (1.70)	<0.01	61.05 (0.98)	<0.01	65.38 (0.98)	<0.01
Ln(Hourly Total Volume)	-1.02 (0.26)	<0.01	-0.98 (0.15)	<0.01	-0.87 (0.15)	<0.01
Period and Site Type						
Before-control sites			*Base Condition*			
Before-increase sites	2.31 (0.58)	0.01	1.38 (0.33)	0.07	0.85 (0.34)	0.01
After-control sites	-0.37 (0.56)	0.51	-0.45 (0.31)	0.14	0.29 (0.32)	0.36
After-increase sites	4.91 (0.57)	<0.01	5.74 (0.32)	<0.01	5.23 (0.28)	<0.01
Cross-section						
Normal/one-way passing			*Base Condition*			
Two-way passing	0.90 (0.52)	0.08	0.55 (0.33)	0.09	1.73 (0.46)	<0.01
Lane Width						
12 feet			*Base Condition*			
11 feet	0.86 (0.36)	0.02	0.15 (0.24)	0.52	0.58 (0.20)	<0.01
Passing						
Restricted			*Base Condition*			
Permitted	2.47 (0.45)	<0.01	1.37 (0.32)	<0.01	0.35 (0.36)	0.33
Degree of Curvature						
0			*Base Condition*			
<5	-7.16 (0.94)	<0.01	-3.43 (0.51)	<0.01	-2.06 (0.50)	<0.01
5-10	-12.23 (0.51)	<0.01	-12.97 (0.64)	<0.01	-9.60 (0.96)	<0.01
>10	-27.34 (0.75)	<0.01	-28.92 (0.84)	<0.01	-18.10 (2.64)	<0.01

In general, these results are also similar to findings from prior studies, which have shown that operating speeds increase by roughly half the magnitude of the actual speed limit increase (Mark Freedman & Esterlitz, 1990b; Gates et al., 2015b; Kockelman, 2006; Lynn & Jernigan, 1992; Upchurch, 1989). Interestingly, speeds either remained unchanged or decreased at the control sites across all quantiles and for both vehicle types. This is in contrast to prior research, which has suggested a potential spillover effect on adjacent roads (Alhomaidat et al., 2020).

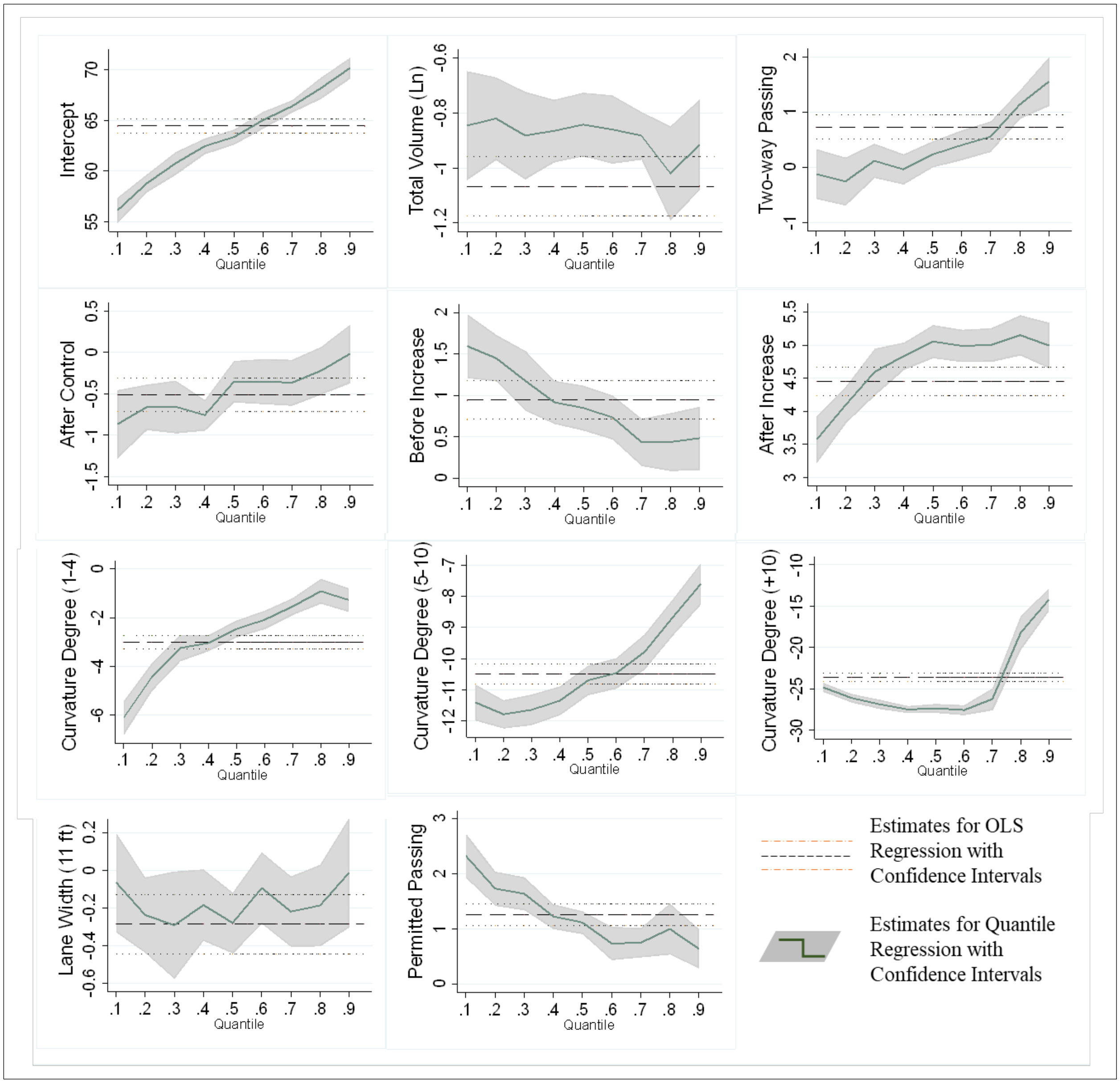

Figure 4.3 Plot of Parameter Estimates for Speed Quantiles for Passenger Cars

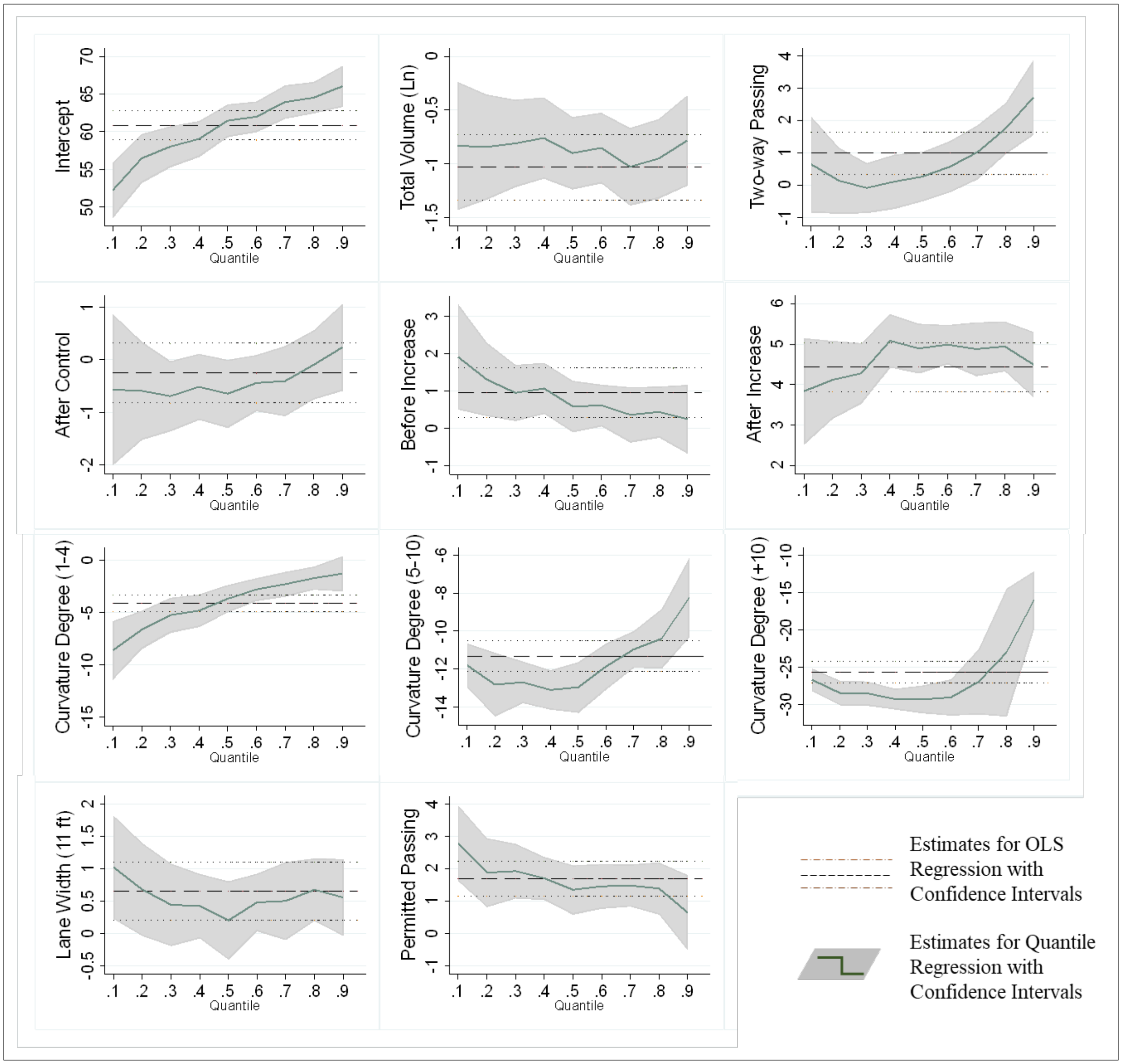

Figure 4.4 Plot of Parameter Estimates for Speed Quantiles for Heavy Vehicles

4.5.2 Effect of Site Characteristics

Turning to the other site characteristics that were found to be related to speed selection, several of the roadway-related variables also showed interesting associations with specific quantiles of the speed distribution. First speeds were consistently reduced during periods when traffic volumes were higher. As all the vehicles included in this analysis included headways of at least 4.0 s, this is likely reflective of the relative density of traffic over the course of the segment, including upstream of the speed observation location.

Similar findings emerged when considering the effects of geometric and traffic characteristics that related to passing. Speeds tended to be marginally different among the 50th percentile vehicles along four-lane cross-sections, which included passing relief lanes in both directions. However, the 15th and the 85th percentile speeds were 0.9 and 1.9 mph higher among passenger vehicles, respectively, and 0.9and 2.0 mph higher among trucks, respectively. This shows that the slower and faster drivers tend to increase their speeds significantly along these extended passing sections.

Related to this result, two-lane segments where passing was allowed (without passing relief lanes) showed higher speeds across the entire distribution, although the magnitude of this difference was greatest at lower speeds. This reinforces some of the same patterns alluded to previously. The lowest speed drivers appear to adapt their speeds more based on changes in the driving environment. It is difficult to determine what the causes are for this behavior, though potential explanations may include greater risk aversion among this group or lower levels of comfort under higher stress driving environments. This finding generally aligns with previous results (Dixon et al., 1999; Russo et al., 2015; Savolainen et al., 2018b).

One of the most interesting results related to horizontal curvature. There was significant variability in the sharpness of the curves included in the sample of study sites. Each site was classified into one of four groups based on its degree of curvature, which ranged from 0 (tangent sections), to 5 (radius= 1,146 ft), to 10 (radius= 574 ft), or more. For both vehicle types and all quantiles, speeds were consistently reduced as the horizontal curves became tighter. These speed reductions were again consistently greater among the lowest speed quantiles and lower among the highest speed quantiles. On the largest radius (i.e., broadest) curves, the 85th percentile vehicles reduced their speeds by only 0.5 and 2.1 mph among passenger vehicles and trucks, respectively. In contrast, speed reductions among the 15th percentile vehicles were 4.9 and 7.2 mph, respectively. These same general trends held for the intermediate radius curves. For the sharpest curves in the sample, reductions were 15.3 and 18.1 mph among the 85th percentile passenger vehicles and trucks and 25.5 and 27.3 mph within the 15th percentile vehicles, respectively.

Lastly, lane width also had significant impacts on speed selection. Passenger vehicles reduced their speeds on 11-ft lanes compared with 12-ft lanes, with the greatest differences being 1.1 mph among the 85th percentile vehicles. Among heavy vehicles, speeds were actually higher on the 11-ft lanes, although the results were not statistically significant at the 50th percentile. Collectively, these results suggest that lane widths may not have a substantive impact on speeds at widths of 11 ft or above for heavy vehicles.

5. EFFECT OF SPEED LIMIT INCREASE ON TRAFFIC SAFETY

The increases in speed limits have significantly affected average travel speeds, as well as the variability in speeds on both the freeway and non-freeway systems as discussed previously. These changes in travel speeds, in turn, are expected to influence safety trends along these same roadways. This chapter presents the results of traffic safety analyses that were conducted to discern changes in crashes that occurred after the speed limit increases were introduced. Analyses are presented separately for the limited-access freeway network, as well as the non-freeway network.

Analyses were done first by comparing between the raw frequency and rate of crashes before and after the increases were introduced, followed by, empirical Bayes (EB) evaluations to account for the regression-to-the-mean effect, as well as changes in other factors, such as weather patterns and economic conditions. Regression model to assess relationship between speed and safety was also developed for freeway network due to availability of system wide speed data. Three years of data were collected in the before period (2014-2016) and two years of data were collected in the after period (2018-2019).

5.1 Data Collection and Preparation

For all analysis purposes, the data were prepared for a total of five years- three years for the before period (2014-2016), and two years for the after period (2018-2019). Crash data for the state of Michigan were obtained from Michigan State Police (MSP). Each crash has details about the location and time of occurrence along with crash severity and several other driver, roadway, and environmental related factors such as weather, driver sobriety, any changes to roadway at the time of crash such as construction, etc. The annual number of crashes occurring on each segment was calculated, both overall, as well as for the most severe level of injury severity sustained in the crash as per the 5-point KABCO scale, where K represents fatal crashes, A, B, and C denote serious, minor, and possible injury crashes, respectively, and O denotes property damage only (PDO) crashes.

5.2 Methodology

5.2.1 Definitions

Independent of the method used, before-after studies are usually accomplished using two tasks (Hauer, 1997):

1. Task 1: Predict what would have been the safety of a site in the after period, had the treatment not been implemented.
2. Task 2: Estimate the safety of the treatment at the site after implementation.

For accomplishing these two tasks, the following terms need to be explained:

- The variable π is defined as the expected number of crashes at a specific site in the after period if the treatment has not been implemented. This variable only applies for the targeted crashes (i.e., total, run-off-road, etc.) and/or their severity (i.e., fatal, incapacitating injury, property damage only, etc.). π is referred to as the 'predicted value'.
- The variable λ is used to define the expected number of crashes in the after period (after the implementation of the treatment). λ is referred to as the 'estimated value'.

The effects of a treatment are estimated by comparing both variables above in the following manner:

- The reduction (or increase) in the expected number of crashes is given as $\delta = \pi - \lambda$. A positive number indicates a decrease in the expected number of crashes.

- The ratio or the Index of Safety Effectiveness is defined as $\theta = {}^{\lambda}/_{\pi}$. If the number of crashes analyzed is below 500 for the before period, θ needs to be adjusted by the following factor: $1 + Var\{\pi\}/\pi^2$. This adjustment is used to minimize the bias caused by a small sample size. The Index of Safety Effectiveness therefore becomes as shown in equation 7. A value below 1.0 indicates a reduction in the number of crashes.

$$\theta = \frac{\lambda/\pi}{1+Var\{\pi\}/\pi^2} \tag{7}$$

The variable $Var\{\pi\}$ is referred to as the variance of π, while the variable $Var\{\lambda\}$ is referred to as the variance λ. The variance is a measure of uncertainty associated with the estimated value. The variance of the reduction, δ, is calculated as shown in equation 8. The variance of the Index of Safety Effectiveness is calculated as shown in equation 9.

$$Var\{\delta\} = Var\{\pi\} + Var\{\lambda\} \tag{8}$$

$$Var\{\theta\} = \theta^2 \left[\frac{(Var\{\lambda\}/\lambda^2)+(Var\{\pi\}/\pi^2)}{(1+Var\{\pi\}/\pi^2)^2}\right] \tag{9}$$

Table 5.1 lists the variables used when a reference/control group is utilized. The Latin characters represent the number of crashes that occurred at the sites under study. The Greek letters represent the expected or estimated number of crashes at those sites. How these variables are used is described below.

Table 5.1 Observed and Expected Number of Crashes

	Treatment Group	Reference Group
Before	K, κ	M, μ
After	L, λ	N, ν

The safety effectiveness of an intervention is estimated using a 4-step process (Hauer, 1997):

1. Estimate λ and π.

2. Calculate the variance of λ and π. As discussed above, they are defined as Var{λ} and Var{π}, respectively.
3. Estimate the difference δ and the Index θ.
4. Calculate the variance of δ and θ. They are defined as Var{δ} and Var{θ}, respectively.

The steps above are done for each site individually and the estimated and predicted values, as well as their variances, are summed for all the sites that are analyzed simultaneously. Additional discussion on this topic is presented in the EB method below. The next three subsections present the characteristics of the three methods used for this study.

5.2.2 Empirical Bayes (EB) Method

This method consists of incorporating the before-after study with the EB method in order to minimize the RTM described above (Hauer, 1997; Persaud et al., 2001). This method allows the estimation of the safety benefits at treated sites using information from reference sites. The expected crash frequency ($E[\kappa|\mathrm{K}]$) at a treated site is a result of the combination of the predicted crash count *(E[κ])* based on the reference sites with similar traits and the crash history (*K*) of that site (usually during the before time period of the treated sites). It should be noted that the terms *κ* and *(E[κ])* are technically the same, but the latter is usually used for statistical models. Hence, for the EB method, we will use *(E[κ])* rather than κ. The expected crash frequency and its variance are shown in equations 10 and 11, respectively.

$$E[\kappa|\mathrm{K}] = w.E[\kappa] + (1 - w).\mathrm{K} \tag{10}$$

$$Var[\kappa|\mathrm{K}] = (1 - w).E[\kappa|\mathrm{K}] \tag{11}$$

Where, *w* is the weight factor between 0 and 1.

The parameter E[κ] is estimated from the safety performance functions (SPFs) developed using a negative binomial (NB) regression (also known as Poisson-gamma) model under the assumption that the covariates in the SPFs represent the main safety traits of the reference sites (Lord & Mannering, 2010). The procedure for using the before-after study with the EB method is described using the following steps.

Step 1. Develop Safety Performance Functions

Using crash, traffic, and geometric data from the reference sites, develop SPFs using NB regression models for all crashes, as well as crashes for various subsets of interest (e.g., fatal and severe injury). The NB regression model is the most common type of model used by transportation safety analysts for modeling traffic crashes (Lord & Mannering, 2010). This model is preferred over other mixed-Poisson models since the gamma distribution is the conjugate of the Poisson distribution. The NB regression model has the following modeling structure: the number of crashes Y_{it} for a particular i^{th} site and time period t when conditional on its mean $E[\kappa]_{it}$ is Poisson distributed and independent over all sites and time periods.

$$Y_{it}|E[\kappa]_{it} \sim Poisson(E[\kappa]_{it}), \text{ i = 1, 2, …, i and t = 1, 2, …, t} \tag{12}$$

The mean of the Poisson is structured as:

$$E[\kappa]_{it} = f(X;\beta)\exp(e_{it}) \tag{13}$$

Where,

$f(.)$ is a function of the explanatory variables (X);

β is a vector of unknown coefficients; and,

e_{it} is the model error independent of all the covariates

The SPFs used in this study are presented in the latter sections. When estimating these SPFs, an offset variable is defined, which means its parameter estimate is fixed at unity. For this study, the natural log of segment length is defined as an offset which introduces an implicit assumption that the crash count increases proportionately with the segment length.

Step 2. Estimate the expected number of crashes in the before period

Using the SPFs developed in Step 1, estimate the expected number of crashes ($E[\kappa]_i$) for the before period at each treatment site. Obtain an EB estimate of the expected number of crashes ($E[\hat{\kappa}_i|K_i]$) before implementation of the countermeasure at each treatment site and an estimate of variance of $E[\hat{\kappa}_i|K_i]$. Recall that "^" refers to an estimate of a variable.

The estimate $E[\hat{\kappa}_i|K_i]$ is given by combining the SPF predictions for the before period ($E[\kappa]_i$) with the total count of crashes during the before period (K_i) as follows:

$$E[\hat{\kappa}_i|K_i] = \widehat{w}_i \cdot E[\hat{\kappa}_i] + (1 - \widehat{w}_i) \cdot K_i \tag{14}$$

The weight $\widehat{w}_i$ is given as shown in equation 15.

$$\widehat{w}_i = \frac{1}{1+\alpha E[\hat{\kappa}_i]} \tag{15}$$

where α is the inverse dispersion parameter of a NB regression model ($Var[Y_i] = E[\kappa_i] + \alpha E[\kappa_i]^2$).

The variance of the estimate is given as

$$Var[E[\hat{\kappa}_i|K_i]] = (1 - \widehat{w}_i) \cdot E[\hat{\kappa}_i|K_i] \tag{16}$$

Step 3. Calculate the proportion of the after period crash estimate to the before period estimate

Using the SPFs developed in Step 1, estimate the expected number of crashes ($E[z]_i$) in the after period at each treatment site. The ratio between the after period crash estimate and the before period estimate (P_i) is calculated as

$$P_i = \frac{E[\hat{z}]_i}{E[\hat{\kappa}]_i} \tag{17}$$

Step 4. Obtain the predicted crashes $\hat{\pi}_i$ and its estimated variance

Calculate the predicted crashes during the after period that would have occurred without implementing the countermeasure (i.e., speed limit increase). The predicted crashes ($\hat{\pi}_i$) are given by:

$$\hat{\pi}_i = P_i \times E[\hat{\kappa}_i|K_i] \tag{18}$$

The estimated variance of $\hat{\pi}_i$ is given by equation 19.

$$Var[\hat{\pi}_i] = {P_i}^2 Var[E[\hat{\kappa}_i|K_i]] = {P_i}^2(1 - \widehat{w}_i) \cdot E[\hat{\kappa}_i|K_i] \tag{19}$$

Step 5. Compute the sum of the predicted and observed crashes over all sites in the treatment group

The after-period crashes and their variances for a group of sites had the treatment not been implemented (i.e., if the speed limits had not been increased) at the treated sites is given by equation 20.

$$\hat{\pi} = \sum_{i=1}^{j} \hat{\pi}_i \tag{20}$$

where j represents the total number of sites in the treatment group, and $\hat{\pi}$ is the expected after-period crashes at all treated sites had there been no treatment, as described above. For a treated site, the crashes in the after-period are influenced by the implementation of the treatment (i.e., the speed limit increase). The safety effectiveness of a treatment is known by comparing the actual crashes with the treatment to the expected crashes without the treatment. The number of after-period crashes for a group of treated sites is given as:

$$\hat{\lambda} = \sum_{i=1}^{j} L_i \tag{21}$$

where L_i is the crash frequency during the after period at site i. The estimate of $\hat{\lambda}$ is equal to the sum of the observed number of crashes at all treated sites during the after study period.

Step 6. Estimate $Var[\hat{\lambda}]$ and $Var[\hat{\pi}]$

Based on the assumption of a Poisson distribution, the estimate of variance of $\hat{\lambda}$ is assumed to be equal to L. The estimate of variance of $\hat{\pi}$ can be calculated from the equation as follows:

$$Var\left[\hat{\lambda}_i\right] = L_i \tag{22}$$

$$Var[\hat{\lambda}] = \sum_{i=1}^{j} Var[\hat{\lambda}_i] \tag{23}$$

$$Var[\hat{\pi}_i] = (1 - \widehat{w}_i) \cdot E[\hat{\kappa}_i|K_i] = (1 - \widehat{w}_i) \cdot \hat{\pi}_i \tag{24}$$

$$Var[\hat{\pi}] = \sum_{i=1}^{j} Var[\hat{\pi}_i] \tag{25}$$

Step 7. Estimate $\hat{\delta}$ and $\hat{\theta}$

The 'change in the safety' (δ) and 'index of safety effectiveness' (θ) are calculated as described below:

$$\hat{\delta} = \hat{\pi} - \hat{\lambda} \tag{26}$$

$$\hat{\theta} = \frac{\left(\frac{\hat{\lambda}}{\hat{\pi}}\right)}{\left(1+\frac{Var(\hat{\pi})}{\hat{\pi}^2}\right)} \tag{27}$$

If $\hat{\delta}$ is greater than zero and $\hat{\theta}$ is less than one, then the treatment has a positive safety effect. In addition, the percent decrease in the number of target crashes due to the treatment is calculated as $100\left(1 - \hat{\theta}\right)\%$.

Step 8. Estimate $Var[\hat{\delta}]$ and $Var[\hat{\theta}]$

The estimated variance and standard error of the estimated safety-effectiveness are given by equation 28 to equation 30:

$$Var\left[\hat{\delta}\right] = \hat{\pi} + \hat{\lambda} \tag{28}$$

$$Var\left[\hat{\theta}\right] = \frac{\hat{\theta}^2 \cdot \left[\frac{Var(\hat{\lambda})}{\hat{\lambda}^2} + \frac{Var(\hat{\pi})}{\hat{\pi}^2}\right]}{\left[1+\frac{Var(\hat{\pi})}{\hat{\pi}^2}\right]^2} \tag{29}$$

$$s.e[\hat{\theta}] = \sqrt{Var[\hat{\theta}]} \tag{30}$$

The 95% confidence interval for $\hat{\theta}$ is calculated as $\hat{\theta} \pm 1.96 s.e[\hat{\theta}]$. If the confidence interval contains the value one, then no significant effect has been observed at the 5% significance level. It should be pointed out that the EB method may not necessarily account for the site selection bias, which is important in this case as speed limit increases were introduced at sites that had historically experienced relatively low numbers of crashes, injuries, and fatalities (Lord & Kuo, 2012).

5.3 Analysis Results

This section presents the results of the analyses for freeway and non-freeway facilities. Separate results were included with and without deer-involved collisions included. The section is divided into two subsections. First section presents high-level summary statistics for both freeway and non-freeway facilities. The seconds section provides the results from the before-after study using the empirical Bayes (EB) method.

5.3.1 Comparing Pre- and Post-Increase Crash Data

First, aggregate statistics are presented to provide a comparison of the total annual average number of crashes that occurred on the routes where speed limits were increased during the years immediately before and after the increases went into effect. The annual average crash frequencies for freeway and non-freeway facilities before and after the speed limit increases are shown in Table 5.2 and Table 5.3, respectively. The percent change between the before and after periods is also shown in each case. When reviewing these percentages, positive numbers are indicative of crash subsets that increased while negative percentages are reflective of categories where fewer crashes were experienced.

Table 5.2 Pre and Post-Increase Annual Crash Frequencies on Freeways

Variable	Crash Type	Group	Before	After	Percent Change
Total (KABCO)	All Crashes	Increase	3,634	4,241	16.7%
		Control	27,725	28,675	3.4%
	Crashes excluding Deer Collisions	Increase	1,968	2,288	16.2%
		Control	25,104	25,808	2.8%
Severe Injury (KA)	All Crashes	Increase	64	80	25.0%
		Control	448	466	4.0%
	Crashes excluding Deer Collisions	Increase	62	76	22.6%
		Control	445	459	3.1%
Minor Injury (B)	All Crashes	Increase	150	204	36%
		Control	1,191	1,280	7.5%
	Crashes excluding Deer Collisions	Increase	133	171	28.6%
		Control	1,160	1,237	6.6%
Possible Injury (C)	All Crashes	Increase	283	319	12.7%
		Control	3,445	3,386	-1.7%
	Crashes excluding Deer Collisions	Increase	243	261	7.4%
		Control	3,358	3,274	-2.5%
Property Damage Only (O)	All Crashes	Increase	3,137	3,638	16.0%
		Control	22,641	23,543	4.0%
	Crashes excluding Deer Collisions	Increase	1,530	1,780	16.3%
		Control	20,141	20,838	3.5%
Traffic Volume (average AADT)	--	Increase	7,469	8,676	16.2%
	--	Control	28,757	30,259	5.2%
Mileage (miles)	--	Increase	1,217.4		
	--	Control	2,472.1		

The results show that crashes tended to increase overall, at both the sites where speed limits were increased, as well as at the selected control sites. However, these increases were significantly larger at the increase sites as compared to the control sites. Total crashes on freeways increased by 16.7 percent where the speed limit was increased, while at the control sites, the increase was only 3.4 percent. On non-freeways, the increases were considerably higher. Total crashes increased by 38.7 percent and 10.7 percent at the speed limit increase and control sites, respectively. It should be noted that traffic volumes also tended to increase overall between these time periods as shown by the changes in annual average daily traffic.

Table 5.3 Pre and Post-Increase Annual Crash Frequencies on Non-Freeways

Variable	Crash Type	Group	Before	After	Percent Change
Total (KABCO)	All Crashes	Increase	1,742	2,416	38.7%
		Control	16,334	18,079	10.7%
	Crashes excluding Deer Collisions	Increase	582	704	21.0%
		Control	7,667	7,492	-2.3%
Severe Injury (KA)	All Crashes	Increase	36	47	30.6%
		Control	382	442	15.7%
	Crashes excluding Deer Collisions	Increase	34	44	29.4%
		Control	370	424	14.6%
Minor Injury (B)	All Crashes	Increase	58	63	8.6%
		Control	680	740	8.8%
	Crashes excluding Deer Collisions	Increase	50	50	0%
		Control	639	682	6.7%
Possible Injury (C)	All Crashes	Increase	86	105	22.1%
		Control	1,291	1,203	-6.8%
	Crashes excluding Deer Collisions	Increase	73	85	16.4%
		Control	1,186	1,082	-8.8%
Property Damage Only (O)	All Crashes	Increase	1,562	2,201	40.9%
		Control	13,981	15,694	12.3%
	Crashes excluding Deer Collisions	Increase	425	525	23.5%
		Control	5,472	5,304	-3.1%
Traffic Volume (average AADT)	--	Increase	2,648	3,003	13.4%
	--	Control	4,971	5,130	3.2%
Mileage (miles)	--	Increase	959		
	--	Control	4,496		

Table 5.4 and Table 5.5 present the crashes per million vehicle miles traveled (MVMT) before and after speed limit increases on both the control and increase sites for freeways and non-freeways, respectively. When controlled for vehicle miles traveled, the percentage increase in crashes tend to be smaller in magnitude. However, the increases in crashes is higher on increase sites compared to control sites for all severity levels. Total crashes per MVMT on freeways increased by 0.47 percent at sites where speed limits were increased. At control sites, crash rates actually declined by 1.7 percent. Again, the increases were higher on non-freeways compared to freeways. Total crash rates increased 22.3 percent and 7.5 percent at the speed limit

increase and control sites, respectively. When animal-related crashes are excluded, the crash rates increased by 6.7 percent at the increase sites, and declined by 5.3 percent at control sites.

Table 5.4 Pre and Post-Increase Crash Rates on Freeways

Variable	Crash Type	Group	Before	After	Percent Change
Total (KABCO)	All Crashes	Increase	1.095	1.100	0.47%
		Control	1.068	1.050	-1.71%
	Crashes excluding Deer Collisions	Increase	0.593	0.593	0.09%
		Control	0.967	0.945	-2.30%
Severe Injury (KA)	All Crashes	Increase	0.019	0.021	7.61%
		Control	0.017	0.017	-1.15%
	Crashes excluding Deer Collisions	Increase	0.019	0.020	5.53%
		Control	0.017	0.017	-1.97%
Minor Injury (B)	All Crashes	Increase	0.045	0.053	17.08%
		Control	0.046	0.047	2.14%
	Crashes excluding Deer Collisions	Increase	0.040	0.044	10.68%
		Control	0.045	0.045	1.34%
Possible Injury (C)	All Crashes	Increase	0.085	0.083	-2.96%
		Control	0.133	0.124	-6.59%
	Crashes excluding Deer Collisions	Increase	0.073	0.068	-7.54%
		Control	0.129	0.120	-7.34%
Property Damage Only (O)	All Crashes	Increase	0.945	0.944	-0.16%
		Control	0.873	0.862	-1.18%
	Crashes excluding Deer Collisions	Increase	0.461	0.462	0.15%
		Control	0.776	0.763	-1.67%
Traffic Volume (average AADT)	--	Increase	7,469	8,676	16.2%
	--	Control	28,757	30,259	5.2%
Mileage (miles)	--	Increase	1,217.4		
	--	Control	2,472.1		

5.3.2 Empirical Bayes Before-After Study

This section describes the results of the EB before-after analysis. Since there were very few reported fatal (K) crashes, they were combined with incapacitating injury crashes (A) to obtain statistically reliable estimates. The analysis was conducted for the following crash severity categories:

- Total crashes
- Fatal (K) plus Incapacitating injury (A) crashes

- Non-incapacitating injury (B) crashes
- Possible injury (C) crashes
- No injury or PDO (O) crashes

Table 5.5 Pre and Post-Increase Crash Rates on Non-Freeways

Variable	Crash Type	Group	Before	After	Percent Change
Total (KABCO)	All Crashes	Increase	1.879	2.298	22.30%
		Control	2.002	2.148	7.25%
	Crashes excluding Deer Collisions	Increase	0.628	0.670	6.66%
		Control	0.940	0.890	-5.31%
Severe Injury (KA)	All Crashes	Increase	0.039	0.045	15.12%
		Control	0.047	0.053	12.12%
	Crashes excluding Deer Collisions	Increase	0.037	0.042	14.11%
		Control	0.045	0.050	11.04%
Minor Injury (B)	All Crashes	Increase	0.063	0.060	-4.22%
		Control	0.083	0.088	5.45%
	Crashes excluding Deer Collisions	Increase	0.054	0.048	-11.82%
		Control	0.078	0.081	3.42%
Possible Injury (C)	All Crashes	Increase	0.093	0.100	7.66%
		Control	0.158	0.143	-9.70%
	Crashes excluding Deer Collisions	Increase	0.079	0.081	2.67%
		Control	0.145	0.129	-11.60%
Property Damage Only (O)	All Crashes	Increase	1.685	2.094	24.25%
		Control	1.714	1.864	8.77%
	Crashes excluding Deer Collisions	Increase	0.459	0.499	8.93%
		Control	0.671	0.630	-6.07%
Traffic Volume (average AADT)	--	Increase	2,648	3,003	13.4%
	--	Control	4,971	5,130	3.2%
Mileage (miles)	--	Increase	959		
	--	Control	4,496		

The database assembled for SPF calibration included reference sites only (control group) and crash frequency is used as a dependent variable and the geometric and traffic variables of each site as independent variables. From the original database, each row (site characteristics) is repeated twice to represent the before and after conditions to capture the safety trend over time. This is important since factors such as driver behavior and vehicle technologies change over time but cannot be easily captured. The results are described separately for freeways and non-freeways in the following sub-sections.

Freeways

For SPF development, different functional forms with various combinations of variables while modeling the total crashes were examined. The form presented below reflects the findings from several preliminary regression analyses. The same form was also used for modeling the crashes by severity. Note that the designation *i* and *t* are removed to simplify the description of the results. The predicted crash frequency is calculated as follows.

$$E[k] = L \times y \times e^{b_0 + b_{aadt}\ln(AADT) + b_{aft} I_{aft} + \sum b_r I_r} \times CMF_{hc} \times CMF_{lw} \times CMF_{osw} \quad (31)$$

With,
$$CMF_{hc} = (1 - p_c) \times 1.0 + p_c(b_{hc} \times D_C)$$

$$CMF_{lw} = e^{b_{lw}(lw-12)}$$

$$CMF_{osw} = e^{b_{osw}(osw-10)}$$

Where,

$E[k]$	=	Predicted annual average crash frequency,
L	=	Segment length, miles,
y	=	Number of years of crash data,
$AADT$	=	Average Annual Daily Traffic, vehicles per day,
I_{aft}	=	Indicator variable for the after period,
I_r	=	Indicator variable for the region,
CMF_{hc}	=	Crash Modification Factor for horizontal curves,
CMF_{lw}	=	Crash Modification Factor for lane width, feet,
CMF_{osw}	=	Crash Modification Factor for outside shoulder width, feet,
p_c	=	Proportion of all horizontal curves on the segment,
D_c	=	Average degree of curvature, degrees,
lw	=	Lane width, feet,
osw	=	Outside shoulder width, feet,
b_j	=	Calibrated coefficients.

The dispersion parameter \alpha is allowed to vary with the segment length and is calculated using equation 32.

$$\alpha = \frac{1}{L \times e^{\alpha_0}} \quad (32)$$

Where,

α = dispersion parameter,

α_0 = calibration coefficient for dispersion parameter

Table 5.6 to Table 5.10 provide calibrated coefficients for total, KA, B, C and O crashes estimated using the control site database. Before any analysis, reference sites with relatively higher AADT compared to the increase sites were removed to allow similar traffic characteristics across control and increase sites. The data were combined by period of study, i.e., each site was repeated twice in the dataset, one representing the before period and the other representing the after period. The crashes were summed over each of their respective periods and average value of traffic volume and truck percentage was taken while the roadway geometric variables remained unchanged. Table 5.11 and Table 5.12 provide calibrated coefficients for total and KA crashes excluding deer collisions. A significance level of 5 percent was used to include the variables in the model. However, the coefficient was also considered even if it was marginally significant but was intuitive and within logical boundaries. The NLMIXED procedure in the SAS software was used to estimate the proposed model coefficients. This procedure was used because the proposed predictive model is both nonlinear and discontinuous. The log-likelihood function for the negative binomial (NB) distribution was used to determine the best-fit model coefficients.

The indicator variable for the after period showed that, when everything remains the same, crashes decreased in the after period. In almost all models, it was shown that crashes increase with the presence of horizontal curves and increase with an increase in the degree of curvature. The increase in lane width or shoulder width decreased crash risk.

Table 5.6 Calibrated Coefficients for Total Crashes on Freeways

Coefficient	Variable		Value	Std. Dev	t-statistic	p-value
b_0	Intercept		-4.9135	0.3760	-13.07	<0.001
b_{aadt}	AADT		0.6903	0.0398	17.33	<0.001
b_{aft}	After period indicator		-0.0776	0.0265	-2.93	0.0034
b_r	Region indicator	Grand Region	0.2063	0.0343	6.02	<0.001
		Bay Region	0.1139	0.0493	2.31	0.021
		University Region	-0.0775	0.0361	-2.15	0.0321
b_{hc}	Horizontal curve		0.1302	0.0393	3.31	0.0009
b_{lw}	Lane width		-0.125	0.0758	-1.65	0.0995
b_{osw}	Outside shoulder width		-0.0842	0.0177	-4.77	<0.001
α_0	Dispersion parameter		1.5238	0.0508	30.01	<0.001

Table 5.7 Calibrated Coefficients for KA Crashes on Freeways

Coefficient	Variable		Value	Std. Dev	t-statistic	p-value
b_0	Intercept		-11.2905	1.6541	-6.83	<0.001
b_{aadt}	AADT		0.9774	0.1732	5.64	<0.001
b_{aft}	After period indicator		-0.2016	0.1068	-1.89	0.0593
b_r	Region indicator	Grand Region	--	--	--	--
		Bay Region	-0.3876	0.2122	-1.83	0.0680
		University Region	-0.3574	0.1229	-2.91	0.0037
b_{hc}	Horizontal curve		0.1929	0.1505	1.28	0.2003
b_{lw}	Lane width		--	--	--	--
b_{osw}	Outside shoulder width		-0.1707	0.0794	-2.15	0.0316
α_0	Dispersion parameter		1.0848	0.4894	2.22	0.0268

Table 5.8 Calibrated Coefficients for B Crashes on Freeways

Coefficient	Variable		Value	Std. Dev	t-statistic	p-value
b_0	Intercept		-10.222	1.1982	-8.53	<0.001
b_{aadt}	AADT		0.9103	0.1261	7.22	<0.001
b_{aft}	After period indicator		-0.0642	0.0744	-0.86	0.3885
b_r	Region indicator	Grand Region	0.3341	0.0848	3.94	<0.001
		Bay Region	--	--	--	--
		University Region	-0.1469	0.0996	-1.47	0.1405
b_{hc}	Horizontal curve		0.1949	0.0950	2.04	0.0416
b_{lw}	Lane width		-0.3536	0.2166	-1.63	0.1027
b_{osw}	Outside shoulder width		-0.0745	0.0452	-1.65	0.0991
α_0	Dispersion parameter		0.9708	0.2419	4.01	<0.001

Table 5.9 Calibrated Coefficients for C Crashes on Freeways

Coefficient	Variable		Value	Std. Dev	t-statistic	p-value
b_0	Intercept		-9.0847	0.8658	-10.49	<0.001
b_{aadt}	AADT		0.8699	0.09128	9.53	<0.001
b_{aft}	After period indicator		-0.1539	0.05559	-2.77	0.0057
b_r	Region indicator	Grand Region	0.2928	0.07035	4.16	<0.001
		Bay Region	0.5771	0.09616	6.00	<0.001
		University Region	-0.1820	0.07886	-2.31	0.0211
b_{hc}	Horizontal curve		0.2100	0.06916	3.04	0.0024
b_{lw}	Lane width		-0.4591	0.158	-2.91	0.0037
b_{osw}	Outside shoulder width		-0.1545	0.03636	-4.25	<0.001
α_0	Dispersion parameter		1.2607	0.169	7.46	<0.001

Table 5.10 Calibrated Coefficients for O Crashes on Freeways

Coefficient	Variable		Value	Std. Dev	t-statistic	p-value
b_0	Intercept		-4.6083	0.3764	-12.24	<0.001
b_{aadt}	AADT		0.6378	0.0396	16.09	<0.001
b_{aft}	After period indicator		-0.0627	0.0271	-2.32	0.0206
b_r	Region indicator	Grand Region	0.1951	0.0302	6.46	<0.001
		Bay Region	--	--	--	--
		University Region	--	--	--	--
b_{hc}	Horizontal curve		0.1308	0.0391	3.34	0.0009
b_{lw}	Lane width		--	--	--	--
b_{osw}	Outside shoulder width		-0.0586	0.0158	-3.71	0.0002
α_0	Dispersion parameter		1.5192	0.0530	28.64	<0.001

Table 5.11 Calibrated Coefficients for Total Crashes Excluding Deer Collisions on Freeways

Coefficient	Variable		Value	Std. Dev	t-statistic	p-value
b_0	Intercept		-9.6201	0.4564	-21.08	<0.001
b_{aadt}	AADT		1.1450	0.0481	23.79	<0.001
b_{aft}	After period indicator		-0.1836	0.0312	-5.89	<0.001
b_r	Region indicator	Grand Region	0.2926	0.0397	7.37	<0.001
		Bay Region	0.2691	0.0572	4.71	<0.001
		University Region	-0.1148	0.0405	-2.83	0.0047
b_{hc}	Horizontal curve		0.2261	0.0420	5.39	<0.001
b_{lw}	Lane width		--	--	--	--
b_{osw}	Outside shoulder width		-0.0759	0.0203	-3.74	0.0002
α_0	Dispersion parameter		1.2417	0.0526	23.61	<0.001

Table 5.12 Calibrated Coefficients for KA Crashes Excluding Deer Collisions on Freeways

Coefficient	Variable		Value	Std. Dev	t-statistic	p-value
b_0	Intercept		-10.952	1.6502	-6.64	<0.001
b_{aadt}	AADT		0.9421	0.1728	5.45	<0.001
b_{aft}	After period indicator		-0.1885	0.1071	-1.76	0.0787
b_r	Region indicator	Grand Region	--	--	--	--
		Bay Region	-0.3553	0.2113	-1.68	0.0929
		University Region	-0.3929	0.1242	-3.16	0.0016
b_{hc}	Horizontal curve		0.2206	0.1440	1.53	0.1259
b_{lw}	Lane width		--	--	--	--
b_{osw}	Outside shoulder width		-0.2070	0.0808	-2.56	0.0105
α_0	Dispersion parameter		1.6174	0.8218	1.97	0.0492

Table 5.13 summarizes the results for the EB estimate. This table shows an increase can be observed for all crash severity levels, except for crash severity level C. The latter one indicated a small non-statistically significant reduction. These results are in line with the findings of previous studies. For instance, a 2004 study (Nilsson, 2004) showed that, for a 5-mph increase in operating speeds, total and KA crashes increase by 15% and 23% respectively. Another study showed that, for a 5-mph increase in operating speeds on rural freeways, fatal, serious injury, slight injury and PDO crashes increase by 33%, 20%, 8% and 11%, respectively (Elvik, 2009).

Table 5.13 Index of Safety Effectiveness for Freeway Facilities

Terminology	Total		KA		B	C	O
Crash Type	All	ND*	All	ND*	All	All	All
θ (The Index)	1.095	1.092	1.333	1.261	1.316	0.927	1.082
Standard Deviation	0.015	0.020	0.110	0.106	0.069	0.039	0.016
Significance (5% level)	Yes	Yes	Yes	Yes	Yes	No	Yes

*ND = Crashes excluding deer collisions

Non-Freeways

For the non-freeway network which include rural two-lane roads, the increase sites included roadway segments where the speed limits were increased to 65 mph while the control sites include sites having similar roadway characteristics and comparable traffic volume to the increase sites but the speed limits were retained at 55 mph. The analysis was done in two parts. First, all the increase sites and control sites were analyzed. Thereafter, segments that were in the influence zone of a signalized or stop-controlled intersection, roundabout, or speed reduction zones (SRZ) were removed from the analysis dataset. Both the analyses generally generated similar results, hence the results here are presented only for the dataset which does not contain any segments close to intersections, roundabouts, or SRZ.

Similar to the freeway analysis, for SPF development, different functional forms with various combinations of variables while modeling the total crashes were examined. The form presented below reflects the findings from several preliminary regression analyses. The same form is also used for modeling the crashes by severity. The predicted crash frequency is calculated as shown in equation 33.

$$E[k] = L \times y \times e^{b_0 + b_{aadt} \ln(AADT) + b_{aft} I_{aft} + \sum b_r I_r} \times CMF_{osw} \times CMF_{ter} \times CMF_{pk} \times CMF_{pass} \times CMF_{turn} \times CMF_{HC} \times CMF_{driveways} \quad (33)$$

With,

$$CMF_{osw} = e^{b_{osw}(osw-10)}$$

$$CMF_{terr} = e^{b_{terr} \times I_{terr}}$$

$$CMF_{turn} = e^{b_{turn} \times n_{turn}}$$

$$CMF_{HC} = e^{b_{HC} \times DOC_{avg}}$$

$$CMF_{turn} = e^{b_{driveways} \times n_{driveway\ per\ mile}}$$

Where,

$E[k]$ = Predicted annual average crash frequency,

L = Segment length, miles,

y = Number of years of crash data,

$AADT$ = Average Annual Daily Traffic, vehicles per day,

I_{aft} = Indicator variable for the after period,

I_r = Indicator variable for the region,

CMF_{osw} = Crash modification factor for outside shoulder width, ft,

CMF_{terr} = Crash modification factor for terrain,

CMF_{turn} = Crash modification factor for turning lanes presence,

CMF_{HC} = Crash modification factor for horizontal curves,

$CMF_{driveways}$ = Crash modification factor for driveways and minor approaches

osw = Outside shoulder width, feet,

I_{terr} = Indicator variable for the terrain,

n_{turn} = Number of turning lanes on the segment,

DOC_{avg} = Average degree of curvature of the horizontal curve

$n_{driveway\ per\ mile}$ = Number of driveways and minor approaches per mile

b_j = Calibrated coefficients.

Table 5.14 to Table 5.18 provide calibrated coefficients for total, KA, B, C and O crashes estimated using the reference site database. Table 5.19 and Table 5.20 provide calibrated coefficients for total and KA crashes excluding deer collisions. Similar to the case of freeways, significance level of 5 percent was used to include the variables in the model with some exceptions as discussed previously.

The indicator variable for the after period showed that, when everything remains the same, crashes decreased for some severities whereas a few severity categories increased in the after period. In almost all models, it was shown that crashes decreased with the increase in shoulder width, when the terrain is level, parking is present, or with the increase in turning lanes. In general, presence of passing lanes decreased the crash occurrence.

Table 5.14 Calibrated Coefficients for Total Crashes on Non-Freeways

Coefficient	Variable		Value	Std. Dev	t-statistic	p-value
b_0	Intercept		-3.4542	0.1398	-24.7000	<0.001
b_{aadt}	AADT		0.5574	0.0174	32.0900	<0.001
b_{aft}	After period indicator		0.1040	0.0188	5.5300	<0.001
b_r	Region indicator	Superior Region	-0.3845	0.0275	-13.9900	<0.001
		North Region	-0.1266	0.0238	-5.3200	<0.001
		Grand Region	--	--	--	--
b_{osw}	Outside shoulder width		--	--	--	--
b_{terr}	Terrain		-0.1302	0.0201	-6.4700	<0.001
b_{turn}	Number of turning lanes		0.0543	0.0130	4.1700	<0.001
b_{HC}	Average DOC of HC		--	--	--	--
$b_{driveways}$	Driveways and minor approaches per mile		0.0093	0.0009	10.3700	<0.001
α_0	Dispersion parameter		1.3310	0.0393	33.880	<0.001

Table 5.15 Calibrated Coefficients for KA Crashes on Non-Freeways

Coefficient	Variable		Value	Std. Dev	t-statistic	p-value
b_0	Intercept		-8.8612	0.5156	-17.1860	<0.001
b_{aadt}	AADT		0.7118	0.0649	10.9700	<0.001
b_{aft}	After period indicator		0.0513	0.0666	0.7710	0.441
b_r	Region indicator	Superior Region	--	--	--	--
		North Region	-0.2011	0.0774	-2.5960	0.009
		Grand Region	--	--	--	--
b_{osw}	Outside shoulder width		--	--	--	--
b_{terr}	Terrain		--	--	--	--
b_{turn}	Number of turning lanes		0.1128	0.0445	2.5320	0.011
b_{HC}	Average DOC of HC		0.0593	0.0150	3.9650	<0.001
$b_{driveways}$	Driveways and minor approaches per mile		0.0132	0.0026	5.0570	<0.001
α_0	Dispersion parameter		0.8831	0.3350	2.6360	0.0084

Table 5.16 Calibrated Coefficients for B Crashes on Non-Freeways

Coefficient	Variable		Value	Std. Dev	t-statistic	p-value
b_0	Intercept		-9.5420	0.5105	-18.6910	<0.001
b_{aadt}	AADT		0.8514	0.0596	14.2910	<0.001
b_{aft}	After period indicator		--	--	--	--
b_r	Region indicator	Superior Region	-0.3418	0.0958	-3.5660	<0.001
		North Region	-0.1534	0.0736	-2.0830	<0.001
		Grand Region	0.2651	0.0694	3.8180	<0.001
b_{osw}	Outside shoulder width		-0.0498	0.0212	-2.3540	<0.001
b_{terr}	Terrain		--	--	--	--
b_{turn}	Number of turning lanes		--	--	--	--
b_{HC}	Average DOC of HC		0.0475	0.0132	3.6060	<0.001
$b_{driveways}$	Driveways and minor approaches per mile		0.0133	0.0022	6.1670	<0.001
α_0	Dispersion parameter		0.9865	0.2392		<0.001

Table 5.17 Calibrated Coefficients for C Crashes on Non-Freeways

Coefficient	Variable		Value	Std. Dev	t-statistic	p-value
b_0	Intercept		-9.3079	0.4284	-21.7280	<0.001
b_{aadt}	AADT		0.8999	0.0508	17.7140	<0.001
b_{aft}	After period indicator		-0.1409	0.0454	-3.1030	0.0019
b_r	Region indicator	Superior Region	-0.2153	0.0707	-3.0450	0.0023
		North Region	-0.1543	0.0542	-2.8490	0.0044
		Grand Region	--	--	--	--
b_{osw}	Outside shoulder width		-0.0385	0.0179	-2.1540	0.0313
b_{terr}	Terrain		-0.1303	0.0489	-2.6640	0.0077
b_{turn}	Number of turning lanes		0.0779	0.0300	2.5980	0.0094
b_{HC}	Average DOC of HC		0.0302	0.0114	2.6590	0.0078
$b_{driveways}$	Driveways and minor approaches per mile		0.0135	0.0018	7.4210	<0.001
α_0	Dispersion parameter		1.4276	0.2400	5.9480	<0.001

Table 5.18 Calibrated Coefficients for O Crashes on Non-Freeways

Coefficient	Variable		Value	Std. Dev	t-statistic	p-value
b_0	Intercept		-3.3724	0.1485	-22.7040	<0.001
b_{aadt}	AADT		0.5339	0.0184	28.9530	<0.001
b_{aft}	After period indicator		0.1233	0.0200	6.1490	<0.001
b_r	Region indicator	Superior Region	-0.3932	0.0293	-13.4370	<0.001
		North Region	-0.1183	0.0254	-4.6670	<0.001
		Grand Region	--	--	--	--
b_{osw}	Outside shoulder width		--	--	--	--
b_{terr}	Terrain		-0.1283	0.0215	-5.9750	<0.001
b_{turn}	Number of turning lanes		0.0532	0.0139	3.8300	<0.001
b_{HC}	Average DOC of HC		--	--	--	--
$b_{driveways}$	Driveways and minor approaches per mile		0.0085	0.0010	8.8150	<0.001
α_0	Dispersion parameter		1.2133	0.0398	30.463	<0.001

Table 5.19 Calibrated Coefficients for Total Crashes Excluding Deer Collisions on Non-Freeways

Coefficient	Variable		Value	Std. Dev	t-statistic	p-value
b_0	Intercept		-7.9746	0.2136	-37.3400	<0.001
b_{aadt}	AADT		0.9518	0.0254	37.4700	<0.001
b_{aft}	After period indicator		-0.0778	0.0232	-3.3500	<0.001
b_r	Region indicator	Superior Region	-0.2127	0.0356	-5.9700	<0.001
		North Region	-0.1321	0.0281	-4.7000	<0.001
		Grand Region	--	--	--	--
b_{osw}	Outside shoulder width		-0.0267	0.0096	-2.8000	0.0051
b_{terr}	Terrain		-0.1640	0.0253	-6.4800	<0.001
b_{turn}	Number of turning lanes		0.0729	0.0157	4.6400	<0.001
b_{HC}	Average DOC of HC		0.0639	0.0061	10.5600	<0.001
$b_{driveways}$	Driveways and minor approaches per mile		0.0142	0.0010	13.8300	<0.001
α_0	Dispersion parameter		1.3609	0.0603	22.553	<0.001

Table 5.20 Calibrated Coefficients for KA Crashes Excluding Deer Collisions on Non-Freeways

Coefficient	Variable		Value	Std. Dev	t-statistic	p-value
b_0	Intercept		-9.1919	0.5535	-16.6080	<0.001
b_{aadt}	AADT		0.7309	0.0697	10.4810	<0.001
b_{aft}	After period indicator		0.0381	0.0685	0.5570	0.5778
b_r	Region indicator	Superior Region	--	--	--	--
		North Region	--	--	--	--
		Grand Region	0.2289	0.0771	2.9700	0.0029
b_{osw}	Outside shoulder width		--	--	--	--
b_{terr}	Terrain		--	--	--	--
b_{turn}	Number of turning lanes		0.1180	0.0454	2.5970	000094
b_{HC}	Average DOC of HC		0.0559	0.0153	3.6460	<0.001
$b_{driveways}$	Driveways and minor approaches per mile		0.0139	0.0027	5.1980	<0.001
α_0	Dispersion parameter		0.8907	0.3568	2.4970	0.0125

Table 5.21 summarizes the results of the EB analysis. This table shows a marginal, but statistically significant, increase in the total number of crashes, total non-deer crashes and PDO crashes. All the other types of collisions showed very small, but non-statistically significant, changes.

Table 5.21 Index of Safety Effectiveness for Non-freeway Facilities

Terminology	Total		KA		B	C	O
Crash Type	All	ND*	All	ND*	All	All	All
θ (The Index)	1.114	1.096	1.017	1.047	0.973	0.996	1.144
Standard Deviation	0.022	0.038	0.113	0.120	0.099	0.082	0.024
Significance (5% level)	Yes	Yes	No	No	No	No	Yes

5.4 Relationship between Speed and Safety on Freeways

Collectively, the results showed that increased speed limits have led to higher travel speeds, as well as increases in crash frequency and severity. In order to better understand the nature of these relationships, additional analyses were conducted to assess the relationship between speed and safety on rural freeways. To this end, a case-control analysis was conducted that compared crash frequency on roads before and after the speed limit increase. The roadway segments where the 70-mph speed limit was maintained were included in the analysis as a control group, while the road segments with a 75-mph speed limit were the increased segments. The control segments were selected based on comparable AADT and road geometric features of the increase sites. The crash, and roadway geometry data were obtained from MDOT as discussed previously for the case of speed data analysis. Probe vehicle speed data for freeways were utilized for this analysis since the speed data were available for the entire freeway corridor of Michigan. The lack of such data for the non-freeway system limited the potential for conducting similar analyses for those facility types.

5.4.1 Data Summary

Table 5.22 presents descriptive statistics (mean and standard deviation) for each of the variables included in the final dataset. These data describe the geometric and traffic characteristics of each site, followed by details of the aggregate trends in before-and-after period crash and speed data. A few points warrant discussion regarding the comparability of the two datasets. First, the sites where the speed limits were increased were selected, in part, based upon geometric and traffic characteristics. The increases predominantly occurred at those sites where traffic volumes were lower (mean = 7,921 veh/day for increase sites; mean = 19,472 veh/day for control sites), as well as where lanes, shoulders, and medians were wider.

Table 5.22 Descriptive Statistics of Pertinent Variables

Parameter	Control Sites		Increase Sites	
	Mean	Std. Dev.	Mean	Std. Dev.
Geometric and Traffic Characteristics				
Annual average daily traffic (veh/day)	19,471.88	7,115.49	7921.31	4012.97
Percent trucks	13.96	7.23	10.24	4.54
Segment length (miles)	1.17	0.55	1.21	0.44
Lane count (1 if 3+, 0 otherwise)	0.11	0.32	0.01	0.11
Lane width (1 if 12ft+, 0 otherwise)	0.98	0.15	1.00	0.00
Cable median barrier present (1 if yes, 0 otherwise)	0.31	0.46	0.05	0.23
Median width (1 if 90ft+, 0 otherwise)	0.24	0.43	0.59	0.49
Right shoulder width (1 if 11ft+, 0 otherwise)	0.29	0.46	0.19	0.39
Left shoulder width (1 if 9ft+, 0 otherwise)	0.15	0.36	0.03	0.16
Road geometry (1 if tangent, 0 otherwise)	0.81	0.39	0.86	0.35
Percent of segment on curve (1 if <40, 0 otherwise)	0.12	0.32	0.09	0.29
Annual Before-Period Crash Data				
Total crashes	7.86	7.01	3.60	3.10
Fatal and serious injury crashes	0.13	0.39	0.06	0.26
Minor and possible injury crashes	1.09	1.5	0.43	0.73
Property-damage-only crashes	6.64	5.89	3.11	2.76
Annual After-Period Crash Data				
Total crashes	8.22	6.86	4.2	3.52
Fatal and serious injury crashes	0.14	0.38	0.08	0.28
Minor and possible injury crashes	1.1	1.41	0.52	0.82
Property-damage-only crashes	6.98	5.91	3.61	3.13
Annual Before-Period Speed Data				
Mean speed (mph)	64.63	2.90	65.16	1.36
15th Percentile speed (mph)	61.64	3.14	62.06	1.4
50th Percentile speed (mph)	64.2	2.95	64.76	1.28
85th Percentile speed (mph)	68.65	2.92	68.94	1.69
Standard deviation (SD) of speed (mph)	4.19	1.10	3.78	0.46
Annual After-Period Speed Data				
Mean speed (mph)	65.70	2.59	66.76	1.18
15th Percentile speed (mph)	63.62	2.97	64.23	1.62
50th Percentile speed (mph)	65.72	2.54	66.5	1.10
85th Percentile speed (mph)	68.89	2.61	69.98	1.47
Standard deviation (SD) of speed (mph)	4.73	1.27	4.39	0.63
Sample size	6970		5045	

The speed data were also generally comparable between the increase (mean = 65.2 mph) and control (mean = 64.6 mph) sites. Given the differences in traffic volumes, it should be noted that the annual number of crashes before the speed limit increases occurred tended to be much higher at the control sites given the higher volumes (mean = 3.60 crashes/year for increase sites; mean = 7.86 crashes/year for control sites). Interestingly, when normalizing by million vehicle-miles-travelled (MVMT), the crash rates are generally comparable as the increase sites experienced an average rate of 1.03 crashes per MVMT compared to 0.95 crashes per MVMT for the control sites. After the speed limit changes occurred, all of the speed metrics were found to increase at both the control sites and the increase sites, though the increases were consistently larger where the speed limit was also increased. Considering the general magnitude of these increases, it is again notable that the sample of probe vehicles included an overrepresentation of heavy vehicles. As shown in previous chapter of the report, data from field LIDAR studies and permanent traffic records were generally 2 to 4 mph across the increase sites while the average increase from the probe vehicles was only 1.6 mph. Turning to the crash data, crashes also increased at all severity levels across both the increase and control sites. However, these increases were much more pronounced at the sites where the speed limits were increased. Total crashes increased by 16.7% (compared to 4.6% at control sites), K/A injury crashes by 33.3% (compared to 7.7%), B/C crashes by 20.9% (compared to 0.9%), and PDO crashes by 16.1% (compared to 5.1%).

5.4.2 Statistical Methodology

A series of regression models were estimated to understand the relationship between speed and safety while accounting for speed limit increases. The annual crash frequency on any given road segment takes the form of a discrete, non-negative integer. Such count data models are generally analyzed by Poisson or negative binomial (NB) regression models. Under a Poisson model, the probability of the number of crashes, y, occurring on a road segment *i*, during a specific time period is given as shown in equation 34.

$$P(y_i) = \frac{e^{-\lambda}\lambda_i^{y_i}}{y_i!} \tag{34}$$

Where, λ_i is the average number of crashes for segment *i* with similar characteristics. NB model is preferred over Poisson model as it accounts for overdispersion generally found in the crash data. Thus, in a NB model, a gamma-distributed error term is included in estimating λ_i as shown in equation 35.

$$\lambda_i = EXP(\beta X_i + \varepsilon_i) \tag{35}$$

The term $EXP(\varepsilon_i)$ is gamma distributed with mean and variance equal to 1 and α, respectively, where α is the overdispersion parameter. As stated previously, the analysis dataset combines cross-sectional and longitudinal data to form a panel dataset wherein roadway segments are repeated for each year for five years. Thus, a random-effects modeling framework is adopted to account for any correlation among crash count observations across different years. The random-effects model allows the constant term to vary across segments as shown in equation 36.

$$\beta_{0i} = \beta_0 + \omega_i \tag{36}$$

Where, ω_i is a randomly distributed random effect for segment *i* and all other variables are as defined previously. The natural logarithm of the segment length was taken as the offset variable.

5.4.3 Results and Discussion

Separate random effects negative binomial models were estimated for crashes at various injury severity levels. Due to the lower frequency of fatal crashes (K), these were aggregated with serious injury (A) crashes. Similarly, minor (B) and possible (C) injury crashes were aggregated, while PDO crashes were evaluated separately due to their relatively higher frequency. Table 5.23

presents the results of these models. For each variable of interest, a parameter estimate is provided, along with the associated standard error (in parentheses). Those parameters that were statistically significant at a 95% confidence level are indicated by an asterisk.

Table 5.23 Regression Results for Crashes by Severity Level on Freeways

Parameter	Estimate (Std. Error)			
	Total Crashes	**KA Crashes**	**BC Crashes**	**PDO Crashes**
Intercept	-2.979 (0.325)*	-8.536 (0.983)*	-6.750 (0.489)*	-2.936 (0.334)*
Period and Site Type				
Before-Control		*Baseline*		
Before-Increase	-0.189 (0.034)*	-0.170 (0.113)	-0.134 (0.054)*	-0.172 (0.036)*
After-Control	-0.019 (0.013)	-0.060 (0.069)	-0.078 (0.027)*	-0.013 (0.013)
After-Increase	-0.139 (0.035)*	-0.120 (0.120)	-0.084 (0.055)	-0.123 (0.036)*
Mean speed (mph)	-0.018 (0.004)*	-0.002 (0.013)	-0.024 (0.006)*	-0.021 (0.004)*
SD of speed (mph)	0.068 (0.007)*	0.140 (0.027)*	0.103 (0.013)*	0.065 (0.008)*
Ln(AADT)	0.591 (0.024)*	0.586 (0.078)*	0.810 (0.038)*	0.585 (0.024)*
Percent tucks	-0.008 (0.002)*	N/A	-0.021 (0.003)*	-0.007 (0.002)*
Road Geometry				
Tangent		*Baseline*		
Curve on <40% of segment length	0.163 (0.035)*	0.163 (0.089)	0.115 (0.045)*	0.164 (0.035)*
Curve on >=40% of segment length	0.197 (0.045)*	0.330 (0.121)*	0.245 (0.060)*	0.189 (0.046)*
Median type				
Graded with ditch		*Baseline*		
Graded with ditch with cable median barrier	0.053 (0.031)	-0.015 (0.075)	0.021 (0.041)	0.067 (0.031)*
Median width (ft)				
<90		*Baseline*		
>=90	-0.102 (0.026)*	N/A	-0.093 (0.037)*	-0.107 (0.027)*
Right shoulder width (ft)				
<11		*Baseline*		
>=11	-0.079 (0.025)*	-0.159 (0.072)*	N/A	-0.085 (0.026)*
Random Effects				
Variance of Intercept	0.218	0.283	0.192	0.22

5.4.4 Effect of Speed Limit Increases

When interpreting the results, it should be noted that a combination of site type (control or increase) and period (before or after) variables were used to distinguish differences that are due to factors that are not directly accounted for in the model. To ensure the model is identifiable, the before-period control site group was left out as a baseline for comparison purposes. As such, the remaining site-type/period variables can be compared to determine how the frequency of crashes vary as compared to this control group.

Table 5.24 provides a summary of the percent change in crashes between the before- and after-periods at both the speed limit increase and control sites. Overall, crashes were shown to decrease by 1.9% overall at the control sites. These decreases were more pronounced among B/C level injuries (7.5%) and K/A injuries (5.8%). In contrast, crashes of all types increased by approximately 5.0% at those sites where the speed limits were increased. It should be noted that the differences between the before- and after-periods and between the site types as shown in Table 5.24 are generally smaller than reflected by the summary statistics in Table 5.22. This is due to the fact that this analysis has controlled for the effects of other important factors, including changes in traffic volumes and speeds, in addition to accounting for factors that were consistent between the two periods such as shoulder width and horizontal curvature.

Table 5.24 Percent Change in Crashes between Before and After Periods by Severity Level and Site Type on Freeways

Site-Type	Percent Change in Crashes by Severity Level			
	Total	KA	BC	O
Control	-1.9%	-5.8%	-7.5%	-1.3%
Speed Limit Increase	5.1%	5.1%	5.1%	5.0%

Figure 5.1 depicts differences in total crashes at the speed limit increase sites based upon different levels of traffic volume while holding other independent variables constant. Differences

were generally smaller across the lower ranges of AADT (i.e., less than 10,000 vehicles/day). However, these differences become more pronounced as the AADT increases.

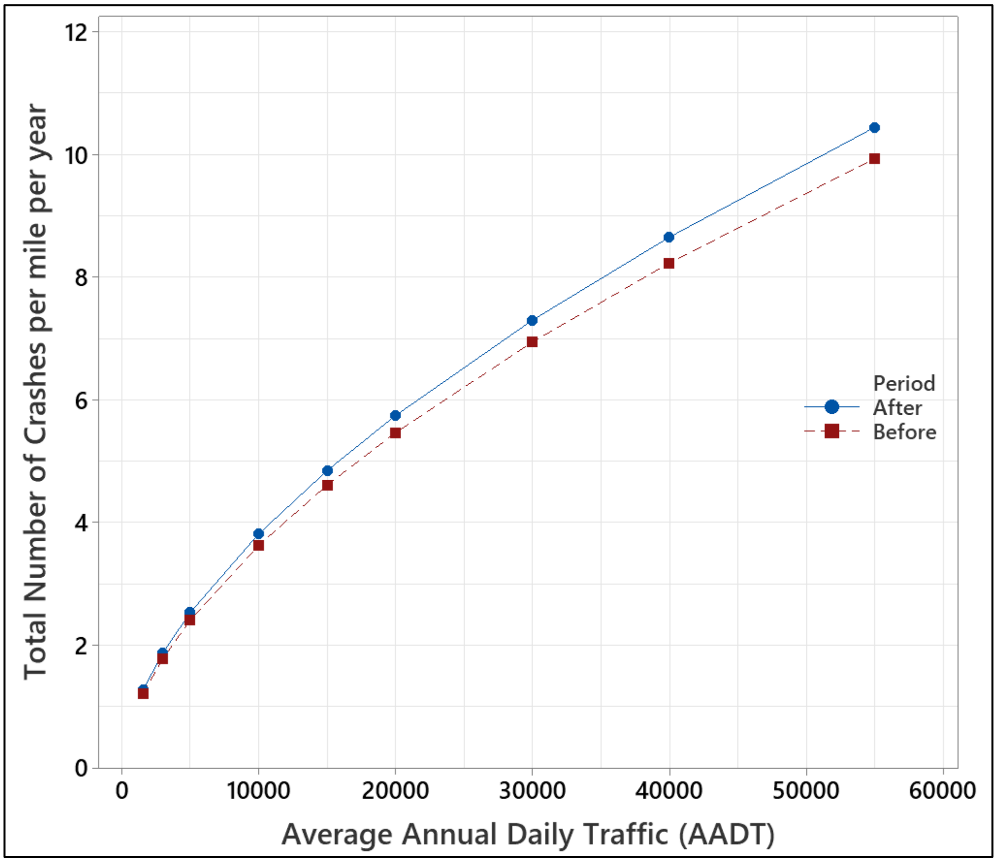

Figure 5.1 Annual Number of Crashes for Increase Site based on Study Period and AADT

5.4.5 <u>Effect of Speed Distribution</u>

In order to assess the relationship between travel speeds and safety, various speed metrics, including mean speed, 15th, 50th, and 85th speed percentiles, were investigated. The analyses considered each of these metrics as a predictor in the regression models. However, due to the strong correlation between these various metrics at each site, only one such metric was included in the final model. The standard deviation of speeds was also calculated and included in the analysis to account for variability in speeds.

The results show that both the mean speeds, as well as the standard deviation of speeds were strong predictors of crash frequency across all severity levels. Interestingly, higher mean speeds were associated with lower crash frequencies. A 1-mph increase in mean speed was associated with a 1.8% reduction in total crashes and these decreases ranged from 0.2% to 2.4% across the various severity levels. This could be reflective of several factors, including less congestion on the freeways with higher speeds, even after controlling for the effects of traffic volume. Similar results have also been shown in the extant literature (Baruya, 1998; Roshandel et al., 2015; Yu et al., 2013).

On the other hand, the relationship between speed variance and crash frequency was positive. This means that the greater the variability in the speed, the higher the frequency of crashes, which was true for total crashes as well as crashes at each of the injury severity levels. Crashes of higher severity were found to be more sensitive to speed variability with a 1-mph increase in standard deviation in speeds resulting in a 15% increase in KA crashes and 11% and 6.7% increases in BC and PDO crashes, respectively. Total crashes increased by 7% for a 1-mph increase standard deviation. Figure 5.2 shows a graphical representation of changes in crashes between before and after period with different ranges of standard deviation of speed while keeping other independent variables constant. Overall, the results suggested that the drivers moving at significantly higher or lower speeds than the mean speeds tend to negatively affect traffic safety. This supports early research by Solomon (Solomon, 1964) and Lave (Charles Lave, 1985), which suggest speed variance to be a particular concern for traffic crashes. It is important to note that, even after controlling for the relationships with mean speed and speed variance, the speed limit increase sites experienced persistent increases in crashes while the control sites experienced fewer crashes after the speed limit changes were introduced.

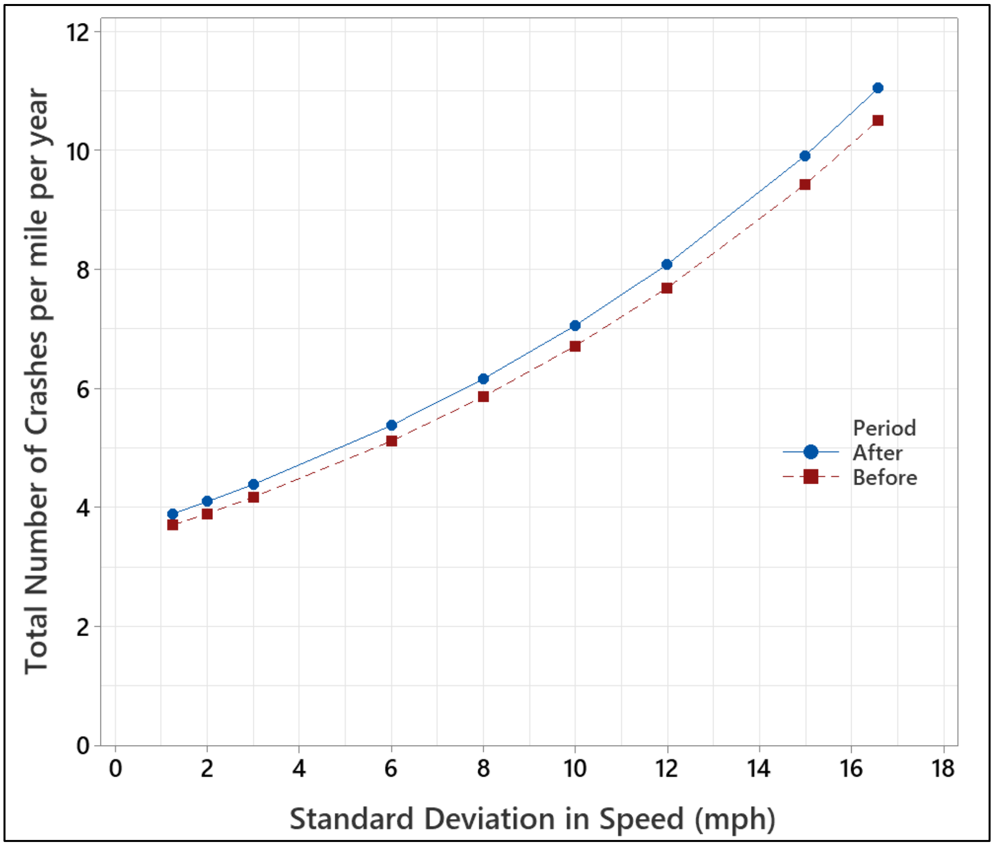

Figure 5.2 Annual Number of Crashes for Increase Sites based on Standard Deviation of Speed

5.4.6 Effect of Site Characteristics

As expected, the crashes were found to increase with traffic volume. The effects were found to be relatively inelastic, with a 1% increase in volume associated with a 0.59% increase in total crashes, KA crashes, and PDO crashes, and a 0.81% increase in BC crashes. The percentage of trucks in the traffic stream was found to have a negative but weak relationship with crash frequency. In general, segments on curves were found to have 12%-39% higher crash frequency compared to the tangent sections. Segments with a greater proportion of their length on a curved section were found to have a higher crash frequency which was found to hold true across all severities. This is expected as curves are generally subjected to lower safety.

Crashes were significantly lower on segments with wider medians and shoulders. This is likely because such conditions provide more room for drivers to regain control of their vehicles or swerve to avoid an impending collision. The installation of cable barriers along the medians on rural freeways led to increased total crash frequency, but reduced fatal and serious injury crashes. This is expected as the primary objective of these barriers is to reduce severity of crashes to minor/possible injury and PDO that would otherwise be a fatal or a serious injury crash. The results show PDO crashes were 6.9% higher, and KA crashes were 1.5% lower at sites with cable median barrier installed compared to sites where these barriers were not present, though this result was only statistically significant among PDO crashes.

6. CONCLUSIONS

The purpose of this research was to evaluate the impacts of speed limits increases that occurred in the state of Michigan during calendar year 2017 on speed selection, and crash and injury risk. Separate analyses were conducted for the freeway and non-freeway networks. On more than 600 miles of limited-access freeways, the speed limits were increased from 70 mph to 75 mph for passenger cars while the limits for trucks were increased from 60 mph to 65 mph statewide. On non-freeways, the speed limits were increased from 55 mph to 65 mph on 943 miles of rural two-lane highways. To this end, several analyses are carried out to evaluate the impacts of these speed limit increase on traffic speed and traffic safety.

6.1 Impacts on Traffic Speed

Much of the prior research has focused on impacts of speed limit increase on just the mean speeds and not other speed percentiles, such as 85th percentile which is still used for setting the speed limits in many states. Thus, the analyses in this research were done for various percentiles (15th, 50th, and 85th) along with variability in speed using various regression methods.

The speed limit increases resulted in increased speeds on both the freeway and the non-freeway network. On the freeway network, the 5-mph increase in speed limits increased the free-flow speeds by 1.1 mph to 2.8 mph, and the aggregated speeds increased by 1.4 mph to 3.2 mph. The magnitude of these increases was found to be the highest among the faster-traveling drivers, while the lowest speed drivers tend to increase their speeds by the lowest amount. These differences in speed selection behavior across drivers leads to higher speed variability which increased by 0.2 mph for free-flow speed, and 0.4 mph to 3.5 mph for aggregated speeds based on data aggregation technique.

On the non-freeway network, the results show that the 10-mph speed limit increases resulted in travel speeds that were generally between 3 mph and 5 mph higher across the distributions of both passenger vehicles and large trucks. Notably, the travel speed increases varied significantly among drivers: the magnitude of these increases tend to be highest among the top end of the speed distribution. In contrast, the lowest speed drivers increased their speeds by the least amount. Again, this leads to increased speed variability which increased by 0.8 mph to 0.9 mph for both the vehicle types.

6.2 Impacts on Traffic Safety

To evaluate the impacts of speed limit increases on traffic safety, several analyses starting with the simplest wherein the annual average crash frequencies and rates were compared, followed by the more sophisticated Empirical Bayes (EB) analysis for both freeways and non-freeways. As a part of the EB analysis, safety performance functions (SPF) were developed based on control sites to predict the crash count by severity for the increase sites. The results from the EB analysis show that the crashes generally increased across all severities as a result of speed limit increases on both freeways and non-freeways. On freeways, total crashes with and without deer collisions increased by 9.5% and 9.2%, respectively. KA crashes increased by the greatest amount (33.3%), while B crashes increased by 31.6% followed by PDO crashes which increased by 8.2%. C crashes reduced by 7.3%. On non-freeways, the EB analysis showed an increase of 11.4% and 9.6% in total crashes with and without deer involved crashes. The KA crashes increased by 1.7% when deer collisions are included, and 4.7% when these are excluded (not statistically significant). The B and C crashes reduced by 2.7% and 0.4%, respectively, although these results were not statistically significant. The PDO crashes increased by 14.4%.

Additional analysis that relates traffic speed and traffic safety was also carried out for the freeway network. The results show that the crashes increased by 5% across all severities due to speed limit increases after controlling for the effects of other important variables related to roadway geometry and traffic volumes. Notably, higher mean speeds were associated with lower crash frequency while greater speed variability was associated with greater crash frequency. However, it should be noted that the mean speeds considered in this analysis were obtained from probe vehicles and were aggregated annually for each of the segments. As such, the speeds are generally biased downwards due to the overrepresentation of heavy vehicles in probe vehicle data. Further, the standard deviation in speeds used in this study is based upon aggregate speeds over 15-minute intervals and does not directly account for differences in speeds of individual vehicles.

6.3 Recommendations

The effects of the speed limit increase were largely similar with the results from prior research conducted both nationally and internationally. Speed limit increases were generally associated with increases in travel speeds, as well as both the frequency and severity of crashes. Broadly speaking, the present study further reinforced these results.

Historically, 85^{th} percentile speeds have been used to set the speed limits on any given roadway. However, a 2018 survey conducted by the National Committee on Uniform Traffic Control Devices (NCUTCD) Task Force shows that those professionals who perform posted speed limit studies rarely use only the 85th percentile speed and, instead, consider the context of the roadway where the speed limit change is being considered (Fitzpatrick et al., 2019). The results from this study have shown that the driver speed selection varies significantly across different groups of drivers. Any changes in the driving environment affects each driver differently and as such 85^{th} percentile speed may not be suitable in determining the speed limit alone. Other factors such as variability in speeds, roadway context, roadway characteristics and historic crash rates should also be considered while setting the speed limits.

From a speed limit policy perspective, safety trends suggest that the higher speed limits are associated with higher frequency and severity of crashes. The detailed analysis of speed data suggests disproportionate increases in speeds among those drivers traveling at the highest speeds. Though it is generally not possible to determine the speeds of individual crash-involved vehicles, it may be that these highest speed drivers are also responsible for a disproportionate number of traffic crashes. Consequently, caution should be exercised as to direct adherence of speed limits to the prevailing 85^{th} percentile speeds. This practice may lead to a persistent cycle of increasing speed limits, resulting in higher operating speeds and lower safety (Donnell et al., 2009).

In Michigan, it is important to note that the speed limits were increased at locations that had historically experienced fewer crashes. In spite of this fact, both the frequency and severity of crashes increased significantly at these locations. Consequently, caution should be exercised in considering additional speed limit increases. This is especially true given the increases in vehicle speeds and in the rate of fatal and severe injuries that were experienced at the sites where the lower speed limits remained in place over the course of the pandemic.

Thus, it is recommended to carefully consider several factors before considering to increase the speed limits on any roadway. These factors include prevailing travel speeds (mean speed, 85th percentile speed, speed variance), long term crash history, roadway geometry, traffic volume, and costs incurred.

6.4 Limitations and Future Research

This study provides important insights as to the impacts of the speed limit increases that occurred throughout Michigan in 2017. However, a few important limitations should be noted.

First, the analyses of speed data allowed for an investigation of differences in speed selection behavior across specific roadway locations. Similarly, the crash analyses provide insights as to aggregate-level trends in safety performance that coincided with the speed limit increases. However, there is still some uncertainty as to the nature of the speed-safety relationship. While the findings consistently show that crashes, injuries, and fatalities increase when speed limits are increased, there is considerable nuance to these relationships and the speed-safety analyses presented herein suggest that variability in travel speeds is perhaps a stronger determinant of safety performance than mean speed. With that being said, the variability in speeds was also shown to increase where speed limit increases went into effect.

This research examined several different sources of speed data, ranging from permanent traffic recorders, to probe vehicles, to LIDAR-based spot-speed studies. As such, the differences in speed metrics before and after the increase tend to vary based on the speed data source. This is primarily due to different data aggregation techniques across different data sources, which makes it difficult to directly compare the results across different sources. As such data are being used with increasing frequency by road agencies, it is important to acknowledge the limitations and inherent differences when using different sources, particularly as it relates to probe vehicle data.

In addition, other contemporaneous changes may have also impacted the analysis, including the fact that marijuana was legalized in December 2018. This factor is essentially considered implicitly through the inclusion of control sites, with the underlying assumption being that the effects will be comparable across sites regardless of whether the speed limits have been increased. However, it is possible that the adverse safety impacts may be more pronounced due to potential interaction effects between impairment and speed selection. The results of this study have advanced our understanding of how mobility and safety are impacted by speed limit policy changes, though additional research is warranted to better understand the complex nature of these relationships.

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