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How is traffic safety affected by changes in traffic speeds following speed limit increases? An evaluation with probe vehicle data

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Abstract: Maximum speed limits continue to be an important policy issue. Research has consistently shown speeds to increase following speed limit increases. These increases have also generally coincided with increases in both the frequency and severity of crashes. However, research has been more limited as to the direct relationship between speed and safety. To this end, the present study evaluates the effects of increasing speed limits on the safety of rural limited access freeways while accounting for contemporaneous changes in the speed profiles of these same roadways. The speed limit increases in Michigan occurred between May 1 and June 12 of 2017, when the maximum speed limits were increased from 70 to 75 mph on approximately 600 miles of freeways. The maximum speed limits for trucks were also increased from 60 to 65 mph on all freeways state-wide at this same time. Speed data were obtained for the Michigan rural freeway network through probe vehicles. These data are merged with pertinent roadway data, as well as police-reported crash data at various levels of injury severity. The impacts of the speed limit increase on safety were evaluated by estimating random effects negative binomial models as part of a case-control before-after study design. The results show that the locations where the speed limits were increased experienced a 5% increase in crashes, while a marginal reduction in crashes was observed where speed limits did not increase. Interestingly, mean speeds were found to be negatively associated with crash frequency, while the standard deviation of speed was found to exhibit a positive relationship. Several site-specific characteristics were also found to be strong predictors of crash frequency. The results provide important insights into the nature of the relationship between speed and safety and will help to guide subsequent speed limit policy decisions.

Keywords: 75 mph, crash frequency modelling, rural freeway, speed limit increase, speed variance

1 Introduction

Posted speed limits are a means of indicating to the driver the maximum permissible speed on a highway under ideal roadway, traffic, and weather conditions (Forbes *et al.* 2012). The issue of how to determine speed limits that are appropriate for specific highways has been an issue of considerable interest 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 crashes (Garber & Gadiraju 1992). Typically, speed limits are established based on the roadway design speed. The American Association of State Highway and Transportation Officials (AASHTO) recommends using above-minimum criteria where practical and, ideally, the statutory speed limit should be set at or below the highway's prevailing design speed (AASHTO 2018).

The travel speeds along a highway are affected by many factors, including the posted speed limit. Roadway geometry, traffic, and weather conditions also influence the choice of speed, while differences are also observed across various groups of and drivers (Savolainen *et al.* 2018; Anastasopoulos & Mannering 2016). Speed limits tend to have a direct relationship with travel speeds. Prior research has shown that raising the speed limits usually leads to higher travel speeds; however, the changes are less pronounced than the magnitude of changes in the speed limit (Musicant *et al.* 2016; Kockelman 2006). These changes in travel speeds, in turn, directly affect the safety trends along the roadway. Higher travel speeds are associated with greater crash frequency as well as a higher proportion of more severe crashes due to higher energy being dissipated during crashes at these speeds. It has been consistently shown that increasing the average speeds leads to a significant increase in crash frequency, (Castillo-Manzano *et al.* 2019; Elvik *et al.* 2019; Imprialou *et al.* 2016; Elvik 2013; Nilsson 2004; Taylor *et al.* 2000) as well as severity (Elvik 2005). Additionally, speed has been shown to be one of the most significant determinants of traffic safety. Any percentage change in mean speeds is likely to have a much greater impact on traffic fatalities than a similar change in any other factor, such as traffic volume (Elvik 2005). Thus, increasing the speed limits tends to increase travel speeds which have significant carryover effects on traffic safety.

1.1 Study objective

The extant research literature has generally shown that the fatalities are consistently higher among states with higher maximum statutory speed limits (Warner *et al.* 2019; Davis *et al.* 2015). However, various states have recently increased or are planning to increase their maximum speed limits since (Donnell *et al.* 2016). In the State of Michigan, the Public Act of 445 and 447 were passed in 2016, which led to a series of increases in posted speed limits throughout 2017. The speed limit on approximately 614 miles of freeways was increased from 70 mph to 75 mph. Speed limits for trucks were also increased to 65 mph on state roads with a passenger car speed limit of 65 mph or higher. These recent increases in speed limits have provided an opportunity to revisit the relationship between speed limits, travel speeds, and safety.

To that end, the objective of this paper is to quantify the effect of speed limit increases on crash frequency following the 2017 speed limit increase by means of a case-control longitudinal study. This relationship is evaluated by estimating a series of random effects negative binomial models for crash frequency by different severity levels while considering various speed metrics, including mean speed, standard deviation of speed, and different percentiles of speed. The estimates of different speed metrics are obtained through probe vehicle data.

2 Literature review

The effect of increasing the posted speed limit on traffic operations and safety has been subject to considerable investigation, particularly following the enactment and subsequent repeal of the

National Maximum Speed Limit (NMSL) of 55 mph in 1987. The extant literature has largely focused on aggregate-level investigations of changes in traffic crashes, particularly fatalities, following various policy changes. The studies focused on limited access roadways have shown that fatal crashes and fatalities increased by 10–57% following the NMSL repeal (Ossiander & Cummings 2002; Houston 1999; Ledolter & Chan 1996; Lynn & Jernigan 1992; Brown *et al.* 1990; Garber & Graham 1990; McKnight & Klein 1990; Streff & Schultz 1990; Wagenaar *et al.* 1990; Baum *et al.* 1989; National Highway Traffic Safety Administration 1989). Also, the increased speed limits of 65 mph lead to higher average as well as 85th percentile speeds considering both short-term and long-term effects with the increase ranging from 2–7 mph (Ossiander & Cummings 2002; Lynn & Jernigan 1992; Mace & Heckard 1991; Freedman & Esterlitz 1990; Upchurch 1989). Following the repeal of NMSL, several states raised the speed limits to 70 or 75 mph on rural interstates. Consequently, total crashes, fatal crashes as well as fatalities were reported to increase significantly by about 4–62% (Dissanayake & Shirazenijad 2018; Shirazinejad *et al.* 2018; Friedman *et al.* 2009; Grabowski & Morrisey 2007; Patterson *et al.* 2002; Farmer *et al.* 1999). Raising the speed limits to 70 mph resulted in the average travel speeds increasing by about 1–2 mph, whereas the corresponding increase in the 85th percentile speeds ranged from 0.5–1.7 mph (Binkowski *et al.* 1998; Pezoldt *et al.* 1997; Retting & Greene 1990). Generally, the changes in the 85th percentile and mean speeds are less pronounced than the magnitude of the change in the speed limit, as evident from the literature. A 5 mph increase in the speed limit was associated with a 1.8–5.0 mph increase in the 85th percentile speeds, and the corresponding increase in the mean speeds ranged from 1.7–3.1 mph (Dissanayake & Shirazenijad 2018; Gayah *et al.* 2018; Hu 2017; Donnell *et al.* 2016; Kockelman 2006). On the other hand, a few of the studies have also reported a system-wide decrease in fatalities as a result of speed limit increase (Houston 1999; Godwin & Lave 1992; Lynn & Jernigan 1992).

As evident from the literature, raising speed limits tend to significantly affect the safety trends along these roadways. However, the increases in crash frequency and/or fatalities cannot be solely attributed to speed limit increase. These increases may also have been influenced by changes in the speed distributions across these locations. Thus, it is important to consider the effect of traffic speeds while modelling crash frequency. Considering the fundamental laws of kinetic energy, one can say without a doubt that crash severity increases as speed increases. However, the effect of changes in travel speeds on crashes is debatable.

The study by Solomon (Solomon 1964) was the first to indicate that the speed and crash frequency are not proportional to each other. The study showed that the crash risk is the highest at very high speeds, but is also heightened considerably at very low speeds. Subsequent studies have utilized mean speeds and variance in speeds to relate crashes with speed. A study in the United Kingdom, (Taylor *et al.* 2000) investigated the speed-crash relationship separately on rural and urban roads and found that the average speed and the spread of speed (measured by the coefficient of variation) are effective predictors of crashes. Another study has reported a positive relationship between speed and crash frequency (Gargoum & El-Basyouny 2016). On the other hand, few studies have reported conflicting results. A meta-analysis conducted to understand traffic characteristics affecting crash occurrence found that average speed has a statistically significant negative relationship with crash occurrence (Roshandel *et al.* 2015). Increasing average speed by one unit reduces the odds ratio of a crash by 4.8%. Speed variation was, however, positively related to crash occurrence with an odds ratio of 1.225. These findings have been supported by other studies in the literature (Yu *et al.* 2013; Baruya 1998). A separate study examined the speed-crash relationship using a spatial and a non-spatial model at the road segment level and found no significant relationship between average speeds and crashes (Quddus 2013). However, the speed variance had a positive relationship with the crash rate.

Similar findings were reported by another study (Lave 1985), which concluded speed variance to have a positive relationship with fatalities and not the average speed. Additionally, the data aggregation approaches seem to affect the relationship between speed and safety. A study reported a negative relationship between speed and crash frequency when crashes are analyzed at the road segment level. However, the relationship was found to be U-shaped when the crashes are grouped based on traffic operating scenarios or when the analysis is carried out at disaggregated crash levels (Yu *et al.* 2018).

Ultimately, the relationship between speed and safety is complex, and the results from existing studies leave several largely unresolved questions. Therefore, the present study contributes to the available literature in understanding the effects of raising speed limits on traffic speeds and safety and also relating traffic safety with travel speeds in the process.

3 Data description

This study evaluates changes in crash frequency along the Michigan rural freeway network. The changes are assessed by considering the recent 2017 speed limit increase as well as changes in speed profiles due to these speed limit increases. To this end, a case-control analysis is conducted that compares crash frequency on roads before and after the speed limit increase. The roadway segments where the 70 mph speed limit is maintained are included in the analysis as a control group, while the road segments with a 75 mph speed limit are the increased segments. The control segments were selected based on comparable annual average daily traffic (AADT) and road geometric features of the increase sites. Additional data required for analysis include crash data and speed data which are merged with the roadway information data to create a segment-level dataset. The following sub-sections provide details of the data collection and merging procedure, followed by the statistical methodology used for analysis.

3.1 Data collection

3.1.1 Traffic crash and roadway data

Statewide crash data were obtained for all limited access freeway segments that had a 70 mph speed limit in place prior to the 2017 speed limit increases. These data were obtained from the Michigan State Police (MSP) for the period from 2014 to 2019. Since the speed limit increase occurred at various points during 2017, crash data for this year were excluded for the purposes of this analysis. Consequently, the before-period ranges from 2014 to 2016 while the after-period includes 2018 and 2019. 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 (resulting in a death within 30 days of the crash), A denotes serious injuries (e.g., severe lacerations, burns, broken bones), B denotes minor injuries (i.e., any injury evident less than K or A), C denotes possible injuries (no evident external injury, but potential injury noted by crash-involved victim), and O denotes property damage only (PDO) crashes (i.e. no injury).

The crash data were integrated with a detailed roadway information database maintained by the Michigan Department of Transportation (MDOT). This dataset contains information detailing roadway geometric characteristics, such as lane and shoulder widths, the number of lanes by type, as well as the presence of features such as medians, among others. All limited access freeways with 70 mph and 75 mph speed limits were selected from the dataset for this study. This resulted in a total of 2 403 roadway segments. The AADT data were also obtained through MDOT's open data portal and was merged with the roadway information data. Additionally, information about the installation of cable median barriers along the freeway network was also obtained from a prior MDOT research study and integrated into the dataset (Savolainen *et al.* 2014).

3.1.2 Speed data

In order to investigate the relationship between crashes and operating speeds, this study leverages extensive speed data on the Michigan freeway network. These data are obtained from probe vehicles, which provide real-time speed data through global positioning systems installed in commercial vehicles, connected passenger vehicles, and cell phones. These data are provided by MDOT dating back to January 1, 2016. Speed information is available at various time intervals, and, for the purposes of this study, the speed data are obtained in 15 minutes intervals. These data are aggregated over each year of the study period in order to calculate mean, 15th percentile, 50th percentile, 85th percentile speeds, as well as the standard deviation of speed for each of the segments included in the analysis. Since these data are available starting in 2016, the same speed metrics are assumed to be representative for each of the three years of the before-period (2014–2016).

During a comprehensive review of the after-period speed data, a significant inflection point was observed from various site-specific speed profiles. It was found that the speeds increased significantly starting in June of 2019. This was due to changes in the composition of the fleet used to estimate speed metrics. Consequently, to allow for a more appropriate comparison between the pre- and post-speed limit increase periods, speed data for 2019 was aggregated only through May of 2019. The aggregated speed data were then merged with the roadway and crash dataset.

3.2 Data summary

Table 1 presents descriptive statistics (mean and standard deviation) for each of the variables included in the final dataset. Separate summary information is provided for the control sites and the speed limit increase sites. 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. 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. 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%).

Table 1 Descriptive statistics of pertinent variables

	Control sites (n = 6970)		Increase sites (n = 5045)	
Parameter	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**
Geometric and Traffic characteristics				
Annual average daily traffic (veh/day)	19 471.88	7 115.49	7 921.31	4 012.97
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
15^{th} Percentile speed (mph)	61.64	3.14	62.06	1.4
50^{th} Percentile speed (mph)	64.2	2.95	64.76	1.28
85^{th} 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
15^{th} Percentile speed (mph)	63.62	2.97	64.23	1.62
50^{th} Percentile speed (mph)	65.72	2.54	66.5	1.10
85^{th} 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

4 Statistical methods

To better understand the nature of these increases, particularly the relationship between speed and safety, a series of regression models were estimated. 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.

Starting with 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 (1):

$$P(y_i) = \frac{e^{-\lambda}\lambda_i^{y_i}}{y_i!}. \tag{1}$$

Where, λ_i is the average number of crashes for segment *i* with similar characteristics. The Poisson parameter, λ_i, can be calculated as shown in Equation (2):

$$\lambda_i = EXP(\beta X_i). \tag{2}$$

Where X_i is the vector of explanatory variables and β is a vector of parameters to be estimated that quantify the effect of these variables.

One of the limitations of the Poisson model is that it assumes the mean and variance of the expected crash counts are equal. This assumption is, however, often not satisfied by crash data, which tend to be overdispersed (i.e., the variance is greater than the conditional mean). The NB model can accommodate overdispersion by including a gamma-distributed error term, as shown in Equation (3):

$$\lambda_i = EXP(\beta X_i + \varepsilon_i). \tag{3}$$

This 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 (4):

$$\beta_{0i} = \beta_0 + \omega_i. \tag{4}$$

Where ω_i is a randomly distributed random effect for segment i and all other variables are as defined previously.

When estimating crash prediction models for road segments, 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. The models are estimated via maximum likelihood using the glmer.nb function under mass package in R-studio.

5 Results

Separate random effects negative binomial models are estimated for crashes at various injury severity levels. Due to the lower frequency of fatal crashes (K), these are aggregated with serious injury (A) crashes. Similarly, minor (B) and possible (C) injury aggregated, while PDO crashes are evaluated separately due to their relatively higher frequency. Table 2 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 are statistically significant at a 95% confidence level are indicated by an asterisk.

To interpret the practical impacts of any of the parameters included in the model, marginal effects ($\Delta\lambda$) can be calculated using Equation (5) for the variable of interest which represent percentage change in crashes corresponding to unit increase in independent variable:

$$\Delta\lambda = 100 \times (e^{\beta_n X_n} - 1). \tag{5}$$

The variables β_n and X_n are as defined previously.

Table 2 Random effects negative binomial parameter estimates based on crash severity

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			
<40% of segment on curve	0.163 (0.035)*	0.163 (0.089)	0.115 (0.045)*	0.164 (0.035)*
>40% of segment on curve	0.197 (0.045)*	0.330 (0.121)*	0.245 (0.060)*	0.189 (0.046)*
Median type				
Graded with ditch	Baseline			
Ditch and cable 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

*Parameter was statistically significant at $\alpha = 0.05$.

6 Discussion

6.1 Changes in crashes following 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 is left out as a baseline for comparison purposes.

Table 3 provides a summary of the percent change in crashes between the before- and after-periods at both the speed limit increase and control sites which are calculated based on the parameter estimates shown in Table 2. For the control sites, since the before-period is the baseline, the percentage increase in total crashes during the after-period can be calculated by plugging the 'After-Control' coefficient from Table 2 (-0.019) into Equation (5). For the sites where speed limits were increased, comparisons can be made between the parameter estimates for the 'Before-Increase' and 'After-Increase' parameters in this same model.

Overall, the model results showed that crashes decreased 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. These results align with much of the research literature, which has shown crashes, injuries, and fatalities to increase following speed limit increases (Dissanayake & Shirazenijad 2018; Shirazinejad *et al.* 2018; Friedman *et al.* 2009; Grabowski & Morrisey 2007; Patterson *et al.* 2002; Farmer *et al.* 1999).

It should be noted that the differences between the before- and after-periods and between the site types are generally smaller than reflected by the summary statistics in Table 1. 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 are consistent between the two periods such as shoulder width and horizontal curvature.

Table 3 Percent change in crashes from before-period to after-period by severity level and site type

	Percent change in crashes by severity level based on regression analysis			
Site type	**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 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.

6.2 Crash trends related to changes in the speed distributions

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 is included in the final model. The standard deviation of speeds is also calculated and included in the modeling framework to account for variability in speeds.

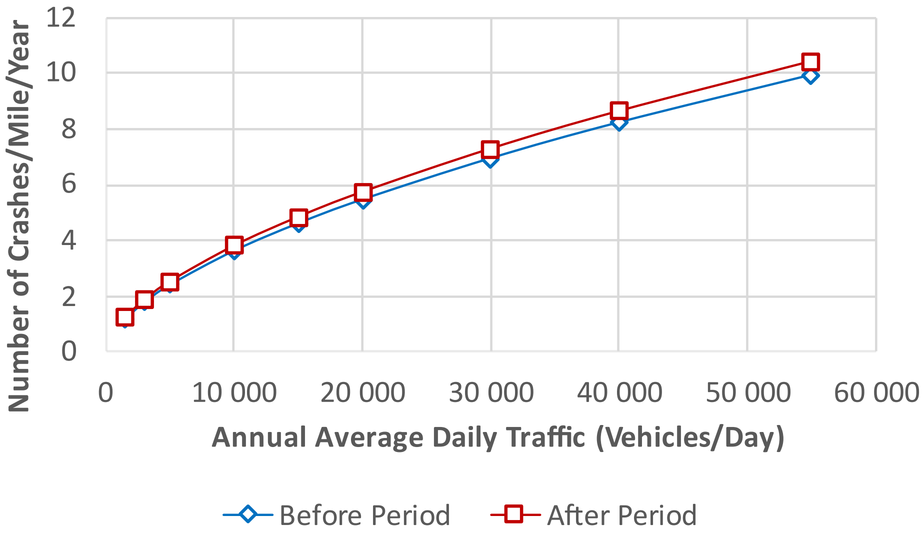

Figure 1 Annual number of crashes for increase site based on study period and AADT

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 1.8% fewer 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 (Roshandel *et al.* 2015; Yu *et al.* 2013; Baruya 1998). Figure 2 graphically shows the variation in crash rate with respect to mean speed before and after the speed limit increase for increase sites. It is important to note that the differences in mean speeds between the speed limit increase and control sites was generally relatively small. This is partly an artifact of the probe vehicle data, which have a disproportionately large number of trucks. As such, additional research is warranted to assess other aspects of this relationship.

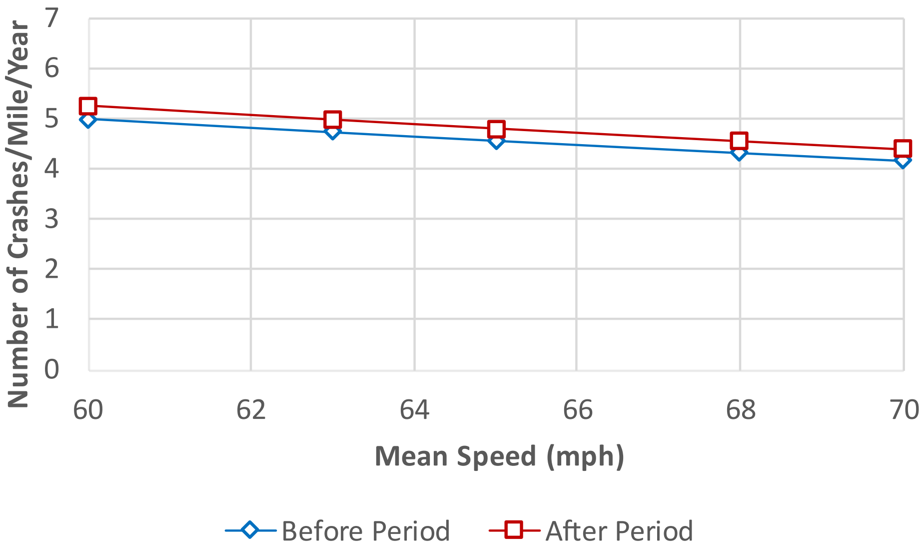

Figure 2 Annual number of crashes for increase sites based on mean speed

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% increase in BC and PDO crashes, respectively. Total crashes increased by 7% when the standard deviation in speeds is increased by 1 mph. Figure 3 shows a graphical representation of changes in crashes between before and after period on increase sites with different ranges of mean speed and standard deviation of speed, respectively, while keeping other independent variables constant. Overall, the results suggest that the drivers moving at significantly higher or lower speeds than the mean speeds tend to negatively affect traffic safety. This supports earlier research by Solomon (1964) and Lave (1985), which showed speed variance to have a more substantive impact on safety than changes in mean speeds.

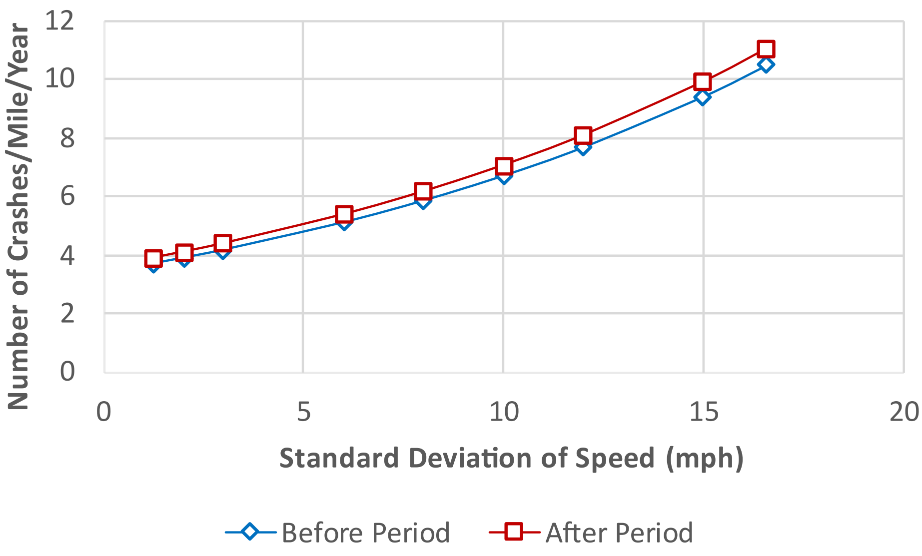

Figure 3 Annual number of crashes for increase sites based on standard deviation of speed

6.3 Differences in crashes based on geometric and traffic characteristics

As expected, crashes were found to consistently 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. This may be reflective of the greater variability in year-to-year crash counts among these higher injury severity categories. 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 (Martens *et al.* 1997).

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 (Kweon & Kockelman 2005). 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 (Russo *et al.* 2016). The model 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.

7 Conclusions

Recent speed limit increases have been associated with significant increases in fatal crashes, though impacts on total crashes, as well as the general relationship between speed and safety have been somewhat under researched. This study provides important insights as to the speed-safety relationship based on data from speed limit increases from 70 mph to 75 mph that occurred on approximately 600 miles of rural freeways in the state of Michigan.

From a big picture perspective, the results show that the 5 mph speed limit increase resulted in persistent increases in traffic crashes across all levels of injury severity. These increases were consistently around 5% across all severity levels after controlling for the effects of other important variables. Notably, both mean speed and speed variants were significant determinants of crash frequencies on these roadways. Interestingly, higher mean speeds were associated with lower crash frequencies, though the nature of this relationship warrants further investigation. This is particularly true because the sites where the speed limit increases occurred still tended to experience more crashes after controlling for differences in mean speeds. Consistent with prior research, more pronounced impacts on crashes were shown when examining the variability in travel speeds. Crashes of all severity levels increased with the standard deviation in travel speeds. When comparing crashes versus mean speed and speed standard deviation, crashes were consistently more sensitive to changes in the latter metric.

Several site-specific characteristics were also found to affect crash frequency, including traffic volume, traffic composition, shoulder and median widths, and the presence of cable median barriers. The findings from this study will be helpful for transportation agencies and policymakers in guiding their decisions to set speed limits.

While this study provides important insights, additional research is warranted to better understand the nature of the speed-safety relationship. The speed data considered in the study were aggregated at an annual level for each individual segment. Further work could investigate how speeds vary based on time of day and at levels of higher fidelity. It is also important to note that the speed data are aggregated and representative of the fleet of probe vehicles. As such, the speeds are generally biased downwards due to the overrepresentation of heavy vehicles. Further, the standard deviation in speeds used in this study is based upon aggregate speeds over 15 minutes intervals and does not directly account for differences in speeds of individual vehicles (and the crash risks of individual drivers). Nevertheless, the results from this study provide valuable information to support policy decisions and future research related to posted speed limits.

CRediT contribution statement

Nischal Gupta: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing—original draft. **Megat Usamah Megat Johari**: Formal analysis, Methodology, Visualization, Writing—original draft. **Hisham Jashami**: Formal analysis, Validation, Visualization, Writing—review & editing, **Peter T. Savolainen**: Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Validation, Writing—review & editing.

Declaration of competing interests

The authors report no competing interests.

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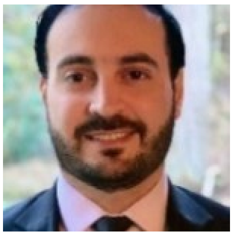

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