70 mph Study

FINAL REPORT

June 30, 2016

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The Thomas D. Larson
Pennsylvania Transportation Institute

COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF TRANSPORTATION

CONTRACT # 4400008014
WORK ORDER # PSU 013

Technical Report Documentation Page

1. Report No. FHWA-PA-2016-009-PSU WO 13	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle 70mph Study		**5. Report Date** June 30, 2016 **6. Performing Organization Code**
7. Author(s) Eric T. Donnell, Bachir Hamadeh, Lingyu Li, and Jonathan S. Wood		**8. Performing Organization Report No.** LTI 2016-26
9. Performing Organization Name and Address The Thomas D. Larson Pennsylvania Transportation Institute The Pennsylvania State University 201 Transportation Research Building University Park, PA 16802		**10. Work Unit No. (TRAIS)** **11. Contract or Grant No.** 4400008014, PSU WO 13
12. Sponsoring Agency Name and Address The Pennsylvania Department of Transportation Bureau of Planning and Research Commonwealth Keystone Building 400 North Street, 6th Floor Harrisburg, PA 17120-0064		**13. Type of Report and Period Covered** Final Report: 12/4/14 – 6/30/16 **14. Sponsoring Agency Code**

15. Supplementary Notes

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16. Abstract

In July and August 2014, the Pennsylvania Department of Transportation (PennDOT) and Pennsylvania Turnpike Commission (PTC) raised the posted speed limit on rural sections of Interstates 80, 380, and 76 from 65 to 70 mph. The purpose of this study was to assess the speed and safety performance of these "pilot" sections. This was done by comparing the operating speeds and crash frequencies before and after the posted speed limit increase. Additionally, operating speed data in several work zones were collected to assess how drivers comply with posted speed limits in work zones on the pilot sections. An inferred design speed method and pavement friction degradation method are proposed as methodologies to assess site conditions on rural Interstate roadways with 65 mph posted speed limits. Collectively, the operating speed, safety, inferred design speed, and friction information can be used by PennDOT and the PTC to identify candidate locations for 70 mph posted speed limits. The findings suggest that mean and 85th-percentile operating speeds increased after increasing the posted speed limit from 65 to 70 mph; however, the increases were less than 5 mph. A framework was developed to estimate the safety effects of the posted speed limit increase, because only 12 to 16 months of after period crash data were available for the analyses included in this study.

17. Key Words Speed limits, safety, operating speed, inferred design speed, pavement friction, work zones		**18. Distribution Statement** No restrictions. This document is available from the National Technical Information Service, Springfield, VA 22161	
19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 145	**22. Price** N/A

Form DOT F 1700.7 **(8-72)** **Reproduction of completed page authorized**

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This work was sponsored by the Pennsylvania Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration. The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of either the Federal Highway Administration, U.S. Department of Transportation, or the Commonwealth of Pennsylvania at the time of publication. This report does not constitute a standard, specification, or regulation.

Acknowledgement

The authors wish to acknowledge Mr. Glenn Rowe, Chief, PennDOT Traffic Engineering and Permits, for initiating this project. The authors are grateful for the technical support and guidance of Mr. Robert Pento, Manager of Traffic Engineering and Permits at PennDOT, during the project. Ms. Heather Heslop, PennDOT Research Program Manager, is acknowledged for her support. The research team also received guidance and assistance from several staff members of the Pennsylvania Turnpike Commission. Mr. Thomas Macchione, Manager of Traffic Engineering, coordinated this effort and provided helpful guidance and support during the project. Finally, the authors wish to acknowledge Messrs. Keith Johnson and Mark Unger from AECOM for answering questions about the data supplied by the Pennsylvania Turnpike Commission, and for offering comments on several project deliverables.

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INTRODUCTION

In July and August 2014, the Pennsylvania Department of Transportation (PennDOT) and Pennsylvania Turnpike Commission (PTC) raised the posted speed limit on rural sections of Interstates 80, 380, and 76 from 65 to 70 miles per hour (mph). This was considered phase one of a broader initiative. The following locations were included in the posted speed limit increase:

- Interstate 80 Eastbound (EB) near Dubois Interchange Exit 101: Segment 1010, Offset 2090 to Interstate 80 EB near State Route (SR) 477 Interchange Exit 185: Segment 1860, Offset 369.
- Interstate 80 Westbound (WB) near Dubois Interchange Exit 101: Segment 1001, Offset 2433 to Interstate 80 WB near SR 477 Interchange Exit 185: Segment 1845, Offset 1057.
- Interstate 380 Southbound (SB) near the Interstate 84 Interchange: Segment 0231, Offset 0045 to Interstate 380 SB near Exit 8: Segment 0095, Offset 1500.
- Interstate 380 Northbound (NB) near Tobyhanna Exit 8: Segment 0094, Offset 1600 to Interstate 380 near the Interstate 84 Interchange: Segment 0230, Offset 0045.
- Interstate 76 EB near Blue Mountain Interchange Exit 201: Milepost 200.90 to Interstate 76 EB near Morgantown Interchange Exit 298: Milepost 299.74.
- Interstate 76 WB near Blue Mountain Interchange Exit 201: Milepost 200.90 to Interstate 76 WB near Morgantown Interchange Exit 298: Milepost 297.40.

In order for PennDOT and the PTC to determine if additional segments of rural Interstate highway should be considered for the 70 mph posted speed, an assessment of the speed and safety performance of the “pilot” sections is needed. The purpose of this project was to compare operating speeds and crash frequencies before and after the posted speed limit was increased. Additionally, operating speed data in several work zones were collected to assess how drivers comply with posted speed limits in work zones, and to evaluate how driver speed choice changes from non-work zone to work zone locations. Additionally, an inferred design speed method and pavement friction degradation method are proposed as methodologies to assess site conditions on rural Interstate roadways with 65 mph posted speed limits. Collectively, the operating speed, safety, inferred design speed, and friction information can be used by PennDOT and the PTC to identify candidate locations for 70 mph posted speed limits.

This report is organized into nine subsequent sections. The first provides background information about posted speed limits in the United States. A general discussion about the relationship between speed and safety is described in the second section of the report. The third section of the report is a literature review of extant literature related to the speed and safety effects of changing posted speed limits. An overview of the objective analyses performed in the present study is provided in the fourth section of the report. The fifth section describes the operating speed evaluations performed at both non-work zone and work zone locations on PennDOT and PTC-operated rural Interstates. The sixth section describes the safety assessment of these same roadways. An inferred design speed evaluation for the PTC is provided in the seventh section, and the eighth section describes the pavement friction assessment. The final section of the report offers conclusions from the evaluation.

BACKGROUND

First instituted in 1901, speed limits are posted with the intent to communicate a safe driving environment for reasonable and prudent drivers. Before 1974, states had the responsibility of setting the speed limit, which was limited to 65 or 70 mph on rural roads. In urban areas, states often posted 55 mph speed limits, prior to establishment of the national maximum speed limit in 1974.

The debate on the effect of speed limit policy on operating speeds and safety has continued since the U.S. Congress established a provision under the Emergency Highway Energy Conservation Act in 1974, which prohibited speed limits higher than 55 miles per hour. The new provision, referred to as the national maximum speed limit (NMSL) law, was drafted in response to the oil embargo imposed during the 1973 oil crisis (Anders 1980). Twelve states had already started lowering speed limits on their roads prior to the enactment of the law. Speed limits were capped at 50 miles per hour for cars and 55 miles per hour for trucks based on anecdotal evidence that vehicles running at such speeds achieve maximum fuel efficiency (United Press International 1973). Estimates varied in regard to the law’s efficacy to reduce fuel consumption and its corresponding impact on actual driving speeds and safety.

Higher speed limits on rural Interstate highways were allowed after the Surface Transportation and Uniform Relocation Assistance Act (STURAA) was passed in 1987, which permitted posted speed limit increases to 65 mph on rural Interstates. Consequently, a few states (e.g., Kansas) reclassified some of their non-Interstate highways, which were built to Interstate roadway standards, later designating them as Interstates (Molotsk 1987).

States later acquired the authority to set Interstate speed limits through legislation such as the National Highway System Designation Act of 1995. This legislation, coupled with several past laws related to posted speed limits, raised interest in research efforts to determine the relationship between speed limits, safety, and operating speeds. Current maximum speed limits among the 50 state transportation agencies (STAs) in the U.S. are shown in Figure 1. As shown, a significant proportion of STAs have maximum speed limits of 70 or 75 mph. Idaho, Utah, Nevada, Wyoming and South Dakota have a maximum posted speed limit of 80 mph, while in Texas, maximum speed limits of 80 mph or 85 mph are allowed only when a highway system is deemed safe following an engineering or traffic study (TXDOT 2015).

The remainder of this literature review is organized into three sections. The first section covers the different relationships between posted speed limits, driving speeds, and safety. In this section, speed variance and safety (i.e., crash frequency and severity) associations are described, as is the relationship between driving speeds and posted speed limits. The effects of increasing posted speed limits on driving speeds and safety is also described in the first section of this report. The second section represents an outreach effort to state transportation agencies that have recently increased posted speed limits on rural Interstate highways. Speed and safety evaluations, when available, are described in this section of the literature review. The final section of this report focuses on recent research that has considered the effects of speed and safety as a function of the difference between free-flow and work zone speed limits.

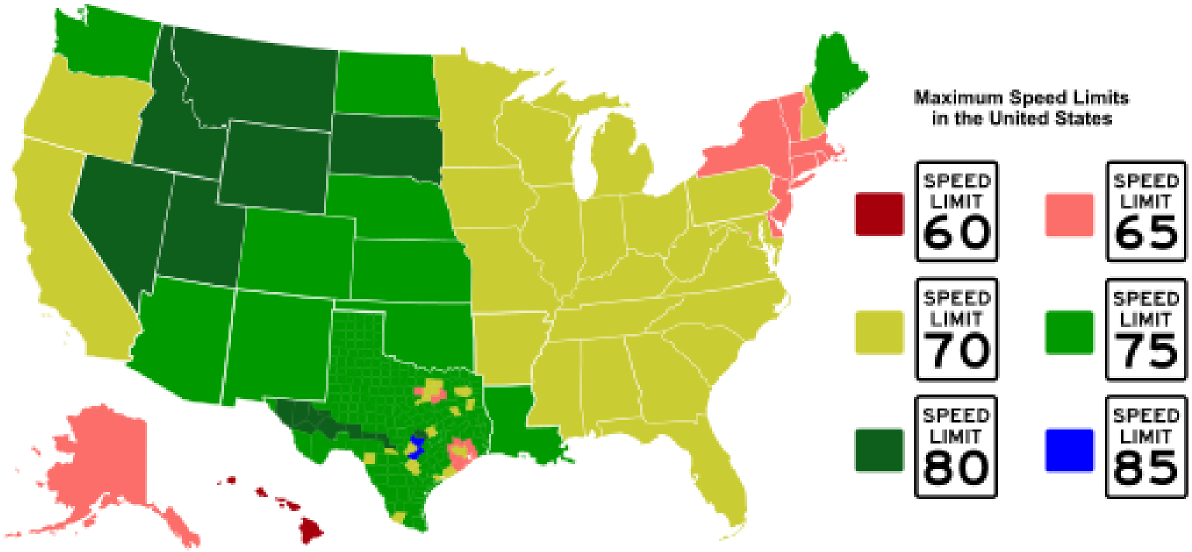


Figure 1. Maximum Speed Limit Laws by State in April 2016
(Wikipedia Contributors 2016; accessed on April 24, 2016)

SPEED AND ROAD SAFETY

Speeding is one of the major factors contributing to deaths and injuries in traffic accidents in the United States. As such, speeding-related crashes are associated with significant costs to society. The National Highway Traffic Safety Administration (NHTSA) estimates economic costs at $40.4 billion annually. In 2012, 10,219 lives were lost in speeding-related crashes, which constitute 30 percent of all fatal crashes in the nation. The relationship between impact speed and resulting injury is clear. Based on the principles of kinetic energy, the higher the speed of vehicles, the greater the probability of a severe crash outcome (energy is proportional to the square of the speed); however, the relationship between vehicle speed and crash involvement remains unclear (NHTSA 2014).

The earliest and most comprehensive study to examine the relationship between average speed and crash rate on rural highways was completed by Solomon in 1964. In an attempt to establish relative crash rates over 10 mph speed increments, the study utilized police crash reports to estimate the speeds of over 10,000 crash-involved vehicles on 600 miles of main rural highways in 11 states. Solomon found that the probability of being involved in a crash per 100 million vehicle-miles of travel, as a function of travel speed, follows a U-shape with the lowest relative crash risk around 65 mph during the daytime, and approximately 60 mph at night, as shown in Figure 2 (Solomon 1964). Higher involvement rates were reported at lower and higher speeds.

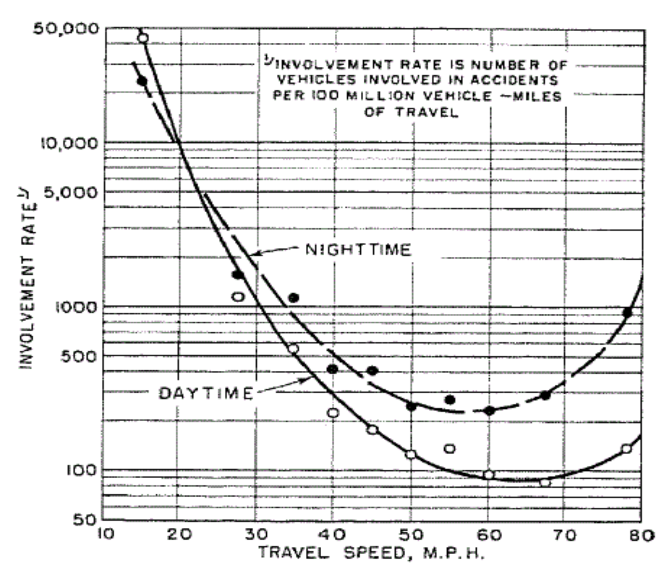


Figure 2. Daytime and Nighttime Crash Involvement Rates as a Function of Estimated Travel Speed (Solomon 1964)

The study also concluded that injury severity rate increased when daytime and nighttime operating speeds moved further away from 55 mph, as shown in the left panel of Figure 3. Property-damage-only (PDO) crashes (in thousands of dollars per 100 million vehicle-miles of travel) followed similar trends to injury rates versus speed, as shown in the right panel of Figure 3. The study also found a relationship between crash involvement rate and the variation between an individual driver speed and average speed of the traffic stream. This relationship is shown in Figure 4, for daytime and nighttime periods, which indicates that crash involvement rates increase as the deviation between individual travel speeds increases relative to average speeds of the traffic stream. This is often referred to as “Solomon’s Curve.” A few drawbacks of the study include the following: (1) crashes involving turning vehicles were not excluded from the sample of police crash reports used in the analysis, (2) operating speed estimates from crash-involved drivers were from police reports rather than speed-measuring systems, and (3) the analysis was limited to crashes involving two or more vehicles travelling in the same direction obtained from police and driver’s reports, sources that are prone to reporting errors and unreliability (Solomon 1964).

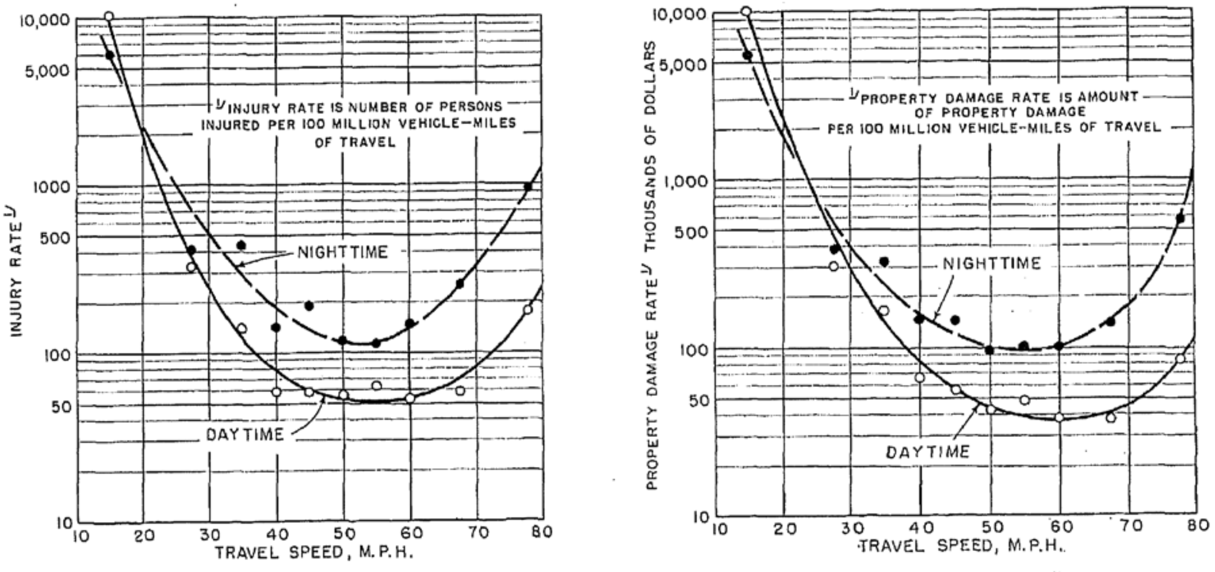


Figure 3. Daytime and Nighttime Injury (Left Panel) and Property Damage (Right Panel) Rates as a Function of Estimated Travel Speed (Solomon 1964)

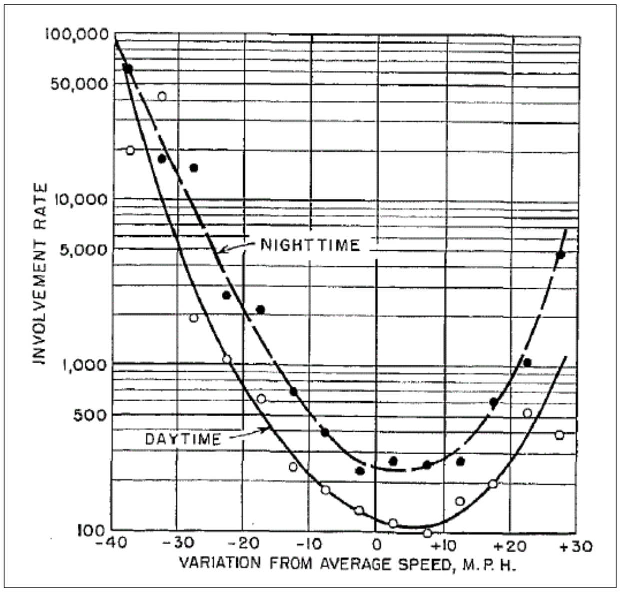


Figure 4. Daytime and Nighttime Crash Involvement Rates as a Function of the Variation from Average Speed (Solomon 1964)

A subsequent study by Cirillo in 1968 confirmed Solomon’s findings. The crash sample size included 2,000 vehicles, which were restricted to two-vehicle, same-direction daytime crashes on urban and rural freeways (Interstates) in 20 states. Cirillo’s study results were compared to Solomon’s U-shaped curves as shown in Figure 5 (Solomon 1964; Cirillo 1968).

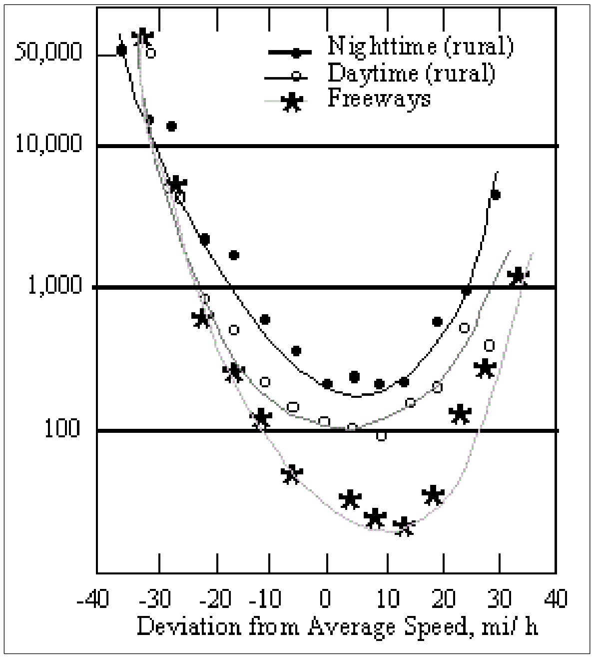


Figure 5. Crash Involvement Rate by Deviation from Average Travel Speed
(Solomon, 1964; Cirillo, 1968)

In Figure 5, the lowest crash rate obtained in Cirillo's study occurs when the driver-involved speed on freeways is approximately 12 mph higher than the average traffic speed, which is comparable to Solomon's study. In both studies, a problem arises when including slowing down or stopped vehicles in rear-end crashes, and thereby attributing such crashes to speeding when they could be caused by congestion or turning vehicles.

Munden (1967) partially verified Solomon and Cirillo's results in the United Kingdom (UK) by observing vehicle speeds and their deviation from the four proceeding and four following vehicle speeds. Speed and registration numbers were recorded for 31,000 vehicles travelling on rural main roads in the evening peak travel period and later matched to 14,000 accident records that did not necessarily occur on the roads surveyed. Identifying vehicles by registration numbers allowed for the identification of regular travelers and the repeated measurement of their speeds. On average, crash involvement for vehicles observed once didn't resemble a U curve; however, isolating vehicles travelling significantly above or below the average speed of the four proceeding and four following vehicles yielded a recognizable U-curve. Crash involvement rate followed a much more discernable U-curve for vehicles observed more than once, with speed variations of over 1.8 standard deviations from the average speed of the vehicles around them.

In contrast to earlier studies that relied on subjective assessment of speed from crash reports, the Research Triangle Institute (RTI) (1970) obtained accurate speed data by using crash scene investigators and sensors embedded in the pavement on a continuous stretch of state highways in Indiana where the speed limit was between 40 and 65 mph. In 9 out of 114 crashes occurring on the study segments, vehicle speeds were matched to specific vehicles involved in those crashes and further validated by the crash scene investigators. This study was also the first to point out the need to separate vehicles slowing down or stopping to initiate a turn from those that were travelling at a slower speed in the traffic stream.

To mitigate the inclusion problem of slowing down or stopped vehicles in the study sample, West and Dunn (1971) examined the Research Triangle Institute results, removed turning vehicles from the sample, and refined the relationship between average relative speed (i.e., difference between crash-involved vehicle speed and average speed of traffic stream) and crash involvement, as shown in Figure 6. Identifying turning vehicles that were travelling much slower than the average speed showed that the effect of excluding those vehicles from the analysis resulted in much lower crash involvement rates for crash-involved vehicles travelling more than 5.5 mph above the mean travel speed.

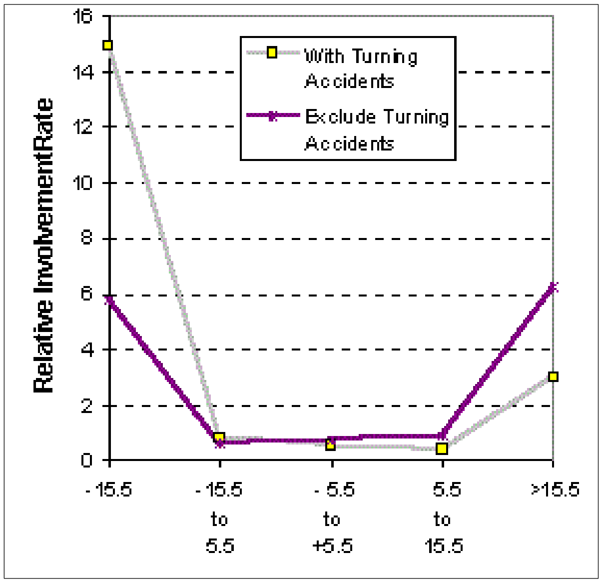


Figure 6. Deviation from Mean Speed, mph (West and Dunn 1971)

Hauer (1971) further validated the relationship between crash involvement and speed variance by calculating the theoretical rate at which vehicle overtaking events (i.e., passing or being passed) happen on rural highways between intersections. The study found that overtaking events followed a U-shaped curve, with the minimum number of overtaking events occurring at the median speed of traffic and, therefore, vehicle crash risk was smallest when the driver was travelling close to the median speed. The study concluded that the slower the vehicle is travelling relative to the median speed, the more likely it is for another vehicle to overtake it, and the higher the speed that the vehicle is travelling relative to other vehicles, the more likely it is for the vehicle to surpass them. This further suggests that significant variability in traffic stream speeds is associated with crash involvement.

Garber and Gadiraju (1988) extended the Dauer results to all types of roads in Virginia, including highways, arterials, and major rural collectors, further emphasizing the relationship between safety and speed variance; however, such a relationship didn't follow a U-shaped curve. Also, increased speed variance potential was tied to the difference between the design speed and speed limit. By combining data from two-lane rural highways, and rural and urban freeways, the authors showed that the minimum variance in vehicle speeds occurs when the speed limit is 5 to 10 mph below the design speed, which is shown in Figure 7. Outside this range, speed variance increases, leading to higher crash rates, as illustrated in Figure 8.

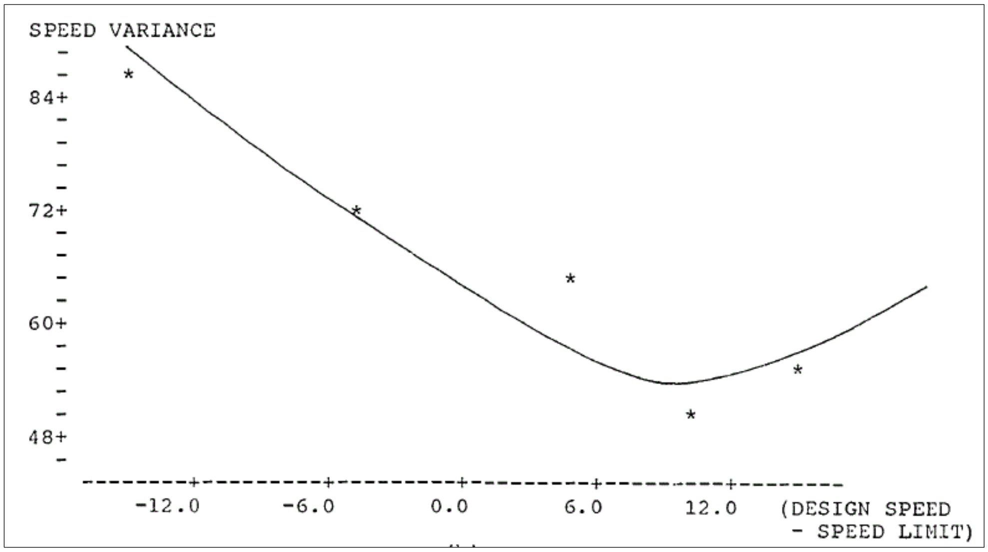


Figure 7. Speed Variance versus Difference between Design Speed and Speed Limit
(Garber and Gadiraju, 1988)

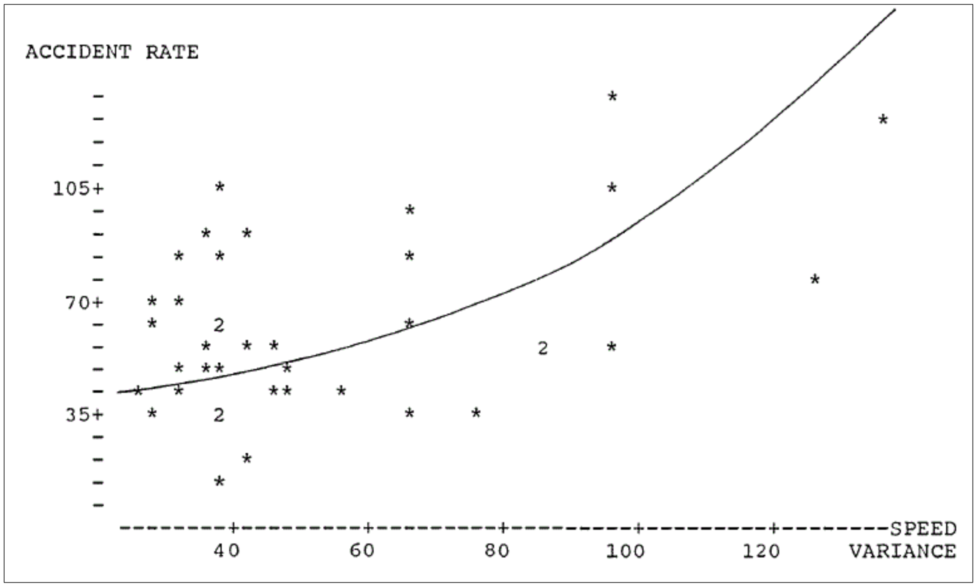


Figure 8. Speed Variance versus Accident Rate (Garber and Gadiraju, 1988)

Fildes et al. (1991) conducted interviews with drivers along the roadside after observing their travel speed relative to the speed limit on two urban (60 kph [35 mph]) and two rural (100 kph [60 mph]) roadways in Australia. The self-reported crash involvement rate during the previous 5 years was analyzed and no statistically significant relationship between speed and crash involvement rate was found for motorists driving at very low speeds, where their reported crash count averaged 0.31 crashes per motorist. Motorists driving at high speeds (20 km/h or more above the speed limit) were associated with a higher reported average crash count of 0.57, which was found to be significantly different from the reported average count of crashes for the entire group of pooled motorists (0.35).

Numerous studies since Fildes et al. (1991) have sought to establish a relationship between absolute speed and crash involvement. Many of these put an emphasis on the role of speed deviation (i.e., difference between travel speed of crash-involved vehicle and average speed of traffic stream) on crash involvement. A meta-analysis study by Elvik (2009) was conducted to validate the power model in describing the relationship between changes in speed and changes in road safety, and to determine the value of exponents in the power model for each category of crashes. The power model was initially proposed by Nilsson (1981) in which the relative change in crash category (fatal, injury, etc.) is estimated by raising the relative speed to an exponent as follows:

$$\frac{Crashes\ after}{Crashes\ before} = (\frac{Speed\ after}{Speed\ before}^{exponent}) \qquad (1)$$

The Elvik meta-analysis included 98 studies with 460 effect estimates (expanded to 115 studies with 526 effect estimates in a 2009 study), which are shown in Figure 9. The power model exponents were found to vary with initial speed and, for that reason, exponents were estimated by functional class, reflecting the range of speeds vehicles would be travelling on such roadways (refer to Table 1). This table includes summary estimates of the exponents (rural roads/freeways, urban/residential roads, and all roads combined) for the stated level of crash or injury severity. The estimated number of crashes after raising the speed limit can be found by multiplying the reported number of crashes before a speed limit increase by the ratio of the estimated 85th percentile speed in the after period to the observed 85th percentile speed in the before period, raised to the exponent found in Table 1. A couple of exponents were not found to be statistically significant at the 5 percent confidence level, yet those estimates serve to validate the significance of speeding in fatal and injury crashes (Elvik 2009).

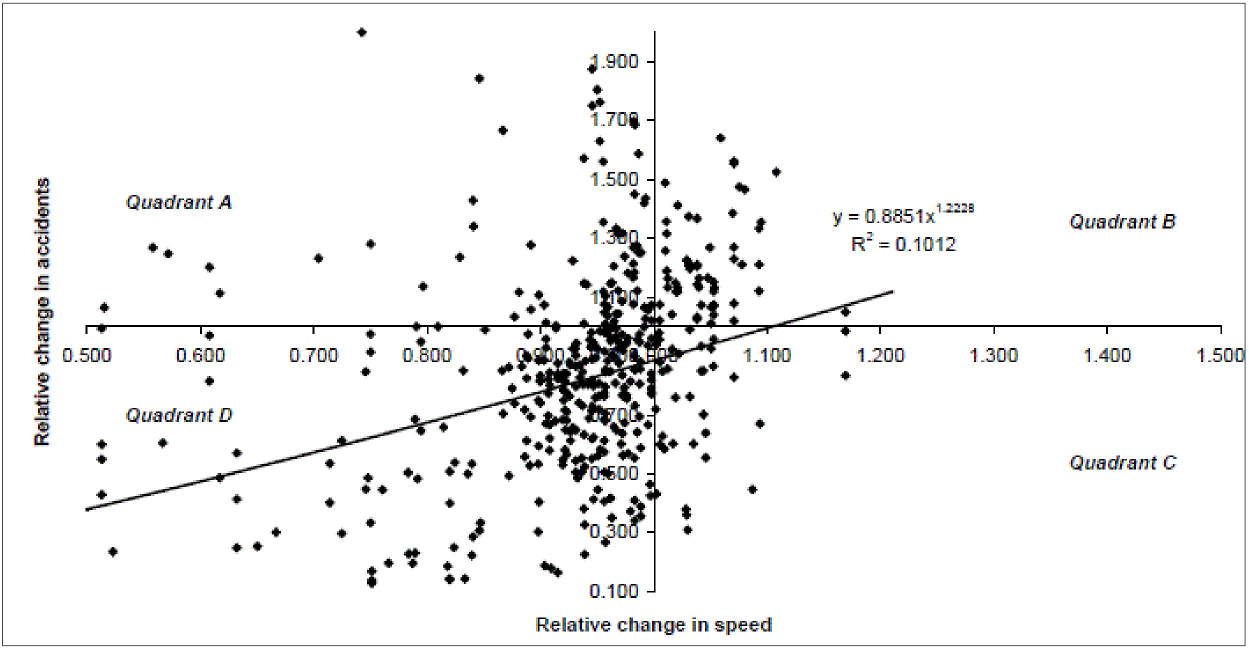


Figure 9. Bivariate Relationship between Changes in Speed and Changes in Accidents (Elvik 2004)

Table 1. Simple Bivariate Relationship between Changes in Speed and Changes in Accidents (ELVIK 2009)

	Summary estimates of exponents by traffic environment					
	Rural roads/freeways		Urban/residential roads		All roads	
Accident or injury severity	**Best estimate**	**95 % confidence interval**	**Best estimate**	**95 % confidence interval**	**Best estimate**	**95 % confidence interval**
Fatal accidents	4.1	(2.9, 5.3)	2.6	(0.3, 4.9)	3.5	(2.4, 4.6)
Fatalities	4.6	(4.0, 5.2)	3.0	(-0.5, 6.5)	4.3	(3.7, 4.9)
Serious injury accidents	2.6	(-2.7, 7.9)	1.5	(0.9, 2.1)	2.0	(1.4, 2.6)
Seriously injured road users	3.5	(0.5, 5.5)	2.0	(0.8, 3.2)	3.0	(2.0, 4.0)
Slight injury accidents	1.1	(0.0, 2.2)	1.0	(0.6, 1.4)	1.0	(0.7, 1.3)
Slightly injured road users	1.4	(0.5, 2.3)	1.1	(0.9, 1.3)	1.3	(1.1, 1.5)
Injury accidents – all	1.6	(0.9, 2.3)	1.2	(0.7, 1.7)	1.5	(1.2, 1.8)
Injured road users – all	2.2	(1.8, 2.6)	1.4	(0.4, 2.4) #	2.0	(1.6, 2.4)
PDO- accidents	1.5	(0.1, 2.9)	0.8	(0.1, 1.5)	1.0	(0.5, 1.5)

Confidence interval specified informally

In contrast to the previous studies, Davis (2002) argues that positive correlations established between crash risk and speed variance apply only to aggregate data and that such correlations are the result of individual crash risk functions, which are either decreasing, increasing, or a U-shaped function of speed. The author alludes to observations made where individual crash risk was independent of speed variance, providing additional evidence against the hypothesis that crash risk is a function of speed variance. Finally, recommendations are made for future studies to study individual risk function properties, which can only be examined given information for each individual vehicle's speed, and the speed of a vehicle in its environment under various circumstances.

In summary, the relationship between speed and crash involvement in this literature review shows that speed variance appears to affect crash frequency more significantly than absolute speed. While higher absolute vehicle speeds may result in more serious injuries (i.e., move severe crash outcomes), higher differences in speed between an individual vehicle and the surrounding traffic have been found as a crash involvement risk factor. In general, this review found that crash risk is minimized when individual driver speeds do not deviate significantly from the average speed of the traffic stream. As such, when increasing posted speed limits on rural Interstates in Pennsylvania, speed variance is considered as a performance metric in the study.

LITERATURE REVIEW

Effect of Posted Speed Limit Changes on Driving Speeds

The American Association of State Highway and Transportation Officials' (AASHTO) *Policy on Geometric Design of Highways and Streets* cites geometric characteristics of the road, weather, speed limit, and congestion to be the main factors affecting driver behavior (AASHTO 2011). Numerous studies (Polus et al. 2000; Andjus and Maletin 1998; Fitzpatrick et al. 2002) have been conducted to model operating speed as a function of different geometric design features, such as degree of curvature, grade, median type, etc., on curved and tangent highway segments. The studies described in this section examined the relationship between speed limit changes and changes in operating speeds and speed variance.

Effect of Lowering Posted Speed Limits on Driving Speeds

Historically, the average speed on free-flow sections of rural highways rose gradually until 1974, when it abruptly declined due to the imposition of the 55 mph national maximum speed limit law. One of the earliest studies that investigated average speed trends following the imposition of the NMSL in 1974 was conducted by Burritt et al. (1976). Highways in Arizona with a speed limit exceeding 55 mph before 1974 were examined in the study. The study generally found that travel speeds were reduced in the range of 5 to 8 mph in the two-year period following the enactment of the national maximum speed limit.

In 1977, Mela (1977) examined average speed changes as a part of a review of information on the safety effects of the 55 mph speed limit in North Carolina. The review found a 5 percent average speed reduction in 1974 with a little more than 10 percent of vehicles exceeding 65 mph in 1974-1975, a significant reduction from 50 percent in 1973. The study also reported a 7.4 mph (11 percent) and 3.9 mph (7 percent) decrease in average speeds on rural and urban Interstates, respectively. Average speeds on rural primary roads declined by 3.6 mph (6 percent).

Dart (1977), using North Carolina, Louisiana, and an Institute of Transportation Engineers Enforcement Survey in an evaluation of the impact of the 55 mph speed limit on traffic operations and safety, concluded that the average speed and speed variation on all classes of highway was reduced by the 55 mph NMSL. The study reported a decrease of average speeds by 10 mph, while the percentage of vehicles exceeding 65 mph was reported to be less than 10 percent. The speed variance was reported to be significantly reduced, leading to reduced crash rate, as Burrit et al. (1976) maintained in an earlier study.

NHTSA data in Highway Statistics (NHTSA, various years) were used to perform a benefit-cost analysis of the 55 mph NMSL. Based on a regression model involving the percentage of drivers under age 24, an indicator variable for the imposition of the 55 mph speed limit, total vehicle miles of travel on rural roads, and the proportion of motorcycles to vehicle registration (which was used to control for different vehicle types), the model predicted a 4.8 mph drop in average speeds in 1974, which the study estimated to be 60.3 mph (Forester et al. 1984).

Effects of Posted Speed Limit Increases on Driving Speeds

Numerous other studies have examined the effect of raising the speed limit on average speeds. A study by Upchurch (1989) sought to estimate crash rates on rural Interstates in Arizona after increasing the posted speed limit from 55 to 65 mph following the Surface Transportation and Uniform Relocation Assistance Act in 1987, which allowed states to raise their speed limits to 65 mph on rural Interstate highways. Urban Interstates, where the speed limit remained at 55 mph, were used as a comparison group. In the process of estimating crash rates, the mean speed (50th percentile speed) was estimated to be 59.5 mph before the speed limit was raised on rural Interstates and 65 mph after.

A similar study was conducted by Virginia's Transportation Research Council, which examined how average and 85th percentile speeds were impacted by raising the posted speed limit on rural Interstates from 55 to 65 mph, while posted speed limits on urban Interstates remained at 55 mph. Three years of before data and three years of after data were included in the analysis (1985-1987 versus 1989-1992). The study reported an increase in average speeds of 5.2 mph and 3.1 mph on rural and urban Interstates, respectively. The 85th percentile operating speeds increased by 6.3 mph and 3.5 mph on rural and urban Interstates, respectively. Despite a constant posted speed limit (55 mph) on urban highways, the study attributes the increase in average and 85th percentile operating speeds on urban Interstates to a spillover effect, whereby drivers were encouraged to sustain higher speeds while transitioning from a rural to an urban freeway (Jernigan et al., 1994).

Ossiander et al. (2002) reported similar increases in average speeds on rural Interstates following an increase in posted speed limits. The authors utilized 10 years of speed data (from 1982 to 1992) collected by the Washington State Department of Transportation (WSDOT) in the evaluation. Average rural Interstate speed for the 5 years before the speed limit change (1982-1987) was 58.5 mph and increased to 64.0 mph in the 5 years following the posted speed limit increase (1987-1992). Over the same period, 85th percentile speeds increased by 6.6 mph, from 64.0 mph to 70.6 mph. The speed variance was not necessarily affected by the speed limit increase, as it was reported to increase steadily during the evaluation period. Figures 10 and 11 show the mean speed and 85th percentile speed changes over a 20-plus year period.

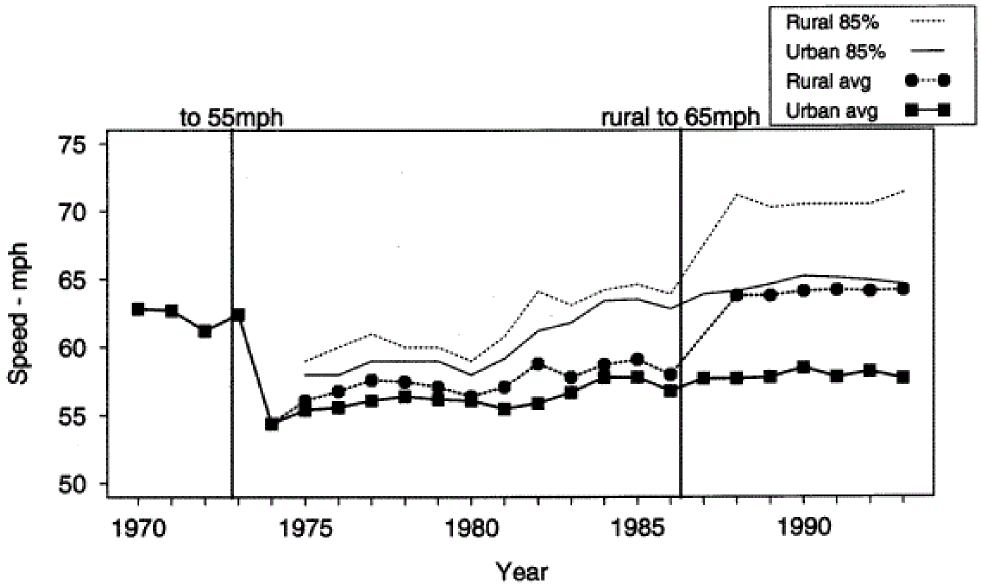


Figure 10. Average and 85th Percentile Speeds on Washington State Interstate Freeways
(Ossiander et al., 2002)

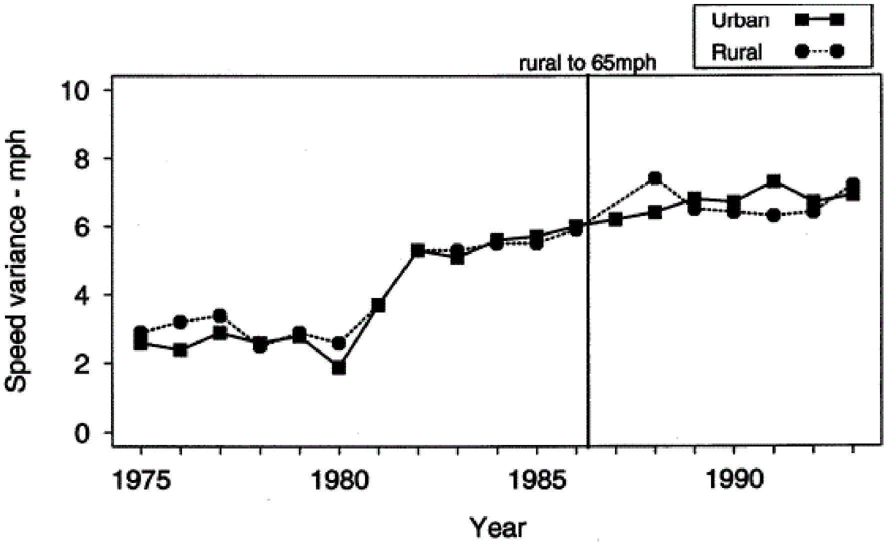


Figure 11. Speed Variance, as Measured by the Difference between the 85th Percentile Speed and the Average Speed, on Washington State Interstate Freeways
(Ossiander et al., 2002)

In a comprehensive speed limit study by Parker (1997), the effects of both lowering posted speed limits following the national maximum speed limit law in 1974, and raising posted speed limits on rural Interstates following the Surface Transportation and Uniform Relocation Assistance Act in 1987 were evaluated. Data were provided by participating transportation agencies that planned posted speed limit changes as a result of routine engineering studies. Control sections were chosen by the researchers to control weather conditions and other factors that may affect speed during data collection periods. Sixty percent of sites chosen for the study (92 total in 22 states) were collected in rural areas, and on segments shorter than 2 miles in length (1.7 miles, on average). Of the 92 sites selected for speed data collection, the posted speed limit was lowered at 57 sites while it was raised at the remaining 41 locations. Only one posted speed limit change was made at each site, in increments of 5, 10, 15, or 20 mph when lowering the speed limit and in increments of 5, 10, or 15 mph when raising the posted speed limit. Differences in mean speeds, standard deviation, and 85th percentile operating speeds, when comparing the before and after periods, were less than 2 mph. When segments were grouped by the magnitude of the speed limit change, differences in percentile speeds were found to be generally less than 1.5 mph, irrespective of whether speed limits were raised or lowered (refer to Figure 12).

In an extensive literature survey conducted in order to evaluate the impact of raising posted speed limits from 55 to 65 mph on highway speeds and safety, McCarthy (1998) found small changes in average speed and speed variance relative to the change in speed limit following the increase of speed limits on non-limited access roads. On higher-speed limited access roads, increasing the posted speed limits resulted in higher average and 85th percentile speeds by 4 mph or less and small increases in speed variance (less than 1 mph). The author also found a positive relationship between speed variance and crash severity on rural Interstates. Furthermore, the study suggests the need for more detailed data to better examine the relationship between average speed, speed variance, and crash experience. In a review of safety studies conducted in the 1980s and 1990s, it was found that most of the studies did not control for other factors that affected crash experience (other than raising the speed limit) and that it is important to include those variables in subsequent safety analyses. Finally, on limited-access roads, average speed and speed variance were found to be inversely related to highway safety in terms of fatal crashes, especially for drivers travelling in the top 15th percentile of speed.

In general, average vehicle speeds were increased by less than the amount of the posted speed limit increase in a report authored by Kockelman (2006). In a before-after study at two urban and two rural sites in Washington State, the study found a 3.4 mph increase in average vehicle speed, corresponding to a 10 mph increase in the posted speed limit. Kockelman also found that, using a cross-sectional statistical model of vehicle speeds, a 6.5 mph difference in average operating speeds was predicted relative to a 10 mph change in posted speed limits on segments in Austin, Texas. Similarly, meta-analysis studies in the United States and several European countries reported little driver sensitivity to speed limit increases concluding, as Kockelman did, that drivers select their operating speed based on their perception of what constitutes a safe speed, which in turn depends on geometric characteristics of the highway, weather, and traffic conditions rather than the posted speed limit (Wilmot and Khanal 1999).

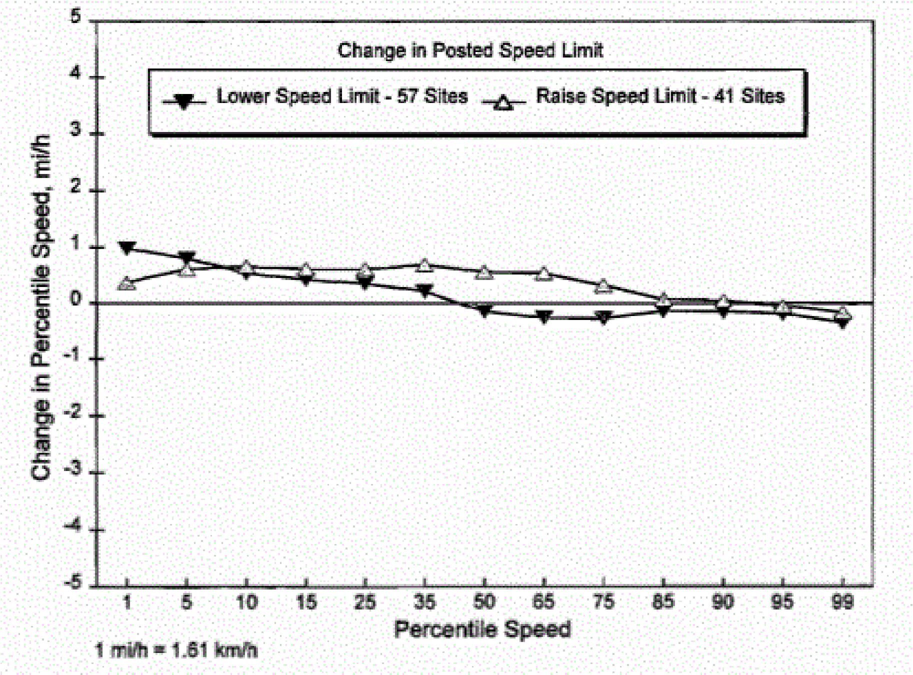


Figure 12. Mean Changes in Percentile Speeds after Speed Limits Were Lowered At 57 Sites and Raised at 41 Sites (Parker 1997)

As a part of providing background to better interpret their crash data, Brown et al. (1990) conducted a speed analysis for rural Interstates, urban Interstates, and other rural principal arterial highways in Alabama, and found that average operating speeds increased by 0.5 mph annually on rural Interstates following the relaxation of the NMSL in 1987, which was statistically significant at the 5 percent level. The overall increase (cumulative effect over several years) in average operating speeds on rural Interstates was found to be around 2.4 mph, which was significantly less than the 10 mph increase in posted speed limit in 1987 (from 55 to 65 mph). The 85th percentile speed was found to increase by 2.2 mph when increasing the posted speed limit, and both average and 85th percentile speed increases were found to be statistically significant at the 5 percent level by comparing the test group (rural Interstates) to a control group (urban Interstates and other rural principal arterial highways).

Freedman et al. (1990) estimated the increase in average travel speeds following the repeal of the NMSL in 1995 by using the fourth power relationship found by Nilsson (1981), which showed that increased travel speeds resulted in increased crash fatalities. By estimating increases in fatalities between 1995 and 2005, the study estimated a 3.7 percent increase in average travel speeds on rural Interstates for states that had raised the speed limit from 55 to 65 mph. States that further increased their speed limits on rural Interstates from 65 mph to 70 mph and from 65 mph to 75 mph had 2.0 and 3.2 percent relative estimated increases in average operating speeds, respectively.

Mace and Heckard (1991) examined the effect of increased speed limits on rural Interstates in 11 states following the relaxation of the maximum speed limit in 1987. Speed data from 1986 to 1988 were analyzed to determine the effect of the new 65 mph speed limit on average travel speeds and speed variance, and any spillover effects on adjacent roads with a 55 mph posted speed limit. The study found a 4-mph increase in average speeds and an approximate 5-mph increase in 85th percentile speed at locations where the posted speed limit was increased from 55 to 65 mph. Speed variance was found to increase by 12 percent, while the percentage of vehicles exceeding 70 mph increased from 6 to 19 percent. Since 1988, only small increases in average speeds were observed, mostly during daytime hours and on weekends, which was explained by lower truck volumes during those periods. Average operating speeds increased by 0.8 mph on surrounding 55 mph rural arterials, suggesting only nominal spillover effects from the increased speed limit sections.

In a recent study, Alemazkoor and Hawkins (2013) evaluated the effect of increasing the speed limit on a freeway section near College Station, Texas, from 70 to 75 mph. The before period operating speed data were collected continuously for 5 days in November 2012 and the after period operating speed data were collected for 5 days in March 2013. Each before and after dataset comprised over 125,000 observations, which were collected 2 months before and 2 months after the speed limit was raised. Speed changes were evaluated by type of day (weekday vs. weekend), lane position, volume level, light condition (daylight or dark), and type of vehicle (car or truck). For the entire data set, the mean speed increased from 69.9 mph to 71.6 mph, while the standard deviation increased from 4.9 to 5.3 mph. The 85th percentile speed increased from 74.5 mph to 76.6 mph, while the percentage of vehicles exceeding the posted speed limit increased from 12.1 to 26.1 percent. The study recommended conducting a large-scale study to validate the results.

Hu and McCartt (2013) evaluated the effect of raising the speed limit in Utah from 75 to 80 mph on two rural sections of Interstate 15 in January 2009. Operating speed data were collected in May for three consecutive years (2008, 2009, and 2010). Furthermore, speed data were collected at several control highway segments with increasing distance from the test segments in an effort to examine any spillover effects that may arise due to raising the speed limit on the two test segments. A log-linear regression model estimated a 2.4 and 7.3 percent decrease in average speeds for passenger cars and trucks, respectively, from 2008 to 2009, while average speeds increased by 0.2 percent for passenger cars (not statistically significant) and decreased by 3.7 percent for trucks between 2008 and 2010. The spillover effects were not statistically significant, except when comparing speeds between 2008 and 2010. During this period, passenger cars and trucks on segments adjacent to sections of Interstate 15 where the speed limit was raised, were found to be travelling 1.9 and 1.6 percent faster than expected. Statistical models for the probability of vehicles exceeding 80 mph were also developed and were found to be 31 percent higher in 2010 than expected, had the speed limit increase not been made, a percentage change that was found to be statistically significant at the 5 percent level.

In a large survey conducted by the U.S. Department of Transportation, drivers were asked to describe their behavior in regard to speeding and other unsafe behaviors. The survey found that most drivers are comfortable driving 7 to 8 mph over the posted speed limit before potentially being cited for speeding by enforcement officers. Approximately 51 percent of survey respondents indicated that they would travel in excess of the posted speed limit, even if it was raised by 10 mph. Overall, an average of 67 mph was reported to be the ideal speed for driving on an Interstate highway (Royal 2003).

In summary, following the implementation of the national maximum speed limit in 1974, many studies reported reductions in average vehicle travel speeds on rural Interstates. The operating speed reductions generally ranged from 4 to 8 mph. When the NMSL was relaxed for rural Interstates in 1987, permitting states to increase speed limits to 65 mph, field studies by various agencies reported that average travel speeds increased by 2.4 to 6.5 mph, while 85th-percentile operating speeds increased by 1.5 to 6.6 mph. After repeal of the NMSL in 1995, average speeds were found to be 1.4 to 2.4 mph higher when speed limits were raised on rural Interstates from 65 mph to 70 mph, or from 65 mph to 75 mph. More recent research has found that average travel speeds increased by 1.7 mph when posted speed limits increased from 70 to 75 mph, while no significant changes were found in average speeds when posted speed limits were raised from 75 to 80 mph. These findings suggest that average travel speeds do not necessarily change in direct proportion to the magnitude increase in the posted limit on rural Interstate highways.

Similar trends were found when considering the percentage of vehicles exceeding the posted speed limit after increasing regulatory speeds. The percentage of vehicles exceeding the speed limit on rural Interstates increased by 13 and 14 percent when speed limits were increased from 55 to 65 mph and from 70 to 75 mph, respectively. Also, many studies concluded that speed variances are reduced when speed limits are lowered, but increase when posted speed limits are raised. Finally, studies reported mixed effects when reporting spillover effects on adjacent road sections, after speed limits are increased.

Relationship between Changing Speed Limits and Crash Frequency and Severity

This section of the literature review describes studies that evaluated the effects of changing posted speed limits on crash frequency and severity. The first section focuses on reducing posted speed limits, while the second section focuses on increasing posted speed limits.

Reducing Posted Speed Limits

Following the enactment of the NMSL law in 1974, Burritt et al. (1976) conducted a study to examine if there was a relationship between lower posted speed limits and decreased crash fatalities in Arizona. The authors first ruled out the role of vehicle and driver characteristics such as age, gender, and driving experience, as these factors remained almost unchanged in Arizona between 1973 and 1974. The study found decreased crash fatalities and rates across all study segments, especially segments sampled on Interstate roads. Total fatal crashes declined by 35.1 percent after the posted speed limit was reduced from 75 to 55 mph. The study concluded that changes in environmental factors that influenced driving conditions and travel patterns between 1973 and 1974 were the primary cause of reduced crash rates and fatalities.

The same year, Labrum (1976) conducted a similar study where fatal crash rates averaged over study segments between 1971 and 1973 were tested for any statistically significant differences between mean fatal crash rates reported in 1974 and 1975, when the posted speed limit was 55 mph. The study found statistically different fatality rates between the two periods, concluding that the implementation of the 55 mph speed limit and other unobserved factors were associated with the reduction in fatalities. The fatality reduction was found to be more pronounced in the same year that the speed limit was reduced (in 1974), and was not as pronounced during the second year after the speed limit reduction in 1975. The author, however, was cautious in attributing the safety improvements to the reduction in speed limit since changes in other unobserved factors were not accounted for when performing the statistical analysis.

A similar before-and-after comparison study was conducted by Dart (1977), considering the influence of speed limit reduction on vehicle speeds and safety. Time-series plots of speed, volume, and crash data were collected in Louisiana, North Carolina, and Mississippi and compared to time-series plots of speed enforcement during various periods before and after the implementation of the NMSL. Initial vehicle speed reductions due to the speed limit changes made in 1974 (approximately 10 mph) returned to pre-1974 speeds within 2 years, except for Interstate highways. The speed limit reduction was also found to reduce the percentage of vehicles exceeding 65 mph to less than 10 percent as well as significantly reducing speed variance, resulting in more uniform traffic flow. The more uniform speed levels were attributed to increased enforcement in the period from 1974 to 1976. The new speed limit law reduced crash fatalities on rural highways by potentially reducing crash rates for speed-involved collision types.

Performing a before-and-after comparison in the states of New York and New Jersey, Weckesser et al. (1977) used crash frequency of different injury severity levels to compare safety performance before and after the NMSL of 1974. The authors found that, when posted speed limits were reduced, crash frequencies and rates declined. Tofany (1981) made state-by-state comparisons of speeds, fatalities, and fatality rates for 2 years preceding and following the NMSL adoption in 1974 and found similar results concerning crash frequency and fatality rates.

A comprehensive study that utilized a regression-based methodology to quantify the impact of reduced speed limits on the number of traffic fatalities was conducted by Forester et al. (1984). The authors accounted for many other variables that were assumed to have an influence on the average speed and speed variance, which in turn affects the number of fatal crashes and total number of fatalities. Those variables included driver income, vehicle miles traveled, age, motorcycle registration rate relative to car registration, price of gasoline divided by the consumer price index, and the concentration of vehicle speeds defined as the percentage of cars travelling between 45 mph and 60 mph. National time-series data between 1952 and 1979 were used in developing a sequential series of equations capturing the relationship between fatalities, average speed, and variability of speed as a function of all other variables, in addition to a dummy variable representing the imposition of the national maximum speed limit of 55 mph. The regression equation for the concentration of vehicle speeds predicted a 28 percent increase in the percentage of vehicles travelling between 45 mph and 60 mph, while the regression equation for average speeds predicted a 4.8 mph reduction in average vehicle speeds (from 60.3 mph) prior to 1974. It should be noted that predicted increase in the concentration of vehicle speeds between 45 mph and 60 mph (reduced variability in speeds) in response to reduced speed limits is in agreement with Dart (1977), where he concluded that reducing speed limits also reduced speed variance. Finally, the regression equation for fatalities was evaluated by substituting the value of average speeds and vehicle concentration into the equation and holding them at their mean values while changing the dummy variable value from 0 to 1, indicating the imposition of the NMSL. The results show that reduced speed limits reduced fatalities by as much as 7,466 fatalities per year nationwide.

Prior to the repeal of the NMSL in 1987, a study was conducted by Hoskin (1986) which provided a glimpse of what to expect when speed limits are raised uniformly on rural highways across the

United States in multiples of 5 mph, beginning at 55 mph and ending at 75 mph. The study used data from the 1984 Fatality Accident Reporting System (FARS) to estimate the increase in the number of fatalities at the end of that year when speed limits were raised by 5, 10, and 15 mph. By implementing the National Safety Council (NSC) method, the author estimated an increase of 200 to 700 annual deaths on rural highways while estimates of increased annual fatalities between 300 and 450 were obtained by implementing the Transportation Research Board (TRB) method, which assumed that posted speed limits would be reset to their pre-1974 values.

Increasing Posted Speed Limits

Following the Surface Transportation and Uniform Relocation Assistance Act in 1987, many states raised speed limits on all or part of their rural Interstate roads, resulting in many research evaluations.

In one of the earliest studies to evaluate the safety aspects of raising the speed limit on Arizona's rural Interstate highways, Epperlein (1989) compiled highway statistics for traffic crashes resulting in injury or a fatality by the Arizona DOT for the period between January 1982 and December 1988. The author then used interrupted time-series methods to measure changes in injury and fatality crash rates when speed limits were raised from 55 mph to 65 mph in May 1987. A control group was also included in the analysis, which included highways that did not undergo a posted speed limit change. The two data time series (sites with and without posted speed limit change) showed statistically significant increases at the point where speed limits were increased. Those increases were large enough to persist for a year and a half through December 1989, resulting in a 36 percent monthly increase in crash-related deaths and injuries and a net increase of 1,100 injuries and fatalities over the period after which the speed limit was raised. As a result, the author suggested retaining the 55 mph speed limit on Arizona's rural Interstates.

Gallaher et al. (1989) examined fatal crashes before and after increasing the posted speed limit from 55 to 65 mph in New Mexico. Fatal crash data on rural Interstates after the speed limit increase were obtained from police crash reports for the period from April 2, 1987 through April 1, 1988, and compared to fatal crashes in the preceding 5 years. The expected fatal crash rate was estimated based on crash trends from the previous 5 years using linear regression and then compared to the reported fatal crash rate after speed limits were raised. The rate of reported crashes on rural highways decreased over the study period; however, the percentage of fatal crashes on rural highways as a percentage of all other road types increased by as much as 3.9 percent when compared to the average proportion of fatal crashes in the 5 previous years. Single-vehicle crashes were found to account for the majority of fatal crashes on rural highways after raising the speed limit. Finally, median speeds of vehicles on rural highways were surveyed in the 12-month period prior to the speed limit increase and ranged from 58 to 60 mph, with 14 to 17 percent of vehicles exceeding the speed limit of 65 mph. Vehicle median speeds were also surveyed in the 12-month period after speed limits were raised, and ranged from 62 to 63 mph with as many as 27 to 35 percent of drivers exceeding the posted speed limit. The author indicated that the results can only be explained by the higher speed limits, because the fatal crash victims had consistent demographic characteristics, alcohol involvement, and seat belt use in the 5-year period prior to increasing the speed limit and in the year following the increase.

Streff and Shultz (1990) conducted a study to examine the effect of raised speed limits on rural limited-access highways in Michigan. The posted speed limit was increased from 55 to 65 mph in December 1987 and January 1988. Crash data were collected for the period from January 1978 through December 1988 and were categorized by highway segments where the speed limit was raised, highway segments where the speed limit remained at 55 mph, and all other road types. In doing so, multiple time-series comparisons could be made to ensure that any observed differences in crash rates could only be explained by speed limit changes on rural highways, and to quantify potential spillover effects on highway segments where the speed limit remained unchanged. The specification of a monthly time series model controls for factors that could potentially affect observed changes in morbidity and mortality. Such factors include random seasonal and multi-year fluctuations in crash and injury rates, policy changes such as the implementation of a primary seat belt law, fluctuations in vehicle miles traveled, and other driver characteristics such as age, gender, unemployment, and alcohol consumption. Fatalities, serious injuries, and moderate injuries on rural highway segments where the speed limit was raised increased by 19.2, 39.8 and 25.4 percent, respectively. Fatalities on limited-access freeway segments where the speed limit remained unchanged increased by 38.4 percent, suggesting that the 65 mph speed limit has spillover effects on segments of freeway where the speed limit remained at 55 mph. Injury and property damage crashes on limited-access freeways where the speed limit remained unchanged were not found to change significantly. Similarly, increases in fatal, injury, and PDO crashes on all other road types were not statistically significant in the analysis. Vehicle speeds were also measured quarterly and annually on 44 sites from 1982 through 1988 to assess the impact of raised speed limits on driving speeds. Driving speeds were found to increase gradually throughout the 1980s, potentially due to the lack of public support for the 55 mph speed limit policy and perhaps due to less stringent police enforcement of the speed limit. Driving speeds increased more substantially in 1988 on segments where the speed limit was increased, resulting in a 21.3 percent increase in the proportion of vehicles exceeding the posted speed limit between 1987 and 1988. Finally, the study estimated the total cost from raising the speed limit from 55 to 65 mph to be approximately $62 million, concluding that reduced travel time from raising the speed limit comes at a significant cost in terms of injury morbidity and mortality.

Chang and Paniati (1990) obtained crash data from 32 states that implemented increased posted speed limits on rural Interstate highways after passage of the STURAA in 1987. Monthly fatality data were obtained for each state using the FARS and were inclusive of all rural Interstates. The data were obtained for the period from January 1975 to December 1989 with the last 15 months serving as an after period to estimate the impact of increased speed limits on fatalities. Similar to Gallaher et al. (1989), a trend analysis was performed. Box-Jenkins models were utilized to predict the estimated number of fatal crashes if the speed limit had not been raised and compared it with reported fatalities occurring after speed limit increases. Unfortunately, the 15-month period of "after" data were not sufficient to quantify the effects of speed limits for each state; however, reported fatalities were found to be higher than predicted fatalities in 14 of the 15 months of "after" data, though only 2 of those months were statistically significant. The authors recommended a follow-up study using more rigorous analytical techniques, such as an intervention analysis, after more years of data became available in the after period.

Garber and Graham (1990) examined the effect of the raised speed limit on rural highway fatality counts in 40 states by estimating separate time-series regression equations for each state. State-specific monthly fatality counts were collected between January 1976 and November 1988 using the Fatal Accident Reporting System. The models controlled for policy variables such as seat belt laws, seasonal effects, economic performance, and exposure variables such as the number of vehicle miles travelled. The results of the study indicated a 15 percent increase in fatalities on rural Interstates as a consequence of raising the speed limit, though such effects were found to substantially differ across states, especially since fatalities were reduced or remained the same in 12 states while increasing in the other 28 states included in the study. Fatality counts on rural non-Interstates increased by 5 percent.

Baum et al. (1989) used FARS data from 38 states to assess the impact of the higher rural Interstate speed limit on fatal crashes. The analysis period included all months following the month in which the speed limit was raised to 65 mph and the same months between 1982 and 1988 in a before-after comparison study that included 8 states with a speed limit of 55 mph used as a control group. Odds ratios were used in this study to assess whether changes in fatalities were significant on 65 mph rural Interstate highways relative to the 55 mph control group. The study found that increased speed limits increase the odds of a fatality by 19 percent on rural Interstates, and by 4 percent on other rural roads, relative to 55 mph states where no significant changes were observed. An overall net 15 percent increase in fatalities was estimated for the 38 states; however, the odds ratios declined for 14 states, suggesting either an improvement in overall safety or increased variability due to factors that had not been accounted for.

In an attempt to control for factors that might have influenced the 1987 study results, Baum et al. (1991) included changes in vehicle miles travelled and passenger vehicle occupancy rates when examining a new dataset extending through 1989. The study found initial increases in the odds of a fatality resulting from a crash on 65 mph rural Interstates in 1989 by as much as 29 percent relative to crashes in the 1982 to 1986 period when exposure and passenger occupancy rates were not included in the model specification. When accounted for, the odds were found to increase by 19 percent suggesting that initial estimates overestimated the impact of increased posted speed limits on crash fatalities.

Pfefer et al. (1991) performed an autoregressive integrated moving average (ARIMA) time-series intervention analysis to examine the presence, magnitude, and nature of changes in speed and accident data following the increase of the posted speed limit on 15 rural Interstate segments in Illinois from 55 to 65 mph in May 1987. The time-series analysis consisted of 52 pre-intervention and 15 post-intervention months and demonstrated a gradual increase in the 85th percentile speeds of cars by 4 mph, while the speed variance for cars and trucks was not found to be affected by the speed limit change. The same study also found an overall increase in total crash frequency experienced on all 15 rural Interstate segments by up to 14.2 percent while no significant changes were found for fatal and injury crashes. However, as opposed to crash frequency, an 18.5 percent increase was detected in fatal and injury crash rates, while no changes were found in the total crash rate on the same segments.

Lave and Elias (1992) argued that other studies have ignored reduced crashes on other roadways when reporting the increase in crashes following increased speed limits on rural Interstates. The authors noted that prior to the increased speed limits on rural Interstates in 1987, drivers may have travelled on secondary highways that are less rigorously patrolled. When the speed limit was raised on rural Interstates, enforcement resources were reallocated to secondary highways. Motorists on the secondary highways then diverted to rural Interstates, which led to fewer crashes on the secondary highways as a result of lower traffic volumes. In evaluating the impact of increasing the speed limit on rural Interstates, crashes were considered on a statewide basis and fatal crashes were found to decrease by 3.4 to 5.1 percent following the repeal of the 55 mph speed limit, a result attributed to diversion of traffic from lower functional class highways to access-controlled Interstate highways.

Pant et al. (1992) analyzed crash data for 36 months before and after the speed limits were raised on select rural Interstates in Ohio. Segments with a speed limit of 55 and 65 mph were included in the study as well as rural non-Interstate highways with a posted speed limit of 55 mph. Average monthly crash data were examined in terms of weather conditions and season, and fatal crash rates were not found to change on rural Interstates and non-Interstates with posted speed limits of 65 mph and 55 mph, respectively. Fatal crash rates on rural Interstates that remained at a speed limit of 55 mph were found to increase following the implementation of the 65 mph speed limit; however, by accounting for weather conditions, no significant changes in fatal crash rates were found. Finally, significant increases in injury and PDO crashes were found on rural Interstates with a posted speed limit of 65 mph.

Jernigan and Lynn (1991) used multiple regression analysis to study changes in operating speeds and crashes after increasing the speed limit on rural Interstates in Virginia from 55 to 65 mph in July 1988. The study utilized annual fatal crash data between 1985 and 1989, resulting in 18 months of data with the higher posted speed limit. The data show an increase in fatal crashes from 40 in 1987 to 59 in 1989, while fatalities resulting from those crashes increased from 44 to 63, representing 47.5 percent and 43.2 percent increases in fatal crashes and fatalities, respectively. No significant increases in fatal crashes and fatalities were observed on urban Interstates during this same analysis time period, where posted speed limits remained at 55 mph during the study period. The authors also argued that weather conditions, changes in traffic volume, trip type or vehicle mix could have accounted for some of the increases reported in fatal crashes and fatalities. Furthermore, average speed on rural Interstates increased from 59.9 mph in the spring of 1987 to 63.5 mph in the spring of 1989, and speed variance also increased by 36.4 percent on rural Interstates and 39.3 percent on urban Interstates that retained the 55 mph speed limit. The study found a positive relationship between increasing average speed and increasing fatalities and a negative relationship between the number of vehicle miles traveled and crash fatalities on rural Interstates.

Rock (1995) used monthly crash data on rural highways between 1982 and 1991 to examine the effect of raising the speed limit from 55 mph to 65 mph on rural Interstates on crash experience in Illinois. An ARIMA intervention regression analysis, along with naïve before-after comparisons, was used in the analysis. A 33 percent increase in total crashes, 40 percent increase in fatalities, and 19 percent increase in injuries were found on rural highways with a posted speed limit of 65 mph. Furthermore, total crashes, fatal crashes, and injury crashes were found to increase by 6 percent, 25 percent, and 6 percent, respectively, on rural highways with a 55 mph speed limit, supporting possible spillover effects when transitioning from 65 to 55 mph speed limit sections of highway.

In 1996, Ledolter and Chan studied the impact of raising the speed limit in 1987 from 55 to 65 mph on crash experience in Iowa using quarterly crash data from 1981 through 1991. By fitting a time-series intervention model relating the number of crashes to traffic volume, including a time trend, intervention variables and quarterly seasonal effects, the study found a 20 percent increase in statewide fatal crashes; fatal crashes were found to increase by 57 percent on rural Interstates that had implemented the speed limit change. No statistically significant changes in major injury crashes were found, and fatal crashes were found to gradually decrease following speed limit increases in 1987.

Ossiander and Cummings (2002) analyzed data for total and fatal crashes, fatalities, and vehicle miles of travel on rural and urban Interstates in Washington State between 1970 and 1994 in an effort to examine the effect of raising the speed limit on rural Interstates in 1987 from 55 to 65 mph. Poisson regression was used to analyze the impact of speed limit increases on fatal crashes and the results indicated a 110 percent increase in fatal crashes on rural Interstate segments following the speed limit change. On the other hand, total crash rates were not found to change significantly. A speed evaluation found that mean operating speeds increased from 58.5 to 64 mph following implementation of the 65 mph posted speed limit on rural Interstates, attributing the large increase in fatal crash rates to the relatively large increase in average speeds.

In addition to the studies described earlier, which focused on the safety effects of increasing posted speed limits on rural Interstates following enactment of STURAA in 1987, there were several studies that assessed the safety effects of speed limit changes following repeal of the NMSL law in 1995. These studies are summarized in this section of the report.

Farmer et al. (1999) assessed the impact of repealing the national maximum speed limit in 24 states that had raised the speed limit on rural Interstates in December 1996 and compared the results to seven states that did not raise speed limits. The data spanned 8 years and were collected from January 1990 through December 1997 using the FARS database. Estimation of model parameters was performed using time-series, cross-section regression for which the indicator variable represents the logarithms of fatality counts and rates for each annual quarter during 1990 through 1997 after adjusting for time trends, the number of people employed, and state group (four study groups and one comparison). The value for the indicator variable was set to zero for all states up until each state's effective annual quarter, during which the speed limit was increased when the value was changed to one. The study estimated that the number of traffic fatalities in states where speed limits were raised increased by 15 percent while fatality rates increased by 17 percent. Changes in fatalities and fatality rates on non-Interstates were close to zero. Given that no significant reductions were observed in fatalities and fatality rates on non-Interstate roads, the authors suggested that increases in fatalities on rural Interstates were not due to increased travel. Also, since only a small fraction of overall state fatalities occur on Interstates, the study concluded that the impact of repealing the NMSL on increased fatalities and fatal crash rates on all types of roads was relatively small.

In an evaluation of the impact of raising the speed limit on fatal crashes, Balkin and Ord (2001) used structural time-series modeling to assess monthly fatal crash trends on rural and urban Interstates in all 50 states. Data were extracted from FARS between 1985 and 1998. The study found that increasing the speed limit on rural Interstates in 1987 resulted in a significant increase in fatal crashes in almost half (19 of 40) of the states studied and that raising the speed limit in 1995 increased fatal crash experience on urban Interstates in 6 of the 31 states studied, and 10 of 36 states for rural Interstates. The study also found that crash trends were gradually moving back to levels experienced prior to changing the speed limit, which was explained by the authors as having to do with drivers adjusting to higher travel speeds, increased enforcement of driving laws after initial speed limit changes, as well as more crashworthy vehicles traveling on roadways.

In the context of raising the speed limit on California state highways, an observational before-after crash study was completed by Haselton et al. (2002). Relevant collision, speed, and traffic volume data were collected at locations where the speed limit was increased from 55 to 65 mph, or from 65 to 70 mph, in early 1996. A comparison group of highways that retained the 55 mph speed limit was also included in the study. The findings indicated that total and fatal crashes increased by 15.3 percent and 35.8 percent, respectively, after the speed limit was raised from 55 to 65 mph, and by 8.9 percent and 33.9 percent, respectively, after the speed limit was raised from 65 to 70 mph. The study also found significant increases in nighttime crash experience (14.4 percent) where the posted speed limit was increased from 55 to 65 mph.

Patterson et al. (2002) developed cross-sectional regression models for fatality rates and controlled for vehicle miles of travel. The models were specified in terms of the year in which a speed limit change was made (between 1994 and 1996) across different states, and whether early, late or no speed limit changes were made for an individual state (relative to the year when the national maximum speed limit was repealed in 1995). Fatality and injury rates were collected for the period from 1992 to 1999 for 34 states (12 states that had retained the speed limit, 12 states that raised the posted speed limit to 70 mph, and 10 states that raised the speed limit to 75 mph). The authors concluded that states which raised posted speed limits to 75 or 70 mph experienced an increase in fatality rates by 38 and 35 percent, respectively.

In the same year, Najjar et al. (2002) analyzed before-after crash data from 1993 to 1998, excluding 1996, during which Kansas increased the speed limit on most of its highways. Statistical tests were used to analyze monthly crash rates and time-series trend plots were used to evaluate yearly crashes. The authors concluded that no statistically significant increases in crashes, including fatal crashes and fatality rates, were found on rural and urban Interstates after repeal of the NMSL law.

In an NCHRP study, Kockelman et al. (2006) evaluated the safety impacts of raising the speed limit on high-speed roads. A cross-sectional comparison of routes with different speed limits in the State of Washington found that increasing the speed limit from 55 to 65 mph resulted in a 3 percent increase in total crashes and a 23 percent increase in fatal crashes, and that routes that increased the speed limit from 65 to 75 mph had a 0.64 percent associated increase in total crashes and a 13 percent increase in fatal crashes. The authors also argued that developing statistical models based on cross-sectional data may have exaggerated the effect of raising the speed limit on crash experience by approximately a factor of 2 when comparing their reported results to observational before-after studies on each of the individual routes examined in the study. In addition to speed limit impacts, geometric roadway features such as horizontal and vertical curves were found to be associated with higher crash rates when the effects of other variables were held constant. As part of the same research effort, Kockelman et al. (2006) reviewed state DOT studies following the repeal of the NMSL. A summary of this review is provided below.

Arkansas: A simple before-and-after comparison of fatal crashes and fatalities was conducted in a study period that extended from 1 year before raising the speed limit to 1 year after. Overall, the study found a 5 percent increase in fatal crashes and a 15 percent increase in fatalities on all rural, suburban, and urban freeways where the speed limit was raised from 55 mph to 70, 65, and 60 mph, respectively.

Iowa: In a 1997 study, crash rates were found to increase in the 2 years following the speed limit increase to 65 mph on rural expressways and freeways. At least 20 percent increases in all crash categories were observed, including fatal, fatal and injury, total, and injury-only crashes. Fatal crashes and fatalities on rural expressways and freeways increased by approximately five- and sixfold, respectively.

Louisiana: Schneider (undated) compared fatal and injury crash counts 1 year before and 1 year after the speed limit was raised on rural Interstates from 65 mph to 70 mph in 1997. The study found a 37 percent increase in fatal crashes, a 1 percent increase in injury crashes, and a 14 percent increase in PDO crashes on rural Interstates, while no significant overall changes in fatal, injury, and PDO crashes were observed across all roadway types.

Michigan: In a comprehensive study by Taylor (2000), the effect of raising the speed limit on rural Interstates from 65 to 70 mph was investigated by comparing crash data before (1994-1996) and after (1997-1999) the speed limit change. The study found a 4.5 percent increase in total crash counts and a 4.5 percent increase in severe crash counts, while fatal crash counts decreased by 9.3 percent on freeways that underwent speed limit changes.

New Jersey: In the 18-month period following a posted speed limit increase from 55 to 65 mph on 475 miles of selected Interstates and highways with similar design features and access control, fatal crashes and fatalities dropped by 7.9 percent and 9.6 percent, respectively. Total crashes increased by 18.3 percent, while the number of injury crashes and injuries increased by 9.4 percent and 5.9 percent, respectively.

New Mexico: In a study by Davis (1998), crash data between 1994 and 1997 were examined to determine the effect of increasing the speed limit on three selected Interstates. The analysis period covered two years before the speed limit change in 1996 and one year after the posted speed limit was increased. The study found that reported tow-away crashes, injury counts, incapacitating injury counts, and fatalities on two of the three selected Interstates significantly increased by 29 percent, 31 percent, 44 percent, and 50 percent, respectively.

New York: As part of a study conducted by the New York State Department of Transportation (NYSDOT), in conjunction with the New York State Thruway Authority (NYSTA), crash data were compared for a period from 3 years prior to 3 years after posted speed limits were increased from 55 to 65 mph on rural Interstates and similar highways. The study found a 4 percent increase in total crash rates, a 29 percent increase in fatal crash rates, and a 5 percent increase in injury crash rates.

Texas: As part of a 1998 study, a longitudinal analysis of injury crashes was conducted following posted speed limit increases on rural Interstates from 65 to 70 mph, and from 55 to 70 mph on urban Interstates, rural and urban divided highways, rural multi-lane undivided highways, and rural, two-lane U.S. and state highways. Four aggregate crash categories were considered in the analysis, including fatal (K); fatal or incapacitating injury (KA); fatal, incapacitating or non-incapacitating injury (KAB); and injury crashes of any level (KABC). The following statistically significant effects of raising the speed limit in the 15-month period following the change are:

- KABC crashes on rural Interstates increased by 16 percent.
- For urban Interstates, KA, KAB, and KABC crashes increased by 75 percent, 49 percent, and 28 percent, respectively.
- On rural non-Interstate, multi-lane divided highways, significant increases in all crash categories were observed following the speed limit change.
- Mixed results by crash category were obtained for urban non-Interstate, multi-lane divided highways.
- KAB and KABC crashes on non-Interstate, rural multi-lane undivided highways increased by 16 and 9 percent, respectively, while no statistically significant changes were observed for K and KA crashes.
- Finally, increases in all crash categories except K (fatal) crashes were observed for rural, two-lane U.S. and state highways.

A study by Vernon et al. (2004) utilized an ARIMA intervention time-series analysis to estimate the effect of increased speed limits on urban and rural Interstates, rural non-Interstate highways, and high-speed non-Interstate uncontrolled access rural highways. Speed limits were increased to 65 mph on urban Interstates in December 1995 and on high-speed, non-Interstate uncontrolled access rural highways in 1997 (with a small proportion of segments of both classes of roads raised to 60 mph). Rural Interstate speed limits were increased to 75 mph (with a small proportion raised to 70 mph) in May 1996. Crash data were compiled for the period between 1992 and 1999. Total crash rates were found to increase on urban Interstates, while no statistically significant changes in fatal and injury crashes were found. No changes in any crash category were observed for rural Interstates, while significant increases in fatal crashes were found on high speed, non-Interstate highways.

Malyshkina and Mannering (2008) considered the influence of posted speed limit on the severity of vehicle crashes in Indiana using crash data 1 year before and 1 year after posted speed limits were raised from 65 to 70 mph on rural Interstates and some multi-lane, non-Interstate routes in 2005. Multinomial logit models of crash severity found that speed limits did not significantly affect injury severity on rural Interstates, which the authors attributed to possible reductions in speed variance associated with speed limit increases, as well as conservative design standards of the Interstate system in Indiana. Contrary to Interstate highways, increased speed limits on non-Interstate highways were associated with a greater likelihood of injury or fatality, suggesting that increasing speed limits on non-Interstate roads should be made on a case-by-case basis, taking into account crash history and geometric and access control features of such roads.

In a recent study by Friedman et al. (2009), the long-term effects of repealing the national maximum speed limit were examined. The data utilized in the study included annual crash counts for all 50 states that increased the speed limit on their rural Interstates between 1995 and 2005, as well as annual crash counts for those states that raised the speed limit on their urban Interstates, and urban and rural non-Interstate highways during the same time period. A Poisson mixed-effects regression was used to estimate the effect of increased speed limits on crash experience. Overall, fatalities increased by 3.2 percent on all road types with the highest increase found on rural Interstates (9.1 percent) and urban Interstates (4.0 percent). Injuries followed a similar trend with an 11.9 percent increase on rural Interstates and a 5.6 percent increase on urban Interstates. Statistically significant increases in fatal and injury crashes on other urban and rural non-Interstates were also observed, except for urban non-Interstates, where fatal crashes were reduced by 1.8 percent. The overall effect of increasing the speed limit in the United States between 1995 and 2005 was estimated to be an additional 36,583 injuries and 12,545 fatalities in fatal crashes. The author concluded by recommending a reduced speed limit and improved enforcement with speed cameras, which would aid in reducing excessive speeds and resulting fatalities.

A recent study by Farmer (2016) investigated the safety effects of increasing state maximum posted speed limits in the United States for the period from 1993 through 2013. A Poisson regression model was used to model traffic fatality rates for 41 states (with at least 10 billion annual vehicle-miles traveled) as a function of time, annual state unemployment rate, percentage of the driving population aged 25 or younger, percentage of the driving population aged 65 and older, state seat belt usage, per capita alcohol consumption, and the maximum posted speed limit on any roadway segment in the state. The model predicts that, for each 5 mph increase in the posted speed limit, an 8 percent increase in the fatality rate is expected on Interstate highways. On other roadway types, a 5 mph increase in the posted speed limit is associated with a 4 percent increase in the fatality rate.

Overall, studies have shown that relative to 55 mph roads, increasing the posted speed limit on rural Interstates and multi-lane rural highways with similar design features and access control resulted in increased injury and fatal crashes. Increases in the number of fatalities following the relaxation of the NMSL on rural Interstates ranged between 14 and 43 percent, while the number of injuries increased between 19 and 40 percent among the studies reviewed for this report. After repeal of the NMSL, fatalities increased between 15 and 50 percent while injuries increased between 6 and 12 percent. The variability in safety results is likely the result of differences in analysis methods, sample size, data collection, and other confounding factors. Similar to a number of speed evaluations, mixed results were found in regards to the impact of raising the speed limit on the safety of adjacent road segments where the speed limit remained unchanged.

Work Zone Speed Limits

Debnath et al. (2014) evaluated speed compliance for three work zones in Australia using a tobit model. The work zones included two-lane undivided highways (with free-flow posted speed limits of 80 to100 km/h [50 to 60 mph]) and a multilane divided highway (with a free-flow posted speed of 100 km/h [60 mph]). During work hours, the posted speed was 40 km/h (25 mph) for the two-lane highways and 60 km/h (35 mph) for the multilane divided highway. During non-work hours, the posted speeds were 60 km/h (35 mph) for the two-lane highways and 70 km/h for the multiline divided highway. The findings indicated that the 40 km/h (25 mph) posted speed during working hours led to a decrease of 5.9 km/h (3.5 mph) in the mean speed for the two-lane highways. No difference was found for the change in posted speed for the multilane divided highway, suggesting that lowering posted speed limits by 40 km/h (25 mph) had little effect on driver speed choice in Australia.

The effects of posting work zone speed limits at 10 mph less than the free-flow speed in Ohio on divided multilane rural highways and freeways was assessed by Finley et al. (2014). Using two work zones with original posted speeds of 60 mph (work zone speed of 50 mph) and eight work zones with original posted speeds of 65 mph (work zone speed of 55 mph), all with lane closures, the change in 85th-percentile operating speeds was assessed. On average, it was found that the work zones with posted speeds of 50 mph experienced a 6 mph decrease in 85th percentile speeds compared to the non-work zone conditions. It was also found that the work zones with posted speeds of 55 mph experienced a decrease of 5 mph from the non-work zone conditions. The findings were all based on the descriptive statistics.

The effectiveness of speed limits in work zones on Interstate 44 in Missouri was analyzed by Ale Mohammadi and Bham (2011). Interstate 44 had a free-flow regulatory speed limit of 70 mph at each work zone location. A total of nine construction zones were included in the evaluation, with posted speed limit reductions ranging from 10 to 20 mph (i.e., 60 and 50 mph work zone posted speeds). T-statistics and descriptive statistics were used to evaluate the data. The findings varied significantly between the work zone locations. Overall, the findings indicated that the operating speeds were significantly higher than the work zone posted speed limits. The operating speeds for the work zone speed limits of 50 mph had a larger difference than the operating speeds in the 60 mph work zones.

NCHRP Report 581 investigated the design of construction work zones on rural freeways (Mahoney et al. 2007). In this report, it was noted that when speed limit reductions for work zones are greater than 10 mph from the free-flow posted speed limit, drivers should be notified through credible and constant complimentary visual information that the speed reduction is warranted (i.e., static advisory and regulatory signage is not sufficient). Along with this report, a speed prediction tool was developed using data from rural freeway work zones in Pennsylvania and Texas. The free-flow posted speed limits ranged from 55 to 70 mph and the work zone speeds ranged from 50 to 60 mph in the tool.

Using the prediction tool, with a free-flow posted speed limit of 70 mph, operating speeds were estimated when deploying various work zone posted speed limits. These speeds are shown in Table 2. The lowest work zone speed that the prediction tool can be used to estimate is 50 mph. As shown in Table 2, the lower work zone speed limits have very little impact on the mean speed, 85th percentile speed, and speed variance, relative to the 10 mph speed limit reduction (70 to 60 mph). This finding suggests that, if posted speed limits are reduced by 15 to 20 mph in work zones with a free-flow posted speed limit of 70 mph, the change in vehicle speeds will not be significantly different than a 10 mph speed limit reduction.

Table 2. Operating Speeds as a Function of Work Zone Speeds (Mahoney et al. 2007)

Work Zone Speed	Mean Speed	85th Percentile Speed	Speed Variance
60 mph (10 mph reduction)	61 mph	66.5 mph	18.1 mph
55 mph (15 mph reduction)	60 mph	65.4 mph	17.9 mph
50 mph (20 mph reduction)	59 mph	64.3 mph	17.7 mph

In a reanalysis of the data collected for NCHRP Report 581, Porter and Wood (2013) used three-stage least squares and panel models with instrumental variables to estimate the mean speed and speed standard deviation for rural freeway work zones. The modeling results indicated that work zones with posted speeds of 50 to 55 mph had mean operating speeds 1.09 mph lower than 60 to 65 mph posted speed limits and 1.14 mph lower than 70 mph posted speeds. The standard deviations for operating speeds in work zones with posted speeds of 50 to 55 mph were 1.10 mph and 1.26 mph lower than the 60 to 65 mph and 70 mph posted speed limits, respectively.

State Transportation Agency Practices Related to Increasing Posted Speed Limits

In addition to summarizing the extant literature related to how increasing posted speed limits on rural freeways affects driver speed choice and safety, the research team contacted several state transportation agencies concerning the processes used to identify segments of rural freeways that were candidates for increased regulatory speed limits. The results of this outreach effort are described below.

Idaho

In early 2014, the governor of Idaho signed into law a bill that permitted the posted speed limit on rural Interstates to be raised to 80 mph (from 75 mph). A telephone interview with the Idaho Transportation Department indicated that rural sections of Interstates 15, 84, and 86, in the southern part of Idaho, traverse level terrain. In these areas, the vertical grades are relatively flat and the horizontal curves are also flat. Speed measurements indicated that 85th-percentile speeds prior to the posted speed limit increase were approximately 80 mph; thus, operating speeds were consistent with the increased regulatory speed limit. Posted speed limits in suburban and mountainous terrain (Interstate 90) were not increased. Anecdotal information suggests that safety performance on the rural freeways with higher posted speed limits has not changed since the speed limit was increased in July 2014; however, data collection is now underway and objective evaluations are planned in the future.

Texas

Effective in October 2012, it was possible to raise the posted speed limit from 70 to 75 mph on any portion of the state highway system in Texas based on a set of formal procedures, provided that the speed was considered reasonable and safe. In addition, procedures also provided for 80 mph posted speed limits on parts of Interstates 10 and 20 in several Texas counties, as well as provisions for 85 mph posted speed limits on highway segments designated to accommodate travel at such speeds. An engineering study is used to identify sections that are candidates for higher regulatory speed limits. Among the considerations in an engineering study are the following: past safety performance, 85th-percentile operating speeds, driver comfort, highway cross-section dimensions, and horizontal and vertical alignment design features. The Texas Department of Transportation "Procedures for Establishing Speed Zones" (2012) includes the following guidelines when selecting speed limits:

- Set speed limits based on spot speed studies of the 85th-percentile operating speed. If the posted speed limit is to be raised on an existing roadway, the roadside features should be examined to determine if modifications may be necessary to maintain roadside safety.
- It is appropriate for posted speed limits to be based on 85th-percentile operating speeds, even if the inferred design speed (i.e., the speed for which all critical design speed-related criteria are met at a prescribed location) is lower than the 85th-percentile operating speed.
- Arbitrarily setting lower posted speed limits at point locations due to stopping sight distance that is perceived as shorter than desirable is neither effective nor good engineering practice.
- If a section of roadway has a posted speed limit that is (or will be) greater than the inferred design speed, and a safety concern exists at the same location, warning or informational signs should be placed at the location.
- New or reconstructed roadways should be designed to accommodate operating speed consistent with the highest anticipated posted speed limit.

When performing spot speed studies in rural areas, the Texas Department of Transportation (TxDOT 2012) recommends that speed check stations be located at intervals greater than 0.25 miles, and perhaps are only necessary at the beginning, end, and mid-point of the speed zone study location, if the roadway characteristics are consistent throughout the study section. It is recommended that all spot speed data be collected during weekdays, under off-peak travel conditions. The weather conditions should be favorable, and the study sample should include only "free-flow" vehicles (i.e., not influenced by other vehicles in the traffic stream). A total of 125 cars (excluding trucks and buses) are recommended for data collection.

TxDOT (2012) recommends that the difference in the posted speed limit between two adjacent speed zones should not exceed 15 mph. If an abrupt change of 85th-percentile speeds between adjacent speed zones is observed, a 0.2 mile or more transition should be used to enable drivers to change their speed.

Once the speed limit and speed zone are established, the nearest 5 mph increment should be used to post the regulatory speed on a roadway segment. The posted speed limit may be lowered or increased by 5 mph from the 85th-percentile speed, under the following special conditions:

- The average of the 85th-percentle operating speed may be used when considering posted speed limits across adjacent segments, except when the adjacent 85th-percentile operating speed is more than 7 mph different from the speed derived from the average among adjacent segments.

- On highway sections with crash rates greater than the average for similar roadway types, the speed zone may be as much as 7 mph lower than the 85th-percentile speed, if enforcement agencies will ensure that the speed zone is effective.

Wyoming

Effective in July 2014, the Wyoming Department of Transportation increased the posted speed limit to 80 mph (from 75 mph) on several rural freeway segments. State transportation agency staff used a "stacked" graph method to identify locations that were candidates for the higher posted speed limit. This method consisted of evaluating 914 miles of rural freeway using the following five factors:

- Safety performance
- Pavement preservation
- Traffic volume
- Speeding violations
- Spot speed studies

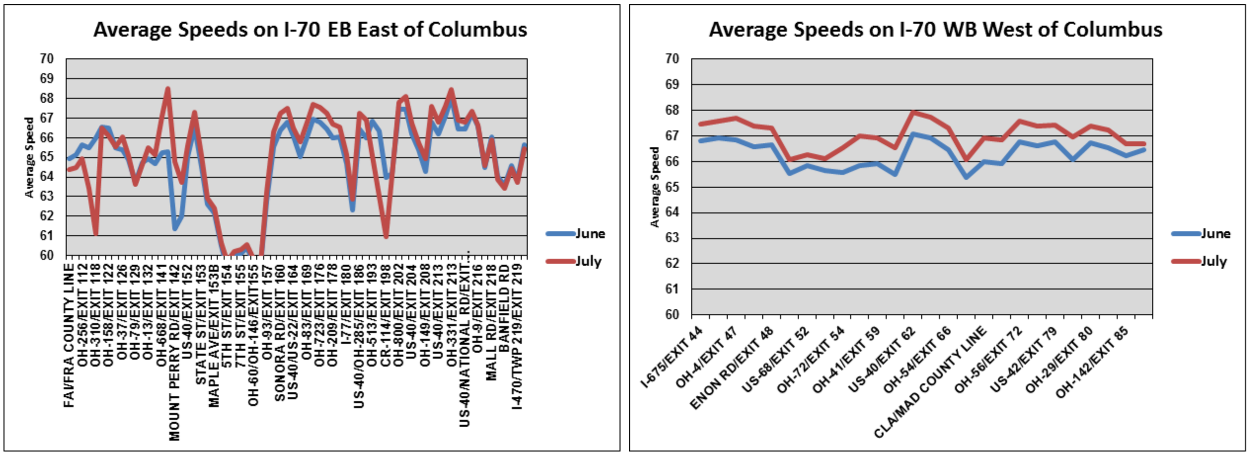
For the safety evaluation, a 5-year average crash history was compared to the statewide average. Fatal and injury, nighttime, animal, weather-related crash severities and types were considered in the safety evaluation. Rutting per mile and pavement surface friction factors were used in the pavement preservation assessment. Vehicle operating speed data were collected at several permanent locations, and 50 spot-speed radar collection sites were included in the speed assessment.

The 80 mph posted speed limit zones were identified in segments that were at least 20 miles long and did not have issues related to the five factors noted above. The 80 mph posted speed limit zones will be re-evaluated in subsequent years.

Ohio

The Ohio Department of Transportation increased the posted speed limit from 65 to 70 mph on several hundred miles of rural freeway in July 2013. In determining candidate sections for the posted speed limit increase, the Ohio DOT identified all freeways that were located outside the urbanized boundary as identified by census data. Engineering studies were used to identify segments within the rural freeway population that should be posted at lower speed limits and, using established speed zoning law retained the posted speed limit in these sections. The posted speed limit was increased to 70 mph on all rural freeways that did not fall into the speed zones identified by engineering studies.

The Ohio DOT collected speed data on several segments of Interstates 70 and 71 near Columbus, immediately before (June 2013) and immediately after (June 2014) the posted speed limits were raised from 65 to 70 mph. Examples of the range of changes observed in the average speed at two locations are shown in Figure 13. The left panel is a section of Interstate 70 east of Columbus. This section shows that average speeds changed only nominally (less than 0.5 mph in many locations) immediately after increasing the posted speed limit to 70 mph. In the right panel, average speeds before and after the posted speed limit increase are shown along a segment of Interstate 70, west of Columbus. The average speeds were approximately 0.5 to 1.0 mph higher immediately after the speed limit was increased from 65 to 70 mph.



Average Speeds on I-70 EB East of Columbus

Average Speeds on I-70 WB West of Columbus

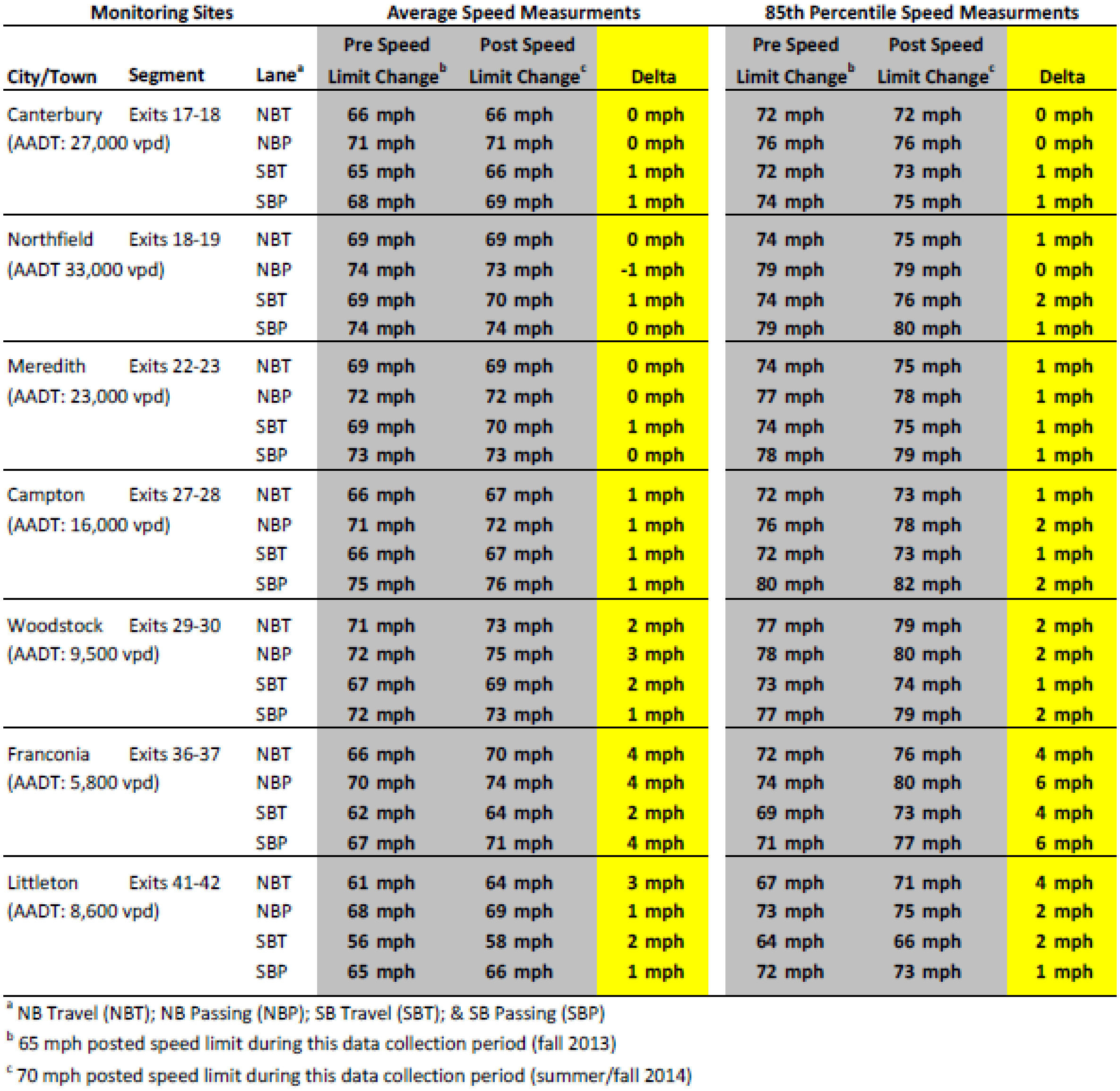
Figure 13. Average Speeds on Interstate 70 Before and After Posted Speed Limits were Increased from 65 to 70 mph
(left panel: east of Columbus; right panel: west of Columbus)

The Ohio DOT has an ongoing project to assess the operational and safety effects of the posted speed limit increase.

New Hampshire

On January 1, 2014, the posted speed limit along Interstate 93 in New Hampshire was raised from 65 to 70 mph. Legislative action facilitated the posted speed limit increase, which began at milemarker 45.0 and extended west to the Vermont border. The Bureau of Traffic collected operating speed data at several locations before and after the posted speed limit increase. The before period included November and December 2013, immediately prior to the speed limit increase. The after period included time between July and September 2014. Before and after period operating speed comparisons are shown in Table 3.

Table 3. Before-after Speed Comparisons on Interstate 93 in New Hampshire
(Personal Communication, from Mr. William Lambert, P.E., Administrator, Bureau of Traffic).



Monitoring Sites			Average Speed Measurments			85th Percentile Speed Measurments		
City/Town	Segment	Lane[a]	Pre Speed Limit Change[b]	Post Speed Limit Change[c]	Delta	Pre Speed Limit Change[b]	Post Speed Limit Change[c]	Delta
Canterbury	Exits 17-18	NBT	66 mph	66 mph	0 mph	72 mph	72 mph	0 mph
(AADT: 27,000 vpd)		NBP	71 mph	71 mph	0 mph	76 mph	76 mph	0 mph
		SBT	65 mph	66 mph	1 mph	72 mph	73 mph	1 mph
		SBP	68 mph	69 mph	1 mph	74 mph	75 mph	1 mph
Northfield	Exits 18-19	NBT	69 mph	69 mph	0 mph	74 mph	75 mph	1 mph
(AADT 33,000 vpd)		NBP	74 mph	73 mph	-1 mph	79 mph	79 mph	0 mph
		SBT	69 mph	70 mph	1 mph	74 mph	76 mph	2 mph
		SBP	74 mph	74 mph	0 mph	79 mph	80 mph	1 mph
Meredith	Exits 22-23	NBT	69 mph	69 mph	0 mph	74 mph	75 mph	1 mph
(AADT: 23,000 vpd)		NBP	72 mph	72 mph	0 mph	77 mph	78 mph	1 mph
		SBT	69 mph	70 mph	1 mph	74 mph	75 mph	1 mph
		SBP	73 mph	73 mph	0 mph	78 mph	79 mph	1 mph
Campton	Exits 27-28	NBT	66 mph	67 mph	1 mph	72 mph	73 mph	1 mph
(AADT: 16,000 vpd)		NBP	71 mph	72 mph	1 mph	76 mph	78 mph	2 mph
		SBT	66 mph	67 mph	1 mph	72 mph	73 mph	1 mph
		SBP	75 mph	76 mph	1 mph	80 mph	82 mph	2 mph
Woodstock	Exits 29-30	NBT	71 mph	73 mph	2 mph	77 mph	79 mph	2 mph
(AADT: 9,500 vpd)		NBP	72 mph	75 mph	3 mph	78 mph	80 mph	2 mph
		SBT	67 mph	69 mph	2 mph	73 mph	74 mph	1 mph
		SBP	72 mph	73 mph	1 mph	77 mph	79 mph	2 mph
Franconia	Exits 36-37	NBT	66 mph	70 mph	4 mph	72 mph	76 mph	4 mph
(AADT: 5,800 vpd)		NBP	70 mph	74 mph	4 mph	74 mph	80 mph	6 mph
		SBT	62 mph	64 mph	2 mph	69 mph	73 mph	4 mph
		SBP	67 mph	71 mph	4 mph	71 mph	77 mph	6 mph
Littleton	Exits 41-42	NBT	61 mph	64 mph	3 mph	67 mph	71 mph	4 mph
(AADT: 8,600 vpd)		NBP	68 mph	69 mph	1 mph	73 mph	75 mph	2 mph
		SBT	56 mph	58 mph	2 mph	64 mph	66 mph	2 mph
		SBP	65 mph	66 mph	1 mph	72 mph	73 mph	1 mph

[a] NB Travel (NBT); NB Passing (NBP); SB Travel (SBT); & SB Passing (SBP)

[b] 65 mph posted speed limit during this data collection period (fall 2013)

[c] 70 mph posted speed limit during this data collection period (summer/fall 2014)

As shown in Table 3, the average speeds changed nominally (± 1 mph) in the segments with higher traffic volumes (AADT > 16,000 vehicles per day). In the locations with lower traffic volumes, the average speeds increased by 1 to 4 mph after the speed limit increase. The 85^{th}-percentile operating speeds exhibited similar characteristics. In the higher-volume sections of Interstate 93, the 85^{th}-percentile speeds changed nominally (0 to 2 mph), but in the locations with lower traffic volumes, the 85^{th}-percentile speeds increased by 1 to 6 mph after the speed limit increase.

Michigan

The Michigan Department of Transportation funded a research project (Gates et al. 2015) to investigate the potential impacts of raising posted speed limits on high-speed non-freeways in the state. Issues related to traffic safety, operational performance (e.g., operating speed and travel time), and economic impacts (e.g., infrastructure costs and fuel consumption) were considered in the assessment. The authors used this information to quantify the risk associated with raising speed limits, which then informed a prioritization strategy to identify roadway segments that might be considered for higher speed limits (i.e., change from 55 to 65 mph). A benefit-cost assessment was also completed to determine the implications of the possible speed limit increase on highway system performance. The evaluation concluded the following:

- Increasing the posted speed limit from 55 to 65 mph on non-freeways would require an assessment of existing passing zones to determine their efficacy with higher speed limits, assessing existing warning and regulatory signs, and upgrading geometric features that do not meet design standards for the 65 mph speed limit. Examples of geometric features that should be included in the geometric design assessment include horizontal curves, vertical curves, bridge width, and vertical clearance.
- Increasing posted speed limits from 55 to 65 mph will result in fuel consumption increases and travel time decreases. The value-of-time savings associated with the reduced travel time benefit outweighed the increased fuel consumption costs for heavy truck and passenger cars.
- Increasing the posted speed limit from 55 to 65 mph is expected to increase crash rates by 3.3 percent. Fatal crashes are expected to increase by 28.1 percent, while incapacitating injury crashes are expected to increase by 12.1 percent. Non-incapacitating and possible injury crashes are expected to increase by 5.0 percent, and PDO crashes are expected to increase by 2.7 percent.

OVERVIEW OF EVALUATIONS

There are four objective evaluations included in the present study. These can be broadly classified into operating speed, safety, pavement friction, and inferred design speed assessments. The speed evaluation is based on operating speed data collected before the speed limit was increased and compared to operating speed data after the speed limits were increased. These data were collected by a PTC contractor (AECOM). A total of 5 years of before-period crash data (with 65 mph speed limits) were included in the safety evaluation, but only 12-18 months of after-period (70 mph speed limits) crash data were available for the safety evaluation. **As such, it is important to note that the safety assessment is preliminary, and no definitive conclusions can be drawn from the evaluation.** Safety performance functions were estimated in the present study, so that an observational before-after study using the empirical Bayes (EB) method can be completed after additional years of after-period data become available.

In addition to the speed and safety assessments, this report presents an assessment of two alternative approaches to determine locations on rural Interstate highways in Pennsylvania that are candidates for 70 mph speed limits. These two approaches involve annual pavement friction data collected by a PTC contractor, as well as an inferred design speed concept that involves use of horizontal curve data along the mainline of Interstate 76. It should be noted that PennDOT collects pavement friction data only on an "as requested" basis, so annualized friction information at the same locations were not available for this project. Additionally, PennDOT does not maintain horizontal curve data in an electronic format, so the inferred design speed concept assessment is not presented using PennDOT horizontal curve data.

The objectives of the objective evaluations are to:

1. Compare vehicle operating speed metrics before and after the 70 mph speed limits were posted on sections of Interstate 80 and 380 along roads that are operated and maintained by the Pennsylvania Department of Transportation. Data collection periods included a period before the speed limits were increased from 65 to 70 mph, and two periods after the speed limits were increased to 70 mph. The speed metrics included mean, 85th-percentile, standard deviation, and percent exceeding the posted speed limit.
2. Compare vehicle operating speed metrics before and after the 70 mph speed limits were posted on a section of Interstate 76 (Pennsylvania Turnpike). The posted speed limit was 65 mph before the speed limit increase. The same data collection periods and speed metrics noted in item #1 were included in the Interstate 76 evaluation.
3. Evaluate speed changes approaching and through work zones (with 55 mph posted speed limits) in the 70 mph posted speed limits sections. Speed profile plots were used to make this evaluation, using data from the Pennsylvania Turnpike's Internet Performance Monitoring System (iPeMS) and the PennDOT INRIX/RITIS vehicle probe data.
4. Compare several safety performance metrics before and after the posted speed limit increase on Interstates 80 and 380, and on Interstate 76. The metrics include the total crash rate as well as the fatal-plus-injury crash rate (per 100 million vehicle-miles traveled). The before period consisted of approximately 5.5 years of data, when the posted speed limit was 65 mph, and the after period consisted of approximately 12-18 months after the speed limit was increased to 70 mph.

5. Develop safety performance functions (SPFs) for the Pennsylvania Turnpike mainline and PennDOT rural Interstate highway system. These statistical models may be used to predict the expected safety performance of locations with 65 mph posted speed limits (reference group), so that an observational before-after evaluation can be completed in the future.
6. Describe an evaluation of annualized pavement friction data from the PTC. This includes descriptive statistics of the data as well as statistical models of pavement friction degradation over time. These models were used to make estimates of the time period associated with various skid resistant qualities of the pavement surface on the Pennsylvania Turnpike mainline.
7. Develop statistical models of expected crash frequency as a function of pavement skid resistance to determine if total and wet-weather crashes are expected to increase as friction levels decrease.
8. A margin of safety evaluation comparing friction demand to friction supply along the entire Turnpike mainline. This assessment uses the Turnpike iPeMS data to determine side friction demand of drivers along all horizontal curves, and compares these demand values to the friction supply at the tire-pavement interface.
9. Develop inferred design speed profile plots along the mainline of the Turnpike based on the geometric features present (e.g., horizontal curve radius, horizontal sightline offset, and crest vertical curve parameters). The plots were developed for the inside (left) and outside (right) lanes and compared to the posted speed limit.

The remainder of the report is organized into five subsequent sections. The first section describes the data collection and analysis methods used to assess driver speed choice and speed limit compliance at the sample of locations where the posted speed limit was increased from 65 to 70 mph. This section also includes speed profile plots at work zone locations along Interstate 80 to illustrate speed compliance approaching, through, and departing work zones. The results of all speed analyses are also included in this section of the report. The second section of the report describes the methods used to collect and analyze crash frequency and severity data for the assessment of safety impacts of increasing posted speed limits from 65 to 70 mph. Additionally, the SPFs developed for the Turnpike mainline and rural PennDOT Interstate highways are included in this section of the report. The results of all safety analyses are included in this section. The third section of this report describes the friction-related assessments, and the fourth section describes the inferred design speed evaluation results. Finally, the fifth section includes a summary of findings to be drawn from the data collection and analysis effort, as well as guidance concerning the application of the methods.

OPERATING SPEED AND SPEED LIMIT COMPLIANCE ASSESSMENT

This section of the report describes the data collection procedures, statistical analysis methods, and results of the operating speed and speed limit compliance assessment.

Data Collection Procedures

Because the posted speed limit was increased at the study site locations prior to the work order notice-to-proceed, speed data were collected by PTC consultants and PennDOT field personnel. All speed data were collected in accordance with PennDOT Publication 212 “Official Traffic Control Devices” procedures, including the following:

- Data were collected using radar.
- Speeds were randomly sampled in both travel lanes, on tangent road segments unaffected by adjacent horizontal curves or steep vertical grades.
- The speed data sample included 100 observations at each location, and the number of truck speeds measured during each data collection session was representative of the proportion of trucks in the traffic stream. If the traffic volumes were considered low-flow during the data collection period, only 50 random speed observations were included in the site survey.

The data collection sites, operating speed measurement locations, data collection time periods, direction of traffic flow during the collection period, and collection dates are shown in Tables 4 and 5, for the PennDOT and PTC sites, respectively. A work zone indicator, along with the work zone posted speed limit, are also shown in Table 5 for the PTC data collection locations. The shaded cells represent the “before” period, in which the posted speed limit was 65 mph, while the cells that are not shaded represent the “after” period, in which the posted speed limit was 70 mph. There were two after periods included in the PennDOT and PTC evaluations. The first was approximately 2 to 4 months after the posted speed limit was increased to 70 mph (this is labeled “After” in Tables 4 and 5), while a second after data collection period occurred approximately 9 to 10 months after the posted speed limit was increased to 70 mph (labeled “After 2” in Tables 4 and 5).

Table 4 shows that the before period speed data collection effort consisted of 17 sites on Interstates 80 and 380 in Clearfield, Clinton, and Lackawanna counties (the east- and westbound and north- and southbound directions were counted as separate sites). In the first after period, there were six sites included in the Interstate 80 study sample, located in Clinton and Centre counties. On Interstate 380, there were six study sites included in the first after-period sample, all in Lackawanna County. As such, there were a total of 12 data collection sites in the first after-period sample. During the second after period, a total of 20 sites were included in the study sample, including locations in Centre, Clearfield, and Lackawanna counties. The before-period data were collected in April, May, or July 2014, while the first after-period data were collected in December 2014 (approximately 4 months after increasing the posted speed limit to 70 mph). The second after-period data collection effort took place approximately 9 months after the speed limits were increased on Interstates 80 and 380, in May 2015.

With regard to Table 4, the before-period operating speeds on Interstates 80 and 380 were collected by PennDOT maintenance forces. In the after periods, a PTC contractor collected the speeds and made every effort to collect data close to many of the locations included in the before-period sample. However, the use of radar and the need to be concealed from traffic during the winter months made it difficult to collect data at the same locations in the first after period. In all cases, the speed data were collected on tangent road segments, unaffected by adjacent horizontal curves or steep vertical grades. Because the first "after" period speeds were often measured at locations between two "before" period speed data collection locations, it is likely that the first "after" period speeds are representative of the speeds along the entire 70 mph speed limit sections on Interstates 80 and 380. During the second "after" period, the PTC data collection contractor was able to closely match the "before" data collection period locations.

Table 5 shows that the before period, non-work zone speed data collection effort consisted of two sites on Interstate 76 in Cumberland County. The same two sites comprised the non-work zone first after-period data collection locations on the Turnpike. There were nine sites included in the work zone speed data collection sample. Of these, three sites contained 40 mph work zone posted speed limits and six sites contained 55 mph work zone speed limits. The PTC discontinued implementation of 40 mph work zone speed limits on July 23, 2014, when the free-flow posted speed limits were raised to 70 mph. As such, only 55 mph posted speed limits were implemented in the first "after" data collection periods on the Turnpike. The second after-period data collection period included six locations with 70 mph posted speed limits, and two locations with 55 mph work zone speed limits. The "before" period data on the Turnpike were collected approximately 1 month prior to the posted speed limit change. The first "after" data collection period occurred in September 2014, approximately 2 months after the posted speed limit was increased to 70 mph, while the second "after" period data collection effort took place in May 2015, approximately 10 months after the posted speed limit was raised to 70 mph on the Turnpike.

Table 4. Speed Data Collection Locations on Interstates 80 and 380 in Pennsylvania

Site ID	County	State Route	Milepost	Period	Direction of Traffic	Date
1	Lackawanna	380	22	Before	NB/SB	7/8/2014
2	Lackawanna	380	15.2	Before	NB/SB	7/8/2014
3	Lackawanna	380	18.4	Before	NB/SB	7/8/2014
4	Lackawanna	380	14.5	Before	SB	4/18/2014
5	Lackawanna	380	13.7	Before	SB	4/18/2014
6	Clearfield	80	102	Before	EB/WB	5/12/2014
7	Clearfield	80	109.4	Before	EB/WB	5/12/2014
8	Clearfield	80	136	Before	EB	4/22/2014
9	Clearfield	80	136.1	Before	WB	4/22/2014
10	Clinton	80	187.4	Before	EB/WB	5/12/2014
11	Clinton	80	190	Before	EB	5/12/2014
12	Centre	80	143.4	After	EB/WB	12/11/2014
13	Centre	80	166.4	After	EB/WB	12/11/2014
14	Clinton	80	178	After	EB/WB	12/11/2014
15	Lackawanna	380	12.6	After	NB/SB	12/11/2014
16	Lackawanna	380	14.6	After	NB/SB	12/11/2014
17	Lackawanna	380	16.7	After	NB/SB	12/11/2014
18	Clearfield	80	102	After 2	EB/WB	5/19/2015
19	Clearfield	80	109.4	After 2	EB/WB	5/19/2015 - 5/29/2015
20	Clearfield	80	136	After 2	EB	5/19/2015
21	Clearfield	80	136.1	After 2	WB	5/19/2015
22	Centre	80	143.4	After 2	EB/WB	5/19/2015
23	Centre	80	166.4	After 2	EB/WB	5/29/2015
24	Clinton	80	178	After 2	EB/WB	5/19/2015 - 5/29/2015
25	Lackawanna	380	12.6	After 2	NB/SB	5/20/2015
26	Lackawanna	380	14.6	After 2	NB/SB	5/20/2015
27	Lackawanna	380	16.7	After 2	NB/SB	5/20/2015
28	Lackawanna	380	21.8	After 2	NB	5/20/2015
29	Lackawanna	380	21.9	After 2	SB	5/20/2015

Table 5. Speed Data Collection Locations on Interstate 76 in Pennsylvania

Site ID	County	State Route	Milepost	Period	Direction of Traffic	Date	WorkZone (Y/N)
8	Cumberland	76	207.7	Before	EB	6/17/14	Y (40 mph)
9	Cumberland	76	207.7	Before	WB	6/17/14	Y (55 mph)
1	Cumberland	76	212	Before	EB	6/17/2014	N
3	Cumberland	76	222	Before	EB	6/17/2014	N
11	Dauphin	76	250	Before	WB	6/17/2014	Y (55 mph)
5	Lebanon	76	261	Before	WB	6/17/2014	Y (40 mph)
6	Lancaster	76	276	Before	EB	6/17/2014	Y (40 mph)
2	Cumberland	76	212	After	EB	9/29/2014	N
4	Cumberland	76	222	After	EB	9/29/2014	N
7	Lancaster	76	278.4	After	EB	9/29/2014	Y (55 mph)
10	Cumberland	76	207.7	After	EB	9/30/14	Y (55 mph)
12	Dauphin	76	250	After	WB	9/29/2014	Y (55 mph)
13	Dauphin	76	256.7	After	EB	9/30/2014	Y (55 mph)
13	Cumberland	76	172.3	After 2	EB	5/28/2015	Y (55 mph)
14	Cumberland	76	207.7	After 2	EB/WB	5/28/2015	N
15	Cumberland	76	212	After 2	EB	5/28/2015	N
16	Cumberland	76	221.3	After 2	EB	5/28/2015	Y (55 mph)
17	Dauphin	76	256.9	After 2	EB	5/29/2015	N
18	Lancaster	76	276	After 2	EB	5/28/2015	N
19	Lancaster	76	278.7	After 2	EB	5/28/2015	N

In addition to the data collection locations noted in Tables 4 and 5, the PTC contractor also collected vehicle operating speed data outside of the 70 mph posted speed limit zones on Interstates 76 and 80. Data were collected using the same procedures noted earlier. The purpose of these data were to determine if drivers were adapting to the lower posted speed limit of 65 mph upon entering and exiting the 70 mph speed zones.

Another objective of the present study was to evaluate driver speed-changing behavior approaching 55 mph work zone speed limits in the 70 mph posted speed limit sections. For this analysis, data were collected from the PennDOT RITIS/INRIX system. This system collects vehicle probe data along Interstate and other highways in the Commonwealth. PennDOT identified an active work zone along Interstate 80, which included the following locations:

- Segment 1704, offset 1400 to segment 1944, offset 0325 in the eastbound direction
- Segment 1901, offset 1611 to segment 1705, offset 1286 in the westbound direction

Mean operating speed data were extracted during non-peak, daytime periods, with high-visibility conditions (December 8, 2015). A speed-versus-distance plot was created to illustrate driver speed choice approaching and traveling through the work zone. The intent of the evaluation was to determine if the work zone traffic control design is effective in producing speed compliance.

Statistical Analysis

The sample of observed operating speeds was used to create speed distributions for use in the statistical analyses. These distributions were used to calculate measures of effectiveness, including the mean operating speed, standard deviation (or variance) of speed, 85th-percentile operating speed, and the proportion of vehicles exceeding the posted speed limit. Once all of the operating speed data were assembled into an analysis database, the following statistical comparisons were made:

- Before vs. after mean speed, speed variance, 85th-percentile speed, and proportion of all non-work zone passenger cars exceeding the posted speed limit. The before-period speeds were compared to the first after period, and the two after-period speed metrics were then compared.
- Before vs. after mean speed, speed variance, 85th-percentile speed, and proportion of all non-work zone trucks exceeding the posted speed limit. The before period speeds were compared to the first after-period speed samples. Additionally, the two after period speed samples were also compared.
- Before vs. after mean speed, speed variance, 85th-percentile speed, and proportion of all work zone passenger cars exceeding the posted speed limit. Work zone speeds were only available along the Turnpike (Interstate 76). As shown in Table 5, work zone speeds were collected in the before, as well as the first and second after periods. In both after periods, the work zone speeds limits were 55 mph. In the before period, the work zone speed limits were 40 and 55 mph.
- Before vs. after mean speed, speed variance, 85th-percentile speed, and proportion of all work zone trucks exceeding the posted speed limit. Only speeds from the Turnpike were used for this assessment. As shown in Table 5, work zone speeds were collected in the before, as well as the first and second after periods. In both after periods, the work zone speeds limits were 55 mph. In the before period, the work zone speed limits were 40 and 55 mph.

The statistical methods used to compare two samples (e.g., before vs. first after periods) include the independent samples t-test for mean and 85th-percentile speeds, the F-test for speed variance, and z-test for the proportion of vehicles exceeding the posted speed limit. Each of these tests is described in detail below.

The t-test for independent samples was applied to determine if the differences in mean and 85th-percentile speed measures were statistically significant. Statistically significant changes in mean or 85th-percentile operating speeds indicate that the observed speeds are different in the two time periods being compared. The t-statistic is commonly used to test the hypothesis of differences in population parameters (Washington et al., 2003). In this study the null and alternative hypotheses for testing the differences in two mean (or 85th-percentile) speed measures, μ_1 and μ_2, are:

Null Hypothesis (H_0): There has not been a change in mean speeds as a result of the 65 to 70 mph posted speed limit increase, or H_0: $\mu_1 - \mu_2 = 0$

Alternative Hypothesis (H_a): There has been a change in mean speeds as a result of the 65 to 70 mph posted speed limit increase, or H_a: $\mu_1 - \mu_2 \neq 0$.

At each study site, a t-statistic was calculated between two data collection periods, including the before vs. first after period, and the first after period vs. the second after period. Independent two-sample t-statistics were applied to test for the difference between two population means at each study site. The t-statistic is given by:

$$t = \frac{\left(\overline{X}_1 - \overline{X}_2\right)}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} \tag{2}$$

where:

$\overline{X}_1, \overline{X}_2$ = mean speed for the before and after periods (or between two after periods);
s_1, s_2 = standard error of speed for the before and after periods (or two after periods);
n_1, n_2 = sample size in before and after periods (or two after periods).

The degrees of freedom (df) value for the independent samples t-statistic is $n_1 + n_2 - 2$. The critical value when $\alpha = 0.05$ for a two-tail test is $\pm$ 1.96. The null hypothesis is rejected when the computed t-statistic exceeds the critical value, thus concluding that the mean speeds being compared differ between the two collection periods being considered. An alternative method to determine the statistical significance of the posted speed limit increase on mean speed is the p-value associated with the t-statistic. A low p-value (i.e., less than or equal to 0.05) indicates a high probability that the difference in the posted speed limit influenced mean speeds between two data collection periods. The t-statistic and p-value were computed for each pair of collection periods at each phase one study site.

In addition to the t-test, the percentage of vehicles exceeding the posted speed limit before and after the posted speed limit increase was computed and compared. The percentage of vehicles traveling above the posted speed limit, P_S, was computed as follows:

$$P_S = \frac{x}{n} \times 100 \tag{3}$$

where: x = number of vehicles exceeding the posted speed limit; and
n = the total number of vehicles in the sample.

By comparing the number of vehicles exceeding the posted speed limit between two data collection periods, it can be determined if the speed limit increase is associated with a change in speed compliance. The percentage of vehicles exceeding the posted speed limit during periods 1 and 2 (i.e., before vs. after or after period 1 vs. after period 2), P_{S1} and P_{S2}, was computed and compared for all work zone and non-work zone locations. In order to determine if the change in vehicles exceeding the posted speed limit is statistically significant, a Z-test for independent samples was computed. The null and alternative hypotheses for the test are as follows:

> Null Hypothesis (H_0): There is no difference between the two sample proportions, or H_0: $P_{S1} - P_{S2} = 0$
>
> Alternative Hypothesis (H_a): There is a difference between the two sample proportions, H_0: $P_{S1} - P_{S2} \neq 0$.

The Z-statistic used to determine the statistical difference between the two sample proportions is as follows:

$$Z = \frac{P_{S1} - P_{S2}}{\sqrt{P(1-P)\left(\frac{1}{n_1} - \frac{1}{n_2}\right)}} \tag{4}$$

where P_{S1} and P_{S2} are the sample proportions from Equation (3), n_1 and n_2 are sample sizes for the corresponding proportions being considered, and P is the combined proportion in both samples, computed as follows:

$$P = \frac{x_1 + x_2}{n_1 + n_2} \tag{5}$$

Similar to the t-statistic, the Z-statistic is associated with a p-value. A p-value of 0.05 or less results in rejecting the null hypothesis and concluding that the difference in the proportion of vehicles exceeding the posted speed limit during the data collection periods was statistically significant.

The final speed performance metric to be considered in the present study is speed variance. A two-sided F-test was used to compare the variance of vehicle operating speeds in the before and after periods, and between the two after periods. The F-test is computed as follows:

$$F = \frac{s_1^2}{s_2^2} \tag{6}$$

which has an F-distribution with ($n_1 - 1$) numerator degrees of freedom and ($n_2 - 1$) denominator degrees of freedom. When the computed F-test exceeds the critical value, the null hypothesis (speed variance is equal in the before and after periods [or is equal between the two after periods]) is rejected and the conclusion is that the speed variance differs between the periods being compared.

To assess the effect of the work zone traffic control design on operating speeds, a speed profile plot was developed for a segment of roadway preceding the work zone, the work zone itself, and the segment downstream of the work zone.

Analysis Results

As noted in Tables 4 and 5, speed data collection for the before period and both after periods is complete. All possible outliers have been removed from each data collection period.

PennDOT Interstates 80 and 380

The statistical comparisons of mean speed, 85th-percentile speed, speed variance, and percentage of vehicles exceeding the posted speed limit are shown in Tables 6 through 13 for PennDOT Interstates 80 and 380. For all comparisons, the before-period speed data at all data collection locations on Interstates 80 and 380 were combined. Similarly, all speed data in after-period 1 and after-period 2 on Interstates 80 and 380 were combined. Table 6 shows the mean speed comparisons for all vehicles, passenger cars only, and heavy trucks only in the before and first after periods. Table 7 shows the mean speed comparison for these same vehicle types in the first and second after periods. Tables 8 and 9 are the 85th-percentile speed comparisons between the before and first after period (Table 8), and the first and second after periods (Table 9). These comparisons also consider all vehicles, passenger cars only, and heavy trucks only. Tables 10 and 11 are the speed variance comparisons for the before and both after periods for all vehicles, passenger cars only, and heavy trucks only. Finally, Tables 12 and 13 are the percentage of vehicles exceeding the posted speed limit comparisons between the before and both after periods for all vehicles, passenger cars only, and heavy vehicles only.

The tests of statistical significance are based on the null and alternative hypotheses described above in the "Statistical Analysis" section. If the null hypothesis is not rejected (p-value > 0.05), there is not enough evidence from the current sample of speeds to indicate that the speed measures (i.e., mean, 85th-percentile, speed variance, or proportion of vehicles exceeding the posted speed limit) differ between the "before" and "after" periods, or between the first and second after periods. If the null hypothesis is rejected (p-value < 0.05), there is enough evidence from the sample to indicate that the speeds differ. Rejecting the null hypothesis indicates that a speed comparison is statistically significant at the 95 percent confidence level, and therefore, it is reasonable to conclude that the difference is attributable to the posted speed limit increase from 65 to 70 mph when comparing the before to the first after period. If a statistically significant change in a speed metric between the two after periods results, it is likely attributable to driver adaptation.

Table 6 shows that the difference in mean speeds was statistically significant between the before and first after period for all vehicles, and for passenger cars and heavy trucks. The mean speed increased by 1.1 mph for all vehicles in the study sample after increasing the posted speed limit from 65 to 70 mph. The mean speed of passenger cars increased by 1.4 mph, and the mean speed of heavy trucks increased by 2.3 mph, after increasing the posted speed limit from 65 to 70 mph.

Table 7 compares the mean speed for all vehicles, passenger cars only, and heavy vehicles only between the first and second after data collection periods. The results indicate that the mean speed of all vehicles was 0.6 mph lower in the second after period, relative to the first after period. The mean speed of passenger cars only was 0.1 mph higher in the second after period, relative to the first after period, and the heavy truck mean speed was 0.3 mph lower in the second after period relative to the first after period. The mean speed comparisons between the first and second after periods were not statistically significant when considering the passenger car and truck operating speeds separately, suggesting that average speeds did not change based on the current sample of speed data between the two after periods.

Table 6. Before-First After Period Mean Speed (mph) Comparisons on PennDOT Interstates

Vehicle Type	Before (mph)	Sample Size	After 1 (mph)	Sample Size	Difference*	t-test
All	68.5	1,550	69.6	1200	1.1	5.36 (<0.0001)**
PC	69.7	1,169	71.1	736	1.4	5.96 (<0.0001)**
Heavy Trucks	64.8	381	67.1	464	2.3	8.65 (<0.0001)**

* Difference = mean speed (first after period) - mean speed (before)

**Statistically significant at the 5% confidence level, so the null hypothesis that the two means are equal can be rejected

Table 7. First After-Second After Period Mean Speed (mph) Comparisons on PennDOT Interstates

Vehicle Type	After 1 (mph)	Sample Size	After 2 (mph)	Sample Size	Difference* (mph)	t-test
All	69.6	1,200	69.0	4,000	-0.6	− 3.32 (0.0008)**
PC	71.1	736	71.2	2,000	0.1	0.34 (0.7341)
Heavy Trucks	67.1	464	66.8	2,000	-0.3	− 1.27 (0.2059)

* Difference = mean speed (after 2) - mean speed (after 1)

** Statistically significant at the 5% confidence level, so the null hypothesis that the two means are equal can be rejected

Table 8 shows that the difference in 85th-percentile operating speeds was not statistically significant between the before and first after period for all vehicles, nor was it statistically significant for passenger cars only. There was a statistically significant increase in the 85th-percentile heavy truck speeds after increasing the speed limit from 65 to 70 mph. The magnitude of the 85th-percentile truck speed increase was 2.3 mph after increasing the posted speed limit on Interstates 80 and 380.

Table 8. Before-First After Period 85th-Percentile Speed (mph) Comparisons on PennDOT Interstates

Vehicle Type	Before (mph)	Sample Size	After 1 (mph)	Sample Size	Difference* (mph)	t-test
All	73.1	1,550	73.4	1,200	0.4	0.42 (0.6774)
PC	74.0	1,169	74.7	736	0.6	0.75 (0.4616)
Heavy Trucks	68.0	381	70.3	464	2.3	4.11 (0.0003)**

*Difference = 85th percentile speed (after 1) - 85th percentile speed (before)

**Statistically significant at the 5% confidence level, so the null hypothesis that the two speeds are equal can be rejected

Table 9 shows that the difference in 85th-percentile operating speeds was not statistically significant between the first and second after periods for all vehicles, nor was it statistically significant for passenger cars only or heavy vehicles only. For all vehicle types, the 85th-percentile speeds increased by approximately 0.4 mph.

Table 9. First After-Second After Period 85th-Percentile Speed (mph) Comparisons on PennDOT Interstates

Vehicle Type	After 1 (mph)	Sample Size	After 2 (mph)	Sample Size	Difference* (mph)	t-test
All	73.4	1,200	73.8	4,000	0.4	0.45 (0.6595)
PC	74.7	736	75.2	2,000	0.5	0.67 (0.5107)
Heavy Trucks	70.3	464	70.8	2,000	0.5	0.94 (0.3571)

*Difference = 85th percentile speed (after 2) - 85th percentile speed (after 1)

**Statistically significant at the 5% confidence level, so the null hypothesis that the speeds are equal can be rejected

Table 10 shows that the speed variance for all vehicles was not statistically significant between the before and first after periods, nor was it statistically significant for passenger cars only. However, the difference in speed variance decreased, and was statistically significant, for heavy trucks when comparing 70 mph to 65 mph speed limits. The speed variance decreased by approximately 3 mph^2 for heavy vehicles after the posted speed limit increase.

Table 10. Before-First After Period Speed Variance (mph^2) Comparisons on PennDOT Interstates

Vehicle Type	Before (mph^2)	Sample Size	After 1 (mph^2)	Sample Size	Difference* (mph^2)	F-test
All	26.0	1,550	24.2	1,200	-1.8	1.07 (0.2011)
PC	23.1	1,169	24.9	736	1.8	1.08 (0.2642)
Heavy Trucks	16.0	381	13.1	464	-2.9	1.23 (0.0371)**

* Difference = speed variance (after 1) - speed variance (before)

**Statistically significant at the 5% confidence level, so the null hypothesis that the two variances are equal can be rejected

Table 11 shows that the speed variance for all vehicles was statistically significant between the first and second after periods, but was not statistically significant for passenger cars only. There was a statistically significant difference in speed variance for heavy trucks only when comparing the first and second after periods. The speed variance increased by approximately 7 mph^2 for heavy vehicles between the first and second after periods.

Table 11. First After-Second After Period Speed Variance (mph^2) Comparisons on PennDOT Interstates

Vehicle Type	After 1 (mph^2)	Sample Size	After 2 (mph^2)	Sample Size	Difference* (mph^2)	F-test
All	24.2	1,200	26.3	4,000	2.1	1.09 (0.0788)**
PC	24.9	736	22.9	2,000	-2.0	0.92 (0.1670)
Heavy Trucks	13.1	464	20.1	2,000	7.0	1.54 (<0.0001)**

* Difference = speed variance (after 2) - speed variance (after 1)

**Statistically significant at the 5% confidence level, so the null hypothesis that the variances are equal can be rejected

Table 12 shows that the percentage of vehicles exceeding the posted speed limit decreased after the posted speed limit was increased from 65 to 70 mph on PennDOT Interstate highways. The results were statistically significant for all vehicle types, and when disaggregated by passenger cars and heavy trucks. The percent reduction of heavy trucks exceeding the posted speed limit was nearly 36, while the percent reduction of passenger cars exceeding the posted speed limit was approximately 33, indicating that speed compliance improved after the posted speed limit increased to 70 mph.

Table 12. Percentage of Vehicles Exceeding the Posted Speed Limit on PennDOT Interstates

Vehicle Type	Before (%)	Sample Size	After 1 (%)	Sample Size	Difference* (%)	z-test
All	72.32%	1,550	34.67%	1,200	-37.66%	− 19.72 (< 0.0001)**
PC	81.95%	1,169	48.51%	736	-33.44%	− 15.37 (< 0.0001)**
Heavy Trucks	48.51%	381	12.72%	464	-35.79%	− 11.76 (<0.0001)**

*Difference = percentage exceeding the speed limit (after) - percentage exceeding the speed limit (before)

**Statistically significant at the 5% confidence level, so the null hypothesis that the two percentages are equal can be rejected

Table 13 shows that the percentage of vehicles exceeding the posted speed limit increased for all vehicle types, passenger cars only, and heavy trucks only, when comparing the first to the second after periods. The results were statistically significant for all vehicle type comparisons. The proportion of passenger cars only and heavy trucks only increased by approximately 9 percent when comparing the first and second after periods.

Table 13. Percentage of Vehicles Exceeding the Posted Speed Limit on PennDOT Interstates

Vehicle Type	After 1 (%)	Sample Size	After 2 (%)	Sample Size	Difference* (%)	z-test
All	34.67%	1,200	39.45%	4,000	4.78%	2.99 (<0.0028)**
PC	48.51%	736	57.60%	2,000	9.09%	4.24 (<0.0001)**
Heavy Trucks	12.72%	464	21.30%	2,000	8.58%	4.19 (<0.0001)**

*Difference = percentage exceeding the speed limit (after 2) - percentage exceeding the speed limit (after 1)

** Statistically significant at the 5% confidence level, so the null hypothesis that the two percentages are equal can be rejected

Table 14 is a comparison of the before, first after, and second after period speed measures of effectiveness for PennDOT Interstates 80 and 380, disaggregated by passenger cars only and heavy trucks only. As shown, the mean passenger car speeds increased from the before to first after period by 1.4 mph, but only increased by 0.1 mph between the first and second after periods. The mean speed of heavy trucks increased by 2.3 mph between the before and first after period, and then decreased by 0.3 mph between the first and second after periods. The 85th-percentile speed of passenger cars increased by 0.7 mph between the before and first after period, and increased by 0.5 mph between the first and second after periods. The 85th-percentile heavy truck speeds increased by 2.3 mph between the before and first after period, and increased by 0.5 mph between the first and second after periods. These findings suggest that the mean and 85th-percentile speed of passenger cars and heavy trucks did not increase in direct proportion to the 5 mph posted speed limit increase.

The speed variance of passenger cars remained nearly unchanged when comparing the before, first after, and second after periods in Table 14. For heavy trucks, the speed variance decreased between the before and first after period, but then increased in the second after period, suggesting less uniformity in truck speeds in the second after period relative to the before and first after period. The percentage of passenger cars exceeding the posted speed limit decreased by 33.5 percent from the before to first after period, but then increased by 9.1 percent from the first to second after periods. A similar trend was found for the heavy truck traffic. Collectively, this suggests that speed compliance improved when raising the posted speed limit from 65 to 70 mph, but the increasing trend in vehicles exceeding the posted speed limit, since the 70 mph speed zones were implemented, should be monitored to determine if this speed measure changes in the future.

Table 14. Comparison of Before, First After, and Second After Period Speed Measures of Effectiveness on PennDOT Interstates 80 and 380

Speed Measure	Vehicle Type	Before Period	First After Period	Second After Period
Mean (mph)	PC	69.7	71.1	71.2
	Trucks	64.8	67.1	66.8
85th-percentile (mph)	PC	74.0	74.7	75.2
	Trucks	68.0	70.3	70.8
Variance (mph^2)	PC	23.1	24.9	22.9
	Trucks	16.0	13.1	20.1
Percent exceeding posted speed limit (%)	PC	82.0	48.5	57.6
	Trucks	48.5	12.7	21.3

Pennsylvania Turnpike Interstate 76 (Non-Work Zones)

Table 15 shows that the difference in mean speeds for all vehicle types combined, passenger cars only, and heavy trucks only was not statistically significant when comparing the before (65 mph posted speed limit) to the first after (70 mph posted speed limit) period on the Turnpike at non-work zone locations. The difference in mean speed between the first after and before periods was less than 1.0 mph for all vehicles, passenger cars only, and heavy trucks only.

Table 16 shows that the difference in mean speeds for all vehicle types combined, passenger cars, and heavy trucks was statistically significant when comparing the first and second after periods on the Turnpike at non-work zone locations. The difference in mean speeds was 1.3 mph for all vehicles, 1.9 mph for passenger cars, and 3.0 mph for heavy trucks.

Table 15. Before-First After Period Non-work Zone Mean Speed Comparisons on the Turnpike

Vehicle Type	Before (mph)	Sample Size	After 1 (mph)	Sample Size	Difference* (mph)	t-test
All	67.3	200	68.1	200	0.8	1.35 (0.1778)
PC	69.5	126	70.3	134	0.8	1.29 (0.1974)
Heavy Trucks	63.5	74	63.5	66	0.0	0.03 (0.9768)

* Difference = mean speed (after 1) - mean speed (before)

**Statistically significant at the 5% confidence level, so the null hypothesis that the two speeds are equal can be rejected

Table 16. First-Second After Period Non-work Zone Mean Speed Comparisons on the Turnpike

Vehicle Type	After 1 (mph)	Sample Size	After 2 (mph)	Sample Size	Difference* (mph)	t-test
All	68.1	200	69.4	1,200	1.3	2.81 (0.54)**
PC	70.3	134	72.2	600	1.9	4.13 (<0.0001)**
Heavy Trucks	63.5	66	66.5	600	3.0	3.99 (<0.0001)**

* Difference = mean speed (after 2) - mean speed (after 1)

**Statistically significant at the 5% confidence level, so the null hypothesis that the two speeds are equal can be rejected

Table 17 shows that the difference in 85th-percentile speeds for all vehicle types combined, passenger cars, and heavy trucks was not statistically significant when comparing the before and first after periods on the Turnpike at non-work zone locations. It should be noted, however, that the sample of speed observations used to compute the t-tests for heavy trucks was small. The mean speed of trucks increased by 5.5 mph after the posted speed limit was increased from 65 to 70 mph at the two locations that were sampled.

Table 18 shows that the difference in 85th-percentile speeds for all vehicle types combined, passenger cars, and heavy trucks was not statistically significant when comparing the first and second after periods on the Turnpike at non-work zone locations.

Table 17. Before-First After Period Non-work Zone 85th-Percentile Speed Comparisons on the Turnpike

Vehicle Type	Before (mph)	Sample Size	After 1 (mph)	Sample Size	Difference* (mph)	t-test
All	73.0	200	73.1	200	0.1	0.08 (0.9484)
PC	74.0	126	75.0	134	1.0	0.95 (0.5158)
Heavy Trucks	64.0	74	69.5	66	5.5	1.29 (0.4204)

*Difference = 85th percentile speed (after) - 85th percentile speed (before)

**Statistically significant at the 5% confidence level, so the null hypothesis that the two speeds are equal can be rejected

Table 18. First-Second After Period Non-work Zone 85th-Percentile Speed Comparisons on the Turnpike

Vehicle Type	After 1 (mph)	Sample Size	After 2 (mph)	Sample Size	Difference* (mph)	t-test
All	73.1	200	74.7	1200	1.6	1.68 (0.3422)
PC	75.0	134	76.5	600	1.5	0.41 (0.3924)
Heavy Trucks	69.5	66	70.5	600	1.0	0.62 (0.6448)

*Difference = 85th percentile speed (after 2) - 85th percentile speed (after 1)

**Statistically significant at the 5% confidence level, so the null hypothesis that the two speeds are equal can be rejected

Table 19 shows that the difference in speed variance for all vehicle types combined and passenger cars only was not statistically significant between the before and first after period at the non-work zone locations on the Pennsylvania Turnpike. For heavy vehicles, the speed variance at the non-work zone locations increased by 22.3 mph^2 after the posted speed limit was increased from 65 to 70 mph, and this result was statistically significant.

Table 20 shows that the difference in speed variance for all vehicle types combined and heavy trucks only was statistically significant between the first and second after periods at the non-work zone locations on the Pennsylvania Turnpike. For heavy vehicles, the speed variance at the non-work zone locations decreased by 19.8 mph^2 in the second after period, relative to the first after period. The passenger car speed variance decreased by 1.7 mph^2 when comparing the second to the first after periods.

Table 19. Before-First After Period Non-work Zone Speed Variance Comparisons on the Turnpike

Vehicle Type	Before (mph^2)	Sample Size	After 1 (mph^2)	Sample Size	Difference* (mph^2)	F-test
All	32.2	200	37.2	200	4.9	1.15(0.3168)
PC	29.1	126	22.0	134	-7.1	1.32 (0.1124)
Heavy Trucks	14.6	74	36.8	66	22.3	2.53 (<0.0001)**

* Difference = speed variance (after 1) - speed variance (before)

**Statistically significant at the 5% confidence level, so the null hypothesis that the two variances are equal can be rejected

Table 20. First-Second After Period Non-work Zone Speed Variance Comparisons on the Turnpike

Vehicle Type	After 1 (mph^2)	Sample Size	After 2 (mph^2)	Sample Size	Difference* (mph^2)	F-test
All	37.2	200	26.6	1,200	-10.6	1.40 (0.0020)**
PC	22.0	134	20.3	600	-1.7	0.92 (0.5236)
Heavy Trucks	36.8	66	17.0	600	-19.8	2.16 (<0.0001)**

*Difference = 85th percentile speed (after 2) - 85th percentile speed (after 1)

**Statistically significant at the 5% confidence level, so the null hypothesis that the two speeds are equal can be rejected

Table 21 shows that the percentage of vehicles exceeding the posted speed limit decreased after the posted speed limit was increased from 65 to 70 mph on the Turnpike. The results were statistically significant for all vehicle types, and when disaggregated by passenger cars and heavy trucks. The percent reduction of heavy trucks exceeding the posted speed limit was nearly 20.5, while the percent reduction of passenger cars exceeding the posted speed limit was 24.8.

Table 21. Before-First After Period Percentage of Vehicles Exceeding the Posted Speed Limit Comparisons on the Turnpike at Non-Work Zone Locations

Vehicle Type	Before (%)	Sample Size	After 1 (%)	Sample Size	Difference* (%)	z-test
All	60.50%	200	39.00%	200	-21.50%	− 4.30 (<0.0001)**
PC	77.78%	126	52.99%	134	-24.79%	− 4.19 (<0.0001)**
Heavy Trucks	31.08%	74	10.61%	66	-20.48%	− 2.95 (0.0030)**

*Difference = percentage exceeding the speed limit (after 1) - percentage exceeding the speed limit (before)

**Statistically significant at the 5% confidence level, so the null hypothesis that the two percentages are equal can be rejected

Table 22 shows that the percentage of vehicles exceeding the posted speed limit increased between the first and second after periods for all vehicle types, passenger cars only, and heavy trucks only. The results were statistically significant for passenger cars only, but not statistically significant for the other vehicle types. The percent increase in vehicles exceeding the posted speed limit was 13.7 percent for passenger cars only, and was 5.9 percent for heavy trucks only, when comparing the second to the first after periods.

Table 22. First-Second After Period Percentage of Vehicles Exceeding the Posted Speed Limit Comparison on the Turnpike at Non-Work Zone Locations

Vehicle Type	After 1 (%)	Sample Size	After 2 (%)	Sample Size	Difference* (%)	z-test
All	39.00%	200	41.58%	1,200	2.58%	− 0.69 (0.4890)
PC	52.99%	134	66.67%	600	13.68%	− 2.99 (0.0028)**
Heavy Trucks	10.61%	66	16.50%	600	5.89%	− 1.24 (0.2150)

*Difference = percentage exceeding the speed limit (after 2) - percentage exceeding the speed limit (after 1)

**Statistically significant at the 5% confidence level, so the null hypothesis that the two percentages are equal can be rejected

Table 23 is a comparison of the before, first after, and second after period speed measures of effectiveness for the non-work zone locations on the Pennsylvania Turnpike Interstate 76 mainline, disaggregated by passenger cars only and heavy trucks only. As shown, the mean passenger car speeds increased from the before to first after period by 0.8 mph, and then increased by 1.9 mph between the first and second after periods. The mean speed of heavy trucks only remained constant between the before and first after periods, and then increased by 3.0 mph between the first and second after periods. The 85th-percentile speed of passenger cars increased by 1.0 mph between the before and first after periods, and decreased by 0.3 mph between the first and second after periods. The 85th-percentile heavy truck speeds increased by 5.5 mph between the before and first after periods, and increased by 1.0 mph between the first and second after periods. These findings suggest that the mean and 85th-percentile speed of passenger cars and heavy trucks did not necessarily increase in direct proportion to the 5 mph posted speed limit increase; however, the 85th-percentile speeds of heavy trucks increased by 6.0 mph when comparing the second after to the before period. This finding may be an artifact of the small sample of heavy trucks collected during the before period.

The speed variance of passenger cars declined when comparing the before, first after, and second after periods in Table 23. For heavy trucks, the speed variance increased between the before and first after period, but then decreased in the second after period to a magnitude similar to the before period. The percentage of passenger cars exceeding the posted speed limit decreased by 24.8 percent from the before to first after period, but then increased by approximately 13.7 percent from the first to second after period. A similar trend was found for the heavy truck traffic. Collectively, this suggests that speed compliance improved when raising the posted speed limit from 65 to 70 mph, but the increasing trend in vehicles exceeding the posted speed limit since the 70 mph speed increase should be monitored to determine if this speed measure changes in the future.

Table 23. Comparison of Before, First After, and Second After Period Speed Measures of Effectiveness on Pennsylvania Turnpike Interstate 76 (Non-work Zone Locations)

Speed Measure	Vehicle Type	Before Period	First After Period	Second After Period
Mean (mph)	PC	69.5	70.3	72.2
	Trucks	63.5	63.5	66.5
85th-percentile (mph)	PC	74.0	75.0	74.7
	Trucks	64.0	69.5	70.5
Variance (mph^2)	PC	29.1	22.0	20.3
	Trucks	14.6	36.8	17.0
Percent exceeding posted speed limit (%)	PC	77.8	53.0	66.7
	Trucks	31.1	10.6	16.5

Pennsylvania Turnpike Interstate 76 (Work Zones)

Tables 24 through 27 compare the mean speed, speed variance, 85th-percentile speed, and percentage of vehicles exceeding the posted speed limit at the 40 and 55 mph work zone locations. Table 24 shows that the mean speed in work zones with 55 mph speed limits was approximately 11 to 13 mph higher than the mean speed in work zones with 40 mph speed limits. The speed variance (Table 25) was not statistically significant when comparing the 55 mph to 40 mph work zone speeds on the Turnpike. The 85th-percencile operating speed is 9 to 12 mph higher in work zones with 55 mph posted speed limits when compared to work zones with 40 mph posted speed limits, and the results for all vehicle types were statistically significant. The percentage of vehicles exceeding the posted speed limit (Table 26) was higher in the 40 mph work zones when compared to the 55 mph work zones, and the results were statistically significant for all vehicle types combined, passenger cars, and heavy trucks. More than 90 percent of passenger cars exceeded the 40 mph posted speed limit in work zones, yet this proportion decreased to 83.7 percent when the work zone speed limit was 55 mph. Nearly 90 percent of heavy trucks exceeded the 40 mph posted speed limit in work zones, but this proportion was 76.4 percent for work zone posted speed limits of 55 mph.

Table 24. Work Zone Mean Speed Comparisons on the Turnpike (40 mph vs. 55 mph)

Vehicle Type	Condition I (40 mph)	Sample Size	Condition II (55 mph)	Sample Size	Difference* (mph)	t-test
All	48.9	400	60.8	500	11.9	29.4 (<0.0001)**
PC	49.4	272	62.1	318	12.7	24.36 (<0.0001)**
Heavy Trucks	47.8	128	58.5	182	10.7	18.18 (<0.0001)**

* Difference = mean speed (Condition II - 55 mph WZ) - mean speed (Condition I - 40 mph)

**Statistically significant at the 5% confidence level, so the null hypothesis that the two speeds are equal can be rejected

Table 25. Work Zone Speed Variance Comparisons on the Turnpike (40 mph vs. 55 mph)

Vehicle Type	Condition I (40 mph)	Sample Size	Condition II (55 mph)	Sample Size	Difference* (mph^2)	F-test**
All	34.3	400	39.0	500	4.7	1.14 (0.1824)
PC	36.2	272	43.7	318	7.4	1.20 (0.114)
Heavy Trucks	28.6	128	22.8	182	-5.8	1.26 (0.1604)

* Difference = variance (Condition II, 55 mph WZ) - variance (Condition I, 40 mph WZ) [variance in mph^2]

**Statistically significant at the 5% confidence level, so the null hypothesis that the two variances are equal can be rejected

Table 26. Work Zone 85th Percentile Speed Comparisons on the Turnpike (40 mph vs. 55 mph)

Vehicle Type	Condition I	Sample Size	Condition II	Sample Size	Difference*	t-test
All	54.8	400	65.8	500	11.1	3.7 (0.0076)**
PC	55.0	272	66.9	318	11.9	3.54 (0.0094)**
Heavy Trucks	52.5	128	61.6	182	9.1	4.33 (0.0034)**

*Difference = 85th percentile speed (after) - 85th percentile speed (before)

**Statistically significant at the 5% confidence level, so the null hypothesis that the two percentiles are the same can be rejected

Table 27. Percentage of Vehicles Exceeding the Posted Speed Limit on Turnpike Work Zones (40 mph vs. 55 mph)

Vehicle Type	Condition I (40 mph)	Sample Size	Condition II (55 mph)	Sample Size	Difference* (%)	z-test
All	91.25%	400	81.00%	500	-10.25%	− 4.35 (<0.0001)**
PC	91.91%	272	83.65%	318	-8.26%	− 3.02 (0.0026)**
Heavy Trucks	89.84%	128	76.37%	182	-13.47%	− 3.04 (0.0022)**

*Difference = percentage exceeding the speed limit (Condition II - 55 mph WZ) - percentage exceeding the speed limit (Condition I - 40 mph)

**Statistically significant at the 5% confidence level, so the null hypothesis that the two percentages are equal can be rejected

Tables 28 through 31 include the mean speed, 85th-percentile speed, speed variance, and percentage of vehicles exceeding the posted speed limit at 55 mph work zone locations that were included in a sample of speeds collected in September 2014 (referred to as “After 1” in Tables 28 through 31), approximately 2 months after the free-flow posted speed limit was raised from 65 to 70 mph. A second period of work zone data collection (referred to as “After 2” in Tables 28 through 31) occurred in May 2015, approximately 9 months after the speed limits were increased from 65 to 70 mph. These data collection periods are compared in Tables 28 through 31. Table 28 shows that the mean speed in work zones with 55 mph speed limits was approximately 2 to 3 mph higher in May 2015 when compared to September 2014 for all vehicles, passenger cars, and heavy trucks. A comparison of 85th-percentile speed between the two after periods is shown in Table 29. The results showed that speeds for all vehicle types increased by 1.7 mph. The 85th-percentile speed of passenger cars increased by 2.3 mph, and heavy vehicle 85th-percentile speeds increased by 3.3 mph, between the first and second after periods. The 85th-percentile speed differences were not statistically significant. The speed variance for the first and second after periods is compared in Table 30. The variance declined by 13 to 18 mph^2 for all vehicles, passenger cars, and heavy trucks, when comparing the second after period to the first after period.

The percentage of vehicles exceeding the posted speed limit was higher in the second after period when compared to the first after period in 55 mph work zones, and the results were statistically significant for all vehicle types combined, passenger cars, and heavy trucks. The percent increase ranged from 20 to 24 percent. Collectively, the 55 mph work zone speed analysis results suggest that drivers are increasing their speed in work zones, but speeds are more uniform. More than 97 percent of passenger car drivers exceeded the 55 mph work zone speed limit, and more than 87 percent of truck drivers exceeded the 55 mph work zone speed limits on the Pennsylvania Turnpike, in sections with 70 mph regulatory speed limits in the free-flow condition.

Table 28. After Period Work Zone Mean Speed Comparisons on the Turnpike

Vehicle Type	After 1 (mph)	Sample Size	After 2 (mph)	Sample Size	Difference* (mph)	t-test
All	60.0	300	62.1	400	2.1	4.63 (<0.0001)**
PC	61.2	203	64.2	200	3.0	4.81 (<0.0001)**
Heavy Trucks	57.4	97	60.1	200	2.7	4.28 (0.0004)**

* Difference = mean speed (55 mph WZ/after 2) - mean speed (55 mph WZ/after 1)

**Statistically significant at the 5% confidence level, so the null hypothesis that the two means are equal can be rejected

Table 29. After Period Work Zone 85th-Percentile Speed Comparisons on the Turnpike

Vehicle Type	After 1 (mph)	Sample Size	After 2 (mph)	Sample Size	Difference* (mph)	t-test
All	65.3	300	67.0	400	1.7	0.33 (0.7616)
PC	66.7	203	69.0	200	2.3	0.40 (0.0.7162)
Heavy	60.7	97	64.0	200	3.3	1.11 (0.3492)

*Difference = 85th percentile speed (after 2) - 85th percentile speed (after 1)

Table 30. After Period Work Zone Speed Variance Comparisons on the Turnpike

Vehicle Type	After 1 (mph^2)	Sample Size	After 2 (mph^2)	Sample Size	Difference* (mph^2)	F-test
All	44.7	300	26.6	400	-18.1	1.68 (<0.0001)**
PC	47.8	203	29.7	200	-18.1	1.62 (0.0020)**
Heavy	29.1	97	15.4	200	-13.7	1.89 (<0.0001)**

* Difference = variance (55 mph WZ/after 2) - variance (55 mph WZ/after 1) [variance in mph^2]

**Statistically significant at the 5% confidence level, so the null hypothesis that the two variances are equal can be rejected

Table 31. After Period Percentage of Vehicles Exceeding the Posted Speed Limit on Turnpike Work Zones

Vehicle Type	After 1 (%)	Sample Size	After 2 (%)	Sample Size	Difference* (%)	z-test
All	72.67%	300	92.50%	400	19.83%	7.07 (<0.0001)**
PC	76.85%	203	97.50%	200	20.65%	6.19 (<0.0001)**
Heavy	63.92%	97	87.50%	200	23.58%	4.75 (<0.0001)**

*Difference = percentage exceeding the speed limit (55 mph WZ/after 2) - percentage exceeding the speed limit (55 mph WZ/after 1)

**Statistically significant at the 5% confidence level, so the null hypothesis that the two percentages are equal can be rejected

Speeds Approaching and Departing 70 mph Speed Limit Zones

The PTC contractor collected vehicle speed data approaching the 70 mph speed zones on the Pennsylvania Turnpike and along Interstate 80 at various locations to determine if drivers were modifying their operating speed in adjacent 65 mph speed limit locations. The speed data were collected in accordance with the procedures described earlier in this report. Plots of the vehicle speeds upstream (approaching the 70 mph speed zone from a 65 mph speed zone) and downstream (exiting the 70 mph speed zone and entering an adjacent 65 mph speed zone) are shown in Figures 14 and 15 for the Turnpike and Interstate 80, respectively.

In Figure 14, "US" and "DS" represent locations upstream and downstream of the work zones. The crosshair symbol and numerical value adjacent to it in the box represent the mean speed, and the red values above and below the mean speed represent the interquartile range of speeds (25th to

75th-percentile values). The lines above and below the boxes (i.e., whiskers) represent values that are 1.5 times higher and lower than the difference in the interquartile range. For example, at 12.4 miles upstream (12.4 US), the 75th-percentile operating speed is 73 mph, and the 25th-percentile operating speed is 66 mph. The difference in the interquartile range is 7 mph. The top and bottom whiskers are ± 1.5 times the interquartile range difference, which is 73 mph plus 10.5 mph, and 66 mph minus 10.5 mph, so the top and bottom whiskers represent 83.5 mph and 55.5 mph, respectively. The asterisk (*) represents operating speeds beyond the whiskers. Figure 14 suggests that driving speeds were relatively consistent both upstream and downstream of the 70 mph speed zone on the Turnpike, when aggregated across all vehicles in the data collection period.

In Figure 15, the crosshair symbol, and "US" and "DS" designations are the same as those defined in Figure 14. Figure 15 indicates that driving speeds were at least 2 mph lower when 9 to 14 miles upstream or downstream of the 70 mph speed zone, suggesting that drivers are adapting their operating speed to the 65 mph posted speed limit signs.

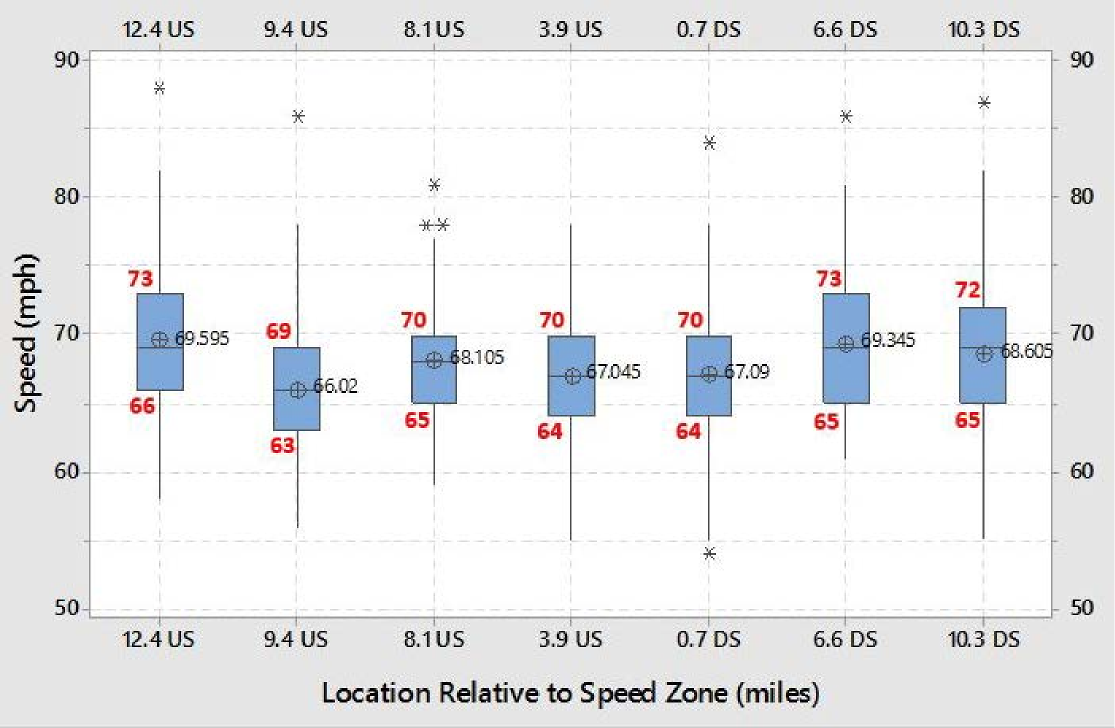


Figure 14. Upstream and Downstream Speeds Adjacent to Turnpike 70 mph Speed Zone
(asterisk [*] represents speed outliers)

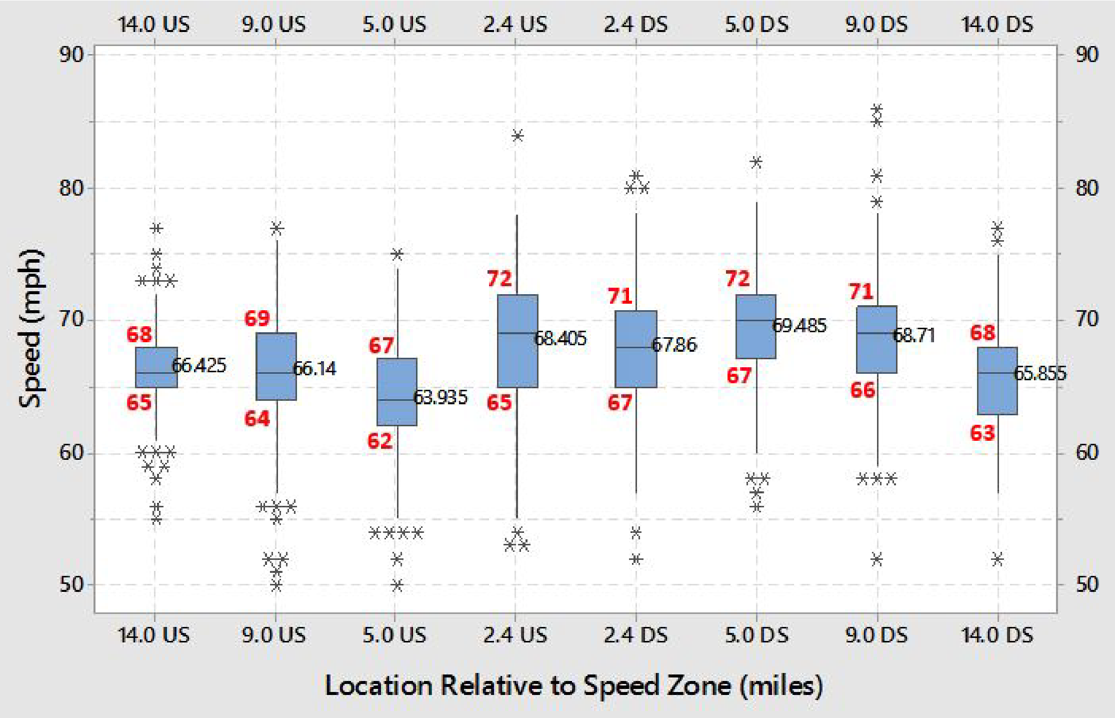


Figure 15. Upstream and Downstream Speeds Adjacent to Interstate 80 70 mph Speed Zone (asterisk [*] represents speed outliers)

Speeds Approaching and Departing Work Zone in 70 mph Speed Limit Zones

Figure 16 shows a speed profile plot for Interstate 80, in the eastbound direction, during non-peak daytime travel periods. The work zone limits range from approximately milepost 170 to milepost 195. The average speed of traffic approaching the work zone is relatively stable from milepost 163 to milepost 172 (nearly 67 mph). Within the active work area, the average operating speed is approximately 58 mph. As drivers approach the end of the work zone limits, the average operating speed increases to about 67 mph. Although this is only one data collection site, the speed profile plot shows that average drivers are decreasing their operating speed by nearly 10 mph when transitioning from a free-flow segment to a work zone segment.

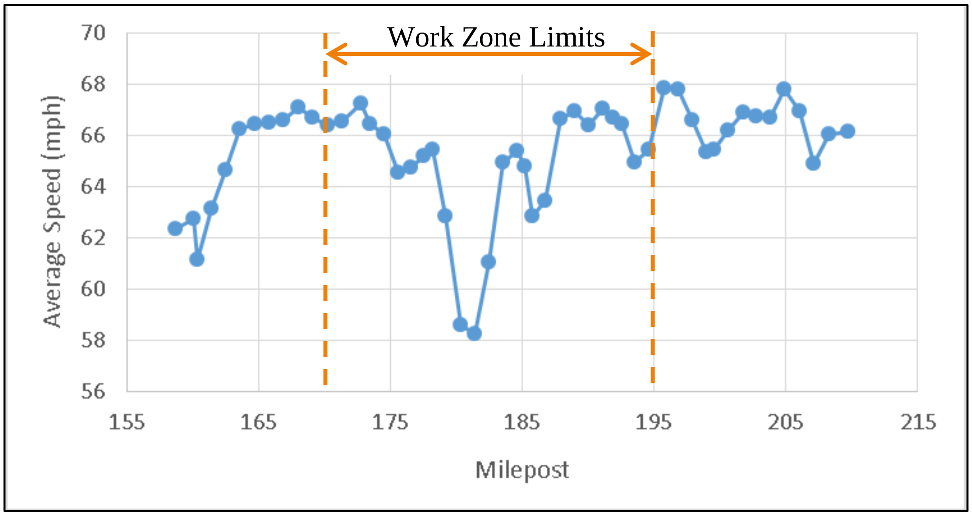


Figure 16. Upstream and Downstream Speeds Adjacent to Interstate 80 Work Zone

SAFETY EVALUATION

This section is organized into two subsections. The first contains the method and results of an observational before-after crash rate analysis. In this evaluation, reported crashes before and after the posted speed limit was increased on the Turnpike and PennDOT Interstates were computed and compared to sections where the speed limit was not changed. The second subsection provides SPFs for segments on the Turnpike, and all rural Interstate highways in Pennsylvania with 65 mph posted speed limits.

Before-After Crash Rate Evaluation

To perform an assessment of the safety effect associated with increasing the posted speed limit on Interstates 76, 80, and 380, a simple observational before-after crash evaluation was undertaken. Roadway inventory, traffic volume, and crash data from both PennDOT and the Pennsylvania Turnpike Commission were requested and compiled for this evaluation. For Turnpike safety assessment, the before period included crashes that were reported between January 1, 2009 and June 30, 2014. Because the posted speed limit was changed on the Turnpike in July 2014, crashes occurring during this month were excluded from the analysis to reduce possible errors in recording the date of the crash, and to avoid drivers learning of the speed limit change via communication channels prior to the regulatory change. The after-period for the Turnpike, therefore, began on August 1, 2014 and includes data through the end of December 2015.

For the PennDOT Interstates, the before-period data included crashes that were reported between January 1, 2009 and July 31, 2014. Because the posted speed limit was raised in August 2014, crashes occurring during this month were eliminated from the evaluation. The after period for the PennDOT Interstates began on September 1, 2014 and includes data through the end of October 2015.

Adjacent section data were compiled for the mainline Turnpike (Interstate 76) and Interstates 80 and 380 to serve as a reference group. The reference group included those sections where the posted speed limit remained 65 mph throughout the study period. Prior to performing the proposed analyses, all roadway inventory, traffic volume, and crash data were merged based on the county, route, and segment number (PennDOT data files), or the Turnpike milepost data.

The state-of-the-art observational before-after evaluation method in traffic safety research is the empirical Bayes (EB) method. To effectively use this method, several years of after period data are necessary at the treatment (or phase one) locations on Interstates 76, 80, and 380. For this report, less than 18 months of after-period data are available to an EB evaluation, and the results will change as more crash data (i.e., at least 3 years of after-period data should be used) are reported. However, Appendix C includes a step-by-step process, with preliminary results, of the EB process based on data from the Turnpike and PennDOT.

The following sections of this safety assessment describe the analyses used in the present study, which is based on reported crashes. Additionally, a series of safety performance functions for the Turnpike and PennDOT were estimated, which can be used in the future to perform the EB evaluation, once additional after-period crash data are available. It is important to note that the results of the safety analyses are preliminary and, as additional crash data are reported over time, the analyses reported herein should be revisited.

A series of crash-based dependent variables were used in the safety assessment. The dependent variables included the following for both the treatment (sites with 70 mph posted speed limits) and reference sites (sites with 65 mph posted speed limits):

- Total crash frequency (all severities and all crash types)
- Total number of fatal and injury (F+I) crashes
- Speeding-related (driving too fast for conditions, speeding, or failure to maintain proper speed)

The primary measure of effectiveness for this evaluation is the estimated change in crash frequency (total, by severity outcome, and speeding-related) before and after the speed limit increase. The reference sites are used to illustrate crash trends during the same time periods that were defined as the before and after periods at the treatment sites (those with 70 mph posted speed limits).

The descriptive statistics computed from the data include annual crash frequency (i.e., total crashes) in the before and after periods at the treatment and reference group locations for each crash type. Additionally, the crash rate in the before and after periods was computed as follows:

$$CR = \frac{C \times 10^8}{AADT \times 365 \times N \times L} \tag{7}$$

where: CR = crash rate (crashes per hundred-million vehicle-miles traveled)
C = number of crashes
$AADT$ = average annual daily traffic (vehicles per day)

N = number of years
L = length of segment (miles)

The percent difference between the crash frequency and crash rate was computed by comparing these metrics in the before and after periods, using odds ratios (after period divided by before period). The results of the safety assessment are shown in Tables 31 and 32 for the PennDOT Interstates and Pennsylvania Turnpike mainline, respectively.

In Table 32, the treated sections include only those locations on Interstates 80 and 380 where the posted speed limit was increased from 65 to 70 mph. The reference group is all remaining rural sections of these same two roadways. As noted previously, the before period included crashes that were reported between January 1, 2009 and July 31, 2014. The after period included crashes that were reported between September 1, 2014 and October 31, 2015. The total crash rate on the treated sections is higher in the after period (38.89 crashes per 100 MVMT) relative to the before period (27.74 crashes per 100 MVMT). The fatal and injury crash rate at the treated locations was also higher in the after period (14.65 crashes per 100 MVMT) relative to the before period (12.02 crashes per 100 MVMT). The speeding-related crashes are higher in the after period (12.46 crashes per 100 MVMT) than in the before period (10.73 crashes per 100 MVMT). The odds ratios for the treated sections reflect the higher after-period crash rates on the treated sections. The reference group crash rate trends are similar to the treatment section crash rates on Interstates 80 and 380. The after-period total crash rates, and fatal and injury crash rates, are higher than the same rates in the before period. In this case, the odds ratios are all greater than 1.0. **These findings are likely the result of random fluctuations commonly found in crash data.**

Table 32. Preliminary Safety Assessment of PennDOT Interstates 80 and 380

Variable	**Treated Location (Speed limits increased from 65 to 70 mph)**	**Reference Group (Speed limits remained < 70 mph during study period)**
Total Crashes Before	1,484	4,556
Total Crashes After	462	1,163
FI Crashes Before	643	1,466
FI Crashes After	174	420
Speed-Related Before	574	1,546
Speed-Related After	148	458
VMT Before	5,349,160,987	11,780,349,163
VMT After	1,188,056,302	2,461,935,406
Total Rate Before (crashes per 100 MVMT)	27.74	38.67
Total Rate After (crashes per 100 MVMT)	38.89	47.23
FI Rate Before (crashes per 100 MVMT)	12.02	12.44
FI Rate After (crashes per 100 MVMT)	14.65	17.06
Speed-Related Rate Before (crashes per 100 MVMT)	10.73	13.12
Speed-Related Rate After (crashes per 100 MVMT)	12.46	18.60
Total Odds (Rate After/ Rate Before)	1.40	1.22
FI Odds (Rate After/ Rate Before)	1.22	1.37
Speed-Related Odds (Rate After/ Rate Before)	1.16	1.42

In Table 33, the treated sections include only the location on Interstate 76 where the posted speed limit was increased from 65 to 70 mph. The reference group is all remaining rural sections along the mainline with 65 mph posted speed limits. As noted previously, the before period included crashes that were reported between January 1, 2009 and June 30, 2014. The after period included crashes that were reported between August 1, 2014 and December 31, 2015. The total crash rate on the treated section is higher in the after period (11.37 crashes per 100 MVMT) relative to the before period (9.60 crashes per 100 MVMT). The fatal and injury crash rate at the treated location was also higher in the after period (3.68 crashes per 100 MVMT) relative to the before period (3.14 crashes per 100 MVMT). The speeding-related crash rate is lower in the after period (2.84 crashes per 100 MVMT) than in the before period (2.97 crashes per 100 MVMT). The odds ratios for the treated sections reflect the higher after-period crash rates on the treated sections. The reference group crash rates show an opposite trend, where the after-period crash rates are lower than the before-period crash rates.

Table 33. Crash Rate Safety Assessment of Interstate 76

Variable	Treated Location (Speed limits increased from 65 to 70 mph)	Reference Group (Speed limits remained < 70 mph during study period)
Total Crashes Before	1,438	5,712
Total Crashes After	380	1,532
FI Crashes Before	471	1,976
FI Crashes After	123	504
Speed-Related Before	445	1,834
Speed-Related After	95	438
VMT Before	14,976,500,600	18,549,608,632
VMT After	3,343,277,995	5,439,472,923
Total Rate Before (crashes per 100 MVMT)	9.60	30.79
Total Rate After (crashes per 100 MVMT)	11.37	28.16
FI Rate Before (crashes per 100 MVMT)	3.14	10.65
FI Rate After (crashes per 100 MVMT)	3.68	9.27
Speed-Related Rate Before (crashes per 100 MVMT)	2.97	9.89
Speed-Related Rate After (crashes per 100 MVMT)	2.84	8.05
Total Odds (Rate After/ Rate Before)	1.18	0.91
FI Odds (Rate After/ Rate Before)	1.17	0.87
Speed-Related Odds (Rate After/ Rate Before)	0.96	0.81

The relative risk of a crash on the 70 mph speed limit zones compared to the 65 mph zones is computed by comparing the odds ratios at the treatment locations relative to the reference group. This computation is shown in Equation (8).

$$RR = \frac{OR_{Treatment}}{OR_{\mathrm{Re}\ ference}} = \frac{\left(\frac{After}{Before}\right)_{treatment}}{\left(\frac{After}{Before}\right)_{\mathrm{Re}\ ference}} \tag{8}$$

where: RR = relative risk
OR = odds ratio
$Treatment$ = treatment location
$Reference$ = reference location
$After$ = after period crash rate
$Before$ = before period crash rate

The relative risk of a crash in the 70 mph posted speed limit zone on Interstates 80 and 380 is 1.15 for total crashes, 0.89 for fatal+injury crashes, and 0.82 for speeding-related crashes. This suggests that, based on the sample of reported crash data, total crashes increased in the 70 mph speed zone relative to the 65 mph reference group on the mainline, but fatal+injury and speeding-related crashes decreased in the 70 mph zones relative to the 65 mph zones. Again, this is likely due to random fluctuations found in reported crash data.

The relative risk of a crash in the 70 mph posted speed limit zone on the Turnpike is 1.30 for total crashes, 1.34 for fatal+injury crashes, and 1.19 for speeding-related crashes. This suggests that, based on the sample of reported crash data, total and fatal+injury, and speeding-related crashes increased in the 70 mph speed zone relative to the 65 mph reference group on the mainline. This is likely the result of random fluctuations in crash data.

Safety Performance Functions

SPFs are statistical models that relate the expected number of crashes (dependent variable) to site-specific characteristics of a roadway segment. Equation (9) is the functional form used in the present study, which is consistent with SPFs in the first edition of the American Association of State Highway and Transportation Officials' *Highway Safety Manual* (AASHTO 2010):

$$N_{spf} = e^{\beta_0} \times L \times AADT^{\beta_1} \times e^{(\beta_2 X_2 + \ldots + \beta_n X_n)} \tag{9}$$

where: N = expected number of crashes per mile per year for a roadway segment
L = segment length (miles)
$AADT$ = average annual daily traffic (vehicles per day)
$\beta_0, \beta_1, \beta_2, \ldots, \beta_n$ = regression parameters to be estimated
$X_2, \ldots, X_n$ = geometric features, traffic control type, or other site-specific features included in the model

This study used negative binomial regression to estimate the expected crash frequency on the Turnpike and rural PennDOT Interstates. The negative binomial distribution has been adopted because it is appropriate for non-negative count data (i.e., crash frequencies) and accounts for the overdispersion commonly found in reported crash data.

The PennDOT Interstate SPFs were estimated for rural Interstate segments that had posted speed limits of 65 mph and did not undergo a speed limit change during the study period (referred to as reference group segments). The Pennsylvania Turnpike SPFs were estimated for reference group segments. Data for the period from 2009 through 2014 (inclusive) were used to estimate the SPFs.

The crash data were appended to roadway inventory data provided by both agencies. The roadway inventory data included traffic volume, segment length, and cross-section dimensions on rural PennDOT Interstates. All PennDOT Interstate data were codified as homogeneous segments, where the roadway features remained relatively consistent throughout the segment. The Turnpike roadway inventory files included information related to horizontal curvature, pavement surface friction, segment length, and average travel speed (annualized using the iPeMS data described earlier). The Turnpike segments were codified based on the limits of horizontal curves. As such, each segment contained either a tangent or a single horizontal curve.

Descriptive statistics of the PennDOT Interstate and Pennsylvania Turnpike data files are shown in Tables 34 and 35, respectively. There were more than 1,700 segment-miles of rural Interstate highway in the Pennsylvania reference group (excludes 70 mph sections). The Pennsylvania Turnpike reference group includes approximately 261 centerline miles.

Table 34. Descriptive Statistics for PennDOT Rural Interstate SPFs

Variable	Mean	Std. Dev.	Minimum	Maximum
Segment Length (miles)	0.495	0.049	0.044	0.745
Average Annual Daily Traffic (veh/day)	12,844	5,437	2,541	39,887
Total Crashes Per Year	0.706	1.069	0	12
Total Fatal+Injury Crashes Per Year	0.269	0.563	0	8
Number of observations = 18,376				

Table 35. Descriptive Statistics for Pennsylvania Turnpike SPFs

Variable	Mean	Std. Dev.	Minimum	Maximum
Segment Length (miles)	0.406	0.425	0.0011	3.153
Average Annual Daily Traffic (veh/day)	32,415	7,949	21,510	65,390
Friction Indicator Variable (1 if smooth tire friction number is 32 or greater; 0 otherwise)	0.845	0.362	0	1
Degree of Curve (degrees)	1.104	1.337	0	6.00
Average Operating Speed (mph)	63.523	1.337	45.22	66.75
Total Crashes per Segment per Year	1.614	2.599	0	27
Wet Weather Crashes per Segment per Year	0.576	1.220	0	17
Number of observations = 3,847				

The PennDOT rural Interstate SPFs for total and fatal+injury crashes are shown in Table 36, and the Turnpike SPFs for total and wet-weather crashes are shown in Table 37. The wet-weather crash frequency model was estimated as part of the friction assessment, so it is described in more detail in the friction section of this report.

Table 36. PennDOT Rural Interstate SPFs

<table>
<tr><th colspan="5">Total Crashes</th></tr>
<tr><th>Variable</th><th>Coefficient</th><th>Standard Error</th><th>z-statistic</th><th>p-value</th></tr>
<tr><td>Constant</td><td>-2.923</td><td>0.250</td><td>-11.67</td><td><0.001</td></tr>
<tr><td>Natural Logarithm of Segment Length (miles)</td><td>0.940</td><td>0.102</td><td>9.21</td><td><0.001</td></tr>
<tr><td>Natural Logarithm of Average Annual Daily Traffic (veh/day)</td><td>0.344</td><td>0.025</td><td>13.58</td><td><0.001</td></tr>
<tr><td>Overdispersion Parameter</td><td>0.736</td><td>0.027</td><td>27.26</td><td><0.001</td></tr>
<tr><td colspan="5">Number of observations = 18,376
Pseudo R^2 = 0.007
Log-likelihood at convergence = -21,098</td></tr>
<tr><th colspan="5">Fatal + Injury Crashes</th></tr>
<tr><th>Constant</th><th>Coefficient</th><th>Standard Error</th><th>z-statistic</th><th>p-value</th></tr>
<tr><td>Constant</td><td>-5.228</td><td>0.361</td><td>-14.50</td><td><0.001</td></tr>
<tr><td>Natural Logarithm of Segment Length (miles)</td><td>0.969</td><td>0.155</td><td>6.27</td><td><0.001</td></tr>
<tr><td>Natural Logarithm of Average Annual Daily Traffic (veh/day)</td><td>0.488</td><td>0.036</td><td>13.50</td><td><0.001</td></tr>
<tr><td>Overdispersion Parameter</td><td>0.490</td><td>0.050</td><td>9.76</td><td><0.001</td></tr>
<tr><td colspan="5">Number of observations = 18,376
Pseudo R^2 = 0.010
Log-likelihood at convergence = -11,910</td></tr>
</table>

For the PennDOT Interstate total and fatal+injury crash frequency models, the segment length was included as an offset variable, since the confidence interval for the coefficient included 1.0. The models for total and fatal + injury crashes can be written as follows:

$$N_{total} = e^{-2.923} \times L^{0.94} \times AADT^{0.344} \tag{10}$$

$$N_{FI} = e^{-5.228} \times L^{0.969} \times AADT^{0.488} \tag{11}$$

where: N_{total} = expected number of total crashes per year for a roadway segment
N_{FI} = expected number of fatal + injury crashes per mile per year for a roadway segment
L = segment length (miles)
$AADT$ = average annual daily traffic (vehicles per day)

Similarly, the Turnpike models for total and wet-weather crashes are shown in Equations (12) and (13). The models show that higher friction numbers are associated with fewer total and wet-weather crashes; expected crashes are associated with higher traffic volumes; and a higher degree of curve (i.e., sharper curves) is associated with higher expected total and wet-weather crash frequencies. The findings were consistent with engineering intuition.

$$N_{total} = e^{-8.885} \times L^{0.871} \times AADT^{1.009} \times e^{-0.522 \times FN} \times e^{0.115 \times DC} \tag{12}$$

$$N_{wet} = e^{-8.885} \times L^{0.862} \times AADT^{0.894} \times e^{-0.414 \times FN} \times e^{0.186 \times DC} \tag{13}$$

where: N_{total} = expected number of total crashes per year for a roadway segment
N_{wet} = expected number of wet weather-related crashes per year for a roadway segment
L = segment length (miles)
FN = friction number indicator (1 if FN is greater than 32; 0 otherwise)
$AADT$ = average annual daily traffic (vehicles per day)
DC = degree of curve

Table 37. Turnpike Mainline SPF.

Total Crashes				
Variable	Coefficient	Standard Error	z-statistic	p-value
Constant	-8.885	0.896	-9.92	<0.001
Natural Logarithm of Segment Length (miles)	0.871	0.027	32.20	<0.001
Natural Logarithm of Average Annual Daily Traffic (veh/day)	1.009	0.085	11.85	<0.001
Friction Indicator Variable (1 if smooth tire friction number is 32 or greater; 0 otherwise)	-0.522	0.048	-10.81	<0.001
Degree of Curve (degrees)	0.115	0.017	6.89	<0.001
Overdispersion Parameter	0.604	0.034	17.76	<0.001
Number of observations = 3,847 Pseudo R^2 = 0.1135 Log-likelihood at convergence = -5,881				
Wet-Weather Crashes				
Variable	Coefficient	Standard Error	z-statistic	p-value
Constant	-8.885	1.330	-6.66	<0.001
Natural Logarithm of Segment Length (miles)	0.862	0.042	20.64	<0.001
Natural Logarithm of Traffic Volume (veh/day)	0.894	0.126	7.08	<0.001
Friction Indicator Variable (1 if smooth tire friction number is 32 or greater; 0 otherwise)	-0.414	0.073	-5.64	<0.001
Degree of Curve (degrees)	0.186	0.025	7.40	<0.001
Overdispersion Parameter	1.161	0.085	13.66	<0.001
Number of observations = 3,847 Pseudo R^2 = 0.0796 Log-likelihood at convergence = -3,604				

PAVEMENT FRICTION ASSESSMENT

The PTC and PennDOT collect pavement friction data. Data from the Pennsylvania Turnpike mainline and PennDOT-maintained Interstates are assessed in this section of the report.

Pennsylvania Turnpike

The Pennsylvania Turnpike Commission collects pavement skid numbers annually and also maintains pavement age data. It appears that all PTC pavement friction data are collected in accordance with ASTM E274, "Test Method for Skid Resistance of Paved Surfaces using a Full-Scale Tire." The test uses a locked-wheel tire dragged over a wet pavement surface at a speed of 40 mph and produces a longitudinal friction number. The PTC collects both ribbed and smooth tire data, in accordance with ASTM E501, "Specification for Ribbed Tire for Pavement Skid Resistance Tests" and ASTM E524, "Specification for Smooth Tire for Pavement Skid Resistance Tests," respectively. The pavement skid resistance tests are not intended to determine the speed at which a vehicle would stop on a dry or wet roadway surface, nor are the tests intended to determine the speed at which a driver would lose control of a vehicle during cornering. However, the tests are intended to provide an opportunity for agencies to evaluate pavement skid resistance changes over time.

Table 38 presents descriptive statistics of the smooth and ribbed tire pavement friction along the mainline of the Pennsylvania Turnpike for each year between 2007 and 2014. These data do not include friction measurements on bridges, tunnels, within work zones, or at toll plazas, and exclude the year 2012. Data from 2012 were excluded because the contractor used different equipment than other years, producing data that were not consistent with prior years. As shown in Table 38, the average friction values on the Turnpike remain relatively constant over time, based on the 7-year period included in the sample. As expected, the smooth tire friction is lower than the ribbed tire friction.

Table 38. Smooth and Ribbed Tire Pavement Friction for the Pennsylvania Turnpike

Year	Smooth Tire Friction (40 mph)				Ribbed Tire Friction (40 mph)			
	Mean	Standard Deviation	Minimum	Maximum	Mean	Standard Deviation	Minimum	Maximum
2007	49.3	7.2	25.4	62.6	53.3	4.3	36.0	64.6
2008	45.1	6.6	25.4	58.4	45.1	6.6	25.4	58.4
2009	47.1	7.2	28.4	63.2	58.4	5.9	25.4	68.7
2010	45.9	5.9	28.4	58.7	53.6	5.1	39.7	62.2
2011	41.7	6.1	27.4	54.6	51.8	5.7	23.2	61.4
2013	46.5	7.3	25.6	61.5	60.4	4.8	45.5	70.7
2014	43.2	7.1	24.4	58.7	54.7	4.1	43.1	64.1

Corsello (1993) developed pavement surface friction guidelines for the Washington State Department of Transportation, which were based on the locked-wheel test described in ASTM E274. In the report, the author noted that a California Department of Transportation study of wet-weather crashes found that crash rates increase substantially when the skid number is less than 25. The author developed a method to determine a minimum friction number for Washington State and concluded that 26 was an acceptable threshold given the variability in testing equipment and temperature, based on smooth tire tests. Lyon and Persaud (2008) reported that the New York State Department of Transportation uses a friction threshold of 32 from the ASTM E274 ribbed tire test to identify pavement in need of surface improvements. A recent study by Larson et al. (2008) recommended that, among other variables, pavement surface intervention should be performed in Ohio when the ASTM E274 ribbed tire friction number is below 32 and the smooth tire friction number is below 23.

Based on the 2014 pavement friction values shown in Table 38, the Turnpike does not contain any sections on the mainline with smooth tire friction values below 24.4, which is greater than the thresholds recommended by Ohio, nor does the Turnpike mainline contain any ribbed tire friction levels below 43.1, which is also greater than the thresholds recommend by New York and Ohio.

Friction Degradation Model

The longitudinal friction data afforded an opportunity to develop a degradation model for the Turnpike mainline pavement surface. In addition to the data summarized above, pavement age, traffic volume, average operating speed, and geometric features data were available for modeling. The data were compiled for the years 2009 through 2014, excluding 2012. The average operating speed data were extracted from the iPeMS tool; the geometric features were developed based on as-built roadway construction plans, and the traffic volume and pavement age data were supplied by the Pennsylvania Turnpike Commission. The analysis unit was based on the limits of each horizontal curve on the Turnpike, so each segment was either a tangent or a curve. A summary of all data compiled for this analysis can be found in Table 39.

Table 39. Summary Statistics for Pavement Friction Degradation Model

Variable	Mean	Standard Deviation	Minimum	Maximum
Pavement Age (in months)	77.3	54.8	0	232
Average Annual Daily Traffic (veh/day)	42,565	24,519	21,510	118,409
Average Operating Speed (mph)	63.8	3.0	45.2	67.7
Radius of Curve (ft)	4772.6	4541.1	954.9	38,197.2
Superelevation (percent)	0.01	0.04	-0.02	0.10
Degree of Curve (degrees)	1.0	1.3	0.0	6.0
Ribbed Tire Friction	55.8	5.1	23.2	70.7
Smooth Tire Friction	44.9	6.7	24.4	63.2

In the present study, duration models were used to estimate pavement friction degradation from the smooth tire test data. This modeling method seeks to determine the probability that a failure (i.e., pavement age falls below a pre-defined threshold) occurs after time *t*. Either a survival function or hazard rate can be used to assess the failure time. The survival function represents the probability that the event lasts at least until time *t* and is expressed as:

$$S(t) = 1 - F(t) = 1 - \int_0^t f(t)dt \qquad (14)$$

where: *S(t)* is the survival function, *f(t)* is the probability density function of random variable *t* (duration time), and *F(t)* is the cumulative failure probability function.

The hazard rate function is the instantaneous probability of failure at time *t* and is expressed as:

$$h(t) = \frac{f(t)}{S(t)} = \frac{-d \ln \mathrm{S(t)}}{dt} \tag{15}$$

There are several forms of the hazard rate function, including Weibull, exponential, logistic and Gamma functions. There are also semi-parametric models, such as the Cox model. The Weibull distribution is widely used in parametric modeling due to its flexibility because, based on the shape parameter γ, it approximates the exponential distribution ($\gamma=1$), normal distribution ($3 \leq \gamma \leq 4$), and Rayleigh distribution ($\gamma=2$). The Weibull hazard and survival functions are in Equations (16) through (18) below:

$$\lambda = e^{-\gamma x \beta} \tag{16}$$

$$h(t, x, \beta) = \lambda \gamma t^{\gamma - 1} \tag{17}$$

$$s(t, x, \beta) = \exp(-\lambda t^{\gamma}) \tag{18}$$

where: λ is the scale parameter and *γ* is the shape parameter, *x* is the vector of explanatory variables, and *β* is the vector of regression coefficients.

In the present study, the Weibull duration model is used to estimate the distribution of pavement friction survival probability. There are four failure values considered in model estimation. These were defined based on the literature. A skid number of 50 is based on research by Giles et al. (1962) and Cairney (1997); a skid number of 40 is based on research by McCullough and Hankins (1966); a skid number of 30 is based on research by Corsello (1993); and a skid number of 26 is based on Corsello (1993).

Pavement friction degradation is caused by several factors, including traffic volume, the weight of vehicles, vehicle speed, geometric features (curves versus tangent segments), and weather. In this model, cumulative traffic loads (AADT * pavement age) is used as the time scale variable in the model. Degree of curvature and operating speed are input as covariates. All four models are shown in Table 40.

In the results shown in Table 40, p is the shape parameter of the Weibull distribution; if p is larger than 1, it means the hazard rate is increasing as the traffic load increases. A coefficient larger than 0 indicates that the coefficient increases the hazard rate. As such, the hazard rate increases as the degree of curve increases. The coefficient for the average operating speed is negative, suggesting that higher speeds increase the hazard. This finding may be the result of little variability in the operating speed data from iPeMs.

Table 40. Weibull Survival Modeling Results

SN < 50				**SN < 40**			
550 observations, 404 failures				701 observations, 185 failures			
Variable	**Coefficient**	**z-stat**	**p-value**	**Variable**	**Coefficient**	**z-stat**	**p-value**
Degree of Curve (degrees)	0.21	5.38	< 0.001	Degree of Curve (degrees)	0.25	4.26	< 0.001
Average Speed (mph)	-0.09	-7.57	< 0.001	Average Speed (mph)	-0.06	-2.79	0.01
Constant	-22.91	-22.29	< 0.001	Constant	-24.45	-15.01	< 0.001
p	1.51			p	1.42		
SN < 30				**SN < 26**			
777 observations, 26 failures				780 observations, 17 failures			
Variable	**Coefficient**	**z-stat**	**p-value**	**Variable**	**Coefficient**	**z-stat**	**p-value**
Degree of Curve (degrees)	0.70	5.22	< 0.001	Degree of Curve (degrees)	0.98	5.55	< 0.001
Average Speed (mph)	-0.15	-3.24	0.001	Average Speed (mph)	-0.11	-1.4	0.16
Constant	-20.87	-5.02	< 0.001	Constant	-26.56	-4.42	< 0.001
p	1.37			p	1.46		

The survival curve for each model is shown in Figure 17. The curves show the probability that the pavement friction remains above the skid number threshold as a function of the traffic load. The vertical axis is the survival probability while the horizontal axis is the cumulative traffic load. The slope of each curve is the degradation rate. A steeper slope indicates more rapid degradation.

In addition to the survival curves, a series of tables were developed to show when the pavement will reach the skid number threshold as a function of the traffic volume. The SN50 threshold is not shown, as more than 70 percent of the skid data were below the failure threshold. Tables 41 and 42 show the survival probabilities between 50 and 90 percent as a function of the traffic volume, for SN40, SN30, and SN26, respectively. All of the data show that, for low-volume roads, the survival probability drops much more slowly than for higher-volume roads. The tables also indicate that higher-volume roads will require more frequent resurfacing to maintain pavement skid resistant properties above the threshold value.

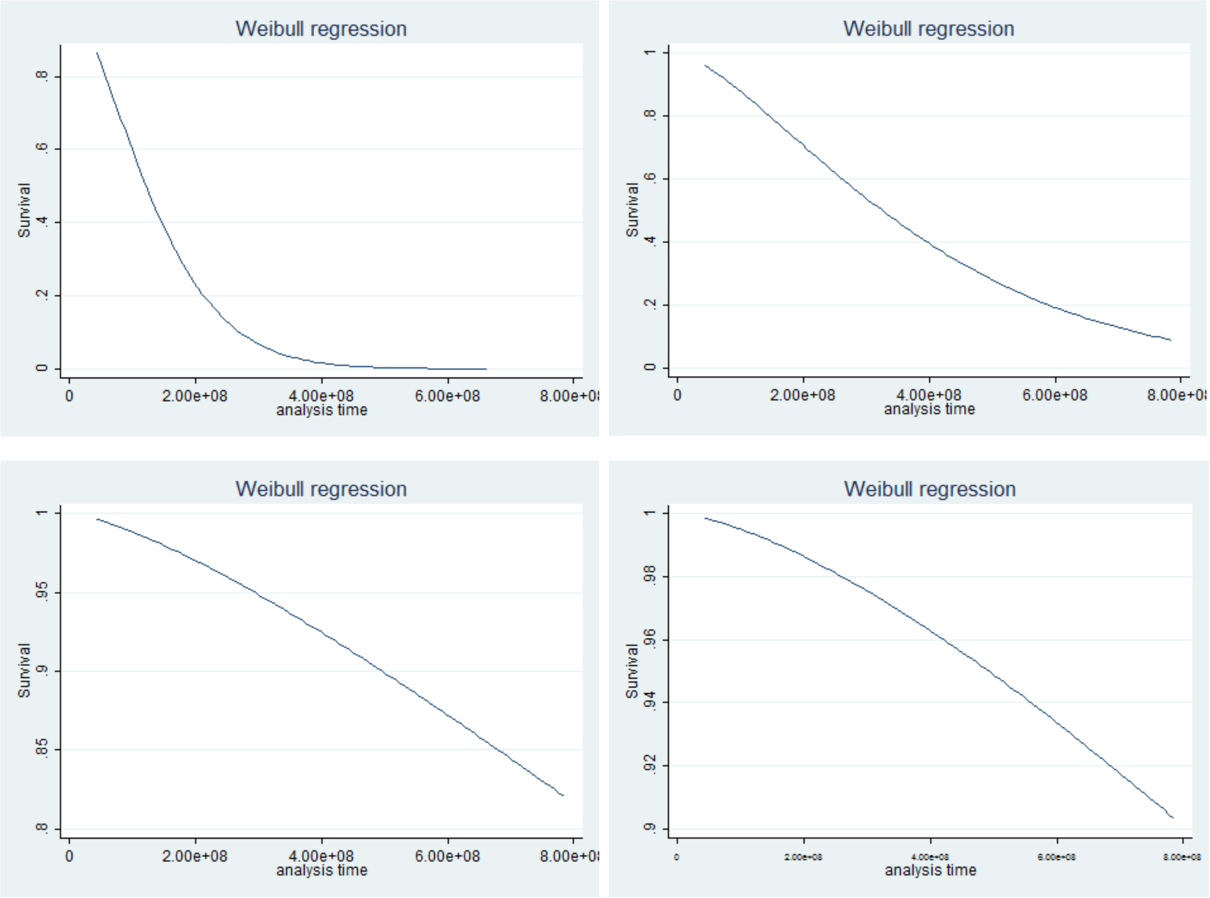


Figure 17. Survival Curves
(The upper left panel is for SN50, the upper right panel is for SN40, the lower left panel is for SN30, and the lower right panel is for SN26.)

Table 41. Survival Probability for Skid Number 40

Traffic Volume Data		Probability of Survival				
		Age (month)				
		P = 0.9	P = 0.8	P = 0.7	P = 0.6	P = 0.5
AADT Range (vph)	Mean (vph)					
< 20,000	15000	192	>240	>240	>240	>240
20,000 to 30, 000	25000	115	195	>240	>240	>240
30,000 to 40, 000	35000	82	139	194	>240	>240
40,000 to 50, 000	45000	64	108	151	195	240
50,000 to 60, 000	55000	52	88	123	159	198
60,000 to 70, 000	65000	44	75	104	135	167
70,000 to 80, 000	75000	38	65	90	117	145
80,000 to 90, 000	85000	33	57	80	103	128
90,000 to 100, 000	95000	30	51	71	92	114
100,000 to 110, 000	105000	27	46	64	83	103
110,000 to 120, 000	115000	25	42	59	76	94
>110,000	125000	23	39	54	70	87

Table 42. Survival Probability for Skid Number 30

Traffic Volume Data		Probability of Survival				
		Age (month)				
		P = 0.9	P = 0.8	P = 0.7	P = 0.6	P = 0.5
AADT Range (mph)	Mean (mph)					
< 20,000	15000	>240	>240	>240	>240	>240
20,000 to 30, 000	25000	>240	>240	>240	>240	>240
30,000 to 40, 000	35000	>240	>240	>240	>240	>240
40,000 to 50, 000	45000	>240	>240	>240	>240	>240
50,000 to 60, 000	55000	>240	>240	>240	>240	>240
60,000 to 70, 000	65000	240	>240	>240	>240	>240
70,000 to 80, 000	75000	220	>240	>240	>240	>240
80,000 to 90, 000	85000	194	>240	>240	>240	>240
90,000 to 100, 000	95000	174	>240	>240	>240	>240
100,000 to 110, 000	105000	157	>240	>240	>240	>240
110,000 to 120, 000	115000	143	240	>240	>240	>240
>110,000	125000	132	228	>240	>240	>240

Table 43. Survival Probability for Skid Number 26

Traffic Volume Data		Probability of Survival				
		Age (month)				
		P = 0.9	P = 0.8	P = 0.7	P = 0.6	P = 0.5
AADT Range (mph)	Mean (mph)					
< 20,000	10000	>240	>240	>240	>240	>240
20,000 to 30, 000	25000	>240	>240	>240	>240	>240
30,000 to 40, 000	35000	>240	>240	>240	>240	>240
40,000 to 50, 000	45000	>240	>240	>240	>240	>240
50,000 to 60, 000	55000	>240	>240	>240	>240	>240
60,000 to 70, 000	65000	>240	>240	>240	>240	>240
70,000 to 80, 000	75000	>240	>240	>240	>240	>240
80,000 to 90, 000	85000	>240	>240	>240	>240	>240
90,000 to 100, 000	95000	>240	>240	>240	>240	>240
100,000 to 110, 000	105000	240	>240	>240	>240	>240
110,000 to 120, 000	115000	223	>240	>240	>240	>240
>110,000	125000	214	>240	>240	>240	>240

Margin of Safety Analysis

In addition to the pavement skid resistance assessment described earlier, this report also compares the mean speed friction demanded by drivers on the Turnpike mainline to the friction supply. These comparisons are made for all horizontal curves, because drivers do not demand friction on tangent segments. The friction demand is derived using the point-mass model shown in Equation (19):

$$e + f = \frac{V^2}{15R} \tag{19}$$

where: e = superelevation (ft/ft)
f = friction demand
V = vehicle operating speed (mph)
R = radius of curve (ft)

A summary of horizontal curve data for the entire Turnpike mainline is shown in Table 44.

Table 44. Pennsylvania Turnpike Mainline Horizontal Curve Data

Horizontal Curve Parameter	Mean	Minimum	Maximum	Standard Deviation
Curve Radius (ft)	4,853	955	38,197	4,689
Degree of Curve (degrees)	1.98	0.15	6.00	1.12
Length of Curve (ft)	1,545	6	10,719	1,165
Superelevation (%)	4.3	0.5	10.0	2.6

The superelevation and curve radius data from Table 41 can be substituted into the point-mass model, along with the operating speed data from iPeMS, to develop friction demand for each driver on each horizontal curve of the Turnpike mainline. This friction demand calculation is shown in Equation (20).

$$f = \frac{V^2}{15R} - e \tag{20}$$

The margin of safety between the friction supply and demand is computed using the following equation:

$$MS = f_s - f_D \tag{21}$$

where: MS = margin of safety
f_D = friction demand based on Equation (19)
f_S = friction supply based on tire-pavement measurements

If the margin is positive (+), then the pavement-tire interface is supplying more friction than the vehicle is demanding based on the point-mass model, so the vehicle will not skid. If the margin of safety is negative (-), the driver is demanding more friction than is available at the tire-pavement interface, and the vehicle may skid. Vehicles (e.g., large trucks) with a high center of gravity may roll before reaching the friction supply threshold on a roadway surface.

Friction supply from the PTC pavement skid resistance testing program cannot be used to directly determine friction supply. The ASTM E274 testing is based on 40 mph tests on wet roadway surfaces. To convert this to a friction supply that is consistent with vehicle travel speeds on the Turnpike, Equations (21) and (22) must be applied (Hall et al. 2009). In Equation (21), a mean pavement texture depth can be derived from the ribbed (FN40R) and smooth (FN40S) tire tests:

$$MTD = 0.039 - (0.0029 \times FN40R) + (0.0035 \times FN40S) \tag{22}$$

where: MTD = mean texture depth (inches)
$FN40R$ = 40 mph ribbed tire friction number from locked-wheel test
$FN40S$ = 40 mph smooth tire friction number from locked-wheel test

The mean texture depth can then be used to compute an International Friction Index (IFI) speed number (S_p) using Equation (23) below:

$$S_p = -11.6 + 113.6 \times MTD \qquad (23)$$

where: S_p = IFI speed number (km/h)
MTD = mean texture depth (mm)

The longitudinal wet pavement friction for highways speeds can then be computed using Equation (24) (Hall et al. 2009):

$$FR(S) = FR(60) \times e^{\frac{(60-S)}{S_p}} \qquad (24)$$

where: $FR(S)$ = friction at selected slip speed, S (km/h)
$FR(60)$ = friction at 60 km/h locked wheel test (this is approximated based on smooth tire)
S_p = IFI speed number (km/h)

Using the 2013 friction data shown in Table 35 as an example, the minimum smooth tire friction (FN40S) is 0.262 and the minimum ribbed tire friction (FN40R) is 0.455. This produces a mean texture depth (MTD) of (Hall et al. 2009):

$$MTD = 0.039 - 0.0029 \times 0.455 + 0.0035 \times 0.262 = 0.0386\, in = 0.980\, mm \qquad (25)$$

Using Equation (23), the IFI speed number (S_p) is:

$$S_p = -11.6 + 113.6 \times 0.980 = 99.73\, km/h \qquad (26)$$

Using Equation (24), the friction at a speed of 115 km/h (~70 mph) is:

$$FR(110) = 0.262 \times e^{\frac{(60-115)}{99.73}} = 0.151 \qquad (27)$$

In the equation above, the FS(60) value is the same as the FN40S value shown in Table 38. The resulting pavement surface friction is 0.151 in the longitudinal direction. Lateral pavement friction, which is used in cornering, is approximately 0.925 times the longitudinal friction (Lamm, 1999). This results in a wet pavement surface lateral friction of 0.140 at 70 mph, on the Turnpike section with the minimum skid resistance values in 2013.

Again, as an illustrative example, when considering the friction demand of drivers on the sharpest horizontal curve along the Turnpike mainline (see Table 44, in the minimum radius cell), which has a posted speed limit of 65 mph, the friction demand would be:

$$f = \frac{(65)^2}{15*955} - 0.063 = 0.232 \tag{28}$$

The friction demand and friction supply values for all horizontal curves on the Turnpike are shown in Appendix A. As shown, all segments on the Turnpike have friction supply values that exceed the mean speed friction demand of drivers, except horizontal curves at mileposts 123.3, 123.5, and 128.0. The mean speed data, however, are based on the iPeMS information, which may not have the granularity necessary to determine driver speeds on these specific curves.

PennDOT Rural Interstates

PennDOT collects pavement friction data on an "as-requested" basis and, therefore, has skid number and pavement age data at several locations along rural Interstates. PennDOT performs all pavement skid resistance testing in accordance with ASTM E274, and reports a skid index for the smooth tire test. A summary of rural Interstate friction data supplied by PennDOT is shown in Table 45, for the period between 1994 and 2014. As shown, the mean value of the 40 mph skid number is comparable to the Pennsylvania Turnpike on asphalt pavements. The mean skid resistance on concrete pavements is lower than on asphalt pavement surfaces. As noted earlier, the Ohio Department of Transportation uses a threshold value of 23 for the smooth tire to identify pavement sections that should be considered for intervention.

Table 45. PennDOT Friction Data

Surface	Sample Size	Mean	Standard Deviation	Minimum	Maximum
Asphalt	756	49.9	9.141	20.0	77.0
Concrete	402	40.1	10.777	14.0	67.0
Total	1,165	46.5	10.806	14.0	77.0

Figure 18 shows the relationship between skid resistance and pavement age for asphalt pavements (left panel) and concrete pavements (right panel) on the PennDOT rural Interstates. The asphalt pavement surfaces appear to exhibit inconsistent skid indexes over time, which is likely the result of PennDOT measuring friction on roadways that have low friction values. The concrete pavement surfaces, however, exhibit a trend consistent with expectations, which is that the skid index generally decreases over time. There appear to be some sections of concrete pavement, however, with skid index numbers below 23. These are locations that PennDOT might consider investigating further.

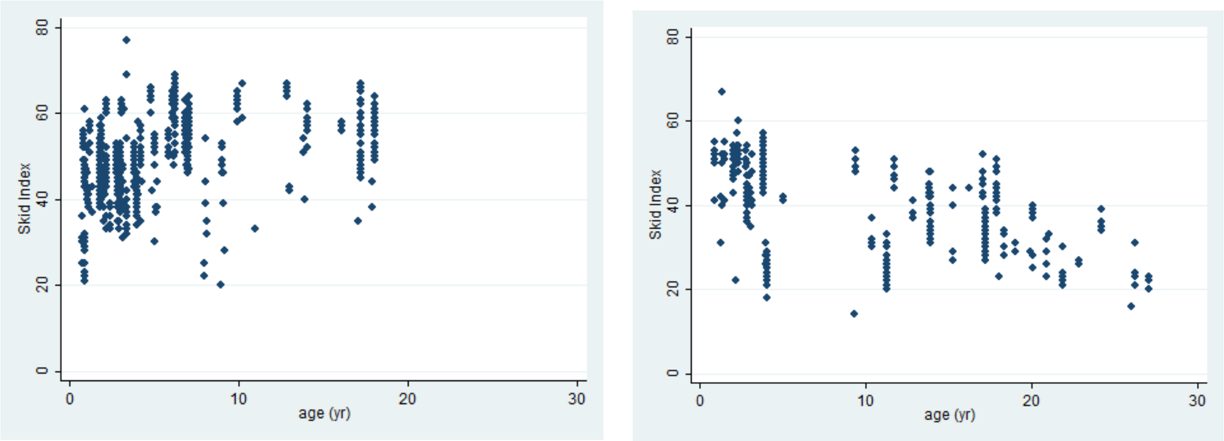


Figure 18. Skid Index versus Pavement Age on PennDOT Rural Interstates
(asphalt is shown in left panel; concrete is shown in right panel)

Wet Weather Pavement-Friction Crash Evaluation using Turnpike Data

The wet weather crash frequency SPF that was estimated in the "Safety Assessment" section of this report for the Pennsylvania Turnpike is shown below in Table 46. This model shows that wet-weather crashes are approximately 38 percent lower when the pavement skid resistance (smooth tire test) exceeds 32 (SN32). All other regression parameters were interpreted earlier.

Table 46. Pennsylvania Turnpike Wet Weather Crash Frequency SPF

Wet-Weather Crashes				
Variable	Coefficient	Standard Error	z-statistic	p-value
Constant	-8.885	1.330	-6.66	<0.001
Natural Logarithm of Segment Length (miles)	0.862	0.042	20.64	<0.001
Natural Logarithm of Traffic Volume (veh/day)	0.894	0.126	7.08	<0.001
Friction Indicator Variable (1 if smooth tire friction number is 32 or greater; 0 otherwise)	-0.414	0.073	-5.64	<0.001
Degree of Curve (degrees)	0.186	0.025	7.40	<0.001
Overdispersion Parameter	1.161	0.085	13.66	<0.001
Number of observations = 3,847 Pseudo R^2 = 0.0796 Log-likelihood at convergence = -3,604				

INFERRED DESIGN SPEED ASSESSMENT

A second method to identify potential locations for an increase in the posted speed limit from 65 to 70 mph is the application of the inferred design speed concept proposed by Donnell et al. (2009). The inferred design speed is defined as "the maximum speed for which all critical design-speed-related criteria are met at a particular location" (Donnell et al., 2009). This speed is computed using a series of geometric criteria, including the point-mass model (see Equation 19), length of vertical curve formula, stopping sight distance model, horizontal sightline offset model, and the cross-section dimensions of the roadway. It is based on distributing side friction and superelevation in accordance with Method 2 in the AASHTO *Policy on Geometric Design of Highways and Streets* (referred to as the Green Book) [2011]. This method uses all of the design side friction (up to f_{max}) before introducing superelevation (e) in the point-mass model, and is preferred on low-speed urban streets.

The PTC maintains horizontal curve data, as well as vertical profile and cross-section information. A limitation of the PTC data is that horizontal sightline offsets are not collected. As such, assumptions were made with regard to driver lane position (assumed to be in the center of the innermost lane), and the median barrier height was determined to equal 52 inches (4.33 ft), which is higher than a typical passenger car driver eye height (3.5 ft). Finally, the median barrier position was assumed to be offset 2 ft from the inside edge of the travel way. With these assumptions, the inferred design speed along the entire mainline section of the Turnpike was computed and plotted graphically along the Turnpike mainline. To complete the analysis, the point-mass model was used to compute an inferred design speed for horizontal curves. Additionally, the stopping sight distance, vertical curvature, and horizontal sightline offset formula was used to compute an inferred design speed. These processes are described below.

Stopping sight distance should be provided along the entire length of every road and street and is computed as follows (AASHTO 2011):

$$SSD = 1.47Vt + \frac{V^2}{30\left(\left(\frac{a}{32.2}\right) \pm G\right)} \tag{29}$$

where:

SSD = required stopping sight distance (ft);
V = designated design speed (mph);
t = driver perception-reaction time (seconds);
a = rate of deceleration (ft per second^2);
G = percent grade divided by 100.

Based on Equation (29), the designated design speed is a fundamental component in computing the minimum required stopping sight distance along a roadway segment. The criteria assume a driver perception-reaction time of 2.5 seconds, deceleration rate of 11.2 ft/second^2, driver eye height of 3.5 ft, and an object height (i.e., tail lights of another vehicle) of 2.0 ft. The assumptions for driver eye height and tail light height reflect the 5th percentile statistics while the assumed perception-reaction time is representative of the 90th percentile driver. On level grades (i.e., less than 3 percent), the grade term (G) is generally assumed to be zero.

A vertical curve is a sight obstruction. Minimum rates of vertical curvature (K) are included in the Green Book (AASHTO, 2011) for different categories of sight distance, designated design speed, and vertical curve type (i.e., crest, sag). The minimum length of vertical curve can be determined by using these rates and Equation (30), shown below.

$$L = KA \qquad (30)$$

where:

L = length of vertical curve (ft)
K = rate of vertical curvature (feet/percent difference in grades)
A = algebraic difference in grades (percent)

Finally, stopping sight distance is related to horizontal sightline offsets along the inside of horizontal curves. Minimum horizontal sightline offsets for a stopping sight distance-horizontal curve radius combination can be computed as follows:

$$HSO = R\left[\left(1 - \cos\frac{28.65S}{R}\right)\right] \qquad (31)$$

where:

HSO = horizontal sightline offset (ft)
R = radius of horizontal curve along the travel path (ft)
S = available stopping sight distance (ft)

Two general methods may be used to compute the inferred design speed. One is based on vertical curve design while the other is based on horizontal curve design. Two inferred design speed checks are required for the horizontal curve method – one based on the radius-superelevation combination and the other based on the horizontal sightline offset.

Consider the sharpest horizontal curve on the Pennsylvania Turnpike, with a radius of 955 ft, and a superelevation of 6.3 percent (see Table 41). Also, assume that the maximum rate of superelevation used in design is 8.0 percent. If the designated design speed were 70 mph, the minimum radius would be 1,810 ft. Assuming lateral acceleration is first used by side friction (method 2 superelevation-side friction distribution), and the rest is distributed to superelevation using the point-mass equation, the following iterative process can be used to determine an inferred design speed, based on Table 3-10b of the 2011 AASHTO Green Book. For a 70 mph design speed, the maximum rate of side friction used in design is 0.10. Beginning with the existing radius of curve, existing superelevation, and a design speed of 70 mph, the first step is to determine if the maximum side friction of 0.10 is exceeded as follows:

$$f = \frac{70^2}{15(955)} - 0.063 = 0.279 \qquad (32)$$

The side friction computed above is 0.279, which exceeds the maximum side friction of 0.10 for a design speed of 70 mph. In the next iteration, a design speed of 60 mph is used, which has a maximum side friction of 0.12. The side friction for this case is 0.188, which exceeds the maximum side friction of 0.12.

$$f = \frac{60^2}{15(955)} - 0.063 = 0.188 \qquad (33)$$

The next iteration is a design speed of 55 mph, which has a maximum side friction of 0.13. In this case, the side friction is 0.148, which is greater than the maximum side friction of 0.13.

$$f = \frac{55^2}{15(955)} - 0.063 = 0.148 \qquad (34)$$

The next iteration is a design speed of 50 mph, which has a maximum side friction of 0.14. In this case, the side friction computed using the point-mass model is 0.112, which is lower than the maximum side friction of 0.14. As such, the inferred design speed for this horizontal curve is between 50 and 55 mph. Further iterations indicate that the maximum 1 mph increment of speed that the existing horizontal curve meets is 53 mph.

$$f = \frac{50^2}{15(955)} - 0.063 = 0.112 \qquad (35)$$

The iterative approach described above can be used to determine the inferred design speed for any curve radius-superelevation combination. For high-speed design (design speed $\geq$ 50 mph), a relationship between the design speed and friction can be developed. This equation is shown below:

$$f = 0.24 - 0.002V \qquad (36)$$

where: f = side friction
V = design speed (mph)

If Equation (36) is substituted for f in the point-mass model, and the radius of curve and superelevation is known, the point-mass model can be solved for V, which is the inferred design speed.

The Turnpike has 54 horizontal curves with radii smaller than the 1,810-ft minimum based on a designated design speed of 70 mph and an 8 percent maximum rate of superelevation. All of these curves are located west of the current 70 mph posted speed limit segment, between mileposts 17.78

and 200.13. It should be noted that horizontal curves in the east- and westbound directions were counted separately for this preliminary assessment. Of these 54 curves, 14 have superelevation rates that exceed 8.0 percent. Most of these 14 curves have superelevation rates of 8.3 percent, while one has a superelevation rate of 9.0 percent, two have superelevation rates of 9.4 percent, and one has a superelevation rate of 9.9 percent. These 14 curves are listed in Table 47. Assuming a maximum side friction factor of 0.10, the minimum radius of curve is computed using the point-mass model and compared to the radius that was constructed for each curve. These results are shown in Table 47. The minimum radius computed based on the existing superelevation and maximum side friction of 0.10 exceeds the as-built radius for all 14 curves.

Table 47. Horizontal Curve on Pennsylvania Turnpike with Superelevation Rates Exceeding 8 Percent.

Milepost	As-built Radius (ft)	Superelevation (ft/ft)	Minimum Radius based on f_{max} = 0.10 and Existing Superelevation
20.45	1443.22	0.083	1785.1
49.85	1432.39	0.083	1785.1
105.72	1432.39	0.094	1683.8
107.54	1637.02	0.094	1683.8
124.22*	1432.39	0.083	1785.1
124.47*	1432.39	0.083	1785.1
126.24*	1432.39	0.083	1785.1
126.44*	1432.39	0.083	1785.1
128.04*	1014.98	0.099	1641.5
128.19*	1442.01	0.083	1785.1
128.56*	1428.82	0.083	1785.1
139.56	1273.24	0.090	1719.3
175.34	1432.39	0.083	1785.1
181.94	1439.39	0.083	1785.1

*Curves that are currently posted with 55 mph speed limits and are not within the limits of the proposed 70 mph speed limit zones.

The inferred design speed process described above was also applied to every horizontal curve and vertical curve along the Turnpike. The horizontal sightline offset controlled all of the calculations on horizontal curves, because the offset from the center of the innermost lane was determined to be 8 ft. At tangent locations, the inferred design speed was limited to 80 mph. Inferred design speed profile plots for the inside (left) and outside (right) lanes of the Turnpike mainline are shown in Appendix B. It should be noted that, in the few cases where the median barrier is offset 4 ft from the inside edge of the traveled way, the inferred design speed in these locations will be higher than the inside lane-speed dimensions shown, but lower than the outside lane-speed dimension.

CONCLUSIONS

Based on the speed, safety, friction, and the inferred design speed evaluations, following is a summary of the findings from the data collection and analysis effort.

1. Speeds on the PennDOT-maintained Interstates, as well as the Pennsylvania Turnpike, increased after raising the posted speed limit from 65 to 70 mph. The mean and 85th-percentile speed increases were smaller than the 5 mph regulatory speed limit increase.
2. The percentage of vehicles exceeding the posted speed limit decreased immediately after the posted speed limit was increased on the PennDOT-maintained Interstates and Pennsylvania Turnpike. However, drivers appeared to be adapting to the higher posted speed limit as the proportion of drivers complying with the 70 mph posted speed limit decreased over time.
3. The preliminary safety assessment completed for this project includes only 12 to 16 months of reported crash data after the speed limits were raised from 65 to 70 mph. Because crash data tend to be random and rare events, it is not possible to draw any preliminary conclusions from the before-after crash data.
4. Several safety performance models were developed in the present study for PennDOT rural Interstates and for the Pennsylvania Turnpike mainline. These models were developed using data from roadways with 65 mph posted speed limits, and can be used in future observational before-after evaluations to determine the safety effects of the 70 mph speed limit. This evaluation should be completed using an empirical Bayes procedure.
5. The friction supply versus demand evaluation (margin of safety) indicates that there are few locations along the Turnpike where drivers may demand more friction than the pavement surface supplies. This finding may be artifact of the limited granularity associated with the iPeMS data; point speed data at these curve locations should be collected to validate the findings, unless the iPeMS data can be further disaggregated by horizontal curve.
6. The friction-safety evaluation found that wet-weather-related crashes are lower when the ribbed tire skid number exceeds 32.
7. The pavement friction degradation model shows that skid resistance declines as traffic loads increase. Several tables were developed to determine the probability that skid resistance levels exceed various threshold values as a function of traffic volume. Based on these probability-traffic volume combinations, estimates for when the pavement friction would fall below a pre-defined threshold value were developed.
8. The PennDOT-maintained rural Interstates appear to have several locations with skid resistance properties that are low and should be further considered if posted speed limits are to be raised from 65 to 70 mph.
9. The inferred design speed analysis indicates that the position of the median barrier creates a horizontal sightline offset limitation on the inside of horizontal curves along various locations of the Turnpike, particularly in the left lane, west of the 70 mph speed limit zones. There are also several horizontal curves that do not comply with the 70 mph design speed-minimum radius criteria found in the AASHTO Green Book at several locations west of the 70 mph speed limit zones.

This project performed operating speed and safety assessments for the Pennsylvania Turnpike and rural Interstates in Pennsylvania to assess the effect of increasing posted speed limits from 65 to 70 mph. In addition to speed and safety, the research effort proposed two additional strategies to identify candidate locations for future implementation of 70 mph posted speed limits on rural Interstate highway segments in Pennsylvania. Guidance on how to use the results of the research in identifying these candidate locations can be found in Appendix D of this report.

As noted previously, it is recommended that the safety performance of the pilot 70 mph segments be re-evaluated once additional crash data are available. Further, it would be useful to monitor vehicle operating speeds on the pilot 70 mph speed limit sections to determine if they remain consistent over time. Increases in operating speed will reduce the margins against skidding along horizontal curve segments.

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APPENDIX A: FRICTION MARGIN OF SAFETY ASSESSMENT

BMP	EMP	Average Speed	Friction Demand	Friction Supply	Margin of Safety
0.168	0.480	65.4	0.014	0.141	0.127
1.076	1.176	65.4	0.001	0.141	0.141
1.381	1.848	65.4	0.005	0.141	0.136
3.308	3.743	65.4	0.005	0.141	0.136
4.904	5.140	65.4	0.028	0.141	0.113
6.849	7.358	65.4	0.017	0.141	0.124
7.988	9.009	65.4	0.010	0.141	0.130
9.632	9.953	63.6	0.056	0.140	0.084
10.119	10.335	63.6	0.063	0.141	0.078
10.566	10.783	63.6	0.050	0.141	0.091
10.976	11.221	63.6	0.071	0.141	0.070
11.667	11.888	63.6	0.079	0.141	0.062
12.172	12.291	63.6	0.071	0.141	0.070
12.888	13.082	64.9	0.023	0.141	0.118
14.047	14.318	66.2	0.056	0.141	0.085
14.558	14.981	66.2	0.056	0.141	0.085
15.179	15.206	66.2	0.090	0.141	0.050
16.053	16.254	66.2	0.037	0.141	0.103
17.617	17.922	66.2	0.106	0.141	0.035
18.354	18.553	66.2	0.071	0.141	0.070
19.690	19.880	66.2	0.091	0.140	0.050
20.074	20.415	66.2	0.037	0.140	0.103
21.669	22.038	66.2	0.037	0.140	0.103
22.536	23.578	66.2	0.027	0.140	0.114
23.904	24.191	66.2	0.056	0.140	0.085
25.196	25.534	66.2	0.037	0.140	0.103
25.990	26.576	66.2	0.012	0.140	0.129
28.221	28.475	66.2	0.012	0.140	0.129
29.537	29.716	62.8	0.075	0.140	0.065
30.376	30.709	62.8	0.043	0.140	0.097
31.586	31.693	62.8	0.068	0.141	0.073
32.382	32.890	62.8	0.054	0.141	0.086
33.407	33.679	62.8	0.088	0.141	0.053
34.004	34.265	62.8	0.075	0.141	0.065
34.626	34.829	62.8	0.075	0.141	0.065
35.225	35.462	62.8	0.088	0.141	0.053
35.976	36.746	62.8	0.007	0.141	0.133

BMP	EMP	Average Speed	Friction Demand	Friction Supply	Margin of Safety
37.054	37.356	62.8	0.075	0.141	0.065
37.810	37.969	62.8	0.058	0.141	0.083
38.347	38.581	62.8	0.058	0.141	0.083
38.886	39.025	62.8	0.010	0.141	0.131
39.419	39.498	59.7	0.018	0.141	0.123
40.221	40.361	56.6	0.062	0.141	0.079
40.523	40.809	56.6	0.043	0.141	0.097
40.964	41.686	56.6	0.023	0.141	0.117
41.998	42.395	56.6	0.047	0.141	0.093
42.634	42.709	56.6	0.049	0.141	0.091
43.134	43.551	56.6	0.035	0.141	0.105
44.334	44.471	56.6	0.043	0.141	0.097
44.706	44.937	56.6	0.043	0.141	0.097
44.937	45.052	56.6	0.023	0.141	0.117
45.147	45.306	56.6	0.035	0.140	0.105
45.605	45.953	56.6	0.049	0.140	0.091
46.187	46.364	56.6	0.043	0.140	0.097
47.062	47.362	56.6	0.033	0.140	0.108
47.456	47.788	56.6	0.001	0.140	0.140
48.347	48.384	62.4	0.026	0.141	0.115
48.588	48.624	62.4	0.056	0.141	0.085
49.020	49.283	62.4	0.096	0.141	0.044
49.419	49.479	62.4	0.073	0.141	0.067
49.709	49.973	62.4	0.098	0.141	0.043
50.098	50.207	62.4	0.073	0.141	0.067
50.676	50.961	62.4	0.073	0.141	0.067
51.201	51.397	62.4	0.066	0.141	0.074
51.633	51.705	62.4	0.066	0.141	0.074
52.421	52.654	62.4	0.066	0.141	0.074
52.980	53.173	62.4	0.066	0.141	0.074
53.607	53.756	62.4	0.009	0.141	0.132
54.650	54.827	62.4	0.031	0.141	0.109
55.210	55.544	62.4	0.047	0.141	0.094
55.963	56.131	62.4	0.059	0.141	0.081
56.653	56.925	63.9	0.050	0.141	0.090
57.329	57.461	65.4	0.078	0.141	0.063
57.696	57.741	65.4	0.078	0.141	0.063
58.018	58.062	65.4	0.087	0.141	0.054
58.498	58.630	65.4	0.087	0.141	0.054

BMP	EMP	Average Speed	Friction Demand	Friction Supply	Margin of Safety
59.263	59.429	65.4	0.068	0.141	0.072
59.659	59.780	65.4	0.068	0.141	0.072
60.701	60.832	65.4	0.078	0.141	0.063
61.207	61.425	65.4	0.011	0.141	0.130
62.106	62.410	65.4	0.102	0.141	0.039
62.634	62.840	65.4	0.068	0.141	0.072
63.439	63.627	65.4	0.078	0.141	0.063
63.998	64.156	65.4	0.054	0.141	0.087
64.311	64.543	65.4	0.054	0.141	0.087
64.836	65.113	65.4	0.054	0.141	0.087
65.113	65.361	65.4	0.051	0.141	0.089
65.410	65.609	65.4	0.052	0.141	0.089
65.679	66.229	65.4	0.001	0.141	0.141
66.229	66.327	65.4	0.001	0.141	0.141
66.832	67.028	65.4	0.087	0.141	0.054
67.198	67.431	65.4	0.098	0.141	0.042
67.655	67.945	63.7	0.020	0.141	0.121
68.776	68.869	63.7	0.011	0.141	0.130
70.335	70.700	63.7	0.062	0.141	0.079
71.664	72.040	63.7	0.062	0.141	0.079
72.363	72.456	63.7	0.062	0.141	0.079
72.981	73.427	63.7	0.029	0.141	0.111
73.558	73.864	63.7	0.043	0.141	0.098
74.244	74.365	63.7	0.029	0.141	0.111
75.154	75.319	63.7	0.029	0.141	0.111
75.595	75.743	64.5	0.065	0.141	0.076
75.942	75.996	64.5	0.077	0.141	0.063
76.143	76.425	64.5	0.077	0.141	0.064
76.748	76.894	64.5	0.065	0.141	0.076
77.445	77.535	64.5	0.007	0.141	0.133
77.792	77.920	64.5	0.007	0.141	0.133
79.119	79.185	64.5	0.024	0.141	0.117
79.517	79.933	64.5	0.020	0.141	0.121
80.193	80.356	64.5	0.065	0.141	0.076
81.098	81.171	64.5	0.008	0.141	0.132
81.575	81.646	64.5	0.025	0.141	0.116
82.419	82.563	64.5	0.025	0.141	0.116
82.784	82.993	64.5	0.114	0.141	0.027
83.172	83.321	64.5	0.032	0.141	0.109

BMP	EMP	Average Speed	Friction Demand	Friction Supply	Margin of Safety
83.948	83.965	64.5	0.065	0.141	0.076
84.084	84.190	64.5	0.114	0.141	0.027
84.327	84.427	64.5	0.065	0.141	0.076
84.759	84.868	64.5	0.025	0.141	0.116
85.255	85.482	64.5	0.134	0.140	0.006
85.578	85.743	64.5	0.114	0.140	0.026
85.925	85.941	64.5	0.074	0.140	0.066
86.115	86.376	64.5	0.134	0.140	0.006
86.574	86.576	64.5	0.044	0.140	0.096
86.717	86.830	64.5	0.114	0.140	0.026
86.950	86.951	64.5	0.074	0.140	0.066
87.095	87.121	64.5	0.074	0.140	0.066
87.553	87.621	64.5	0.014	0.140	0.126
87.861	88.099	64.5	0.069	0.140	0.071
88.552	88.737	64.5	0.067	0.140	0.073
89.225	89.361	64.5	0.089	0.140	0.051
89.532	89.850	64.5	0.049	0.140	0.091
90.812	90.836	62.9	0.042	0.140	0.098
91.135	91.366	62.9	0.080	0.140	0.060
91.520	91.810	62.9	0.016	0.140	0.125
92.227	92.306	62.9	0.001	0.140	0.140
93.610	93.645	62.9	0.021	0.140	0.119
95.023	95.157	62.9	0.040	0.141	0.101
95.638	95.888	62.9	0.104	0.141	0.037
96.351	96.557	62.9	0.058	0.141	0.083
96.666	97.013	62.9	0.104	0.141	0.037
97.205	97.223	62.9	0.040	0.141	0.101
97.570	97.750	62.9	0.027	0.141	0.114
97.987	98.164	62.9	0.027	0.141	0.114
98.328	98.541	62.9	0.040	0.141	0.101
98.692	98.703	62.9	0.027	0.141	0.114
99.092	99.513	62.9	0.058	0.141	0.083
100.627	101.082	62.9	0.058	0.141	0.083
101.299	101.692	62.9	0.045	0.141	0.096
101.692	101.747	62.9	0.027	0.141	0.114
101.747	102.073	62.9	0.058	0.141	0.083
102.073	102.544	62.9	0.070	0.141	0.071
102.649	103.237	62.9	0.048	0.141	0.093
103.501	104.040	62.9	0.029	0.141	0.111

BMP	EMP	Average Speed	Friction Demand	Friction Supply	Margin of Safety
104.291	104.576	62.9	0.032	0.141	0.109
105.053	105.410	62.9	0.044	0.141	0.097
105.566	105.843	62.9	0.090	0.141	0.051
105.850	106.013	62.9	0.044	0.141	0.097
106.436	106.554	62.9	0.044	0.141	0.097
107.042	107.200	62.9	0.044	0.141	0.097
107.418	107.650	62.9	0.067	0.141	0.074
107.738	108.099	62.9	0.044	0.141	0.097
108.708	108.925	62.9	0.036	0.141	0.105
109.375	109.627	62.9	0.020	0.140	0.121
110.038	110.169	64.5	0.041	0.140	0.099
110.897	111.114	64.5	0.041	0.140	0.099
111.693	111.906	64.5	0.041	0.140	0.099
112.085	112.244	64.5	0.041	0.140	0.099
113.366	113.507	64.5	0.019	0.140	0.121
114.526	114.676	64.5	0.001	0.140	0.140
115.393	115.674	64.5	0.003	0.140	0.137
116.834	117.226	64.5	0.003	0.140	0.137
118.138	118.657	64.5	0.003	0.140	0.137
121.653	121.836	64.5	0.056	0.140	0.085
121.836	121.855	64.5	0.070	0.140	0.070
121.855	121.908	64.5	0.065	0.140	0.075
122.025	122.135	64.5	0.022	0.140	0.118
123.335	123.522	64.5	0.227	0.140	-0.087
123.522	123.564	64.5	0.191	0.140	-0.051
124.033	124.366	64.5	0.111	0.140	0.030
124.446	124.503	64.5	0.111	0.140	0.030
124.650	124.927	64.5	0.004	0.140	0.136
125.205	125.807	64.5	0.092	0.141	0.049
126.190	126.291	64.5	0.111	0.141	0.030
126.401	126.472	64.5	0.111	0.141	0.030
127.000	127.034	64.5	0.105	0.141	0.036
127.260	127.534	64.5	0.007	0.141	0.134
127.691	127.806	64.5	0.023	0.141	0.118
128.039	128.044	64.5	0.174	0.141	-0.033
128.193	128.194	64.5	0.109	0.141	0.032
128.367	128.702	64.5	0.111	0.141	0.030
129.638	129.855	64.5	0.074	0.141	0.067
130.234	130.427	64.5	0.065	0.141	0.075

BMP	EMP	Average Speed	Friction Demand	Friction Supply	Margin of Safety
132.571	132.933	64.5	0.065	0.141	0.075
134.299	135.328	64.5	0.033	0.141	0.108
136.349	136.637	64.5	0.038	0.141	0.103
138.216	139.020	64.5	0.074	0.140	0.066
139.020	139.471	64.5	0.128	0.140	0.012
140.569	140.764	64.5	0.053	0.140	0.087
143.036	143.470	64.5	0.060	0.140	0.081
144.158	144.504	64.5	0.038	0.140	0.102
144.976	145.105	64.5	0.060	0.140	0.081
145.421	145.814	61.9	0.065	0.140	0.075
145.903	146.139	61.9	0.059	0.140	0.081
146.200	146.300	61.9	0.074	0.140	0.067
146.393	146.506	61.9	0.059	0.140	0.081
146.833	146.958	61.9	0.035	0.140	0.106
147.058	147.314	61.9	0.059	0.140	0.081
147.551	147.886	61.9	0.035	0.140	0.106
148.610	148.791	61.9	0.035	0.140	0.106
148.909	149.439	61.9	0.061	0.140	0.079
150.319	150.597	61.9	0.071	0.140	0.069
151.175	151.539	61.9	0.065	0.140	0.075
152.045	152.496	61.9	0.064	0.140	0.076
152.607	153.186	61.9	0.071	0.140	0.069
153.370	153.516	61.9	0.064	0.140	0.076
153.613	153.886	61.9	0.064	0.140	0.076
154.347	154.707	61.9	0.052	0.140	0.088
155.137	155.291	61.9	0.046	0.140	0.094
155.522	155.774	61.9	0.058	0.140	0.082
156.102	156.284	61.9	0.064	0.140	0.076
156.675	156.827	61.9	0.071	0.140	0.069
156.897	157.070	61.9	0.071	0.140	0.069
157.229	157.396	61.9	0.064	0.140	0.076
157.858	158.044	61.9	0.083	0.140	0.057
158.288	158.480	61.9	0.071	0.140	0.069
158.829	159.027	61.9	0.066	0.140	0.074
159.286	159.509	61.9	0.059	0.140	0.081
159.674	159.935	61.9	0.059	0.140	0.081
160.224	160.489	61.9	0.047	0.140	0.094
160.968	162.023	63.3	0.021	0.140	0.119
162.184	162.860	64.8	0.066	0.140	0.074

BMP	EMP	Average Speed	Friction Demand	Friction Supply	Margin of Safety
163.313	163.576	64.8	0.023	0.140	0.118
164.098	164.365	64.8	0.035	0.140	0.105
164.694	165.231	64.8	0.052	0.140	0.088
165.385	165.634	64.8	0.052	0.140	0.088
166.479	167.254	64.8	0.015	0.141	0.125
167.481	167.678	64.8	0.052	0.141	0.088
167.913	168.117	64.8	0.075	0.141	0.066
168.834	169.115	64.8	0.108	0.141	0.032
169.517	169.721	64.8	0.047	0.141	0.094
170.058	170.436	64.8	0.059	0.141	0.081
170.806	171.270	64.8	0.052	0.141	0.088
171.534	171.949	64.8	0.084	0.141	0.057
172.654	172.817	64.8	0.052	0.141	0.088
173.114	173.298	64.8	0.035	0.141	0.106
173.774	173.930	64.8	0.052	0.141	0.088
173.930	174.241	64.8	0.067	0.140	0.073
174.321	174.511	64.8	0.084	0.140	0.056
174.721	174.858	64.8	0.086	0.140	0.054
175.002	175.121	64.8	0.084	0.140	0.056
175.201	175.458	64.8	0.112	0.140	0.028
175.602	175.946	64.8	0.084	0.140	0.056
176.819	177.531	64.8	0.052	0.140	0.087
177.702	177.886	64.8	0.052	0.140	0.087
178.385	178.599	64.8	0.052	0.140	0.087
179.055	179.311	64.8	0.066	0.140	0.074
179.972	180.216	59.1	0.059	0.141	0.081
180.316	180.443	59.1	0.069	0.141	0.072
180.520	180.640	59.1	0.055	0.141	0.086
180.734	180.818	59.1	0.059	0.141	0.081
181.274	181.646	59.1	0.069	0.141	0.072
181.699	182.097	59.1	0.079	0.141	0.062
182.589	182.779	59.1	0.054	0.141	0.086
183.593	183.808	59.1	0.045	0.141	0.096
183.977	184.694	59.1	0.045	0.141	0.096
185.634	185.983	59.1	0.059	0.141	0.081
185.983	186.049	59.1	0.059	0.141	0.081
187.456	187.721	58.0	0.081	0.140	0.059
187.721	187.746	58.0	0.077	0.140	0.063
187.934	188.014	58.0	0.015	0.140	0.125

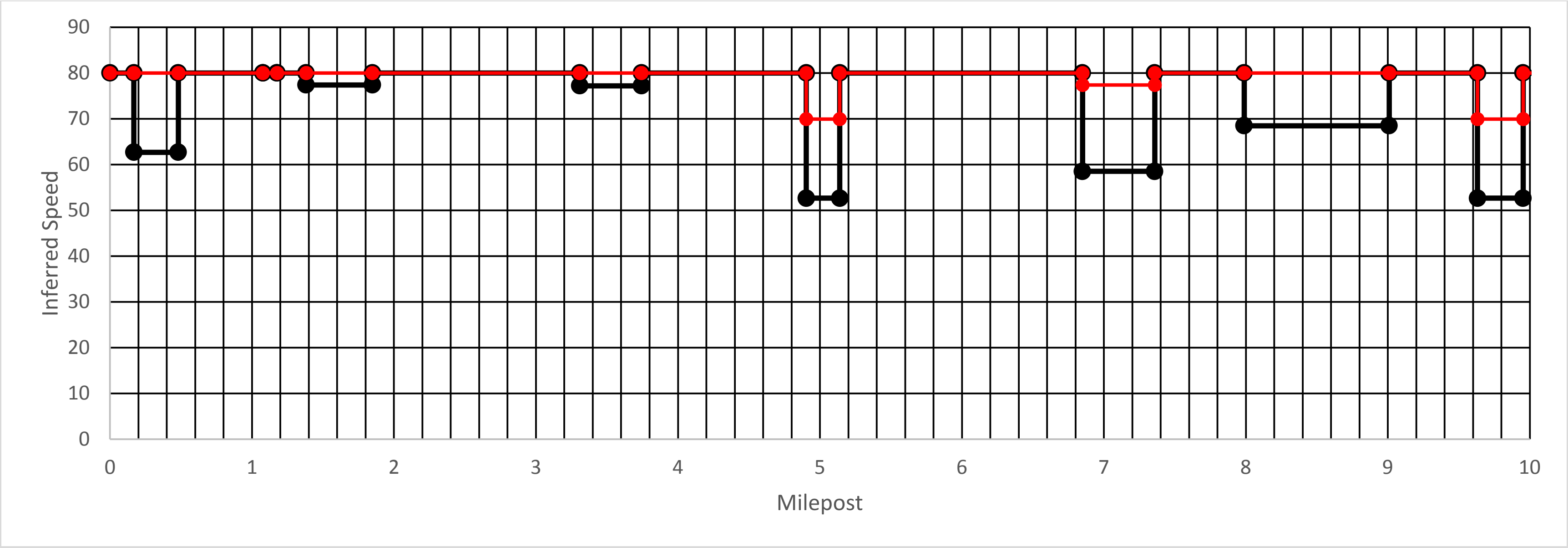
BMP	EMP	Average Speed	Friction Demand	Friction Supply	Margin of Safety
191.168	191.413	59.7	0.001	0.140	0.140
192.611	193.140	59.7	0.002	0.141	0.139
195.826	195.893	59.7	0.011	0.141	0.130
196.814	197.005	59.7	0.052	0.141	0.089
199.451	199.698	59.7	0.127	0.141	0.013
199.698	199.711	59.7	0.127	0.141	0.013
200.002	200.245	59.7	0.065	0.141	0.075
200.324	200.482	59.7	0.052	0.141	0.089
200.768	200.919	59.7	0.031	0.141	0.109
201.858	202.303	46.0	0.014	0.141	0.126
214.268	215.014	46.0	0.001	0.141	0.141
220.665	222.695	46.0	0.001	0.140	0.140
225.828	226.607	56.6	0.001	0.140	0.140
227.088	228.313	67.1	0.001	0.140	0.140
230.915	231.012	67.1	0.012	0.140	0.128
233.637	233.947	67.1	0.058	0.140	0.083
235.339	235.668	67.1	0.012	0.140	0.128
236.198	237.256	65.7	0.011	0.141	0.129
237.709	237.994	65.7	0.079	0.141	0.062
238.794	239.472	65.7	0.049	0.141	0.092
240.184	240.444	65.7	0.011	0.141	0.129
241.588	242.274	63.8	0.056	0.141	0.084
242.596	242.799	61.9	0.031	0.141	0.110
243.319	243.486	61.9	0.031	0.141	0.110
243.996	245.228	61.9	0.012	0.141	0.129
245.400	245.695	61.9	0.030	0.141	0.110
246.773	246.971	66.7	0.075	0.141	0.065
247.469	247.716	66.7	0.021	0.141	0.120
248.913	249.301	66.7	0.012	0.141	0.129
250.269	250.341	66.7	0.012	0.141	0.129
251.380	251.876	66.7	0.025	0.141	0.116
252.113	252.490	66.7	0.012	0.141	0.129
253.027	253.229	66.7	0.072	0.141	0.069
253.744	253.969	66.7	0.051	0.141	0.090
254.099	254.340	66.7	0.093	0.141	0.048
254.484	255.416	66.7	0.012	0.141	0.129
256.150	256.903	66.7	0.012	0.141	0.129
257.057	257.550	66.7	0.012	0.141	0.129
258.987	259.401	66.7	0.012	0.141	0.129

BMP	EMP	Average Speed	Friction Demand	Friction Supply	Margin of Safety
259.827	260.040	66.7	0.038	0.141	0.103
260.170	260.908	66.7	0.038	0.141	0.103
261.998	262.411	66.7	0.057	0.141	0.084
263.439	263.691	66.7	0.057	0.140	0.084
263.956	264.392	66.7	0.038	0.140	0.103
264.950	265.140	66.7	0.038	0.140	0.103
265.480	265.707	66.7	0.038	0.140	0.103
266.063	266.197	66.7	0.072	0.140	0.068
266.880	267.188	66.1	0.090	0.140	0.050
267.356	267.748	66.1	0.090	0.140	0.050
268.954	269.214	66.1	0.012	0.141	0.129
270.720	271.021	66.1	0.012	0.141	0.129
271.536	271.785	66.1	0.012	0.141	0.129
272.239	272.462	66.1	0.012	0.141	0.129
273.201	273.602	66.1	0.012	0.141	0.129
274.414	274.750	66.1	0.012	0.141	0.129
276.029	276.254	66.1	0.012	0.141	0.129
276.708	276.856	66.1	0.012	0.141	0.129
277.963	278.606	66.1	0.001	0.141	0.141
280.496	280.690	66.1	0.012	0.141	0.129
281.518	281.799	66.1	0.012	0.141	0.129
282.863	283.200	66.1	0.090	0.140	0.049
283.347	283.624	66.1	0.090	0.140	0.049
284.172	284.467	66.1	0.012	0.140	0.128
285.128	285.392	66.1	0.037	0.140	0.103
285.768	286.528	66.1	0.001	0.140	0.140
288.004	288.470	67.7	0.013	0.140	0.127
289.030	289.400	67.7	0.075	0.140	0.064
290.167	290.802	67.7	0.013	0.140	0.127
291.137	291.472	67.7	0.059	0.140	0.081
291.639	291.819	67.7	0.059	0.140	0.081
292.540	293.095	67.7	0.086	0.140	0.054
293.284	293.707	67.7	0.075	0.140	0.065
293.886	294.580	67.7	0.039	0.140	0.101
295.397	295.772	67.7	0.075	0.140	0.065
296.246	296.820	67.7	0.026	0.140	0.114
297.248	297.543	67.7	0.083	0.140	0.057
298.314	298.575	67.2	0.058	0.140	0.082
299.880	300.263	66.8	0.072	0.140	0.068

BMP	EMP	Average Speed	Friction Demand	Friction Supply	Margin of Safety
300.697	300.900	66.8	0.093	0.140	0.047
301.245	301.465	66.8	0.057	0.140	0.083
301.860	302.068	66.8	0.057	0.140	0.083
302.632	303.724	66.8	0.012	0.140	0.128
304.127	304.570	66.8	0.038	0.140	0.102
305.622	305.781	66.8	0.093	0.140	0.047
306.540	307.238	66.8	0.055	0.140	0.085
307.677	307.821	66.8	0.093	0.140	0.047
308.536	308.873	66.8	0.063	0.140	0.077
309.297	309.599	66.8	0.057	0.140	0.083
310.186	310.617	66.8	0.047	0.140	0.093
312.573	313.267	66.4	0.020	0.140	0.119
313.523	313.820	66.4	0.081	0.140	0.059
314.202	314.499	66.4	0.091	0.140	0.049
314.711	315.090	66.4	0.081	0.140	0.059
315.208	315.717	66.4	0.012	0.140	0.128
316.722	316.972	66.4	0.081	0.140	0.059
317.196	317.440	66.4	0.081	0.140	0.059
317.675	318.051	66.4	0.056	0.140	0.084
321.161	321.559	66.1	0.037	0.140	0.103
321.689	322.007	66.1	0.037	0.140	0.103
323.791	324.149	66.1	0.020	0.140	0.120
326.508	327.359	65.6	0.010	0.140	0.131
328.812	329.021	65.6	0.030	0.140	0.111
329.437	329.645	65.6	0.070	0.140	0.070
330.112	330.317	65.6	0.035	0.140	0.105
330.776	330.917	65.6	0.001	0.140	0.140
331.510	331.646	65.6	0.024	0.141	0.117
331.923	332.169	65.6	0.006	0.141	0.135
332.993	333.070	64.6	0.004	0.141	0.136
334.426	334.797	64.6	0.035	0.140	0.106
334.998	335.242	64.6	0.052	0.140	0.088
336.116	336.326	64.6	0.010	0.140	0.130
337.250	337.424	64.6	0.010	0.140	0.130
339.148	339.578	65.4	0.011	0.140	0.129
340.255	340.798	65.4	0.011	0.140	0.129
341.185	341.458	65.4	0.011	0.140	0.129
343.691	343.905	66.0	0.037	0.140	0.104
345.119	345.413	66.0	0.015	0.140	0.126

BMP	EMP	Average Speed	Friction Demand	Friction Supply	Margin of Safety
346.425	346.910	66.0	0.055	0.140	0.085
347.746	348.059	66.0	0.011	0.140	0.128
349.168	349.541	66.0	0.011	0.140	0.128
350.327	350.502	66.0	0.070	0.140	0.070
352.353	352.485	61.3	0.056	0.141	0.084
355.544	355.777	61.3	0.030	0.140	0.111
357.599	357.775	61.3	0.030	0.140	0.111

APPENDIX B: INFERRED DESIGN SPEED PLOTS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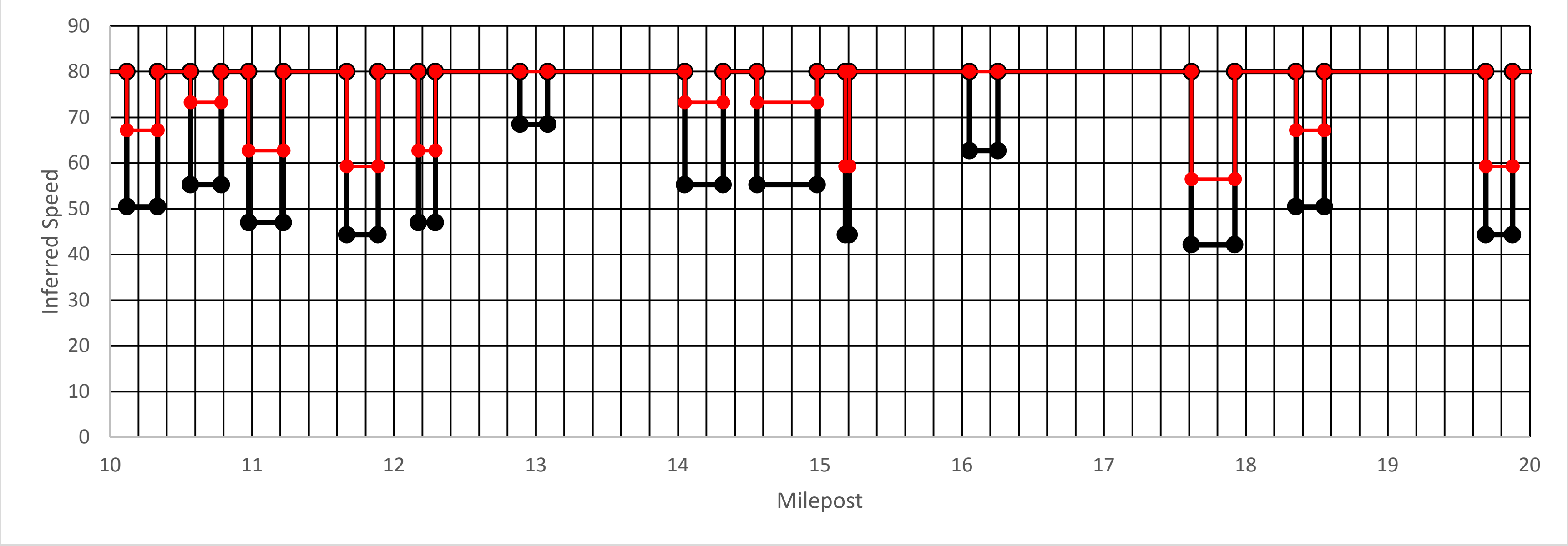
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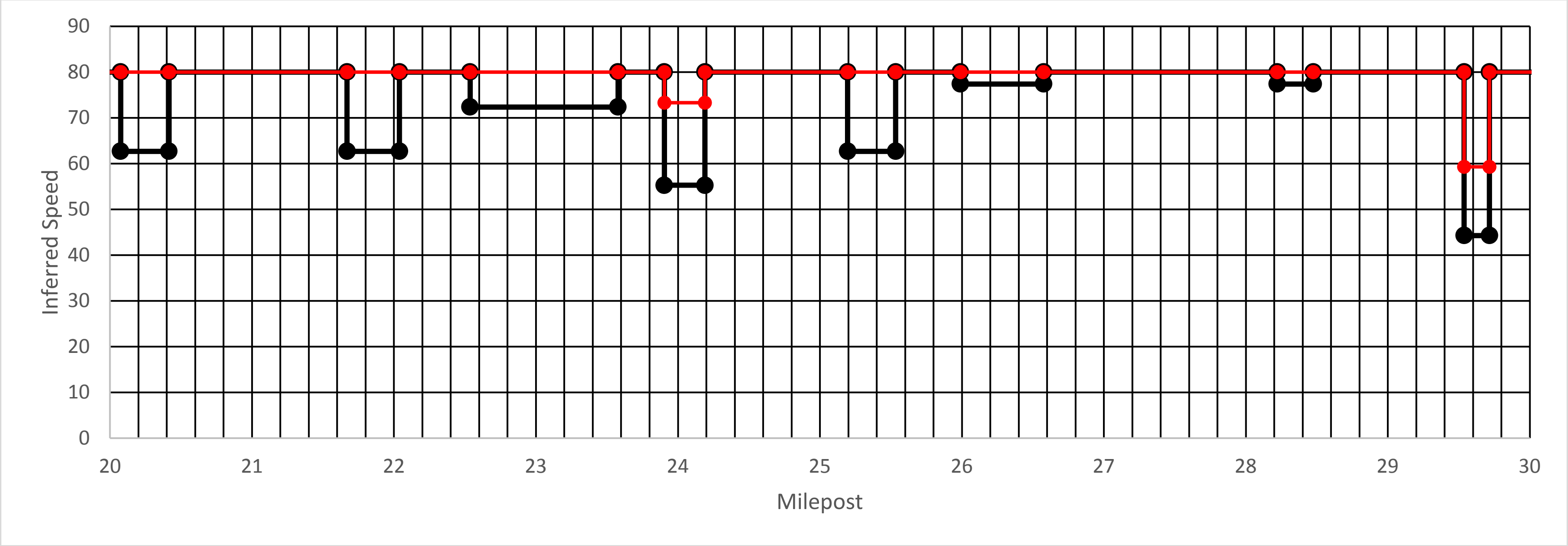
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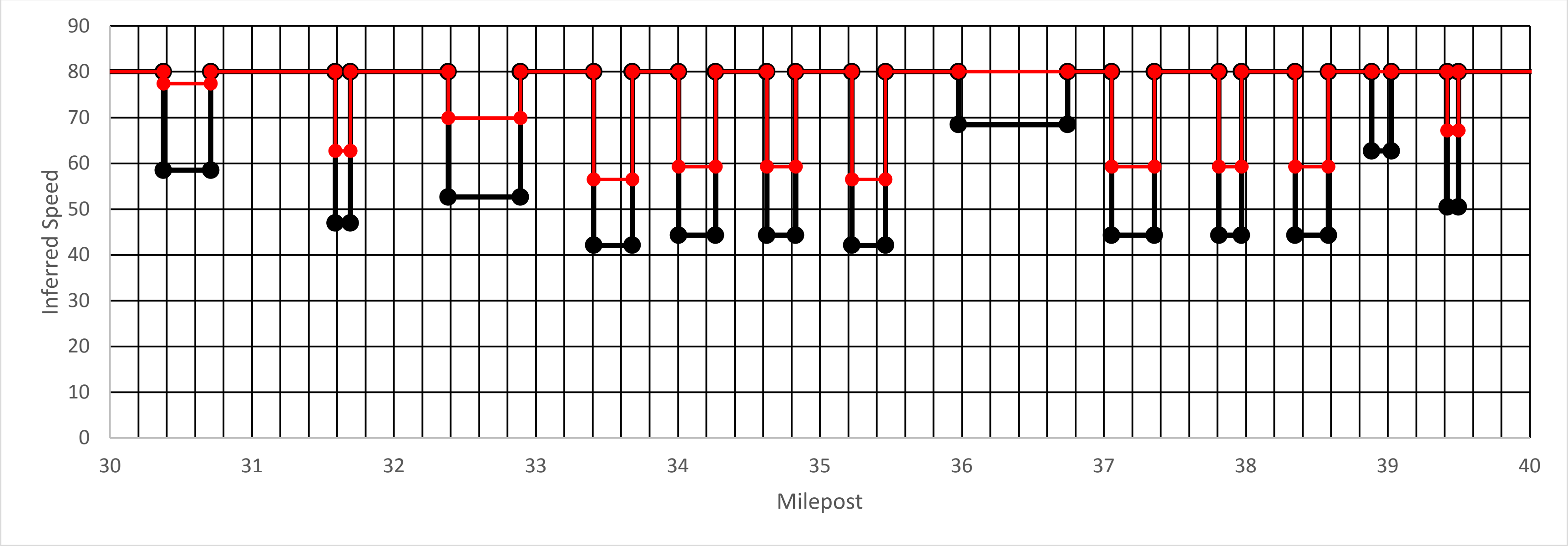
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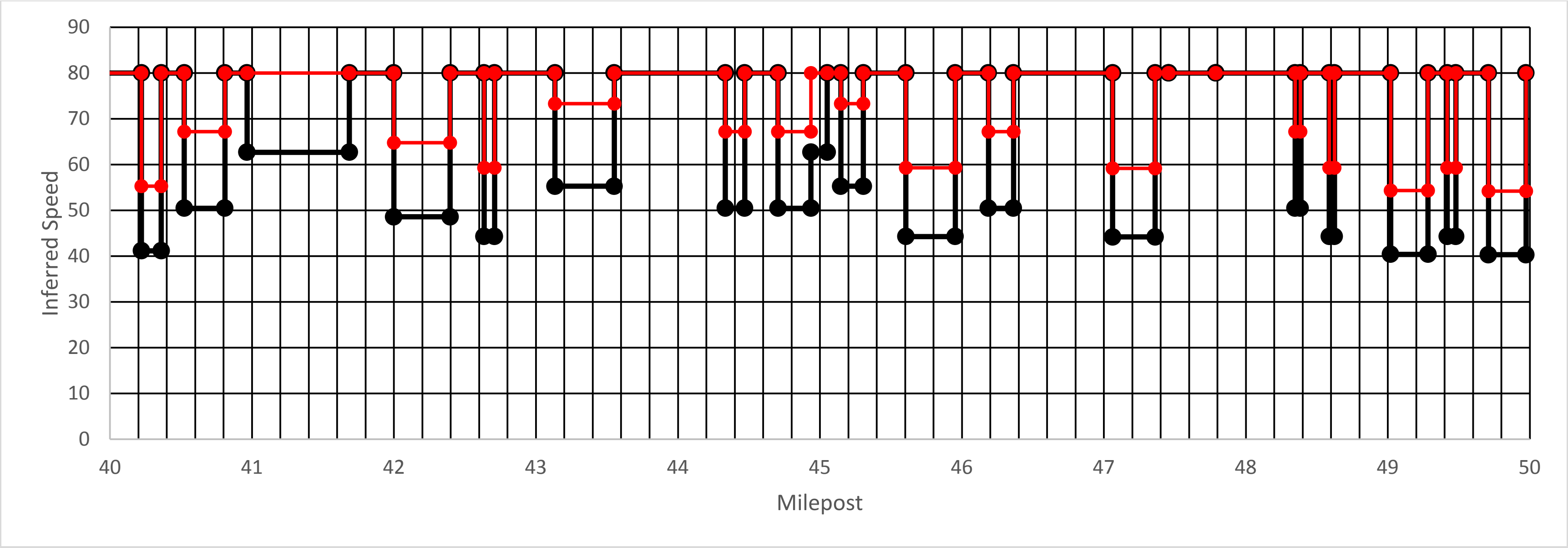

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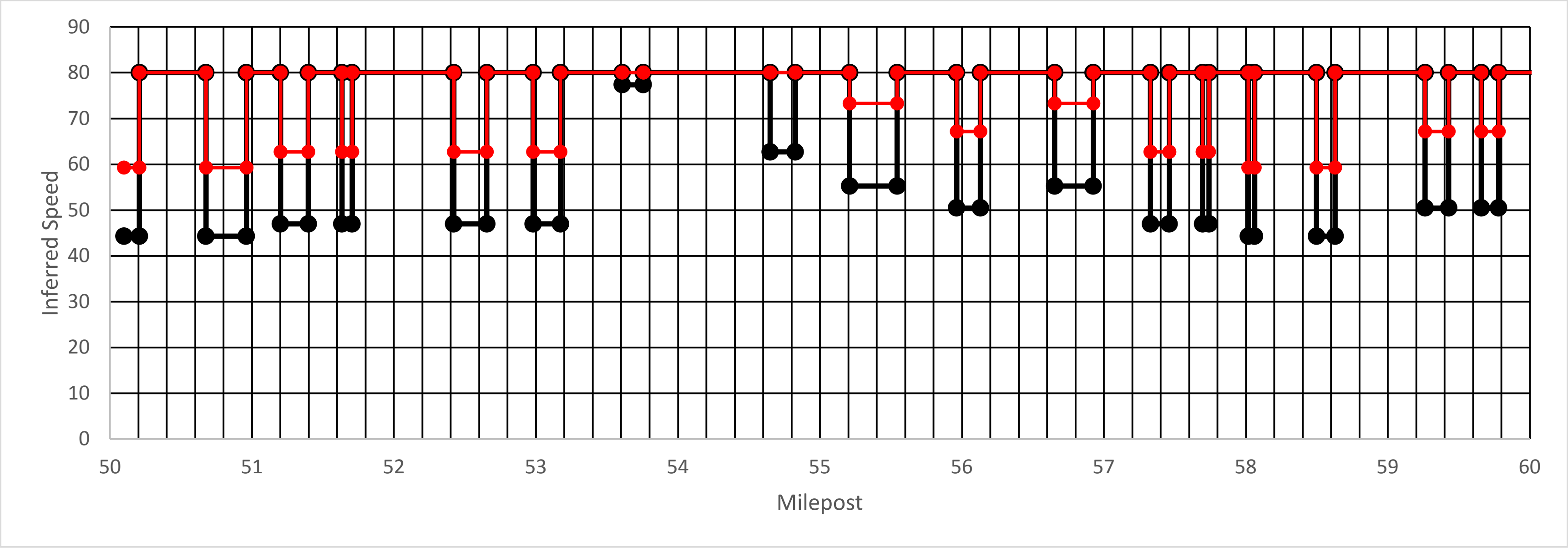

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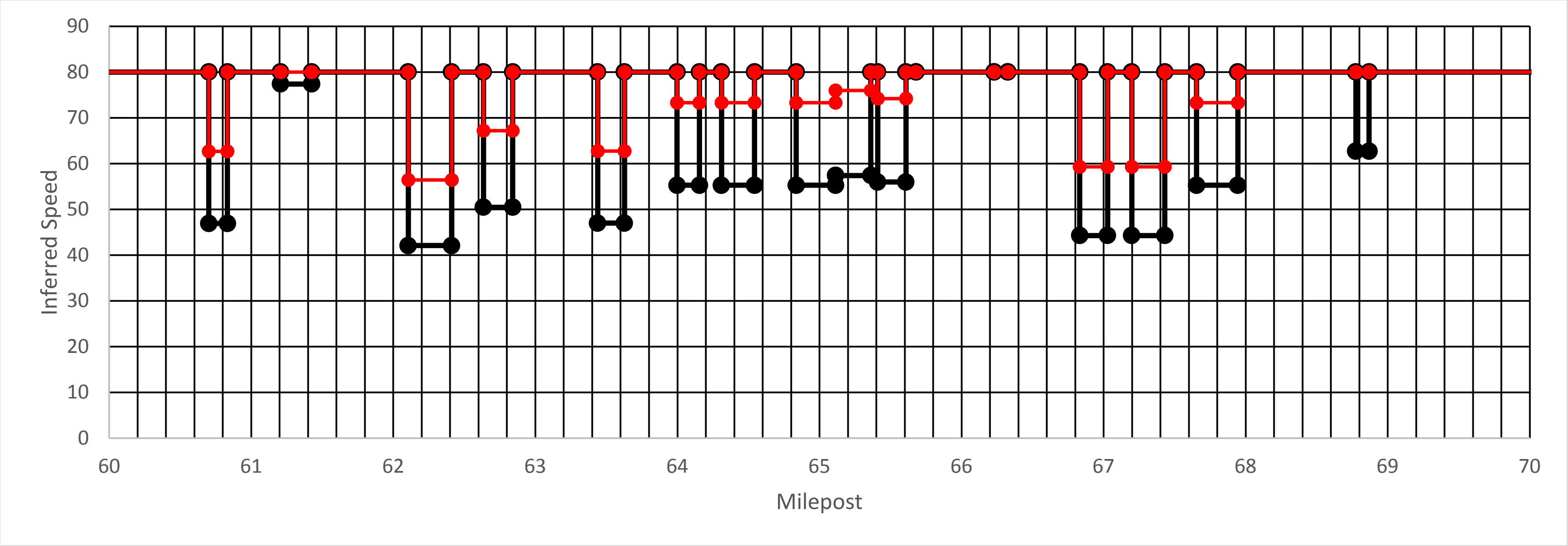

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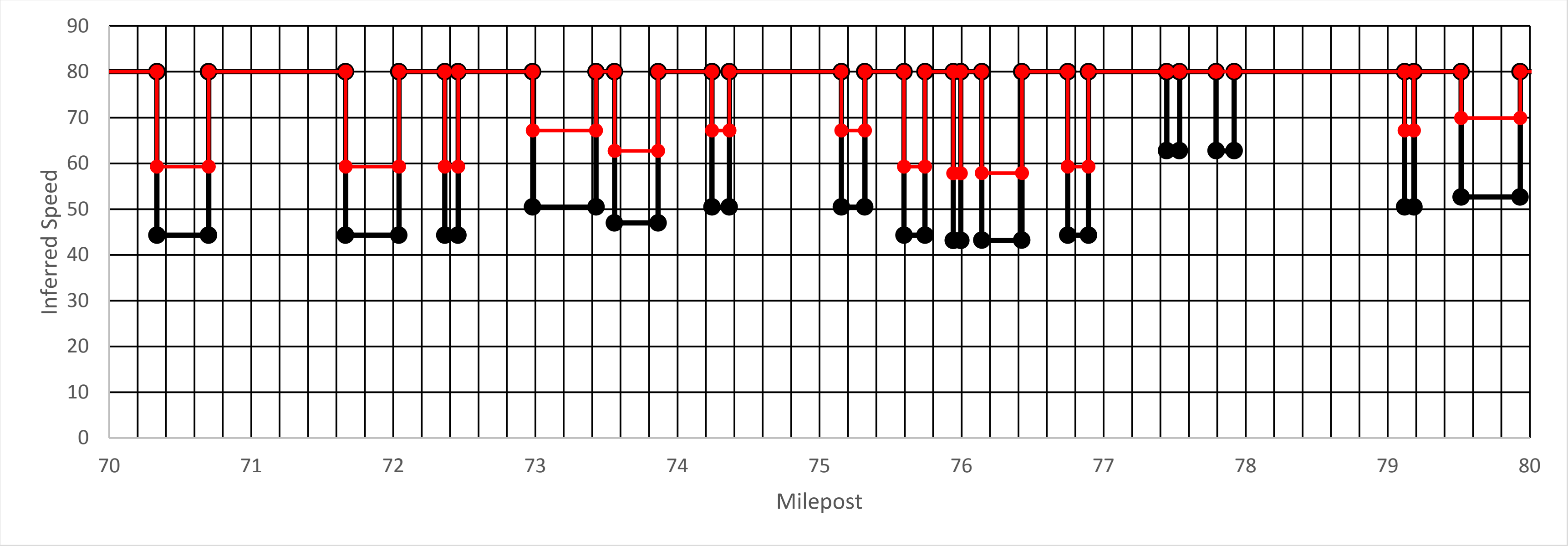
Milepost



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79
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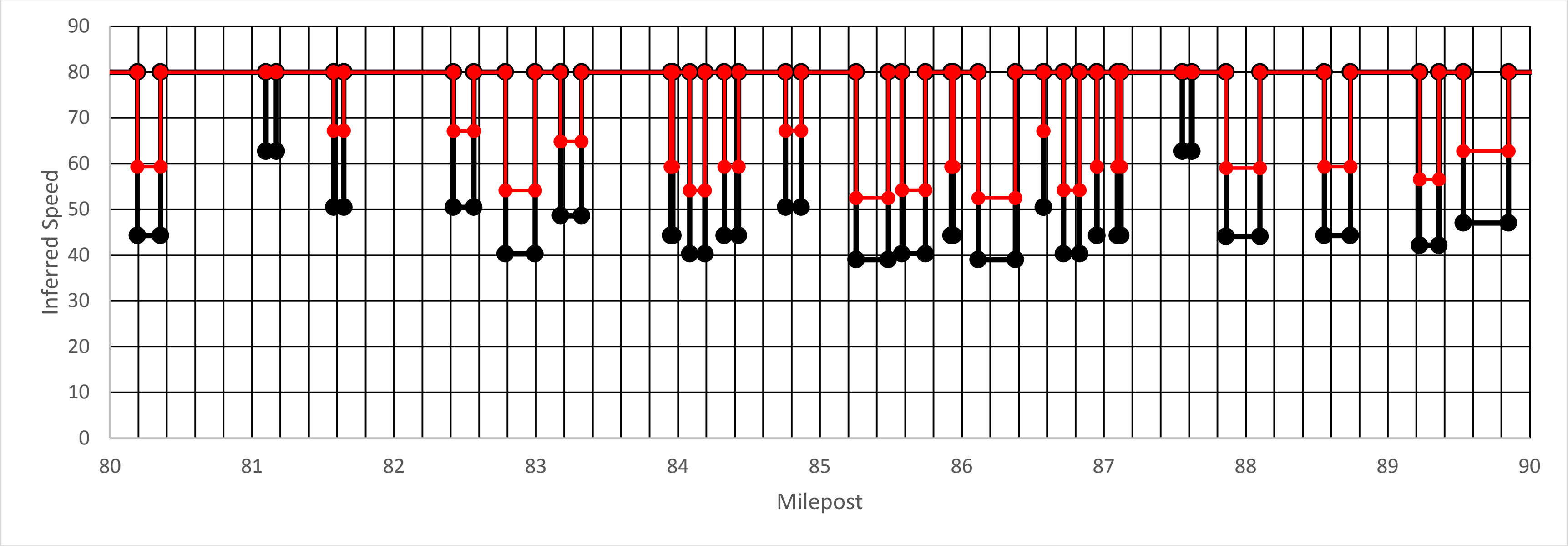
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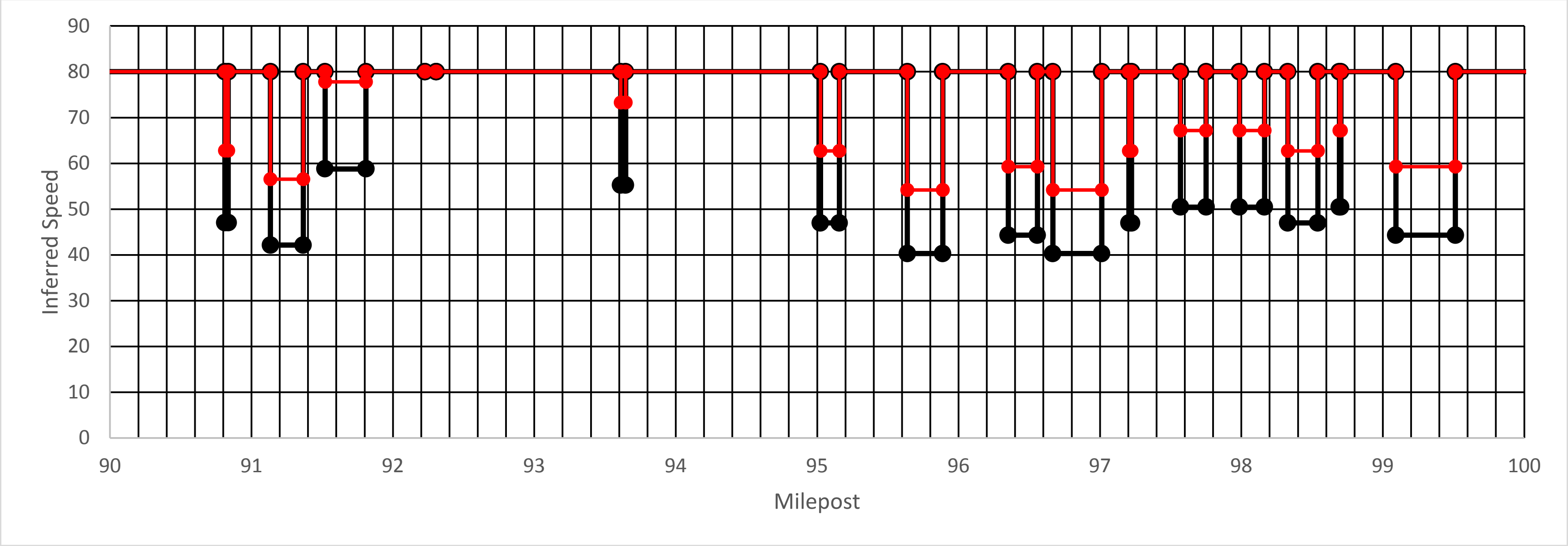
89
90
Milepost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93
94
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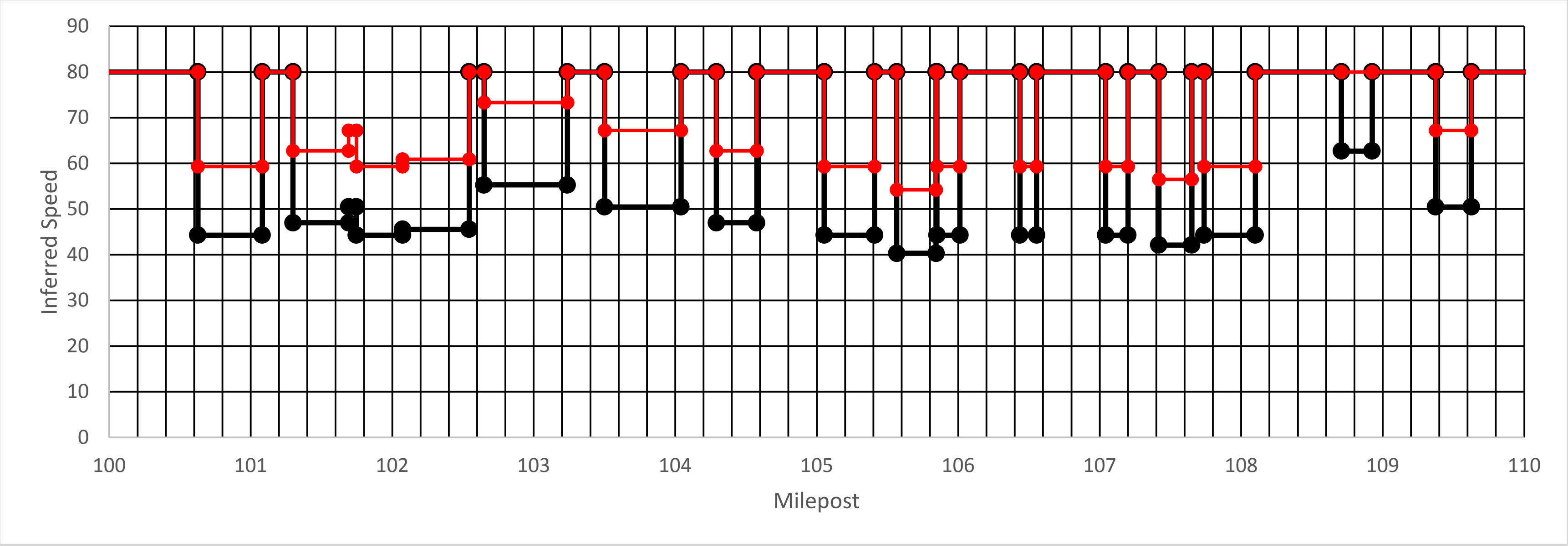
98
99
100
Milepost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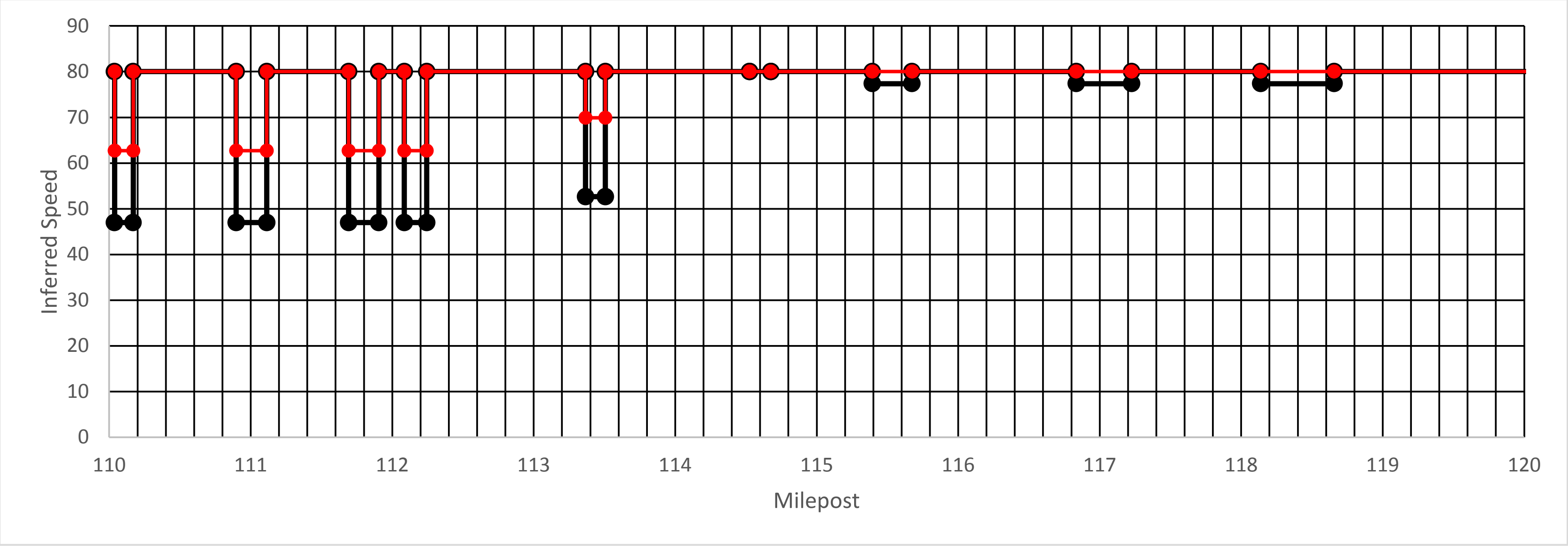
109
110
Milepost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119
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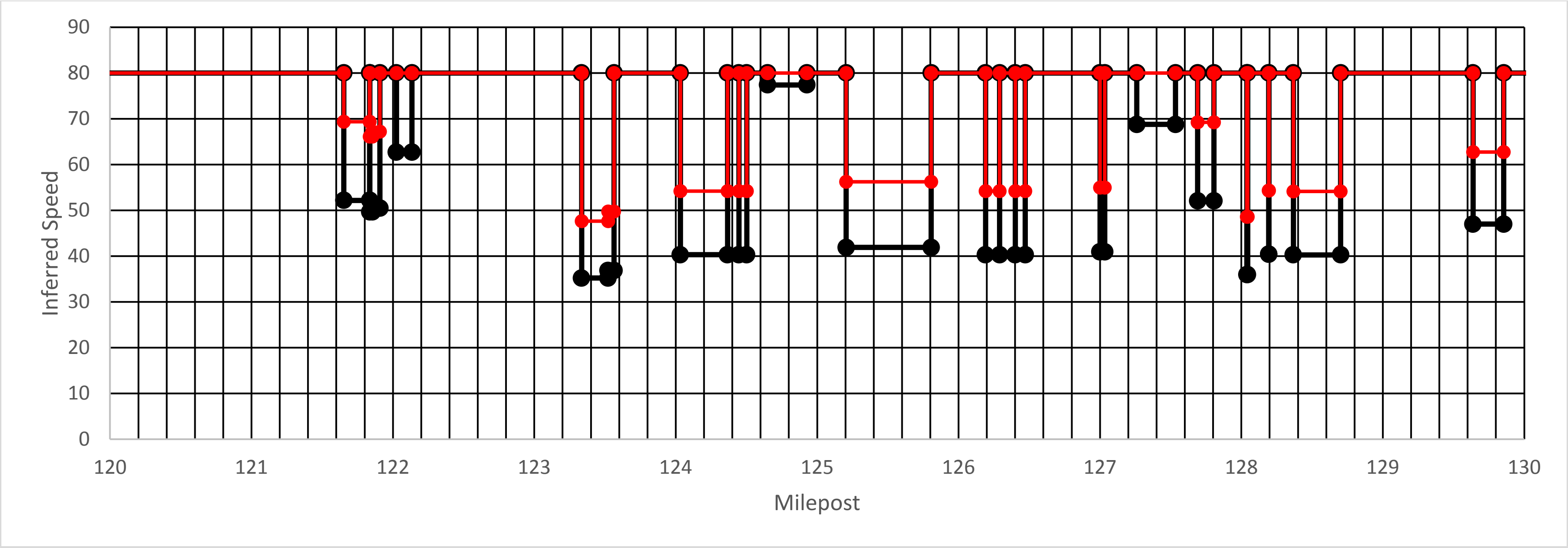
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128
129
130
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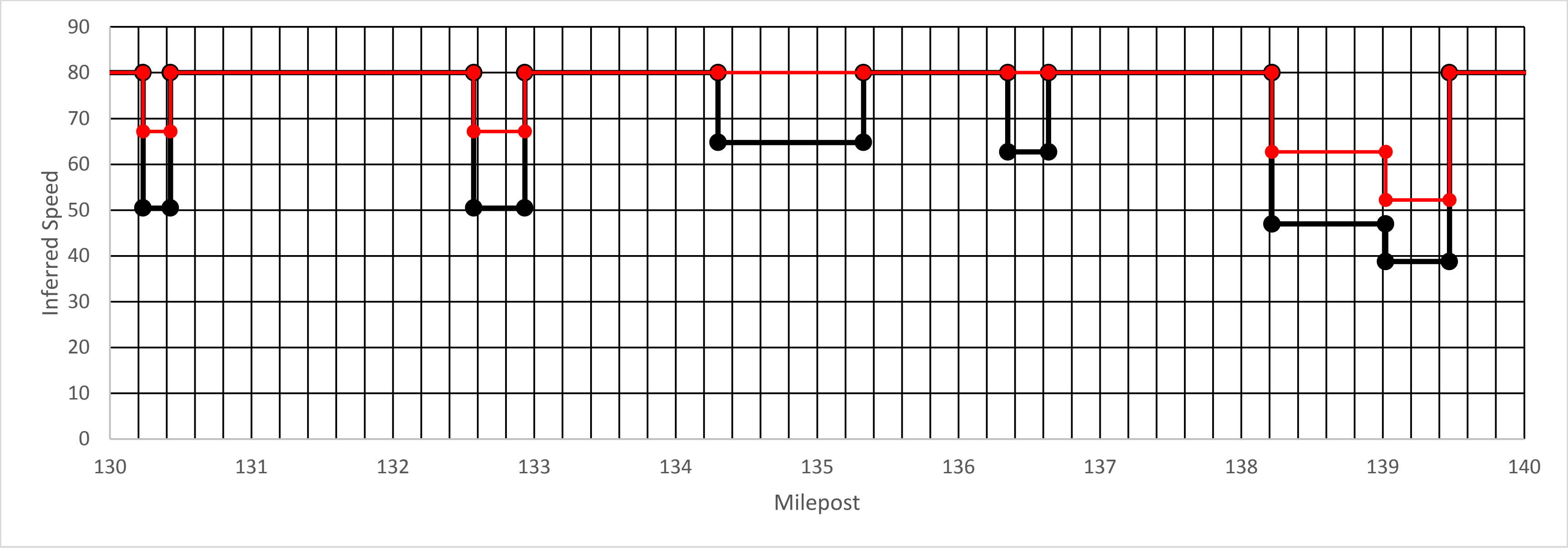
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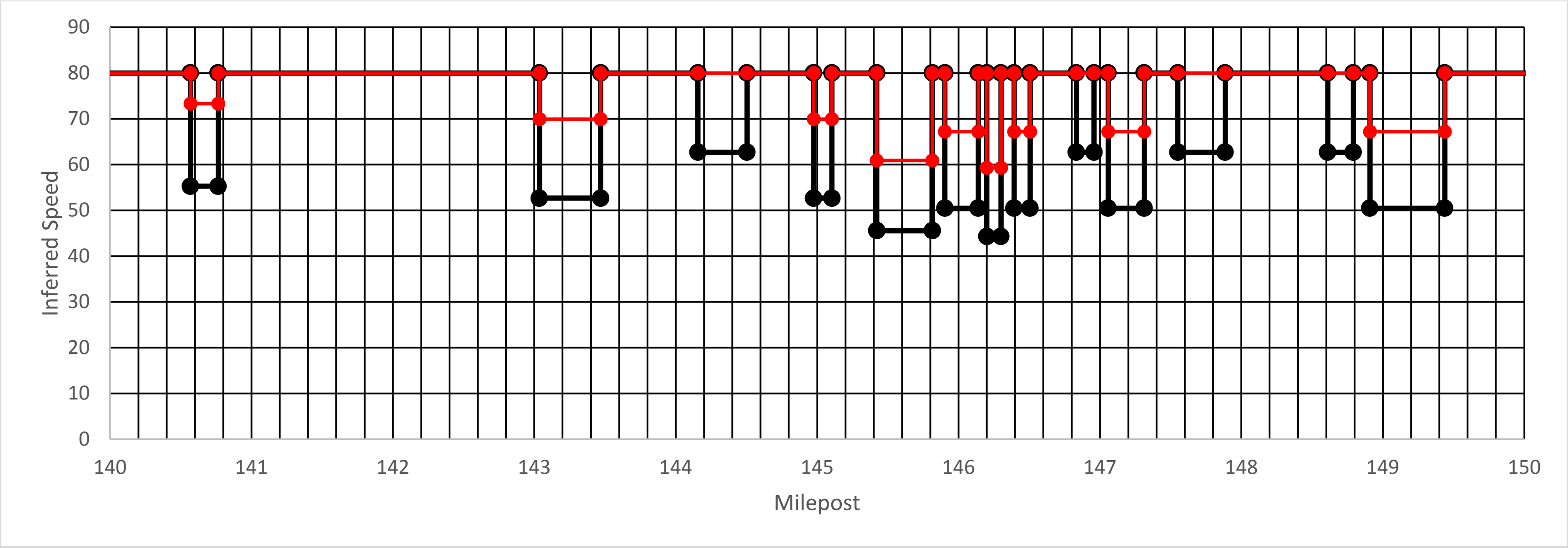
138
139
140
Milepost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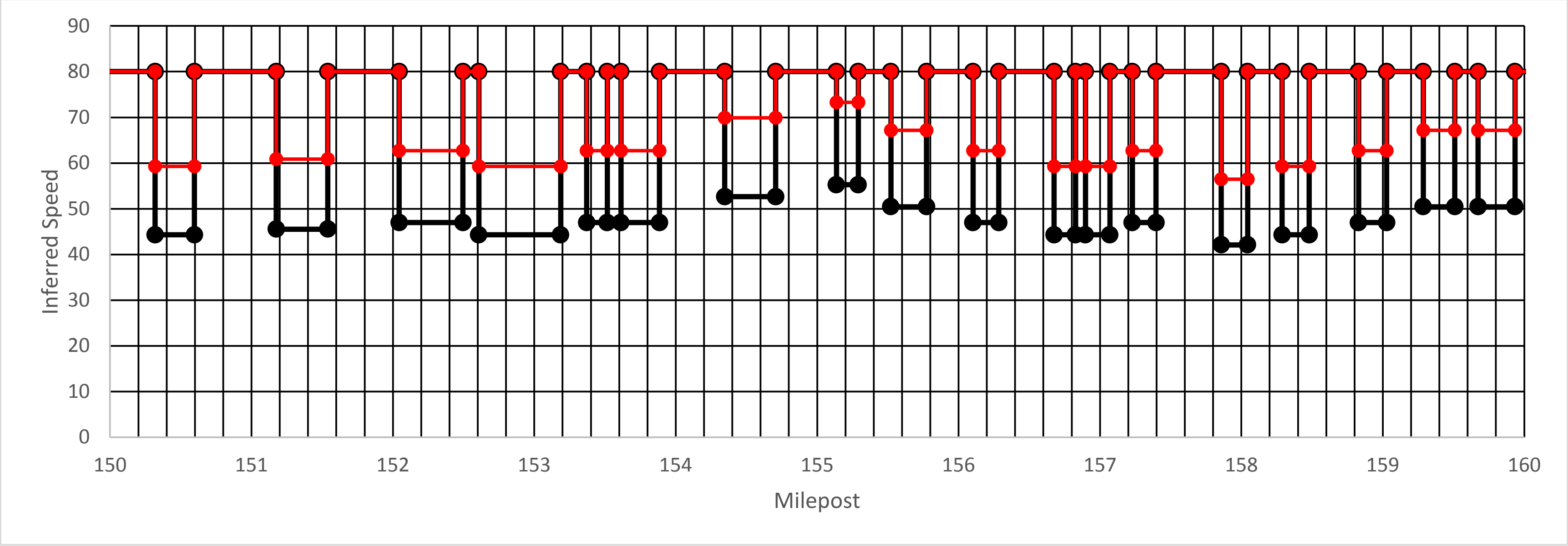
148
149
150
Milepost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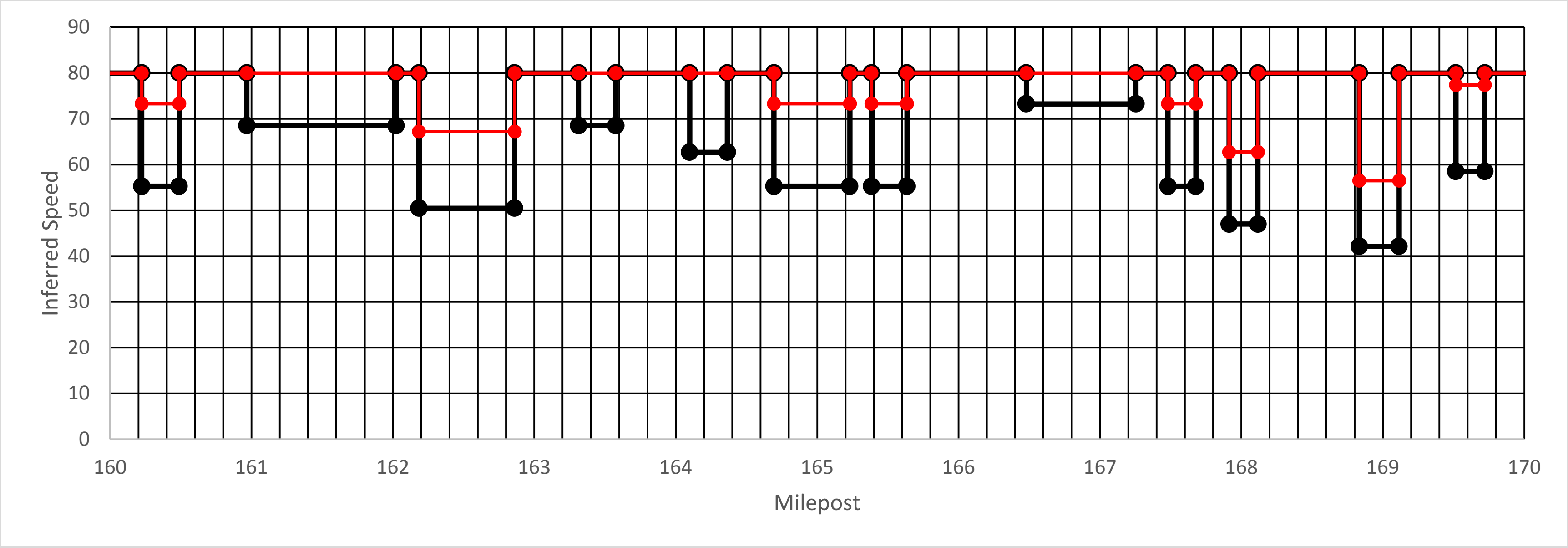
158
159
160
Milepost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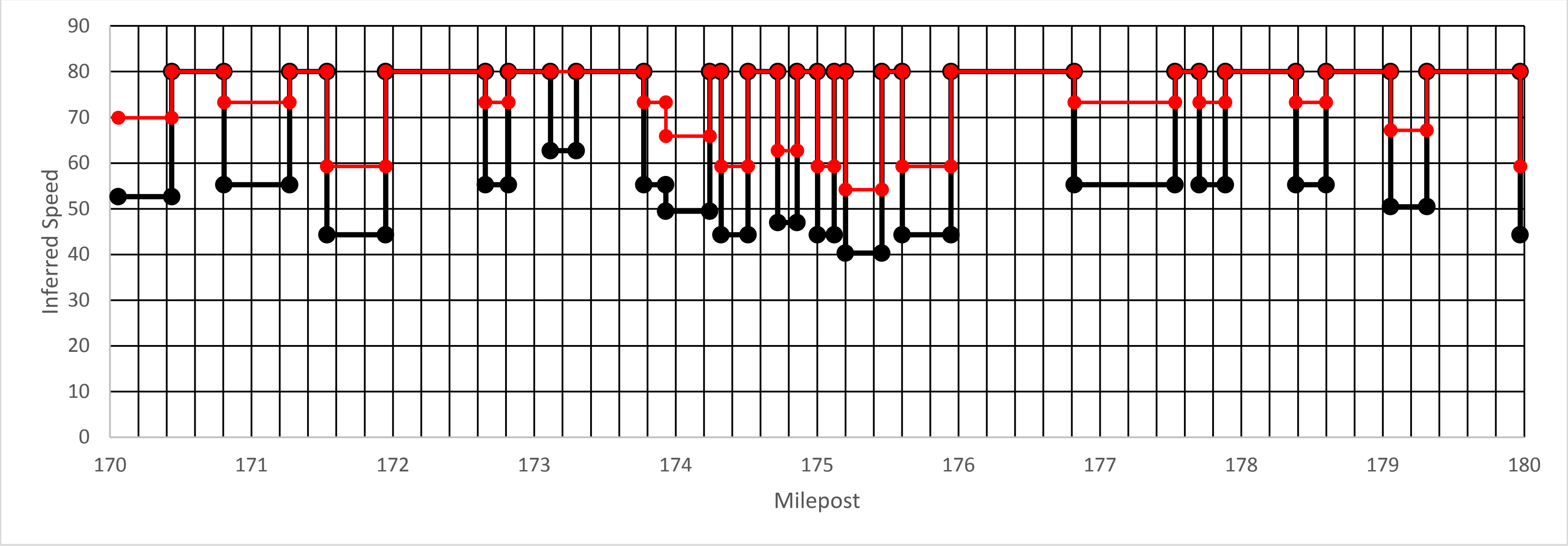
168
169
170
Milepost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Inferred Speed
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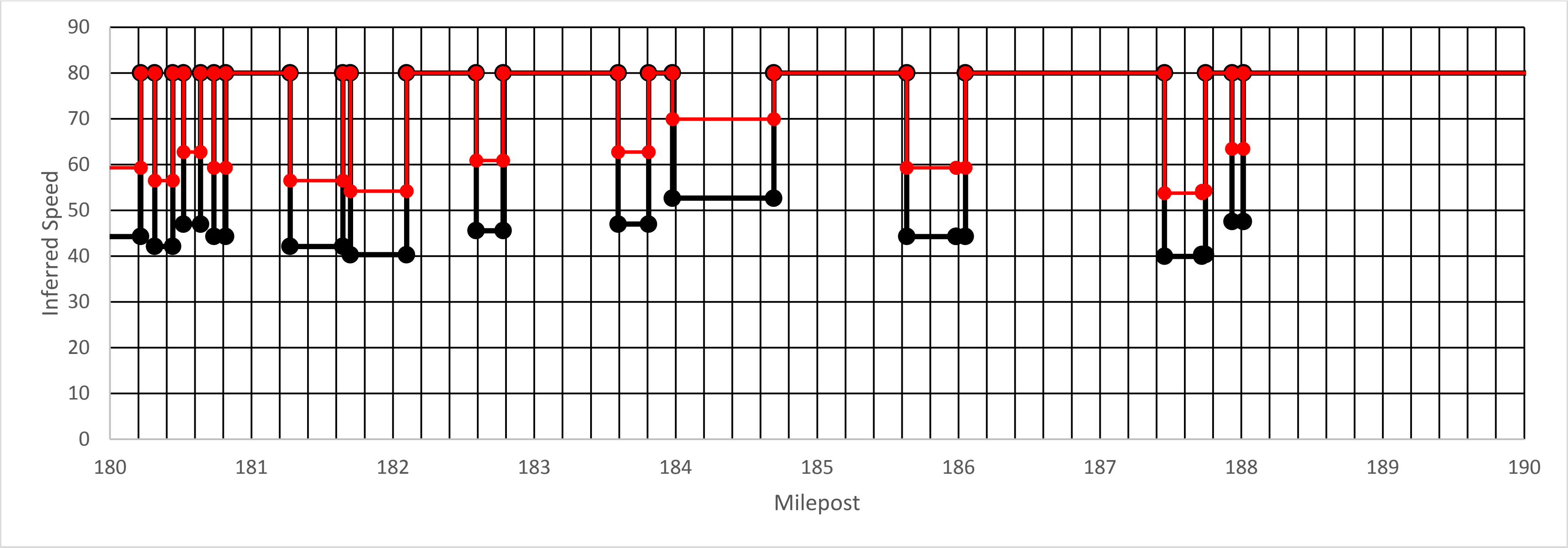
179
180
Milepost



Inferred Speed
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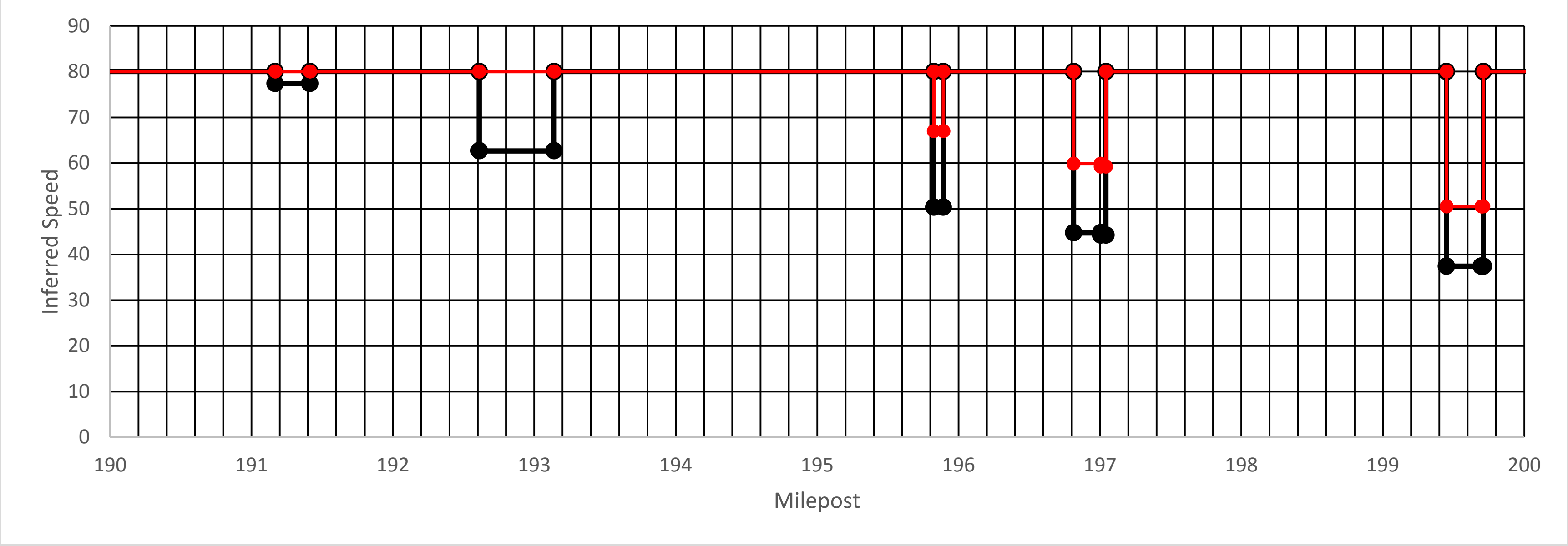
190
Milepost



Inferred Speed
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20
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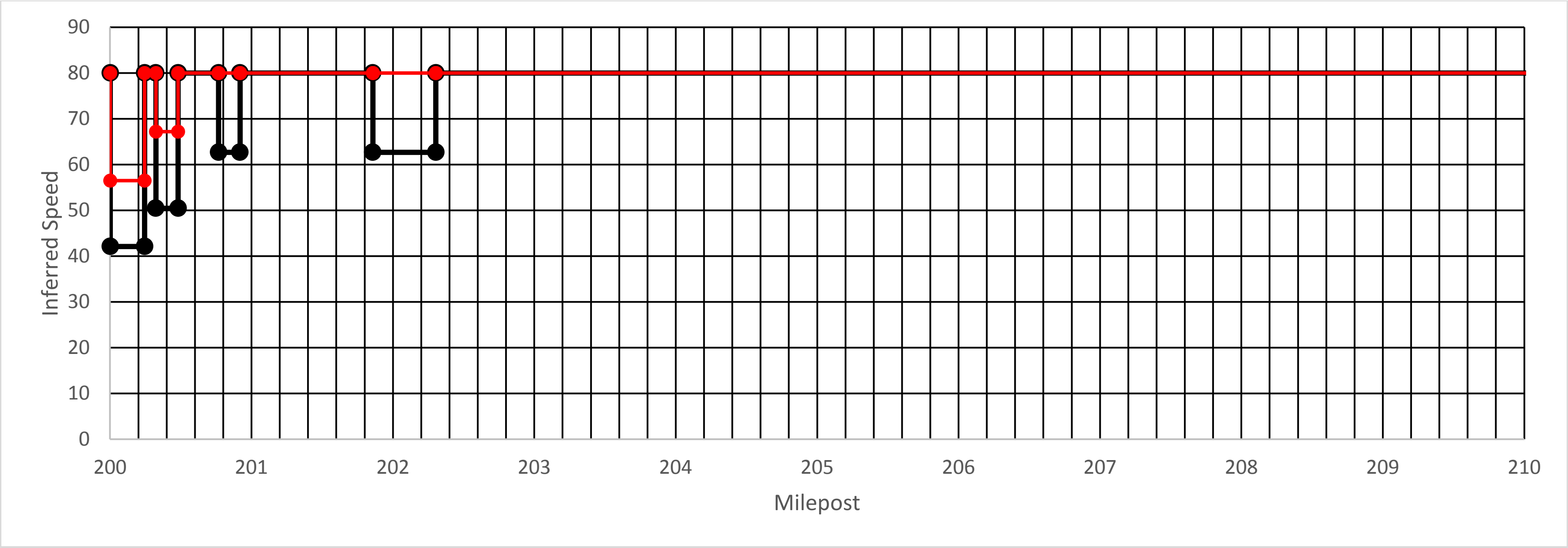
190
191
192
193
194
195
196
197
198
199
200
Milepost



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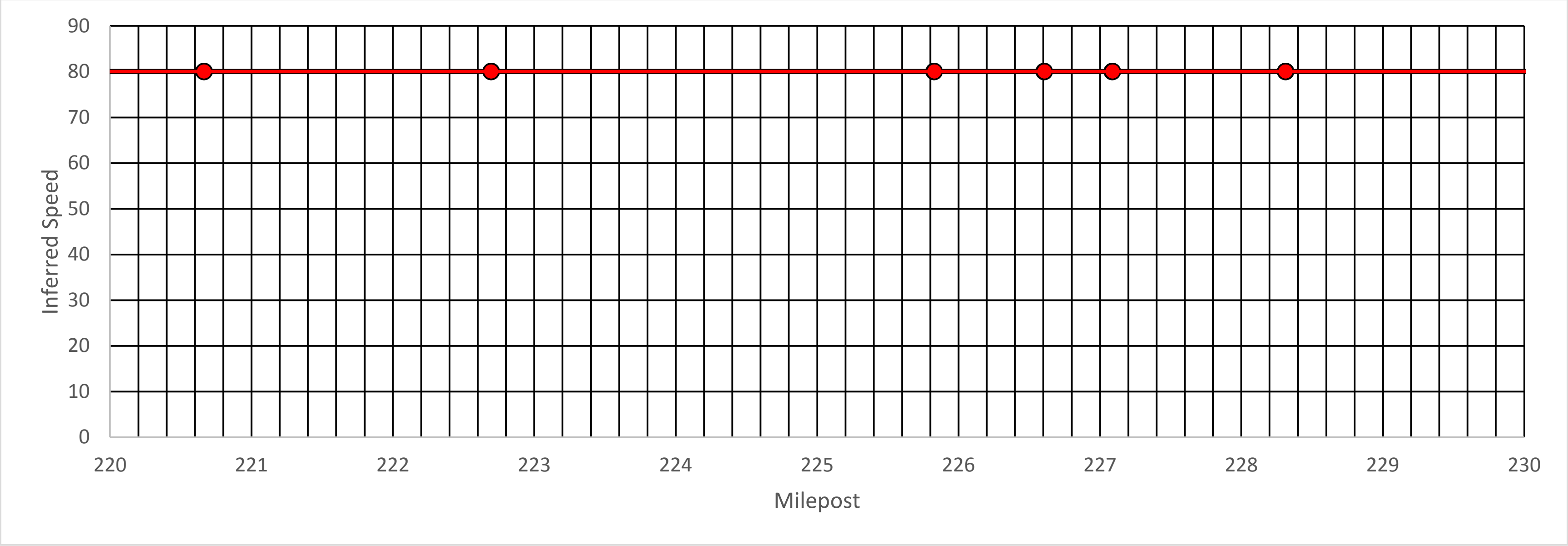

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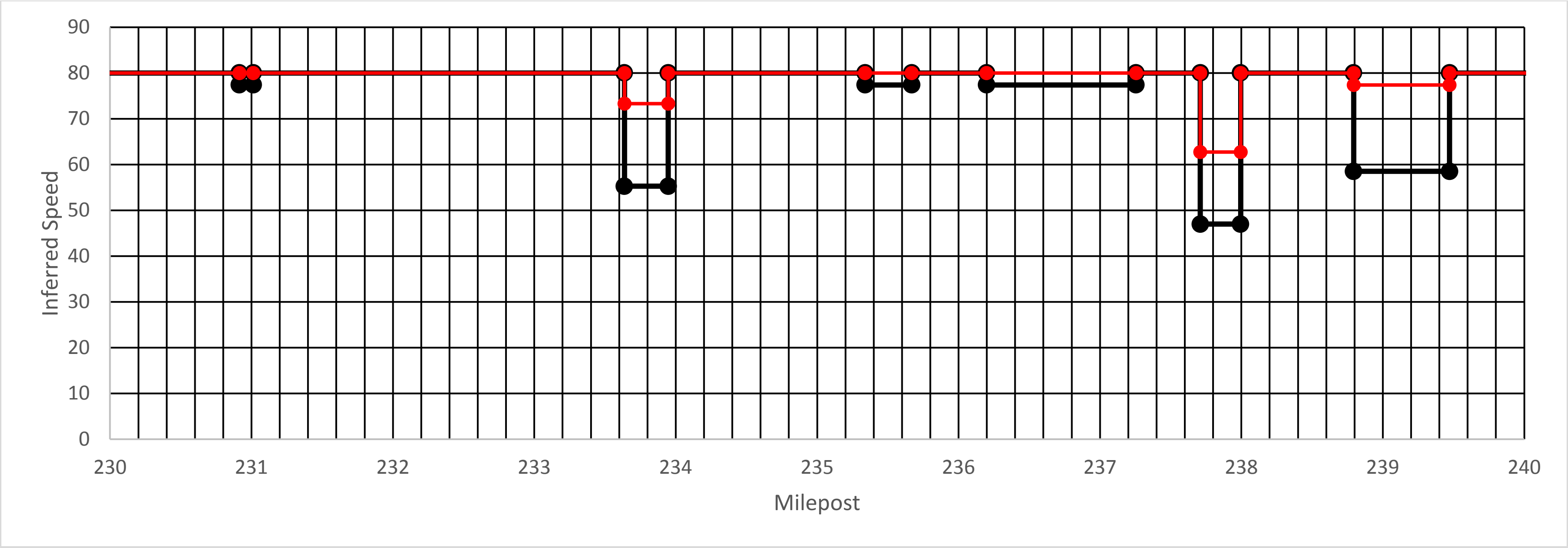

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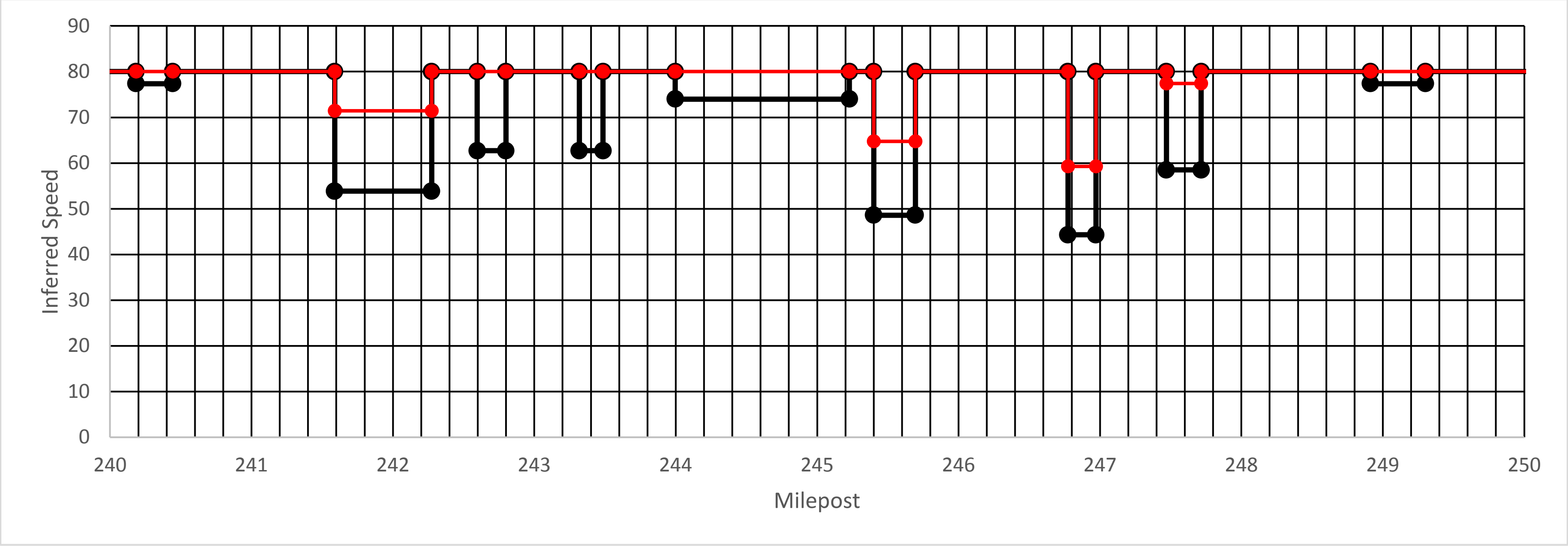

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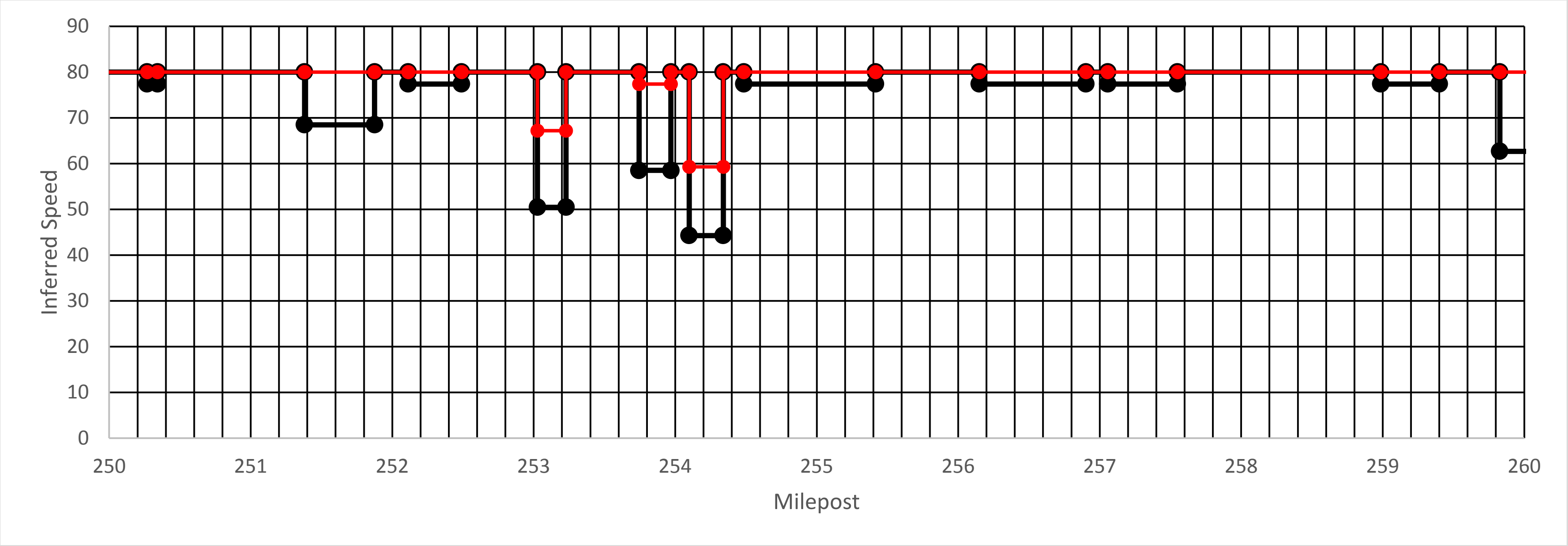
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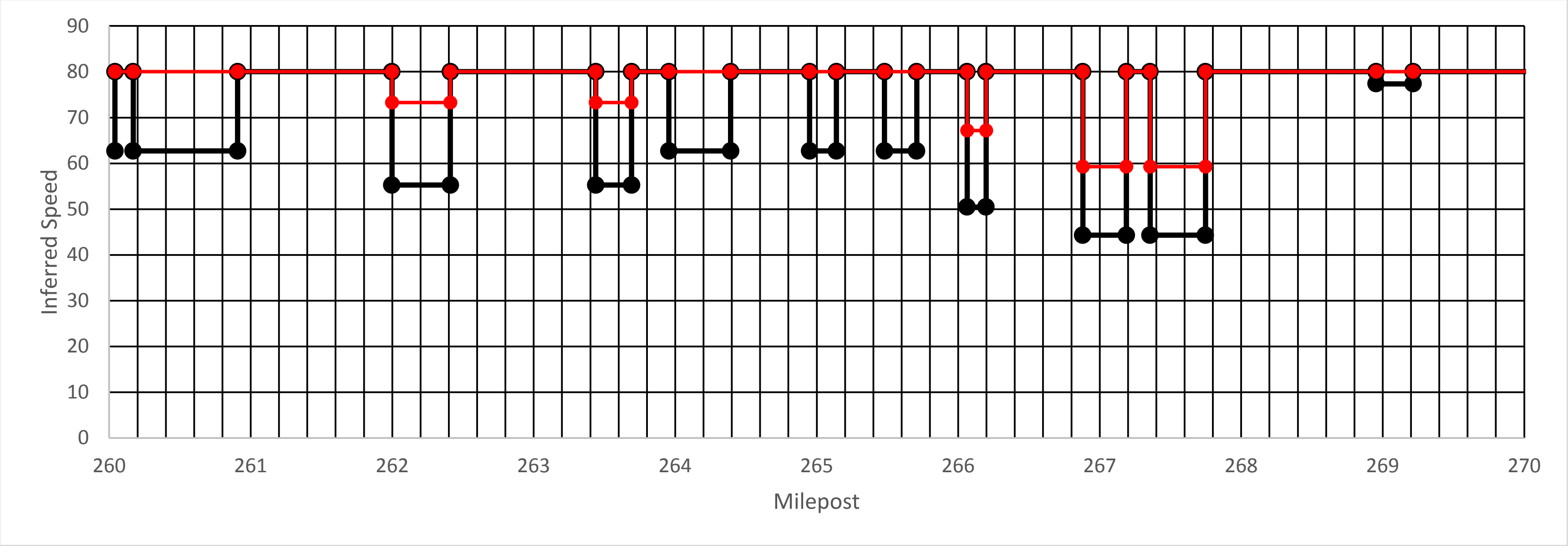
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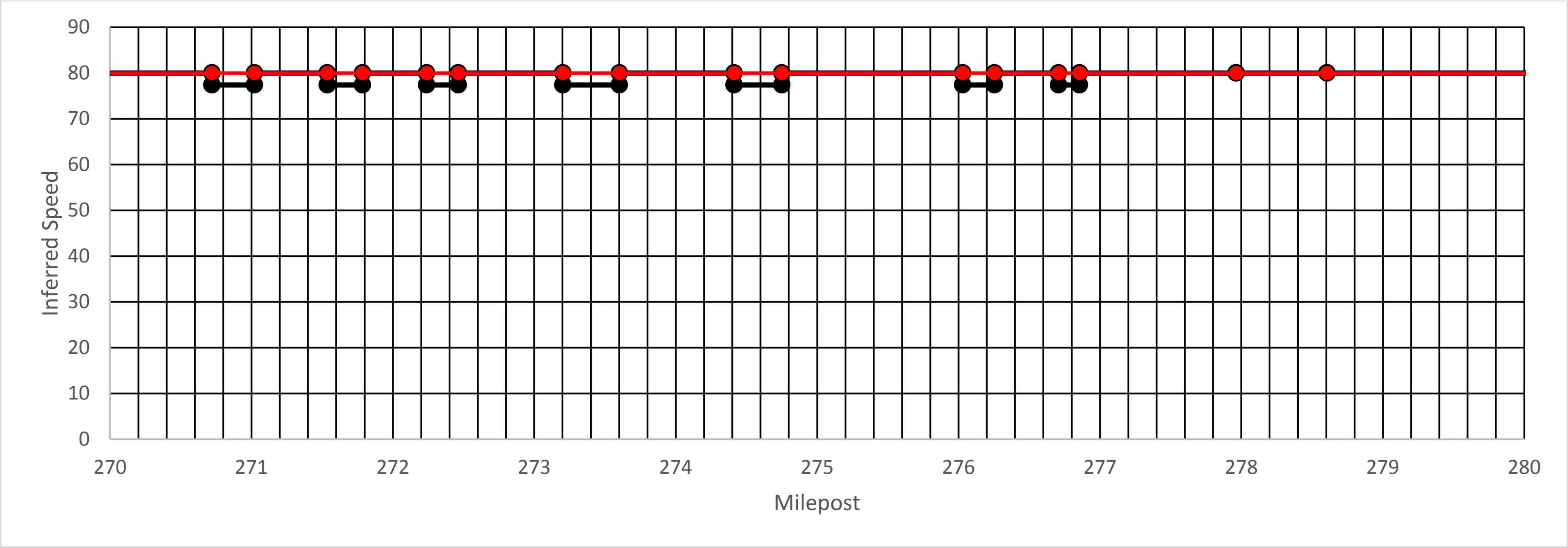

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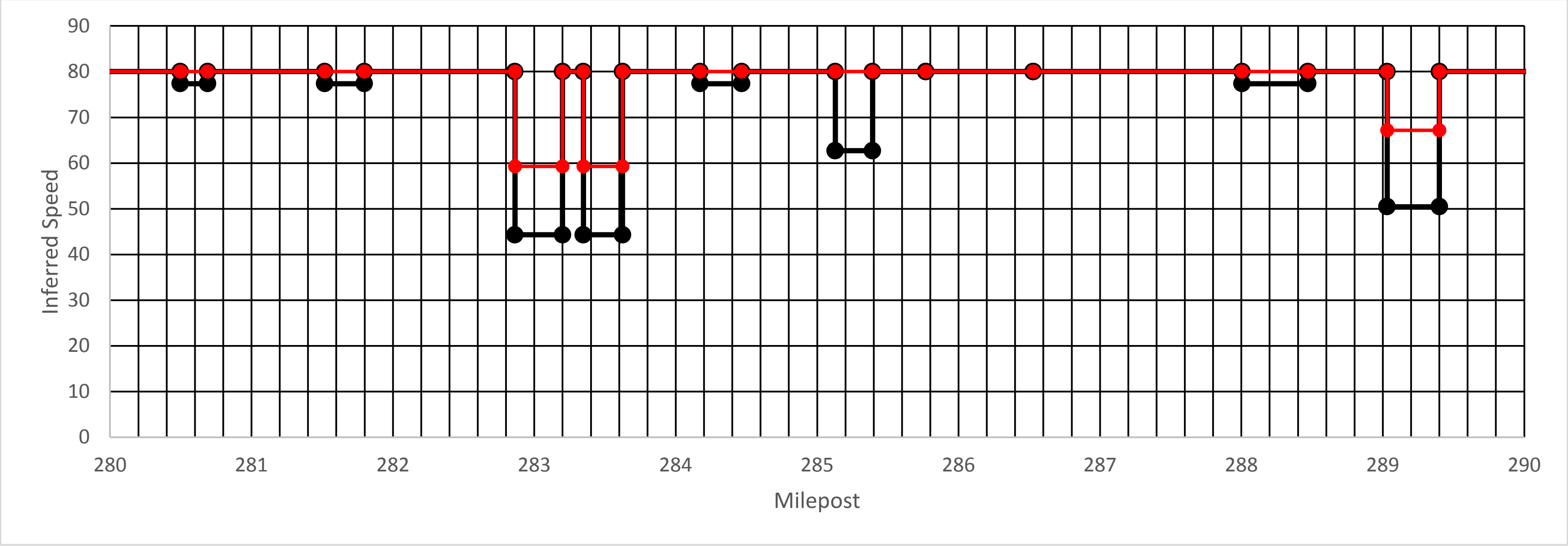

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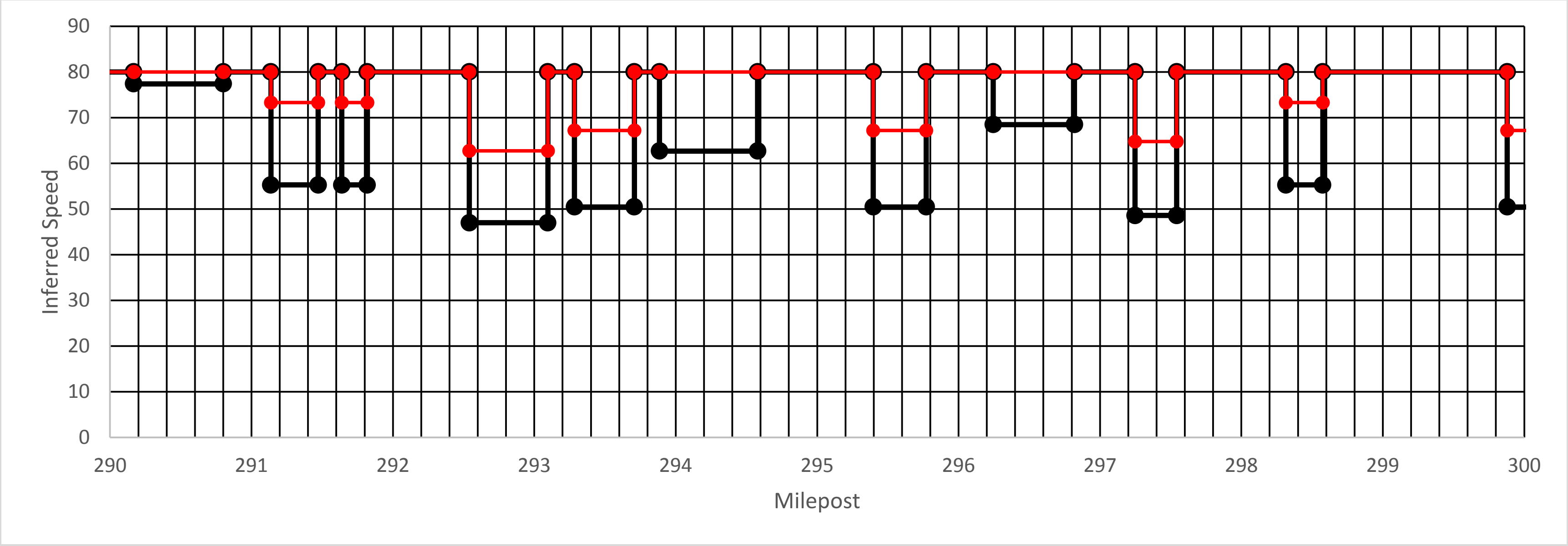
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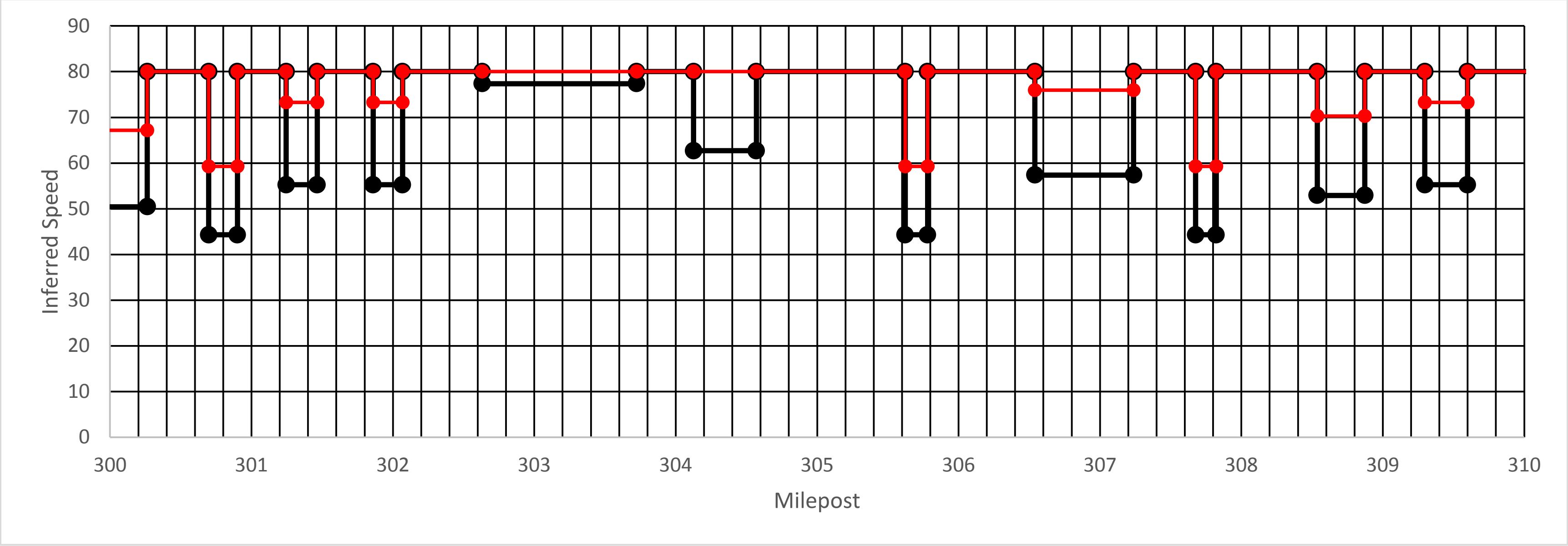
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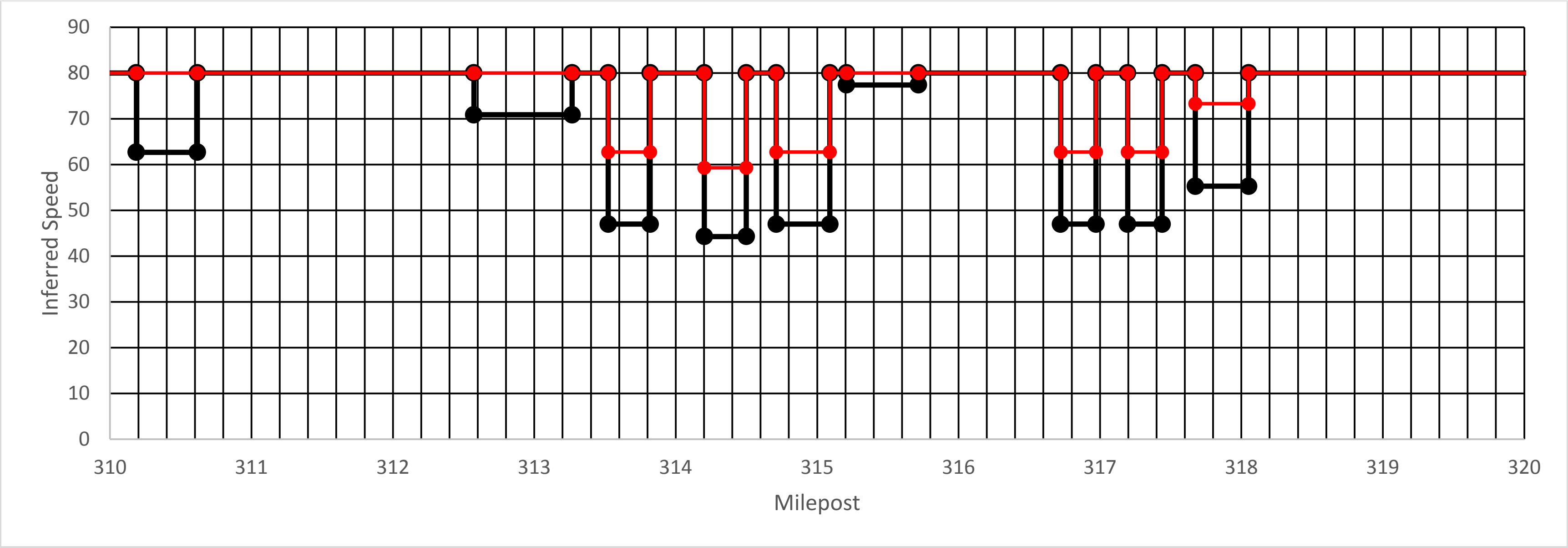
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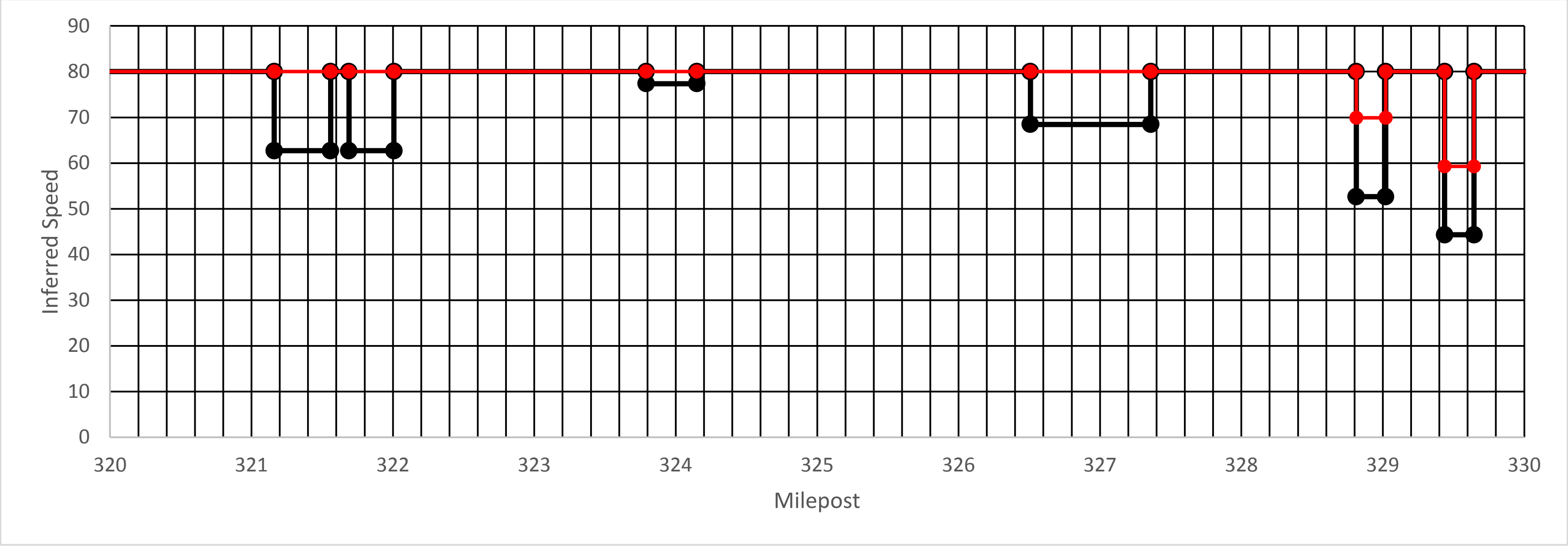
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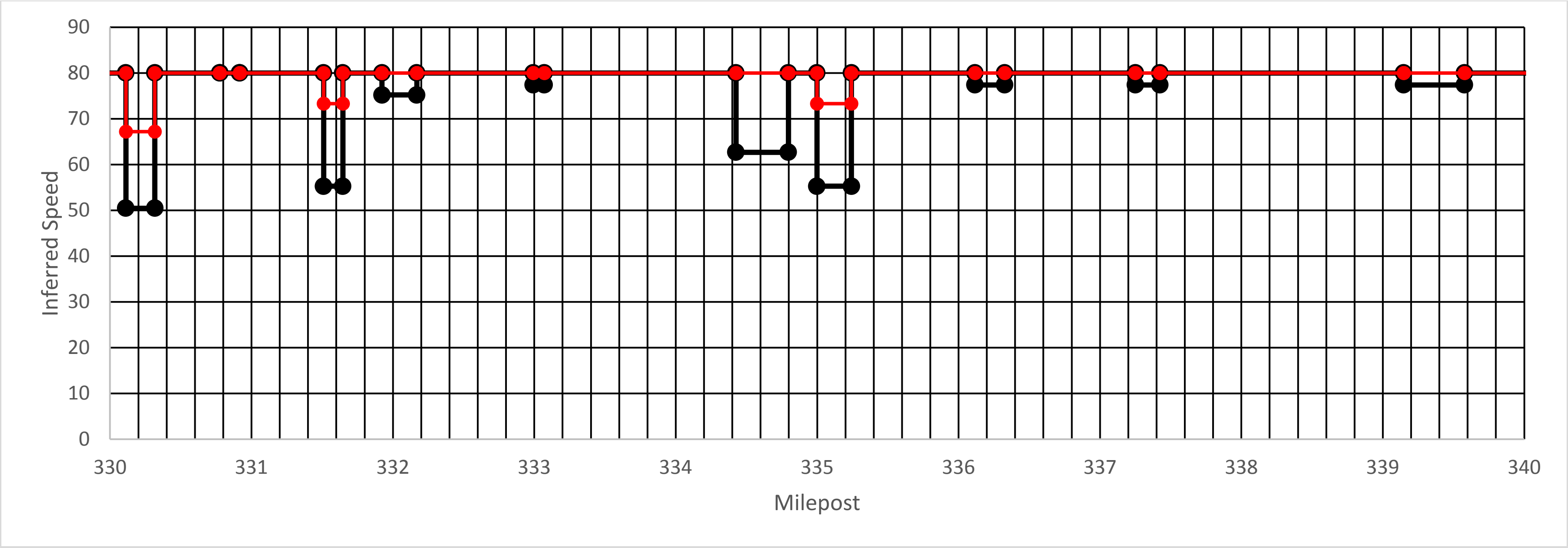
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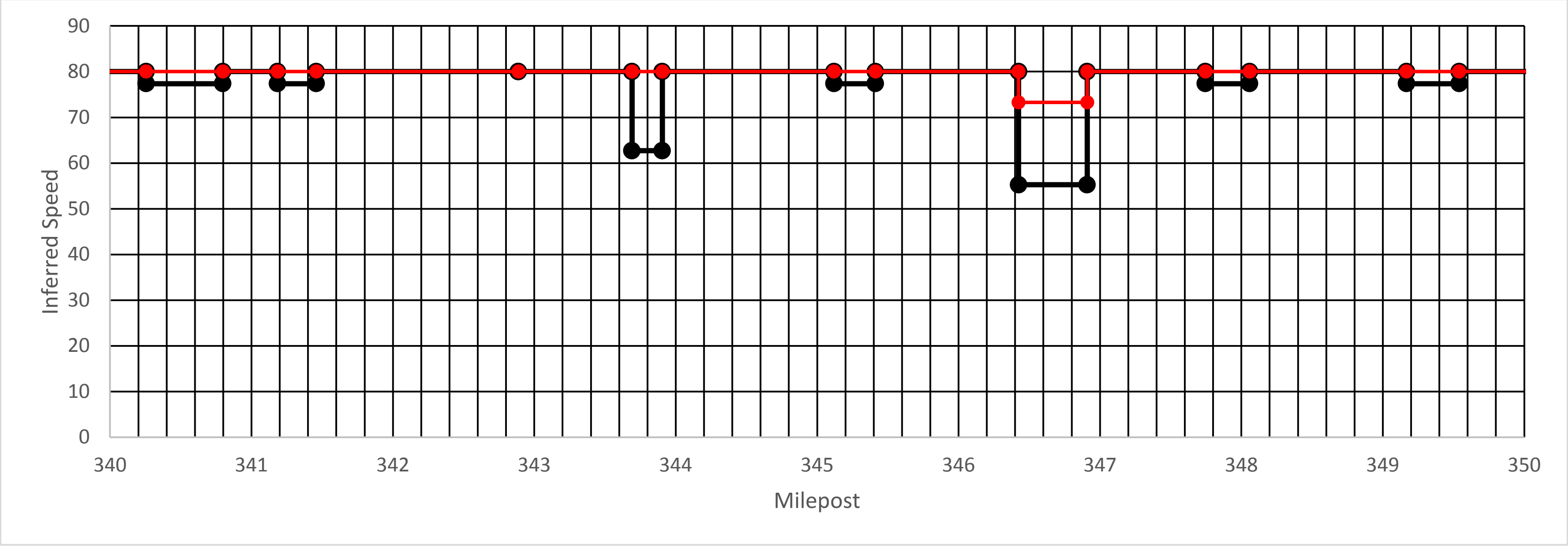
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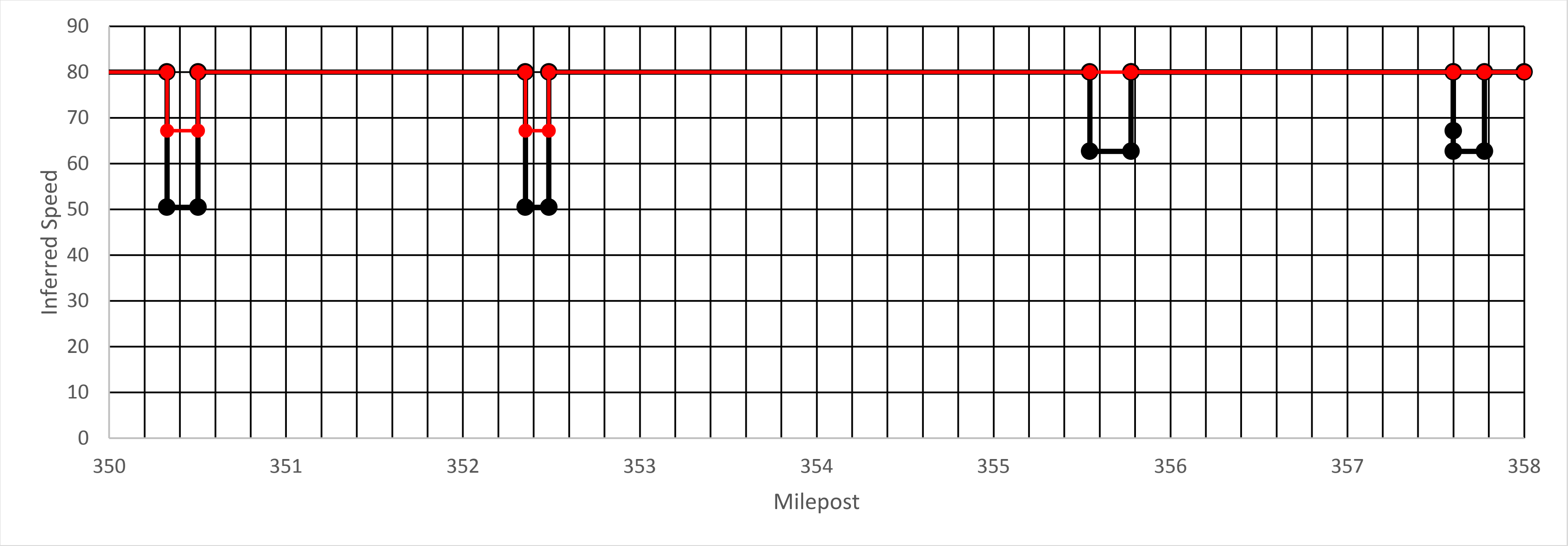

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APPENDIX C: EMPIRICAL BAYES BEFORE-AFTER ANALYSIS METHODOLOGY WITH A REFERENCE GROUP

An observational before-after safety study is considered a robust evaluation method to assess the effectiveness of safety countermeasures. This method requires that data be available from both before and after the implementation of the countermeasure. Further, crash data must be available from a reference group of sites (similar to the treatment site, but no treatment applied). An overview of the empirical Bayes (EB) method, which is the recommended before-after approach in traffic safety research, is provided below:

- **Step 1:** Predict what the safety performance would have been in the after period had the countermeasure not been implemented.
- **Step 2:** Estimate what the actual safety performance was in the after period with the countermeasure (i.e., reported number of crashes).
- **Step 3:** Compare the results of Step 1 and Step 2.

When applying the EB method, several years of after-period data are typically recommended. Because the index of effectiveness from the EB method will change as more years of after-period data are compiled, the process described in this section of the report should be updated as additional years of after-period data become available. As such, it is not possible to draw conclusions from the preliminary analyses described herein; however, the documentation below illustrates the EB methodology using the PennDOT rural Interstate and Pennsylvania Turnpike data. The following variables are used in the method.

List of Variables:

- N_{ij} : predicted crash frequency for a given segment *i* and a given year *j*
- L_i : the length of segment *i*
- AADT_{ij} : annual average daily traffic for a given segment *i* and a given year *j*
- FN_{ij} : friction number indicator for segment *i* and year *j*
- DC_{ij} : degree of curvature for segment *i* and year *j*
- $N_{\mathrm{pred,before}}$: predicted number of crashes for a given segment *i* and year *j* in the before period
- $\Sigma N_{\mathrm{pred,before}}$: total number of predicted crashes for a given segment *i* for all years in the before period
- $N_{\mathrm{pred,after}}$: predicted number of crashes for a given segment *i* and year *j* in the after period
- $\Sigma N_{\mathrm{pred,after}}$: total number of predicted crashes for a given segment *i* for all years in the after period
- w : adjustment factor used to estimate the expected number of crashes in the treatment group before the treatment is applied using predicted and observed crashes
- $\sum N_{Obs,before}$: total number of observed crashes for a given segment *i* in the before period
- $N_{EB,before}$: expected number of crashes for a given segment *i* in the treatment group in the before period

- r : factor applied to $N_{EB,before}$ to account for the length of the after period and differences in traffic volumes between the before and after periods
- $N_{EB,after}$: expected number of crashes for a given segment *i* in the treatment group in the after period had no treatment been applied
- k : dispersion parameter obtained from developing a safety performance function
- $VAR\left(N_{EB,before}\right)$: variance of the expected number of crashes for a given segment *i* in the treatment group in the before period
- $VAR\left(N_{EB,after}\right)$: variance of the expected number of crashes for the treatment group in the after period for any given segment *i*
- $\sum VAR\left(N_{EB,after}\right)$: the sum of the variance of the expected number of crashes for the treatment group in the after period for all segments
- $\sum N_{Obs,after}$: The total number of observed crashes in the after period for all segments
- θ : index of effectiveness θ or the treatment effect (i.e., crash modification factor (CMF))
- $stdev(\theta)$: standard deviation of the index of effectiveness

PENNDOT

- **Step 1: Estimate a safety performance function:**

  The safety performance function (SPF) developed using the PennDOT rural Interstate reference group is used to relate the expected total crash frequency to segment length (*L*) and average annual daily traffic (AADT). This SPF is based on a reference group of non-treated sites with a posted speed limit of 65 mph.

  $$N_{ij} = e^{-2.923} \times L_i^{0.940} \times AADT_{ij}^{0.344}$$

  where N_i is the predicted crash frequency for a given segment *i* and a given year *j*

- **Step 2: Estimate the number of predicted crashes for each year in the before period for all the segments in the treatment group:**

  The example shown above was performed for segment 1382 on Interstate 80 in Centre County in the year 2009 for the treatment group. This particular segment is 0.478 miles long with an AADT of 10,318 vehicles per day in the year 2009.

  $N_{pred,before} = e^{-2.923} \times L^{0.940} \times AADT^{0.344}$
  $N_{pred,before} = e^{-2.923} \times 0.478^{0.940} \times 10318^{0.344}$
  $N_{pred,before} = 0.646$ crashes

  This same calculation should be done for all segments and years in the before period (2009-2014). For the year 2014, the predicted number of crashes should be multiplied by a fraction of the year for which the before period is defined, which in this case is 7/12 (January 2014 through July 2014) because the posted speed limit for the treatment group was increased from 65 to 70 mph in August 2014.

- **Step 3: Estimate the total number of predicted crashes in the before period for each segment in the treatment group:**

  This computation was also performed for the sample segment (Interstate 80, segment 1382, in Centre County) for the years 2009 through 2014, and should be repeated for all roadway segments in the treatment group.

  $\Sigma N_{\text{pred,before}} = 0.646 + 0.646 + 0.646 + 0.646 + 0.646 + 0.377 = 3.61$ crashes

- **Step 4: Estimate the number of predicted crashes for each year in the after period for the treatment group:**

  The calculations below are for the after period of segment 1382 in the treatment group for the year 2014.

  $N_{\text{pred,after}} = e^{-2.923} \times L^{0.940} \times AADT^{0.344}$
  $N_{\text{pred,after}} = e^{-2.923} \times 0.478^{0.940} \times 10318^{0.344} * (4/12)$
  $N_{\text{pred,after}} = 0.215$ crashes

  These same calculations should be done for all segments and years in the after period (2014-2015). In the calculation sample shown above, the 4/12 fraction represents the time period in 2014 when the posted speed limit was 70 mph (posted speed limit was increased in August 2014).

- **Step 5: Estimate the total number of predicted crashes in the after period for the treatment group:**

  The equation below represents the total number of predicted crashes in the after period for the sample segment (Interstate 80, segment 1382, in Centre County) in the treatment group. The first value (0.215) is for the year 2014 (see step 4) and the second value (0.539) is for the year 2015. For the purposes of this report, the year 2015 was multiplied by 10/12, as the crash data included crashes through October 2015. Future analyses should include additional years of after-period data.

  $\Sigma N_{\text{pred,after}} = 0.215 + 0.539 = 0.754$ crashes

  The calculation shown above should be completed for all segments in the treatment group.

- **Step 6: Estimate the expected number of crashes in the treatment group before the treatment is applied:**

In this step of the evaluation, the predicted number of crashes for each segment in the treatment group is combined with the reported number of crashes on the same segments using the following equation:

$$N_{EB,before} = w\sum N_{pred,before} + (1-w)\sum N_{Obs,before}$$
$$w = \frac{1}{(1+k\sum N_{pred,before})}$$

where *k* is the dispersion parameter obtained from developing a safety performance function.

$$w = \frac{1}{(1+0.736*3.61)} = 0.274$$
$$N_{EB,before} = 0.274*3.61+(1-0.274)*1$$
$$N_{EB,before} = 1.713 \text{ crashes}$$

The calculations shown above are for segment 1832. Overall, little weight is given to the SPF prediction, mostly due to a relatively large number of years in the before period.

- **Step 7: Estimate the *r* factor for each segment**

  A factor *r* is applied to $N_{EB,before}$ to account for the length of the after period and differences in traffic volumes between the before and after periods. This factor is the sum of the annual SPF predictions for the after period $\sum N_{pred,after}$ divided by the sum of the predictions in the before period for the sample segment (Interstate 80, segment 1382, in Centre County).

$$r = \frac{\sum N_{pred,after}}{\sum N_{pred,before}} = \frac{0.754}{3.61} = 0.209$$

- **Step 8: Estimate the expected number of crashes for the treatment group in the after period had no treatment been applied:**

  After applying the factor from step 7, the following estimate of $N_{EB,After}$ for the sample segment (Interstate 80, segment 1382, in Centre County) results:

$$N_{EB,after} = N_{EB,before} \times r$$
$$N_{EB,after} = 1.713*0.209 = 0.358 \text{ crashes}$$

- **Step 9: Estimate the variance of the expected number of crashes for the treatment group in the after period:**

The variance of the effect estimate for the sample segment (Interstate 80, segment 1382, in Centre County) is determined as follows:

$$VAR\left(N_{EB,before}\right) = (1\text{-}\ w)^* N_{EB,before}$$

$$VAR\left(N_{EB,before}\right) = (1\text{-}0.274)^*1.713 = 1.245$$

$$VAR\left(N_{EB,after}\right) = VAR\left(N_{EB,before}\right)^* r^2$$

$$VAR\left(N_{EB,after}\right) = 1.245^*\ 0.209^2 = 0.054$$

Upon summing the variance over all treatment segments, we get the following result:

$$\sum VAR\left(N_{EB,after}\right) = 51.293$$

- **Step 10: Estimate the index of effectiveness *θ*:**

The unbiased estimate for the index of effectiveness for all sites in the PennDOT rural Interstate sample of treatment sites is determined as follows:

$$\theta = \frac{\sum N_{Obs,after} \Big/ \sum N_{EB,after}}{1 + \sum VAR\left(N_{EB,after}\right) \Big/ \left(\sum N_{EB,after}\right)^2}$$

$$\theta = \frac{426 \big/ 339.88}{1 + 51.293 \big/ 115519} = 1.253$$

The index of effectiveness is a measure of the EB-adjusted difference in the reported crashes in the after period to the expected number of crashes that would have occurred had the treatment (increasing the posted speed limit from 65 to 70 mph) not been applied. In this case, the index of effectiveness indicates that increasing the posted speed limit from 65 to 70 mph is associated with a 25.3% increase in total crashes. This value was relatively close to the reported relative risk of 1.15 (see Equation 7 in the report).

- **Step 11: Estimate the variance standard deviation of the index of effectiveness *θ*:**

The standard deviation of *θ* is calculated as shown below:

$$stdev(\theta) = \sqrt{\theta^2 \left(\frac{\frac{1}{\sum N_{Obs,after}} + \frac{\sum VAR(N_{EB,after})}{\left(\sum N_{EB,after}\right)^2}}{1 + \sum VAR(N_{EB,after}) \Big/ \left(\sum N_{EB,after}\right)^2} \right)}$$

$$stdev(\theta) = \sqrt{1.253^2 \left(\frac{\frac{1}{426} + \frac{3.271}{115519}}{1 + 51.293 \Big/ 115519} \right)} = 0.066$$

- **Step 12: Estimate the 95% upper and lower bounds of θ:**

  The 95% confidence interval for θ is found by adding and subtracting 1.96 times $stdev(\theta)$ from θ:

  95% Lower bound = θ – (1.96* $stdev(\theta)$) = 1.253 - (1.96*0.066) = 1.123
  95% Upper bound = θ + (1.96* $stdev(\theta)$) = 1.253 + (1.96*0.066) = 1.383

It is again important to note that this evaluation is based on 14 months of after-period crash data at the treatment locations. The 12 steps outlined above should be repeated as additional months (and years) of crash data are reported in the treatment sections, because the index of effectiveness will change as the sample size increases.

TURNPIKE

- **Step 1: Estimate a safety performance Function:**

  The safety performance function developed for the Turnpike is used here to estimate the expected number of crashes for the reference group as a function of the segment length, average annual daily traffic (AADT), friction number indicator (FN), and degree of horizontal curve (DC) on the roadway segment.

$$N_{ij} = e^{-8.885} \times L_i^{0.871} \times AADT_{ij}^{1.01} \times e^{-0.522 \times FN_{ij}} \times e^{0.115 \times DC_{ij}}$$

  where N_i is the predicted crash frequency for a given segment *i* and a given year *j*

- **Step 2: Estimate the number of predicted crashes for each year in the before period for all the segments in treatment group:**

  The example shown below was performed for the segment between milepost 200.77 and milepost 200.92 in the year 2009 for the treatment group. This particular segment is 0.152

miles long with an AADT of 35,085 vehicles per day in the year 2009. The smooth tire friction number is above 32 (indicator is 1), and the degree of curve is 1 degree.

$N_{\text{pred,before}} = e^{-8.885} \times L^{0.871} \times AADT^{1.01} \times e^{-0.522 \times FN} \times e^{0.115 \times DC}$

$N_{\text{pred,before}} = e^{-8.885} \times 0.152^{0.871} \times 35085^{1.01} \times e^{-0.522 \times 1} \times e^{0.115 \times 1}$

$N_{\text{pred,before}}$ = 0.694 crashes

These same calculations should be repeated for all segments and years in the before period (2009-2014). Because the Pennsylvania Turnpike increased the posted speed limit on the treatment group from 65 to 70 mph in July 2014, the 2014 total crash predictions should be multiplied by 6/12.

- **Step 3: Estimate the total number of predicted crashes in the before period for the treatment group:**

  The calculations below were performed for segments for the years 2009 through 2014.

  $\Sigma N_{\text{pred,before}}$ = 0.694 + 0.694 + 0.756 + 0.752 + 0.760 + 0.383 = 4.040 crashes

  The same process should be completed for all segments in the treatment group.
  .

- **Step 4: Estimate the number of predicted crashes for the treatment sites in each year of the after period:**

  The following equation is used to estimate the predicted number of total crashes for the sample segment in the after period for the year 2014. Because the Pennsylvania Turnpike increased the posted speed limit from 65 to 70 mph in July 2014, the result is multiplied by the remaining fraction of the year 2014, which is 5/12.

  $N_{\text{pred,after}} = e^{-8.885} \times L^{0.871} \times AADT^{1.01} \times e^{-0.522 \times FN} \times e^{0.115 \times DC}$
  $N_{\text{pred,after}} = e^{-8.885} \times 0.152^{0.871} \times 38742^{1.01} \times e^{-0.522 \times 1} \times e^{0.115 \times 1}$ *(5/12)
  $N_{\text{pred,after}}$ = 0.320 crashes
  These same calculations should be repeated for each segment in the treatment group for each year. In the current data files, all reported crashes for the year 2015 were included.

- **Step 5: Estimate the total number of predicted crashes in the after period for each segment in the treatment group:**

  For the sample segment on the Turnpike, the predicted number of crashes in the after period (portion of year 2014 and all of year 2015) are shown below:

  $\Sigma N_{\text{pred,after}}$ = 0.320 + 0.767 = 1.09 crashes

The same calculation should be repeated for all segments in the treatment group as more years of after period crash data are reported.

- **Step 6: Estimate the expected number of crashes in the treatment group before the treatment is applied:**

In this step of the evaluation, the predicted number of crashes for each segment in the treatment group is combined with the reported number of crashes on the same segments using the following equation:

$$N_{EB,before} = w \sum N_{pred,before} + (1-w) \sum N_{Obs,before}$$

$$w = \frac{1}{(1 + k \sum N_{pred,before})}$$

where *k* is the dispersion parameter obtained from developing a safety performance function.

$$w = \frac{1}{(1 + 0.604 * 4.04)} = 0.292$$

$$N_{EB,before} = 0.292 * 4.04 + (1 - 0.292) * 1$$

$$N_{EB,before} = 1.180 \text{ crashes}$$

The calculations above were performed for segment in question. Like the PennDOT example shown earlier in this appendix, little weight is given to the SPF prediction, mostly due to a relatively large number of years in the reported crash data from the before period.

- **Step 7: Estimate the *r* factor for each segment in the treatment group:**

A factor *r* is applied to $N_{EB,before}$ to account for the length of the after period and differences in traffic volumes between the before and after periods. This factor is the sum of the annual SPF predictions for the after period $\sum N_{pred,after}$ divided by the sum of the predictions in the before period for the sample segment.

$$r = \frac{\sum N_{pred,after}}{\sum N_{pred,before}} = \frac{1.09}{4.04} = 0.269$$

- **Step 8: Estimate the expected number of crashes in the after period had no treatments been applied:**

After applying the factor from step 7, an estimate of $N_{EB,After}$ for the sample segment results:

$$N_{EB,after} = N_{EB,before} \times r$$

$$N_{EB,after} = 1.180 * 0.269 = 0.317 \text{ crashes}$$

- **Step 9: Estimate the variance of the expected number of crashes in the after period:**

  The variance of the sample segment is determined as follows:

  $$VAR(N_{EB,before}) = (1\text{-} w)* N_{EB,before}$$

  $$VAR(N_{EB,before}) = (1\text{-}0.292)*1.180 = 0.835$$

  $$VAR(N_{EB,after}) = VAR(N_{EB,before})* r^2$$

  $$VAR(N_{EB,after}) = 0.835* 0.269^2 = 0.060$$

  Upon summing the variance over all treatment segments, we get the following result:

  $$\sum VAR(N_{EB,after}) = 81.813$$

- **Step 10: Estimate the index of effectiveness *θ* for the treatment group:**

  The unbiased estimate for the index of effectiveness for the treatment group is determined as follows:

  $$\theta = \frac{\sum N_{Obs,after} \Big/ \sum N_{EB,after}}{1 + \sum VAR(N_{EB,after}) \Big/ \left(\sum N_{EB,after}\right)^2}$$

  $$\theta = \frac{377/368}{1 + 81.813/135404} = 1.024$$

  This result suggests that increasing the posted speed limit from 65 to 70 mph results in a 2.4% increase in total crashes. This value is lower than the estimated relative risk of 1.30 (see Equation 7 in the report). It is important to note that, because only 17 months of after-period data were included in this evaluation, additional after-period crash data are needed to further assess the effect of increasing the posted speed limit on the Pennsylvania Turnpike. It is recommended that at least three years of reported crash data be used in this

EB framework before concluding the effects of the posted speed limit increase on the Turnpike.

Step 11: Estimate the variance standard deviation of the index of effectiveness *θ* of the treatment group:

The standard deviation of *θ* is calculated as shown below.

$$stdev(\theta) = \sqrt{\theta^2 \left(\frac{\frac{1}{\sum N_{Obs,after}} + \frac{\sum VAR(N_{EB,after})}{\left(\sum N_{EB,after}\right)^2}}{1 + \sum VAR(N_{EB,after}) \Big/ \left(\sum N_{EB,after}\right)^2} \right)}$$

$$stdev(\theta) = \sqrt{1.024^2 \left(\frac{\frac{1}{377} + \frac{7.368}{135404}}{1 + 81.813 \big/ 135404} \right)} = 0.058$$

- **Step 12: Estimate the 95% upper and lower bounds of *θ*:**

The 95% confidence interval for *θ* is found by adding and subtracting 1.96 times $stdev(\theta)$ from *θ*.

95% Lower bound = θ – (1.96* $stdev(\theta)$) = 1.024 - (1.96*0.058) = 0.909
95% Upper bound = θ + (1.96* $stdev(\theta)$) = 1.024 + (1.96*0.058) = 1.138

APPENDIX D: FRAMEWORK TO IDENTIFY CANDIDATE 70 MPH POSTED SPEED LIMIT LOCATIONS ON RURAL INTERSTATES

This appendix is organized into four sections, which outlines a framework to identify candidate 70 mph posted speed locations on rural Interstates in Pennsylvania. The first section describes how to use geometric design information to assess the existing alignment features. The second section describes how to use the pavement friction models to determine the skid resistance qualities of existing asphalt pavements. The third section discusses performance of a margin of safety assessment. Finally, safety performance functions are demonstrated to assess how they can be used and compared to reported crash histories. Collectively, these metrics can be used to assess the geometric design, friction, and safety performance of existing rural Interstate highways with 65 mph posted speed limits.

Inferred Design Speed

For rural Interstate highways in Pennsylvania, stopping sight distance, vertical curve length, horizontal sightline offset, and horizontal curve-superelevation data may be used to determine the inferred design speed for a roadway section. The process to compute the inferred design speed is described and demonstrated in the "Inferred Design Speed Assessment" section of this report. For the Turnpike, inferred design speeds are plotted in Appendix B of this report. For PennDOT, horizontal and vertical curve data are not available in electronic records. To perform an inferred design speed assessment, data from as-built or roadway construction plans should be acquired, and the inferred design speed methods should be applied. A graphical plot of the data could be displayed in a manner similar to Figure D-1 below.

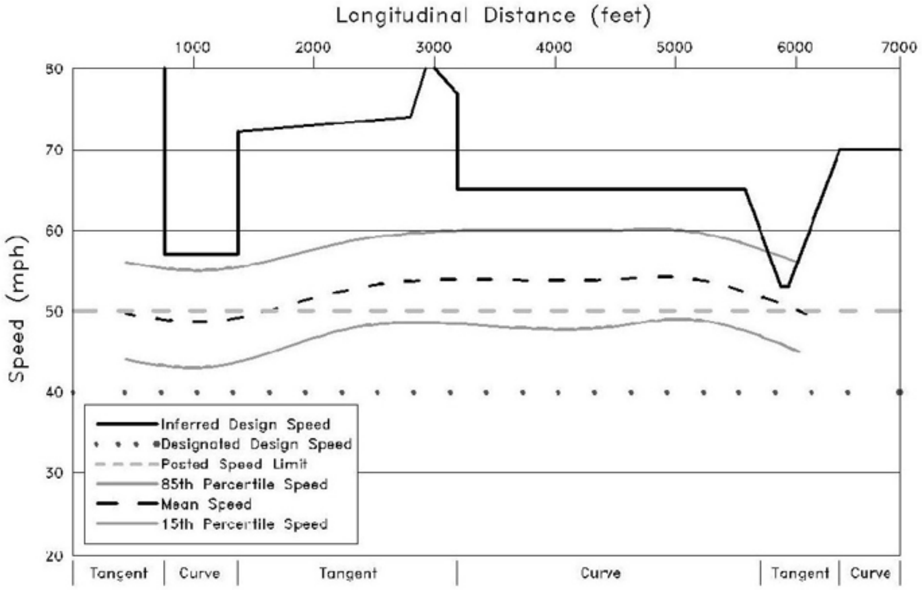

Figure D-1. Plot of Speed Relationships (Donnell et al. 2009)

The inferred design speed is related directly to the geometry of the roadway. The designated design speed, which is the speed used to establish the geometric features of the roadway, only relates to minimum or limiting values of geometric design criteria, and is generally constant for long segments on rural Interstate highways in Pennsylvania. The designated design speed can be plotted and compared to the inferred design speed. If the inferred design speed is equal to or exceeds the designated design speed for all geometric features on a section of rural Interstate highway, this may indicate that the existing roadway section is a candidate for the 70 mph posted speed limit. The posted speed limit can be plotted on the same plot and, if operating speed data are available, they may also be shown on the same plot. The operating speed assessment that was completed for the current study found that mean and 85th-percentile operating speeds increase by 1 to 3 mph when the posted speed limit is increased by 5 mph.

Friction Applications

As noted in the "Pavement Friction Assessment" section of the report, several authors have proposed skid number thresholds that appear to be associated with an increase in wet weather-related crashes. The thresholds range from 23 to 26 for smooth tire tests; a threshold of 32 has been suggested for the ribbed tire in the published research. There were few smooth tire friction numbers available from the Pennsylvania Turnpike that reached the threshold of 26 (only 17 measurements of 780 over several years); however, a friction degradation model was developed for this condition. The survival probabilities from this model are shown in Table D-1.

Table D-1. Probability of Survival for Smooth Tire Friction Number of 26

Traffic Volume Data		Probability of Survival				
		Age (month)				
		P = 0.9	P = 0.8	P = 0.7	P = 0.6	P = 0.5
AADT Range (mph)	Mean (mph)					
< 20,000	10000	>240	>240	>240	>240	>240
20,000 to 30, 000	25000	>240	>240	>240	>240	>240
30,000 to 40, 000	35000	>240	>240	>240	>240	>240
40,000 to 50, 000	45000	>240	>240	>240	>240	>240
50,000 to 60, 000	55000	>240	>240	>240	>240	>240
60,000 to 70, 000	65000	>240	>240	>240	>240	>240
70,000 to 80, 000	75000	>240	>240	>240	>240	>240
80,000 to 90, 000	85000	>240	>240	>240	>240	>240
90,000 to 100, 000	95000	>240	>240	>240	>240	>240
100,000 to 110, 000	105000	240	>240	>240	>240	>240
110,000 to 120, 000	115000	223	>240	>240	>240	>240
>110,000	125000	214	>240	>240	>240	>240

If a transportation agency were to make a policy decision that smooth tire friction numbers would be at least equal to 26 on rural Interstates, Table D-1 can be used to determine the probability that new asphalt pavements, which are similar to the Turnpike design, will last for a certain duration based on the traffic volume of the newly-paved surface. For example, a new asphalt pavement is applied to a roadway segment with an average annual daily traffic of 100,000 to 110,000 vehicles per day. There is a 90 percent probability that this pavement surface will maintain a smooth tire skid number of 26 or greater for 240 months (20 years). With the exception of the highest-volume roadways, there is a 90 percent probability that the smooth tire skid number will be 26 or higher for at least 240 months. It is important to note that, as the skid number threshold increases, the age of the pavement for various survival probabilities will decrease. Consider the survival probabilities for a smooth tire skid number of 30, which is shown in Table D-2.

Table D-2. Probability of Survival for Smooth Tire Friction Number of 30

Traffic Volume Data		Probability of Survival Age (month)				
		P = 0.9	P = 0.8	P = 0.7	P = 0.6	P = 0.5
AADT Range (mph)	Mean (mph)					
< 20,000	15000	>240	>240	>240	>240	>240
20,000 to 30, 000	25000	>240	>240	>240	>240	>240
30,000 to 40, 000	35000	>240	>240	>240	>240	>240
40,000 to 50, 000	45000	>240	>240	>240	>240	>240
50,000 to 60, 000	55000	>240	>240	>240	>240	>240
60,000 to 70, 000	65000	240	>240	>240	>240	>240
70,000 to 80, 000	75000	220	>240	>240	>240	>240
80,000 to 90, 000	85000	194	>240	>240	>240	>240
90,000 to 100, 000	95000	174	>240	>240	>240	>240
100,000 to 110, 000	105000	157	>240	>240	>240	>240
110,000 to 120, 000	115000	143	240	>240	>240	>240
>110,000	125000	132	228	>240	>240	>240

The same roadway segment, with an average annual daily traffic of 100,000 to 110,000 vehicles per day, has a 90 percent probability of maintaining a smooth tire skid number of 30 or higher for 157 months (~13 years). Other look-up tables are provided in the report in case an agency wishes to set the threshold higher than 26 for the smooth tire test.

Alternatively, the friction survival probability tables can be used to assess the skid resistance of existing pavements. Using the same example provided above, assume that the roadway segment with 100,000 to 110,000 vehicles per day has a pavement surface that is seven years old. Because there is a 90 percent probability that the pavement surface will have a smooth tire skid resistance level of 26 or higher for at least 240 months (20 years), this suggests that it will take approximately 13 years for this existing pavement to reach the skid number threshold of 26.

Margin of Safety Assessment

The "Pavement Friction Assessment" section of the report describes a procedure to determine the margin of safety against skidding at horizontal curve locations on rural Interstates. This analysis was completed for the Pennsylvania Turnpike using the data provided (see Appendix A). For rural Interstate segments owned and operated by PennDOT, smooth and ribbed tire friction tests may be conducted on horizontal curve locations. The procedure described in the "Margin of Safety" section of the report can be used to compute the friction supply in curves. Then, the radius of curve and superelevation of the curve can be obtained from as-built or roadway construction plans, and a friction demand for a 70 mph operating speed can be computed. If the friction supply exceeds the demand by a pre-defined threshold, the existing roadway section (with a 65 mph posted speed limit) may be a candidate for the 70 mph posted speed limit.

Safety Applications

The "Safety Evaluation" section of the report includes a section with several PennDOT and Pennsylvania Turnpike safety performance functions. These SPFs were developed using a reference group of sites where the posted speed limit remained at 65 mph throughout the evaluation period. These SPFs are intended to be used in the empirical Bayes (EB) observational before-after evaluation for the treatment sections, where the posted speed limit was raised to 70 mph in the evaluation period. However, there are alternative uses for the SPFs. For rural Interstates in Pennsylvania that currently maintain a 65 mph posted speed limit, the SPFs can be used to assess the safety performance of the roadways. For example, the SPF can be used to estimate the expected number of total or fatal+injury crashes on an existing segment. This can be compared to the reported number of crashes to determine if the segment is experiencing fewer or more crashes than expected. For example, consider the PennDOT total crash SPF below:

$$N_{total} = e^{-2.923} \times L^{0.940} \times AADT^{0.344}$$

where: N_{total} = expected number of total crashes per mile per year for a roadway segment
L = segment length (miles)
$AADT$ = average annual daily traffic (vehicles per day)

Assume that an existing rural Interstate highway, with a posted speed limit of 65 mph, has an average annual daily traffic of 20,000 vehicles per day, and the length of the analysis segment is 5 miles. This roadway segment is expected to experience the following number of total crashes annually:

$$N_{total} = e^{-2.923} \times 5^{0.940} \times 20{,}000^{0.344} = 7.36\, crashes/year$$

Assume that, on average, 10 crashes per year occur on this roadway segment. The difference in reported crashes to expected total crashes is 2 crashes per year. This suggests that the safety performance of this roadway section is worse than for similar rural Interstates that are maintained by the Pennsylvania Department of Transportation. This is one of the factors that may be used when determining sections of the rural Interstate network in Pennsylvania that may be candidates for 70 mph posted speed limits.

Similarly, consider the total crash SPF for 65 mph posted speed limit sections of the Turnpike:

$$N_{total} = e^{-8.885} \times L^{0.871} \times AADT^{1.009} \times e^{-0.522 \times FN} \times e^{0.115 \times DC}$$

where: N_{total} = expected number of total crashes per year for a roadway segment
N_{wet} = expected number of wet weather-related crashes per year for a roadway segment
L = segment length (miles)
FN = friction number indicator (1 if FN is greater than 32; 0 otherwise)
$AADT$ = average annual daily traffic (vehicles per day)
DC = degree of curve

Assume that a roadway section with a 65 mph posted speed limit is one mile long, has a single horizontal curve that is two degrees, and the average annual daily traffic is 20,000 vehicles per day. The smooth tire friction number is 40, so the indicator for this variable is 1. The expected number of total annual crashes is as follows:

$$N_{total} = e^{-8.885} \times 1^{0.871} \times 20{,}000^{1.009} \times e^{-0.522 \times 1} \times e^{0.112 \times 2} = 2.3\, crashes / year$$

If there are, on average, two total crashes reported per year on this segment, there are fewer reported crashes than expected for similar rural Interstate segments on the Turnpike. This is one factor that may be used to consider existing 65 mph posted speed limit sections as candidates for a 70 mph posted speed limit.

Similar computations may be done for PennDOT rural Interstate and Pennsylvania Turnpike sections with existing posted speed limits of 65 mph. A comparison of the reported to expected number of crashes can offer additional insight concerning the feasibility of raising the posted speed limit to 70 mph.