# Indoor Simulator Study and Field Study Evaluation of Sequential Flashing Chevron Signs on Two-lane Rural Highways

## FHWA Safety Program


U.S. Department of Transportation
**Federal Highway Administration**


Safe Roads for a Safer Future
*Investment in roadway safety saves lives*

http://safety.fhwa.dot.gov

## Notice



## Quality Assurance Statement

## TECHNICAL DOCUMENTATION PAGE

| | | |
|---|---|---|
| 1.Report No. FHWA-SA-18-075 | 2. Government Accession No. | 3. Recipient's Catalog No. |
| 4. Title and Subtitle<br>Indoor Simulator and Field Study Evaluation of Sequential Flashing Chevron Signs on Two-lane Rural Highways | | 5. Report Date<br>November 30, 2017 |
| | | 6. Performing Organization Code |
| 7. Author(s)<br>Donnell, E. T., Porter, R. J., Zlatkovic, M., Cooper, J., Li, L., Strayer, D., and Lin, M. | | 8. Performing Organization Report No. LTI 2018-07 |
| 9. Performing Organization Name and Address<br>Thomas D. Larson Pennsylvania Transportation Institute<br>The Pennsylvania State University<br>201 Transportation Research Building<br>University Park, PA 16802 | | 10. Work Unit No. |
| | | 11. Contract or Grant No. |
| 12. Sponsoring Agency Name and Address<br>U.S. Department of Transportation<br>Federal Highway Administration<br>Office of Safety<br>1200 New Jersey Avenue, SE<br>Washington, DC 20590 | | 13. Type of Report and Period<br>Final Report 10/1/12-9/30/18 |
| | | 14. Sponsoring Agency Code:<br>FHWA - HSA |
| 15. Supplementary Notes.<br>The Contract Officer's Technical Representative was Joseph Cheung (joseph.cheung@dot.gov). | | |

16. Abstract Past research has found that the average crash rate along horizontal curves of two-lane rural highways is three times higher than on tangent road segments. Single-vehicle run-off-road crashes are four times more likely on horizontal curves relative to tangent roadway sections. One sign application that offers potential safety improvements along horizontal curves on two-lane rural highways is the Sequential Dynamic Curve Warning System (SDCWS), which uses solar powered flashing lights embedded in the sign to delineate the curve. The flashing lights can be simultaneous (i.e., each sign is flashing at the same time as the other signs) or a sequence of lights moving toward or away from the driver. The purpose of this study was to identify the optimal flash rate, speed-activation threshold, and flashing sequence when deploying the SDCWS along horizontal curves on two-lane rural highways. This was accomplished using two independent evaluations. A driver simulator study was undertaken to identify several SDCWS settings that produced the lowest operating speeds along a horizontal curve on two-lane rural highways. The results of this effort found that a low flash rate and a flashing pattern moving away from the driver, as well as a high flash rate with a simultaneous flashing pattern, produced the desirable speed reduction effects on study participants. A field study was then undertaken to further assess the flash rate and flashing patterns identified in the simulator study. Four different conditions were studied in the field, including a speed-activation threshold that was either 5 or 10 mph above the curve advisory speed, two different flash rates, and two different flashing patterns. These conditions were compared to a baseline condition (static chevron signs) and to the settings used in a previous study. The findings, based on comparisons to a previous study at the same sites, indicate that a flashing pattern away from the driver, at a 1 Hz flashing rate, with a speed-activation threshold equal to the curve advisory speed, was the optimal setting for the SDCWS, based on several speed-based performance metrics.

| | | | |
|---|---|---|---|
| 17. Key Words: Operating speed, driving simulator, sequential flashing chevrons, two-lane rural highways | | 18. Distribution Statement | |
| 19. Security Classif. (of this report)<br>Unclassified | 20. Security Classif. (of this page)<br>Unclassified | 21. No. of Pages:<br>115 | 22. Price |

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

# SI* (MODERN METRIC) CONVERSION FACTORS

## APPROXIMATE CONVERSIONS TO SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | 25.4 | millimeters | mm |
| ft | feet | 0.305 | meters | m |
| yd | yards | 0.914 | meters | m |
| mi | miles | 1.61 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 645.2 | square millimeters | $mm^2$ |
| $ft^2$ | square feet | 0.093 | square meters | $m^2$ |
| $yd^2$ | square yard | 0.836 | square meters | $m^2$ |
| ac | acres | 0.405 | hectares | ha |
| $mi^2$ | square miles | 2.59 | square kilometers | $km^2$ |
| | | **VOLUME** | | |
| fl oz | fluid ounces | 29.57 | milliliters | mL |
| gal | gallons | 3.785 | liters | L |
| $ft^3$ | cubic feet | 0.028 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.765 | cubic meters | $m^3$ |
| | NOTE: volumes greater than 1000 L shall be shown in $m^3$ | | | |
| | | **MASS** | | |
| oz | ounces | 28.35 | grams | g |
| lb | pounds | 0.454 | kilograms | kg |
| T | short tons (2000 lb) | 0.907 | megagrams (or "metric ton") | Mg (or "t") |
| | | **TEMPERATURE (exact degrees)** | | |
| °F | Fahrenheit | 5 (F-32)/9 or (F-32)/1.8 | Celsius | °C |
| | | **ILLUMINATION** | | |
| fc | foot-candles | 10.76 | lux | lx |
| fl | foot-Lamberts | 3.426 | candela/$m^2$ | cd/$m^2$ |
| | | **FORCE and PRESSURE or STRESS** | | |
| lbf | poundforce | 4.45 | newtons | N |
| lbf/$in^2$ | poundforce per square inch | 6.89 | kilopascals | kPa |

## APPROXIMATE CONVERSIONS FROM SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimeters | 0.039 | inches | in |
| m | meters | 3.28 | feet | ft |
| m | meters | 1.09 | yards | yd |
| km | kilometers | 0.621 | miles | mi |
| | | **AREA** | | |
| $mm^2$ | square millimeters | 0.0016 | square inches | $in^2$ |
| $m^2$ | square meters | 10.764 | square feet | $ft^2$ |
| $m^2$ | square meters | 1.195 | square yards | $yd^2$ |
| ha | hectares | 2.47 | acres | ac |
| $km^2$ | square kilometers | 0.386 | square miles | $mi^2$ |
| | | **VOLUME** | | |
| mL | milliliters | 0.034 | fluid ounces | fl oz |
| L | liters | 0.264 | gallons | gal |
| $m^3$ | cubic meters | 35.314 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.307 | cubic yards | $yd^3$ |
| | | **MASS** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.202 | pounds | lb |
| Mg (or "t") | megagrams (or "metric ton") | 1.103 | short tons (2000 lb) | T |
| | | **TEMPERATURE (exact degrees)** | | |
| °C | Celsius | 1.8C+32 | Fahrenheit | °F |
| | | **ILLUMINATION** | | |
| lx | lux | 0.0929 | foot-candles | fc |
| cd/$m^2$ | candela/$m^2$ | 0.2919 | foot-Lamberts | fl |
| | | **FORCE and PRESSURE or STRESS** | | |
| N | newtons | 0.225 | poundforce | lbf |
| kPa | kilopascals | 0.145 | poundforce per square inch | lbf/$in^2$ |

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

# TABLE OF CONTENTS

# LIST OF TABLES

# LIST OF FIGURES

# LIST OF ABBREVIATIONS

| | |
|---|---|
| AADT | annual average daily traffic (vehicles per day) |
| AS | advisory speed along a horizontal curve (miles per hour) |
| DCWS | dynamic curve warning signs |
| DSDS | dynamic speed display signs |
| FHWA | Federal Highway Administration |
| ITE | Institute of Transportation Engineers |
| MC | midpoint of a simple horizontal curve |
| MOE | measures of effectiveness |
| MUTCD | Manual on Uniform Traffic Control Devices |
| OBS | number of observations in a sample of operating speeds |
| OLS | ordinary least squares |
| PC | point of curvature, or the beginning of a simple horizontal curve |
| PSL | posted speed limit |
| PT | point of tangency, or the end of a simple horizontal curve |
| SD | standard deviation of observed operating speed (miles per hour) |
| SDWCS | Sequential Dynamic Curve Warning System |
| TAPCO | Traffic Parking and Control Company |
| TCDs | traffic control devices |

# EXECUTIVE SUMMARY

Past research has found that the average crash rate along horizontal curves of two-lane rural highways is three times higher than on tangent road segments. Single-vehicle run-off-road crashes are four times more likely on horizontal curves relative to tangent roadway sections. A recent FHWA publication, *Low-cost Treatments for Horizontal Curve Safety*, offers guidance concerning the safety effects of various countermeasures intended to mitigate roadway departure crashes along horizontal curves. One sign application that was shown to offer potential safety improvements along horizontal curves on two-lane rural highways was the Sequential Dynamic Curve Warning System (SDCWS). The SDCWS is a series of horizontal curve chevron signs with solar-powered flashing lights embedded in the sign. The flashing lights can be simultaneous (i.e., each sign is flashing at the same time as the other signs) or a sequence of lights moving toward or away from the driver.

The purpose of this study was to identify the optimal flash rate, speed-activation threshold, and flashing sequence when deploying SDCWS along horizontal curves on two-lane rural highways. This was accomplished using two independent evaluations. A driver simulator study was undertaken to identify several SDCWS settings that produced the lowest operating speeds along a horizontal curve on two-lane rural highways. The results of this effort indicate that a low flash rate and a flashing pattern moving away from the driver, as well as a high flash rate with a simultaneous flashing pattern, produced the desirable speed reduction effects on study participants.

A field study was then undertaken to further assess the flash rate and flashing patterns identified in the simulator study. Four different conditions were studied in the field, including a speed-activation threshold that was either 5 or 10 mph above the curve advisory speed, two different flash rates, and two different flashing patterns. These conditions were compared to a baseline condition (static chevron signs) and to the settings used in a previous study. The findings, based on comparisons to a previous study at the same sites, indicate that a flashing pattern away from the driver, at a 1-Hz flashing rate, with a speed-activation threshold equal to the curve advisory speed, was the optimal setting for the SDCWS.

# CHAPTER 1. INTRODUCTION

In 2015, there were nearly 6.3 million police-reported crashes, resulting in 35,092 fatalities and more than 2.4 million injuries, on highways and streets in the United States.(NHTSA 2015) More than 30 percent of all fatal crashes involved a single vehicle and occurred off of the roadway. There are a variety of factors that contribute to a roadway departure, many of which are related to the driver. One plausible safety management approach aims to prevent vehicles from leaving the roadway via use of traffic control devices.

A comprehensive, four-state study by Glennon et al. found that the average crash rate for horizontal curves on two-lane rural highways is three times higher than on tangent road segments.(Glennon et al. 1985) The authors also found that the average single-vehicle, run-off-road (SVROR) crash rate was four times higher on horizontal curves than on tangent segments. The severity of roadway departure crashes on horizontal curves was also higher than roadway departure crashes on tangent segments.

A recent FHWA publication, *Low-cost Treatments for Horizontal Curve Safety* offers guidance concerning the safety effects of various countermeasures intended to mitigate roadway departure crashes along horizontal curves.(Albin et al. 2016) The authors identified many strategies that could be implemented individually, or in combination, to reduce roadway departure crashes on horizontal curves. The strategies could generally be classified as pavement markings, signs, roadway surface countermeasures, roadside countermeasures, and intersection treatments.

One sign application that was shown to offer potential safety improvements along horizontal curves on two-lane rural highways was the SDCWS. Figure 1 shows a sample application of the SDCWS along a horizontal curve. The SDCWS is a series of horizontal curve chevron signs with solar-powered flashing lights embedded in the signs. The flashing lights can be simultaneous (i.e., each sign is flashing at the same time as the other signs) or a sequence of lights moving toward or away from the driver. In the latter case, this is typically accomplished by having each sign flash at least once per second, with each flash lasting at least 100 milliseconds. Each sign begins flashing at a time that is offset relative to the adjacent sign, producing a sequential flashing effect.

A recent study by Smadi et al. evaluated the speed and safety effects of the SDCWS at 12 horizontal curve locations on two-lane rural highways.(Smadi et al. 2015) The signs were installed in Missouri, Texas, Washington, and Wisconsin. The Traffic Parking and Control Company (TAPCO) version of the sign was deployed at each study site location. All curves selected for treatment with SDCWS were on two-lane rural paved roads with a posted speed limit of 50 mph or higher, existing chevrons, a high crash history, and travel speeds that often exceeded the advisory or regulatory speed limit. All installations of SDCWS at the curves occurred between June and September of 2012.

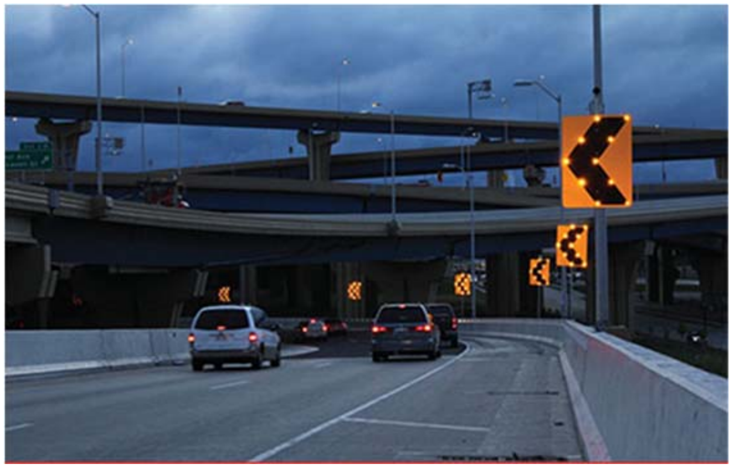


**Figure 1. Photo. Sequential dynamic curve warning system.**

**(Source: http://www.fhwa.dot.gov/hfl/partnerships/safety_eval/brochure_tapco.cfm)**

Speed data were collected before installation as well as 1 month, 12 months, 18 months, and 24 months after installation of the SDCWS. Crash data were also compiled for each of the SDCWS and control sites, including five years before and two years after implementation. The results showed that vehicle operating speeds were lower at the beginning and midpoint of horizontal curves for all periods after the SDCWS were installed. The mean and 85th-percentile speeds were 1.1 to 1.7 mph lower in the 1 month, 12 month, 18 month, and 24 month periods after installing the SDCWS. The results were generally consistent when comparing speeds at the beginning and the midpoint of horizontal curves. The percentage of vehicles exceeding the posted and advisory speed limits was also lower after installing the SDCWS, and the results were generally consistent across all time periods after implementation. The change in the fraction of vehicles exceeding the advisory speed by 20 mph or more decreased by an average of 32 percent at the beginning of the horizontal curve. Similarly, the change in the fraction of vehicles exceeding the advisory speed by 15 mph or more decreased by an average of 30 percent at the beginning of the horizontal curve. The fraction of vehicles exceeding the advisory speed by 20 mph or more at the midpoint of the curve decreased by 26 percent, while the fraction of vehicles exceeding the advisory speed by 15 mph or more declined by 16 percent after SDCWS installation. The results of the study suggest that SDCWS have a long-term and consistent effect on vehicle operating speeds. While the magnitude of the effect was relatively small, there was a pronounced effect on those vehicles substantially exceeding the advisory speed.

The Smadi et al. study considered a sequential flashing pattern that moved away from the driver.[Smadi et al. 2015] Each chevron sign was programmed to flash for at least one second with a flash "on" time of 100 milliseconds. If at least nine chevron signs existed in an array along a horizontal curve, the array was subdivided into two separate groups in which the separate groups flashed in harmony (e.g., the first and fifth signs of nine flashed at the same time, followed by the second and sixth signs, etc.).

The purpose of the present study was to identify, using an indoor driving simulator study, a set of flashing patterns, rates, and sequences that produced speed reductions when traveling from an approach tangent into a horizontal curve. The patterns were then assessed in a field study and compared to the pattern, sequence, and flash rates used in the Smadi et al. study.[(Smadi et al. 2015)] The intent of the effort was to identify the optimal combination of flash rates, speed-activation thresholds, and flash sequences that minimized operating speeds along horizontal curves along two-lane rural highways. By lowering operating speeds, it is inferred that traffic safety may also improve.

The following acronyms and terms are used frequently throughout the remainder of this report and are defined as follows:

- $85^{th}$-percentile speed: The speed at which 85 percent of the motor vehicles are traveling at or below (mph).
- Lane departure: An event in which a least one vehicle tire leaves the intended travel lane by crossing over a longitudinal pavement marking.
- Operating speed: The speed at which motor vehicles are observed traveling on a given roadway during free-flow conditions (mph).
- Posted speed limit (PSL): The maximum speed that can be legally driven on a given roadway. The speed limit is typically posted on regulatory signs (mph).
- Vehicle lateral position: The position of the vehicle in the travel lane, which is measured from the center of the travel lane to the lateral center of the vehicle

This report is organized into five subsequent chapters. Chapter 2 critically reviews the extant literature related to SDCWS. Chapter 3 describes the indoor driving simulator study, while Chapter 4 explains the field evaluation of SDCWS. Chapter 5 offers a discussion and conclusions from the studies.

# CHAPTER 2. LITERATURE REVIEW

The literature review is organized into three sections. The first section describes field studies of dynamic curve warning signs, which are similar to the sequential flashing chevron signs evaluated in the present study. The second section includes a review of speed feedback signs, which are another form of communication to drivers, warning of instances when operating speeds exceed the posted speed limit. The third section summarizes several studies related to speed-activated signs in work zones, which also communicate instances when driving speeds exceed work zone speed limits.

## DYNAMIC CURVE WARNING SIGNS

The impact of dynamic curve warning signs (DCWS) on vehicle operating speeds has been investigated by many researchers in recent years. Most of the studies have demonstrated the effectiveness of DCWS using observational before-after field studies. The focus of this review is on the effectiveness of DCWS when applied along horizontal curves of two-lane rural highways.

Preston and Schoenecker evaluated the effectiveness of DCWS in reducing vehicle operating speeds on County Highway 54 in Minnesota.[(Preston and Schoenecker 1999)] The site was a two-lane rural highway with a 55 mph posted speed limit. The AADT was approximately 3,250 vehicles per day. The advisory speed on the static curve warning sign was 40 mph. The DCWS system had a changeable message sign and a radar unit. During the morning, midday, and evening peak periods, the dynamic sign was activated and displayed the message “CURVE AHEAD.” If the radar detected vehicles traveling above 53 mph, the vehicle was recorded for 18 seconds. In addition, during the time when the sign was activated, the message “CURVE AHEAD, REDUCE SPEED” was randomly displayed to approaching vehicles that exceeded 53 mph. The operating speeds were measured when the vehicles were entering and navigating the curve. The data were collected during a two-week period with only the static signs in place and a two-week period when the DCWS were activated. The results indicated that the difference between the highest and lowest speeds of vehicles entering and navigating the curve was 12.3 mph, which was produced by the sequential message “CURVE AHEAD, REDUCE SPEED.” In the static sign condition, the difference between the highest and lowest operating speed was 11.5 mph. Among the sample of vehicles traveling faster than 60 mph, the dynamic sign was more effective in reducing operating speeds than the static sign. In addition, 35 percent of vehicles exposed to only the static sign were unable to successfully navigate the curve within the limits of the lane lines, while only 26 percent of vehicles encountering the “CURVE AHEAD, REDUCE SPEED” dynamic sign were unable to navigate the curve within the limits of the lane lines.

Tribbett evaluated the effectiveness of five dynamic curve warning systems in the Sacramento River Canyon.[(Tribbett 2000)] The study area was located in mountainous terrain and experienced high heavy truck crash frequencies. The traffic volumes at the study sites ranged from 7,650 to 9,300 vehicles per day. The posted speed limits at the five sites ranged from 55 to 65 mph. The DCWS included a radar detector and a changeable message sign to display the site-specific advisory speed (50 mph or 60 mph) and warning information. The message was displayed on a light-emitting diode (LED) sign. Each DCWS had a specific message. The messages could be rotated every 3 to 4 seconds, managed by the controller. The study focused on determining the effectiveness of DCWS on reducing vehicle operating speeds, crashes, and erratic driving maneuvers. The speed data were collected at the DCWS location and at the beginning of the horizontal curve, before and after the DCWS system was installed. The data collection period included 9 months prior to DCWS installation and during three time periods after installation of DCWS. The first after-period condition was immediately after the DCWS was installed, while the next two after-period data collection periods occurred 3 and 8 months after DCWS installation, respectively. The analysis of operating speeds at the point of curvature (PC) showed that there was a statistically significant reduction in mean truck speed at site #1 (from 2.4 to 5.4 mph), site #3 (from 1.9 to 3.7 mph), and site #5 (4.5 mph for one time period). For mean passenger car speeds, there was a statistically significant reduction at site #1 (from 3.0 to 4.5 mph), site #3 (from 5.2 to 7.8 mph), site #4 (1.4 mph for one time period), and site #5 (from 2 to 3 mph) after the DCWS were installed.

A speed-activated curve warning sign was tested in the United Kingdom by Winnett and Wheeler.[(Winnett and Wheeler 2002)] The curve warning message "SLOW DOWN" was activated if the vehicle speed exceeded a preset threshold, which was equal to the $50^{th}$-percentile operating speed of traffic. The signs were placed on two-lane roads before a horizontal curve. The study sites were located in Norfolk (30 sites), West Sussex (4 sites), Wiltshire (4 sites), and Kent (5 sites). The posted speed limits on these roads ranged from 20 to 60 mph. The operating speeds were measured at downstream locations close to the vehicle-activated signs. Operating speed data were collected using loop or tube detectors before sign installation, and 1 month and 1 year after installation. The results showed that the DCWS reduced the mean speed by 2.1 mph at the West Sussex sites, 3.0 mph at the Wiltshire sites, and 6.9 mph at the Norfolk sites. The study concluded that the speed-activated signs are very effective in reducing vehicle operating speeds as well as the proportion of vehicles exceeding the posted speed limit.

Monsere and Bertini evaluated the effectiveness of DCWS on Interstate 5 near Myrtle Creek in Oregon.[(Monsere and Bertini 2005,2006)] The sites were located along a section of roadway with a 50 mph posted speed limit, and an advisory speed of 45 mph. The system displayed a warning message such as "Caution, Sharp Curves Ahead" or "Slow Down, Your Speed Is xx mph" or "Slow Down, Your Speed Is Over 70 mph" on the dynamic signs based on the operating speed of approaching vehicles. Vehicle operating speed data were collected approximately 420 ft downstream of the sign in the northbound direction (some data were collected 114 ft upstream). For the southbound traffic, data were collected upstream of the sign. The data were collected before and after installation of the DCWS. The statistical analysis indicated that, in terms of the mean speed of vehicles traversing the curve, both passenger car and truck operating speeds were reduced by 3 mph in the southbound and 2 mph in the northbound direction. In the zone following the sign location, the maximum mean speed reduction in the southbound was 3.3 mph for passenger cars and 3.0 mph for commercial vehicles. In the northbound direction, the mean speed reduction was 2.6 mph for passenger cars and 1.9 mph for commercial vehicles. The distribution of vehicles in different speed bins differed, and the difference was statistically significant. A lower number of vehicles fell into higher speed bins (> 55 mph), and a higher concentration of vehicles traveled near the mean speed of traffic. Diercksen et al. conducted a second evaluation of this system four years after the installation.(Diercksen et al. 2008) This evaluation found that the speed reduction associated with the DCWS increased. When considering the northbound direction, the mean speed of traffic three years after installing the DCWS was 2 mph lower than the mean operating speed four months after DCWS installation, and lower than the before period by 4 mph.

Vest evaluated the effect of several types or combinations of curve warning signs on vehicle operating speeds when traversing a horizontal curve at three test sites in Kentucky.(Vest 2005) The site characteristics included a sharp horizontal curve on a rural highway, high history of speed-related incidents, long tangent section approaching the horizontal curve, no substantial vertical grade, and no intersections, driveways, or commercial activity that could adversely affect operating speed data. All of the sites had a horizontal alignment sign with an advisory speed plaque in advance of the curve for the existing condition. Several curve warning signs were added to the existing condition to represent the treatment condition. These included a one-direction large arrow sign, chevron alignment sign, the combination of horizontal alignment sign and advisory speed sign, existing warning sign with and without flags, and a new combination sign with flashing lights, post delineators, and transverse lines. Speeds were measured at locations along the approach tangent, PC, and midpoint of the curve. The study estimated the effectiveness of each treatment. In addition, one year after these treatments were tested, additional treatments were added to the sites, including rumble strips and the combination of rumble strips, as well as treatments from the initial field implementation of speed-reduction countermeasures. The study indicated that most treatments have the potential to reduce vehicle operating speeds within the horizontal curve. The most effective treatments were the combination of the horizontal curve and advisory speed signs, flashing lights on both existing and new warning signs, transverse lines, rumble strips, and post delineators. Comparing the combination of all proposed treatments and the existing condition, the mean operating speed at the midpoint of the curve decreased by 0.6 to 7.1 percent. The 85$^{th}$-percentile operating speed at the midpoint of the curve was reduced by 0.7 to 6.1 percent. In addition, the average speed of those vehicles exceeding the 85$^{th}$-percentile speed at the center of the curve was reduced by -0.2 to 7.8 percent when a combination of signs was used to delineate the horizontal curve.

The City of Bellevue, Washington, installed and evaluated 31 dynamic speed feedback signs, including two curve advisory warning signs on urban arterials.(The City of Bellevue, Washington 2009) The posted speed limit on these roads was 35 mph and the advisory speed was 25 mph. Operating speeds were detected using radar, which was displayed on the sign if the vehicle traveled faster than a pre-set threshold of 31 mph. The operating speed was measured at the location of the sign in advance of the curve. Data were collected before and during a period of 18 months to 2 years after installation. The results showed that the 85$^{th}$-percentile operating speed was reduced by 3.3 mph at one site and by 3.5 mph at another site, four months after the speed feedback sign installation.

Knapp and Robinson evaluated the vehicle speed impact of DCWS on low-volume rural local highways in Minnesota.(Knapp and Robinson 2012) The sites were two-lane rural highways with posted speed limits of 40 to 55 mph and an advisory speed warning of 40 or 50 mph. The speeds were measured at three locations within each site, including a control point on the approach tangent, PC, and within the horizontal curve. The speed data were collected 1 month before DCWS installation and 1 month, 6 months, 1 year, and 18 months after installation at three sites. The before-after study showed that the unadjusted average speed reduction was 1.0 to 8.8 mph at the PC and 1.8 to 6.3 mph within the curve after installation of DCWS. The study also concluded that the signs had a larger proportional impact on higher-speed vehicles compared to vehicles traveling closer to the advisory speed. For the site that had the advisory speed of 40 mph, the percentage of vehicles traveling at least 5 mph above the advisory speed decreased by 26.8 percent, while the percentage of vehicles traveling more than 20 mph above the advisory speed decreased by 87.4 percent. For the site that had an advisory speed of 50 mph, the percentage of vehicles traveling at least 5 mph above the advisory speed declined by 44.7 percent, while the percentage of vehicles traveling at least 20 mph higher than the advisory speed decreased by 61.2 percent.

Montella studied driver behavior along horizontal curves on rural two-lane highways in relation to different traffic control devices, including static curve warning signs, curve warning signs with flashing beacons, and curve warning signs with driver speed feedback displays.[(Montella 2015)] A dynamic driving simulator experiment was performed on a route with three horizontal curves and a 70 km/h (45 mph) posted speed limit. The curve warning signs were placed 150 m (500 ft) before the curve with transverse rumble strips 75 m (250 ft) before the curve. The mean speeds were recorded 500 m (1,640 ft), 350 m (1,150 ft), 200 m (660 ft), and 100 m (330 ft) before the curve, and at the PC, 1/4 curve, mid-curve, 3/4 curve, and PT locations, as well as 100 m, 200 m, 350 m, and 500 m after the curve. The results showed that, when comparing the scenario with the curve warning sign alone, adding flashing beacons produced deceleration 120 m (390 ft) further ahead of the curve. Adding a driver feedback sign produced a deceleration 60 m (200 ft) further ahead of the curve.

Hallmark evaluated the effectiveness of DCWS at 22 horizontal curve locations on rural two-lane highways in Arizona, Florida, Iowa, Ohio, Oregon, Texas, and Washington.[(Hallmark 2015)] The posted speed limits on these roads ranged from 50 to 70 mph, and the advisory speeds ranged from 15 to 50 mph. The system consisted of a curve warning sign and a speed feedback sign. The curve warning sign was activated by a vehicle traveling above the $50^{th}$-percentile speed and displayed the warning message "SLOW DOWN." The speed feedback sign was activated by a vehicle traveling above the $50^{th}$-percentile speed and displayed "YOUR SPEED XX" and the message changed to "SPEED LIMIT XX" if the vehicle traveled 20 mph or more over the posted speed limit. The speeds were measured at locations one-half mile prior to the curve, PC, and midpoint of the curve. The data were collected before the signs were installed and during time periods 1, 12, and 24 months after installation. The results showed that, for both trucks and passenger cars, the mean operating speeds were reduced by 1.8 mph 1 month after installation, 2.6 mph 12 months after installation, and 2.0 mph 24 months after installation, when measured at the PC location. At the midpoint of the curve, the mean speed reductions were 2.1 mph, 1.7 mph, and 1.8 mph during periods 1 month, 12 months, and 24 months after DCWS installation. When considering the 85th-percentile operating speed, the speed reductions were between two and three mph at the PC location during the periods 1 month, 12 months, and 24 months after DCWS installation. At the midpoint of the horizontal curve, the 85th-percentile speed reductions were 2.5 mph 1 month after DCWS installation, 1.6 mph 12 months after DCWS installation, and 1.9 mph 24 months after DCWS installation. The percentage of vehicles exceeding the posted speed limit decreased by approximately 70 percent at the PC and mid-curve locations after installing the DCWS.

Smadi investigated the effectiveness of the SDWCS at 12 horizontal curve locations on two-lane rural highways in Iowa, Missouri, Texas, Washington, and Wisconsin.(Smadi et al. 2015) The posted speed limit on these roads ranged from 55 to 60 mph, and the advisory speeds ranged from 25 to 40 mph. The SDCWS consisted of an advance curve warning sign ahead of the curve and an array of sequential flashing chevrons along the outside of the horizontal curve. When the approaching vehicle speeds exceeded the curve advisory speed, the chevrons would flash sequentially at a frequency of once per second. The data were collected at these sites before installation of the signs, and 1 month, 12 months, 18 months, and 24 months after installation of the SDCWS. The speeds were measured upstream approximately 500 to 1,000 ft prior to the curve, PC location, and at the center of the horizontal curve. Only passenger cars were included in the before-after analysis. The results showed that the change in mean speed was consistent between all data collection periods. The speed reduction at the PC was 1.7 mph 1 month after implementation and 1.3 mph during the periods 12 and 18 months after implementation. The 85th-percentile speeds at the PC also decreased 1.7 mph 1 month after implementation of the SDCWS. The analysis also indicated that there were reductions in the percentage of vehicles exceeding the posted speed limit or curve advisory speed by 5, 10, 15, and 20 mph, particularly in the higher ranges. On average, the percentage of vehicles exceeding the curve advisory speed by 5 mph decreased by 11 percent. The percentage of vehicles exceeding the curve advisory speed by 10 mph, 15 mph, and 20 mph decreased by 22 percent, 30 percent, and 32 percent, respectively, after the SDCWS were installed.

In summary, the speed reductions associated with DCWS occurred upstream prior to the curve, at the PC location, and at the midpoint of horizontal curves on two-lane rural highways. The reduction has been observed for both passenger cars and trucks. The metrics used to quantify the reduction were mean and 85th-percentile operating speeds and the percentage of vehicles exceeding the posted speed limit. For both passenger cars and trucks, the mean speed reduction associated with DCWS ranged from 1.4 to 7.8 mph before the beginning of a horizontal curve, 1.3 to 2.9 mph at the PC location, and 1.7 to 2.1 mph at the midpoint of the horizontal curve. The 85th-percentile speed reductions ranged from 1.7 to 2.9 mph at the PC location and 1.9 to 2.5 mph at the midpoint of the curve. Furthermore, past studies found that DCWS are associated with a reduction in the percentage of vehicles exceeding the posted speed limit and curve advisory speeds on two-lane rural highways.

## SPEED FEEDBACK SIGNS

The 3M Company carried out a before-after observational study of speed feedback signs implemented along two single-lane, one-way streets in Durham, and 10 sites including two-lane rural roads, in Doncaster, United Kingdom.[3M Company 2006] The posted speed limits were 40 mph at all sites. Vehicle operating speeds were measured before and after the speed feedback signs were installed, at a location prior to the sign. The study showed that the 85$^{th}$-percentile operating speed was reduced by up to 15 percent at the study sites.

Cruzado and Donnell evaluated the effectiveness of dynamic speed display signs (DSDS) on rural two-lane highway transition zones in Pennsylvania.[Cruzado and Donell 2009] The posted speed limits were 45 to 55 mph at all study sites. Vehicle operating speed data were collected at 12 transition zones during three periods: before implementation, during the first week that the DSDS were in use, and one week after the DSDS were removed. The speeds were measured 0.5 miles upstream of the DSDS, adjacent to the DSDS, and 500 ft downstream of the DSDS. The results indicated that the dynamic speed display signs reduced mean operating speeds by an average of 6 mph. However, the speed reduction associated with the DSDS dissipated after the devices were removed from the sites.

Santiago-Chaparro evaluated the effectiveness of speed feedback signs along a two-lane rural highway in Wisconsin.[Santiago-Chaparro 2012] Operating speed trajectories of vehicles approaching and passing the signs were collected. The study verified the effect of speed feedback signs on reducing the operating speed of vehicles. At the upstream location, more than 50 percent of vehicles lowered their operating speed by at least one mph. This proportion of drivers reduced their speed 1,200 to 1,400 ft upstream of the speed feedback signs. However, after passing the speed feedback sign location, more than 50 percent of the observed vehicles increased their operating speed by at least one mph, indicating that the presence of speed feedback signs has a positive effect on vehicles as they approach the sign, but a diminished effect immediately after the vehicle passes the sign.

## WORK ZONE SPEED-ACTIVATED SIGN

Fontaine conducted a before-after study to assess the effectiveness of a portable speed display sign in Texas.[Fontaine, 2000] The work zone had a posted speed limit of 70 mph. The speed data were collected at two sites. The study found that mean passenger car speeds were reduced by 2 to 9 mph, and mean truck speeds were reduced by 3 to 10 mph, when the portable speed display sign was present in a work zone, relative to no speed display sign. The percentage of cars exceeding the posted speed limit decreased by 15 percent after the portable speed display sign was activated.

Mattox evaluated the effectiveness of a work zone speed-activated warning system in South Carolina.[Mattox, 2008] The system included a radar detector, fixed-message sign, speed-activated sign, and flashing beacon. The speed-activated sign and flashing beacon were activated if vehicles exceeded the speed threshold, which was 3 mph above the posted speed limit. The three sites were on secondary highways with a work zone speed limit of 45 mph. The speeds were measured before, adjacent to, and after the speed-activated sign. The study found that the reduction in mean operating speed ranged from 2 to 6 mph with an average of 3.3 mph for all sites. At the sites where more than 50 percent of vehicles were speeding before implementation of the warning system, the mean speed reduction was 4.1 mph.

Sun investigated the effect of sequential lights at nighttime work zones.[(Sun 2012)] The lights were expected to improve driver recognition of lane closures and work zone tapers. Vehicle lateral position, vehicle merge location data, and speed data were collected on three short-term work zones on Interstate 70 in Missouri. The three sites involved a right-lane closure, so traffic operated in the passing lane only. The speed limit in the work zone was 60 mph. Operating speed data were collected upstream of the tapers. The results showed that the sequential lights were associated with a decrease in mean operating speed of 2.2 mph for all vehicles, 2.2 mph for passenger cars, and 2.5 mph for trucks. The decrease in the 85$^{th}$-percentile speed was 1.0 mph for all vehicles, 1.0 mph for passenger cars, and 1.0 mph for trucks. In addition, the driver speed compliance rate increased by 6.7 percent at night.

# CHAPTER 3. INDOOR SIMULATOR EVALUATION

## INTRODUCTION AND BACKGROUND

This section of the report describes the methodologies, data, and findings from a driving simulator evaluation of speed-activated traffic control devices (TCDs) on horizontal curves along rural, two-lane roads. A previous simulator study found that post delineators with lights that moved toward approaching drivers were the most effective treatment for reducing speeds on horizontal curves.[Molino et al. 2010] "Toward the driver" flashing patterns are intended to provide drivers with an exaggerated sense of their speed. Some "toward the driver" sequencing patterns are programed to flash at slower and slower rates as drivers reduce their speed.[Carson et al. 2008] The authors of the referenced simulator study recommended field validation; however, field study conclusions at this stage have been limited to the devices and flashing sequences installed at the treatment sites. Significant knowledge gaps still remain. Total effects and relative effects of varying flash rates, sequencing patterns, and speed thresholds are still unknown. Steps toward filling these knowledge gaps were explored in the present simulator study and were further field tested in a subsequent field study (see Chapter 4 of this report). The objective of this simulator study was to identify optimum flash rates, sequencing patterns, and thresholds for speed-activated TCDs on horizontal curves along rural, two-lane roads. The number of sequencing variables involved (e.g., flash rate, flash duration, sequencing direction) made a driving simulator study a strong methodological alternative to inform follow-on field-testing that is described in Chapter 4 of this report.

A driving simulator located in the University of Utah's Utah Traffic Lab was used to conduct the simulator study. The Utah Traffic Lab simulator was built by AAI, a contractor specializing in advanced human simulation systems and consultant to FHWA. The driving simulator was built with a custom VISSIM interface to pass traffic, car-following, lane changing, and signal data in real time. The driving simulator draws on metrics generated by VISSIM, scenarios coded in CREATOR, and representations generated by ARCHER. Calibrated VISSIM models can be replicated in the driving simulator to study driver behavior in traffic conditions observed in the field at different points in time (e.g., during morning peak, afternoon peak, evening peak, night). Most applicable to this study, the VISSIM connection was used to vary the flashing characteristics of the studied treatments. The VISSIM connection was also used to gather operational measures of interest (e.g., speed profile, lane position). The Utah Traffic Lab simulator has an "open" driver cockpit, three 55-inch full HD LCD based TVs, and three 7-inch LCD displays representing rear-view and side mirrors.

The Utah Traffic Lab driving simulator includes a model of a six-mile-long stretch of Pennsylvania Route 851. This is a rural, two-lane road in Pennsylvania with significant horizontal curvature along the alignment. It has been used for previous FHWA research efforts and is shown in figure 2. The Utah Traffic Lab established a VISSIM connection to this scenario, which was then used to control the flashing sequences and rates on the TCDs. The PA Route 851 scenario was ultimately used for the simulator experiments conducted during this research based on input received during the kick-off meeting for this project, where FHWA expressed interest in using this scenario if possible, and after consideration of other possible scenarios. The advantage of this approach is the use of an actual roadway, serving as an intermediate step between Molino et al.'s recommendations and the field test described in Chapter 4 of this report.[(Molino et al. 2010)] The disadvantage is less direct control over the curve characteristics and curve directions presented to the driver.

**Figure 2. Photo. Representation of PA Route 851 in Utah Traffic Lab driving simulator.**

***Source: Department of Civil and Environmental Engineering, University of Utah***

### Speed-Dependent Flashing

The possibility of including a speed-dependent flashing condition (i.e., flashing rates change as the detected vehicle speed changes) was explored during the early stages of this simulator study. The research team considered this alternative, but pilot testing recommended removing the speed-dependent flashing manipulation from the current experimental design. This recommendation was based on two factors:

1) Precise speed-dependent behavior can only be applied to a global scenario such that a particular flashing rate would occur at a particular speed regardless of the curve design encountered by subjects. This is problematic because not all curves can be safely or comfortably navigated at the same speed. The requirement to convey over-speed urgency to drivers *should* be curve dependent. That is, speed-dependent flashing rates should be governed not only by absolute speed, but speed through a given curve with a given super elevation. This was not feasible with the current simulator technology and study size.

2) Implementing this type of dynamic experimental condition would necessarily result in a highly unbalanced sampling of speed modulation throughout the changes in flashing patterns and rates. That is, speed-dependent flashing would necessarily create a "messy" experimental design under the current sample size scope with results that would be difficult or impossible to cleanly interpret.

Through pilot testing, the research team concluded that the experimental manipulation of carefully controlled speed-independent flashing rates and sequencing patterns would allow more precise statements about the effect of a given flashing rate and pattern on changes in vehicle speed approaching horizontal curves. Controlling flashing patterns and rates would increase the chances of providing unambiguous results related to these characteristics of the treatment, which could then be applied in future speed-dependent flashing TCDs to accurately attain the desired effect.

### Speed-Activation Thresholds

While speed-dependent flashing was not addressed by this test plan, studying and recommending possible speed-activation thresholds for the follow-on field study described in Chapter 4 of this report was an important objective of the simulator effort. It is discussed both in the following "Methods and Data" section as well as the section titled, "Regression Analysis to Detect Possible Speed-Activation Thresholds." The results of the simulator study are presented in the "Analysis Results" section of this chapter. The experimental methods and data compiled during the simulator study are described in the "Methods and Data" section below.

## METHODS AND DATA

This study was approved by the University of Utah Institutional Review Board (IRB) on June 18, 2014 (#00072404).

Fifty-four subjects (27 male, 27 female) between the ages of 18 and 25 were initially recruited to participate in this research. The proposed age range was based on the research team's previous experience with simulator studies (see the discussion on motion sickness at the conclusion of this section). This target sample size was based on the need to have an appropriately counterbalanced research design as well as on the anticipated effect sizes of the proposed treatment manipulations for investigation. Subjects were recruited from a local population of university students and the surrounding community and were compensated with course credit or $30 for participation. In the end, project resources allowed the research team to run a total of 68 subjects (35 male, 33 female) to improve the power of the statistical analysis and account for any possible missing data following data reduction and quality control.

A 3 (flash pattern) x 2 (flashing rate) experimental design was used with a hanging control group. The three flashing patterns that were explored were: (1) flashing in sequence toward the driver, (2) flashing in sequence away from the driver, and (3) flashing in unison. The two flashing rates that were used were: (1) slow flashing, defined as one flash per second, and (2) fast flashing, defined as five flashes per second. In order to remove any confounding effects, each of the flashing treatments was implemented as flashing post delineators. The hanging control group scenario consisted of the actual PA Route 851 TCDs without any flashing. An example of the flashing post-mounted delineators along one of the PA Route 851 horizontal curves is provided in figure 3.

**Figure 3. Photo. Example treatment-flashing in unison.**

***Source: Department of Civil and Environmental Engineering, University of Utah***

In order to implement this experimental design, the previously described six-mile stretch of PA Route 851 was divided into three distinct groups of curves, each roughly two miles in length. One of the flashing treatments (with a treatment distinguished by the combination of flashing pattern and rate) was applied to each of these curve sections. The curve sections, curve identification numbers, and individual curve radii are summarized in table 1 and table 2.

Overall, six distinct simulator scenarios were created, each scenario with three distinct flashing treatments, one on each of the three curve sections. As noted, a seventh scenario was created where each of the curves had the actual PA Route 851 TCDs without flashing. The seven scenarios and their relationships to the curve groups, flashing sequences, and flashing rates are shown in table 3. During experimentation, subjects drove one practice scenario, two of the six possible treatment scenarios shown in table 3, and the hanging control scenario (Scenario 7). As demonstrated in table 3, each subject drove either treatment scenarios 1 and 4, 2 and 5, or 3 and 6, in addition to the control scenario, which was driven by all subjects. This resulted in every subject seeing each of the six total treatments, with each treatment previously defined by the flashing sequence (3 levels) and flashing rate (2 levels). The precise scenarios driven by each subject were assigned in a counterbalanced order so that all treatment-curve combinations were driven an equal number of times over the course of the study and to minimize the effect of ordering/learning. All scenarios represented nighttime, clear-weather conditions on the 6-mile stretch of PA Route 851.

**Table 1. Curve groups.**

| Curve Sections | PA Route 851 Curve Identification Number | | | | | |
|---|---|---|---|---|---|---|
| Curve section 1 | 3 | 4 | 6 | 7 | 8 | -- |
| Curve section 2 | 11 | 12 | 13 | 14 | 15 | 17 |
| Curve section 3 | 20 | 21 | 24 | 27 | 28 | 32 |

-- no data available.

**Table 2. Curve data.**

| Curve No. | Radius (ft) | Average Vertical Grade | Curve to Curve tangent (ft) | Direction |
|---|---|---|---|---|
| 3 | 1165 | 6.4% | 174.89 | Right |
| 4 | 874 | -1.2% | 1348.13 | Right |
| 6 | 292 | -2.2% | 1152.1 | Right |
| 7 | 326 | -5.9% | 311.07 | Left |
| 8 | 136 | 3.2% | 1375.73 | Right |
| 11 | 539 | -5.7% | 610.81 | Right |
| 12 | 128 | -13.3% | 235.72 | Left |
| 13 | 283 | -11.3% | 263.14 | Right |
| 14 | 186 | -2.2% | 89.51 | Left |
| 15 | 371 | 7.8% | 81.16 | Right |
| 17 | 315 | 9.9% | 65.7 | Right |
| 20 | 123 | -8.4% | 43.35 | Right |
| 21 | 310 | -9.8% | 207.77 | Left |
| 24 | 302 | 1.6% | 28.2 | Left |
| 27 | 84 | -9.8% | 168.19 | Right |
| 28 | 698 | 2.8% | 47.96 | Left |
| 32 | 213 | 2.2% | 157.85 | Right |

**Table 3. Scenario and curve combinations with the hanging control group.**

| Curve Group Number | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 5 | Scenario 6 | Scenario 7 |
|---|---|---|---|---|---|---|---|
| 1 | 1.1 | 3.1 | 2.1 | 1.2 | 3.2 | 2.2 | control |
| 2 | 2.2 | 1.2 | 3.2 | 2.1 | 1.1 | 3.1 | control |
| 3 | 3.1 | 2.1 | 1.1 | 3.2 | 2.2 | 1.2 | control |

*Sequence X._ = 1– toward the driver; 2 – non-directional (simultaneous flashing); 3 – away from the driver. Flashing rate _.X = 1 – low (1Hz); 2 – high (5 Hz).

Varying levels of speed-activation thresholds were not explicitly included in the experimental design shown in table 3 for two main reasons:

- Speed-activation thresholds will likely be site-specific in the field, a function of operating speeds, curve radius, superelevation (and resulting side friction demand), and (potentially) sight obstructions; and
- Since experimenters were not restricting the speeds at which subjects could drive to a certain range, there could be frequent "holes" in the data (when the flashing devices are not activated), resulting in an unbalanced design—the effective sample for studying the main flashing characteristics (sequence and rate) would then be a function of the actual sample minus instances where drivers did not trigger the devices at all.

While not explicitly included in the experimental design, the richness of the data being collected allowed speed-activation threshold recommendations to be developed indirectly through the data analysis activities. The end goal of the speed-activation threshold analysis was insights and recommendations that inform the follow-on field study. Further advancement of the exploration of these threshold levels in an outdoor setting is described in Chapter 4.

### Testing Procedure

During the course of participating in this experiment, research participants first filled out a brief driving survey that assessed driving habits, history, and demographics (see Appendix A). Following this survey, participants were introduced to the simulator through a practice scenario, which was the same PA Route 851 scenario driven with the actual TCDs in the opposite direction of travel as the experimental runs. Once fully accustomed to the dynamics of the simulator, participants drove the three experimental scenarios (two treatment scenarios and one control scenario) as described in the previous section. Following each scenario, participants were encouraged to take a brief break in order to reduce the potential for motion sickness. Data collection ran over a full 2 months.

One concern related to the investigation of driver performance characteristics in a simulated environment is motion sickness. In order to minimize the incidence and severity of motion sickness, a number of precautionary measures were taken. First, only participants between the ages of 18 and 25 were eligible to participate in this research. Experience from previous research suggests that this group is significantly less susceptible to motion sickness than older drivers. If incidence of motion sickness does occur, younger drivers tend to recover more quickly than older drivers. In addition to these age criteria, researchers were trained to look for early signs of motion sickness and they followed a detailed response plan if any signs were observed. This aggressive approach proved very effective at reducing the incidence of motion sickness and reducing its severity when it did occur.

**Data Reduction and Quality Control**

As noted previously, the research team ran 68 subjects (35 male, 33 female) between the ages of 18 and 25 through the experiment. There were some cases of simulator sickness symptoms, where some participants were not feeling well and could not complete the entire experiment. Additional technical challenges due to the complexity of the scenarios and simulator itself would sometimes prolong or postpone the experiment. These events resulted in eliminating data from 5 of the 68 subjects.

Prior to data analysis, a series of custom data cleaning and preparation scripts were written. The purpose of these scripts was to comb through each of the recorded performance files, identify curve steps at each desired distance or time interval, and record the nearest performance measurement for that curve step. This approach allowed the research team to generate very precise speed and location profiles for each driver at each curve step under each condition. These data were then aggregated to form the basis for the final analysis. This step was critical in order to transform the time series results (in the form of continuous profiles) into the type of geospatially synchronized format needed to appropriately analyze changes in different performance measures as participants enter and exit each curve.

Each scenario run consisted of 17 curves that were negotiated by the participants. For each participant/scenario/curve combination, three performance measures were ultimately recorded, including vehicle lateral position, speed, and the occurrence of one or more lane departures. For lateral position and speed, recordings began about 200 ft upstream of the beginning of each curve (point of curvature, or PC) and continued through the entire curve. Table 2 shows the upstream tangent length for each tested curve and curve direction. The main locations where the parameters were recorded for analysis were selected relative to the PC point. With "L" as the length of the entire horizontal curve and PT representing the point of tangency, lateral position and speed were recorded for the following points inside and upstream of the curve: PC, PC+1/4L, PC+1/2L, PC+3/4L, PT, PC-50ft, PC-100ft, PC-150ft, and PC-200ft.

The simulator output data were analyzed at these critical locations inside and upstream of each curve. If the tangent length between two curves was less than the predefined recording location (e.g., if the PC-200 was actually inside of a previous curve), than those data were not taken into account. For instance, if the tangent length between two consecutive curves was less than 200 ft, then the results recorded at 200 ft upstream of the PC were removed. Table 4 shows which locations were removed for this reason.

**Table 4. Recording locations removed from the database.**

| Removal Location | PC-200 | PC-150 | PC-100 | PC-50 |
|---|---|---|---|---|
| Curve Number | 3,14,15,17,20,24, 27,28,32 | 14,15,17,20,24,28 | 14,15,17,20,24,28 | 20, 24, 28 |

Additionally, an analysis of possible outliers was conducted using box-and-whisker plots of speed and lateral position. After visual inspection of the box-and-whisker plots, extreme outliers were eliminated from the dataset. In terms of process, the distributions of lateral positions and speeds for each identified location were observed using box-and-whisker and histograms generated with STATA. The extreme outliers were easily distinguished in the box-and-whisker plots for lateral position, and appeared to be due to the simulator measurement error or some random operator error. Figure 4 and figure 5 show examples of the box-and-whisker plots and histograms for curve 13, where two extreme outliers at locations PC and PC+1/4L are easily identified. After checking the trajectory for this particular case from the original dataset, it was observed that a severe run-off-road event happened at this location, as shown in figure 6. Table 5 provides details on outliers that were removed from the database.

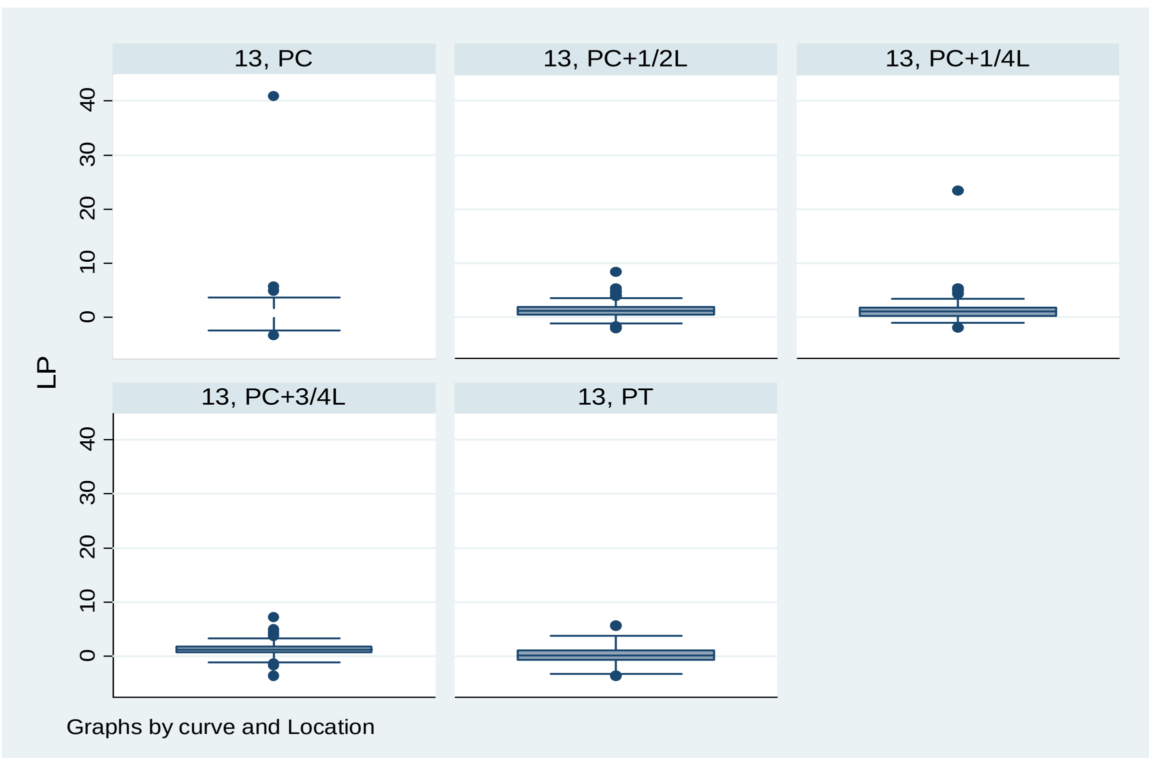



**Figure 4. Graph. Box-and-whisker plots for lateral position.**

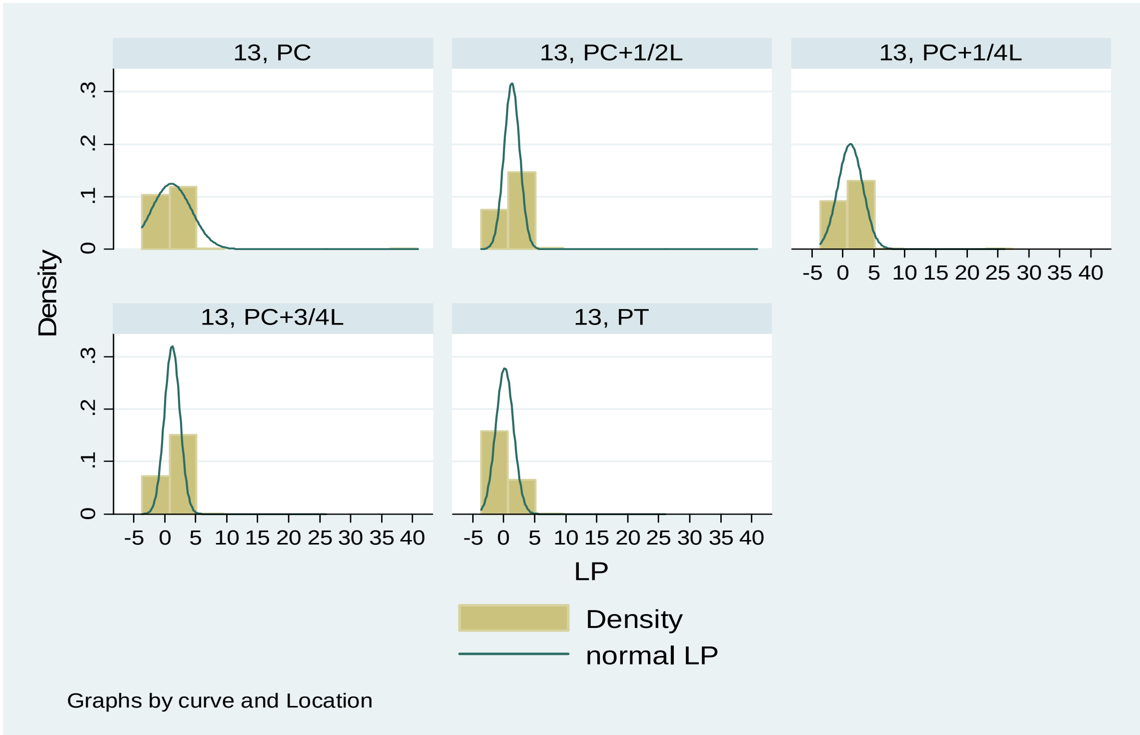



**Figure 5. Graph. Histograms of lateral position.**

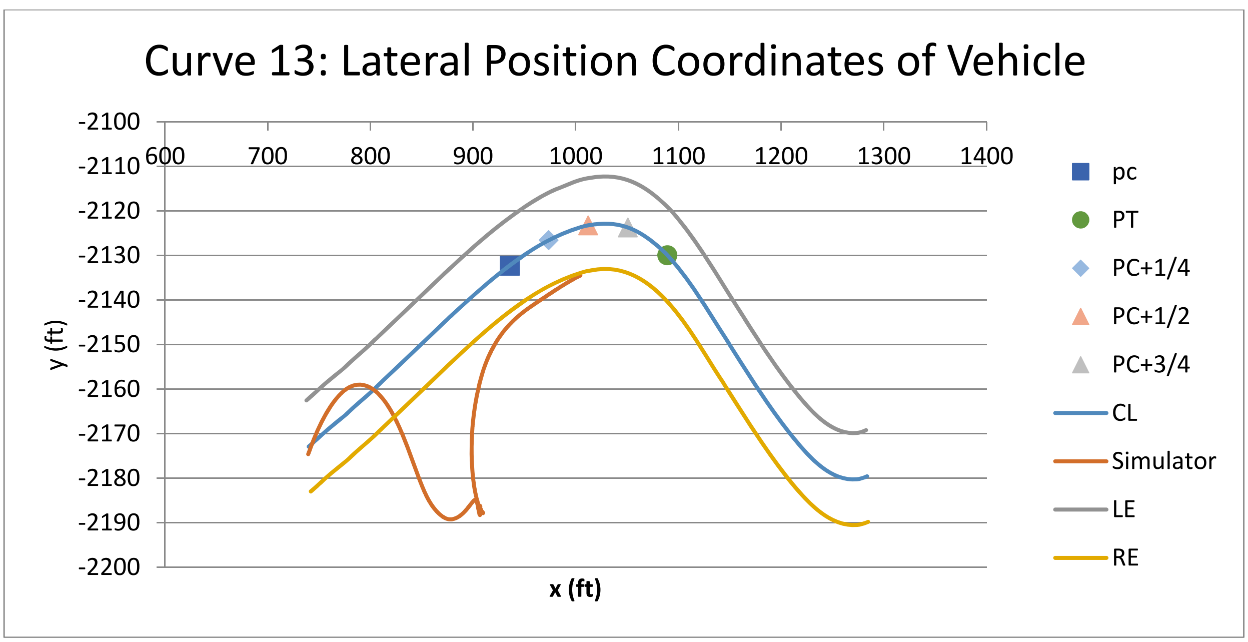



**Figure 6. Graph. Lateral position coordinate profile through curve 13: scenario 1, participant 1 vehicle position test.**

**Table 5. Outliers deleted from the database.**

| Subject ID | Scenario | Curve | Location |
|---|---|---|---|
| 8 | 6 | 28 | PC-50,PC,PC+1/4L |
| 37 | 3,6 | 28 | PC-50, PC, PC+1/4L |
| 38 | 6 | 28 | PC-50, PC |
| 44 | 5 | 28,32 | All locations |
| 57 | 1 | 13 | All locations |

In summary, 63 participants drove 3 scenarios, each with 17 curves, with each curve having between 5 and 9 data recording points (depending on the upstream tangent length). All the output data were checked using quality control procedures to eliminate outliers, leading to a total number of 23,450 successful observations.

**Datasets**

Three different datasets were prepared from the raw simulator data. Table 6 shows descriptive statistics for all variables extracted from the simulation runs, including speed and lateral position at the nine critical locations upstream and within the horizontal curves (i.e., PC, PC+1/4L, PC+1/2L, PC+3/4L, PT, PC-50ft, PC-100ft, PC-150ft, and PC-200ft). There were 23,450 observations in this dataset. All roadway data were obtained from the roadway files of the simulator scenario, which were built from data collected on the actual PA Route 851. The research team used "x,y,z" coordinates to develop geometric variables such as radii and vertical grade.

Speed was measured directly from the simulator-generated profiles. The unit of speed was miles per hour (mph). The mean speed across all data points in this first dataset was 32.04 mph. According to the Permanent International Association of Road Congresses (PIARC) Road Safety Manual, the ideal position of a vehicle along a horizontal curve is in the center of the lane. (PIARC 2003,Babaee et al. 2014) Therefore, vehicle lateral position was calculated as the distance between the middle of the travel lane and the center of the simulator vehicle. Left of center was "negative" and right of center was "positive." The mean lateral position across all data points in this first dataset was +1.37 ft (i.e., 1.37 ft to the right of the center of the travel lane).

For illustration purposes, table 7 shows descriptive statistics for all variables extracted from the simulation runs, including speed and lateral position, but for only the five critical locations within the horizontal curves (i.e., PC, PC+1/4L, PC+1/2L, PC+3/4L, and PT). The observations in this dataset totaled 15,449. The average of mean speed across all data points inside of the horizontal curves was 29.98 mph which, as expected, is lower than the mean speed from table 6

The mean lateral position across all data points in this second dataset was +1.32 ft (i.e., 1.32 ft to the right of center).

Table 8 shows descriptive statistics for the database used to analyze lane departures. The occurrence of one or more lane departures was determined by creating computer algorithm in MATLAB to track vehicle trajectory versus center and edge line locations in the simulator. For each pass through a horizontal curve, an indicator variable for "lane departure" was coded as "1" if at least one lane departure outside of the travel lane occurred and "0" if the vehicle stayed within the travel lane for the entire stretch through the curve. A total of 3,087 observations, with an observation defined as one vehicle pass through a horizontal curve from curve PC to PT, make up the dataset in table 8.

**Table 6. Descriptive statistics for dataset of nine critical horizontal curve and upstream locations.**

| Variable | Obs. | Mean | Std. Dev. | Min. | Max. |
|---|---|---|---|---|---|
| Speed (mph) | 23450 | 32.04 | 8.39 | 7.98 | 63.93 |
| Lateral position (ft) | 23450 | 1.37 | 2.15 | -22.92 | 20.48 |
| Inverse of horizontal curve radius (ft) | 23450 | 0.00283 | 0.00310 | 0 | 0.01195 |
| Vertical grade (%) | 23450 | -2.80 | 6.99 | -15.94 | 12.43 |
| Indicator variable for flashing rate and sequence (1 = low rate toward the driver, 0=otherwise) | 23450 | 0.11 | 0.31 | 0 | 1 |
| Indicator variable for flashing rate and sequence (1 = low rate with flashing in unison, 0=otherwise) | 23450 | 0.11 | 0.31 | 0 | 1 |
| Indicator variable for flashing rate and sequence (1 = low rate away from the driver, 0=otherwise) | 23450 | 0.11 | 0.31 | 0 | 1 |
| Indicator variable for flashing rate and sequence (1 = high rate toward the driver, 0=otherwise) | 23450 | 0.11 | 0.31 | 0 | 1 |
| Indicator variable for flashing rate and sequence (1 = high rate with flashing in unison, 0=otherwise) | 23450 | 0.11 | 0.31 | 0 | 1 |
| Indicator variable for flashing rate and sequence (1 = high rate away from the driver, 0=otherwise) | 23450 | 0.11 | 0.31 | 0 | 1 |

| | | | | | |
|---|---|---|---|---|---|
| Indicator variable for control scenario (1 = control, 0=otherwise) | 23450 | 0.34 | 0.47 | 0 | 1 |
| Indicator variable for location (1= upstream 200 ft from PC (PC-200), 0 = otherwise) | 23450 | 0.06 | 0.24 | 0 | 1 |
| Indicator variable for location (1 = upstream 150 ft from PC (PC-150), 0 = otherwise) | 23450 | 0.09 | 0.28 | 0 | 1 |
| Indicator variable for location (1 = upstream 100 ft from PC (PC-100), 0 = otherwise) | 23450 | 0.09 | 0.28 | 0 | 1 |
| Indicator variable for location (1 = upstream 50 ft from PC (PC-50), 0 = otherwise) | 23450 | 0.11 | 0.31 | 0 | 1 |
| Indicator variable for location (1 = point of curvature (PC), 0 = otherwise) | 23450 | 0.13 | 0.34 | 0 | 1 |
| Indicator variable for location (1= middle point of curve (PC+1/2L), = 0 = otherwise) | 23450 | 0.13 | 0.34 | 0 | 1 |
| Indicator variable for location (1 = quarter point inside curve (PC+1/4L) , 0 = otherwise) | 23450 | 0.13 | 0.34 | 0 | 1 |
| Indicator variable for location (1 = three-quarter point inside curve (PC+3/4L), 0 = otherwise) | 23450 | 0.13 | 0.34 | 0 | 1 |
| Indicator variable for location (1 = point of tangency (PT), 0 = otherwise) | 23450 | 0.13 | 0.34 | 0 | 1 |
| Indicator variable for curve direction to the left (1=left, 0=right) | 23450 | 0.33 | 0.47 | 0 | 1 |

**Table 7. Descriptive statistics for dataset of five critical horizontal curve locations.**

| Variable | Obs. | Mean | Std. Dev. | Min. | Max. |
|---|---|---|---|---|---|
| Speed (mph) | 15449 | 29.98 | 7.73 | 7.98 | 63.82 |
| Lateral position (ft) | 15449 | 1.32 | 2.19 | -22.92 | 20.48 |
| Inverse of horizontal curve radius (ft) | 15449 | 0.0043 | 0.0029 | 0.0009 | 0.0119 |
| Vertical grade (%) | 15449 | -2.12 | 7.37 | -15.94 | 12.43 |
| Indicator variable for flashing rate and sequence (1 = low rate toward the driver, 0=otherwise) | 15449 | 0.11 | 0.31 | 0 | 1 |
| Indicator variable for flashing rate and sequence (1 = low rate with flashing in unison, 0=otherwise) | 15449 | 0.11 | 0.31 | 0 | 1 |
| Indicator variable for flashing rate and sequence (1 = low rate away from the driver, 0=otherwise) | 15449 | 0.11 | 0.31 | 0 | 1 |
| Indicator variable for flashing rate and sequence (1 = high rate toward the driver, 0=otherwise) | 15449 | 0.11 | 0.31 | 0 | 1 |
| Indicator variable for flashing rate and sequence (1 = high rate with flashing in unison, 0=otherwise) | 15449 | 0.11 | 0.31 | 0 | 1 |
| Indicator variable for flashing rate and sequence (1 = high rate away from the driver, 0=otherwise) | 15449 | 0.11 | 0.32 | 0 | 1 |

| | | | | | |
|---|---|---|---|---|---|
| Indicator variable for control scenario (1 = control, 0=otherwise) | 15449 | 0.34 | 0.47 | 0 | 1 |
| Indicator variable for location (1 = point of curvature (PC), 0 = otherwise) | 15449 | 0.2 | 0.4 | 0 | 1 |
| Indicator variable for location (1= middle point of curve (PC+1/2L), = 0 = otherwise) | 15449 | 0.2 | 0.4 | 0 | 1 |
| Indicator variable for location (1 = quarter point inside curve (PC+1/4L) , 0 = otherwise) | 15449 | 0.2 | 0.4 | 0 | 1 |
| Indicator variable for location (1 = three-quarter point inside curve (PC+3/4L), 0 = otherwise) | 15449 | 0.2 | 0.4 | 0 | 1 |
| Indicator variable for location (1 = point of tangency (PT), 0 = otherwise) | 15449 | 0.2 | 0.4 | 0 | 1 |
| Indicator variable for curve direction to the left (1=left, 0=right) | 15449 | 0.35 | 0.48 | 0 | 1 |

**Table 8. Descriptive statistics for lane departure dataset.**

| Variable | Obs. | Mean | Std. Dev. | Min. | Max. |
|---|---|---|---|---|---|
| Speed at upstream 200 ft (mph) | 3087 | 35.02 | 9.04 | 8.46 | 63.79 |
| Speed at upstream 150 ft (mph) | 3087 | 34.81 | 8.74 | 9.77 | 63.88 |
| Speed at upstream 100 ft (mph) | 3087 | 34.31 | 8.34 | 10.63 | 63.93 |
| Speed at upstream 50 ft (mph) | 3087 | 33.38 | 7.97 | 11.59 | 63.93 |
| Speed at PC (mph) | 3087 | 32.01 | 7.82 | 8.85 | 63.82 |
| Speed at PC+1/4L (mph) | 3087 | 30.61 | 7.83 | 8.34 | 59.81 |
| Speed at PC+1/2L (mph) | 3087 | 29.41 | 7.82 | 10.08 | 56.21 |
| Speed at PC+3/4L (mph) | 3087 | 28.79 | 7.47 | 9.06 | 55.35 |
| Speed at PT (mph) | 3087 | 29.11 | 7.20 | 7.98 | 55.10 |
| Inverse of horizontal curve radius (ft) | 3087 | 0.0043 | 0.0029 | 0.0009 | 0.0119 |

| | | | | | |
|---|---|---|---|---|---|
| Average vertical grade (%) | 3087 | -2.12 | 6.84 | -13.26 | 9.94 |
| Lane departure (1=yes, 0= otherwise) | 3087 | 0.58 | 0.49 | 0.00 | 1.00 |
| Lateral Position at upstream 200 ft (ft) | 3087 | 1.27 | 2.43 | -14.59 | 8.90 |
| Lateral Position at upstream 150 ft (ft) | 3087 | 1.09 | 2.33 | -13.21 | 10.04 |
| Lateral Position at upstream 100 ft (ft) | 3087 | 0.92 | 2.13 | -18.95 | 14.59 |
| Lateral Position at upstream 50 ft (ft) | 3087 | 0.92 | 1.88 | -21.41 | 19.37 |
| Lateral Position at PC (ft) | 3087 | 1.21 | 1.61 | -9.53 | 12.09 |
| Lateral Position at PC+1/4L (ft) | 3087 | 1.25 | 1.88 | -8.26 | 9.54 |
| Lateral Position at PC+1/2L (ft) | 3087 | 1.52 | 2.42 | -13.11 | 9.21 |
| Lateral Position at PC+3/4L (ft) | 3087 | 1.16 | 2.38 | -18.75 | 14.92 |
| Lateral Position at PT (ft) | 3087 | 1.49 | 2.45 | -22.92 | 20.48 |

| | | | | | |
|---|---|---|---|---|---|
| Indicator variable for curve direction to the left (1=left, 0=right) | 3087 | 0.35 | 0.48 | 0.00 | 1.00 |
| Indicator variable for flashing rate and sequence (1 = low rate toward the driver, 0=otherwise) | 3087 | 0.11 | 0.31 | 0.00 | 1.00 |
| Indicator variable for flashing rate and sequence (1 = low rate with flashing in unison, 0=otherwise) | 3087 | 0.11 | 0.31 | 0.00 | 1.00 |
| Indicator variable for flashing rate and sequence (1 = low rate away from the driver, 0=otherwise) | 3087 | 0.11 | 0.31 | 0.00 | 1.00 |
| Indicator variable for flashing rate and sequence (1 = high rate toward the driver, 0=otherwise) | 3087 | 0.11 | 0.31 | 0.00 | 1.00 |
| Indicator variable for flashing rate and sequence (1 = high rate with flashing in unison, 0=otherwise) | 3087 | 0.11 | 0.31 | 0.00 | 1.00 |
| Indicator variable for flashing rate and sequence (1 = high rate away from the driver, 0=otherwise) | 3087 | 0.11 | 0.32 | 0.00 | 1.00 |
| Indicator variable for control scenario (1 = control, 0=otherwise) | 3087 | 0.34 | 0.47 | 0.00 | 1.00 |

## ANALYSIS RESULTS

### Verification of Speed and Lateral Position Performance in Simulator

An effort to verify the speed and lateral position behavior of drivers in the simulator environment created for this study was conducted using previous empirical research that studied vehicle speed and lateral position "in the field." First, an ordinary least squares, linear regression model was estimated with the recorded simulator speed for this study at the curve midpoint as a dependent variable. The inverse of horizontal curve radius and vertical grade were defined as the right-hand side (RHS) independent variables. The resulting model is shown in figure 7.

$$V = \frac{-1655.48}{R} - 0.344393 \times G + 35.81$$

**Figure 7. Equation. Expected mean speed at horizontal curve midpoint.**

Where:

$V$ = expected mean speed at horizontal curve midpoint (mph)

$R$ = radius of horizontal curve (ft)

$G$ = vertical grade (%)

The expected speed and the variability around the regression line were then used to estimate an 85th-percentile speed in the driving simulator at the horizontal curve midpoints.

Next, several existing speed models for rural, two-lane horizontal curves were identified. Table 9 shows various 85th-percentile speed prediction models identified in the rural, two-lane highway literature. For the first three models in table 9, estimation used data from roads with significantly higher posted speed limits than the section of PA Route 851 used for this study. However, developed a speed model applicable to roads with lower posted speed limits (30 mph-40 mph).(Banihashemi et al. 2011) The posted speed limit is 40-45 mph on the test segments of PA Route 851.

A plot of these various speed prediction models for rural, two-lane highways is shown in figure 8. Overall, results show very similar speed behavior between drivers in the simulator study conducted as part of this research effort and drivers observed in the field as part of these previous efforts. Findings are very comparable to those from Banihashemi et al., the most important comparison given Banihashemi et al.'s focus on roadways with posted speed limits similar to PA Route 851.(Banihashemi et al. 2011) It is important to note here that drivers in this study were not asked to "obey" the posted speed limit. The nature of this particular road (e.g., alignment, cross section, roadside) led to what some might consider the "slower" operating speeds in figure 6, around or below the posted speed limit. In other words, the posted speed limits on the simulated PA Route 851 appeared to be very credible given the alignment and cross section of the road.

**Table 9. Published 85th-percentile speed models.**

| Authors | Models |
|---|---|
| Taragin (1954) | V85=(88.87-2554.76/R)*0.621 |
| Glennon et al. (1985) | V85=(103.96-4524.94/R)*0.621 |
| Krammes (1995) | V85=(102.44-2471.81/R+0.012Lc-0.10Δ)*0.621 |
| Banihashemi et al.(2011) | V85=44.25-1462/R |

Note: Lc represents length of horizontal curve, Δ represents defection angle, R represents horizontal curve radius.

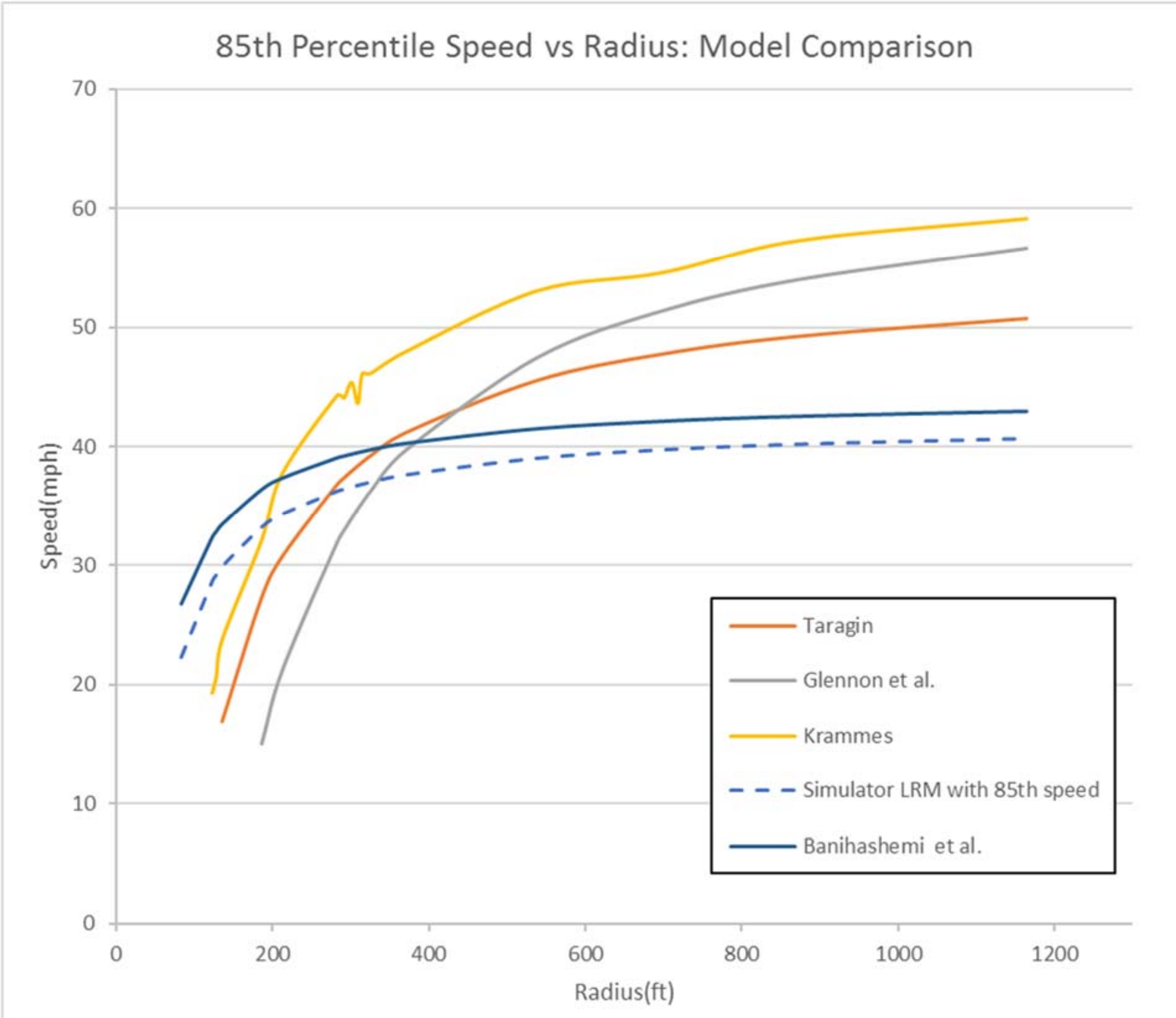



**Figure 8. Graph. Modeled 85th- percentile speed versus radius of horizontal curve.**

To verify the lateral vehicle position measurements in the simulator, a comparison was made between the simulator data and one previous field study. Table 10 shows the mean distance between the roadway centerline and the center of the simulator vehicle under different flashing treatments and the control condition in this study. The lateral vehicle positions were closer to the middle of the travel lane for each treatment when compared to the control condition, but in all cases were more than 1 ft to the right of the center of the lane.

Table 11 presents the descriptive statistics for the lateral vehicle position, again measured as the vehicle centroid position in relation to the centerline, from a published field study on centerline rumble strips.(Porter et al. 2004) The field study data also showed vehicles positioned to the right of the center of the lane, but not as far right as in the driving simulator. Variability in lateral vehicle placement was also smaller in the field than in the simulator. Observed differences may be due to the simulator's "open cockpit," with only one seat (the driver seat). Still, the numbers are within reason and indicate that lateral position behavior was generally replicated in the simulator environment.

In summary, the results of the validation effort increased the research team's confidence in their ability to capture actual speed and lateral vehicle position behavior in the driving simulator.

**Table 10. Distance between the center of the simulator vehicle and the middle of the lane.**

| Treatment | n | Lane Width (ft) | Std. | Mean (ft) | Lower Bound* | Upper Bound* |
|---|---|---|---|---|---|---|
| Low toward | 1688 | 10.42 | 2.23 | 6.51 | 6.40 | 6.61 |
| Low simultaneously | 1705 | 10.41 | 2.21 | 6.49 | 6.39 | 6.60 |
| Low away | 1710 | 10.44 | 2.25 | 6.45 | 6.35 | 6.56 |
| High toward | 1711 | 10.42 | 2.40 | 6.51 | 6.40 | 6.62 |
| High simultaneously | 1715 | 10.41 | 2.23 | 6.44 | 6.34 | 6.55 |
| High away | 1735 | 10.44 | 2.17 | 6.49 | 6.39 | 6.59 |
| Control | 5185 | 10.43 | 2.05 | 6.64 | 6.59 | 6.70 |

Note: * denotes the 95-percent confidence interval.

**Table 11. Distance between vehicle centroid and centerline for CRS sites (from Porter et al., 2004).**

| Category | Designation | Period | Lane Width (ft) | n | Mean (ft) | Std. | Lower Bound | Upper Bound |
|---|---|---|---|---|---|---|---|---|
| 1 | Treatment | Before | 12 | 107 | 6.16 | 1.71 | 5.84 | 6.48 |
| 1 | Treatment | After | 12 | 171 | 6.62 | 1.31 | 6.42 | 6.82 |
| 2 | Comparison | Before | 12 | 157 | 6.19 | 1.29 | 5.99 | 6.39 |
| 2 | Comparison | After | 12 | 190 | 6.22 | 1.35 | 6.03 | 6.41 |
| 3 | Treatment | Before | 11 | 280 | 6.02 | 1.2 | 5.88 | 6.16 |
| 3 | Treatment | After | 11 | 278 | 6.27 | 1.17 | 6.13 | 6.41 |
| 4 | Comparison | Before | 12 | 199 | 6.1 | 1.35 | 5.91 | 6.29 |
| 4 | Comparison | After | 12 | 294 | 6.18 | 1.34 | 6.03 | 6.33 |

Note: * denotes the 95-percent confidence interval.

## Aggregate Analysis of Speed and Lateral Position

The data described in previous sections of this report were analyzed with a focus on lateral vehicle positions and speeds. Occurrences of lane departures are analyzed at a more disaggregate level (e.g., probability of a vehicle lane departure) in the next section. As already noted, there were three curve sections identified in the PA 851 scenario with six flashing device treatments and the existing TCDs (with no flashing devices) control group (for additional details, see Appendix B).

In general, the aggregate analyses do not appear to show any statistically significant differences in mean speed across the various flashing treatments. The mean speeds are generally lowest for the control condition. With regards to lateral vehicle position, there were no consistent and statistically significant differences in lateral position across all treatment conditions and the control.

## Disaggregate Analysis of Lane Departure Probability

This section describes an analysis of lane departures under the various treatments and the control condition. Binary logit models were estimated using the occurrence (or not) of one or more lane departures as a driver traverses a horizontal curve as the dependent variable and roadway characteristics (including curve treatments) as independent variables. In other words, an observation was considered one pass of a driver through a horizontal curve from the PC to the

PT. Lane departures were defined as any part of the simulator vehicle leaving the appropriate travel lane either to the driver's left or right. Descriptive statistics for the lane departure database were provided in table 8.

In the binary logit model, a set of linear functions ($S_{in}$), shown in general form in figure 9, is used to define how lane departure outcome *i* (i.e., one or more lane departures or no lane departures) for observation *n* (i.e., one pass of a driver through a horizontal curve from the PC to the PT) is determined.

$$S_{in} = X_{in}\beta_i + \varepsilon_{in}$$

**Figure 9. Equation. Linear function of binary logit model.**

Where:

$X_{in}$ = a row of observed characteristics (e.g., driver, vehicle, roadway, environment) associated with observation *n* that have an impact on lane departure outcome *i*;

$\beta_i$ = a vector of parameters to be estimated that quantify how the characteristics in $X_{in}$ impact lane departure outcome *i*; and

$\varepsilon_{in}$ = a disturbance term that accounts for unobserved and unknown characteristics of observation *n* that impact lane departure outcome *i*.

There are as many such linear functions as there are possible lane departure outcomes. In this case, there are two possible outcomes: (1) one or more lane departures occur as a driver traverses a horizontal curve, or (2) no lane departures occur as a driver traverses a horizontal curve. With the disturbance terms of the two "$S_{in}$ functions" for these outcomes identically and independently distributed as extreme value, the binary logit model results, shown in figure 10.

$$P_n(i) = \frac{EXP(X_{in}\beta_i)}{1 + EXP(X_{in}\beta_i)}$$

**Figure 10. Equation. Binary logit model for the probability of lane departures.**

Model outcome *i* in this analysis represented the outcome of one or more lane departures occurring; therefore, $Pn(i)$ represents the probability of a lane departure as a subject traverses a horizontal curve for observation *n*.

The estimation results for the binary logit model of lane departures are shown in table 12. For ease of interpretation, the odds ratios (as opposed to the actual parameter estimate) are reported. An odds ratio of more than one in this table indicates that the variable is positively associated with the possibility of a lane departure (i.e., an increase in that variable's value increases the probability of one or more lane departures); an odds ratio less than one indicates the variable is negatively associated with the possibility of a lane departure (i.e., an increase in that variable's value reduces the probability of one or more lane departures).

The odds ratio for the inverse of horizontal curve radius indicates smaller radii will increase the probability of one or more lane departures, as expected. Vertical grade indicates that more positive and steeper vertical grades will also increase the probability of one or more lane departures. However, the indicator variables for the six treatments indicated that none of the six applied treatments showed statistically significant impacts on lane departure probabilities at the 95 or 90 percent confidence level compared to the control condition. However, the treatment of low flashing rate away from the driver is associated with a lower probability of one or more lane departures and the odds ratio is statistically significant at slightly more than the 85 percent confidence level. This is particularly interesting because findings to be discussed in the next section also show the "low-away" treatment resulting in a horizontal curve speed nearly 4 mph less than the control condition for drivers that approach a horizontal curve at 50 mph or more.

**Table 12. Binary logit model of lane departure occurrence.**

| Variable | Odds Ratio | Standard Error | p-value |
|---|---|---|---|
| Inverse of horizontal curve radius (ft) | 1.60E+59 | 2.59E+60 | <0.001 |
| Average Vertical Grade (%) | 1.014635 | 0.006607 | 0.026 |
| Indicator variable for curve direction to the left (1=left, 0=right) | 0.450576 | 0.036931 | <0.001 |
| Indicator variable for flashing rate and sequence (1 = low rate toward the driver, 0=otherwise) | 0.984032 | 0.129083 | 0.902 |
| Indicator variable for flashing rate and sequence (1 = low rate with flashing in unison, 0=otherwise) | 1.048085 | 0.137075 | 0.720 |
| Indicator variable for flashing rate and sequence (1 = low rate away from the driver, 0=otherwise) | 0.817384 | 0.106161 | 0.121 |
| Indicator variable for flashing rate and sequence (1 = high rate toward the driver, 0=otherwise) | 1.09018 | 0.143449 | 0.512 |
| Indicator variable for flashing rate and sequence (1 = high rate with flashing in unison, 0=otherwise) | 1.085951 | 0.142125 | 0.529 |
| Indicator variable for flashing rate and sequence (1 = high rate away from the driver, 0=otherwise) | 1.111789 | 0.145497 | 0.418 |
| Constant | 1.059988 | 0.100821 | 0.540 |

Note: Number of obs. = 3087; Log_likelihood = -1993.7254.

## Regression Analysis to Detect Possible Speed-Activation Thresholds

While not explicitly included in the experimental design, the richness of the data collected allowed the research team to indirectly explore possible speed-activation thresholds through the data analysis activities. The results of this exploration are reported in this section. The end goal of the speed-activation threshold analysis was insights and recommendations that inform the follow-on field study (see Chapter 4 of this report), which will further advance the exploration of these threshold levels in an outdoor setting.

Ordinary least squares regression was used to model the potential linear-in-parameters relationship between the six different treatments, the control condition, and mean horizontal curve speed, while also controlling for the effect of other driver and roadway characteristics. The basic structure of the OLS regression model is shown in the equation in figure 11.

$$V_i = \beta X_i + \varepsilon_i$$

**Figure 11. Equation. Regression equation of horizontal curve speed.**

Where:

$V_i$ = mean horizontal curve speed (mean of instantaneous speed at PC, PC+1/4L, PC+1/2L, PC+3/4L, and PT);

$\beta$ = regression coefficients to be estimated;

$\varepsilon_i$ = disturbance terms for each observation; and

$X_i$ = explanatory variables that are associated with $V_i$, including the curve treatments.

Model estimation was repeated with five different datasets:

1. All data (which reinforced findings already reported of no statistically significant differences between treatments and controls for speed except for, in some cases, a lower expected speed for the control condition.
2. Data for observations of mean horizontal curve speed only for cases where the curve approach speed (measured at 200 ft upstream from the PC) was 40 mph or more.
3. Data for observations of mean horizontal curve speed only for cases where the curve approach speed (measured at 200 ft upstream from the PC) was 45 mph or more.
4. Data for observations of mean horizontal curve speed only for cases where the curve approach speed (measured at 200 ft upstream from the PC) was 50 mph or more.;
5. Data for observations of mean horizontal curve speed only for cases where the curve approach speed (measured at 200 ft upstream from the PC) was 55 mph or more.

Model estimation results are reported in table 13. As already noted, estimation results using all data generally reinforced findings already reported of no statistically significant differences between treatments and controls for speed except for, in some cases, a lower expected speed for the control condition. Estimation results using data only for cases where the curve approach speed was either 40 mph or more, or 45 mph or more, are generally consistent with the “all data” model. Some interesting results are uncovered in the estimation results using data only for cases where the curve approach speed was 50 mph or more. These results show four different flashing treatments associated with lower speeds than the control condition: low toward, low simultaneous, low away, and high simultaneous by 0.89, 1.0, 3.8, and 2.4 mph, respectively. The findings for low-away and high-simultaneous are statistically significant at the 95 percent confidence level. A curve approach speed of 50 mph or more represents an operating speed that is at least 5 to 10 mph above the posted speed of PA Route 851, depending on the location. This indicates that while the flashing treatments were not associated with any change in speed across all drivers, they may be effective at reducing speeds for drivers approaching a curve at a “high” operating speed (identified for this scenario as 50 mph or more, at least 5 to 10 mph above the posted speed). The low-away treatment was associated with the lowest mean curve speed of all treatment and control conditions (and from the previous section, with a reduction in lane departure probability compared to all other treatments and the control condition). Estimation results using only observations where the curve approach speed (measured at 200 ft upstream from the PC) was 55 mph or more are reported in the shaded columns, but sample size issues make it difficult to have any confidence in the estimates.

In summary, the findings presented in this section are promising in terms of the flashing treatments resulting in speed reductions for drivers approaching horizontal curves at “excessive speeds.” Excessive speeds were identified for this stretch of PA Route 851 as 50 mph or more. The low-away and high-simultaneous treatments had the greatest and most statistically significant effects on this faster group of drivers. It is likely that the threshold speed over which the flashing treatments show this type of speed reduction effect will vary from location to location and will be a function of the road design characteristics.

**Table 13. Comparison of mean speed models for various approach speeds.**

| | All Mean Speed | | Mean Speed >40mph | | Mean Speed >45mph | | Mean Speed >50 mph | | Mean Speed >55 mph | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Variables** | Coef. | P>z | Coef. | P>z | Coef. | P>z | Coef. | P>z | Coef. | P>z |
| Inverse of horizontal curve radius (ft) | -1152 | 0.000 | -696 | 0.000 | -640 | 0.000 | -813 | 0.000 | -808 | 0.041 |
| Average Vertical Grade (%) | -0.218 | 0.000 | 0.041 | 0.131 | 0.068 | 0.145 | -0.046 | 0.613 | -0.096 | 0.711 |
| Speed at PC-50(ft) | 0.613 | 0.000 | 0.861 | 0.000 | 0.991 | 0.000 | 0.963 | 0.000 | 1.038 | 0.002 |
| Indicator variable for flashing rate and sequence (1=low rate toward the driver, 0=otherwise) | 0.170 | 0.468 | 0.597 | 0.149 | 0.913 | 0.154 | -0.893 | 0.441 | -1.169 | 0.657 |
| Indicator variable for flashing rate and sequence (1=low rate with flashing in unison, 0=otherwise) | 0.068 | 0.773 | 0.319 | 0.431 | 0.104 | 0.866 | -1.033 | 0.346 | -1.228 | 0.580 |
| Indicator variable for flashing rate and sequence (1=low rate away from the driver, 0=otherwise) | -0.004 | 0.985 | -0.273 | 0.513 | -0.339 | 0.617 | -3.841 | 0.003 | -0.050 | 0.986 |
| Indicator variable for flashing rate and sequence (1=high rate toward the driver, 0=otherwise) | 0.181 | 0.440 | 0.328 | 0.419 | 1.059 | 0.091 | 0.588 | 0.584 | -0.607 | 0.828 |
| Indicator variable for flashing rate and sequence (1=high rate with flashing in unison, 0=otherwise) | -0.064 | 0.785 | -0.365 | 0.387 | -0.096 | 0.880 | -2.404 | 0.039 | -3.277 | 0.216 |
| Indicator variable for flashing rate and sequence (1=high rate away from the driver, 0=otherwise) | 0.519 | 0.025 | 0.515 | 0.217 | 1.073 | 0.089 | 0.478 | 0.692 | 1.374 | 0.611 |
| Constant | 13.938 | 0.000 | 1.736 | 0.086 | -4.965 | 0.007 | -2.787 | 0.536 | -8.367 | 0.618 |
| Number of observation | 3087 | | 944 | | 424 | | 140 | | 30 | |

## SUMMARY OF SIMULATOR STUDY

The objective of this simulator study was to explore optimum flash rates, sequencing patterns, and thresholds for speed-activated TCDs on horizontal curves along rural, two-lane roads to inform follow-on field testing of these devices. A driving simulator located in the University of Utah's Utah Traffic Lab was used to conduct the simulator study and a PA Route 851 scenario, used for some previous FHWA research efforts, was ultimately used for the simulator experiments. Sixty-eight subjects (35 male, 33 female) between the ages of 18 and 25 participated in this research; data from 63 subjects were useable for analysis. A 3 (flash pattern) x 2 (flashing rate) experimental design was used with a hanging control group. The three flashing patterns that were explored were flashing in sequence toward the driver, flashing in sequence away from the driver, and flashing in unison. The two flashing rates that were used were slow flashing, defined as one flash per second, and fast flashing, defined as five flashes per second. Overall, six distinct simulator scenarios were created, each with three distinct flashing treatments. A seventh scenario was created where each of the curves had the actual PA Route 851 TCDs, but without flashing. The precise scenarios driven by each subject were assigned in a counterbalanced order so that all treatment-curve combinations were driven an equal number of times over the course of the study and to minimize the effect of ordering/learning.

All scenarios represented nighttime, clear-weather conditions on the six-mile stretch of PA Route 851. An effort to verify the speed and lateral position behavior of drivers in the simulator environment created for this study was conducted using previous empirical research that studied vehicle speed and lateral position "in the field." The results of the validation effort increased the research team's confidence in their ability to capture actual speed and lateral vehicle position behavior in the driving simulator.

Data analysis considered various measures of speed, lateral position, and lane departures. An aggregate analysis of all data points showed no statistically significant differences in mean speed across the various flashing treatments. Generally speaking, mean speeds were lowest for the control condition and this difference was statistically significant at several locations. Similarly, there were no consistent and statistically significant differences in lateral position across all treatment conditions and the control.

None of the six applied treatments showed statistically significant impacts on lane departure probabilities at the $95^{th}$- or $90^{th}$-percentile confidence level compared to the control condition. However, the "low flashing rate away from the driver" treatment was associated with a lower probability of one or more lane departures and the odds ratio was statistically significant at slightly more than the $85^{th}$-percentile confidence level.

The research team also indirectly explored possible speed-activation thresholds through the data analysis activities. Results showed that while the flashing treatments were not associated with any change in speed across all drivers, they may be effective at reducing speeds for drivers approaching a curve at a "high" operating speed (identified for this experiment as 50 mph or more, at least 5 to 10 mph above the posted speed). For these higher approach speeds, four different flashing treatments were associated with lower speeds than the control condition: low toward, low simultaneous, low away, and high simultaneous by 0.89, 1.0, 3.8, and 2.4 mph, respectively. The low-away treatment was associated with the lowest mean curve speed of all treatment and control conditions, followed by the high-simultaneous flashing treatment. Sample size limitations did not allow the research team to determine if this trend continued for approach speeds of 55 mph or more.

Limiting participant ages to fall between 18 and 25 years old is one limitation of the study. This simulator study was part of a larger, multifaceted study on roadway departure crashes. There were some practical limitations on this study's size and cost. This particular trade-off associated with age ranges was made to give the research team more efficient access to potential subjects, and fewer possible cases of simulator sickness. Older drivers are likely to exhibit different visual scanning patterns and have different nighttime driving performance capabilities and behaviors. It is possible that results could be different for older drivers. Future research should therefore expand subject age ranges to increase generalizability of findings.

As already noted, findings of this speed threshold analysis were promising in terms of the flashing treatments resulting in speed reductions for drivers approaching horizontal curves at "excessive speeds." The low-away and high-simultaneous treatments had the greatest and most statistically significant effects on this faster group of drivers. It is likely that the threshold speed over which the flashing treatments show this type of speed reduction effect will vary from location to location and will be a function of the road design characteristics. Additional work on how to determine this speed threshold from site-to-site is needed.

The following recommendations are based on the overall findings of this simulator study and are offered for consideration as this study moves forward to the field evaluation:

- Continue to explore "low-away" and "high-simultaneous" flashing treatments, as both resulted in the greatest and most statistically significant speed reduction effects on drivers approaching horizontal curves at higher speeds; "low-away" also resulted in the lowest probability of one or more lane departures along the horizontal curves;
- Expand the driver age ranges beyond 18-25 years old to include older drivers; and
- Establish a procedure for determining a "threshold speed" over which the flashing treatments will be effective that can be applied across a range of roadway designs; using an empirical approach, the simulator study showed this threshold speed to be 50 mph for the study section of PA Route 851.

# CHAPTER 4. OUTDOOR FIELD STUDY EVALUATION

## OBJECTIVES

The objective of this study was to perform additional field studies of the SDCWS at some of the same sites included in the Smadi et al. study to validate the findings of the indoor simulator experiment described in Chapter 3 of this report.(Smadi et al. 2015) For this evaluation, vehicle operating speeds were collected at several locations approaching and within a horizontal curve to determine the optimal SDCWS flash rates, speed activation, and flashing sequence settings. The settings that were tested included the following:

- Baseline: the chevrons are not flashing, so that a baseline condition can be established for a static array of chevrons. This is equivalent to the "before" condition used in the Smadi et al. study.(Smadi et al. 2015)
- Condition #1: speed-activation threshold is 5 mph above the advisory speed for the horizontal curve; flash sequence is simultaneous; flash rate is three flashes per second.
- Condition #2: speed activation threshold is 10 mph above the advisory speed for the horizontal curve: flash sequence is simultaneous; flash rate is three flashes per second.
- Condition #3: speed-activation threshold is 5 mph above the advisory speed for the horizontal curve; flash sequence is away from the driver; flash rate is one flash per second.
- Condition #4: speed activation threshold is 10 mph above the advisory speed for the horizontal curve: flash sequence is away from the driver; flash rate is one flash per second.

## STUDY SITES

The study sites for the present study are located in Wisconsin. Characteristics of the sites are shown in table 14. It should be noted that a driveway was present near the midpoint of the horizontal curve at the Wisconsin Route 213 site, so the chevron array began immediately after the driveway and did not span the entire length of the curve.

**Table 14. Characteristics of Wisconsin study sites.**

| Route | Direction | AADT (veh/day) | Lane Width (ft) | Shoulder Width (ft) | Posted Speed Limit (mph) | Curve Advisory Speed Limit (mph) | Curve Radius* (ft) | Curve Length* (ft) | Number of Chevrons | Chevron Signs* Spacing (ft) |
|---|---|---|---|---|---|---|---|---|---|---|
| 20 | WB | 3,583 | 12 | 2 | 55 | 30 | 259.23 | 473.05 | 9 | 50 |
| 67 | SB | 3,494 | 12 | 3 | 55 | 25 | 249.86 | 531.80 | 5 | 100 |
| 213 | SB | 2,369 | 12 | 3 | 55 | 50 | 464.16 | 511.56 | 5 | 50 |

* = Curve radius, curve length and chevron sign spacing were estimated from aerial imagery.

The existing SDCWS at the study sites is equipped with a radar device that can detect vehicles approximately 800 ft in advance of the horizontal curve, and is set to activate only when it detects approaching vehicles exceeding a certain speed threshold. A wireless communication system maintains synchronization among the chevron signs within the system.

## SPEED LIMIT COMPLIANCE AND OPERATING SPEED FIELD ASSESSMENT

The research team collected observational speed data at the three locations identified in table 14. A sample of speeds were collected at each site under the five conditions noted in the "Objectives" section above, beginning with the baseline condition. For each, operating speeds were measured at a point upstream (and beyond the detection range of the SDCWS) to act as a control point, which allowed the research team to confirm that speeds were not changing at the data collection locations due to ancillary factors in the area. The control point also provided an indication of the voluntary speed limit compliance rate by vehicles on the roadways prior to reaching the SDCWS curve locations. A sample data collection configuration is shown in figure 12.

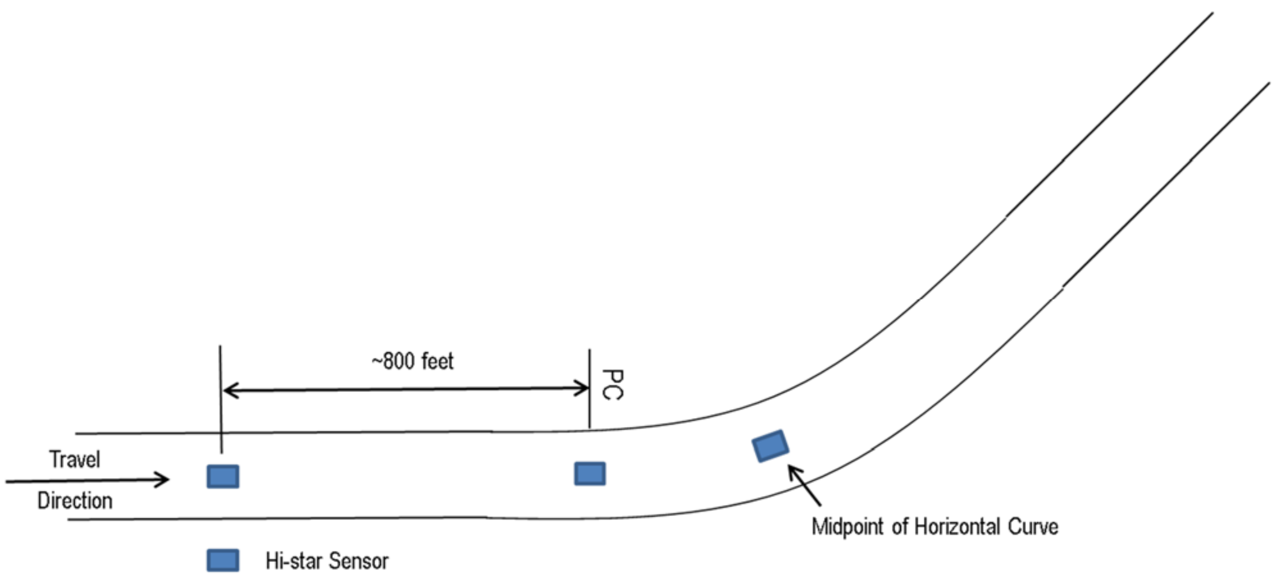



**Figure 12. Graphic. Data collection layout.**

Figure 12 shows a data collection point approximately 800 ft prior to the beginning of a horizontal curve, where the SDCWS first detects vehicles. Some field experimentation prior to beginning the data collection effort was undertaken to confirm this location at each study site. The upstream sensor was moved to a location just beyond the limit of the detection range prior to commencing field data collection, and was placed as close as possible to the previous field data collection location used by Smadi et al.(Smadi et al. 2015) Another data collection location was positioned at the beginning of the horizontal curve. The mid-point of the horizontal curve was the final data collection location at each Wisconsin site.

The results of the field study are presented in the "Analysis Results" section that follows. The data collection protocols, sample size requirements, and data analysis methods are described in detail in Appendix C. The field evaluation methods and data compiled during the field study are also detailed in Appendix C.

### Variables

The primary data in the present study were the free-flow operating speeds of vehicles at all study locations. A sample of observed operating speeds was used to create speed distributions that show the range of driver behavior at each study site. These distributions were used to calculate measures of performance, such as the mean operating speed, standard deviation (or variance) of speed, specific speed percentiles (e.g., 85th-percentile operating speed), proportion of vehicles traveling within the pace (defined as the 10 mph range that has the highest proportion of observed speeds), and the proportion of vehicles exceeding the horizontal curve advisory speed (a measure of speed limit non-compliance). These measures of performance served as the dependent variables in the operating speed assessment. Several independent variables were considered in the SDCWS evaluation, including the following:

- Time of day (night vs. day).
- Flashing condition (baseline and conditions #1 through #4).
- Data collection location (~800 ft before the curve, PC location, and midcurve location).

## ANALYSIS RESULTS

The analyses from this part of the study are presented in detail in Appendix D of the report. The analyses are organized into four sections. First, the difference in the mean and 85$^{th}$-percentile operating speeds at each data collection location for each condition is presented. This analysis includes tabular and graphical summaries for the entire data collection period at each site, and is then disaggregated by daytime and nighttime speeds. The second section presents the difference in mean and 85$^{th}$-percentile speeds between adjacent data collection locations at each site. These data are presented for each data collection period, and then disaggregated by daytime and nighttime periods. The third section presents information about the proportion of vehicles exceeding the posted speed limit as well as the horizontal curve advisory speed. The final part of this section includes all of the statistical tests that were completed to compare the various speed metrics across the test conditions.

### Speed Difference Results

The purpose of this analysis was to compare the mean and 85$^{th}$-percentile operating speeds between each data collection condition at each data collection location. Appendix D presents detailed results in three subsections. The first considers all of the data collection time periods combined (daytime and nighttime). The second subsection considers only the daytime data collection period, while the final subsection considers only the nighttime data collection period.

### *Summary of Speed Difference Results*

When considering the collective results of the speed difference analysis, there appears to be a more significant operating speed benefit for the sequential flashing signs during nighttime conditions than during the daytime conditions. This was expected because the signs may be one of only a few cues that drivers received at night, while other cues likely exist during the day, when traversing a horizontal curve on rural two-lane highways. During the nighttime conditions, condition #1 (simultaneous flashing pattern at a rate of 3Hz, with a speed activation threshold 5 mph above the advisory speed) produced the lowest mean and 85$^{th}$-percentile operating speeds relative to the baseline and other active, sequential flashing patterns. For condition #1, the mean operating speeds at the midpoint of the curve were 0.0 to 3.3 mph lower during the active condition relative to the baseline (inactive) condition, while the 85$^{th}$-percentile operating speeds were 0 to 4 mph lower than the baseline condition, at the three study sites. At the beginning of the curve, the speed reduction effect of condition #1 was more significant. Mean speeds were 1.1 to 3.3 mph lower than the baseline condition, while the 85$^{th}$-percentile operating speeds were 2.5 to 4.0 mph lower than the baseline condition. Condition #2 (same as condition #1 with speed activation threshold that is 10 mph above the curve advisory speed) produced operating speeds at night that were also generally lower than the baseline condition. Conditions #3 and #4 (flashing pattern away from the driver) did not have a consistent, significant effect on vehicle operating speeds at night in the present study.

## Operating Speed Differences between Data Collection Locations

The analysis considered the mean and 85$^{th}$-percentile operating speed differences between each data collection location for all five conditions (baseline plus conditions #1 through #4). For each condition, the data were aggregated for the entire data collection period (daytime and nighttime combined) and then disaggregated into daytime and nighttime periods only. The speed differences were calculated between the following data collection locations:

- Upstream (800 ft before the curve) minus the point of curvature.
- Upstream minus the midpoint of the horizontal curve.
- PC minus the midpoint of the horizontal curve.

In this analysis, all of the speed differences have a positive value, indicating that the speed at the upstream location is greater than the operating speed at a downstream location. A summary of the data used for this analysis is shown in table 15 through table 23. In the present study, an active flashing condition for the sequential chevron array was considered effective if the difference between the upstream and midpoint of horizontal curve locations exceeded the speed difference at these same points during the baseline (inactive flashing) condition.

**Table 15. Difference in mean and 85th- percentile operating speeds between data collection locations – WI 213 upstream-PC.**

| Condition | Difference in Mean Speed | | | Difference in 85th Speed | | |
|---|---|---|---|---|---|---|
| | All-day | Daytime | Nighttime | All-day | Daytime | Nighttime |
| Baseline | 5.39 | 4.60 | 6.35 | 4.00 | 3.00 | 5.00 |
| Condition #1 | 5.71 | 4.53 | 6.56 | 5.00 | 4.00 | 7.00 |
| Condition #2 | 5.74 | 5.39 | 6.07 | 6.00 | 6.00 | 5.00 |
| Condition #3 | 4.89 | 4.69 | 5.16 | 4.00 | 4.00 | 5.00 |
| Condition #4 | 5.70 | 5.25 | 6.25 | 4.00 | 3.00 | 5.00 |

**Table 16. Difference in mean and 85th- percentile operating speeds between data collection - WI 213 upstream - midcurve.**

| Condition | Difference in Mean Speed | | | Difference in 85th Speed | | |
|---|---|---|---|---|---|---|
| | All-day | Daytime | Nighttime | All-day | Daytime | Nighttime |
| Baseline | 10.33 | 9.38 | 11.50 | 8.00 | 7.00 | 10.00 |
| Condition #1 | 10.38 | 9.03 | 11.37 | 9.00 | 8.00 | 9.00 |
| Condition #2 | 9.19 | 8.05 | 10.29 | 7.00 | 7.00 | 7.00 |
| Condition #3 | 7.98 | 6.81 | 9.51 | 5.00 | 5.00 | 7.00 |
| Condition #4 | 8.88 | 7.87 | 10.09 | 6.00 | 4.00 | 8.00 |

**Table 17. Difference in mean and $85^{th}$- percentile operating speeds between data collection locations – WI 213 PC-midcurve.**

| Condition | Difference in Mean Speed | | | Difference in 85th Speed | | |
|---|---|---|---|---|---|---|
| | All-day | Daytime | Nighttime | All-day | Daytime | Nighttime |
| Baseline | 4.94 | 4.77 | 5.15 | 4.00 | 4.00 | 5.00 |
| Condition #1 | 4.67 | 4.50 | 4.80 | 4.00 | 4.00 | 2.00 |
| Condition #2 | 3.45 | 2.66 | 4.22 | 1.00 | 1.00 | 2.00 |
| Condition #3 | 3.09 | 2.12 | 4.35 | 1.00 | 1.00 | 2.00 |
| Condition #4 | 3.17 | 2.62 | 3.84 | 2.00 | 1.00 | 3.00 |

**Table 18. Difference in mean and $85^{th}$- percentile operating speeds between data collection locations – WI 20 upstream-PC.**

| Condition | Difference in Mean Speed | | | Difference in 85th Speed | | |
|---|---|---|---|---|---|---|
| | All-day | Daytime | Nighttime | All-day | Daytime | Nighttime |
| Baseline | 11.44 | 11.31 | 11.69 | 12.00 | 11.00 | 13.00 |
| Condition #1 | 12.80 | 11.90 | 14.10 | 14.00 | 13.00 | 16.00 |
| Condition #2 | 11.69 | 11.34 | 12.25 | 12.00 | 11.00 | 12.00 |
| Condition #3 | 12.92 | 12.87 | 12.99 | 13.00 | 12.00 | 14.00 |
| Condition #4 | 13.63 | 13.98 | 13.26 | 13.00 | 13.00 | 13.00 |

**Table 19. Difference in mean and 85th- percentile operating speeds between data collection locations – WI 20 upstream-midcurve.**

| Condition | Difference in Mean Speed | | | Difference in 85th Speed | | |
|---|---|---|---|---|---|---|
| | All-day | Daytime | Nighttime | All-day | Daytime | Nighttime |
| Baseline | 18.06 | 17.87 | 18.41 | 18.00 | 17.00 | 18.00 |
| Condition #1 | 17.85 | 17.34 | 18.60 | 19.00 | 18.00 | 20.00 |
| Condition #2 | 16.87 | 17.10 | 16.49 | 18.00 | 17.00 | 16.00 |
| Condition #3 | 18.58 | 18.69 | 18.43 | 19.00 | 19.00 | 19.00 |
| Condition #4 | 18.38 | 19.33 | 17.35 | 18.00 | 20.00 | 17.00 |

**Table 20. Difference in mean and 85th- percentile operating speeds between data collection locations – WI 20 PC-midcurve.**

| Condition | Difference in Mean Speed | | | Difference in 85th Speed | | |
|---|---|---|---|---|---|---|
| | All-day | Daytime | Nighttime | All-day | Daytime | Nighttime |
| Baseline | 6.62 | 6.57 | 6.72 | 6.00 | 6.00 | 5.00 |
| Condition #1 | 5.06 | 5.44 | 4.50 | 5.00 | 5.00 | 4.00 |
| Condition #2 | 5.18 | 5.75 | 4.24 | 6.00 | 6.00 | 4.00 |
| Condition #3 | 5.66 | 5.83 | 5.44 | 6.00 | 7.00 | 5.00 |
| Condition #4 | 4.75 | 5.35 | 4.10 | 5.00 | 7.00 | 4.00 |

**Table 21. Difference in mean and 85th- percentile operating speeds between data collection locations – WI 67 upstream-PC.**

| Condition | Difference in Mean Speed | | | Difference in 85th Speed | | |
|---|---|---|---|---|---|---|
| | All-day | Daytime | Nighttime | All-day | Daytime | Nighttime |
| Baseline | 6.31 | 5.65 | 6.74 | 6.00 | 5.00 | 7.00 |
| Condition #1 | 7.25 | 6.15 | 9.20 | 8.50 | 7.00 | 11.00 |
| Condition #2 | 7.51 | 6.45 | 8.64 | 9.00 | 7.00 | 9.00 |
| Condition #3 | 6.58 | 6.21 | 7.24 | 7.00 | 8.00 | 7.00 |
| Condition #4 | 6.12 | 6.21 | 7.24 | 7.00 | 8.00 | 7.00 |

**Table 22. Difference in mean and 85th- percentile operating speeds between data collection locations - WI 67 (upstream-midcurve).**

| Condition | Difference in Mean Speed | | | Difference in 85th Speed | | |
|---|---|---|---|---|---|---|
| | All-day | Daytime | Nighttime | All-day | Daytime | Nighttime |
| Baseline | 10.54 | 10.19 | 10.77 | 11.00 | 11.00 | 11.00 |
| Condition #1 | 10.73 | 9.48 | 12.94 | 12.50 | 10.00 | 15.00 |
| Condition #2 | 11.51 | 10.40 | 12.72 | 13.00 | 12.00 | 12.00 |
| Condition #3 | 10.88 | 10.87 | 10.90 | 12.00 | 12.00 | 11.00 |
| Condition #4 | 10.74 | 10.82 | 10.63 | 12.00 | 11.00 | 12.00 |

**Table 23. Difference in mean and $85^{th}$- percentile operating speeds between data collection locations - WI 67 (PC-midcurve).**

| Condition | Difference in Mean Speed | | | Difference in 85th Speed | | |
|---|---|---|---|---|---|---|
| | All-day | Daytime | Nighttime | All-day | Daytime | Nighttime |
| Baseline | 4.23 | 4.55 | 4.03 | 5.00 | 6.00 | 4.00 |
| Condition #1 | 3.48 | 3.33 | 3.74 | 4.00 | 3.00 | 4.00 |
| Condition #2 | 4.01 | 3.95 | 4.08 | 4.00 | 5.00 | 3.00 |
| Condition #3 | 4.29 | 4.66 | 3.66 | 5.00 | 4.00 | 4.00 |
| Condition #4 | 4.62 | 4.95 | 4.15 | 5.00 | 4.00 | 5.00 |

When considering the difference between the upstream and midpoint curve locations, the baseline condition produced the highest mean operating speed difference at the Wisconsin Route 213 site for the daytime period and the nighttime period. Condition #1 produced the highest mean speed difference for the combined daytime and nighttime conditions at the Wisconsin Route 213 site. Condition #1 produced the highest $85^{th}$-percentile speed difference for the daytime only period, as well as the combined daytime and nighttime periods. The baseline condition produced the highest $85^{th}$-percentile operating speed difference between the upstream location and midpoint of the horizontal curve during the nighttime only condition. There is little difference in the speed difference metrics between the baseline and condition #1 at the Wisconsin Route 213 site.

At the Wisconsin Route 20 site, conditions #1, #3, and #4 all produced mean or $85^{th}$-percentile operating speed differences that exceeded the speed difference during the baseline condition, depending on the data collection period (daytime only, nighttime only, or daytime and nighttime combined). During the nighttime condition only, condition #1 produced the largest speed reduction between the upstream location and the midpoint of the horizontal curve.

At the Wisconsin Route 67 site, conditions #1, #3, and #4 all produced mean or $85^{th}$-percentile operating speed differences that exceeded the speed difference during the baseline condition, depending on the data collection period (daytime only, nighttime only, or daytime and nighttime combined). During the nighttime condition only, condition #1 produced the largest speed reduction between the upstream location and the midpoint of the horizontal curve.

Figure 13 through figure 18 show the speed difference data graphically for the sites on Wisconsin routes 213, 20, and 67, respectively. In the top panel of each figure, the mean speed difference is shown, while the bottom panel in each figure shows the $85^{th}$-percentile speed difference.

This analysis generally supports the previous analysis, which indicates that the simultaneous flashing pattern, which is activated when vehicle operating speeds exceed the advisory curve warning speed by 5 mph or more, produces the greatest speed difference between the upstream and midpoint curve locations at night.

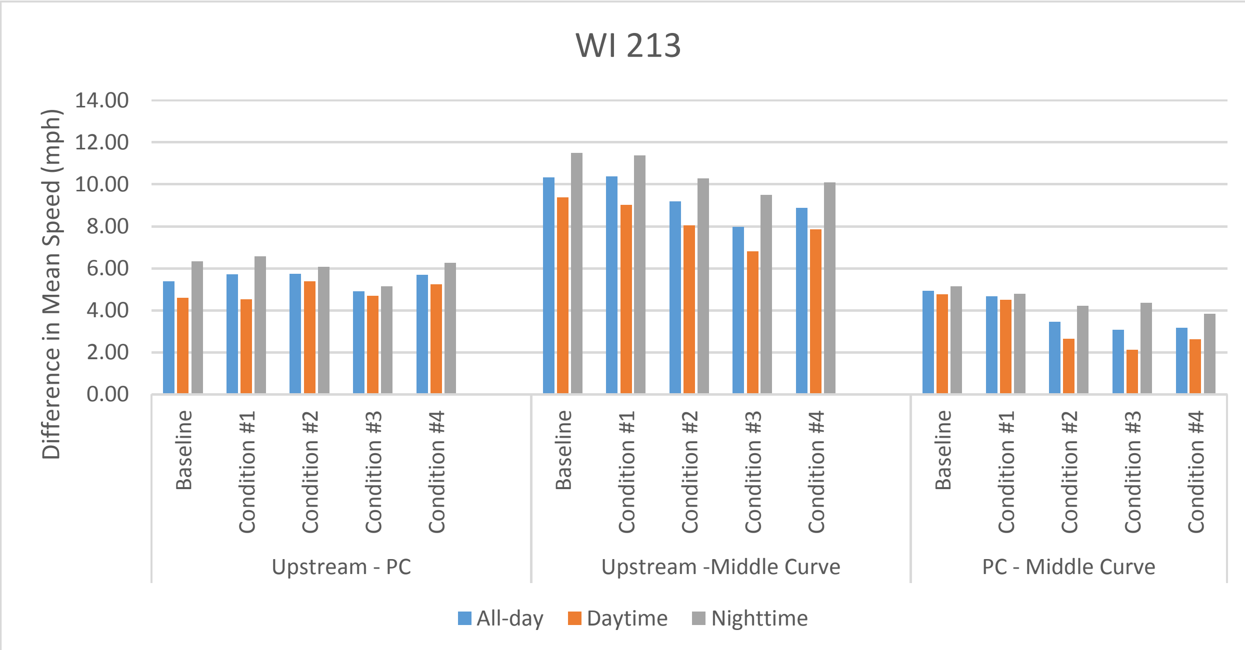



**Figure 13. Graph. Mean operating speed difference at the WI 213 site.**

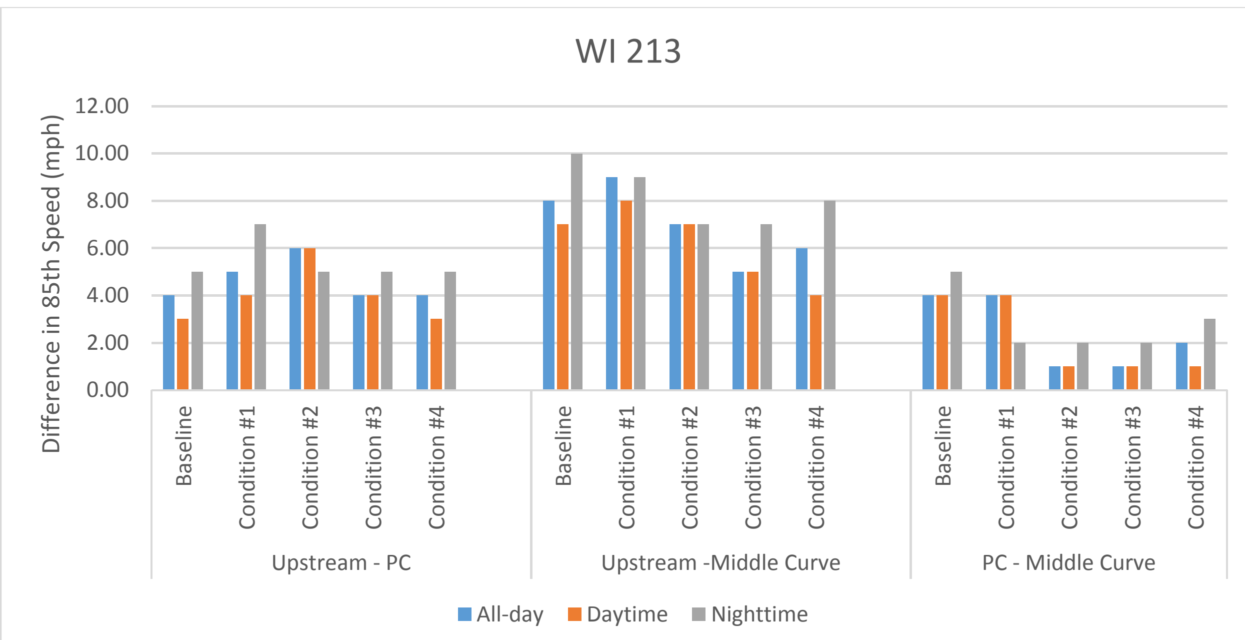



**Figure 14. Graph. 85th-percentile operating speed difference at the WI 213 site.**

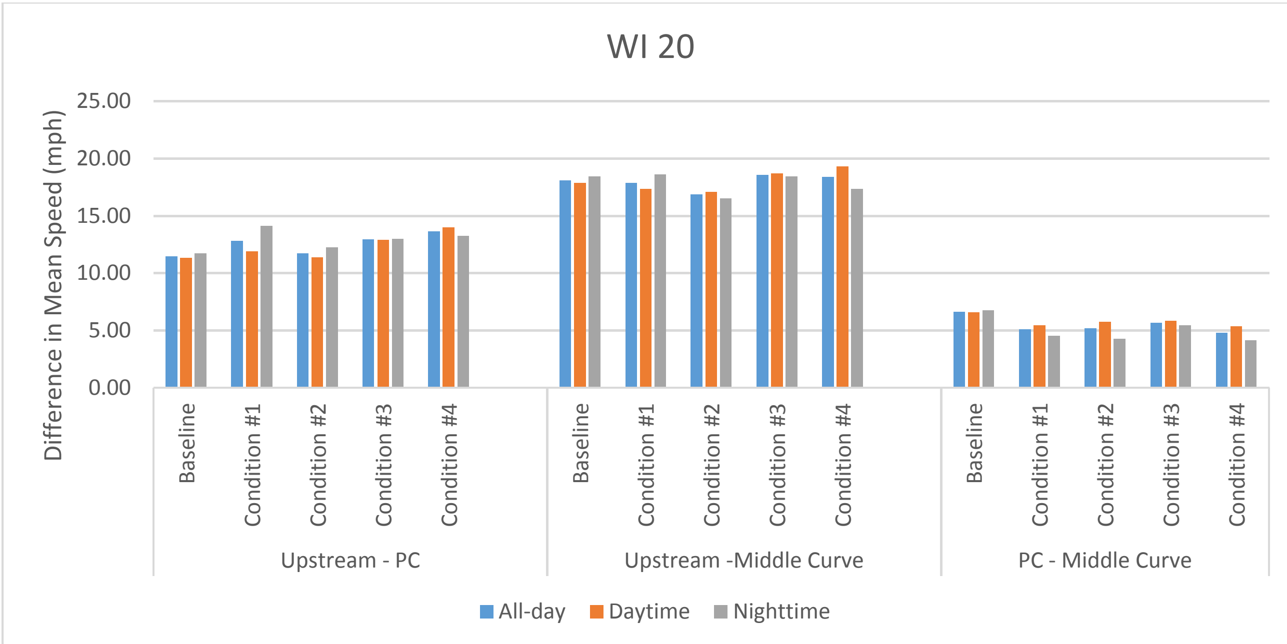



**Figure 15. Graph. Mean operating speed difference at the WI 20 site.**

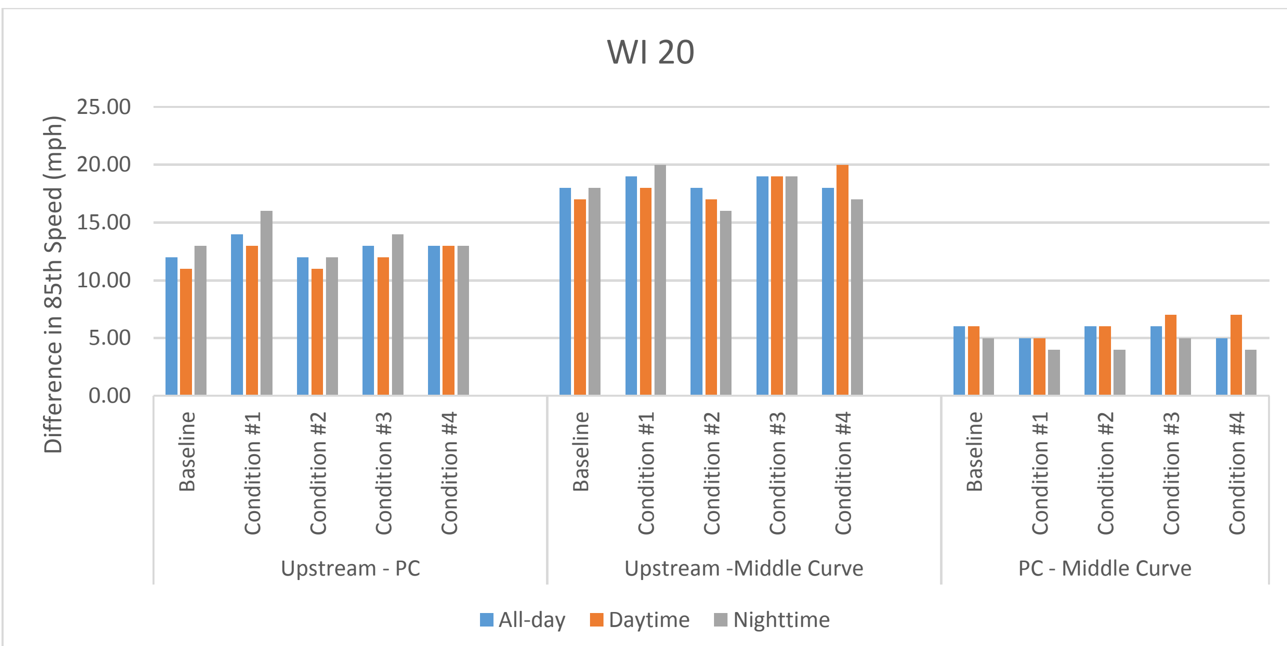



**Figure 16. Graph. 85th-percentile operating speed difference at the WI 20 site.**

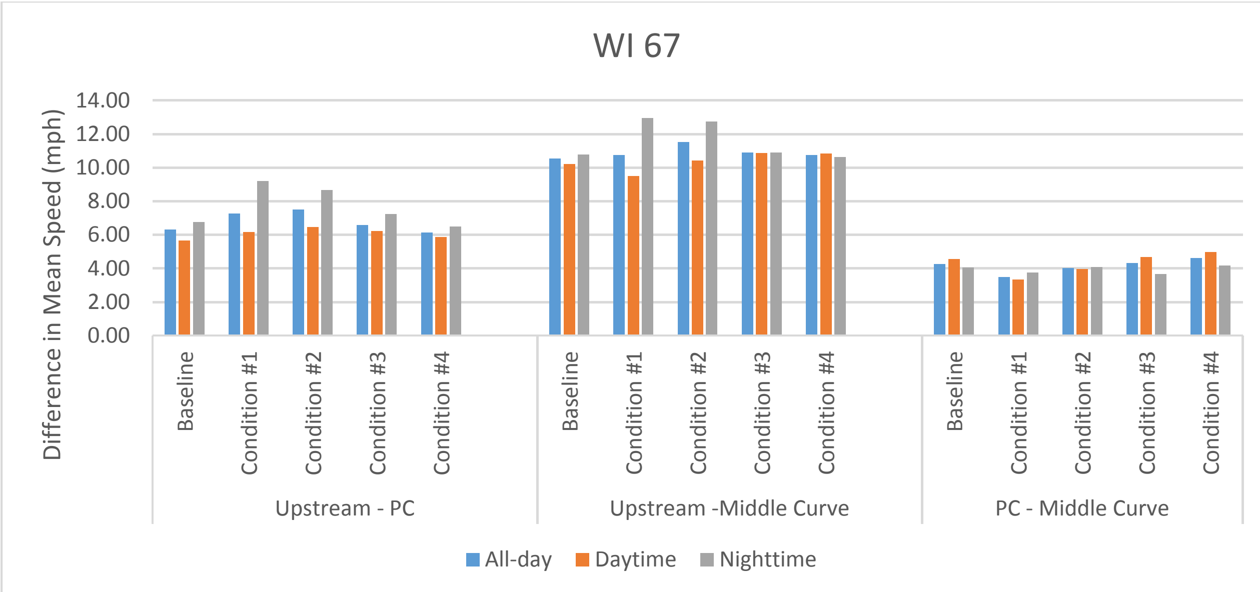



**Figure 17. Graph. Mean operating speed difference at the WI 67 site.**

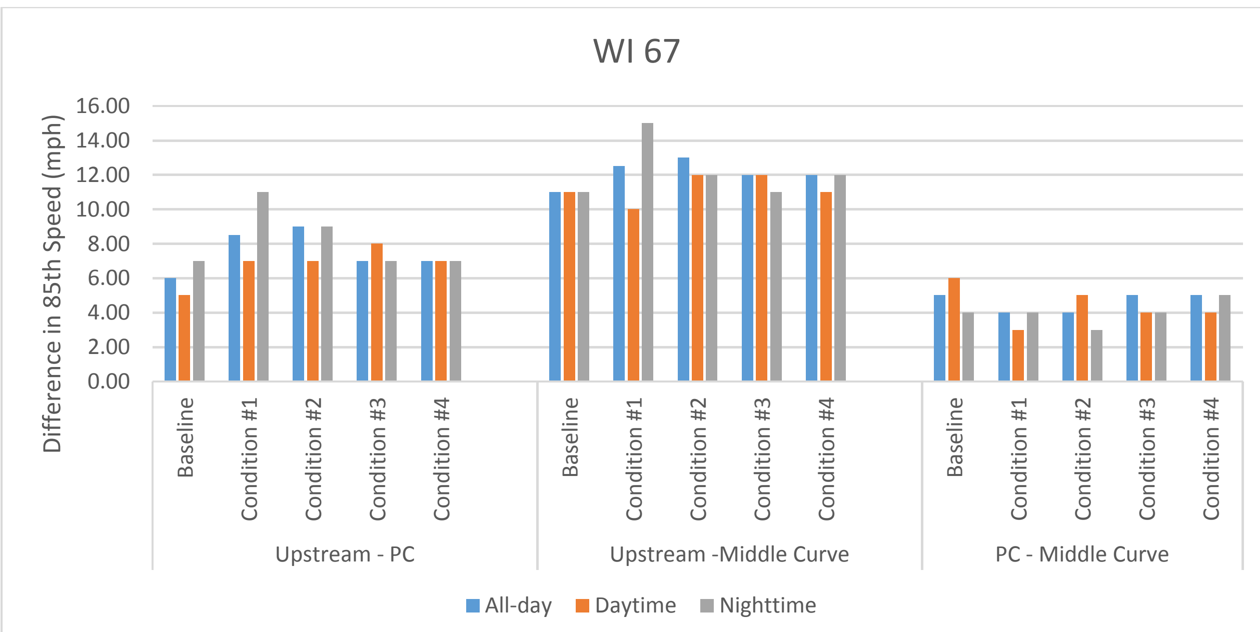



**Figure 18. Graph. 85th-percentile operating speed difference at the WI 67 site.**

### Proportion of Vehicles Exceeding the Posted Speed Limit

This analysis considered the proportion of vehicles exceeding the advisory speed limit by 5 and 10 mph, respectively. Operating speed data were collected at three locations at each Wisconsin study site: 800 ft before the beginning of the horizontal curve, the point of curvature, and the midpoint of the horizontal curve. A lower proportion of vehicles exceeding the posted speed limit indicated a desirable outcome for the chevron condition being evaluated. The data presented in table 24 through table 26 are for a full data collection period (daytime and nighttime combined), daytime only, and nighttime only, respectively.

**Table 24. Proportion of vehicles exceeding the advisory speed (daytime and nighttime combined – WI 213).**

| Period | Percent of vehicles exceeding advisory speed by 5 mph | | | Percent of vehicles exceeding advisory speed by 10 mph | | |
|---|---|---|---|---|---|---|
| | 800 ft prior | PC | Midcurve | 800 ft prior | PC | Midcurve |
| Baseline | 76.25% | 43.44% | 24.06% | 40.31% | 16.56% | 3.75% |
| Condition #1 | 75.92% | 36.73% | 20.82% | 43.67% | 12.24% | 2.04% |
| Condition #2 | 77.16% | 38.58% | 29.44% | 40.61% | 11.17% | 6.60% |
| Condition #3 | 78.64% | 43.73% | 34.58% | 40.68% | 18.31% | 10.85% |
| Condition #4 | 84.13% | 39.05% | 30.16% | 40.63% | 15.24% | 9.84% |

**Table 25. Proportion of vehicles exceeding the advisory speed (daytime and nighttime combined – WI 20).**

| Period | Percent of vehicles exceeding advisory speed by 5 mph | | | Percent of vehicles exceeding advisory speed by 10 mph | | |
|---|---|---|---|---|---|---|
| | 800 ft prior | PC | Midcurve | 800 ft prior | PC | Midcurve |
| Baseline | 98.73% | 89.81% | 54.14% | 98.73% | 60.19% | 18.15% |
| Condition #1 | 96.94% | 82.99% | 52.04% | 94.56% | 45.24% | 12.24% |
| Condition #2 | 99.46% | 81.23% | 49.06% | 97.59% | 43.43% | 14.75% |
| Condition #3 | 100.00% | 85.76% | 54.85% | 98.79% | 55.45% | 17.88% |
| Condition #4 | 98.83% | 85.38% | 57.31% | 98.54% | 50.29% | 21.05% |

**Table 26. Proportion of vehicles exceeding the advisory speed (daytime and nighttime combined – WI 67).**

| Period | Percent of vehicles exceeding advisory speed by 5 mph | | | Percent of vehicles exceeding advisory speed by 10 mph | | |
|---|---|---|---|---|---|---|
| | 800 ft prior | PC | Midcurve | 800 ft prior | PC | Midcurve |
| Baseline | 97.98% | 100.00% | 99.60% | 95.97% | 96.37% | 85.48% |
| Condition #1 | 98.42% | 99.47% | 96.58% | 95.26% | 93.16% | 81.58% |
| Condition #2 | 98.63% | 99.32% | 96.58% | 95.67% | 93.39% | 79.04% |
| Condition #3 | 99.16% | 99.72% | 96.91% | 98.03% | 96.35% | 87.36% |
| Condition #4 | 97.65% | 99.36% | 97.65% | 96.79% | 96.37% | 84.40% |

In table 27, the lowest proportion of vehicles exceeding the curve advisory speed by 5 mph resulted during condition #1 at the midpoint of the horizontal curve for Wisconsin Route 213. Condition #2 produced the lowest proportion of vehicles exceeding the curve advisory speed at Wisconsin routes 20 and 67. When considering the proportion of vehicles exceeding the advisory speed plus 10 mph, condition #1 produced the lowest proportion at Wisconsin routes 213 and 20. The lowest proportion of vehicles exceeding the curve advisory speed by 10 mph was found during condition #2 at the midpoint horizontal curve location along the Wisconsin Route 67 study site. These findings were similar at the point of curve data collection location, where conditions #1 and #2 both produced the smallest proportions among the five conditions evaluated.

Table 27 through table 29 shows the proportion of vehicles exceeding the advisory curve speed during the daytime only. At the midpoint of the horizontal curve, the lowest proportion of vehicles exceeding the posted speed limit occurred in condition #1 at all three Wisconsin sites. The only exception was for Wisconsin Route 67, when considering the proportion of vehicles exceeding the advisory speed plus 10 mph – in this case, Condition #2 resulted in the lowest proportion of vehicles exceeding the curve advisory speed. Condition #1 and #2 produced the lowest proportion of vehicles exceeding the curve advisory speed at the point of curvature.

**Table 27. Proportions of vehicles exceeding the curve advisory speed during the daytime only – WI 213.**

| Period | Percent of vehicles exceeding advisory speed by 5 mph | | | Percent of vehicles exceeding advisory speed by 10 mph | | |
|---|---|---|---|---|---|---|
| | 800 ft prior | PC | Midcurve | 800 ft prior | PC | Midcurve |
| Baseline | 80.11% | 49.43% | 29.55% | 39.20% | 17.05% | 3.98% |
| Condition #1 | 82.52% | 51.46% | 23.30% | 43.69% | 15.53% | 2.91% |
| Condition #2 | 80.41% | 40.21% | 34.02% | 43.30% | 14.43% | 9.28% |
| Condition #3 | 76.65% | 41.32% | 37.72% | 41.92% | 16.17% | 11.38% |
| Condition #4 | 84.30% | 40.70% | 34.88% | 42.44% | 16.28% | 12.21% |

**Table 28. Proportions of vehicles exceeding the curve advisory speed during the daytime only – WI 20.**

| Period | Percent of vehicles exceeding advisory speed by 5 mph | | | Percent of vehicles exceeding advisory speed by 10 mph | | |
|---|---|---|---|---|---|---|
| | 800 ft prior | PC | Midcurve | 800 ft prior | PC | Midcurve |
| Baseline | 99.03% | 89.37% | 51.69% | 99.03% | 59.42% | 16.91% |
| Condition #1 | 95.40% | 79.89% | 44.83% | 91.95% | 42.53% | 10.34% |
| Condition #2 | 99.57% | 83.55% | 46.75% | 97.40% | 44.16% | 10.39% |
| Condition #3 | 100.00% | 83.60% | 48.15% | 98.94% | 50.26% | 12.70% |
| Condition #4 | 99.44% | 80.90% | 47.75% | 98.88% | 44.94% | 14.61% |

**Table 29. Proportions of vehicles exceeding the curve advisory speed during the daytime only – WI 67.**

| Period | Percent of vehicles exceeding advisory speed by 5 mph | | | Percent of vehicles exceeding advisory speed by 10 mph | | |
|---|---|---|---|---|---|---|
| | 800 ft prior | PC | Midcurve | 800 ft prior | PC | Midcurve |
| Baseline | 97.98% | 100.00% | 98.99% | 95.96% | 94.95% | 84.85% |
| Condition #1 | 97.94% | 99.59% | 96.30% | 95.47% | 94.24% | 84.77% |
| Condition #2 | 98.25% | 99.12% | 96.93% | 94.74% | 95.61% | 79.82% |
| Condition #3 | 99.12% | 100.00% | 97.79% | 97.35% | 96.46% | 87.61% |
| Condition #4 | 97.81% | 98.91% | 96.35% | 97.08% | 95.62% | 82.85% |

Table 30 through table 32 shows the proportion of vehicles exceeding the advisory curve speed during the nighttime only. At the midpoint of the horizontal curve, the lowest proportion of vehicles exceeding the curve advisory speed by 10 mph occurred for condition #1 at all three Wisconsin sites. When using the advisory speed plus 5 mph criterion, the lowest proportion of vehicles exceeding this speed at the midpoint of the curve occurred during the baseline at Wisconsin Route 213, during condition #2 for Wisconsin Route 20, and during condition #3 for Wisconsin Route 67. When considering the point of curvature location, the lowest proportion of vehicles exceeding the advisory speeds by 5 and 10 mph were during conditions #1 and #2.

**Table 30. Proportion of vehicles exceeding the curve advisory speed during the nighttime only - WI 213.**

| Period | Percent of vehicles exceeding advisory speed by 5 mph | | | Percent of vehicles exceeding advisory speed by 10 mph | | |
|---|---|---|---|---|---|---|
| | 800 ft prior | PC | Midcurve | 800 ft prior | PC | Midcurve |
| Baseline | 71.53% | 36.11% | 17.36% | 41.67% | 15.97% | 3.47% |
| Condition #1 | 71.13% | 26.06% | 19.01% | 43.66% | 9.86% | 1.41% |
| Condition #2 | 74.00% | 37.00% | 25.00% | 38.00% | 8.00% | 4.00% |
| Condition #3 | 81.25% | 46.88% | 30.47% | 39.06% | 21.09% | 10.16% |
| Condition #4 | 83.92% | 37.06% | 24.48% | 38.46% | 13.99% | 6.99% |

**Table 31. Proportion of vehicles exceeding the curve advisory speed during the nighttime only - WI 20.**

| Period | Percent of vehicles exceeding advisory speed by 5 mph | | | Percent of vehicles exceeding advisory speed by 10 mph | | |
|---|---|---|---|---|---|---|
| | 800 ft prior | PC | Midcurve | 800 ft prior | PC | Midcurve |
| Baseline | 98.13% | 90.65% | 58.88% | 98.13% | 61.68% | 20.56% |
| Condition #1 | 99.17% | 87.50% | 62.50% | 98.33% | 49.17% | 15.00% |
| Condition #2 | 99.30% | 77.46% | 52.82% | 97.89% | 42.25% | 21.83% |
| Condition #3 | 100.00% | 88.65% | 63.83% | 98.58% | 62.41% | 24.82% |
| Condition #4 | 98.17% | 90.24% | 67.68% | 98.17% | 56.10% | 28.05% |

**Table 32. Proportion of vehicles exceeding the curve advisory speed during the nighttime only - WI 67.**

| Period | Percent of vehicles exceeding advisory speed by 5 mph | | | Percent of vehicles exceeding advisory speed by 10 mph | | |
|---|---|---|---|---|---|---|
| | 800 ft prior | PC | Midcurve | 800 ft prior | PC | Midcurve |
| Baseline | 97.99% | 100.00% | 100.00% | 95.97% | 97.32% | 85.91% |
| Condition #1 | 99.27% | 99.27% | 97.08% | 94.89% | 91.24% | 75.91% |
| Condition #2 | 99.05% | 99.53% | 96.21% | 96.68% | 91.00% | 78.20% |
| Condition #3 | 99.23% | 99.23% | 95.38% | 99.23% | 96.15% | 86.92% |
| Condition #4 | 97.42% | 100.00% | 99.48% | 96.39% | 97.42% | 86.60% |

Figure 19 through figure 27 show the analysis results graphically. In figure 19 through figure 21, the proportion of vehicles exceeding the curve advisory speed is shown for all three data collection sites when aggregating the daytime and nighttime data. Figure 22 through figure 24 includes data for the daytime period only, while figure 25 through figure 27 includes data for the nighttime period only. In each figure, all three data collection sites are shown separately. The proportion of vehicles exceeding the advisory speed by 5, 10, 15, and 20 mph are shown in each figure. As expected, the proportion of vehicles exceeding the advisory speeds generally declines from the location 800 ft prior to the horizontal curve to the midpoint of the horizontal curve.

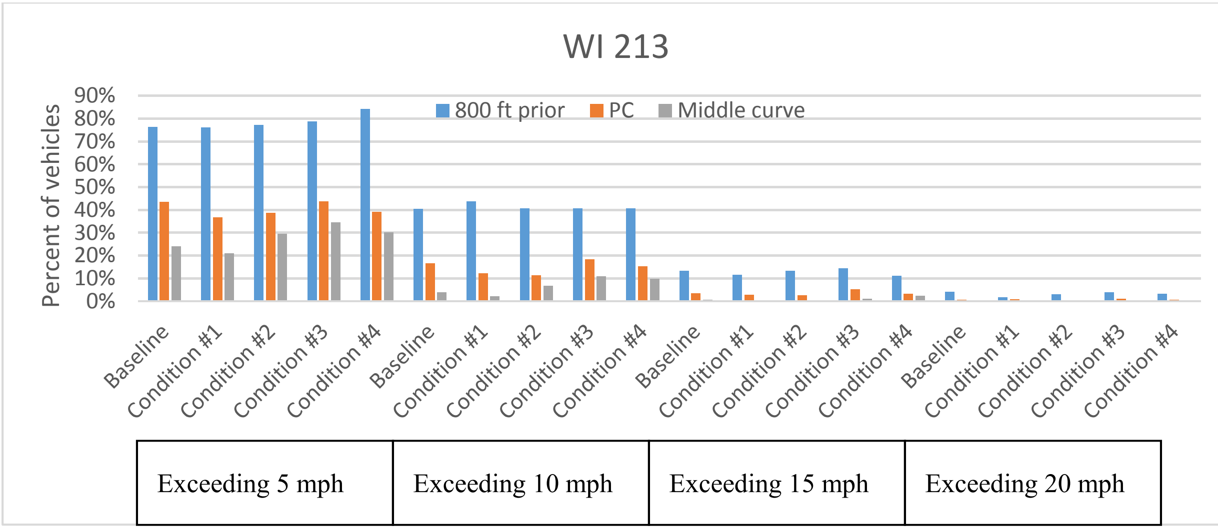



**Figure 19. Graph. Proportion of vehicles exceeding the advisory speed (daytime and nighttime combined) – WI 213.**

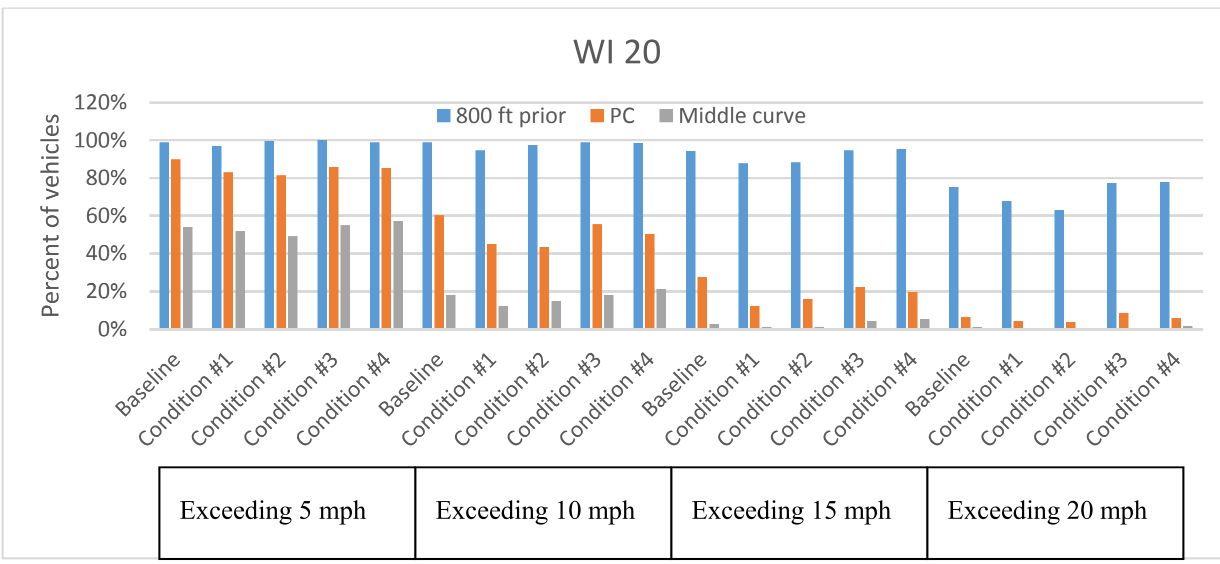



**Figure 20. Graph. Proportion of vehicles exceeding the advisory speed (daytime and nighttime combined) – WI 20.**

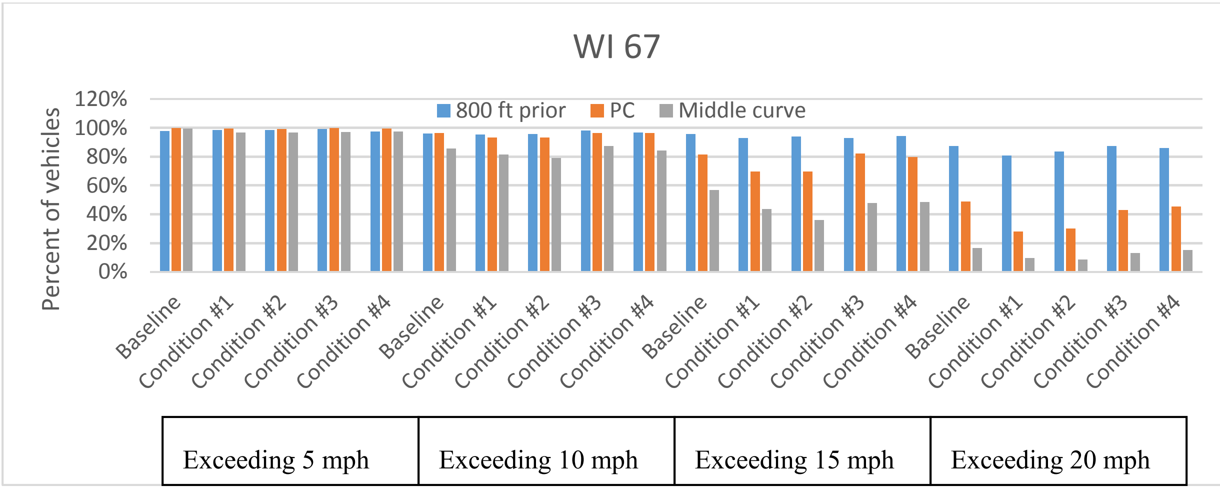



**Figure 21. Graph. Proportion of vehicles exceeding the advisory speed (daytime and nighttime combined) – WI 67.**

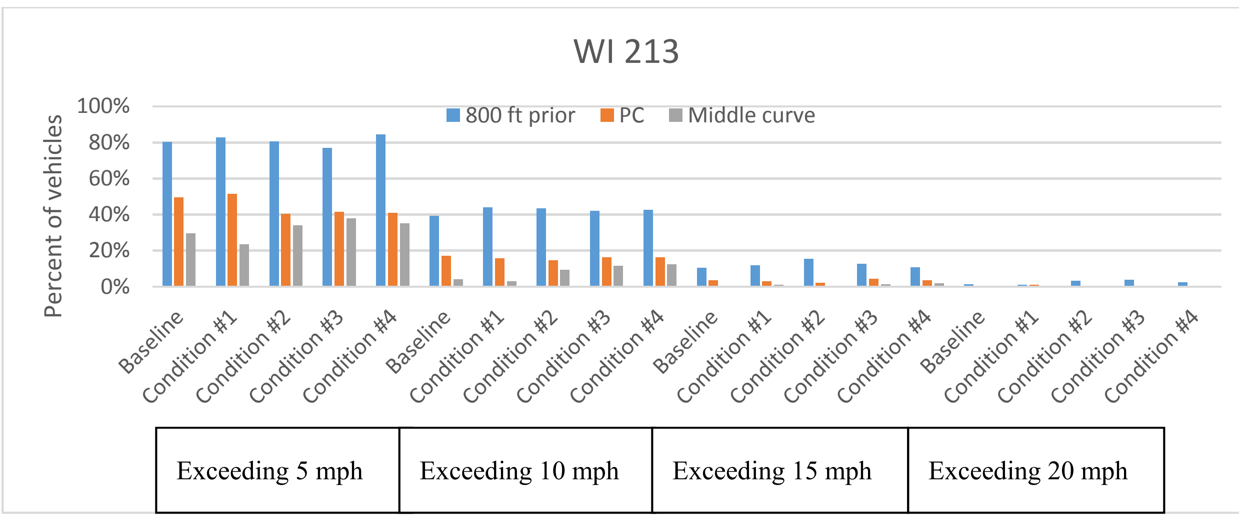



**Figure 22. Graph. Proportion of vehicles exceeding the advisory speed during the daytime – WI 213.**

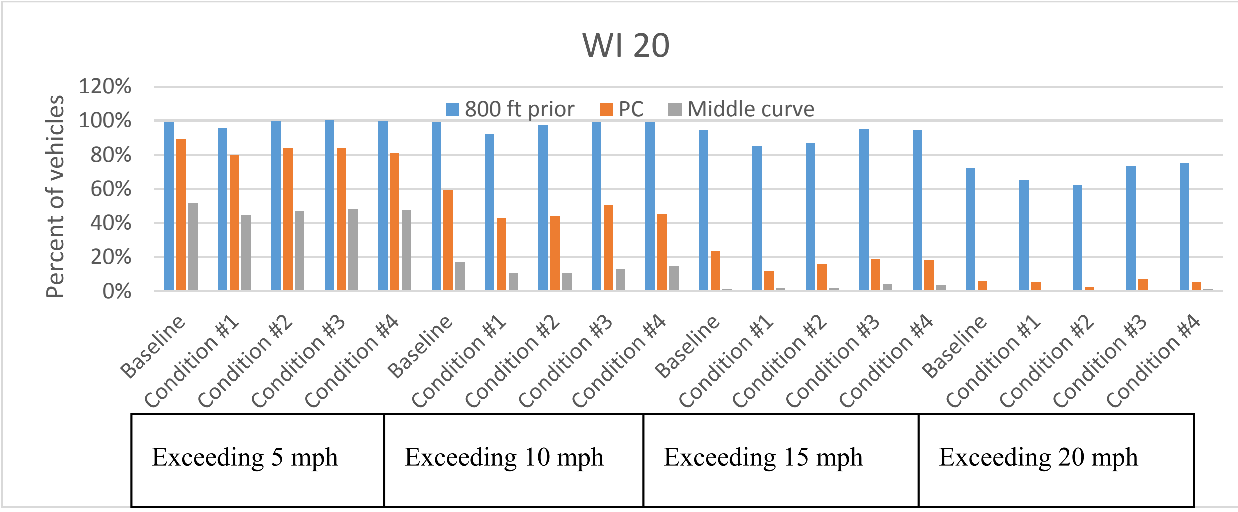



**Figure 23. Graph. Proportion of vehicles exceeding the advisory speed during the daytime – WI 20.**

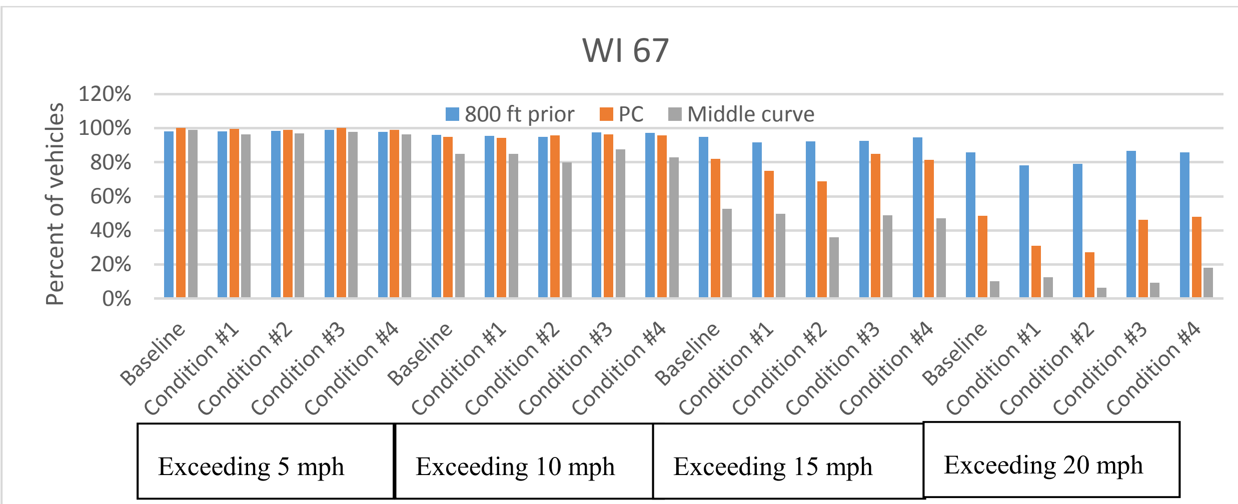



**Figure 24. Graph. Proportion of vehicles exceeding the advisory speed during the daytime – WI 67.**

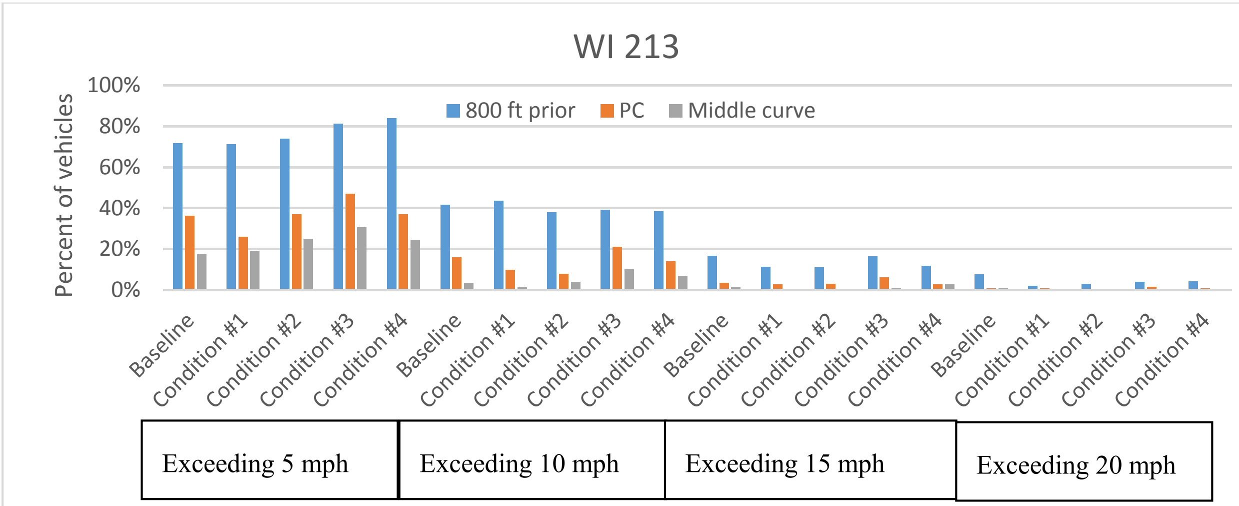



**Figure 25. Graph. Proportion of vehicles exceeding the advisory speed during the nighttime – WI 213.**

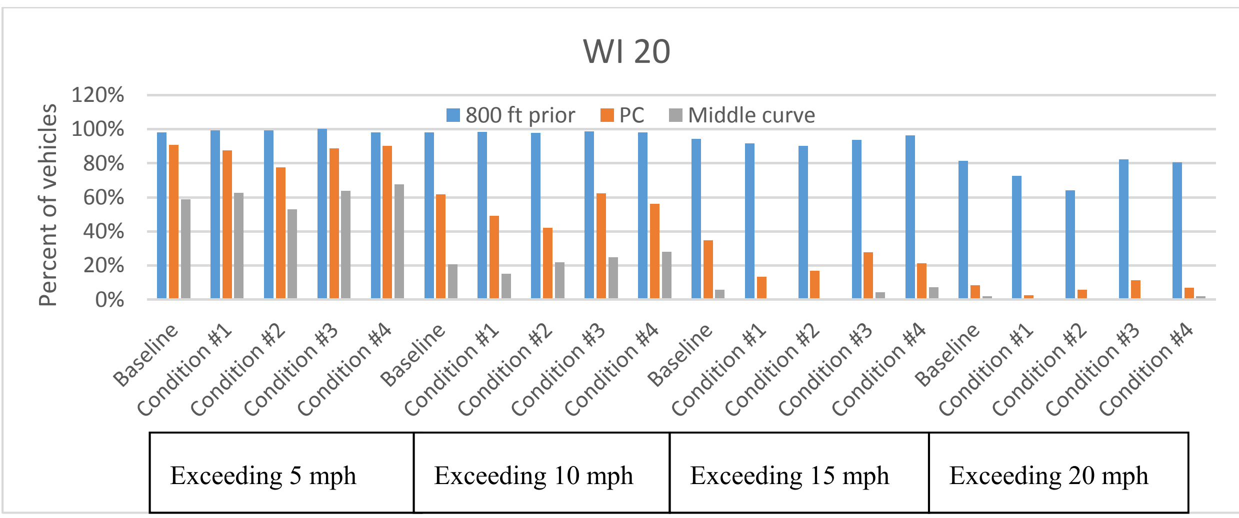



**Figure 26. Graph. Proportion of vehicles exceeding the advisory speed during the nighttime – WI 20.**

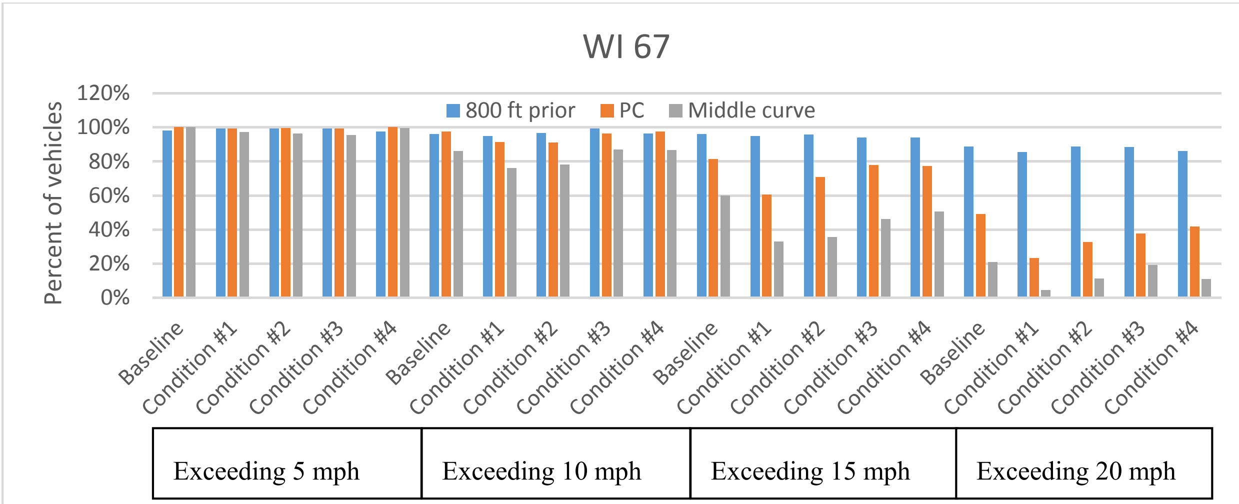



**Figure 27. Graph. Proportion of vehicles exceeding the advisory speed during the nighttime – WI 67.**

***Summary of Proportion of Vehicles Exceeding Advisory Speed Analysis***

This analysis considered the proportion of vehicles exceeding the advisory speed by increments of 5 mph. In general, conditions #1 and #2 (simultaneous flashing pattern, with a flashing rate of 3 Hz, and speed activation thresholds 5 and 10 mph above the advisory speed) produced the greatest level of speed compliance among the five conditions tested. A large portion of the observed operating speeds exceeding the curve advisory warning speed by 5 mph at all three study sites; however, the proportion of vehicles exceeding the curve advisory speed by 15 or more mph was very low at all three study sites.

### Statistical Tests

Several statistical tests were performed to compare the active flashing sequential conditions (conditions #1 through #4) to the baseline condition. These included the following:

- Comparison of mean speeds
- Comparison of speed variance
- Test of proportions for vehicles exceeding the horizontal curve advisory speed

All of these tests were performed for the daytime and nighttime data collection periods combined, the daytime period only, and the nighttime period only. The results of the statistical tests are presented in appendix E.

### Comparison of Speed Measures

The results of the present study were compared to the results from a previous study of sequential flashing chevron signs.(Smadi et al. 2015) Only the three Wisconsin study sites were compared. All of the data were aggregated into combined daytime and nighttime operating speeds. The three data collection locations were located at the same points in both studies. The flashing pattern evaluated in the previous study was set to flash away from the driver at a rate of one flash per second (1 Hz). The speed activation threshold in the previous study was set equal to the curve speed advisory. In the present study, four conditions were evaluated. The results of the speed comparisons are shown in table 33 through table 38. The baseline and before periods are the same – an array of static chevrons were present at the study site without any active flashing pattern. The four conditions tested in the present study are based on operating speed data collected during a period approximately 24 hours after the flashing settings were programmed. As such, the most meaningful comparison to the previous study is for the period 1, 12, 18, and 24 months after the setting was programmed.

When comparing the baseline and before conditions in the following tables, the mean speed at the location 800 ft before the beginning of the horizontal curve was identical (59.4 mph) at Wisconsin Route 213. The baseline and before period mean speeds differed by approximately 2.3 mph at the Wisconsin Route 20 site (53.6 mph in the present study versus 55.9 mph in the previous study). Finally, the baseline and before period mean speeds differed by approximately 0.5 mph at the Wisconsin Route 67 site (51.6 mph in the present study versus 51.1 mph in the previous study). This suggests that operating speeds approaching the horizontal curve at each site were generally consistent during two different time periods, so drivers were generally selecting a speed that was similar when the static signs were present without an active flashing pattern.

When comparing the baseline mean speeds at the PC and midpoint of the horizontal curve from the present study, to the mean speeds at these same locations 24 months after the flashing pattern was established in the previous study, there are similarities. At Wisconsin Route 213, the mean speed at the PC in the baseline condition of the present study was 54.0 mph. In the previous study, the mean speed at the PC 24 months after the flashing pattern was set was 54.2 mph. At the Wisconsin Route 20 and 67 sites, the baseline mean speeds at the PC and midpoint curve locations are similar to the mean speeds 24 months after the flashing pattern was set in the previous study. This suggests that there is a long-term effect of the flashing pattern from the previous study.

The final set of comparisons are for each condition tested in the present study to the period 1, 12, 18, and 24 months after the flashing pattern was set in the previous study. The mean and 85$^{th}$-percentile operating speeds for conditions #1 and #2 in the present study were generally about one to two mph lower than the mean and 85$^{th}$-percentile operating speeds from the previous study at all three study sites. The mean and 85$^{th}$-percentile operating speeds for conditions #3 and #4 were similar to the mean and 85$^{th}$-percentile operating speeds from the previous study when compared to the speeds 1 month, 12 months, 18 months, and 24 months after the flashing pattern was established in the previous study. In the present study, however, the speed variance was generally higher for conditions #1 and #2 when compared to the previous study. This suggests that the simultaneous flashing pattern from the present study (conditions #1 and #2) may produce lower mean and 85$^{th}$-percentile operating speeds when compared to the sequential flashing pattern used in the present study; however, the speed variability associated with the simultaneous flashing pattern may be associated with an increase in the speed variance.

**Table 33. Operating speed for WI 213 – this study.**

| Period (Obs) | Location | Mean | SD | 85th speed |
|---|---|---|---|---|
| Baseline (N=320) | 800 ft prior | 59.41 | 6.17 | 65 |
| | PC | 54.02 | 6.98 | 61 |
| | Midcurve | 49.08 | 8.82 | 57 |
| Condition #1 (N=245) | 800 ft prior | 59.18 | 5.59 | 65 |
| | PC | 53.47 | 6.24 | 60 |
| | Midcurve | 48.8 | 7.32 | 56 |
| Condition #2 (N=197) | 800 ft prior | 59.44 | 5.68 | 65 |
| | PC | 53.7 | 6.28 | 59 |
| | Midcurve | 50.25 | 8.15 | 58 |
| Condition #3 (N=295) | 800 ft prior | 59.56 | 5.82 | 65 |
| | PC | 54.66 | 6.39 | 61 |
| | Midcurve | 51.58 | 8.22 | 60 |
| Condition #4 (N=315) | 800 ft prior | 59.86 | 4.92 | 65 |
| | PC | 54.15 | 5.91 | 61 |
| | Midcurve | 50.98 | 8.3 | 59 |

**Table 34. Operating speed for WI 213 – Smadi et al., 2015.**

| Period (Obs) | Location | Mean | SD | 85th speed |
|---|---|---|---|---|
| Before* (N=773) | 800 ft prior | 59.4 | -- | -- |
| | PC | 56.2 | 5.9 | 62 |
| | Midcurve | 55.5 | 7.1 | 62 |
| After 1 Month* (N=785) | 800 ft prior | 60.1 | -- | -- |
| | PC | 55 | 5.8 | 61 |
| | Midcurve | 54.3 | 7.1 | 61 |
| After 12 Months (N=775) | 800 ft prior | 60.9 | -- | -- |
| | PC | 56.2 | 5.6 | 62 |
| | Midcurve | 56 | 6.7 | 62 |
| After 18 Months (N=694) | 800 ft prior | 60.7 | -- | -- |
| | PC | 54.9 | 5.5 | 60 |
| | Midcurve | 55.9 | 6.5 | 62 |
| After 24 Months (N=1,473) | 800 ft prior | 59.6 | -- | -- |
| | PC | 54.2 | 5.5 | 60 |
| | Midcurve | 54.6 | 6.6 | 61 |

Note: -- no data available, * denotes the 95-percent confidence interval.

**Table 35. Operating speed for WI 20 – this study.**

| Period (Obs) | Location | Mean | SD | 85th speed |
|---|---|---|---|---|
| Baseline (N=314) | 800 ft prior | 53.57 | 5.39 | 59 |
| | PC | 42.13 | 5.48 | 47 |
| | Midcurve | 35.52 | 5.66 | 41 |
| Condition #1 (N=294) | 800 ft prior | 52.87 | 6.8 | 59 |
| | PC | 40.07 | 5.41 | 45 |
| | Midcurve | 35.01 | 5.46 | 40 |
| Condition #2 (N=373) | 800 ft prior | 52 | 5.62 | 58 |
| | PC | 40.31 | 5.67 | 46 |
| | Midcurve | 35.13 | 5.4 | 40 |
| Condition #3 (N=330) | 800 ft prior | 54.53 | 5.59 | 60 |
| | PC | 41.61 | 6.02 | 47 |
| | Midcurve | 35.95 | 5.5 | 41 |
| Condition #4 (N=342) | 800 ft prior | 54.76 | 5.73 | 60 |
| | PC | 41.13 | 5.8 | 47 |
| | Midcurve | 36.38 | 5.84 | 42 |

**Table 36. Operating speed for WI 20 – Smadi et al., 2015.**

| Period (Obs) | Location | Mean | SD | 85th speed |
|---|---|---|---|---|
| Before (N=743) | 800 ft prior | 55.9 | -- | -- |
| | PC | 43.3 | 5.3 | 49 |
| | Midcurve | 38.4 | 4.4 | 43 |
| After 1 Month (N=740) | 800 ft prior | 56.7 | -- | -- |
| | PC | 41 | 4.7 | 46 |
| | Midcurve | 36.5 | 3.9 | 40 |
| After 12 Months (N=775) | 800 ft prior | 56.4 | -- | -- |
| | PC | 40.9 | 5.1 | 46 |
| | Midcurve | 37.5 | 4.6 | 42 |
| After 18 Months (N=688) | 800 ft prior | 56.5 | -- | -- |
| | PC | 42.1 | 5 | 47 |
| | Midcurve | 37.2 | 4.3 | 42 |
| After 24 Months (N=1,470) | 800 ft prior | 55.3 | -- | -- |
| | PC | 41 | 5 | 46 |
| | Midcurve | 36.8 | 4.1 | 41 |

Note: * denotes the 95-percent confidence interval; -- no data available.

**Table 37. Operating speed for WI 67 – this study.**

| Period (Obs) | Location | Mean | SD | 85th speed |
|---|---|---|---|---|
| Baseline (N=248) | 800 ft prior | 51.63 | 6.59 | 57 |
| | PC | 45.32 | 5.57 | 51 |
| | Midcurve | 41.08 | 4.98 | 46 |
| Condition #1 (N=380) | 800 ft prior | 50.23 | 6.98 | 56.5 |
| | PC | 42.98 | 5.01 | 48 |
| | Midcurve | 39.5 | 4.9 | 44 |
| Condition #2 (N=439) | 800 ft prior | 50.62 | 6.52 | 57 |
| | PC | 43.11 | 5.01 | 48 |
| | Midcurve | 39.1 | 4.69 | 44 |
| Condition #3 (N=356) | 800 ft prior | 51.35 | 6.4 | 57 |
| | PC | 44.77 | 4.93 | 50 |
| | Midcurve | 40.47 | 4.75 | 45 |
| Condition #4 (N=468) | 800 ft prior | 51.01 | 6.73 | 57 |
| | PC | 44.89 | 5.27 | 50 |
| | Midcurve | 40.27 | 5.07 | 45 |

**Table 38. Operating speed for WI 67 – Smadi et al., 2014.**

| Period (Obs) | Location | Mean | SD | 85th speed |
|---|---|---|---|---|
| Before (N=905) | 800 ft prior | 51.1 | -- | -- |
| | PC | 47.4 | 5.3 | 53 |
| | Midcurve | 40.7 | 4.7 | 45 |
| After 1 Month (N=1,008) | 800 ft prior | 50.2 | -- | -- |
| | PC | 45.4 | 5.7 | 51 |
| | Midcurve | 38.3 | 4.7 | 43 |
| After 12 Months (N=912) | 800 ft prior | 51.1 | -- | -- |
| | PC | 46 | 5.4 | 51 |
| | Midcurve | 39.7 | 4.7 | 45 |
| After 18 Months (N=910) | 800 ft prior | 52 | -- | -- |
| | PC | 47 | 5.4 | 53 |
| | Midcurve | 40.1 | 4.9 | 45 |
| After 24 Months (N=1,848) | 800 ft prior | 51.7 | -- | -- |
| | PC | 46.1 | 5.3 | 51 |
| | Midcurve | 40.3 | 4.6 | 45 |

Note: * denotes the 95-percent confidence interval; -- no data available.

## Speed Differential Comparisons between Study Periods

The differences in mean and 85$^{th}$-percentile operating speeds were compared from the present and previous studies. For this comparison, the differences in operating speeds between the flashing pattern and the baseline (or before period from the previous study) were computed. A negative value indicates that the operating speeds were lower for the flashing pattern relative to the baseline (or before period) condition. Like the previous comparisons, the present study results were compared to the results obtained 1, 12, 18, and 24 months after the flashing pattern was set in the previous study. The results of the comparison are shown in table 39 through table 41.

**Table 39. Comparison of speed differentials between present and previous study – WI 213.**

| Location | This Study | | | | Smadi et al., 2015 | | | |
|---|---|---|---|---|---|---|---|---|
| | Condition #1 | Condition #2 | Condition #3 | Condition #4 | After 1 month | After 12 months | After 18 months | After 24 months |
| Change in Mean Speed 800 ft prior | -0.23 | 0.03 | 0.15 | 0.45 | 0.7 | 1.5 | 1.3 | 0.2 |
| Change in Mean Speed PC | -0.55 | -0.32 | 0.64 | 0.13 | -1.2 | 0 | -1.3 | -2 |
| Change in Mean Speed Midcurve | -0.28 | 1.17 | 2.5 | 1.9 | -1.2 | 0.5 | 0.4 | -0.9 |
| Change in 85th Speed 800 ft prior | 0 | 0 | 0 | 0.00 | -- | -- | -- | -- |
| Change in 85th Speed PC | -1 | -2 | 0 | 0 | -1 | 0 | -2 | -2 |
| Change in 85th Speed Midcurve | -1 | 1 | 3 | 2 | -1 | 0 | 0 | -1 |

Note: -- no data available; * negative value is the speed reduction between the flashing condition and the baseline (or before period) condition.

**Table 40. Comparison of speed differentials between present and previous study – WI 20.**

| Location | This Study | | | | Smadi et al., 2015 | | | |
|---|---|---|---|---|---|---|---|---|
| | Condition #1 | Condition #2 | Condition #3 | Condition #4 | After 1 month | After 12 months | After 18 months | After 24 months |
| Change in Mean Speed 800 ft prior | -0.71 | -1.58 | 0.96 | 1.19 | 0.8 | 0.5 | 0.6 | -0.6 |
| Change in Mean Speed PC | -2.06 | -1.83 | -0.52 | -1 | -2.3 | -2.4 | -1.2 | -2.3 |
| Change in Mean Speed Midcurve | -0.5 | -0.38 | 0.44 | 0.87 | -1.9 | -0.9 | -1.2 | -1.6 |
| Change in 85th Speed 800 ft prior | 0 | -1 | 1 | 1 | -- | -- | -- | -- |
| Change in 85th Speed PC | -2 | -1 | 0 | 0 | -3 | -3 | -2 | -3 |
| Change in 85th Speed Midcurve | -1 | -1 | 0 | 1 | -3 | -1 | -1 | -2 |

Note: -- no data available; * negative value is the speed reduction between the flashing condition and the baseline (or before period) condition.

**Table 41. Comparison of speed differentials between present and previous study – WI 67.**

| Location | This Study | | | | Smadi et al., 2015 | | | |
|---|---|---|---|---|---|---|---|---|
| | Condition #1 | Condition #2 | Condition #3 | Condition #4 | After 1 month | After 12 months | After 18 months | After 24 months |
| Change in Mean Speed 800 ft prior | -1.4 | -1.01 | -0.27 | -0.61 | -0.9 | 0 | 0.9 | 0.6 |
| Change in Mean Speed PC | -2.34 | -2.21 | -0.55 | -0.43 | -2 | -1.4 | -0.4 | -1.3 |
| Change in Mean Speed Midcurve | -1.58 | -1.98 | -0.61 | -0.81 | -2.4 | -1 | -0.6 | -0.4 |
| Change in 85th Speed 800 ft prior | -0.5 | 0 | 0 | 0 | -- | -- | -- | -- |
| Change in 85th Speed PC | -3 | -3 | -1 | -1 | -2 | -2 | 0 | -2 |
| Change in 85th Speed Midcurve | -2 | -2 | -1 | -1 | -2 | 0 | 0 | 0 |

Note: -- no data available; * negative value is the speed reduction between the flashing condition and the baseline (or before period) condition.

Based on the data shown in table 39 through table 41, the operating speed data collected 1 month after establishing the flashing pattern in the previous study shows the most significant reduction in mean and 85th-percentile operating speeds relative to an inactive flashing pattern. The flashing pattern used in the previous study was away from the driver, with a flashing rate of 1 Hz. The speed activation threshold was set equal to the curve advisory speed. Conditions #1 and #2 in the present study also produced a negative speed differential, indicating that both patterns produced operating speeds lower than the baseline (or inactive flashing) condition. However, the magnitude of these speed reductions was not as large in most cases to the flashing pattern used in the previous study.

**Operating Speed Differences along Horizontal Curve Comparisons**

The mean and 85th-percentile operating speeds were compared between data collection locations along the horizontal curve, and compared between the present and previous studies. The operating speeds for this comparison all produced a positive value, because the operating speed differences were computed for an upstream location relative to a downstream location. For example, the difference in operating speeds between the upstream locations (800 ft prior to the horizontal curve) were higher than the operating speeds at the midpoint of the horizontal curve. Larger positive values in the table 42 through table 44 indicate a more desirable outcome.

Like the previous comparisons, the present study data were compared to the data 1, 12, 18, and 24 months after the flashing was set in the previous study. When comparing each flashing condition in the present study to the baseline, condition #1 generally produced a larger speed reduction between data collection locations along the horizontal curve than other conditions. For example, consider Wisconsin Route 213 operating speed differences between the upstream and midpoint curve locations. During the baseline condition (no active flashing pattern), the mean and 85th-percentile speed differences were 10.33 and 8.00 mph, respectively. Condition #1 produced mean and 85th-percentile operating speed differences of 10.38 and 9.00 mph, respectively, which is 0.05 and 1.00 mph greater than the baseline. From the previous study, this same site produced mean and 85th-percentile operating speed differences of 3.90 and 9.00 mph, respectively, for the before condition. One, 12,18, and 24 months after the flashing pattern was set in the previous study, the mean and 85th-percentile operating speed differences were 5.80 and 11.00 mph, respectively, which is 1.90 and 2.00 mph larger than the before period. In general, the flashing pattern in the previous study produced larger mean and 85th-percentile operating speed differences along the horizontal curve than any of the flashing conditions tested in the present study.

**Table 42. Comparison of speed differentials across data collection locations between present and previous studies – WI 213.**

| Location | This Study | | | | | Smadi et al., 2015 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Baseline | Condition #1 | Condition #2 | Condition #3 | Condition #4 | Before | After 1 month | After 12 months | After 18 months | After 24 months |
| Upstream-PC Mean | 5.39 | 5.71 | 5.74 | 4.89 | 5.70 | 3.20 | 5.10 | 4.80 | 5.90 | 5.40 |
| Upstream-PC 85th | 4.00 | 5.00 | 6.00 | 4.00 | 4.00 | 8.00 | 10.00 | 10.00 | 10.00 | 10.20 |
| Upstream-Midcurve Mean | 10.33 | 10.38 | 9.19 | 7.98 | 8.88 | 3.90 | 5.80 | 5.00 | 4.80 | 5.00 |
| Upstream-Midcurve 85th | 8.00 | 9.00 | 7.00 | 5.00 | 6.00 | 9.00 | 11.00 | 10.00 | 10.00 | 10.00 |
| PC-Midcurve Mean | 4.94 | 4.67 | 3.45 | 3.09 | 3.17 | 0.60 | 0.70 | 0.20 | 1.10 | -0.40 |
| PC-Midcurve 85th | 4.00 | 4.00 | 1.00 | 1.00 | 2.00 | 2.00 | 2.00 | 1.00 | 0.00 | 0.00 |

**Table 43. Comparison of speed differentials across data collection locations between present and previous studies – WI 20.**

| Location | This Study | | | | | Smadi et al., 2015 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Baseline | Condition #1 | Condition #2 | Condition #3 | Condition #4 | Before | After 1 month | After 12 months | After 18 months | After 24 months |
| Upstream-PC Mean | 11.44 | 12.80 | 11.69 | 12.92 | 13.63 | 12.60 | 15.60 | 15.50 | 14.40 | 13.60 |
| Upstream-PC 85th | 12.00 | 14.00 | 12.00 | 13.00 | 13.00 | 18.00 | 20.00 | 20.00 | 19.00 | 19.00 |
| Upstream-Midcurve Mean | 18.06 | 17.85 | 16.87 | 18.58 | 18.38 | 17.60 | 20.20 | 18.90 | 19.20 | 18.00 |
| Upstream-Midcurve 85th | 18.00 | 19.00 | 18.00 | 19.00 | 18.00 | 23.00 | 25.00 | 24.00 | 24.00 | 23.40 |
| PC-Midcurve Mean | 6.62 | 5.06 | 5.18 | 5.66 | 4.75 | 4.90 | 4.60 | 3.40 | 4.90 | 4.20 |
| PC-Midcurve 85th | 6.00 | 5.00 | 6.00 | 6.00 | 5.00 | 8.00 | 8.00 | 6.00 | 8.00 | 7.00 |

**Table 44. Comparison of speed differentials across data collection locations between present and previous studies – WI 67.**

| Location | This Study | | | | | Smadi et al., 2015 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Baseline | Condition #1 | Condition #2 | Condition #3 | Condition #4 | Before | After 1 month | After 12 months | After 18 months | After 24 months |
| Upstream-PC Mean | 6.31 | 7.25 | 7.51 | 6.58 | 6.12 | 3.70 | 4.80 | 5.10 | 5.00 | 5.60 |
| Upstream-PC 85th | 6.00 | 8.50 | 9.00 | 7.00 | 7.00 | 11.00 | 13.00 | 12.00 | 12.00 | 11.00 |
| Upstream-Midcurve Mean | 10.54 | 10.73 | 11.51 | 10.88 | 10.74 | 10.40 | 11.90 | 11.40 | 11.90 | 11.40 |
| Upstream-Midcurve 85th | 11.00 | 12.50 | 13.00 | 12.00 | 12.00 | 18.00 | 21.00 | 19.00 | 19.00 | 18.00 |
| PC-Midcurve Mean | 4.23 | 3.48 | 4.01 | 4.29 | 4.62 | 6.60 | 7.00 | 6.20 | 6.90 | 5.80 |
| PC-Midcurve 85th | 5.00 | 4.00 | 4.00 | 5.00 | 5.00 | 9.00 | 10.00 | 9.00 | 10.00 | 8.00 |

## Comparison of Proportion of Vehicles Exceeding the Advisory Curve Speed

The proportion of vehicles exceeding the horizontal curve advisory speed was computed and compared between the present and previous studies. A higher proportion indicates that more vehicles are exceeding the advisory speed warning, so a lower proportion is a desirable outcome. The results of the comparisons are shown in table 45 through table 56. Table 45 through table 50 show the comparison for instances when the vehicle operating speeds exceeded the curve advisory speed by 5 and 10 mph. Table 51 through table 56 shows the comparisons when the operating speeds exceed the curve advisory speed by 15 and 20 mph.

The proportions are presented for only the PC and midpoint of the horizontal curves. The baseline condition in the present study shows that fewer vehicles exceeded the curve advisory speed plus 5 mph relative to the before period in the previous study. This may be the result of a "carryover" effect from the flashing pattern used in the previous study being deactivated for the present study baseline condition. In the present study, Conditions #1 and #2 (simultaneous flashing at a rate of 3 Hz) produce the lowest proportion of vehicles exceeding the advisory speed by 5 and 10 mph relative to the other conditions tested in the present study. When compared to the previous study during the period 1, 12, 18, and 24 months after the flashing pattern was established, the proportion of vehicles exceeding the curve advisory speed by 5 and 10 mph was lower for Conditions #1 and #2 relative to the previous study.

Table 51 through table 56 show the proportion of vehicles exceeding the curve advisory speed by 15 and 20 mph. Again, only data collected at the PC and midpoint of the horizontal curve locations are shown. In the present study, conditions #1 and #2 (simultaneous flashing at a rate of 3 Hz) produce the lowest proportion of vehicles exceeding the advisory speed by 15 and 20 mph relative to the other conditions tested in the present study. When compared to the previous study during the period 1, 12, 18, and 24 months after the flashing pattern was established, the proportion of vehicles exceeding the curve advisory speed by 15 and 20 mph was similar for conditions #1 and #2 relative to the previous study. This suggests that the previous sequential flashing pattern (flashing away from the driver at 1 Hz) and simultaneous flashing patterns (flashing at a rate of 3 Hz) were equally effective in limiting the proportion of drivers exceeding the advisory curve speeds by 15 and 20 mph.

**Table 45. Comparison of proportion of vehicles exceeding curve advisory speed by 5 and 10 mph at WI 213 – this study..**

| Period | Percent of Vehicles Exceeding AS by 5 mph | | Percent of Vehicles Exceeding AS by 10 mph | |
|---|---|---|---|---|
| | PC | MC | PC | MC |
| Baseline | 43.44% | 24.06% | 16.56% | 3.75% |
| Condition #1 | 36.73% | 20.82% | 12.24% | 2.04% |
| Condition #2 | 38.58% | 29.44% | 11.17% | 6.60% |
| Condition #3 | 43.73% | 34.58% | 18.31% | 10.85% |
| Condition #4 | 39.05% | 30.16% | 15.24% | 9.84% |

**Table 46. Comparison of proportion of vehicles exceeding curve advisory speed by 5 and 10 mph at WI 213 – Smadi et al., 2015.**

| Period | Percent of Vehicles Exceeding AS by 5 mph | | Percent of Vehicles Exceeding AS by 10 mph | |
|---|---|---|---|---|
| | PC | MC | PC | MC |
| Before | 67.00% | 66.00% | 31.00% | 29.00% |
| 1 Month | 59.00% | 57.00% | 23.00% | 23.00% |
| 12 Months | 66.00% | 67.00% | 30.00% | 31.00% |
| 18 Months | 56.00% | 66.00% | 19.00% | 29.00% |
| 24 Months | 51.00% | 57.00% | 17.00% | 23.00% |

**Table 47. Comparison of proportion of vehicles exceeding curve advisory speed by 5 and 10 mph at WI 20 – this study.**

| Period | Percent of Vehicles Exceeding AS by 5 mph | | Percent of Vehicles Exceeding AS by 10 mph | |
|---|---|---|---|---|
| | PC | MC | PC | MC |
| Baseline | 89.81% | 54.14% | 60.19% | 18.15% |
| Condition #1 | 82.99% | 52.04% | 45.24% | 12.24% |
| Condition #2 | 81.23% | 49.06% | 43.43% | 14.75% |
| Condition #3 | 85.76% | 54.85% | 55.45% | 17.88% |
| Condition #4 | 85.38% | 57.31% | 50.29% | 21.05% |

**Table 48. Comparison of proportion of vehicles exceeding curve advisory speed by 5 and 10 mph at WI 20 – Smadi et al., 2015.**

| Period | Percent of Vehicles Exceeding AS by 5 mph | | Percent of Vehicles Exceeding AS by 10 mph | |
|---|---|---|---|---|
| | PC | MC | PC | MC |
| Before | 95.00% | 83.00% | 77.00% | 38.00% |
| 1 Month | 92.00% | 69.00% | 63.00% | 20.00% |
| 12 Months | 91.00% | 75.00% | 64.00% | 33.00% |
| 18 Months | 93.00% | 75.00% | 72.00% | 30.00% |
| 24 Months | 91.00% | 72.00% | 64.00% | 25.00% |

**Table 49. Comparison of proportion of vehicles exceeding curve advisory speed by 5 and 10 mph at WI 67 – this study.**

| Period | Percent of Vehicles Exceeding AS by 5 mph | | Percent of Vehicles Exceeding AS by 10 mph | |
|---|---|---|---|---|
| | PC | MC | PC | MC |
| Baseline | 100.00% | 99.60% | 96.37% | 85.48% |
| Condition #1 | 99.47% | 96.58% | 93.16% | 81.58% |
| Condition #2 | 99.32% | 96.58% | 93.39% | 79.04% |
| Condition #3 | 99.72% | 96.91% | 96.35% | 87.36% |
| Condition #4 | 99.36% | 97.65% | 96.37% | 84.40% |

**Table 50. Comparison of proportion of vehicles exceeding curve advisory speed by 5 and 10 mph at WI 67 – Smadi et al., 2015.**

| Period | Percent of Vehicles Exceeding AS by 5 mph | | Percent of Vehicles Exceeding AS by 10 mph | |
|---|---|---|---|---|
| | PC | MC | PC | MC |
| Before | 99.00% | 99.00% | 99.00% | 92.00% |
| 1 Month | 99.00% | 97.00% | 97.00% | 80.00% |
| 12 Months | 99.00% | 98.00% | 97.00% | 88.00% |
| 18 Months | 99.00% | 99.00% | 99.00% | 88.00% |
| 24 Months | 99.00% | 99.00% | 98.00% | 90.00% |

**Table 51. Comparison of proportion of vehicles exceeding curve advisory speed by 15 and 20 mph at WI 213 – this study.**

| Period | Percent of Vehicles Exceeding AS by 15 mph | | Percent of Vehicles Exceeding AS by 20 mph | |
|---|---|---|---|---|
| | PC | MC | PC | MC |
| Baseline | 3.44% | 0.63% | 0.63% | 0.31% |
| Condition #1 | 2.86% | 0.41% | 0.82% | 0.00% |
| Condition #2 | 2.54% | 0.00% | 0.00% | 0.00% |
| Condition #3 | 5.08% | 1.02% | 1.02% | 0.00% |
| Condition #4 | 3.17% | 2.22% | 0.63% | 0.32% |

**Table 52. Comparison of proportion of vehicles exceeding curve advisory speed by 15 and 20 mph at WI 213 – Smadi et al., 2015.**

| Period | Percent of Vehicles Exceeding AS by 15 mph | | Percent of Vehicles Exceeding AS by 20 mph | |
|---|---|---|---|---|
| | PC | MC | PC | MC |
| Before | 4.00% | 3.00% | 1.00% | 0.00% |
| 1 Month | 3.00% | 2.00% | 0.00% | 0.00% |
| 12 Months | 4.00% | 5.00% | 0.00% | 0.00% |
| 18 Months | 2.00% | 4.00% | 1.00% | 1.00% |
| 24 Months | 1.00% | 2.00% | 0.00% | 0.00% |

**Table 53. Comparison of proportion of vehicles exceeding curve advisory speed by 15 and 20 mph at WI 20 – this study.**

| Period | Percent of Vehicles Exceeding AS by 15 mph | | Percent of Vehicles Exceeding AS by 20 mph | |
|---|---|---|---|---|
| | PC | MC | PC | MC |
| Baseline | 27.39% | 2.55% | 6.69% | 0.96% |
| Condition #1 | 12.24% | 1.36% | 4.08% | 0.34% |
| Condition #2 | 16.09% | 1.34% | 3.75% | 0.00% |
| Condition #3 | 22.42% | 4.24% | 8.79% | 0.61% |
| Condition #4 | 19.59% | 5.26% | 5.85% | 1.46% |

**Table 54. Comparison of proportion of vehicles exceeding curve advisory speed by 15 and 20 mph at WI 20 – Smadi et al., 2015.**

| Period | Percent of Vehicles Exceeding AS by 15 mph | | Percent of Vehicles Exceeding AS by 20 mph | |
|---|---|---|---|---|
| | PC | MC | PC | MC |
| Before | 39.00% | 9.00% | 13.00% | 1.00% |
| 1 Month | 22.00% | 2.00% | 4.00% | 0.00% |
| 12 Months | 23.00% | 6.00% | 4.00% | 1.00% |
| 18 Months | 32.00% | 3.00% | 6.00% | 0.00% |
| 24 Months | 25.00% | 3.00% | 4.00% | 0.00% |

**Table 55. Comparison of proportion of vehicles exceeding curve advisory speed by 15 and 20 mph at WI 67 – this study.**

| Period | Percent of Vehicles Exceeding AS by 15 mph | | Percent of Vehicles Exceeding AS by 20 mph | |
|---|---|---|---|---|
| | PC | MC | PC | MC |
| Baseline | 81.45% | 56.85% | 48.79% | 16.53% |
| Condition #1 | 69.74% | 43.68% | 28.16% | 9.47% |
| Condition #2 | 69.70% | 35.76% | 29.84% | 8.66% |
| Condition #3 | 82.30% | 47.75% | 42.98% | 12.92% |
| Condition #4 | 79.70% | 48.50% | 45.30% | 14.96% |

**Table 56. Comparison of proportion of vehicles exceeding curve advisory speed by 15 and 20 mph at WI 67 – Smadi et al., 2015.**

| Period | Percent of Vehicles Exceeding AS by 15 mph | | Percent of Vehicles Exceeding AS by 20 mph | |
|---|---|---|---|---|
| | PC | MC | PC | MC |
| Before | 92.00% | 61.00% | 74.00% | 19.00% |
| 1 Month | 84.00% | 40.00% | 56.00% | 9.00% |
| 12 Months | 89.00% | 52.00% | 63.00% | 16.00% |
| 18 Months | 92.00% | 55.00% | 67.00% | 18.00% |
| 24 Months | 89.00% | 58.00% | 63.00% | 17.00% |

## SUMMARY OF FIELD STUDY

This study collected data at three two-lane rural highway sites with sequential flashing chevron signs. Five data collection periods were included in the evaluation: baseline (inactive flashing chevron) and four different flashing patterns. The mean and 85$^{th}$-percentile operating speeds, speed deviation, and proportion of vehicles exceeding the advisory curve speed were also computed and compared. Among the conditions tested in the present study, the simultaneous flashing pattern, set to active 5 mph above the curve advisory speed at a rate of 3 Hz, produced the most desirable outcome based on the speed metrics considered in the present study. When compared to the previous study, several operating speed comparisons indicate that a flashing pattern away from the driver, with a flashing rate of 1 Hz set to active when operating speeds exceed the curve advisory speed, is the optimal among all conditions tested in the present and previous studies based on data collected in Wisconsin.

# CHAPTER 5. DISCUSSION AND RECOMMENDATIONS

In the Federal Highway Administration's *Manual on Uniform Traffic Control Devices* (MUTCD), the Chevron Alignment sign (W1-8) is used as a horizontal alignment warning sign to provide additional emphasis and guidance to motorists when there is a change in the horizontal alignment of a roadway.[(FHWA, 2009)] The placement of the chevron alignment sign is based on the difference between the posted speed limit and the curve advisory speed. According to MUTCD (Table 2C-5), when this difference is 5 mph, the use of the chevron alignment sign is optional.[(2009)] When this difference is 10 mph, the chevron alignment sign is recommended. In locations where the difference in the posted speed limit and curve advisory speed exceeds 15 mph, chevron alignment signs are required.

According to the MUTCD, chevron alignment signs shall be installed on the outside of a turn or curve, in line with and at approximately a right angle to approaching traffic. The signs shall be installed at a minimum height of 4 ft, measured vertically from the bottom of the sign to the elevation of the near edge of the traveled way. The typical spacing of the chevron alignment signs on horizontal curves is shown in table 57.

**Table 57. Typical spacing of chevron alignment signs on horizontal curves**

| Advisory Speed | Curve Radius | Sign Spacing |
|---|---|---|
| 15 mph or less | Less than 200 ft | 40 ft |
| 20 to 30 mph | 200 to 400 ft | 80 ft |
| 35 to 45 mph | 401 to 700 ft | 120 ft |
| 50 to 60 mph | 701 to 1,250 ft | 160 ft |
| More than 60 mph | More than 1,250 ft | 200 ft |

Regarding the three study sites, the differences between posted speed limit and curve advisory speed at WI 20 and WI 67 sites were more than 25 mph, so the chevron alignment signs are required. For the WI 213 site, the use of chevron alignment signs is optional based on the MUTCD guidance. With respect to the spacing of signs, the WI 20 and WI 67 sites have curve advisory speeds of 30 mph and 25 mph, respectively, so the spacing between each chevron alignment sign should be 80 ft (measured from PC). The curve advisory speed at the WI 213 site was 50 mph, so the spacing should be 160 ft. The chevron spacing at the WI 20 and WI 213 sites was 50 ft; which is closer than the MUTCD recommended spacing. The chevron sign spacing at the WI 67 site was 100 ft, which is slightly longer than recommended in the MUTCD. Nevertheless, all of the sequential flashing chevron arrays were effective in reducing vehicle operating speeds and the proportion of vehicles exceeding the speed limit when the array was operational.

Based on the indoor simulator study, a flashing sequence away from the driver at a low flash rate (1 Hz), or a simultaneous flashing pattern with a high flash rate (e.g., 3 Hz), offered two conditions that produced the greatest speed reduction effects on drivers approaching horizontal curves on two-lane rural highways. The flashing sequence away from the driver also produced the lowest probability of a roadway departure event. These two conditions were then evaluated in the field at three locations in Wisconsin. In addition to the flashing pattern and flash rate, the speed-activation threshold was also varied.

The present field study found that, among the conditions tested, the simultaneous flashing pattern, set to active 5 mph above the curve advisory speed at a rate of 3 Hz, produced the most desirable outcome based on the speed metrics considered in the present study. When compared to the previous study by Smadi et al., several operating speed comparisons indicate that a flashing pattern away from the driver, with a flashing rate of 1 Hz set to active when operating speeds exceed the curve advisory speed, is the optimal among all conditions tested in the present and previous studies based on data collected in Wisconsin.(Smadi et al. 2015)

# APPENDIX A

**INTAKE QUESTIONNAIRE**

1. Date of birth (mm/dd/yy) ____/____/___¬_

2. Gender Male Female

3. Do you have normal or corrected-to-normal vision?

Yes No

4. Are you color blind? * If you don't know, please tell us.

Yes No

5. Are you a native or equally fluent speaker of English?

Yes No

6. Have you had your normal amount of caffeine today?

Yes No

7. Did you get a normal amount of sleep last night?

Yes No

If no, please specify the number of hours of sleep you got: ____________

8. Do you have a valid driver's license?

Yes No

9. Have you ever participated in a study in which you drove or observed someone drive in an instrumented vehicle?

Yes No

# APPENDIX B

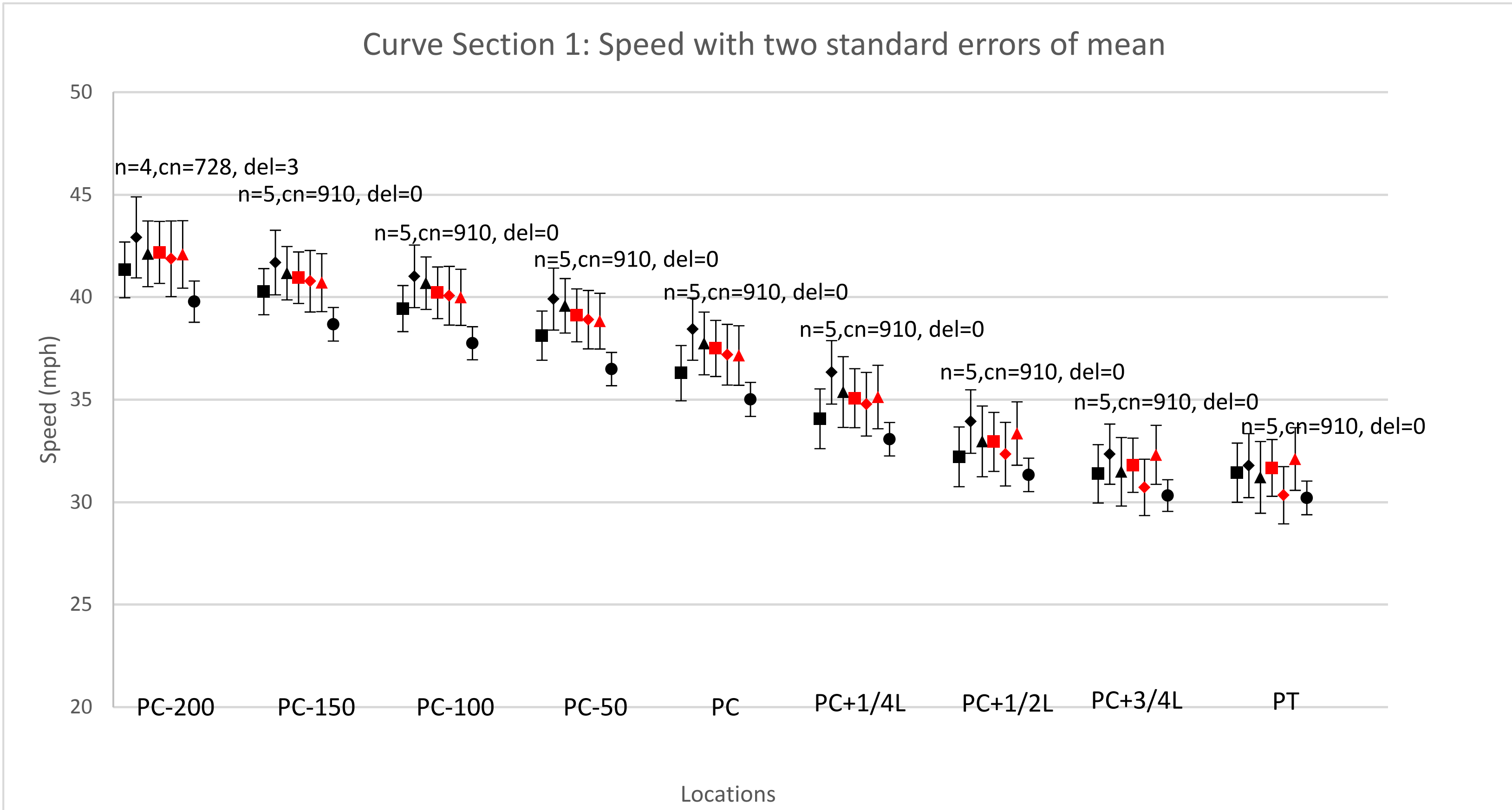
As noted in Chapter 3, there were three curve sections identified in the PA 851 scenario with six flashing device treatments and the existing TCDs (with no flashing devices) control group. These are described in greater detail below.

Figure 28 through figure 30 show the mean speed at each curve location (i.e., PC, PC+1/4L, PC+1/2L, PC+3/4L, PT, PC-50ft, PC-100ft, PC-150ft, and PC-200ft) for each treatment and the control. The error bars represent "plus or minus" two standard errors of the mean. If the counterbalanced experimental design was successful, a direct comparison of these estimates should provide an indication of whether or not the treatments were associated with speed and lateral position at the various points along and upstream of the horizontal curve. Generally speaking, the mean speed is decreasing in all scenarios (treatment scenarios or control) as the drivers approach the curve. The lowest mean speeds are observed inside of the curves at locations PC+1/2L or PC+3/4L, at which point drivers begin to accelerate as they exit the curve. This replicates speed behavior that has been observed in the field on other research efforts.

There do not appear to be any statistically significant differences in mean speed across the various flashing treatments. Generally speaking, mean speeds are lowest for the control condition and this difference is statistically significant at various locations, primarily in curve section 3. While this may at first seem surprising, other previous and ongoing research has indicated a possible increase in speeds as nighttime curve delineation improves.

Figure 31 through figure 33 show the mean lateral position at each curve location (i.e., PC, PC+1/4L, PC+1/2L, PC+3/4L, PT, PC-50ft, PC-100ft, PC-150ft, and PC-200ft) for each treatment and the control. The error bars represent "plus or minus" two standard errors of the mean. Generally speaking, there are no consistent and statistically significant differences in lateral position across all treatment conditions and the control.

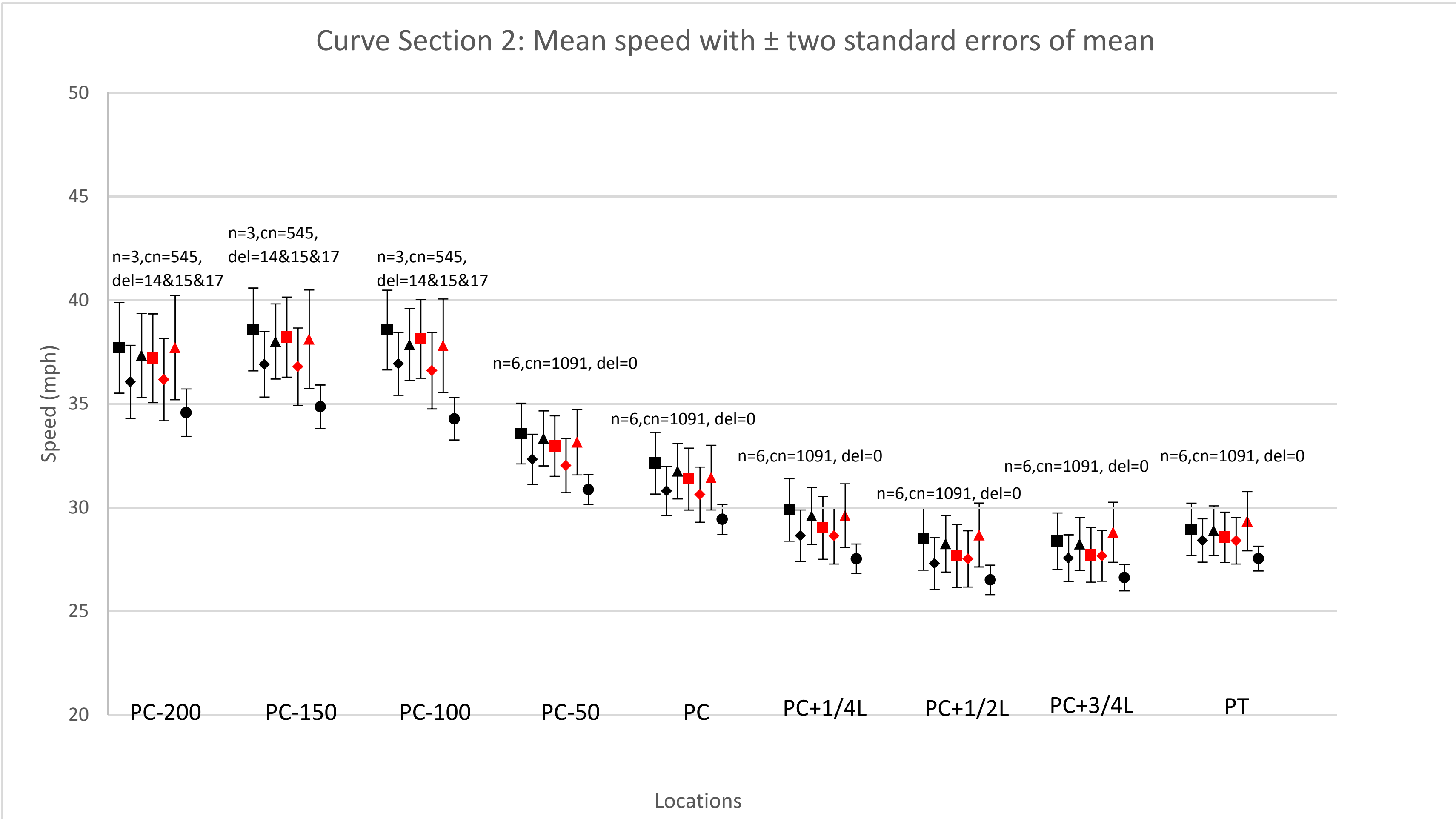
At this point, the research team also executed a number of other analyses to quantify the association between speed, lateral position, and the treatment/control conditions, including ordinary least squares (OLS) regression, fixed-effects models (representing a within-subjects estimator), and random-effects models (representing a weighted average of within and between subjects estimators). All model estimation results reinforced the patterns shown in figure 28 through figure 33: no statistically significant differences between treatments and controls for speed and lateral position were noted except for, in some cases, a lower expected speed for the control condition.




| ■ | Low frequency, flashing toward driver | ◆ | Low frequency, flashing in unison | ▲ | Low frequency, flashing away from the driver | ■ (red) | High frequency, flashing toward driver | ◆ (red) | High frequency, flashing in unison | ▲ (red) | High frequency, flashing away from the driver | ● | Control |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

*n - number of curves included at the location in each section; cn - number of data points at the location in each section; del - number of curves are excluded at the location in each section*

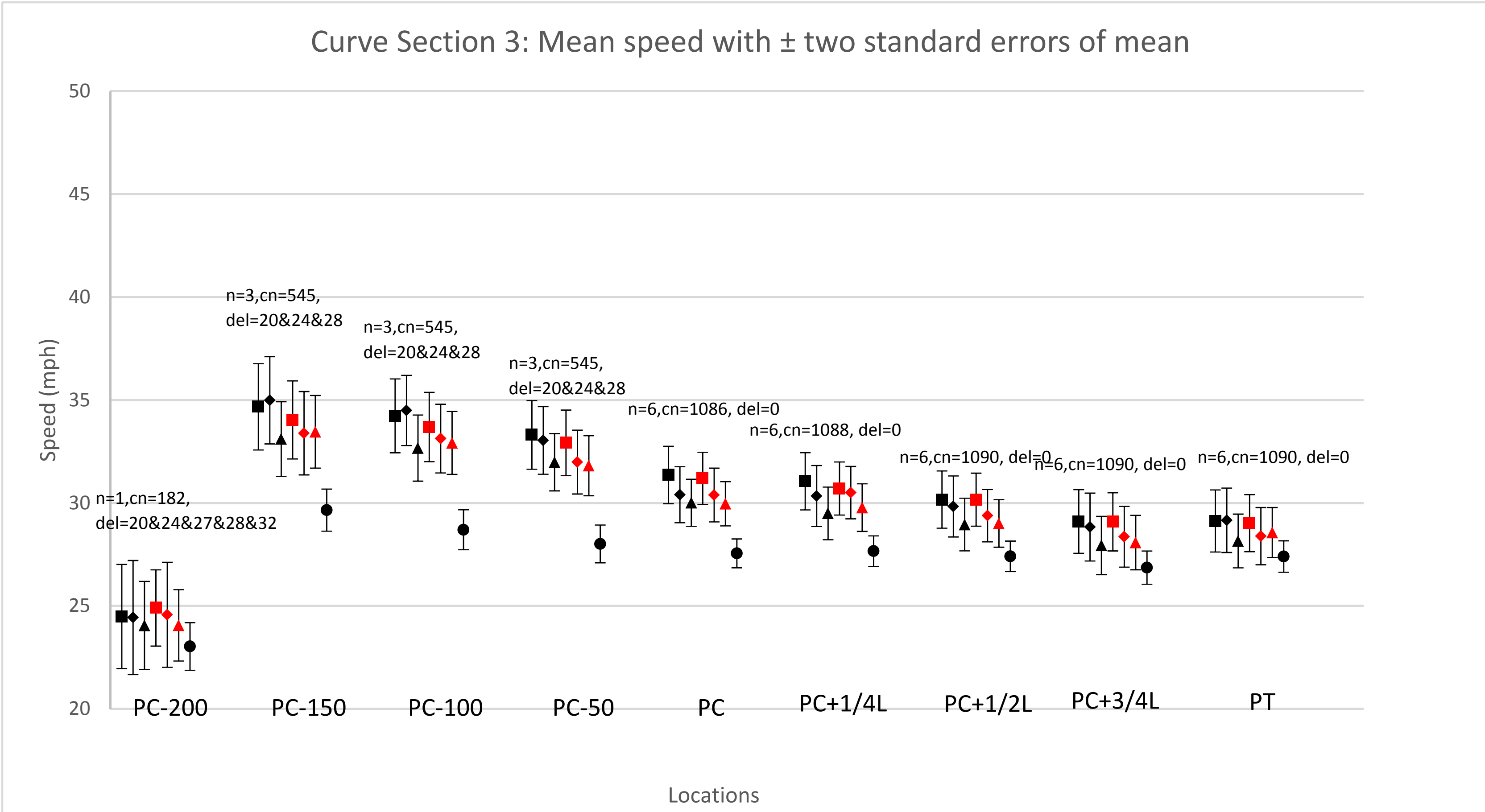
**Figure 28. Graph. Mean speed ± two standard errors of mean in curve section 1.**




| ■ | Low frequency, flashing toward driver | ◆ | Low frequency, flashing in unison | ▲ | Low frequency, flashing away from the driver | ■ | High frequency, flashing toward driver | ◆ | High frequency, flashing in unison | ▲ | High frequency, flashing away from the driver | ● | Control |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

*n - number of curves included at the location in each section; cn - number of data points at the location in each section; del - number of curves are excluded at the location in each section.*

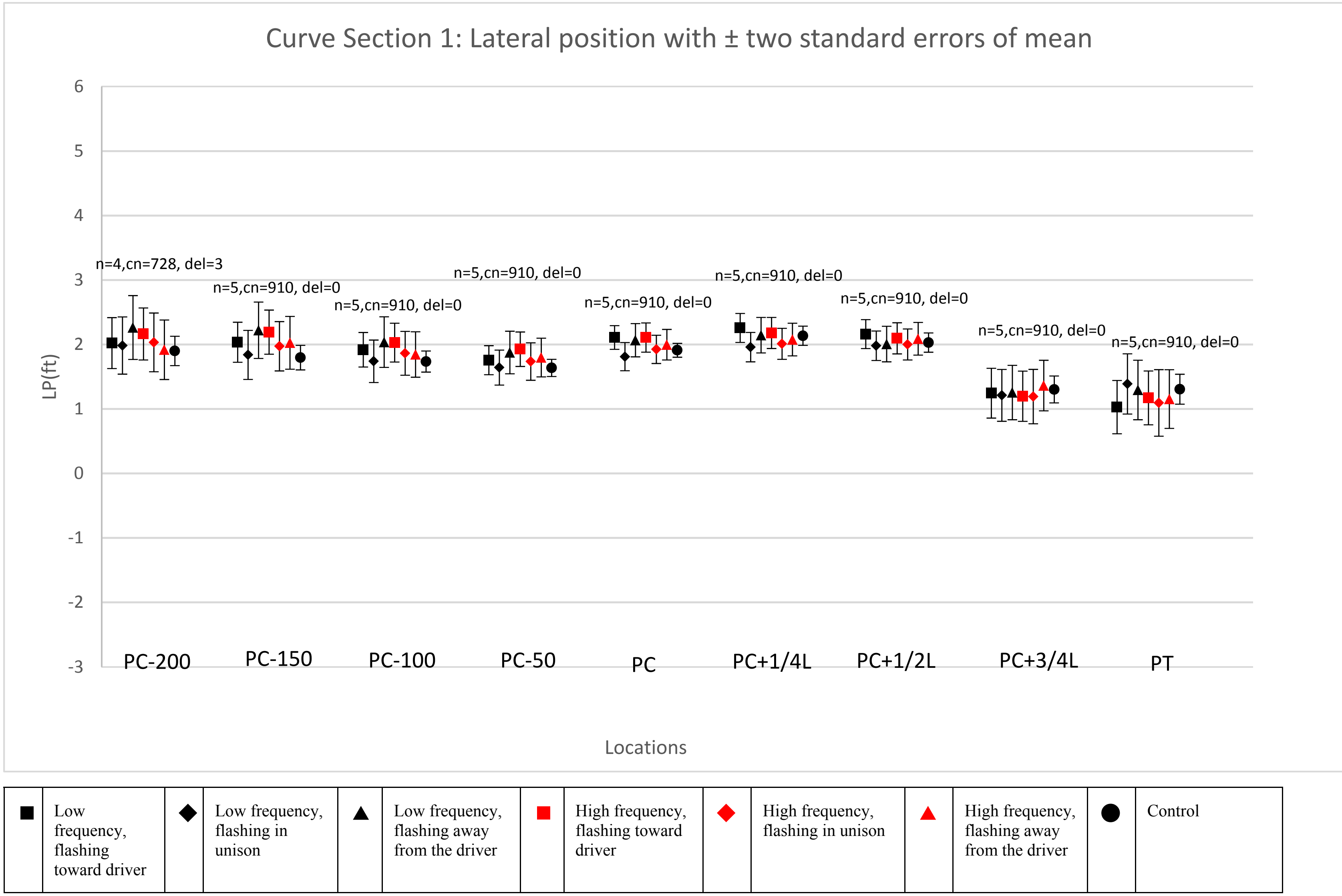
**Figure 29. Graph. Mean speed ± two standard errors of mean in curve section 2.**




| ■ | Low frequency, flashing toward driver | ◆ | Low frequency, flashing in unison | ▲ | Low frequency, flashing away from the driver | ■ (red) | High frequency, flashing toward driver | ◆ (red) | High frequency, flashing in unison | ▲ (red) | High frequency, flashing away from the driver | ● | Control |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

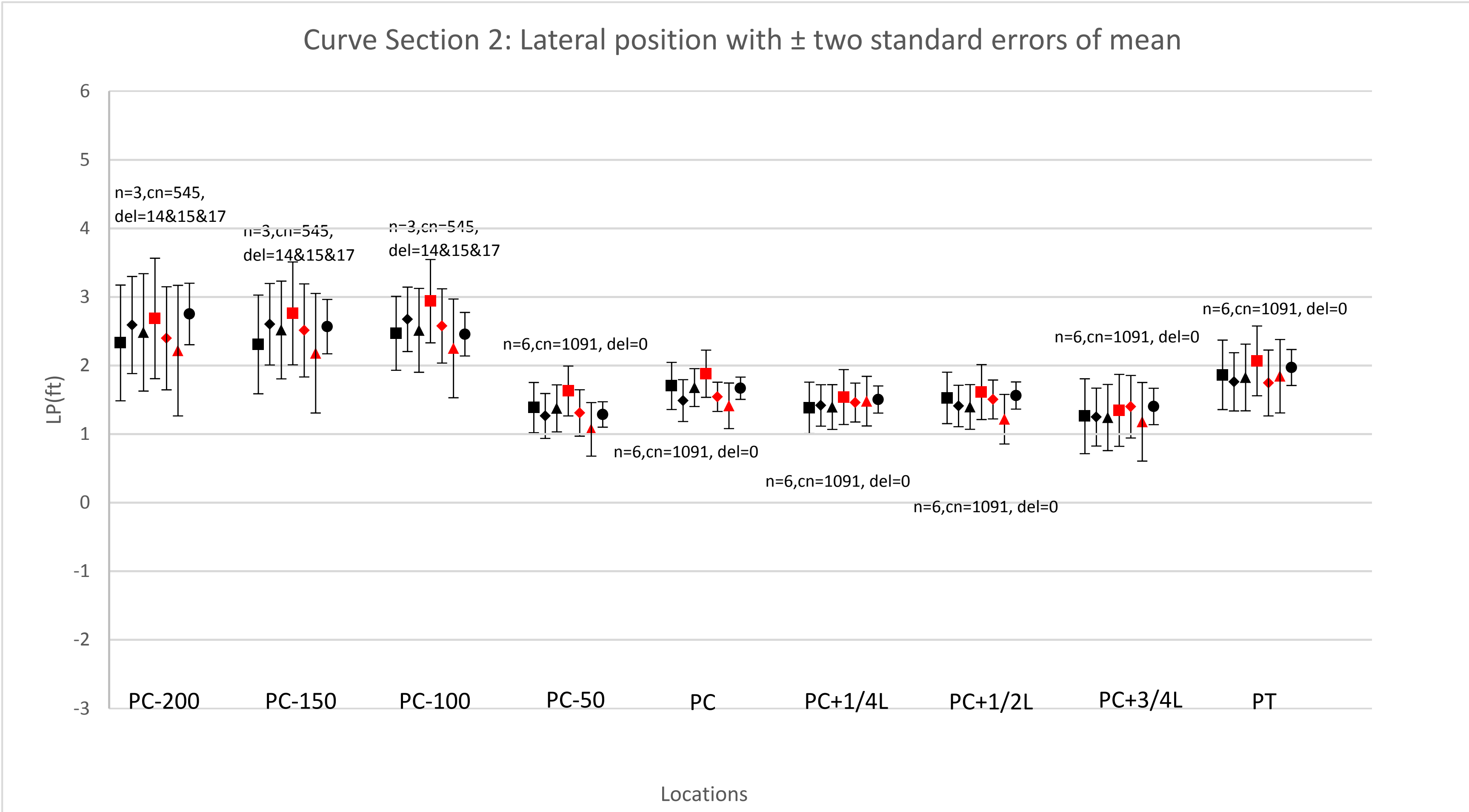
*n - number of curves included at the location in each section; cn - number of data points at the location in each section; del - number of curves are excluded at the location in each section.*

**Figure 30. Graph. Mean speed ± two standard errors of mean in curve section 3.**




*n - number of curves included at the location in each section; cn - number of data at the location in each section; del - number of curves are excluded at the location in each section.*

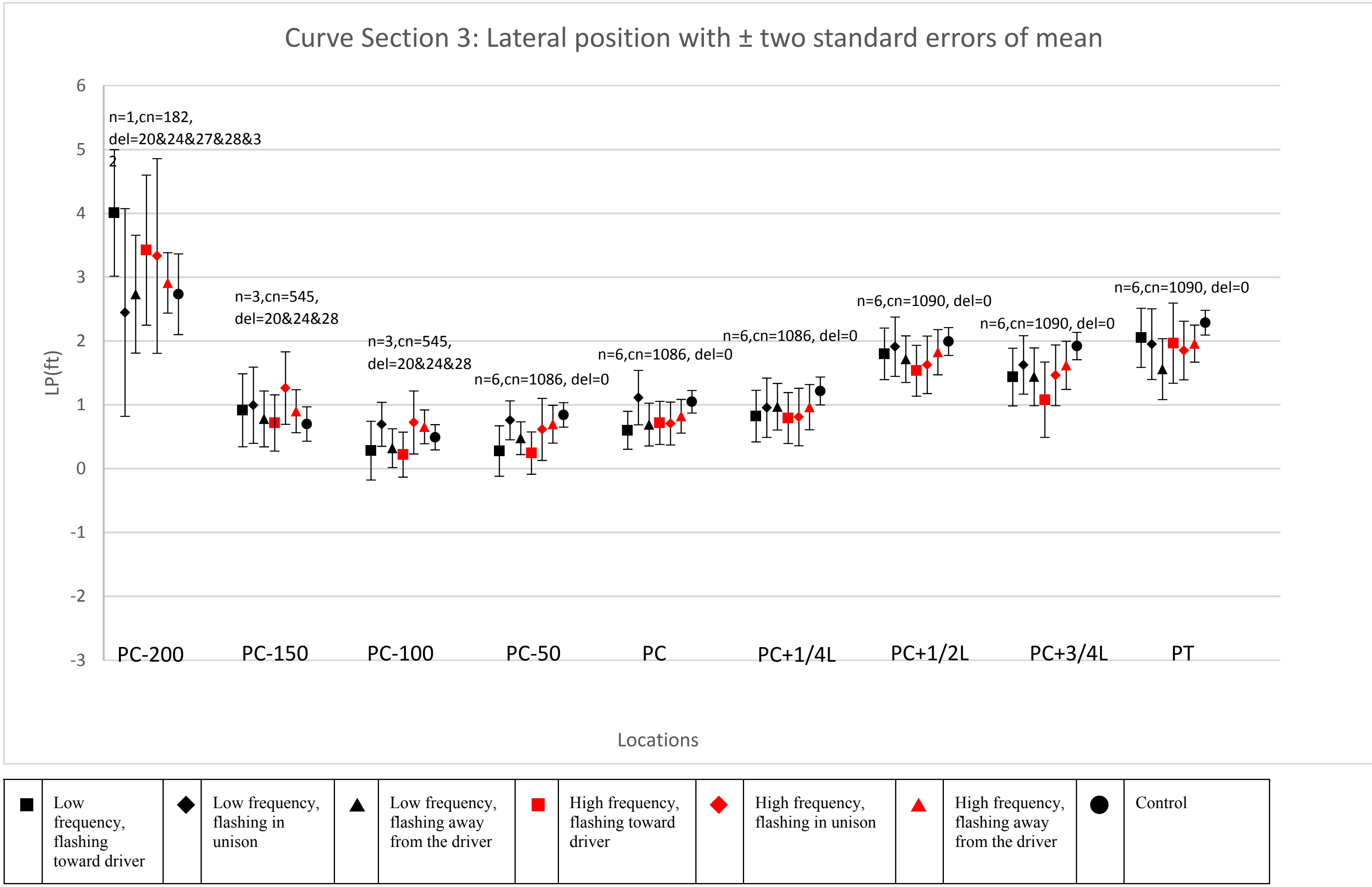
**Figure 31. Graph. Mean lateral placement ± two standard errors of mean in curve section 1.**




| ■ | Low frequency, flashing toward driver | ◆ | Low frequency, flashing in unison | ▲ | Low frequency, flashing away from the driver | ■ (red) | High frequency, flashing toward driver | ◆ (red) | High frequency, flashing in unison | ▲ (red) | High frequency, flashing away from the driver | ● | Control |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

*n - number of curves included at the location in each section; cn - number of data at the location in each section; del - number of curves are excluded at the location in each section.*

**Figure 32. Graph. Mean lateral placement ± two standard errors of mean in curve section 2.**




*n - number of curves included at the location in each section; cn - number of data at the location in each section; del - number of curves are excluded at the location in each section.*

**Figure 33. Graph. Mean lateral placement ± two standard errors of mean in curve section 3.**

# APPENDIX C

## Data Collection Protocols

The research team collected vehicle operating speed data at three point locations shown in figure 12 and at the three sites shown in table 14. At each location, operating speeds were measured in the direction in which the SDCWS were visible to the driver. The research team collected data during five periods at each site (baseline and conditions #1 through #4) in November 2016.

Data were collected on weekdays to eliminate any irregularities in traffic flow resulting from recreational traffic or special events. The weather was clear during all data collection periods. At each site, the data collection session included both daytime and nighttime conditions. The data collection period lasted approximately 16 hours (from 3 p.m. to 5 a.m.), which was long enough to capture the most free-flow vehicles traveling at all sites and satisfy the sample size requirements after the data were screened (see "Sample Size Determination" section below). The speed data were collected using Nu-Metrics Hi-Star on-pavement sensors. These sensors measure 6.5 x 5.5 x 0.63 inches, and are preferred because they are less conspicuous than other data collection equipment.[Poe et al., 1996] All Fthree of the Wisconsin study sites had an asphalt pavement surface. A 22-caliber nail gun was used to fasten the sensors to the pavement surface, and a black, rubber mat was used to cover the sensor, in order to further conceal it and protect it from traffic.

Each sensor was installed in the center of the travel lane. The intent of the data collection effort was to collect free-flow vehicle speeds, which represent driver speeds that are uninfluenced by leading or following vehicles. In this case, operating speeds are a function of the roadway features, traffic control devices, and other site-specific features. The definition of a free-flow vehicle is provided below.

After each data collection period, the sensors were removed and the data were downloaded to a laptop computer. Data were then transferred into Microsoft Excel to develop the analysis data files.

## Sample Size Determination

There are two sample size considerations in collecting an adequate number of vehicle operating speeds in field evaluations. The first corresponds to the number of observations needed during any specific data collection period (i.e., baseline condition and conditions #1 through #4) to minimize sampling error. A second considers the differences in measures of effectiveness (MOEs) between data collection periods to detect a statistically significant difference in the MOE. The following discussion provides a brief overview of the methods that were used to compute minimum sample size requirements in the present study.

When the mean speed is the variable of interest, the minimum sample size needed for any data collection period is based the equation shown in figure 34.(Institute of Transportation Engineers 2010)

$$N = (S\frac{K}{E})^2$$

**Figure 34. Equation. Minimum number of measured free-flow operating speeds.**

Where:

$N$ = minimum number of measured free-flow operating speeds

$S$ = estimated sample standard deviation (mph)

$K$ = constant corresponding to the desired confidence level

$E$ = permitted error in the average operating speed estimate (mph)

To obtain a range of possible sample sizes, multiple values for the confidence level *K* were input into the equation. The values correspond to confidence levels of 90, 95, and 99 percent. The permitted error in the average speed estimate, *E*, was input as the most conservative value of ±1 percent. The estimate of sample standard deviation, *S*, is a function of traffic area and highway type. A standard deviation of 5.3 mph was representative of a rural, two-lane highway.(Institute of Transportation Engineers 2010) The resulting sample size estimates, based on the varying input parameters, are shown in table 58.

**Table 58. Values for speed sample size determination.**

| ***S*** | ***K*** | ***E*** | ***N*** |
|---|---|---|---|
| 5.3 | 1.64 (90%) | ±1 | 76 |
| | 1.96 (95%) | ±1 | 108 |
| | 2.58 (99%) | ±1 | 187 |

For comparative research studies, such as a before-after observational evaluation, the expected difference in means (or proportions) between two different data collection periods can be used to estimate sample sizes. An equation used to estimate the sample size required in an observational before-after study is shown figure 35:(Snedecor and Cochran 1989)

$$N = \frac{4\sigma^2\left(z_{critical} + z_{power}\right)^2}{D^2}$$

**Figure 35. Equation. Speed sample in comparison groups.**

Where:

$N$ = sum of the sample in both comparison groups (before-after);

$s$ = standard deviation of the comparison groups (assumed equal) (mph);

$z_{critical}$ = level of statistical significance assumed from the standard normal distribution

$z_{power}$ = desired statistical power from the standard normal distribution

$D$ = minimum expected difference between the sample means (mph).

In considering the speed example from above, table 59 shows different sample size estimates, assuming that the standard deviation in speeds is 5.3 mph, for varying levels of critical and power statistics, and for different minimum expected differences in sample means.

It is common in traffic engineering field studies to use the 95$^{th}$-percentile confidence level to estimate sample size requirements; therefore, based on the data shown in table 58, a minimum sample of 108 free-flow operating speed during each data collection period was considered desirable. From the literature review, it is common that the presence of enforcement reduces mean operating speeds by 5.9 km/h (3.67 mph).[Hauer et al. 1981] Based on the 95$^{th}$-percentile critical values in table 59, the level of speed reduction corresponds to a minimum sample size of 73 free-flow vehicle speeds. For the present study, the research team used the more conservative sample size (i.e., the largest), thus a sample of at least 100 free-flow vehicle operating speeds was desirable for each data collection period (day and night), at each study location.

**Table 59. Sample size estimates for comparative research studies.**

| Difference in Means (mph) | 90% Level of Statistical Significance ($z_{critical}$ = 1.645) | | 95% Level of Statistical Significance ($z_{critical}$ = 1.96) | |
|---|---|---|---|---|
| | *90% Desired Statistical Power ($z_{power}$ = 1.282)* | *95% Desired Statistical Power ($z_{power}$ = 1.645)* | *90% Desired Statistical Power ($z_{power}$ = 1.282)* | *95% Desired Statistical Power ($z_{power}$ = 1.645)* |
| 1.0 | 500 | 822 | 709 | 1169 |
| 2.0 | 125 | 206 | 177 | 292 |
| 3.0 | 56 | 91 | 79 | 130 |
| 4.0 | 31 | 51 | 44 | 73 |
| 5.0 | 20 | 33 | 28 | 47 |

## Data Reduction and Analysis

Prior to data analysis, the raw data from the study sites were screened to separate larger vehicles from passenger vehicles, and to identify vehicles whose operations may have been affected by the presence of other vehicles (i.e., vehicles that are not free-flow). Single-unit trucks were included in the data set, but larger vehicles (e.g., buses with more than two axles, combination trucks, and vehicles with trailers) were not, because the sample size requirement for these vehicle types could not be met during a 24-hour data collection session. Vehicles were also excluded if they were closely following another vehicle through the study site. Based on a previous study, vehicles with a time-headway less than 4 sec were considered to not be traveling in free-flow and were eliminated from consideration in the evaluation.(Mahoney et al. 2003) Free-flow vehicles were identified using the time-stamp included in the on-pavement sensor output. Because the data were time-stamped, they could be "tracked" through each study site so that individual driver speed choice could be evaluated during each data collection period.

After data screening, mean and 85$^{th}$-percentile operating speeds, as well as the standard deviation of speed, were calculated at each sensor location for all sites and all data collection periods. The percentage of vehicles exceeding the posted speed limit was also determined, as was the pace and percentage of vehicles in the pace.

An initial comparison between corresponding speed parameters (mean speed, 85$^{th}$-percentile speed, standard deviation of speed, percentage of vehicles exceeding the posted speed limit) at each site for each data collection period was made by calculating the numerical differences in these speed parameters. The control location that was located prior to the sequential flashing chevron array was used to confirm that the speed metrics were consistent from one data collection period to the next.

The t-statistic for independent samples was applied to determine if the differences in mean speed were statistically significant at all data collection locations and among all time periods. Statistically significant changes in mean operating speeds indicated that the observed speeds were 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 hypothesis for testing the differences in two mean speed measures was the samples were equal. The alternative hypothesis was that the difference in the two observed speed samples was less than zero (i.e., the speed in the first sample was less than the speed from the second sample).

The t-statistic for two independent samples is computed as show in figure 36.

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

**Figure 36. Equation. Formula of t-statistics.**

Where:

$\overline{X}_1, \overline{X}_2$ = mean speed for the first and second periods;

$S_1, s_2$ = standard deviation of speed for the first and second periods;

$n_1, n_2$ = sample size in first and second periods.

In figure 36, conditions 1 and 2 represent the two data collection periods being compared. For example, the baseline condition is period 1 and condition #1 is period 2, or the baseline condition is period 1 and condition #2 is period 2. Each SDCWS setting was compared to the baseline. The optimal outcome was the SDCWS condition that produced the lowest mean operating speed relative to the baseline condition.

The point speed measurements provide an indication of how vehicle operating speeds differ at each data collection location and during each time period. Because the data collection effort produced time stamps, it was possible to "track" each vehicle through a data collection site. In this case, the difference in operating speeds between two data collection points (e.g., speed 800 ft before the curve and the midpoint of the horizontal curve, or the difference in operating speeds between the PC and midpoint locations of a horizontal curve) was also computed. The t-test described above was used to compare the mean vehicle operating speeds between two point locations to assess how individual drivers modify their operating speeds when the SDCWS are in operation.

In addition to the t-test, the percentage of vehicles exceeding the posted or advisory speed limit at the data collection locations was calculated and compared between data collection periods. The percentage of speeding vehicles, $P_S$, was computed as show in figure 37.

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

**Figure 37. Equation. Percentage of vehicles exceeding posted or advisory speed limit.**

Where:

$x$ = number of vehicles exceeding the posted or advisory speed limit; and

$n$ = the total number of vehicles in the sample.

By comparing the number of vehicles exceeding the posted or advisory speed limit between two data collection periods, it can be determined if the SDCWS was associated with a reduction in the proportion of posted or advisory speed limit violations. The percent reduction of speeding vehicles, $\%R_S$, between two periods, 1 and 2, at the SDCWS locations was computed as shown in figure 38.

$$\%R_S = \frac{P_{S1} - P_{S2}}{P_{S1}} \times 100$$

**Figure 38. Equation. Percentage reduction of speeding vehicles between two periods.**

Where:

$P_{S1}$ = the proportion of vehicles speeding during the first data collection period; and

$P_{S2}$ = the proportion of vehicles speeding during the second data collection period.

In order to determine if the proportion of vehicles exceeding the posted or advisory speed limit at the SDCWS locations changes between any of the data collection periods, a Z-test for independent samples was computed. The null hypothesis for this test was that the two proportions were equal, while the alternative hypothesis was that the two samples differed. The Z-statistic used to determine the statistical difference between the two proportions was computed as show in figure 39.

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

**Figure 39. Equation. Formula of Z-statistic.**

Where $P_{S1}$ and $P_{S2}$ are the sample proportions from the equation in figure 39, $n_1$ and $n_2$ are sample sizes for the corresponding proportions being considered, and $P$ is the combined proportion in both samples, computed as show in figure 40.

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

**Figure 40. Equation. Combined proportion of speeding vehicles in two samples.**

The final speed performance metric considered in the present study was speed variance. A two-sided F-test was used to compare the variances of vehicle operating speeds during any two data collection periods. The F-test is computed as show in figure 41.

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

**Figure 41. Equation. Formula of F-statistic.**

Values of speed variance considered in this study are those related to the time of day (day or night) and data collection time period (baseline and conditions #1 through #4).

### Summary

The operating speed field evaluation of the SDCWS considered three locations in Wisconsin. These three locations had differing site characteristics, including the number of chevrons in the SDCWS array, horizontal curve radii, and posted (and advisory) speed limits. The data collection protocol considered three data collection points at each study site. These included operating speed measurement locations approaching and within the limits of a horizontal curve. The flashing rates, sequences, and speed-activation thresholds are consistent with those found to produce the lowest curve operating speeds in the indoor driving simulator study described in Chapter 3 of this report. The measures and statistical comparisons considered in the present study are shown in table 60.

**Table 60. Summary of data collection periods, measures of effectiveness, and statistical tests.**

| Statistical Measure | Speed Variable | Comparisons | Statistical Test(s) |
|---|---|---|---|
| Mean Speed (mph) | Point Speeds at all Four Locations<br>Speed Differentials between Approach and Midcurve Locations* | Baseline → Condition #1<br>Baseline → Condition #2<br>Baseline → Condition #3<br>Baseline → Condition #4 | t-test |
| $85^{th}$-percentile Speed (mph) | Point Speeds at all Four Locations<br>Speed Differentials between Approach and Midcurve Locations | Baseline → Condition #1<br>Baseline → Condition #2<br>Baseline → Condition #3<br>Baseline → Condition #4 | Descriptive Statistics Only |
| Standard Deviation of Speed (mph) or Speed Variance ($mph^2$) | Point Speeds at all Four Locations<br>Speed Differentials between Approach and Midcurve Locations | Baseline → Condition #1<br>Baseline → Condition #2<br>Baseline → Condition #3<br>Baseline → Condition #4 | F-test |
| Percent Exceeding Posted or Advisory Speed Limit (%) | Point Speeds at all Four Locations | Baseline → Condition #1<br>Baseline → Condition #2<br>Baseline → Condition #3<br>Baseline → Condition #4 | z-test |
| Pace (mph) and Percent Vehicles in Pace | Point Speeds at all Four Locations | Baseline → Condition #1<br>Baseline → Condition #2<br>Baseline → Condition #3<br>Baseline → Condition #4 | Descriptive Statistics Only |

*The speed differentials were determined using "tracked" vehicles and computed as follows: (1) difference in individual driving speeds between the sensor located 300 ft prior to the beginning of the curve and the mid-point of the curve, and (2) difference in individual driving speeds between the sensor located at the beginning of the curve and the midpoint of the curve.

## DESCRIPTIVE STATISTICS

The field data collection effort took place over a period of two weeks in November 2016. Both daytime and nighttime speeds were collected at all three study sites. The first condition observed was the baseline, in which the flashing sequential chevron signs were inactive, so they appeared much like the W1-8 horizontal alignment warning sign found in the *Manual on Uniform Traffic Control Devices.*[FHWA 2009] After collecting speed data in the baseline condition, the following four conditions were programmed for a period of nearly 24 hours each to permit a full period of daytime and nighttime data collection:

- Condition #1: Speed-activation threshold is 5 mph above the advisory speed; flash sequence is simultaneous; flash rate is three flashes per second (3 Hz)
- Condition #2: Speed-activation threshold is 10 mph above the advisory speed; flash sequence is simultaneous; flash rate is three flashes per second
- Condition #3: Speed activation threshold is 5 mph above the advisory speed; flash sequence is away from the driver; flash rate is one flash (1 Hz) per second
- Condition #4: Speed activation threshold is 10 mph above the advisory speed; flash sequence is away from the driver; flash rate is one flash per second

Table 61 through table 63 shows the descriptive statistics for all of the speed data collected at each study site, for all five data collection conditions. The number of free-flow vehicle operating speeds collected at each site, the mean speed, standard deviation of speed, 85$^{th}$-percentile operating speed, percentage of vehicles exceeding the posted and advisory speed limits, the 10 mph pace, and the percentage of vehicles in the pace are also included in table 61 through table 69. Table 64 through table 66 show the same descriptive statistics for the daytime and table 67 through table 69 show the same descriptive statistics for nighttime periods.

Because the operating speed data were collected on approach tangents and within the limits of a horizontal curve, it was expected that the mean and 85$^{th}$-percentile operating speeds would be highest at the measurement location approximately 800 ft prior to the beginning of the curve. It was also expected that the mean and 85$^{th}$-percentile operating speeds would be lowest at the midpoint of the horizontal curve. The descriptive statistics in table 61 through table 69 confirm that vehicles were decreasing their operating speed from the approach tangent through the midpoint of the horizontal curve. It was also anticipated that the standard deviation of speed would increase as vehicles move from the approach tangent through the horizontal curve. The data summarized in table 61 through table 69 are consistent with this expectation. Because the horizontal curves all have chevron signs, it was expected that the percentage of vehicles exceeding the posted speed limit would be lower at the midpoint of the horizontal curve than on the approach tangent or at the beginning of the curve due to the restrictive curve feature. Finally, the operating speeds during the daytime generally appear to be higher than the nighttime operating speeds.

**Table 61. Descriptive statistics for all operating speeds – WI 213.**

| Condition (Obs) | Location | Mean | SD | 85th speed | % of vehicles exceeding PSL | % of vehicles exceeding AS | Pace | % of vehicles in the pace |
|---|---|---|---|---|---|---|---|---|
| Baseline (N=320) | 800 ft prior | 59.41 | 6.17 | 65 | 76.25% | 93.75% | 54 - 64 | 71.25% |
| | PC | 54.02 | 6.98 | 61 | 43.44% | 72.81% | 51 - 61 | 61.56% |
| | Midcurve | 49.08 | 8.82 | 57 | 24.06% | 49.69% | 47 - 57 | 57.19% |
| Condition #1 (N=245) | 800 ft prior | 59.18 | 5.59 | 65 | 75.92% | 93.88% | 55 - 65 | 70.20% |
| | PC | 53.47 | 6.24 | 60 | 36.73% | 68.57% | 48 - 58 | 63.67% |
| | Midcurve | 48.80 | 7.32 | 56 | 20.82% | 42.86% | 46 - 56 | 56.33% |
| Condition #2 (N=197) | 800 ft prior | 59.44 | 5.68 | 65 | 77.16% | 96.45% | 54 - 64 | 73.60% |
| | PC | 53.70 | 6.28 | 59 | 38.58% | 73.10% | 49 - 59 | 66.50% |
| | Midcurve | 50.25 | 8.15 | 58 | 29.44% | 55.33% | 49 - 59 | 56.35% |
| Condition #3 (N=295) | 800 ft prior | 59.56 | 5.82 | 65 | 78.64% | 95.93% | 55 - 65 | 70.51% |
| | PC | 54.66 | 6.39 | 61 | 43.73% | 72.20% | 50 - 60 | 61.69% |
| | Midcurve | 51.58 | 8.22 | 60 | 34.58% | 62.71% | 50 - 60 | 58.64% |
| Condition #4 (N=315) | 800 ft prior | 59.86 | 4.92 | 65 | 84.13% | 97.46% | 55 - 65 | 77.46% |
| | PC | 54.15 | 5.91 | 61 | 39.05% | 75.56% | 48 - 58 | 68.89% |
| | Midcurve | 50.98 | 8.3 | 59 | 30.16% | 57.78% | 49 - 59 | 55% |

**Table 62. Descriptive statistics for all operating speeds – WI 20.**

| Condition (Obs) | Location | Mean | SD | 85th speed | % of vehicles exceeding PSL | % of vehicles exceeding AS | Pace | % of vehicles in the pace |
|---|---|---|---|---|---|---|---|---|
| Baseline (N=320) | 800 ft prior | 53.57 | 5.39 | 59 | 36.94% | 99.68% | 50 - 60 | 73.89% |
| | PC | 42.13 | 5.48 | 47 | 1.91% | 98.41% | 37 - 47 | 73.25% |
| | Midcurve | 35.52 | 5.66 | 41 | 0.00% | 80.57% | 32 - 42 | 68.47% |
| Condition #1 (N=245) | 800 ft prior | 52.87 | 6.8 | 59 | 36.39% | 99.66% | 50 - 60 | 64.97% |
| | PC | 40.07 | 5.41 | 45 | 0.68% | 95.92% | 35 - 45 | 74.83% |
| | Midcurve | 35.01 | 5.46 | 40 | 0.34% | 80.27% | 29 - 39 | 72.11% |
| Condition #2 (N=197) | 800 ft prior | 52.00 | 5.62 | 58 | 26.27% | 100.00% | 47 - 57 | 69.97% |
| | PC | 40.31 | 5.67 | 46 | 1.34% | 97.59% | 35 - 45 | 70.78% |
| | Midcurve | 35.13 | 5.4 | 40 | 0.00% | 82.57% | 31 - 41 | 71.31% |
| Condition #3 (N=295) | 800 ft prior | 54.53 | 5.59 | 60 | 44.24% | 100.00% | 50 - 60 | 67.58% |
| | PC | 41.61 | 6.02 | 47 | 2.12% | 97.27% | 35 - 45 | 69.09% |
| | Midcurve | 35.95 | 5.5 | 41 | 0.00% | 86.06% | 31 - 41 | 72.42% |
| Condition #4 (N=315) | 800 ft prior | 54.76 | 5.73 | 60 | 47.66% | 99.71% | 50 - 60 | 73.98% |
| | PC | 41.13 | 5.8 | 47 | 1.75% | 97.66% | 36 - 46 | 69.59% |
| | Midcurve | 36.38 | 5.84 | 42 | 0.29% | 85.67% | 31 - 41 | 68.13% |

**Table 63. Descriptive statistics for all operating speeds – WI 67.**

| Condition (Obs) | Location | Mean | SD | 85th speed | % of vehicles exceeding PSL | % of vehicles exceeding AS | Pace | % of vehicles in the pace |
|---|---|---|---|---|---|---|---|---|
| Baseline (N=248) | 800 ft prior | 51.63 | 6.59 | 57 | 26.61% | 100.00% | 48 - 58 | 74.19% |
| | PC | 45.32 | 5.57 | 51 | 2.82% | 100.00% | 40 - 50 | 68.55% |
| | Midcurve | 41.08 | 4.98 | 46 | 0.00% | 100.00% | 35 - 45 | 74.60% |
| Condition #1 (N=380) | 800 ft prior | 50.23 | 6.98 | 56.5 | 18.42% | 99.74% | 46 - 56 | 65.79% |
| | PC | 42.98 | 5.01 | 48 | 0.79% | 100.00% | 37 - 47 | 74.74% |
| | Midcurve | 39.50 | 4.9 | 44 | 0.53% | 99.47% | 35 - 45 | 75.53% |
| Condition #2 (N=439) | 800 ft prior | 50.62 | 6.52 | 57 | 19.82% | 100.00% | 47 - 57 | 69.93% |
| | PC | 43.11 | 5.01 | 48 | 0.91% | 100.00% | 38 - 48 | 74.03% |
| | Midcurve | 39.10 | 4.69 | 44 | 0.23% | 99.54% | 34 - 54 | 76.54% |
| Condition #3 (N=356) | 800 ft prior | 51.35 | 6.4 | 57 | 23.88% | 100.00% | 47 - 57 | 69.10% |
| | PC | 44.77 | 4.93 | 50 | 1.40% | 100.00% | 40 - 50 | 76.97% |
| | Midcurve | 40.47 | 4.75 | 45 | 0.28% | 99.72% | 36 - 46 | 78.65% |
| Condition #4 (N=468) | 800 ft prior | 51.01 | 6.73 | 57 | 21.58% | 100.00% | 46 - 56 | 68.59% |
| | PC | 44.89 | 5.27 | 50 | 2.14% | 100.00% | 40 - 50 | 72.01% |
| | Midcurve | 40.27 | 5.07 | 45 | 0.21% | 99.15% | 35 - 45 | 73.08% |

Table 64. Descriptive statistics for daytime operating speeds – WI 213.

| Condition (Obs) | Location | Mean | SD | 85th speed | % of vehicles exceeding PSL | % of vehicles exceeding AS | Pace | % of vehicles in the pace |
|---|---|---|---|---|---|---|---|---|
| Baseline (N=176) | 800 ft prior | 59.20 | 5.26 | 64 | 80.11% | 94.32% | 53 - 63 | 76.14% |
| | PC | 54.60 | 7.08 | 61 | 49.43% | 77.27% | 51 - 61 | 65.91% |
| | Midcurve | 49.82 | 8.64 | 57 | 29.55% | 51.70% | 47 - 57 | 61.36% |
| Condition #1 (N=103) | 800 ft prior | 59.74 | 4.68 | 65 | 82.52% | 98.06% | 55 - 65 | 77.67% |
| | PC | 55.20 | 5.88 | 61 | 51.46% | 80.58% | 51 - 61 | 70.87% |
| | Midcurve | 50.71 | 6.43 | 57 | 23.30% | 55.34% | 47 - 57 | 62.14% |
| Condition #2 (N=97) | 800 ft prior | 60.11 | 5.36 | 66 | 80.41% | 97.94% | 54 - 64 | 75.26% |
| | PC | 54.72 | 5.56 | 60 | 40.21% | 79.38% | 49 - 59 | 73.20% |
| | Midcurve | 52.06 | 6.84 | 59 | 34.02% | 60.82% | 49 - 59 | 59.79% |
| Condition #3 (N=167) | 800 ft prior | 59.32 | 6.05 | 65 | 76.65% | 94.61% | 55 - 65 | 70.66% |
| | PC | 54.63 | 6.03 | 61 | 41.32% | 73.65% | 50 - 60 | 67.07% |
| | Midcurve | 52.51 | 7.71 | 60 | 37.72% | 70.66% | 50 - 60 | 65.27% |
| Condition #4 (N=172) | 800 ft prior | 59.92 | 4.73 | 64 | 84.30% | 97.67% | 55 - 65 | 79.65% |
| | PC | 54.67 | 5.73 | 61 | 40.70% | 81.40% | 48 - 58 | 69.19% |
| | Midcurve | 52.06 | 7.96 | 60 | 34.88% | 64.53% | 47 - 57 | 56.40% |

**Table 65. Descriptive statistics for daytime operating speeds – WI 20.**

| Condition (Obs) | Location | Mean | SD | 85th speed | % of vehicles exceeding PSL | % of vehicles exceeding AS | Pace | % of vehicles in the pace |
|---|---|---|---|---|---|---|---|---|
| Baseline (N=207) | 800 ft prior | 53.11 | 5.17 | 58 | 33.82% | 99.52% | 49 - 59 | 76.81% |
| | PC | 41.80 | 5.38 | 47 | 1.45% | 98.07% | 37 - 47 | 72.95% |
| | Midcurve | 35.24 | 5.52 | 41 | 0.00% | 78.74% | 31 - 41 | 67.63% |
| Condition #1 (N=174) | 800 ft prior | 51.64 | 7 | 58 | 27.01% | 99.43% | 49 - 59 | 68.39% |
| | PC | 39.75 | 5.5 | 45 | 0.00% | 94.25% | 35 - 45 | 72.99% |
| | Midcurve | 34.30 | 5.59 | 40 | 0.83% | 75.86% | 30 - 40 | 71.26% |
| Condition #2 (N=231) | 800 ft prior | 51.61 | 5.46 | 57 | 25.11% | 100.00% | 47 - 57 | 70.56% |
| | PC | 40.27 | 5.51 | 46 | 0.87% | 97.40% | 35 - 45 | 71.43% |
| | Midcurve | 34.52 | 5.54 | 40 | 0.00% | 78.79% | 30 - 40 | 71.43% |
| Condition #3 (N=189) | 800 ft prior | 53.75 | 5.08 | 59 | 39.15% | 100.00% | 49 - 59 | 73.54% |
| | PC | 40.88 | 5.55 | 47 | 1.59% | 97.35% | 34 - 44 | 74.60% |
| | Midcurve | 35.06 | 5.46 | 40 | 0.00% | 82.54% | 31 - 41 | 74.07% |
| Condition #4 (N=99) | 800 ft prior | 54.56 | 5.7 | 60 | 43.82% | 100.00% | 49 - 59 | 76.22% |
| | PC | 40.58 | 6.12 | 47 | 2.81% | 97.75% | 34 - 44 | 73.78% |
| | Midcurve | 35.24 | 5.66 | 40 | 0.00% | 81.46% | 30 - 40 | 69.66% |

**Table 66. Descriptive statistics for daytime operating speeds – WI 67.**

| Condition (Obs) | Location | Mean | SD | 85th speed | % of vehicles exceeding PSL | % of vehicles exceeding AS | Pace | % of vehicles in the pace |
|---|---|---|---|---|---|---|---|---|
| Baseline (N=99) | 800 ft prior | 50.80 | 6.28 | 56 | 21.21% | 100.00% | 48 - 58 | 74.75% |
| | PC | 45.15 | 5.8 | 51 | 5.05% | 100.00% | 40 - 50 | 68.69% |
| | Midcurve | 40.61 | 4.73 | 45 | 0.00% | 100.00% | 35 - 45 | 79.80% |
| Condition #1 (N=243) | 800 ft prior | 49.59 | 6.83 | 55 | 14.81% | 100.00% | 44 - 54 | 67.49% |
| | PC | 43.44 | 4.94 | 48 | 0.82% | 100.00% | 38 - 48 | 76.13% |
| | Midcurve | 40.11 | 5.01 | 45 | 0.41% | 99.18% | 36 - 46 | 76.13% |
| Condition #2 (N=228) | 800 ft prior | 49.48 | 6.47 | 55 | 14.04% | 100.00% | 44 - 54 | 69.74% |
| | PC | 43.03 | 4.89 | 48 | 0.88% | 100.00% | 37 - 47 | 75.44% |
| | Midcurve | 39.08 | 4.45 | 43 | 0.00% | 99.56% | 35 - 45 | 79.39% |
| Condition #3 (N=226) | 800 ft prior | 51.21 | 6.47 | 57 | 22.12% | 100.00% | 47 - 57 | 69.91% |
| | PC | 45.00 | 4.7 | 49 | 1.33% | 100.00% | 40 - 50 | 79.20% |
| | Midcurve | 40.35 | 4.26 | 45 | 0.00% | 100.00% | 35 - 45 | 82.74% |
| Condition #4 (N=274) | 800 ft prior | 51.06 | 6.76 | 57 | 22.26% | 100.00% | 46 - 56 | 68.25% |
| | PC | 45.19 | 5.45 | 50 | 2.19% | 100.00% | 40 - 50 | 71.17% |
| | Midcurve | 40.24 | 5.43 | 46 | 0.36% | 98.54% | 36 - 46 | 69.34% |

**Table 67. Descriptive statistics for nighttime operating speeds – WI 213.**

| Condition (Obs) | Location | Mean | SD | 85th speed | % of vehicles exceeding PSL | % of vehicles exceeding AS | Pace | % of vehicles in the pace |
|---|---|---|---|---|---|---|---|---|
| Baseline (N=144) | 800 ft prior | 59.67 | 7.14 | 66 | 71.53% | 93.06% | 54 - 64 | 67.36% |
| | PC | 53.32 | 6.83 | 61 | 36.11% | 67.36% | 49 - 59 | 59.03% |
| | Midcurve | 48.17 | 8.98 | 56 | 17.36% | 47.22% | 46 - 56 | 54.86% |
| Condition #1 (N=142) | 800 ft prior | 58.77 | 6.15 | 65 | 71.13% | 90.85% | 55 - 65 | 64.79% |
| | PC | 52.21 | 6.21 | 58 | 26.06% | 59.86% | 48 - 58 | 66.20% |
| | Midcurve | 47.41 | 7.63 | 56 | 19.01% | 33.80% | 41- 51 | 56.34% |
| Condition #2 (N=100) | 800 ft prior | 58.78 | 5.92 | 64 | 74.00% | 95.00% | 54 - 64 | 72.00% |
| | PC | 52.71 | 6.79 | 59 | 37.00% | 67.00% | 50 - 60 | 61.00% |
| | Midcurve | 48.49 | 8.94 | 57 | 25.00% | 50.00% | 49 - 59 | 53.00% |
| Condition #3 (N=128) | 800 ft prior | 59.87 | 5.52 | 66 | 81.25% | 97.66% | 53 - 63 | 73.44% |
| | PC | 54.71 | 6.86 | 61 | 46.88% | 70.31% | 51 - 61 | 55.47% |
| | Midcurve | 50.36 | 8.72 | 59 | 30.47% | 52.34% | 50 - 60 | 50.00% |
| Condition #4 (N=143) | 800 ft prior | 59.78 | 5.16 | 65 | 83.92% | 97.20% | 54 - 64 | 76.22% |
| | PC | 53.52 | 6.07 | 60 | 37.06% | 68.53% | 48 - 58 | 59.44% |
| | Midcurve | 49.69 | 8.55 | 57 | 24.48% | 49.65% | 47 - 57 | 50.35% |

**Table 68. Descriptive statistics for nighttime operating speeds – WI 20.**

| Condition (Obs) | Location | Mean | SD | 85th speed | % of vehicles exceeding PSL | % of vehicles exceeding AS | Pace | % of vehicles in the pace |
|---|---|---|---|---|---|---|---|---|
| Baseline (N=107) | 800 ft prior | 54.47 | 5.7 | 60 | 42.99% | 100.00% | 50 - 60 | 70.09% |
| | PC | 42.78 | 5.63 | 47 | 2.80% | 99.07% | 37 - 47 | 73.83% |
| | Midcurve | 36.06 | 5.92 | 42 | 0.00% | 84.11% | 32 - 42 | 71.03% |
| Condition #1 (N=120) | 800 ft prior | 54.64 | 6.11 | 60.5 | 50.00% | 100.00% | 50 - 60 | 65.00% |
| | PC | 40.54 | 5.27 | 44.5 | 1.67% | 98.33% | 36 - 46 | 78.33% |
| | Midcurve | 36.04 | 5.12 | 40.5 | 0.00% | 86.67% | 32 - 42 | 75.83% |
| Condition #2 (N=142) | 800 ft prior | 52.63 | 5.85 | 58 | 28.17% | 100.00% | 47 - 57 | 69.01% |
| | PC | 40.37 | 5.95 | 46 | 2.11% | 97.89% | 34 - 44 | 70.42% |
| | Midcurve | 36.13 | 5.04 | 42 | 0.00% | 88.73% | 32 - 42 | 76.06% |
| Condition #3 (N=141) | 800 ft prior | 55.57 | 6.07 | 62 | 51.06% | 100.00% | 51 - 61 | 63.83% |
| | PC | 42.59 | 6.49 | 48 | 2.84% | 97.16% | 38 - 48 | 70.21% |
| | Midcurve | 37.15 | 5.35 | 43 | 0.00% | 90.78% | 33 - 43 | 71.63% |
| Condition #4 (N=164) | 800 ft prior | 54.98 | 5.77 | 60 | 51.83% | 99.39% | 50 - 60 | 73.83% |
| | PC | 41.73 | 5.39 | 47 | 0.61% | 97.56% | 36 - 46 | 68.46% |
| | Midcurve | 37.63 | 5.8 | 43 | 0.61% | 90.24% | 33 - 43 | 72.56% |

**Table 69. Descriptive statistics for nighttime operating speeds – WI 67.**

| Condition (Obs) | Location | Mean | SD | 85th speed | % of vehicles exceeding PSL | % of vehicles exceeding AS | Pace | % of vehicles in the pace |
|---|---|---|---|---|---|---|---|---|
| Baseline (N=149) | 800 ft prior | 52.17 | 6.76 | 58 | 30.20% | 100.00% | 48 - 58 | 73.83% |
| | PC | 45.43 | 5.42 | 51 | 1.34% | 100.00% | 40 - 50 | 68.46% |
| | Midcurve | 41.40 | 5.13 | 47 | 0.00% | 100.00% | 37 - 47 | 71.81% |
| Condition #1 (N=137) | 800 ft prior | 51.36 | 7.13 | 58 | 24.82% | 99.27% | 47 - 57 | 67.88% |
| | PC | 42.17 | 5.05 | 47 | 0.73% | 100.00% | 36 - 46 | 75.18% |
| | Midcurve | 38.42 | 4.52 | 43 | 0.73% | 100.00% | 33 - 43 | 78.83% |
| Condition #2 (N=211) | 800 ft prior | 51.84 | 6.37 | 57 | 26.07% | 100.00% | 47 - 57 | 71.56% |
| | PC | 43.19 | 5.15 | 48 | 0.95% | 100.00% | 38 - 48 | 73.46% |
| | Midcurve | 39.12 | 4.94 | 45 | 0.47% | 99.53% | 34 - 44 | 73.93% |
| Condition #3 (N=130) | 800 ft prior | 51.60 | 6.28 | 57 | 26.92% | 100.00% | 46 - 56 | 70.00% |
| | PC | 44.36 | 5.29 | 50 | 1.54% | 100.00% | 40 - 50 | 73.08% |
| | Midcurve | 40.70 | 5.5 | 46 | 0.77% | 99.23% | 36 - 46 | 74.62% |
| Condition #4 (N=194) | 800 ft prior | 50.94 | 6.7 | 57 | 20.62% | 100.00% | 45 - 55 | 69.59% |
| | PC | 44.47 | 4.99 | 50 | 2.06% | 100.00% | 39 - 49 | 74.23% |
| | Midcurve | 40.31 | 4.53 | 45 | 0.00% | 100.00% | 35 - 45 | 79.90% |

# APPENDIX D

The analyses presented here are organized into four sections. First, the difference in the mean and 85$^{th}$-percentile operating speeds at each data collection location for each condition is presented. This analysis includes tabular and graphical summaries for the entire data collection period at each site, and is then disaggregated by daytime and nighttime speeds. The second section presents the difference in mean and 85$^{th}$-percentile speeds between adjacent data collection locations at each site. These data are presented for each data collection period, and then disaggregated by daytime and nighttime periods. The third section presents information about the proportion of vehicles exceeding the posted speed limit as well as the horizontal curve advisory speed. The final part of this section includes all of the statistical tests that were completed to compare the various speed metrics across the test conditions.

*Daytime and Nighttime Conditions Combined*

The data used in this analysis are summarized in table 70 through table 75 . These data include the entire data collection period (daytime and nighttime) at each study location. The difference in the operating speed during condition *i* (*i* = 1, 2, 3, or 4) was compared to the operating speed during the baseline condition using the equation in figure 42.

$$\Delta V = V_i - V_{Baselin}$$

**Figure 42. Equation. Speed difference between data conditions and periods.**

Where:

$\Delta V$ = difference in mean or 85$^{th}$-percentile operating speed (mph)

$V_i$ = mean or 85$^{th}$-percentile operating speed during condition *i*, *i* = 1, 2, 3, 4

$V_{Baseline}$ = mean or 85$^{th}$-percentile operating speed during the baseline condition.

In this analysis, a positive value for $\Delta V$ indicates that an active condition for the sequential flashing chevrons was associated with higher operating speeds than the baseline condition. A negative value for $\Delta V$ indicates that an active condition for the sequential flashing chevrons was associated with lower operating speeds than the baseline condition. The speed differences are shown in table 76 through table 78. At the location 800 ft before the beginning of the horizontal curve, it was anticipated that the mean and 85$^{th}$-percentile operating speeds would be similar across all conditions. The data in table 76 through table 78 indicate that mean and 85$^{th}$-percentile speeds varied by less than 1.6 mph between the baseline and all four conditions at a location 800 ft before the beginning of the horizontal curve. Conditions #1 and #2 produced the lowest mean and 85$^{th}$-percentile operating speed difference relative to the baseline condition at the point of curvature and the midpoint of the horizontal curve relative to the baseline condition when aggregating the operating speed data across both the daytime and nighttime data collection periods.

Because the purpose of the sequential flashing chevron signs is to warn drivers of a horizontal curve, the condition that produced the lowest operating speed among the sample of drivers was considered the most effective condition in the present study. Figure 43 through figure 45 show the mean and 85th-percentile operating speeds for each condition at all three data collection sites.

**Table 70. Mean speed data for all time periods – WI 213.**

| Period | 800 ft prior | PC | Midcurve |
|---|---|---|---|
| Baseline | 59.41 | 54.02 | 49.08 |
| Condition #1 | 59.18 | 53.47 | 48.80 |
| Condition #2 | 59.44 | 53.7 | 50.25 |
| Condition #3 | 59.56 | 54.66 | 51.58 |
| Condition #4 | 59.86 | 54.15 | 50.98 |

**Table 71. 85th-percentile operating speed data for all time periods – WI 213**

| Period | 800 ft prior | PC | Midcurve |
|---|---|---|---|
| Before | 65 | 61 | 57 |
| 1 Month | 65 | 60 | 56 |
| 12 Months | 65 | 59 | 58 |
| 18 Months | 65 | 61 | 60 |
| 24 Months | 65 | 61 | 59 |

**Table 72. Mean speed data speed for all time periods – WI 20.**

| Period | 800 ft prior | PC | Midcurve |
|---|---|---|---|
| Baseline | 53.57 | 42.13 | 35.52 |
| Condition #1 | 52.87 | 40.07 | 35.01 |
| Condition #2 | 52 | 40.31 | 35.13 |
| Condition #3 | 54.53 | 41.61 | 35.95 |
| Condition #4 | 54.76 | 41.13 | 36.38 |

**Table 73. 85th-percentile operating speed data for all time periods – WI 20.**

| Period | 800 ft prior | PC | Midcurve |
|---|---|---|---|
| Before | 59 | 47 | 41 |
| 1 Month | 59 | 45 | 40 |
| 12 Months | 58 | 46 | 40 |
| 18 Months | 60 | 47 | 41 |
| 24 Months | 60 | 47 | 42 |

**Table 74. Mean speed data for all time periods – WI 67.**

| Period | 800 ft prior | PC | Midcurve |
|---|---|---|---|
| Baseline | 51.63 | 45.32 | 41.08 |
| Condition #1 | 50.23 | 42.98 | 39.5 |
| Condition #2 | 50.62 | 43.11 | 39.1 |
| Condition #3 | 51.35 | 44.77 | 40.47 |
| Condition #4 | 51.01 | 44.89 | 40.27 |

**Table 75. 85th-percentile operating speed data for all time periods – WI 67.**

| Period | 800 ft prior | PC | Midcurve |
|---|---|---|---|
| Before | 57 | 51 | 46 |
| 1 Month | 56.5 | 48 | 44 |
| 12 Months | 57 | 48 | 44 |
| 18 Months | 57 | 50 | 45 |
| 24 Months | 57 | 50 | 45 |

At Wisconsin Route 213 (see figure 43), condition #1 produced the lowest mean and 85$^{th}$-percentile operating speed at the midpoint of the horizontal curve. All other active flashing conditions produced operating speeds that exceeded the baseline condition (inactive flashing) when aggregating all of the data collection periods. The mean speed associated with condition #1 at the midpoint of the horizontal curve is the only active flashing condition that produced operating speeds below the advance curve warning speed limit. At the point of curvature, conditions #1 and #2 produced operating speeds that were lower than the baseline condition when aggregating all of the data collection periods.

At Wisconsin Route 20 (see figure 44), conditions #1 and #2 produced the lowest mean and 85$^{th}$-percentile operating speeds at the midpoint of the horizontal curve. All other active flashing conditions produced operating speeds that exceeded the baseline condition (inactive flashing) when aggregating all of the data collection periods. All of the mean and 85$^{th}$-percentile operating speeds at the midpoint of the curve were at least 5 mph higher than the curve advisory warning speed limit. At the point of curvature, conditions #1 and #2 produced operating speeds that were lower than the baseline condition when aggregating all of the data collection periods.

**Table 76. Difference in mean and 85th-percentile operating speeds between all conditions for all time periods – WI 213.**

| Performance Measure | Condition #1 | Condition #2 | Condition #3 | Condition #4 |
|---|---|---|---|---|
| Change in Mean Speed 800 ft prior | -0.23 | 0.03 | 0.15 | 0.45 |
| Change in Mean Speed PC | -0.55 | -0.32 | 0.64 | 0.13 |
| Change in Mean Speed Midcurve | -0.28 | 1.17 | 2.50 | 1.90 |
| Change in 85th Speed 800 ft prior | 0.00 | 0.00 | 0.00 | 0.00 |
| Change in 85th Speed PC | -1.00 | -2.00 | 0.00 | 0.00 |
| Change in 85th Speed Midcurve | -1.00 | 1.00 | 3.00 | 2.00 |

**Table 77. Difference in mean and 85th-percentile operating speeds between all conditions for all time periods – WI 20.**

| Performance Measure | Condition #1 | Condition #2 | Condition #3 | Condition #4 |
|---|---|---|---|---|
| Change in Mean Speed 800 ft prior | -0.71 | -1.58 | 0.96 | 1.19 |
| Change in Mean Speed PC | -2.06 | -1.83 | -0.52 | -1.00 |
| Change in Mean Speed Midcurve | -0.50 | -0.38 | 0.44 | 0.87 |
| Change in 85th Speed 800 ft prior | 0.00 | -1.00 | 1.00 | 1.00 |
| Change in 85th Speed PC | -2.00 | -1.00 | 0.00 | 0.00 |
| Change in 85th Speed Midcurve | -1.00 | -1.00 | 0.00 | 1.00 |

**Table 78. Difference in mean and 85th-percentile operating speeds between all conditions for all time periods – WI 67.**

| Performance Measure | Condition #1 | Condition #2 | Condition #3 | Condition #4 |
|---|---|---|---|---|
| Change in Mean Speed 800 ft prior | -1.40 | -1.01 | -0.27 | -0.61 |
| Change in Mean Speed PC | -2.34 | -2.21 | -0.55 | -0.43 |
| Change in Mean Speed Midcurve | -1.58 | -1.98 | -0.61 | -0.81 |
| Change in 85th Speed 800 ft prior | -0.50 | 0.00 | 0.00 | 0.00 |
| Change in 85th Speed PC | -3.00 | -3.00 | -1.00 | -1.00 |
| Change in 85th Speed Midcurve | -2.00 | -2.00 | -1.00 | -1.00 |

At Wisconsin Route 67 (see figure 45), conditions #1 and #2 produced the lowest mean and 85$^{th}$-percentile operating speeds at the midpoint of the horizontal curve when aggregating all of the data collection periods. All of the mean and 85$^{th}$-percentile operating speeds at the midpoint of the curve were at least 10 mph higher than the curve advisory warning speed limit. At the point of curvature, conditions #1 and #2 produced operating speeds that were lower than the baseline condition when aggregating all of the data collection periods.

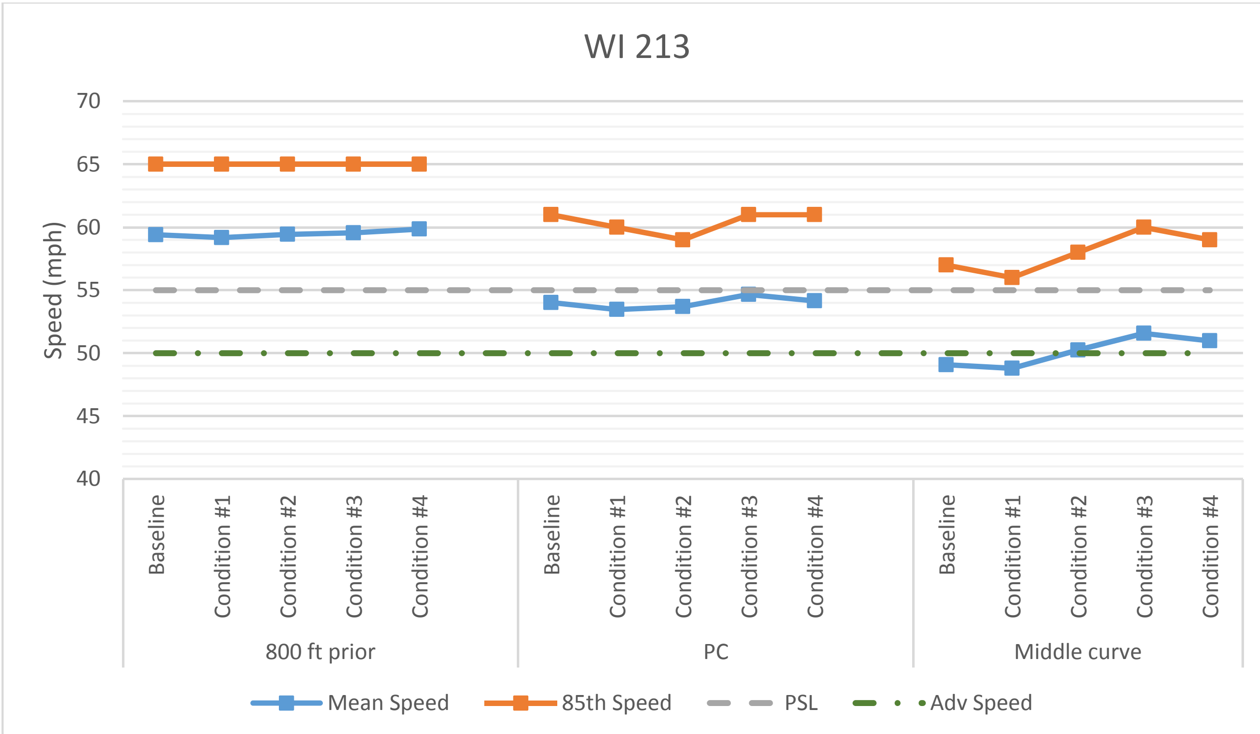



**Figure 43. Graph. Mean and 85th-percentile operating speeds at WI 213 site for all time periods.**

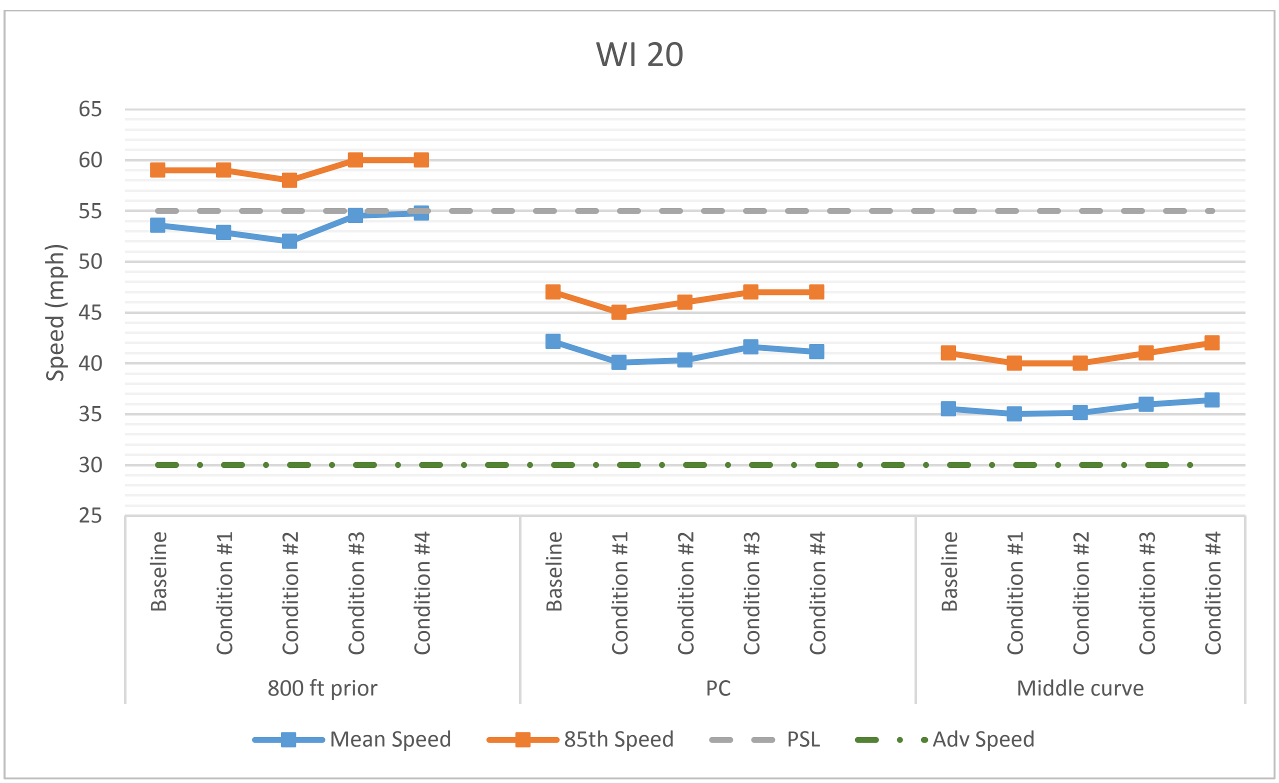


**Figure 44. Graph. Mean and 85th-percentile operating speeds at WI 20 site for all time periods.**


**Figure 45. Graph. Mean and 85th-percentile operating speeds at WI 67 site for all time periods.**

*Daytime Conditions Only*

The data used in this analysis are for the daytime period only, and are summarized in table 79 through table 84. The difference in the operating speed during condition *i* (*i* = 1, 2, 3, or 4) was compared to the operating speed during the baseline condition using the equation shown in figure 42. The mean and 85th-percentile operating speeds decreased from the approach tangent (800 ft prior to the beginning of the horizontal curve) to the midpoint of the horizontal curve at all sites during all data collection periods.

The speed differences for the daytime operating speed data are shown in table 85 through table 84. At the location 800 ft before the beginning of the horizontal curve, it was anticipated that the mean and 85th-percentile operating speeds would be similar across all conditions. The data indicate that mean and 85th-percentile speeds varied by not more than 2.0 mph between the baseline and all four conditions at this location. Conditions #1 and #2 generally produced the lowest mean and 85th-percentile operating speed difference relative to the baseline condition at the point of curvature and the midpoint of the horizontal curve relative to the baseline condition when aggregating the operating speed data across both the daytime and nighttime data collection periods. Figure 43 through figure 45 show the mean and 85th-percentile operating speeds for each condition at all three data collection sites.

**Table 79. Mean speed data for daytime conditions – WI 213.**

| Period | 800 ft prior | PC | Midcurve |
|---|---|---|---|
| Baseline | 59.2 | 54.6 | 49.82 |
| Condition #1 | 59.74 | 55.2 | 50.71 |
| Condition #2 | 60.11 | 54.72 | 52.06 |
| Condition #3 | 59.32 | 54.63 | 52.51 |
| Condition #4 | 59.92 | 54.67 | 52.06 |

**Table 80. 85th-percentile operating speed data for daytime conditions – WI 213**

| Period | 800 ft prior | PC | Midcurve |
|---|---|---|---|
| Before | 64 | 61 | 57 |
| 1 Month | 65 | 61 | 57 |
| 12 Months | 66 | 60 | 59 |
| 18 Months | 65 | 61 | 60 |
| 24 Months | 64 | 61 | 60 |

**Table 81. Mean speed data for daytime conditions – WI 20.**

| Period | 800 ft prior | PC | Midcurve |
|---|---|---|---|
| Baseline | 53.11 | 41.8 | 35.24 |
| Condition #1 | 51.64 | 39.75 | 34.3 |
| Condition #2 | 51.61 | 40.27 | 34.52 |
| Condition #3 | 53.75 | 40.88 | 35.06 |
| Condition #4 | 54.56 | 40.58 | 35.24 |

**Table 82. 85th-percentile operating speed data for daytime conditions – WI 20.**

| Period | 800 ft prior | PC | Midcurve |
|---|---|---|---|
| Before | 58 | 47 | 41 |
| 1 Month | 58 | 45 | 40 |
| 12 Months | 57 | 46 | 40 |
| 18 Months | 59 | 47 | 40 |
| 24 Months | 60 | 47 | 40 |

**Table 83. Mean speed data for daytime conditions – WI 67.**

| Period | 800 ft prior | PC | Midcurve |
|---|---|---|---|
| Baseline | 50.8 | 45.15 | 40.61 |
| Condition #1 | 49.59 | 43.44 | 40.11 |
| Condition #2 | 49.48 | 43.03 | 39.08 |
| Condition #3 | 51.21 | 45 | 40.35 |
| Condition #4 | 51.06 | 45.19 | 40.24 |

**Table 84. 85th-percentile operating speed data for daytime conditions – WI 67.**

| Period | 800 ft prior | PC | Midcurve |
|---|---|---|---|
| Before | 56 | 51 | 45 |
| 1 Month | 55 | 48 | 45 |
| 12 Months | 55 | 48 | 43 |
| 18 Months | 57 | 49 | 45 |
| 24 Months | 57 | 50 | 46 |

At Wisconsin Route 213 (see figure 46), the baseline and condition #1 produced the lowest mean and $85^{th}$-percentile operating speeds at the midpoint of the horizontal curve. The mean operating speeds during these two conditions were nearly equal to the curve advisory warning speed limit. All other active flashing conditions produced operating speeds that exceeded the baseline condition (inactive flashing) and condition #1 at the midpoint of the horizontal curve. The mean and $85^{th}$-percentile operating speeds at the point of curvature were similar across the baseline and all four active conditions for the sequential flashing chevrons.

At Wisconsin Route 20 (see figure 47), condition #1 produced the lowest mean and $85^{th}$-percentile operating speeds at the midpoint of the horizontal curve and at the beginning of the curve. The mean operating speed for condition #1 was approximately 5 mph above the advance curve warning speed limit. At the beginning of the horizontal curve, the mean speed for condition #1 was approximately 10 mph above the advance curve warning speed limit. At this site, all of the active flashing conditions generally produced vehicle operating speeds lower than the baseline condition.

**Table 85. Difference in mean and 85th-percentile operating speeds between all conditions for daytime conditions – WI 213.**

| Performance Measure | Condition #1 | Condition #2 | Condition #3 | Condition #4 |
|---|---|---|---|---|
| Change in Mean Speed 800 ft prior | 0.54 | 0.91 | 0.12 | 0.73 |
| Change in Mean Speed PC | 0.61 | 0.13 | 0.03 | 0.08 |
| Change in Mean Speed Midcurve | 0.88 | 2.24 | 2.69 | 2.23 |
| Change in 85th Speed 800 ft prior | 1.00 | 2.00 | 1.00 | 0.00 |
| Change in 85th Speed PC | 0.00 | -1.00 | 0.00 | 0.00 |
| Change in 85th Speed Midcurve | 0.00 | 2.00 | 3.00 | 3.00 |

**Table 86. Difference in mean and 85th-percentile operating speeds between all conditions for daytime conditions – WI 20.**

| Performance Measure | Condition #1 | Condition #2 | Condition #3 | Condition #4 |
|---|---|---|---|---|
| Change in Mean Speed 800 ft prior | -1.47 | -1.50 | 0.64 | 1.45 |
| Change in Mean Speed PC | -2.05 | -1.53 | -0.92 | -1.22 |
| Change in Mean Speed Midcurve | -0.93 | -0.72 | -0.18 | 0.00 |
| Change in 85th Speed 800 ft prior | 0.00 | -1.00 | 1.00 | 2.00 |
| Change in 85th Speed PC | -2.00 | -1.00 | 0.00 | 0.00 |
| Change in 85th Speed Midcurve | -1.00 | -1.00 | -1.00 | -1.00 |

**Table 87. Difference in mean and 85th-percentile operating speeds between all conditions for daytime conditions – WI 67.**

| Performance Measure | Condition #1 | Condition #2 | Condition #3 | Condition #4 |
|---|---|---|---|---|
| Change in Mean Speed 800 ft prior | -1.21 | -1.32 | 0.41 | 0.26 |
| Change in Mean Speed PC | -1.71 | -2.12 | -0.15 | 0.04 |
| Change in Mean Speed Midcurve | -0.50 | -1.52 | -0.26 | -0.37 |
| Change in 85th Speed 800 ft prior | -1.00 | -1.00 | 1.00 | 1.00 |
| Change in 85th Speed PC | -3.00 | -3.00 | -2.00 | -1.00 |
| Change in 85th Speed Midcurve | 0.00 | -2.00 | 0.00 | 1.00 |

At Wisconsin Route 67 (see figure 48), condition #2 produced the lowest mean and 85$^{th}$-percentile operating speeds at the midpoint of the horizontal curve during the daytime period. However, the baseline and other active flashing conditions produced vehicle operating speeds that were nominally higher than condition #2. At the point of curvature, conditions #1 and #2 produced operating speeds that were lower than the baseline condition and other active flashing conditions.

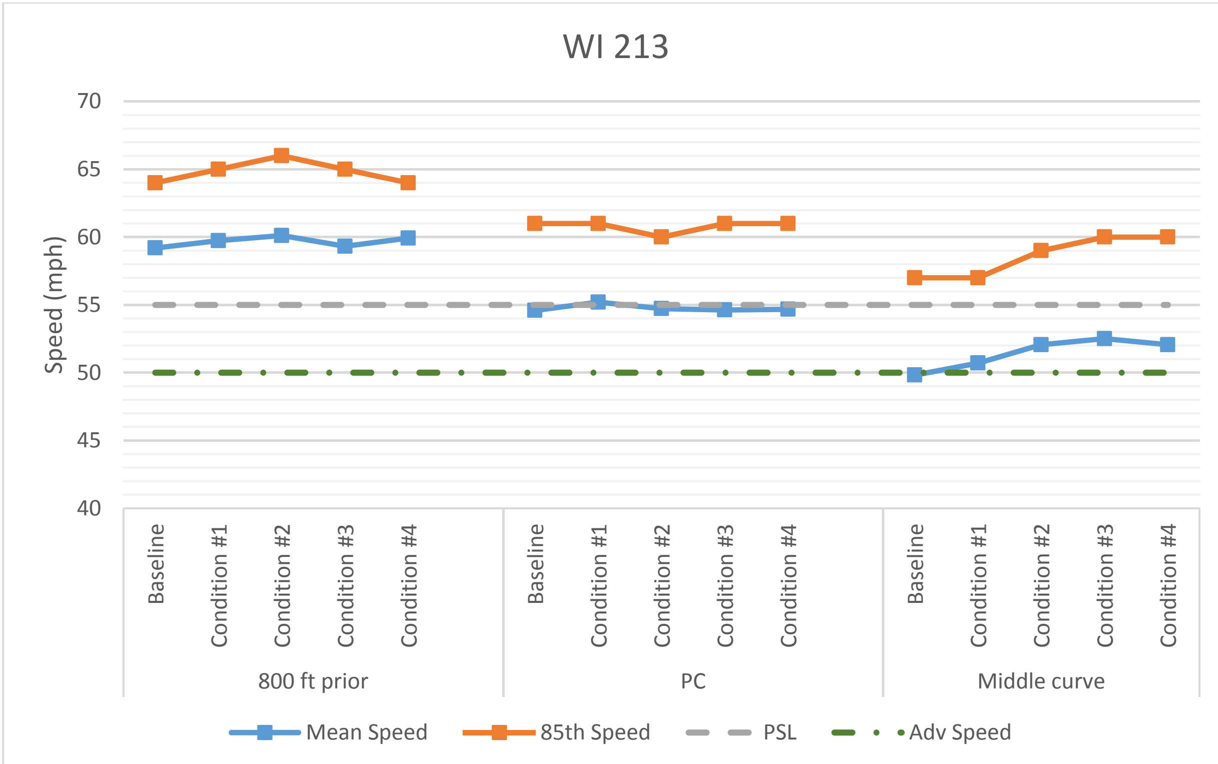



**Figure 46. Graph. Mean and 85th-percentile operating speeds at WI 213 site for daytime period.**

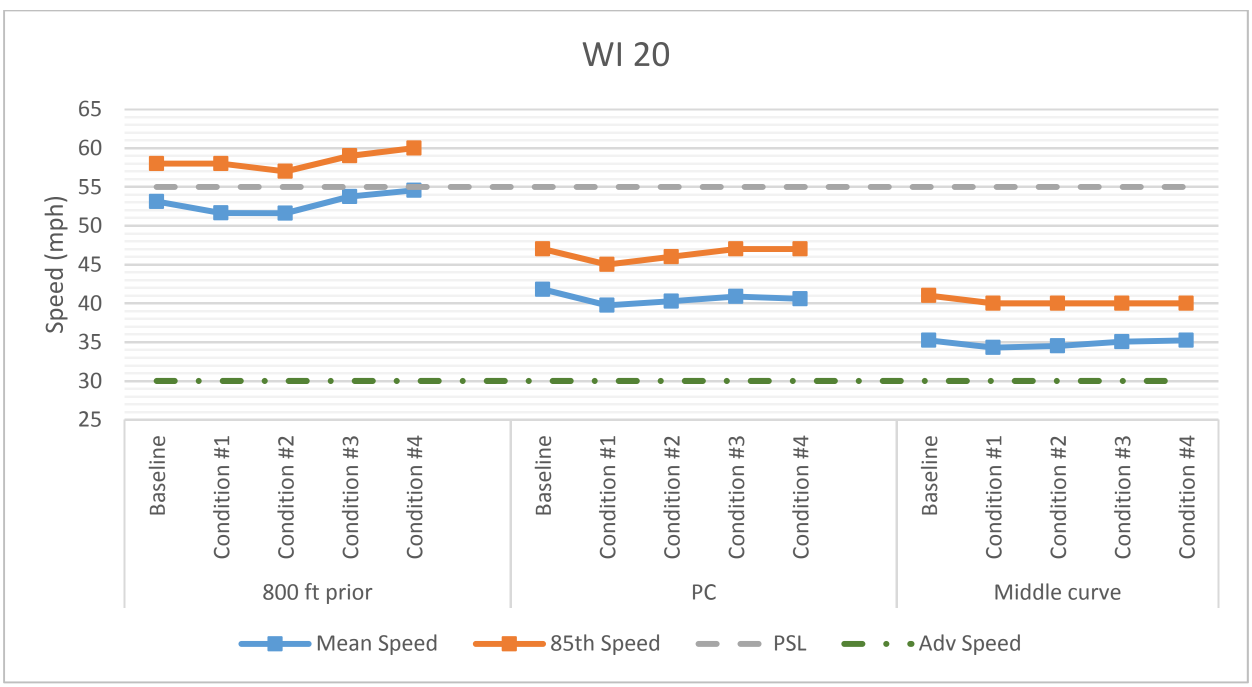



**Figure 47. Graph. Mean and 85th-percentile operating speeds at WI 20 site for daytime period.**


**Figure 48. Graph. Mean and 85th-percentile operating speeds at WI 67 site for daytime period.**

*Nighttime Conditions Only*

The data used in this analysis are for the nighttime period only, and are summarized in table 88 through table 93. The difference in the operating speed during condition $i$ ($i$ = 1, 2, 3, or 4) was compared to the operating speed during the baseline condition using the equation shown in figure 42. The mean and 85$^{th}$-percentile operating speeds decreased from the approach tangent (800 ft prior to the beginning of the horizontal curve) to the midpoint of the horizontal curve at all sites during all data collection periods.

The speed differences for the nighttime operating speed data are shown in table 88 through table 93. At the location 800 ft before the beginning of the horizontal curve, it was anticipated that the mean and 85$^{th}$-percentile operating speeds would be similar across all conditions. The data indicate that mean and 85$^{th}$-percentile operating speeds varied by not more than 2.0 mph between the baseline and all four conditions at each location. Conditions #1 and #2 generally produced the lowest mean and 85$^{th}$-percentile operating speed difference relative to the baseline condition at the point of curvature and the midpoint of the horizontal curve relative to the baseline condition during the nighttime data collection period. Figure 49 through figure 51 show the mean and 85$^{th}$-percentile operating speeds for each condition at all three data collection sites.

**Table 88. Mean operating speed data for nighttime conditions WI 213.**

| Period | 800 ft prior | PC | Midcurve |
|---|---|---|---|
| Baseline | 59.67 | 53.32 | 48.17 |
| Condition #1 | 58.77 | 52.21 | 47.41 |
| Condition #2 | 58.78 | 52.71 | 48.49 |
| Condition #3 | 59.87 | 54.71 | 50.36 |
| Condition #4 | 59.78 | 53.52 | 49.69 |

**Table 89. $85^{th}$ - percentile operating speed data for nighttime conditions WI 213.**

| Period | 800 ft prior | PC | Midcurve |
|---|---|---|---|
| Before | 66 | 61 | 56 |
| 1 Month | 65 | 58 | 56 |
| 12 Months | 64 | 59 | 57 |
| 18 Months | 66 | 61 | 59 |
| 24 Months | 65 | 60 | 57 |

**Table 90. Mean operating speed data for nighttime conditions WI 20.**

| Period | 800 ft prior | PC | Midcurve |
|---|---|---|---|
| Baseline | 54.47 | 42.78 | 36.06 |
| Condition #1 | 54.64 | 40.54 | 36.04 |
| Condition #2 | 52.63 | 40.37 | 36.13 |
| Condition #3 | 55.57 | 42.59 | 37.15 |
| Condition #4 | 54.98 | 41.73 | 37.63 |

**Table 91. $85^{th}$ - percentile operating speed data for nighttime conditions WI 20.**

| Period | 800 ft prior | PC | Midcurve |
|---|---|---|---|
| Baseline | 60 | 47 | 42 |
| Condition #1 | 60.5 | 44.5 | 40.5 |
| Condition #2 | 58 | 46 | 42 |
| Condition #3 | 62 | 48 | 43 |
| Condition #4 | 60 | 47 | 43 |

**Table 92. Mean operating speed data for nighttime conditions WI 67.**

| Period | 800 ft prior | PC | Midcurve |
|---|---|---|---|
| Baseline | 52.17 | 45.43 | 41.4 |
| Condition #1 | 51.36 | 42.17 | 38.42 |
| Condition #2 | 51.84 | 43.19 | 39.12 |
| Condition #3 | 51.6 | 44.36 | 40.7 |
| Condition #4 | 50.94 | 44.47 | 40.31 |

**Table 93. 85th - percentile operating speed data for nighttime conditions WI 67.**

| Period | 800 ft prior | PC | Midcurve |
|---|---|---|---|
| Baseline | 58 | 51 | 47 |
| Condition #1 | 58 | 47 | 43 |
| Condition #2 | 57 | 48 | 45 |
| Condition #3 | 57 | 50 | 46 |
| Condition #4 | 57 | 50 | 45 |

At Wisconsin Route 213 (see figure 49), the baseline and condition #1 produced the lowest mean and 85th-percentile operating speeds at the midpoint of the horizontal curve. The mean operating speeds during these two conditions were lower than the curve advisory warning speed limit. All other active flashing conditions produced operating speeds that exceeded the baseline condition (inactive flashing) and condition #1 at the midpoint of the horizontal curve. The mean and 85th-percentile operating speeds at the point of curvature were lowest for conditions #1 and #2. The mean speeds during these conditions were approximately 2 mph higher than the curve advisory speed limit.

At Wisconsin Route 20 (see figure 50), conditions #1 and #2 produced the lowest mean and 85th-percentile operating speeds at the midpoint and the beginning of the horizontal curve during the nighttime condition. The mean operating speed for conditions #1 and #2 was approximately 5 mph above the advance curve warning speed limit. At the beginning of the horizontal curve, the mean speed for conditions #1 and #2 was approximately 10 mph above the advance curve warning speed limit.

**Table 94. Difference in mean and 85th-percentile operating speeds between all conditions for nighttime conditions – WI 213.**

| Performance Measure | Condition #1 | Condition #2 | Condition #3 | Condition #4 |
|---|---|---|---|---|
| Change in Mean Speed 800 ft prior | -0.89 | -0.89 | 0.20 | 0.11 |
| Change in Mean Speed PC | -1.11 | -0.61 | 1.39 | 0.21 |
| Change in Mean Speed Midcurve | -0.76 | 0.32 | 2.19 | 1.52 |
| Change in 85th Speed 800 ft prior | -1.00 | -2.00 | 0.00 | -1.00 |
| Change in 85th Speed PC | -3.00 | -2.00 | 0.00 | -1.00 |
| Change in 85th Speed Midcurve | 0.00 | 1.00 | 3.00 | 1.00 |

**Table 95. Difference in mean and 85th-percentile operating speeds between all conditions for nighttime conditions – WI 20.**

| Performance Measure | Condition #1 | Condition #2 | Condition #3 | Condition #4 |
|---|---|---|---|---|
| Change in Mean Speed 800 ft prior | 0.17 | -1.84 | 1.11 | 0.51 |
| Change in Mean Speed PC | -2.23 | -2.40 | -0.19 | -1.05 |
| Change in Mean Speed Midcurve | -0.01 | 0.08 | 1.09 | 1.57 |
| Change in 85th Speed 800 ft prior | 0.50 | -2.00 | 2.00 | 0.00 |
| Change in 85th Speed PC | -2.50 | -1.00 | 1.00 | 0.00 |
| Change in 85th Speed Midcurve | -1.50 | 0.00 | 1.00 | 1.00 |

**Table 96. Difference in mean and 85th-percentile operating speeds between all conditions for nighttime conditions – WI 67.**

| Performance Measure | Condition #1 | Condition #2 | Condition #3 | Condition #4 |
|---|---|---|---|---|
| Change in Mean Speed 800 ft prior | -0.81 | -0.34 | -0.57 | -1.23 |
| Change in Mean Speed PC | -3.26 | -2.24 | -1.07 | -0.96 |
| Change in Mean Speed Midcurve | -2.98 | -2.28 | -0.70 | -1.09 |
| Change in 85th Speed 800 ft prior | 0.00 | -1.00 | -1.00 | -1.00 |
| Change in 85th Speed PC | -4.00 | -3.00 | -1.00 | -1.00 |
| Change in 85th Speed Midcurve | -4.00 | -2.00 | -1.00 | -2.00 |

At Wisconsin Route 67 (see figure 51), conditions #1 and #2 produced the lowest mean and $85^{th}$-percentile operating speeds at the midpoint and at the beginning of the horizontal curve during the nighttime period. All of the flashing patterns produced mean and $85^{th}$-percentile operating speeds lower than the baseline condition (inactive flashing patterns) at the beginning and midpoint locations along the horizontal curve. At the Wisconsin Route 67 site, the mean and $85^{th}$-percentile operating speeds were more than 10 mph higher than the curve advisory speed limit.

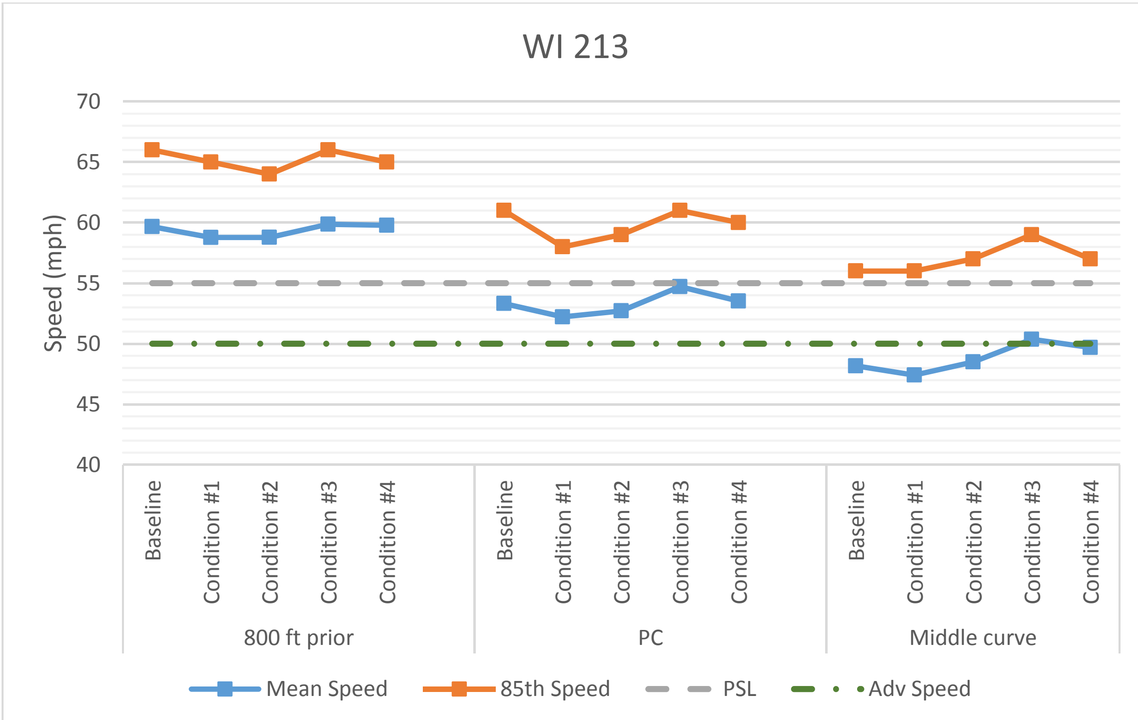



**Figure 49. Graph. Mean and 85th-percentile operating speeds at WI 213 site for nighttime period.**

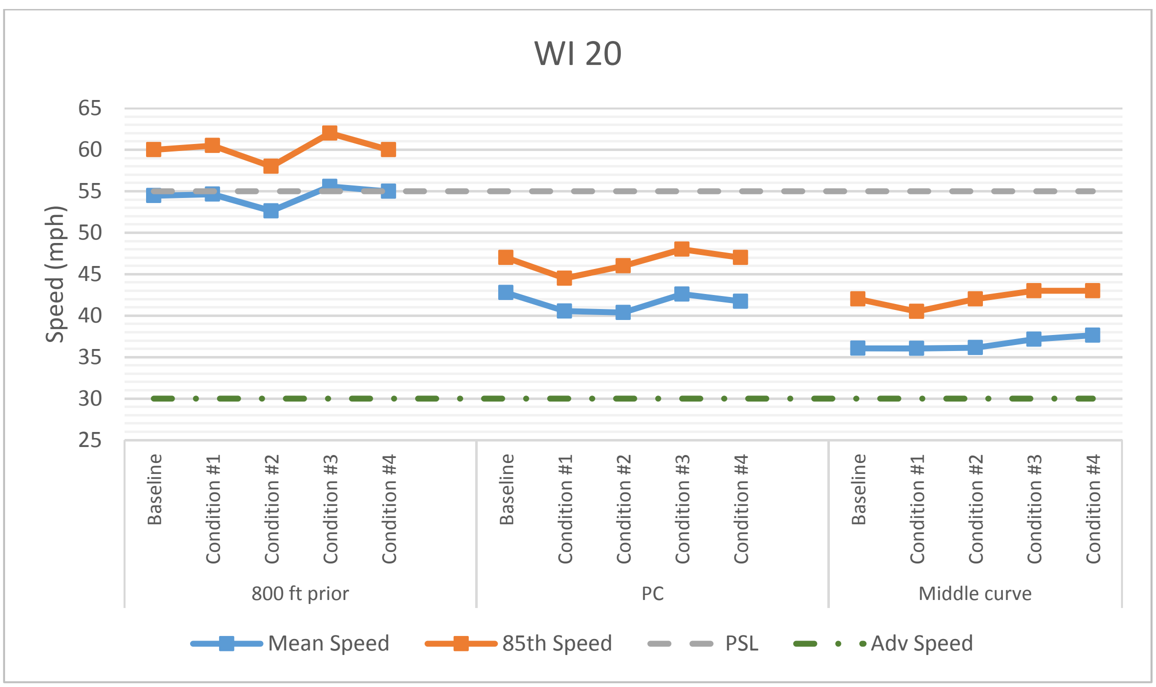



**Figure 50. Graph. Mean and 85th-percentile operating speeds at WI 20 site for nighttime period.**

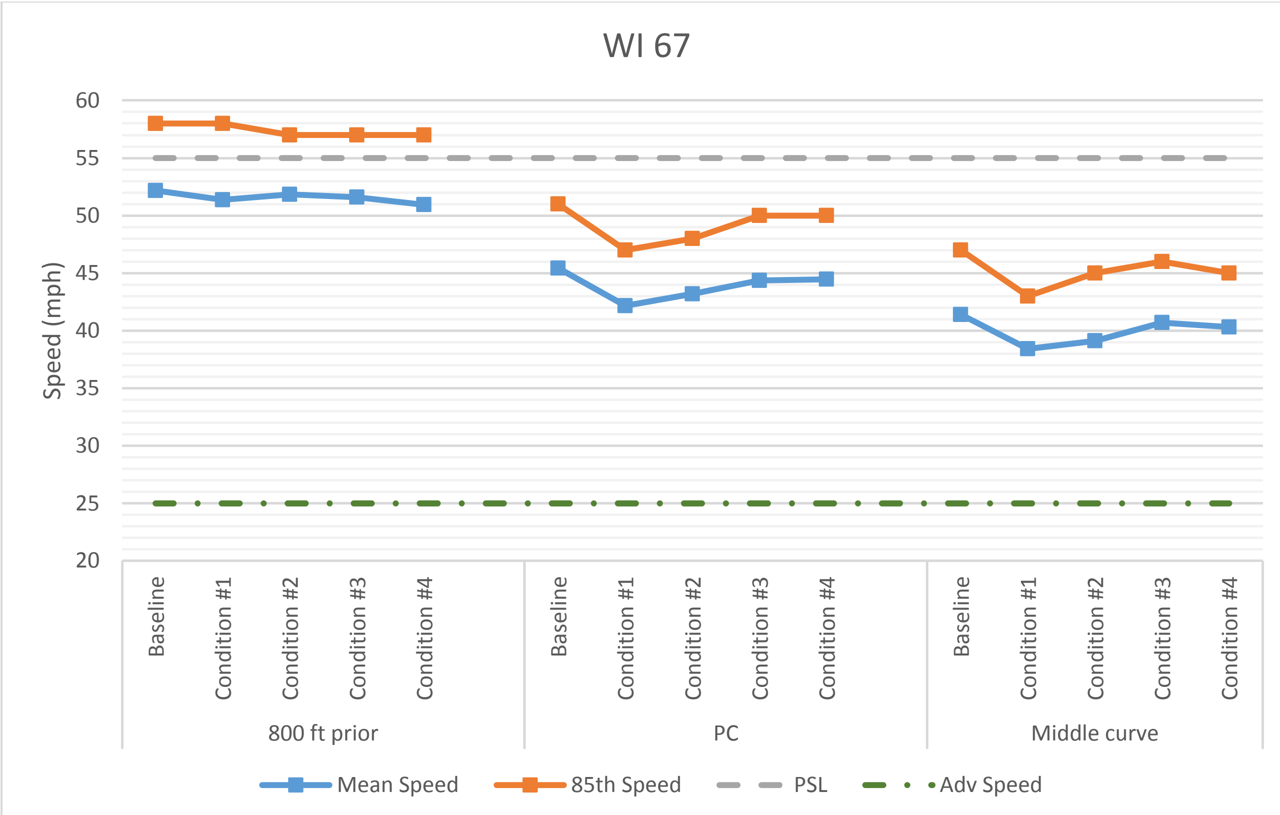



**Figure 51. Graph. Mean and 85th-percentile operating speeds at WI 67 site for nighttime period.**

# APPENDIX E

**Statistical Tests**

Several statistical tests were performed as part of the field studies to compare the active flashing sequential conditions (conditions #1 through #4) to the baseline condition. These included the following:

- Comparison of mean speeds
- Comparison of speed variance
- Test of proportions for vehicles exceeding the horizontal curve advisory speed

All of these tests were performed for the daytime and nighttime data collection periods combined, the daytime period only, and the nighttime period only. The results of the statistical tests are shown below.

**Difference in Mean Speeds**

For this test, the mean speed at all three data collection locations (800 ft before the horizontal curve, beginning of the curve, and midpoint of the horizontal curve) were compared between each condition (baseline and conditions #1 through #4). The null hypothesis is the difference in mean speed between two conditions (e.g., condition #1 relative to baseline, condition #2 relative to baseline, etc.) is equal to zero. The probability of type I error was set at 0.05, so the null hypothesis is rejected if the p-value exceeds 0.05. It should be noted that a one-sided t-test was used in this case, so a statistically significant test indicates that the mean speed for the baseline condition differs from the mean speed in the flashing condition. A negative sign for the t-test indicates that the baseline condition has a higher mean speed than the flashing condition, which is a desirable result. Table 97 through note: * denotes the 95-percent confidence interval.

table 105 shows the statistical tests for the daytime and nighttime mean speeds combined, the daytime mean speeds only, and the nighttime speeds only, respectively.

**Table 97. Statistical tests for mean speeds during daytime and nighttime periods combined - WI 213.**

| Performance Measure | Baseline → Condition #1 | | Baseline → Condition #2 | | Baseline → Condition #3 | | Baseline → Condition #4 | |
|---|---|---|---|---|---|---|---|---|
| | t-statistic | p-value | t-statistic | p-value | t-statistic | p-value | t-statistic | p-value |
| 800 ft prior | -0.457 | 0.324 | 0.05 | 0.52 | 0.309 | 0.621 | 1.01 | 0.844 |
| PC | -0.976 | 0.165 | -0.528 | 0.299 | 1.187 | 0.882 | 0.254 | 0.6 |
| Midcurve | -0.405 | 0.343 | 1.508 | 0.934 | 3.626 | 1 | 2.799 | 0.997 |

Note: * denotes the 95-percent confidence interval.

**Table 98. Statistical tests for mean speeds during daytime and nighttime periods combined - WI 20.**

| Performance Measure | Baseline → Condition #1 | | Baseline → Condition #2 | | Baseline → Condition #3 | | Baseline → Condition #4 | |
|---|---|---|---|---|---|---|---|---|
| | t-statistic | p-value | t-statistic | p-value | t-statistic | p-value | t-statistic | p-value |
| 800 ft prior | -1.423 | 0.078 | -3.73 | <0.001* | 2.211 | 0.986 | 2.734 | 0.997 |
| PC | -4.666 | <0.001* | -4.268 | <0.001* | -1.148 | 0.125 | -2.27 | 0.012* |
| Midcurve | -1.112 | 0.133 | -0.909 | 0.182 | 0.99 | 0.839 | 1.927 | 0.973 |

Note: * denotes the 95-percent confidence interval.

**Table 99. Statistical tests for mean speeds during daytime and nighttime periods combined - WI 67.**

| Performance Measure | Baseline → Condition #1 | | Baseline → Condition #2 | | Baseline → Condition #3 | | Baseline → Condition #4 | |
|---|---|---|---|---|---|---|---|---|
| | t-statistic | p-value | t-statistic | p-value | t-statistic | p-value | t-statistic | p-value |
| 800 ft prior | -2.504 | 0.006* | -1.942 | 0.026* | -0.506 | 0.307 | -1.167 | 0.122 |
| PC | -5.469 | <0.001* | -5.331 | <0.001* | -1.277 | 0.101 | -1.008 | 0.157 |
| Midcurve | -3.937 | <0.001* | -5.209 | <0.001* | -1.523 | 0.064 | -2.055 | 0.020* |

Note: * denotes the 95-percent confidence interval.

As shown in table 97 through note: * denotes the 95-percent confidence interval.

table 99, the baseline to condition #1 and the baseline to condition #2 comparisons are almost all negative, which confirms that conditions #1 and #2 are generally producing lower mean operating speeds than the baseline condition. The two-sample t-test is statistically significant at the point of curve along Wisconsin Route 20 for both flashing conditions relative to the baseline (inactive) condition. All of the condition #1 and #2 speeds are lower than the baseline condition at Wisconsin Route 67 when combining the daytime and nighttime mean speeds. Conditions #3 and #4 produced few statistically different mean operating speeds relative to the baseline condition.

The daytime mean speed comparisons, which are shown in table 100 through note: * denotes the 95-percent confidence interval.

table 102table 100 also show several statistically significant differences between the baseline condition and conditions #1 and #2 during the daytime data collection period. The statistically significant results were found at the PC locations of Wisconsin routes 20 and 67, suggesting that the flashing sequence is effective in reducing mean operating speeds at the beginning of the curve when compared to the baseline condition. Conditions #3 and #4 produced few statistically different mean operating speeds relative to the baseline condition.

The nighttime mean speed comparisons, which are shown in note: * denotes the 95-percent confidence interval.

table 103 through note: * denotes the 95-percent confidence interval.

table 105, also show several statistically significant differences between the baseline condition and conditions #1 and #2. The statistically significant results were found at the PC locations of Wisconsin routes 20 and 67, suggesting that the flashing sequence is effective in reducing mean operating speeds at the beginning of the curve when compared to the baseline condition. Statistically significant differences in the mean speed at the midpoint of the horizontal curve were found at Wisconsin site 67 when comparing conditions #1 and #2 to the baseline condition. This indicates that the sequential flashing pattern was effective in reducing mean operating speeds at the midpoint of the horizontal curve at one site during the nighttime conditions. Conditions #3 and #4 produced few statistically different mean operating speeds relative to the baseline condition.

**Table 100. Statistical tests for mean speeds during daytime period – WI 213.**

| Performance Measure | Baseline → Condition #1 | | Baseline → Condition #2 | | Baseline → Condition #3 | | Baseline → Condition #4 | |
|---|---|---|---|---|---|---|---|---|
| | t-statistic | p-value | t-statistic | p-value | t-statistic | p-value | t-statistic | p-value |
| 800 ft prior | 0.859 | 0.805 | 1.366 | 0.913 | 0.204 | 0.581 | 1.352 | 0.911 |
| PC | 0.735 | 0.769 | 0.150 | 0.560 | 0.045 | 0.518 | 0.113 | 0.545 |
| Midcurve | 0.903 | 0.816 | 2.199 | 0.986 | 3.031 | 0.999 | 2.508 | 0.994 |

**Table 101. Statistical tests for mean speeds during daytime period – WI 20.**

| Performance Measure | Baseline → Condition #1 | | Baseline → Condition #2 | | Baseline → Condition #3 | | Baseline → Condition #4 | |
|---|---|---|---|---|---|---|---|---|
| | t-statistic | p-value | t-statistic | p-value | t-statistic | p-value | t-statistic | p-value |
| 800 ft prior | -2.350 | 0.010* | -2.946 | 0.002* | 1.241 | 0.892 | 2.617 | 0.995 |
| PC | -3.674 | <0.001* | -2.940 | 0.002* | -1.671 | 0.048* | -2.077 | 0.019* |
| Midcurve | -1.633 | 0.052 | -1.364 | 0.087 | -0.323 | 0.373 | -0.001 | 0.500 |

Note: * denotes the 95-percent confidence interval.

**Table 102. Statistical tests for mean speeds during daytime period – WI 67.**

| Performance Measure | Baseline → Condition #1 | | Baseline → Condition #2 | | Baseline → Condition #3 | | Baseline → Condition #4 | |
|---|---|---|---|---|---|---|---|---|
| | t-statistic | p-value | t-statistic | p-value | t-statistic | p-value | t-statistic | p-value |
| 800 ft prior | -1.521 | 0.065 | -1.704 | 0.045* | 0.536 | 0.704 | 0.339 | 0.633 |
| PC | -2.760 | 0.003* | -3.402 | <0.001* | -0.241 | 0.405 | 0.064 | 0.526 |
| Midcurve | -0.849 | 0.198 | -2.788 | 0.003* | -0.491 | 0.312 | -0.593 | 0.277 |

Note: * denotes the 95-percent confidence interval.

**Table 103. Statistical tests for mean speeds during nighttime period – WI 213.**

| Performance Measure | Baseline → Condition #1 | | Baseline → Condition #2 | | Baseline → Condition #3 | | Baseline → Condition #4 | |
|---|---|---|---|---|---|---|---|---|
| | t-statistic | p-value | t-statistic | p-value | t-statistic | p-value | t-statistic | p-value |
| 800 ft prior | -1.132 | 0.129 | -1.022 | 0.154 | 0.257 | 0.601 | 0.149 | 0.559 |
| PC | -1.436 | 0.076 | -0.688 | 0.246 | 1.675 | 0.952 | 0.269 | 0.606 |
| Midcurve | -0.769 | 0.221 | 0.277 | 0.609 | 2.038 | 0.979 | 1.467 | 0.928 |

**Table 104. Statistical tests for mean speeds during nighttime period – WI 20.**

| Performance Measure | Baseline → Condition #1 | | Baseline → Condition #2 | | Baseline → Condition #3 | | Baseline → Condition #4 | |
|---|---|---|---|---|---|---|---|---|
| | t-statistic | p-value | t-statistic | p-value | t-statistic | p-value | t-statistic | p-value |
| 800 ft prior | 0.222 | 0.588 | -2.484 | 0.007* | 1.460 | 0.927 | 0.721 | 0.764 |
| PC | -3.089 | 0.001* | -3.229 | 0.001* | -0.238 | 0.406 | -1.541 | 0.062 |
| Midcurve | -0.020 | 0.492 | 0.112 | 0.544 | 1.521 | 0.935 | 2.164 | 0.984 |

Note: * denotes the 95-percent confidence interval.

**Table 105. Statistical tests for mean speeds during nighttime period – WI 67.**

| Performance Measure | Baseline → Condition #1 | | Baseline → Condition #2 | | Baseline → Condition #3 | | Baseline → Condition #4 | |
|---|---|---|---|---|---|---|---|---|
| | t-statistic | p-value | t-statistic | p-value | t-statistic | p-value | t-statistic | p-value |
| 800 ft prior | -0.986 | 0.163 | -0.480 | 0.316 | -0.732 | 0.233 | -1.681 | 0.047* |
| PC | -5.254 | <0.001* | -3.969 | <0.001* | -1.660 | 0.049* | -1.702 | 0.045* |
| Midcurve | -5.193 | <0.001* | -4.252 | <0.001* | -1.104 | 0.135 | -2.083 | 0.019* |

Note: * denotes the 95-percent confidence interval.

### Speed Variance

For the analysis, the speed variance in the baseline condition was compared to the speed variance for each flashing condition. The null hypothesis was that the two conditions produced an equal speed variance. The probability of type I error was set at 0.05. If the null hypothesis was rejected, the variable in the baseline condition was either smaller or larger than the flashing condition. An F-statistic exceeding 1.0 indicates that the speed variance in the baseline condition exceeded the speed variance in the flashing condition, a desirable result. The statistical tests were conducted for all speeds combined (daytime and nighttime), daytime speeds only, and nighttime speeds only. The results of the speed variance tests are shown in table 106 through table 114, respectively.

**Table 106. Speed variance tests for daytime and nighttime periods combined - WI 213.**

| Performance Measure | Baseline → Condition #1 | | Baseline → Condition #2 | | Baseline → Condition #3 | | Baseline → Condition #4 | |
|---|---|---|---|---|---|---|---|---|
| | F-statistic | p-value | F-statistic | p-value | F-statistic | p-value | F-statistic | p-value |
| 800 ft prior | 0.820 | 0.103 | 0.846 | 0.198 | 0.891 | 0.313 | 0.636 | <0.001* |
| PC | 0.798 | 0.063 | 0.809 | 0.103 | 0.838 | 0.123 | 0.716 | 0.003* |
| Midcurve | 0.690 | 0.002* | 0.855 | 0.228 | 0.869 | 0.220 | 0.887 | 0.285 |

Note: * denotes the 95-percent confidence interval.

**Table 107. Speed variance tests for daytime and nighttime periods combined - WI 20.**

| Performance Measure | Baseline → Condition #1 | | Baseline → Condition #2 | | Baseline → Condition #3 | | Baseline → Condition #4 | |
|---|---|---|---|---|---|---|---|---|
| | F-statistic | p-value | F-statistic | p-value | F-statistic | p-value | F-statistic | p-value |
| 800 ft prior | 1.594 | <0.001* | 1.091 | 0.426 | 1.077 | 0.507 | 1.132 | 0.265 |
| PC | 0.976 | 0.834 | 1.072 | 0.525 | 1.207 | 0.093 | 1.120 | 0.306 |
| Midcurve | 0.930 | 0.528 | 0.911 | 0.386 | 0.944 | 0.603 | 1.064 | 0.574 |

Note: * denotes the 95-percent confidence interval.

**Table 108. Speed variance tests for daytime and nighttime periods combined - WI 67.**

| Performance Measure | Baseline → Condition #1 | | Baseline → Condition #2 | | Baseline → Condition #3 | | Baseline → Condition #4 | |
|---|---|---|---|---|---|---|---|---|
| | F-statistic | p-value | F-statistic | p-value | F-statistic | p-value | F-statistic | p-value |
| 800 ft prior | 1.121 | 0.329 | 0.979 | 0.843 | 0.942 | 0.602 | 1.042 | 0.721 |
| PC | 0.809 | 0.064 | 0.810 | 0.058 | 0.783 | 0.036* | 0.897 | 0.321 |
| Midcurve | 0.970 | 0.785 | 0.888 | 0.286 | 0.909 | 0.412 | 1.039 | 0.744 |

Note: * denotes the 95-percent confidence interval.

Few speed variance tests were statistically significant for the daytime and nighttime periods combined, as shown in table 106. In only one case (800 ft before the horizontal curve on Wisconsin Route 20) was the variance lower for the flashing condition relative to the baseline condition. This suggests that the flashing sequential chevron signs have little effect on the speed variance when combining the daytime and nighttime operating speed data.

When considering the daytime speed variance only, there are several statistically significant differences between the speed variance in the baseline condition and several flashing conditions, as shown in table 109 through note: * denotes the 95-percent confidence interval.

table 111. The location 800 ft before the horizontal curve on Wisconsin Route 20 was the only location where the flashing condition (condition #1) produced a speed variance lower than the baseline condition during the daytime period.

**Table 109. Speed variance tests for daytime period – WI 213.**

| Performance Measure | Baseline → Condition #1 | | Baseline → Condition #2 | | Baseline → Condition #3 | | Baseline → Condition #4 | |
|---|---|---|---|---|---|---|---|---|
| | F-statistic | p-value | F-statistic | p-value | F-statistic | p-value | F-statistic | p-value |
| 800 ft prior | 0.792 | 0.198 | 1.036 | 0.831 | 1.323 | 0.068 | 0.808 | 0.162 |
| PC | 0.690 | 0.041* | 0.617 | 0.010* | 0.726 | 0.038* | 0.656 | 0.006* |
| Midcurve | 0.554 | 0.001* | 0.626 | 0.012* | 0.797 | 0.141 | 0.849 | 0.283 |

Note: * denotes the 95-percent confidence interval.

**Table 110. Speed variance tests for daytime period – WI 20.**

| Performance Measure | Baseline → Condition #1 | | Baseline → Condition #2 | | Baseline → Condition #3 | | Baseline → Condition #4 | |
|---|---|---|---|---|---|---|---|---|
| | F-statistic | p-value | F-statistic | p-value | F-statistic | p-value | F-statistic | p-value |
| 800 ft prior | 1.834 | <0.001* | 1.116 | 0.422 | 0.967 | 0.815 | 1.219 | 0.171 |
| PC | 1.044 | 0.765 | 1.047 | 0.740 | 1.061 | 0.677 | 1.291 | 0.078 |
| Midcurve | 1.025 | 0.861 | 1.006 | 0.968 | 0.978 | 0.875 | 1.052 | 0.722 |

Note: * denotes the 95-percent confidence interval.

**Table 111. Speed variance tests for daytime period – WI 67.**

| Performance Measure | Baseline → Condition #1 | | Baseline → Condition #2 | | Baseline → Condition #3 | | Baseline → Condition #4 | |
|---|---|---|---|---|---|---|---|---|
| | F-statistic | p-value | F-statistic | p-value | F-statistic | p-value | F-statistic | p-value |
| 800 ft prior | 1.183 | 0.341 | 1.064 | 0.734 | 1.063 | 0.742 | 1.161 | 0.390 |
| PC | 0.724 | 0.049* | 0.709 | 0.039* | 0.656 | 0.011* | 0.884 | 0.438 |
| Midcurve | 1.123 | 0.514 | 0.888 | 0.469 | 0.811 | 0.209 | 1.320 | 0.109 |

Note: * denotes the 95-percent confidence interval.

When considering the nighttime speed variance only, there were very statistically significant differences between the speed variance in the baseline condition and several flashing conditions, as shown in table 112 through table 114. In none of these cases did the flashing condition produce a speed variance lower than the baseline condition during the nighttime period.

**Table 112. Speed variance tests for nighttime period – WI 213.**

| Performance Measure | Baseline → Condition #1 | | Baseline → Condition #2 | | Baseline → Condition #3 | | Baseline → Condition #4 | |
|---|---|---|---|---|---|---|---|---|
| | F-statistic | p-value | F-statistic | p-value | F-statistic | p-value | F-statistic | p-value |
| 800 ft prior | 0.742 | 0.077 | 0.688 | 0.048* | 0.598 | 0.003* | 0.523 | <0.001* |
| PC | 0.827 | 0.258 | 0.989 | 0.963 | 1.009 | 0.957 | 0.792 | 0.165 |
| Midcurve | 0.723 | 0.054 | 0.991 | 0.969 | 0.943 | 0.736 | 0.906 | 0.557 |

Note: * denotes the 95-percent confidence interval.

**Table 113. Speed variance tests for nighttime period – WI 20.**

| Performance Measure | Baseline → Condition #1 | | Baseline → Condition #2 | | Baseline → Condition #3 | | Baseline → Condition #4 | |
|---|---|---|---|---|---|---|---|---|
| | F-statistic | p-value | F-statistic | p-value | F-statistic | p-value | F-statistic | p-value |
| 800 ft prior | 1.147 | 0.473 | 1.052 | 0.788 | 1.132 | 0.503 | 1.022 | 0.911 |
| PC | 0.877 | 0.484 | 1.118 | 0.548 | 1.332 | 0.122 | 0.917 | 0.616 |
| Midcurve | 0.748 | 0.124 | 0.726 | 0.075 | 0.816 | 0.261 | 0.959 | 0.802 |

**Table 114. Speed variance tests for nighttime period – WI 67.**

| Performance Measure | Baseline → Condition #1 | | Baseline → Condition #2 | | Baseline → Condition #3 | | Baseline → Condition #4 | |
|---|---|---|---|---|---|---|---|---|
| | F-statistic | p-value | F-statistic | p-value | F-statistic | p-value | F-statistic | p-value |
| 800 ft prior | 1.113 | 0.522 | 0.887 | 0.424 | 0.865 | 0.398 | 0.982 | 0.900 |
| PC | 0.867 | 0.397 | 0.902 | 0.492 | 0.953 | 0.781 | 0.847 | 0.277 |
| Midcurve | 0.779 | 0.139 | 0.930 | 0.627 | 1.152 | 0.405 | 0.780 | 0.106 |

### Test of Proportions for Vehicles Exceeding Advisory Speed Warning

This analysis considered the proportion of vehicles exceeding the advisory speed. A test of proportions was used to compare the baseline condition to one of the four flashing chevron conditions. The probability of type I error was set equal to 0.05. The null hypothesis was that the baseline and the flashing chevron conditions were equal. A one-sided test of proportions was used to compare the baseline to each flashing condition. When the proportion of vehicles exceeding the advisory speed for the baseline condition was higher than the proportion of vehicles exceeding the advisory speed for one of the flashing conditions, the z-statistic was positive, which was an undesirable result.

Results of the analysis are shown in table 115 through table 123. In table 115 through note: * denotes the 95-percent confidence interval.

table 117, the speed data for the daytime and nighttime conditions were combined. Table 118 and table 123 show the results of the analysis for the daytime and nighttime conditions, respectively. Few flashing conditions produced speed compliance relative to the baseline condition. This analysis indicates that the flashing sequential conditions evaluated in the present study did not produce improved speed compliance relative to the baseline condition.

**Table 115. Proportion of vehicles exceeding advisory speed (daytime and nighttime combined) - WI 213.**

| Performance Measure | Baseline → Condition #1 | | Baseline → Condition #2 | | Baseline → Condition #3 | | Baseline → Condition #4 | |
|---|---|---|---|---|---|---|---|---|
| | z-statistic | p-value | z-statistic | p-value | z-statistic | p-value | z-statistic | p-value |
| 800 ft prior | -0.064 | 0.525 | -1.340 | 0.910 | -1.216 | 0.888 | -2.277 | 0.989 |
| PC | 1.100 | 0.136 | -0.072 | 0.529 | 0.169 | 0.433 | -0.792 | 0.786 |
| Midcurve | 1.613 | 0.053 | -1.246 | 0.894 | 0.894 | 0.999 | -2.044 | 0.980 |

**Table 116. Proportion of vehicles exceeding advisory speed (daytime and nighttime combined) - WI 20.**

| Performance Measure | Baseline → Condition #1 | | Baseline → Condition #2 | | Baseline → Condition #3 | | Baseline → Condition #4 | |
|---|---|---|---|---|---|---|---|---|
| | z-statistic | p-value | z-statistic | p-value | z-statistic | p-value | z-statistic | p-value |
| 800 ft prior | 0.043 | 0.483 | -1.093 | 0.863 | -1.028 | 0.848 | -0.070 | 0.528 |
| PC | 1.862 | 0.031* | 0.758 | 0.224 | 0.992 | 0.161 | 0.689 | 0.246 |
| Midcurve | 0.093 | 0.463 | -0.675 | 0.750 | -1.871 | 0.969 | -1.747 | 0.960 |

Note: * denotes the 95-percent confidence interval.

**Table 117. Proportion of vehicles exceeding advisory speed (daytime and nighttime combined) - WI 67.**

| Performance Measure | Baseline → Condition #1 | | Baseline → Condition #2 | | Baseline → Condition #3 | | Baseline → Condition #4 | |
|---|---|---|---|---|---|---|---|---|
| | z-statistic | p-value | z-statistic | p-value | z-statistic | p-value | z-statistic | p-value |
| 800 ft prior | 0.804 | 0.211 | 0.000 | 0.500 | 0.000 | 0.500 | 0.001 | 0.500 |
| PC | 0.001 | 0.500 | 0.001 | 0.500 | 0.001 | 0.500 | 0.001 | 0.500 |
| Midcurve | 1.148 | 0.125 | 1.148 | 0.125 | 0.834 | 0.202 | 1.456 | 0.073 |

**Table 118. Proportion of vehicles exceeding advisory speed during daytime – WI 213.**

| Performance Measure | Baseline → Condition #1 | | Baseline → Condition #2 | | Baseline → Condition #3 | | Baseline → Condition #4 | |
|---|---|---|---|---|---|---|---|---|
| | z-statistic | p-value | z-statistic | p-value | z-statistic | p-value | z-statistic | p-value |
| 800 ft prior | -1.486 | 0.931 | -1.397 | 0.919 | -0.117 | 0.547 | -1.590 | 0.944 |
| PC | -0.649 | 0.742 | -0.403 | 0.657 | 0.779 | 0.218 | -0.951 | 0.829 |
| Midcurve | -0.588 | 0.722 | -1.450 | 0.926 | -3.597 | 1.000 | -2.425 | 0.992 |

**Table 119. Proportion of vehicles exceeding advisory speed during daytime – WI 20.**

| Performance Measure | Baseline → Condition #1 | | Baseline → Condition #2 | | Baseline → Condition #3 | | Baseline → Condition #4 | |
|---|---|---|---|---|---|---|---|---|
| | z-statistic | p-value | z-statistic | p-value | z-statistic | p-value | z-statistic | p-value |
| 800 ft prior | 0.122 | 0.452 | -1.054 | 0.854 | -0.954 | 0.830 | -0.926 | 0.823 |
| PC | 1.974 | 0.024 | 0.469 | 0.320 | 0.480 | 0.316 | 0.220 | 0.413 |
| Midcurve | 0.670 | 0.252 | -0.013 | 0.505 | -0.954 | 0.830 | -0.665 | 0.747 |

**Table 120. Proportion of vehicles exceeding advisory speed during daytime – WI 67.**

| Performance Measure | Baseline → Condition #1 | | Baseline → Condition #2 | | Baseline → Condition #3 | | Baseline → Condition #4 | |
|---|---|---|---|---|---|---|---|---|
| | z-statistic | p-value | z-statistic | p-value | z-statistic | p-value | z-statistic | p-value |
| 800 ft prior | 0.001 | 0.500 | 0.001 | 0.500 | 0.001 | 0.500 | 0.001 | 0.500 |
| PC | 0.001 | 0.500 | 0.001 | 0.500 | 0.001 | 0.500 | 0.001 | 0.500 |
| Midcurve | 0.904 | 0.183 | 0.661 | 0.254 | 0.001 | 0.500 | 1.209 | 0.113 |

**Table 121. Proportion of vehicles exceeding advisory speed during nighttime – WI 213.**

| Performance Measure | Baseline → Condition #1 | | Baseline → Condition #2 | | Baseline → Condition #3 | | Baseline → Condition #4 | |
|---|---|---|---|---|---|---|---|---|
| | z-statistic | p-value | z-statistic | p-value | z-statistic | p-value | z-statistic | p-value |
| 800 ft prior | 0.687 | 0.246 | -0.621 | 0.733 | -1.776 | 0.962 | -1.628 | 0.948 |
| PC | 1.318 | 0.094 | 0.059 | 0.477 | -0.524 | 0.700 | -0.212 | 0.584 |
| Midcurve | 2.311 | 0.010* | -0.427 | 0.665 | -0.843 | 0.800 | -0.412 | 0.660 |

Note: * denotes the 95-percent confidence interval.

**Table 122. Proportion of vehicles exceeding advisory speed during nighttime – WI 20.**

| Performance Measure | Baseline → Condition #1 | | Baseline → Condition #2 | | Baseline → Condition #3 | | Baseline → Condition #4 | |
|---|---|---|---|---|---|---|---|---|
| | z-statistic | p-value | z-statistic | p-value | z-statistic | p-value | z-statistic | p-value |
| 800 ft prior | 0.000 | 0.500 | 0.000 | 0.500 | 0.000 | 0.500 | 0.809 | 0.209 |
| PC | 0.487 | 0.313 | 0.734 | 0.232 | 1.060 | 0.145 | 0.903 | 0.183 |
| Midcurve | -0.546 | 0.708 | -1.064 | 0.856 | -1.595 | 0.945 | -1.508 | 0.934 |

**Table 123. Proportion of vehicles exceeding advisory speed during nighttime – WI 67.**

| Performance Measure | Baseline → Condition #1 | | Baseline → Condition #2 | | Baseline → Condition #3 | | Baseline → Condition #4 | |
|---|---|---|---|---|---|---|---|---|
| | z-statistic | p-value | z-statistic | p-value | z-statistic | p-value | z-statistic | p-value |
| 800 ft prior | 1.045 | 0.148 | 0.000 | 0.500 | 0.000 | 0.500 | 0.000 | 0.500 |
| PC | 0.000 | 0.500 | 0.000 | 0.500 | 0.000 | 0.500 | 0.000 | 0.500 |
| Midcurve | 0.000 | 0.500 | 0.838 | 0.201 | 1.073 | 0.142 | 0.000 | 0.500 |

# ACKNOWLEDGMENTS

The Federal Highway Administration would like to express appreciation to the professional industry practitioners and researchers for providing information for the field study conducted as part of this research effort.

# REFERENCES

3M. *A Before and After Study of 3M Driver Feedback Signs.* Traffic Safety Systems, 3M United Kingdom PLC, 2006.

Albin, R., V. Brinkly, J. Cheung, F. Julian, C. Satterfield, W. Stein, E. T. Donnell, H. McGee, A. Holzem, M. Albee, J. Wood, and F. Hanscom. *Low-Cost Treatments for Horizontal Curve Safety 2016*. Report No. FHWA-SA-15-084, Federal Highway Administration, Washington, DC, January 2016.

Babaee, S., Y. Shen, E. Hermans, G. Wets, T. Brijs, and C. Ariën. *Assessing individual driver's relative performance at curve: Applying data envelopment analysis on simulator data.* Transport Research Arena (TRA) 5th Conference: Transport Solutions from Research to Deployment, 2014, 10 pp.

Banihashemi, M., M. Dimaiuta, and H. Wang. Operating Speed Model for Low-Speed Rural Two-Lane Highways. *Transportation Research Record: Journal of the Transportation Research Board, No. 2223*, 2011, pp. 63-71.

Bertini, R. L., C. M. Monsere, C. Nolan, P. Bosa, and T. A. El-Seoud. *Field Evaluation of the Myrtle Creek Advanced Curve Warning System*. Oregon Department of Transportation, Report No. FHWA-OR-RD-06-13, 2006.

Carson, J. L., J. Tydlacka, L. S. Gray, and A.P. Voigt. *NCHRP Synthesis 380: Applications of Illuminated, Active, In-Pavement Marker Systems*. Transportation Research Board of the National Academies, Washington, DC, 2008.

City of Bellevue Transportation Department. *Stationary Radar Sign Program Report*. Accessed at: http://jkheneghan.com/city/meetings/2009/Apr/04302009_radar_sign_report_BellevueWA.pdf on November 28, 2017.

Cruzado, I., and E. T. Donnell. Evaluating Effectiveness of Dynamic Speed Display Signs in Transition Zones of Two-Lane, Rural Highways in Pennsylvania. *Transportation Research Record: Journal of the Transportation Research Board, No. 2122*, Transportation Research Board of the National Academies, 2009, pp. 1–8.

Diercksen, L., C. M. Monsere, and R. L. Bertini. A Second Look at the Effectiveness of the Myrtle Creek Dynamic Advanced Curve Warning System. *Proceedings from 15th World Congress on Intelligent Transport Systems and ITS America's 2008 Annual Meeting*, New York, NY, November 2008, 12 pp.

Fontaine, M., P. Carlson, and H. Hawkins. *Evaluation of traffic control devices for rural high-speed maintenance work zones: Second year activities and final recommendations.* Texas Transportation Institute, No. FHWA/TX-01/1879-2, College Station, TX, 2000.

Glennon, J. C., T. R. Neuman, and J. E. Leisch. *Safety and Operational Considerations for Design of Rural Highway Curves*. Report No. FHWA-RD-86-035, Federal Highway Administration, Washington, DC, 1985.

Hallmark S. L., N. Hawkins, and O. Smadi. *Evaluation of Dynamic Speed Feedback Signs on Curves: A National Demonstration Project*. Report No. FHWA-HRT-14-020, Federal Highway Administration, Washington, DC, 2015.

Hauer, E., F. J. Ahlin, and J. S. Bowser. Speed Enforcement and Speed Choice. *Accident Analysis & Prevention*, Vol. 14, No. 4, 1981, pp. 267-278.

Institute of Transportation Engineers. *Manual of Transportation Engineering Studies*. Prentice Hall, Englewood Cliffs, NJ, 2010, 2nd Edition.

Knapp, K. K., and F. Robinson. *The Vehicle Speed Impacts of a Dynamic Horizontal Curve Warning Sign on Low-Volume Local Roadways*. Report No. CTS 12-12, 2012, Humphrey School of Public Affairs, University of Minnesota, 96 pp.

Krammes, R., R. O. Brackett, M. Shafer, J. Ottesen, I. Anderson, K. Fink, K. Collins, O. Pendleton, and C. Messer. *Horizontal Alignment Design Consistency for Rural Two-Lane Highways*. Report No. FHWA-RD94-034., Federal Highway Administration, Washington, DC, 1995.

Federal Highway Administration. *Manual on Uniform Traffic Control Devices* (MUTCD). Washington, DC, 2009.

Mahoney, K. M., R. J. Porter, E. T. Donnell, D. Lee, and M. T. Pietrucha. *Evaluation of Centerline Rumble Strips on Lateral Vehicle Placement and Speed on Two-Lane Highways*. Report No. FHWA-PA-2002-034-97-04, Pennsylvania Transportation Institute, Penn State University, University Park, PA, 2003.

Mattox III, J., W. Sarasua, J. H. Ogle, R. T. Eckenrode, and A. Dunning. Development and Evaluation of Speed-Activated Sign to Reduce Speeds in Work Zones. *Transportation Research Record: Journal of the Transportation Research Board, No. 2015*, Transportation Research Board of the National Academies, Washington, DC, 2008, pp. 3–11.

Molino, J. A., B. Katz, and M. B. Hermosillo. *Simulator Evaluation of Low-Cost Safety Improvements on Rural Two-Lane Undivided Roads: Nighttime Delineation for Curves and Traffic Calming for Small Towns*. Report No. FHWA-HRT-09-061. Federal Highway Administration, McLean, VA, 2010.

Monsere, C., C. Nolan, R. Bertini, E. Anderson, and T. El-Seoud. Measuring the Impacts of Speed Reduction Technologies: Evaluation of Dynamic Advanced Curve Warning System. *Transportation Research Record: Journal of the Transportation Research Board, No. 1918*, Transportation Research Board of the National Academies, Washington, DC, 2005, pp. 98–107.

Montella, A., F. Galante, F. Mauriello, and L. Pariota. Effects of Traffic Control Devices on Rural Curve Driving Behavior. *Transportation Research Record: Journal of the Transportation Research Board, No. 2492*, Transportation Research Board of the National Academies, Washington, DC, 2015, pp. 10–22.

National Highway Traffic Safety Administration. *Traffic Safety Facts 2015*. Report No. DOT HS 812 384, US Department of Transportation, Washington, DC, 2015.

Permanent International Association of Road Congresses. *Road Safety Manual – Recommendations from the World Road Association*. 2003.

Poe, C. M., J. P. Tarris, and J. M. Mason. *Operating Speed Approach to Geometric Design of Low-Speed Urban Streets*. Report No. PTI 9606, Pennsylvania Transportation Institute, Penn State University, University Park, PA, 1996.

Porter, R. J., E. T. Donnell, and K. M. Mahoney, *Evaluation of effects of centerline rumble strips on lateral vehicle placement and speed. Transportation Research Record: Journal of the Transportation Research Board, No.1882*, Transportation Research Board of the National Academies, Washington, DC, 2004, pp.10-16.

Preston, H., and T. Schoenecker. *Potential Safety Effects of Dynamic Signing at Rural Horizontal Curves*. Report No. MN/RC-2000-14, University of Minnesota, 1999.

Santiago-Chaparro, K. R., M. Chitturi, A. Bill, and D. Noyce. Spatial Effectiveness of Speed Feedback Signs. *Transportation Research Record: Journal of the Transportation Research Board, No. 2281*, Transportation Research Board of the National Academies, Washington, DC, 2012, pp. 8-15.

Smadi, O., N. Hawkins, S. Knickerbocker, S. Hallmark, and A. Pike. *Evaluation of the Sequential Dynamic Curve Warning System: Final Report.* Report No. FHWA-15-CAI-012-B. Federal Highway Administration, Washington, DC, November 2015.

Snedecor, G. W., and W. G. Cochran. *Statistical Methods*, *8th Edition*. Iowa State University Press, Ames, IA, 1989.

Sun, C., P. Edara, Y. Hou, and A. Robertson. Safety Evaluation of Sequential Warning Lights in Tapers at Nighttime Work Zones. *Transportation Research Record: Journal of the Transportation Research Board, No. 2272*, Transportation Research Board of the National Academies, Washington, DC, 2012, pp. 1–8.

Taragin, A., and J. E. Leisch. Driver Performance on Horizontal Curves. *Proceedings of the 33rd Annual Meeting of the Highway Research Board*, Washington, DC, 1954, pp. 446-466.

Tribbett, L., J. Mounce, and P. McGowen. *An Evaluation of Dynamic Curve Warning Systems in the Sacramento River Canyon.* Western Transportation Institute, Montana State University, Bozeman, MT, April 2000.

Vest, A., S. Nikiforos, A. Clayton, and J. Pigman. *Effect of Warning Devices on Curve Operating Speeds.* Report No. No. KTC-05-20/SPR-259-03-1F, Kentucky Transportation Center, Lexington, KY, 2005, 44 pp.

Winnett, M. A., and A. H. Wheeler. *Vehicle-activated Signs: A Large-scale Evaluation*. Report No. TRL548, Department of Transport, UK, 2002.

FHWA, Office of Safety
Joseph Cheung

202-366-6994

joseph.cheung@dot.gov

FHWA-SA-18-075