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16. Abstract This report is a compilation of research papers written by students participating in the 2012 Undergraduate Transportation Scholars Program. The 10-week summer program, now in its 22nd year, provides undergraduate students in Civil Engineering the opportunity to learn about transportation engineering through participating in sponsored transportation research projects. The program design allows students to interact directly with a Texas A&M University faculty member or Texas A&M Transportation Institute researcher in developing a research proposal, conducting valid research, and documenting the research results through oral presentations and research papers. The papers in this compendium report on the following topics: 1) Analysis of Factors Influencing Run-off Road Crashes on Horizontal Curves; and 2) Impact of Nighttime Work Zone Lighting on Motorists' Detection of Objects.			
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**COMPENDIUM OF STUDENT PAPERS:
2012 UNDERGRADUATE
TRANSPORTATION SCHOLARS PROGRAM**



(left to right) Ms. Brook Ullman (Mentor), Amelia Celoza (Student),
Dr. H. Gene Hawkins (Program Director), Kayla Weimert (Student), and Ms. Melisa Finley (Mentor)

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PREFACE

The Southwest Region University Transportation Center (SWUTC), through the Transportation Scholars Program, the Texas A&M Transportation Institute (TTI) and the Zachry Department of Civil Engineering at Texas A&M University, established the Undergraduate Transportation Engineering Fellows Program in 1990. The program design allows students to interact directly with a Texas A&M University faculty member or TTI researcher in developing a research proposal, conducting valid research, and documenting the research results through oral presentations and research papers. The intent of the program is to introduce transportation engineering to students who have demonstrated outstanding academic performance, thus developing capable and qualified future transportation leaders.

In the summer of 2012, the following students and their faculty/staff mentors were:

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Amelia Celozza
Arizona State University, Phoenix, AZ

Kayla Wimert
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Ms. Brook Ullman

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Sincere appreciation is extended to the following individuals:

- Mrs. Cathy Bryan, who assisted with program administrative matters and in the preparation of the final compendium.

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Analysis of Factors Influencing Run-off Road Crashes on Horizontal Curves

by Amelia Celozza.....1

Impact of Nighttime Work Zone Lighting on Motorists' Detection of Objects

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Analysis of Factors Influencing Run-off Road Crashes on Horizontal Curves

Prepared for
Undergraduate Transportation Scholars Program

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August 3, 2012



STUDENT BIOGRAPHY

Amelia Celozza is a senior at Arizona State University in Tempe, Arizona. She is majoring in civil engineering with a minor in mathematics. She will graduate in May 2013 with a Bachelor of Science in Engineering. She is a student in Barrett, The Honors College and completed her honors thesis in the spring 2012 semester, which focused on sustainability in transportation policies and programs and their applications in the Phoenix Metropolitan Area. Amelia was awarded the Sharon D. Banks Memorial Undergraduate Scholarship by the Phoenix Metropolitan Chapter of Women's Transportation Seminar in 2012.

Amelia is actively involved in many student organizations at Arizona State University, including American Society of Civil Engineers, the Institute of Transportation Engineers, Tau Beta Pi, and Chi Epsilon. She has previous work experience with the City of Scottsdale's Department of Planning, Neighborhood, and Transportation where she worked with engineers and planners to serve the residents of Scottsdale. Amelia plans to pursue graduate school in civil engineering.

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The research described in this paper was conducted as part of Project 0-6714, Surface Treatments to Alleviate Crashes on Horizontal Curves, sponsored by the Texas Department of Transportation (TxDOT). The research activities were conducted in support of the Undergraduate Transportation Scholars Program. The findings and recommendations included in this paper are based on the student's summer activities. They should be considered preliminary and not as representative of the findings and recommendations of the parent project. This paper has not been reviewed or approved by the sponsor. The contents of this paper reflect the views of the author, who is responsible for the facts and the accuracy of these data presented herein. The contents do not necessarily reflect the official view or policies of TxDOT.

The author would like to express her appreciation to Mr. Michael Pratt, P.E., and Dr. Srinivas Geedipally, P.E., for their contributions in data collection and analysis.

SUMMARY

Horizontal curves play an important role in roadways and highways as they allow vehicles to turn gradually; however, they can present many safety challenges. Horizontal curve characteristics, such as radius and superelevation rate, affect drivers' ability to safely negotiate curves. Traffic control devices, surface treatments, pavement markings, and geometric improvements can be implemented to reduce crash rates on horizontal curves. Run-off road (ROR) crashes are of significant concern to researchers as half of all fatal crashes on horizontal curves were ROR crashes.

Two sets of data were collected with the first describing high ROR crash locations in Texas and the other describing control locations that were randomly chosen. Researchers collected data related to geometric, cross section, traffic control and other treatments, and crash characteristics on horizontal curves. These sets were compared to identify factors affecting ROR crashes on horizontal curves. Researchers identified radius, deflection angle, shoulder width, and lane width as factors affecting ROR crash rates. Radius and deflection angle describe a curve's severity, with a large radius and small deflection angle indicating a less severe curve. Less severe curves are easier for drivers to negotiate and are associated with lower ROR crash rates. Wider shoulder widths and lane widths allow for drivers to correct mistakes while traversing curves. Additionally, wider shoulder widths provide more distance between opposing traffic on divided highways. Similarly, wider lane widths provide more distance between opposing traffic on undivided highways. Both wider shoulder widths and lane widths are associated with lower ROR crash rates.

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INTRODUCTION

Horizontal curves play an important role in roadways and highways as they allow vehicles to turn gradually; however, they can present many safety challenges. Characteristics of horizontal curves, such as radius and design speed greatly affect safety. Research conducted on roadway departure or run-off road (ROR) crashes in Texas shows that the average crash rate on horizontal curves is double that of the rate on tangent segments (1). Furthermore, in 2009 the Federal Highway Administration (FHWA) reported that roadway departure crashes accounted for 53 percent of fatal crashes in the United States. Safety concerns stem from a driver's ability or inability to detect a curve, judge the sharpness of a curve, and negotiate the curve by traveling at the appropriate speed.

Pavement markings and signs, surface treatments, and geometric improvements serve as safety improvements on horizontal curves. These improvements increase the margin of safety of horizontal curves, which relates the supply and demand of side friction. Pavement markings and signs indicate the presence and sharpness of a curve, surface treatments increase the supply of side friction, and geometric improvements include straightening the curve, increasing the radius, or increasing superelevation rate, which decrease the side friction demand.

This research examined the influence of horizontal curve characteristics on crash rates. Identifying the influence of geometric factors on horizontal curve crash rates allows targeted safety measures to be implemented to attempt to decrease crash rates. This project related to its parent project, Surface Treatments to Alleviate Crashes on Horizontal Curves, Texas Department of Transportation (TxDOT) 0-6714, because it fulfilled the objective that focuses on identifying factors that influence ROR crashes. The next steps of this project include identifying potential surface treatments and conducting field tests. The last objective focuses on developing guidelines for implementing surface treatments and other traffic control devices.

To conduct this research, a database of curves was assembled. The first set of data in this database consisted of horizontal curves that were chosen based upon four considerations: ROR crash rate, total crash rate, ROR crash count, and total crash count. The second set of data consisted of a set of randomly chosen curves to be used as a base comparison of curve factors. These two sets of curves were combined to identify factors related to run-off road crash rate or severity. The parent research project will benefit from the identification of factors and subsequent surface treatments can be identified and field-tested. This will result in a set of guidelines describing when it is appropriate to implement surface treatments or traffic control devices.

BACKGROUND

Horizontal curves change the alignment or direction of a roadway. Horizontal curves connect two tangent segments of a roadway and allow vehicles to gradually turn rather than making a sharp turn. Degree of curvature, curve length, and deflection angle describe the physical characteristics and the geometry of horizontal curves and these characteristics play a key role in safety. Traffic control characteristics, such as speed limit and advisory speed, also affect safety.

Many elements affect horizontal curve safety, including physical characteristics and operational factors. Physical characteristics describe geometric design, including degree of curvature and curve length. Operational factors describe driver behavior, perceptions, and reactions to the roadway. Centripetal force acts on vehicles traversing horizontal curves. This force is counteracted by the side friction provided by the roadway surface. If there is not enough side friction available to a vehicle traveling along a curve, vehicles can depart from a travel lane, often leading to ROR crashes.

Horizontal Curve Design

The American Association of State Highway Transportation Officials (AASHTO) provides agencies with a guide to designing curves in *A Policy on Geometric Design of Highways and Streets (Green Book)*. This guide describes the design of horizontal curves as a relationship between speed, side friction, superelevation rate, and degree of curvature as described below in Equation 1 (2).

$$f_D = \frac{v^2}{gR} - \frac{e}{100} \quad (1)$$

The variables in this relationship are defined as follows:

- f_D = side friction demand (lateral acceleration divided by g),
- v = vehicle speed (ft/s),
- g = gravitational constant (= 32.2 ft/s²),
- R = radius (ft), and
- e = superelevation rate (%).

When designing horizontal curves, the amount of side friction necessary is often based upon driver comfort levels. This level determines the other factors of horizontal curve design. Additionally, when designing curves, the side friction considered is based upon the worst-case scenario in which worn tires are driven on wet pavement. The reasoning behind this is that the majority of vehicles will not encounter this worst-case scenario and should be able to safely traverse the curve.

Margin of safety in horizontal curves is described as the difference between side friction demand and side friction supply. When the side friction demand exceeds the side friction supply, a vehicle will experience a sliding failure. The side friction demand is based upon the design relationship described above in Equation 1. Side friction supply is affected by tire-pavement interface properties, including tire tread condition, pavement texture, and the presence of environmental or weather conditions, like water or physical contaminants, that can affect the pavement surface (3, 4, 5). Side friction supply can be increased by altering the pavement texture through the use of an overlay and/or increasing the radius and/or superelevation rate.

Driver Behavior

The model used to design horizontal curves is often referred to as the “point-mass model,” illustrated above by Equation 1. This model describes the behavior of a vehicle as if it were a

point traveling along a curve. This model assumes that drivers traverse curves “with geometric exactness,” which is often not the case (5, 6). Steering fluctuations, as well as braking and accelerating through a curve, change variables affecting safety. Steering fluctuations affect the lateral position of a vehicle in a travel lane, changing the effective radius of the travel path, ultimately affecting the relationship between radius, speed, and side friction demand. When a driver brakes or accelerates within a curve, the supply of side friction changes due to the interaction between a vehicle’s tires and the pavement surface. Operator factors must be considered when exploring and evaluating potential safety improvements.

Safety Trends

Current research efforts focus on ROR crashes on horizontal curves because of the disproportionate number of fatal crashes occurring in these locations. According to the Fatality Analysis Reporting System (FARS), of the 38,000 fatal crashes on the U.S. highway system in 2002, approximately 25 percent of them occurred along horizontal curves (7). Additionally, approximately half of all fatal crashes were roadway departure, or run-off road crashes (8).

Previous research conducted found that many ROR crashes resulted from vehicles traveling too fast for the curve or too fast for the weather or roadway conditions of the curve (1). Available safety tools attempt to alleviate these challenges. Geometric improvements, such as curve straightening or increasing radius, make it easier for drivers to negotiate curves. This class of improvements is often expensive and has a possibility of needing to acquire right-of-way. Other improvements include traffic control improvements or surface treatments. Traffic control improvements alert drivers to the presence of a curve. These improvements include curve advisory speed signs, which communicate to drivers the importance of reducing speeds to safely negotiate a curve. Pavement treatments, such as rumble strips or profiled markings, provide drivers with an auditory and tactile warning that their vehicle is departing the travel lane. Additionally, centerlines and edge lines have been proposed as low-cost enhancements to improve safety. Edge lines serve as a pavement marking to “define or delineate the edge of a roadway” and act as a visual reference to prevent motorists from drifting their travel lane (9). Surface treatments increase the amount of side friction present on a curve, increasing the ease of travel for drivers. Appropriate use of these treatments will be determined by the parent project TxDOT 0-6714, Surface Treatments to Alleviate Crashes on Horizontal Curves.

DATA COLLECTION

Two sets of horizontal curves were assembled for analysis. The first consisted of the top 101 curve ROR crash locations in Texas and the second was 400 randomly chosen (“control”) horizontal curves.

Curve Identification

There were multiple tools utilized in identifying curves. District identification numbers associated with a curve indicated which Control Section Map was to be used. The control section number of the roadway containing the curve was used to locate specific roadways on Control Section Maps. The curve was then located in Google Earth. First, a city or town’s name

was used to determine the approximate location of the curve on Google Earth. Then, the curve was located in the Texas Reference Marker (TRM) database using district identification number and control section number. Intersection data for a particular control section were noted to locate an individual curve. Each curve was associated with a milepoint, which indicated its location. Additional intersections on a control section were associated with a milepoint. Using Google Earth's "path measure" tool, the curve was located by starting at a known milepoint at an intersection and proceeding to a curve. A placemark was then put on the curve with the curve identification number. Figure 1 illustrates the top 101 ROR crash locations in Texas. Figure 2 illustrates the additional 400 locations chosen as control locations.

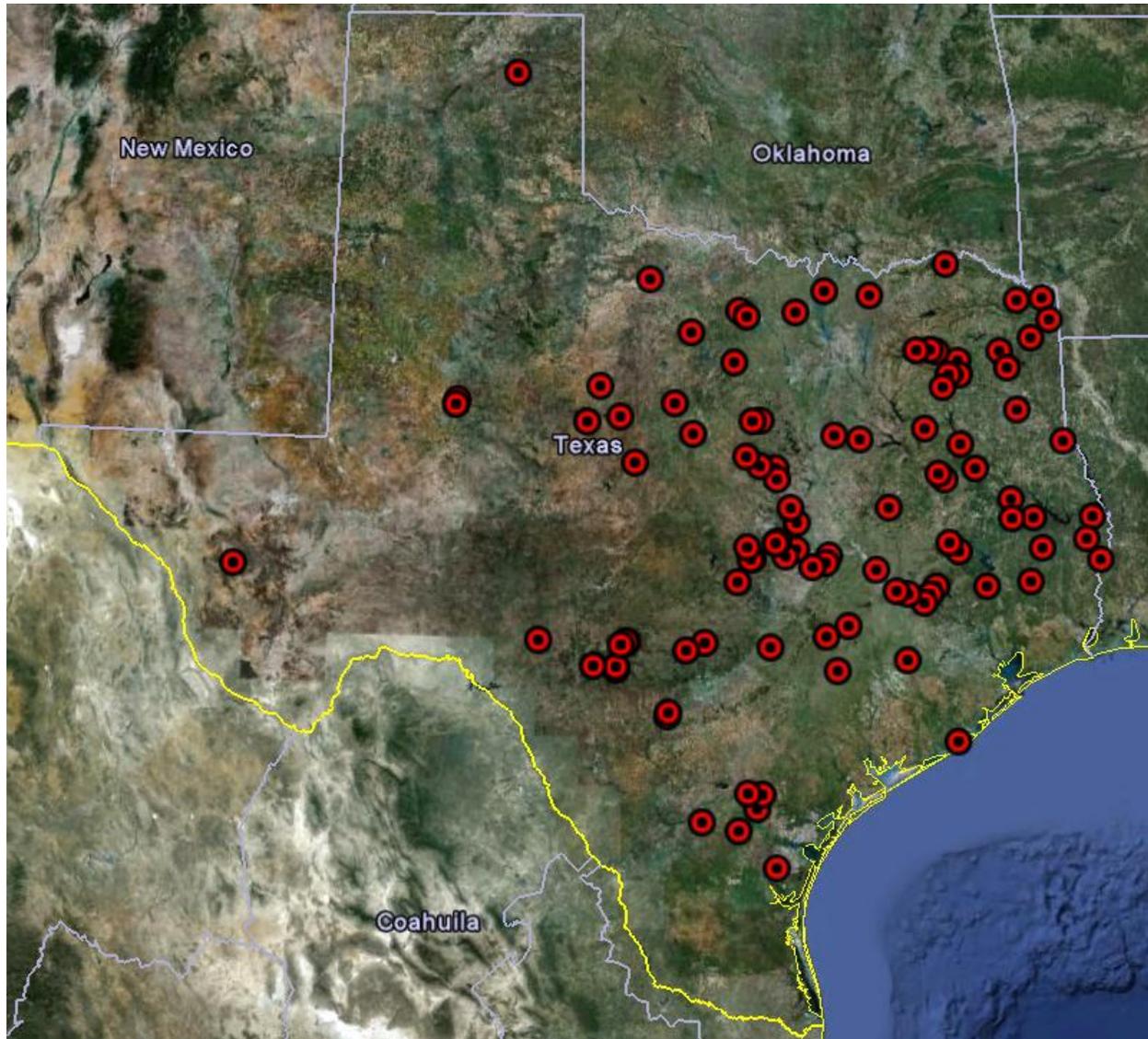


Figure 1. Top 101 ROR Crash Rate Locations.

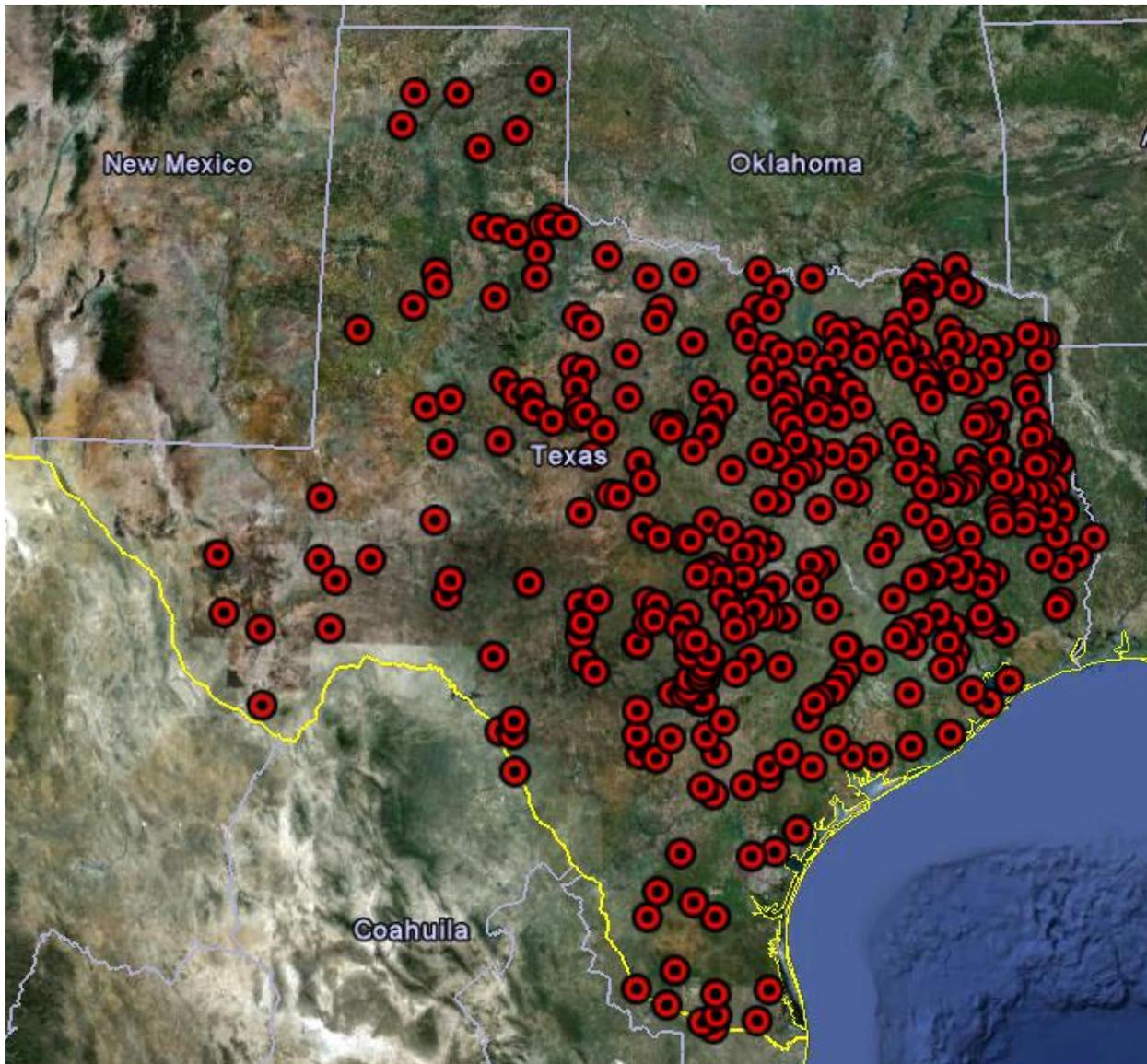


Figure 2. Additional 400 Locations.

Geometric Characteristics

After curves were identified, geometric data were collected. In Google Earth, placemarks were put on specific locations of the curve, starting before the point of curvature and ending after the point of tangency, as illustrated in Figure 3. The file was then saved as .kml with the curve identification number as the file name. A Microsoft Excel program, “Earth Tools,” utilized the placemarks’ latitude and longitude coordinates from the .kml file and calculated the radius, length, and deflection angle.



Figure 3. Google Earth Placemarks.

Cross Sectional Data

Aerial and street view images in Google Earth were used to compile cross sectional data. These data included number of lanes, lane width, and shoulder widths.

Traffic Control and Other Treatments

Traffic control characteristics were found using street view images on Google Earth. These characteristics included regulatory speed limit, curve advisory speed, delineators, Chevrons, Large Arrow Sign, shoulder rumble strips, and centerline rumble strip.

Crash Data

Crash data were retrieved from the Crash Record Information System (CRIS) database. These data consisted of information describing date and location of the crash, severity, weather conditions. These data were from the period of 2007 to 2011.

For this analysis, four crash severity levels were reported and are defined as follows:

- fatal (K),
- incapacitating injury (A),
- non-incapacitating injury (B), and
- minor injury (C).

The CRIS data were linked to the TRM database to obtain the crash counts for each curve of interest. Surface type and traffic volume come from the TRM database. The crash rate is computed using the crash counts from CRIS and the traffic volumes and curve lengths from TRM. The value was calculated using the following equation:

$$Rate = \frac{10^8 \times (\text{Sum of Crashes from 2007 to 2011})}{365 \times \text{Traffic Volume} \times \text{Curve Length}} \quad (2)$$

DATA REDUCTION

Researchers attempted to collect data from 500 sites including geometric, cross section, and traffic control characteristics. However, due to the low quality of aerial images and street view images, some of the curves had incomplete data. Additionally, curves that had a less than 5-degree deflection angle were omitted from analysis. When geometric characteristics were analyzed, 458 sites had the appropriate data available and had a total of 511 crashes, including 306 ROR crashes. For other analyses, complete data were required, so 386 sites were analyzed with a total of 470 crashes, including 272 ROR crashes. Tables 1 through 5 describe the database utilized in subsequent analyses.

Table 1. Sample Size.

	High ROR Crash Locations			Control			Total
	Curves	All Crashes	ROR Crashes	Curves	All Crashes	ROR Crashes	
Complete Data	88	183	158	298	287	113	386
Partial Data	12	34	29	60	7	6	72
Grand Total	100	217	187	358	294	119	458

Table 2. Data Range of Curve Characteristics.

	High ROR Crash Locations		Control	
	Min	Max	Min	Max
Radius (feet)	224	5986	486	40807
Length (miles)	0.10	0.96	0.10	0.47
Deflection Angle (degrees)	5.25	143.90	0.67	95.56
Lane Width (width)	8.40	13.40	8.30	22.95
Shoulder Width (feet)	0	6.95	0	14.10

Table 3. Traffic Control.

	High ROR Crash Locations		Control	
	Present	Not Present	Present	Not Present
Chevrons	24	64	4	84
Delineators	8	79	1	297
Large Arrow	0	88	1	297

Table 4. Count of Locations by Surface Type.

Surface Type	High ROR Crash Locations	Control
2	68	142
3	3	2
4	15	109
5	0	22
6	2	23

Table 5. Presence of Rumble Strips.

	Undivided		Divided	
	High ROR Crash Locations	Control	High ROR Crash Locations	Control
Rumble Strips	0	2	0	27
No Rumble Strips	88	249	0	20
Centerline Rumble Strip	0	3	n/a	n/a

RESULTS

The results are divided into two sections. The first consists of the combined high ROR crash locations and the control locations. This section considers ROR crash rate and a variety of horizontal curve characteristics. The second consists of comparisons between high ROR crash locations and control locations.

Combined Data

This section considers data from a combined set of the high ROR crash locations and the randomly chosen control locations.

Geometric

Geometric characteristics of horizontal curves were compared with crash rates. Crash rates utilized in this analysis relate the overall crash rate with traffic volume and length of curve. Two rates were analyzed: rates of all crashes and run-off road crashes. Figure 4 illustrates that as the radius of curvature increases the crash rate decreases. Making curves less severe by increasing the radius is an option to consider when adequate right-of-way and funds are available. This relationship could also be used to identify curves where the use of traffic control devices or high-friction surface treatments are an appropriate measure to alleviate ROR crashes.

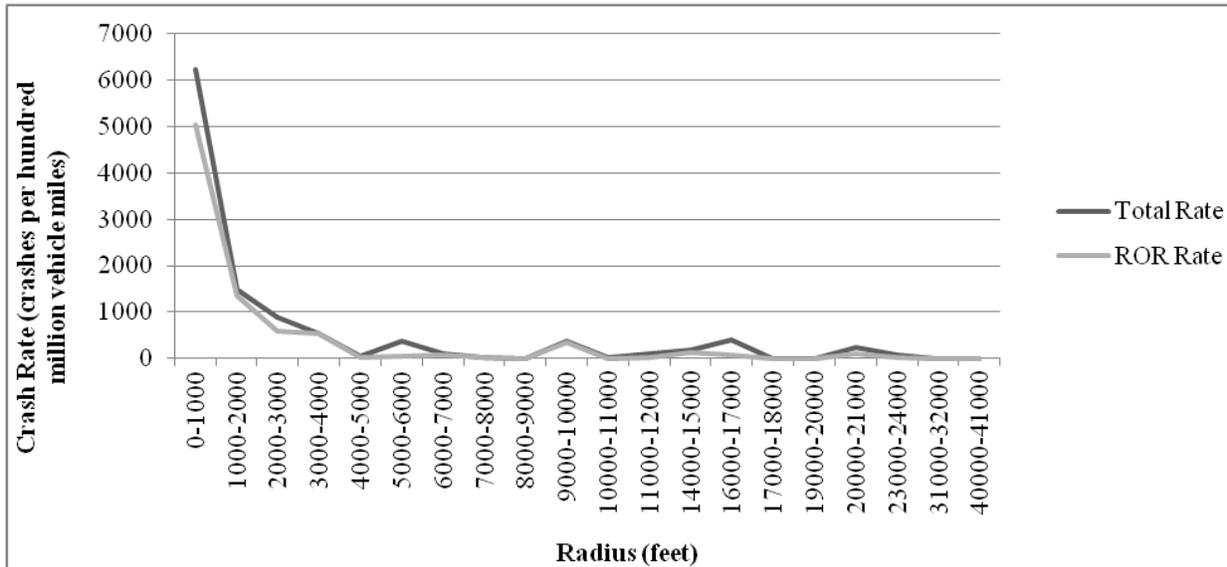


Figure 4. Crash Rate versus Radius.

Figure 5 illustrates the relationship between curve length and crash rate. As the length of the curve increases, crash rate decreases. This trend is consistent with the relationship between crash rate and radius seen in Figure 2 because radius and curve length are directly proportional, as illustrated below in Equation 3:

$$L = \frac{R\Delta\pi}{180} \quad (3)$$

where:

- L = length of curve,
- R = radius, and
- Δ = deflection angle of the curve (degrees).

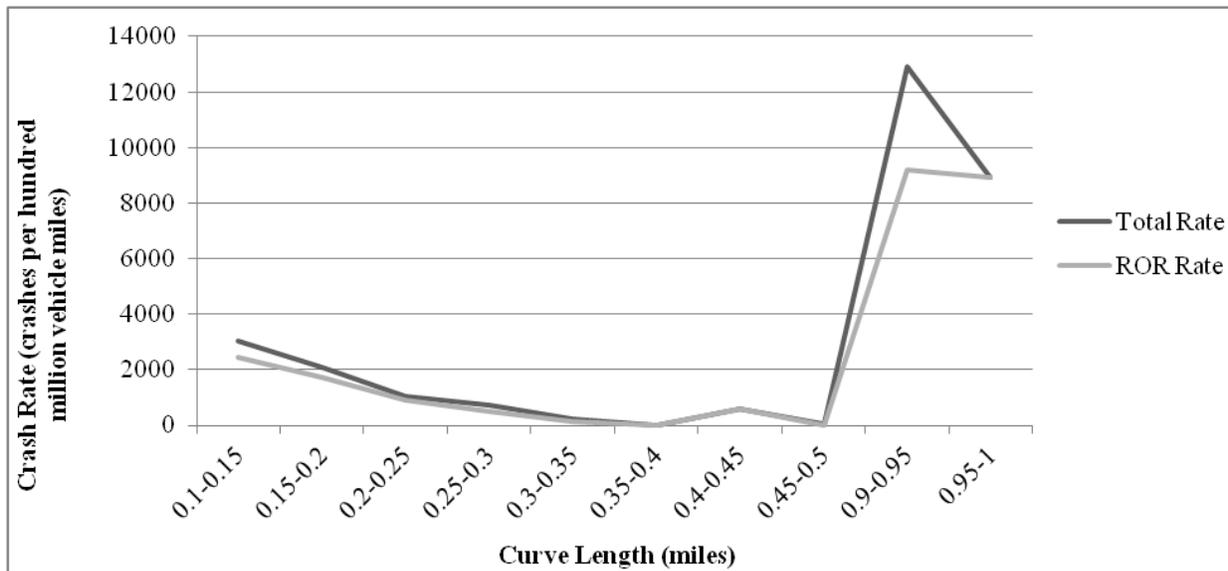


Figure 5. Crash Rate versus Curve Length.

Figure 6 illustrates the relationship between deflection angle and crash rate. This graph shows that crash rates are relatively low when curves have a small deflection angle. A small deflection angle indicates a less severe curve, which is consistent with the relationship between crash rate and radius.

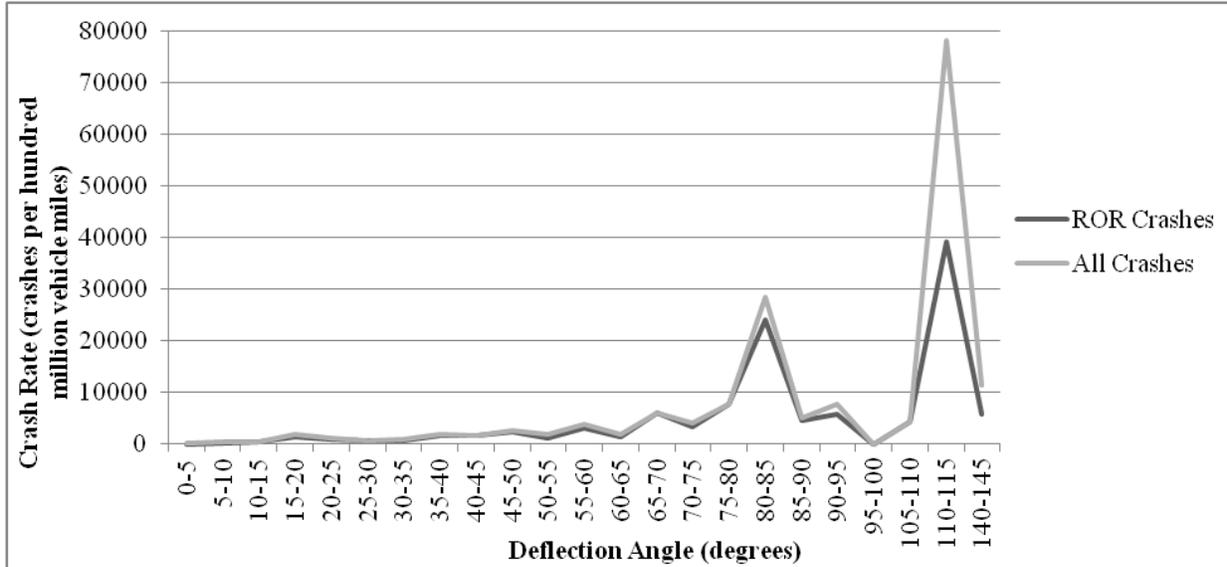


Figure 6. ROR Crash Rate and Deflection Angle.

Cross Section

Cross sectional data were compared to the number and rate of ROR crashes. These characteristics include number of lanes, lane width, and shoulder width.

Figure 7 summarizes the number of ROR crashes by crash rate and average shoulder width. Overall, as the average shoulder width increases, the crash rate decreases. Additionally, higher crash rates are seen more frequently in narrower shoulder widths than in wider ones.

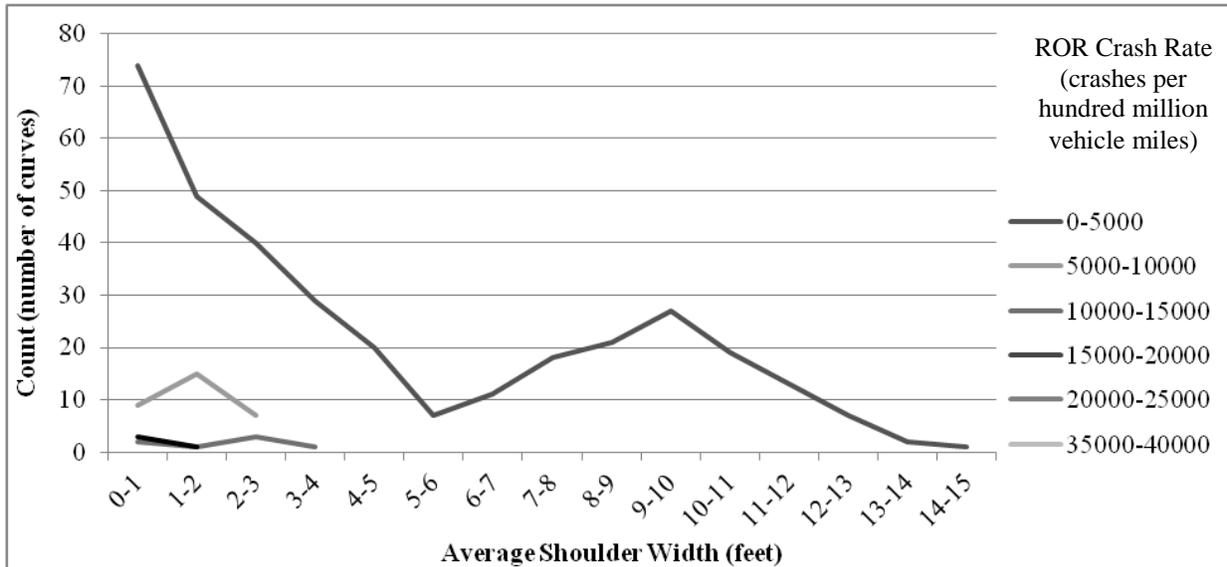


Figure 7. ROR Crash Rate and Average Shoulder Width.

Traffic Control and Other Treatments

Figure 8 illustrates the relationship between ROR crash rates and shoulder rumble strips on divided highways. When comparing ROR crash rate between sites that have and do not have shoulder rumble strips, it can be seen that for crashes of severities A and C that sites with rumble strips have a lower ROR crash rate.

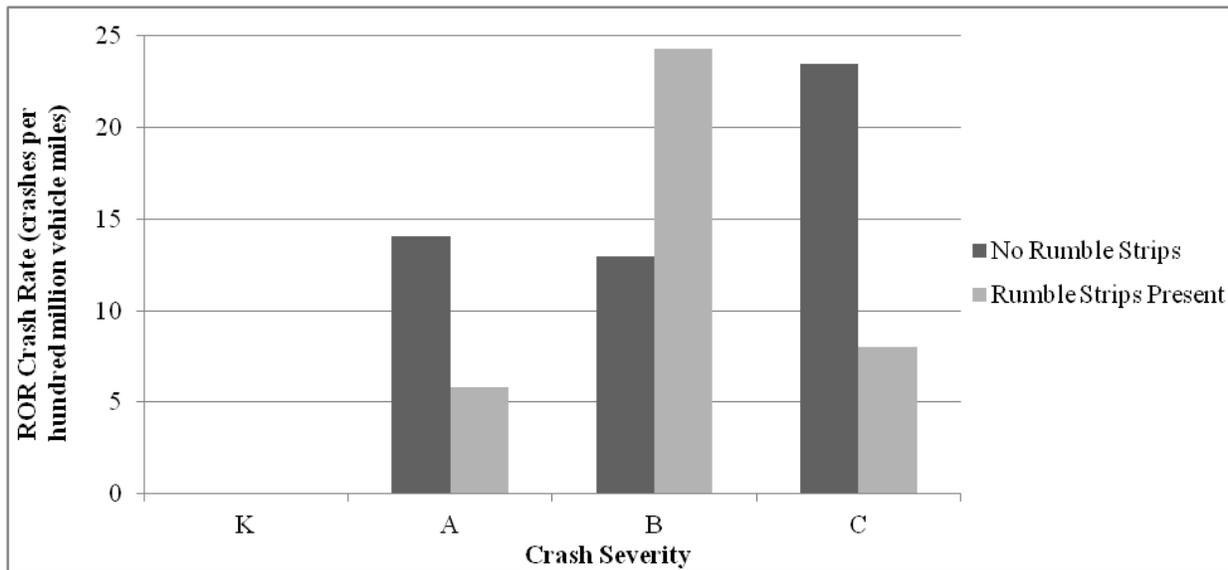


Figure 8. ROR Crash Rates and Shoulder Rumble Strips on Divided Highways.

When investigating the relationship between ROR crash rates and shoulder rumble strips on undivided highways there were no sites with rumble strips present on the outside shoulders, so no comparisons could be made with available data.

Figure 9 illustrates the relationship between ROR crash rate and the centerline rumble strips. It can be seen that the ROR crash rate is significantly higher at sites without a centerline rumble strip.

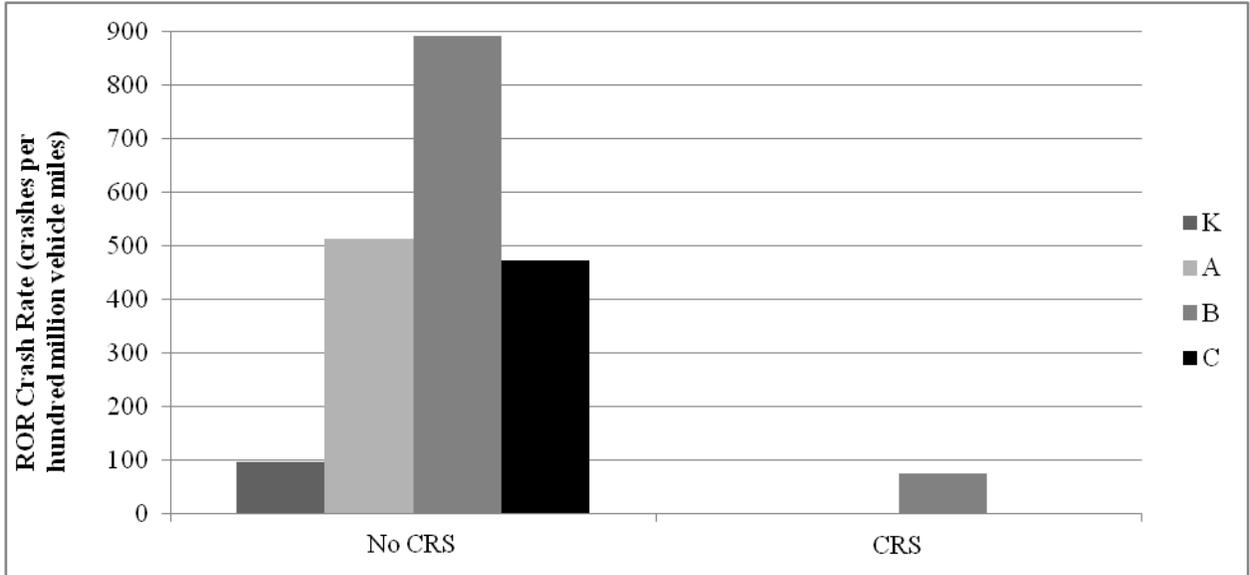


Figure 9. ROR Crash Rate and Presence of Centerline Rumble Strip (CRS).

Figure 10 describes the relationship between ROR crash rate and the presence of Chevrons. Trends present describe the state of the practice where traffic control devices are installed in locations with high crash rates. Further study could explore the effect of these devices on ROR crash rate.

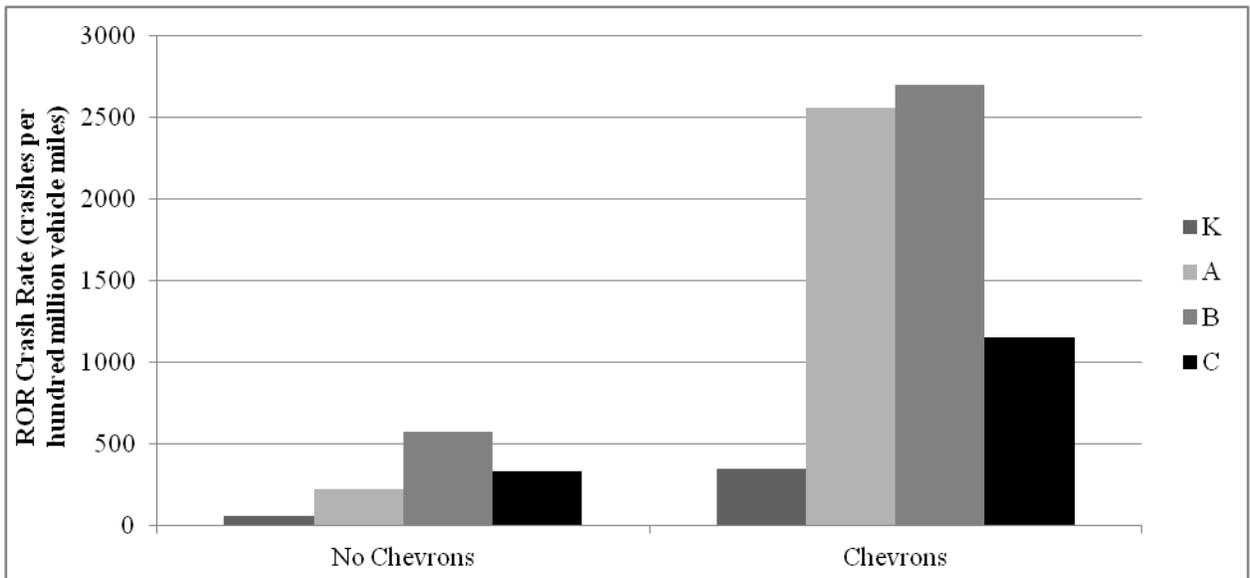


Figure 10. ROR Crash Rate and Presence of Chevrons.

Figure 11 describes the relationship between the presence of delineators and the ROR crash rate. The ROR crash rate for severity K is significantly lower on curves with delineators. This trend is similar to that in Figure 8, which could result from the trend in installing traffic control devices in locations with high crash rates.

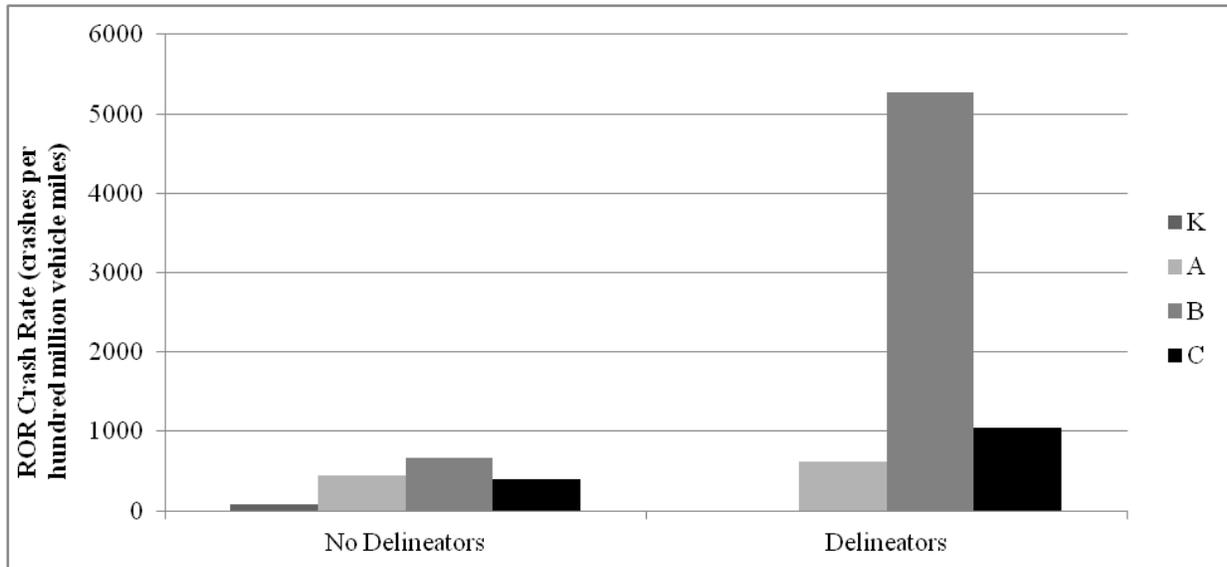


Figure 11. ROR Crash Rate and Presence of Delineators.

Researchers attempted to collect data regarding the presence of arrows. However, there was only one site where an arrow was present, leading to the inability to see any significant trends.

Figure 12 illustrates ROR crash rate by severity according to surface type. Surface types are defined as follows:

- 2 = low type bituminous surface-treated,
- 3 = intermediate type mixed,
- 4 = high type flexible,
- 5 = high type rigid, and
- 6 = high type composite.

ROR crash rate on surface type 5, high type rigid, is low compared to other surface types. Surface type 3 experienced the highest ROR crash rate. Further investigation could focus on the friction provided by different surface types.

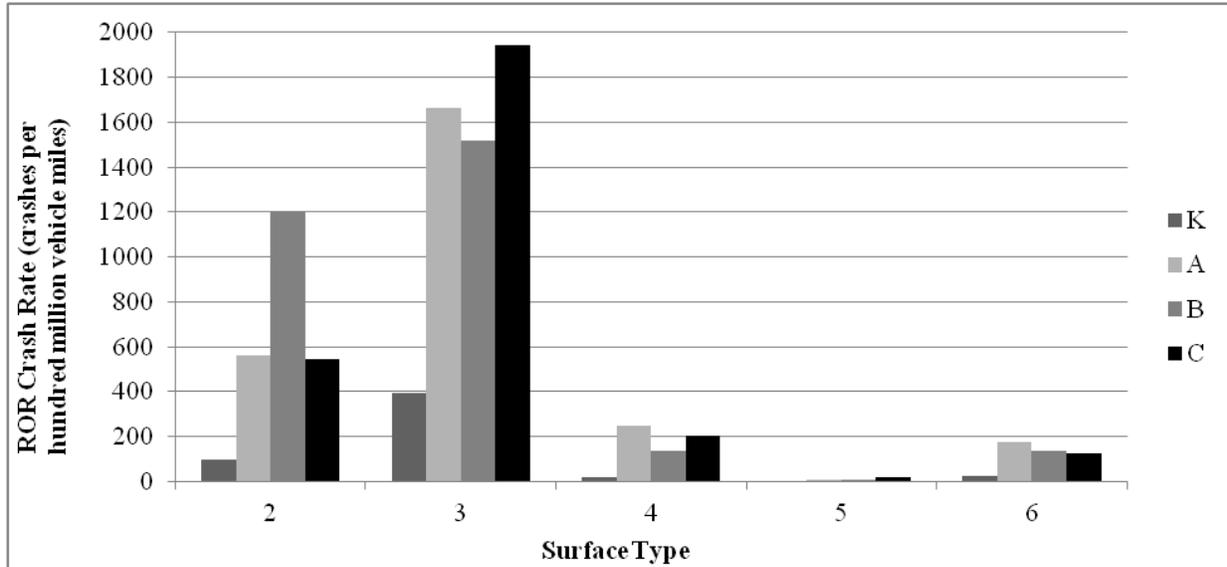


Figure 12. ROR Crash Rate and Surface Type.

Figure 13 illustrates the relationship between ROR crash rate and the speed differential, which is described by the difference between the regulatory speed and the curve advisory speed. When the difference between the regulatory and curve advisory speed is 0 mph, it indicates that no advisory speed is posted preceding the curve.

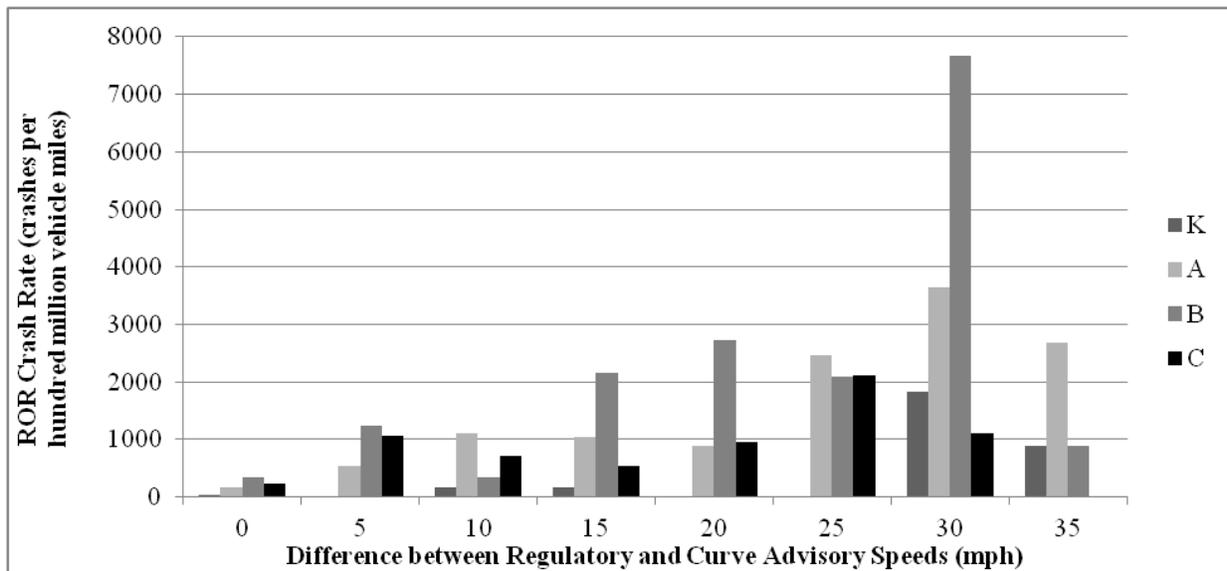


Figure 13. ROR Crash Rate and Speed Differential.

Comparison of High ROR Crash Locations and Control Locations

This section considers the high ROR crash locations and the control locations as separate data sets with the intention of identifying trends specific to the high ROR crash locations.

Geometric

Figure 14 compares high ROR crash locations and control locations based upon radius. It can be seen that high ROR crash locations have a higher percentage of curves with smaller radii. Smaller radii indicate a more severe curve, which present more challenges to drivers attempting to negotiate the curve.

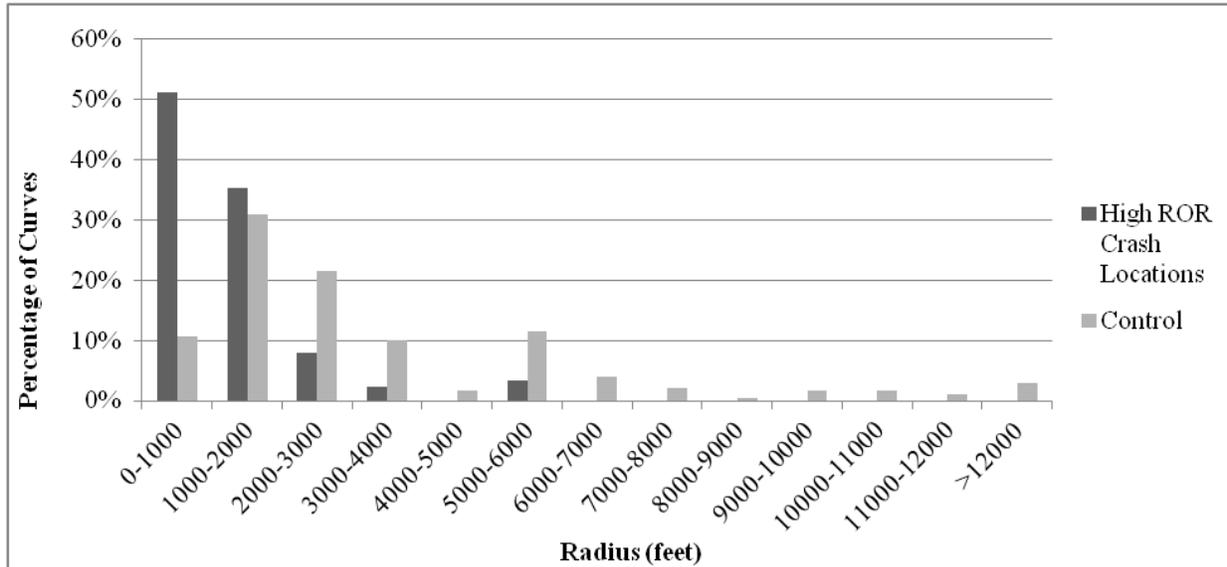


Figure 14. Percentage of Curves and Radius.

Figure 15 compares high ROR crash locations and control locations by deflection angle. The control locations have a higher percentage of curves with small deflection angles. The high ROR crash locations have more curves with a large deflection angle, indicating a sharper curve.

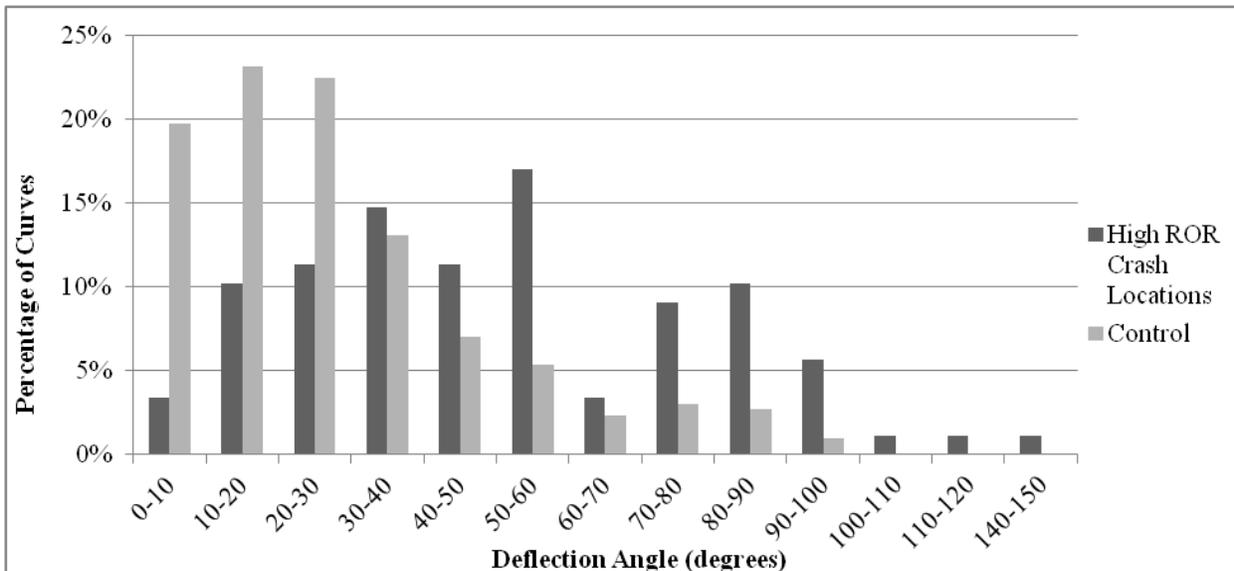


Figure 15. Percentage of Curves and Deflection Angle.

Cross Section

Figure 16 compares high ROR crash locations and control locations by lane width. Both sets follow a similar trend with the control set having slightly wider lanes, as seen in the 12 to 13 foot lane widths. More generous lane widths could allow drivers to correct mistakes. Additionally, on undivided roadways, wider lanes could increase the separation between vehicles in opposing directions.

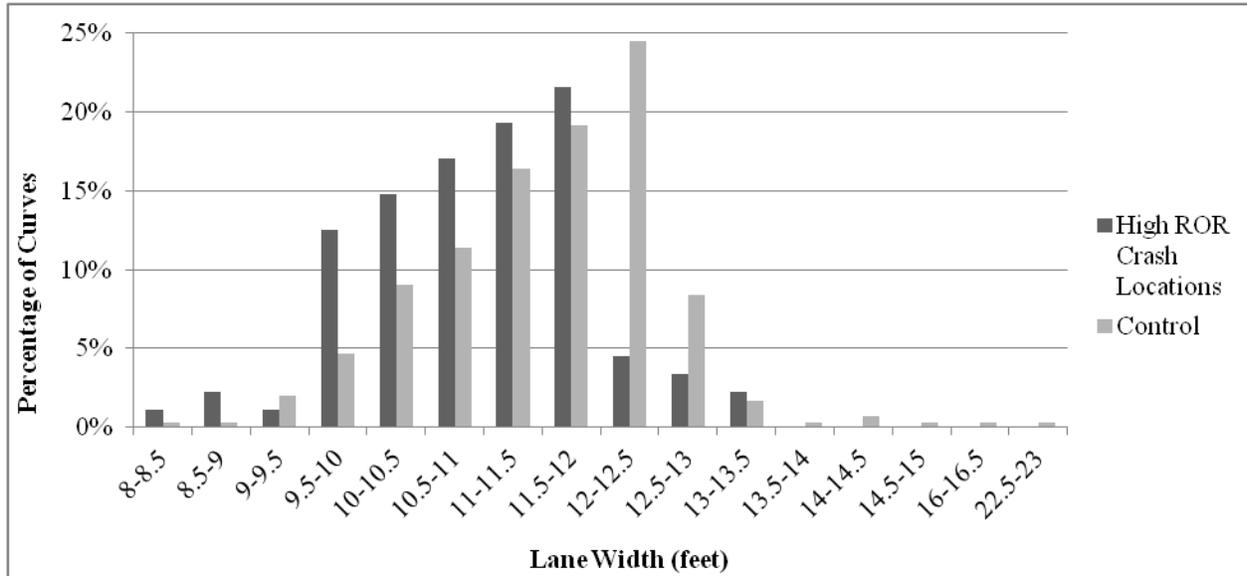


Figure 16. Percentage of Curves and Lane Width.

Figure 17 compares high ROR crash locations and control locations by average shoulder width. The control set has a higher percentage of curves with larger shoulder widths. The wider shoulders allow drivers to return to the lane if they begin to depart the lane. Additionally, on divided highways, wider shoulders allow for more distance between opposing traffic.

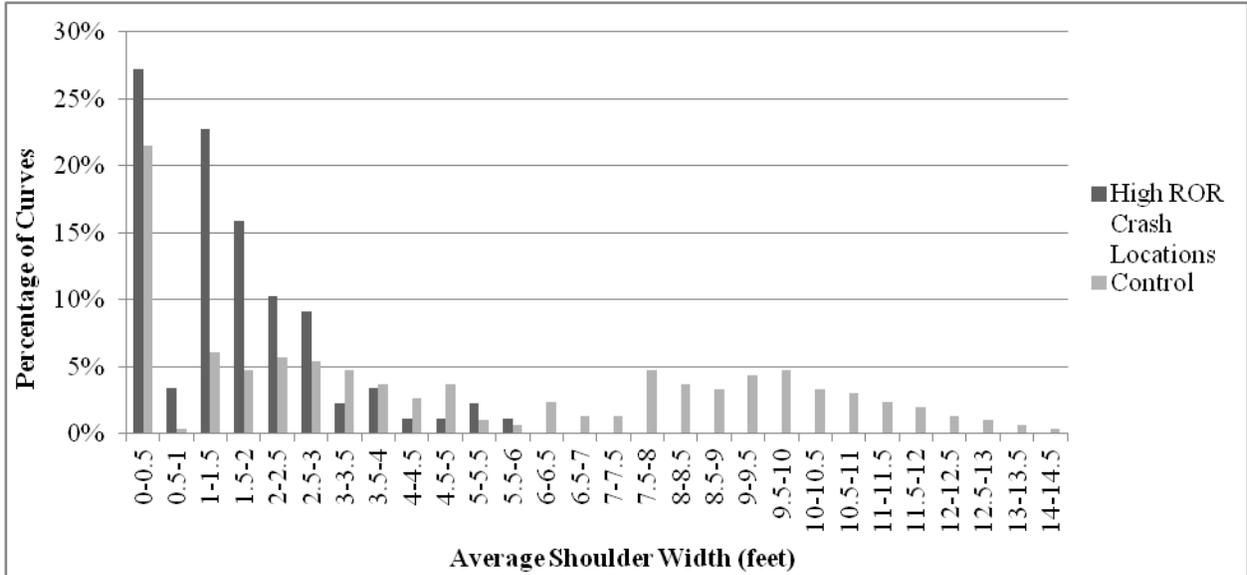


Figure 17. Percentage of Curves and Average Shoulder Width.

Traffic Control and Other Treatments

The only trend identified with comparing the high ROR crash locations and the control locations was that the high ROR crash locations identified for this particular project did not have any rumble strips, neither shoulder nor centerline.

Figures 18 and 19 illustrate the percentage of curves that had Chevrons and delineators, respectively. A higher percentage of high ROR crash locations have Chevrons or delineators than in control locations, which is a trend similar to that seen in Figures 10 and 11. This could indicate that traffic control devices were installed to mitigate high crash rates in these locations.

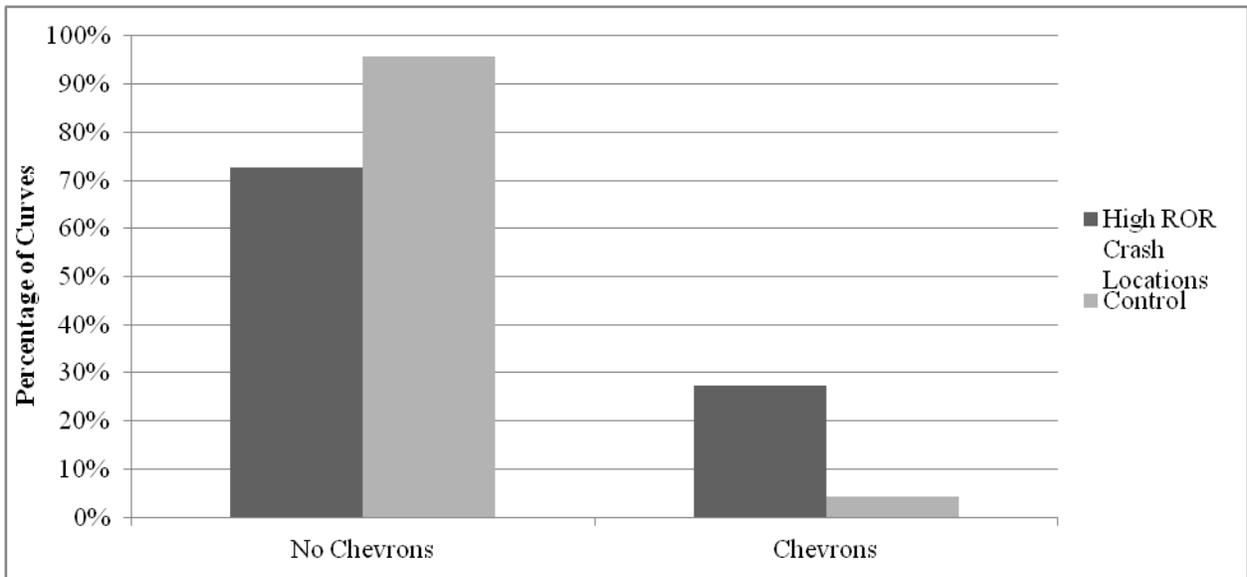


Figure 18. Percentage of Curves and Chevrons.

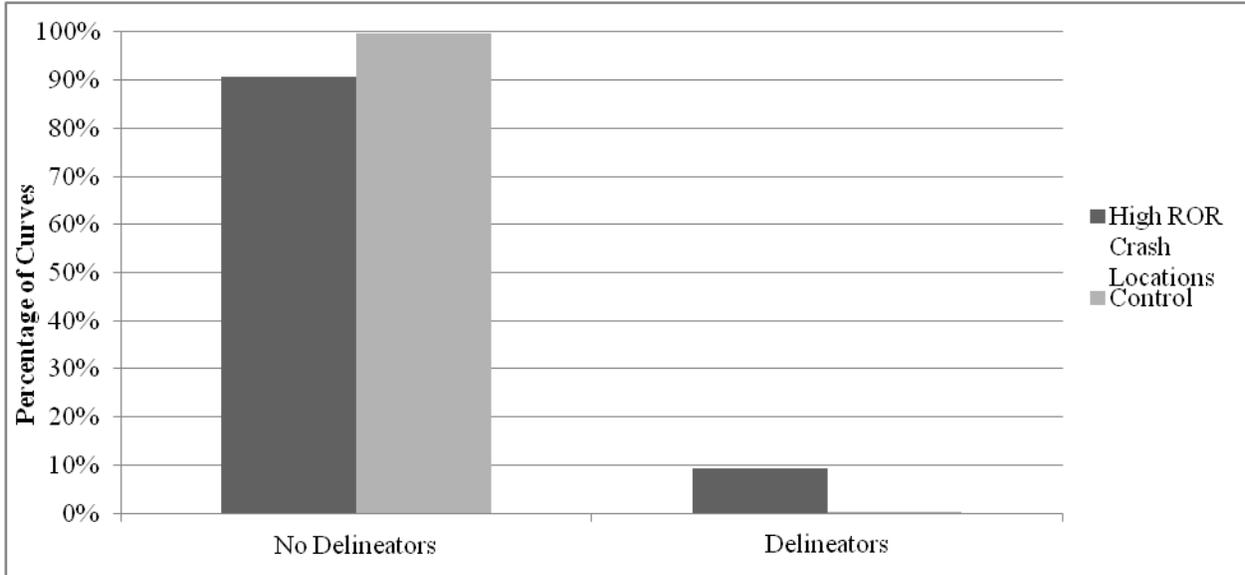


Figure 19. Percentage of Curves and Delineators.

Figure 20 illustrates the difference between regulatory and curve advisory speeds on high ROR crash locations and control locations. A difference of 0 mph indicates that a curve advisory speed was not posted. More curve advisory speed signs are posted on high ROR crash locations. This could result from the high ROR crash rates in these locations and curve advisory speeds were posted to alleviate this problem.

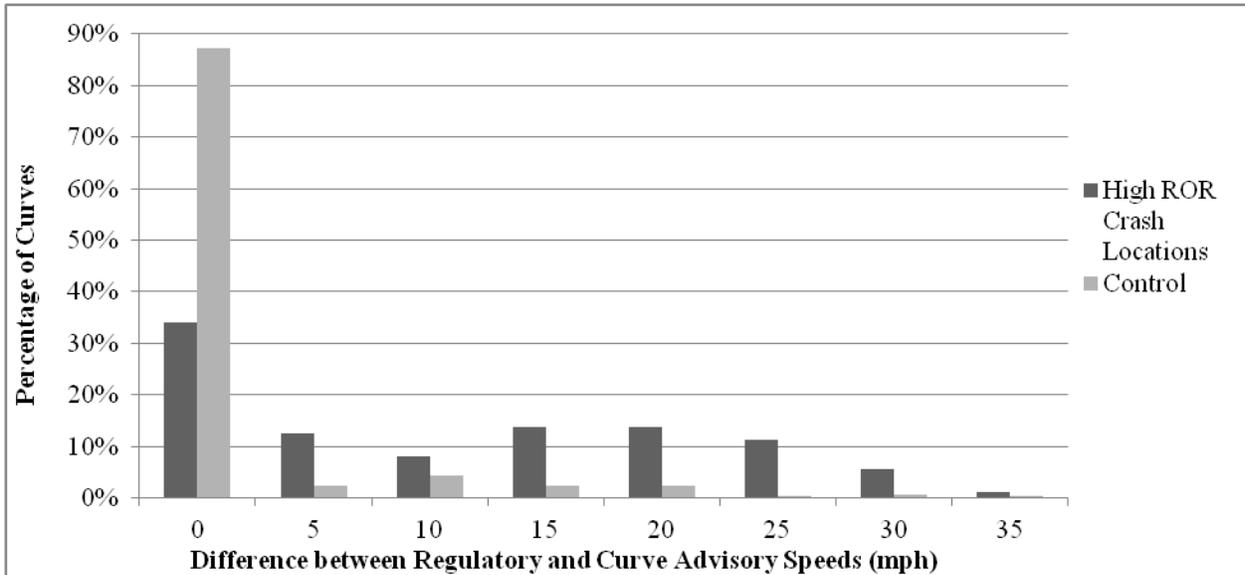


Figure 20. Percentage of Curves and Speed Differentials.

Figure 21 compared crash rates of high ROR crash locations and control locations based upon surface type. A larger portion of high ROR crash locations have surface type 2, low type bituminous surface-treated. Further investigation is necessary to determine the friction supply of these surfaces and to evaluate their effects on ROR crash rates.

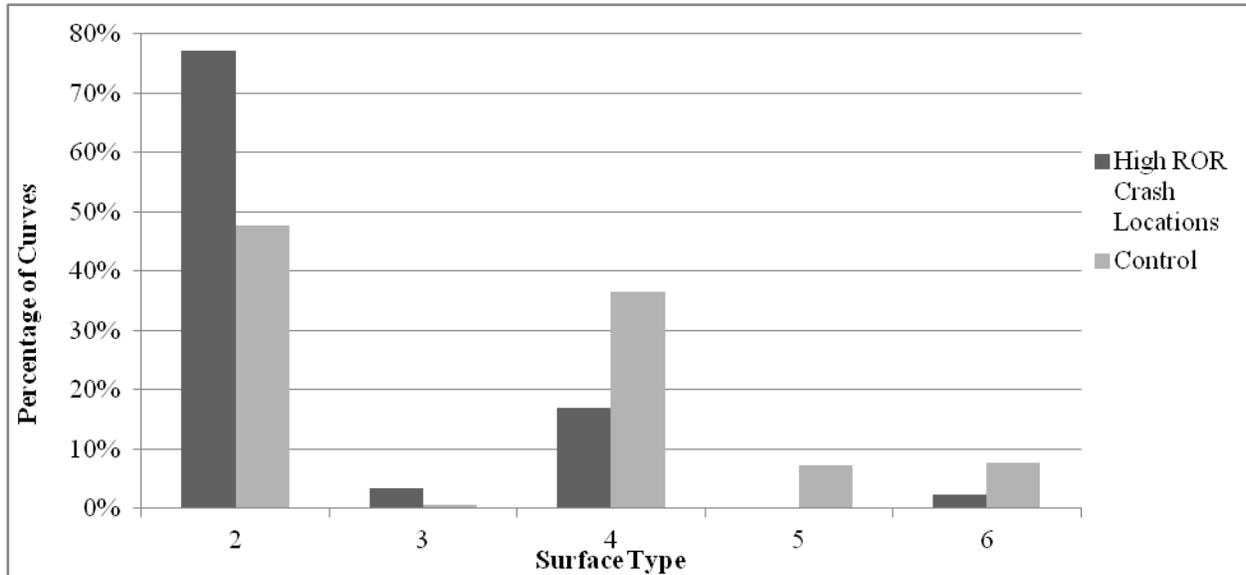


Figure 21. Percentage of Curves and Surface Type.

FINDINGS

This research identified important variables when comparing ROR crash rates on high ROR crash locations and control locations. Radius and deflection angle describe the severity of horizontal curves. Locations with high ROR crash rates had smaller radii and larger deflection angle, indicating a severe curve. The severity of a curve relates to a driver's ability to safely negotiate a curve. The lane width and shoulder widths of the high ROR crash locations and control locations were compared. The lane widths of control locations were than those seen in high ROR crash locations, indicating that more generous lane widths allow drivers to correct mistakes when traveling through a curve. Additionally, wider lane widths on undivided highways allows for more distance between opposing vehicles. Wider shoulders allow for more space to correct mistakes while traveling through a curve. They also allow for more space between opposing vehicles on divided highways.

Further research is necessary to investigate the effects of traffic control devices and the surface type on ROR crash rates. This research indicated that traffic control devices (e.g., Chevrons and delineators) were present on a larger percentage of high ROR crash locations. This could reflect the state of the practice where traffic control devices are installed in locations with high crash rates. Further investigation is needed to assess the effects of these traffic control devices on ROR crash rates. Comparisons between high ROR crash locations and control locations were made based upon surface type. It was seen that more high ROR crash locations had surface type 2, low type bituminous surface-treated. Additional data regarding surface type and available friction supply could aid researchers in identifying possible treatments to alleviate ROR crashes on horizontal curves.

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Impact of Nighttime Work Zone Lighting on Motorists' Detection of Objects

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STUDENT BIOGRAPHY

Kayla Weimert is a senior at Norwich University located in Northfield, Vermont. She will be graduating in May 2013 with a Bachelor of Science in Civil Engineering and a Bachelor of Science in Architecture.

Kayla is a national member of the American Society of Civil Engineers (ASCE) as well as a member of the Norwich University student chapter where she is currently serving as President. Additionally, Kayla is an active member of Tau Beta Pi and the Society of Women Engineers (SWE) at her university. Service to others is important to Kayla; Habitat for Humanity is an organization she devotes time to, helping with the local chapters as well as the Norwich University student chapter.

After graduation, Kayla plans to earn a Master's degree in hopes to one day design structures for extreme weather and disastrous conditions.

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The author would like to express her appreciation to both Melisa Finley and Jeff Miles for their guidance during the course of this research effort.

SUMMARY

Construction work along high volume roadways is performed during night hours to reduce traffic delays and congestion; however, nighttime construction presents safety concerns for both the workers and the passing motorists. Lighting in these nighttime work zones is one of the most important aspects as it affects both the workers and motorists.

Utilizing human subjects, researchers conducted a closed-course study at Texas A&M University (TAMU) Riverside campus to evaluate the impact of various nighttime work zone lighting conditions on a motorist's ability to detect objects in the work area. Objects ranged from low contrast objects that simulated debris commonly found in work zones to a high contrast worker. The objects were presented under two temporary work zone lighting conditions: a portable

balloon light and a portable light tower. Global Positioning System (GPS) data were collected to determine the motorists' detection distances for each object in the different lighting conditions.

As expected, the high contrast worker was detected far sooner than any of the low contrast objects. Analysis was done separately on the high contrast and low contrast objects to determine the specific impact of the lighting conditions. The type of light used, the travel direction of the vehicle, and the position of the object under the light all contributed to the ability to detect the objects. It was determined that traveling in the direction of the light tower presented a glare that impeded a motorist's ability to detect the objects in certain positions, but the contrast created between the objects and the background typically surpassed that of the balloon light. While the balloon light provided consistent detection distances through the varying scenarios, the light tower tended to allow for higher detection distances in the region where most work would take place.

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INTRODUCTION

Construction and maintenance work along high-volume roadways is becoming more prominent in the nighttime hours. While nighttime work can reduce daytime travel congestion and delays and provide other benefits, there are certain safety concerns and issues surrounding nighttime work zones. Lighting is one of the most important factors for nighttime construction as it affects motorist and worker safety, quality of work, productivity, and worker morale.

Current guidelines set in place for work zone lighting mostly consider the visual needs of the workers, but fail to recognize the issues that pertain to the needs of the motorists. Research has not been done to evaluate the impact of work zone lighting on motorists approaching and driving through the work zone. Utilizing a closed-course of various simulated work zone lighting conditions, the following research was conducted to determine the extent of the impact of nighttime work zone lighting on a motorist's ability to detect objects before, in, and after a work zone.

BACKGROUND INFORMATION

This section provides information necessary to further understand the research that was conducted.

Parent Project

This research is a component of a larger project sponsored by the Texas Department of Transportation (TxDOT), Assessment of the Impact of Nighttime Work Zone Lighting on Motorists (Project 0-6641). The goal of the project is to develop work zone lighting guidelines for nighttime operations with considerations of both motorists and workers. The project began in September 2010 and is scheduled for completion in August 2012.

A field study was conducted in reference to this research project in the summer of 2011. In the field study, TTI staff members collected photometric data, as well as data that tracked the eye of participants, and measured participants' pupil size. Based upon that study, it was recommended that the simulated nighttime work zones for the closed-course study consist of lighting that produced vertical illuminance levels:

- from approximately 0 to 20 lux, and
- that reach or exceed 60 lux.

The field study also indicated that the study should be designed in such a way that participants go into and out of several dark and lit sections.

Lighting Design Criteria

The quality of light represents the ability of observers to identify contrast differences and enables them to detect objects quickly, accurately, and comfortably. Quality of lighting is dependent upon illuminance, uniformity, luminance, and glare.

Illuminance represents the quantity of lighting. It is the amount of light falling on a surface, and is measured in either lux (lx) or footcandles (fc). Illuminance may be increased by increasing the intensity of a light source, increasing the number of light sources, or decreasing the distance of light sources from the surface area (1).

Uniformity identifies how evenly the light reaches the different parts of the target areas. The uniformity of illuminance is defined as the ratio of the average or maximum illuminance to the minimum illuminance over the work area. The average to minimum ratio is considered to be more practical for highway construction work areas since lighting is usually directed toward the pavement to avoid causing glare to workers and motorists; thus, yielding higher maximum to minimum ratios that do not practically represent the uniformity of the lighting in nighttime construction zones (1).

Luminance is the measure of light reflected from a surface (e.g., the pavement) and is the quantitative measure of brightness. It is expressed in candelas per square meter (cd/m²) or foot lamberts. Object luminance depends on several factors including quantity of light reaching the object, reflection characteristics of the object, relative angle of incidence, and location of the observer (1).

Glare occurs when the illuminance in the visual field is significantly greater than that to which the eyes are adapted. Glare can be direct (i.e., a light source shining directly into the eye) or reflected off the visual task being performed (i.e., the pavement). There are two types of glare: discomfort and disability. Discomfort glare is measured subjectively and has no direct effect on vision. In contrast disability glare effectively reduces contrast and thus the visibility of objects (1).

Types of Work Zone Lighting

Generally, work zone illumination is provided by three types of lighting systems: temporary (fixed) systems, portable systems, or equipment-mounted systems. Temporary (fixed) systems use existing or temporary poles to mount standard roadway lighting luminaires such that the entire work zone area is lit. Temporary systems allow luminaires to be uniformly spaced at relatively high mounting heights that result in a uniform lighting with low glare (2).

Portable systems, including trailer-mounted light towers, combine the luminaire, power supply, and pole into one device that can be easily moved from one location to another. The spacing, positioning, and low mounting height (12 to 30 feet) of portable systems can result in very non-uniform illumination and severe glare hazard (2).

Equipment-mounted systems offer better mobility and are useful to increase the level of lighting in front of or behind equipment. Required brackets and hardware to mount the lighting fixtures on equipment should be designed so that light fixtures can be aimed and positioned as necessary to reduce glare and provide the required illuminance (2).

Another type of lighting recently available for nighttime highway construction and maintenance activities is balloon lights. Typically, these lights are attached to towers, but can also be mounted on equipment. Balloon lights have been used to help control glare by distributing the brilliance of visible light (i.e., luminous flux) over a relatively large area (1).

The type of work zone illumination used is dependent upon the duration of work activity and geometric constraints. Geometric constraints include limited or no shoulders, bridges, working adjacent to open lanes of traffic, horizontal and vertical curvature, and intersections. Glare to motorists is an issue especially when the work activity is adjacent to open lanes of traffic.

GOALS AND OBJECTIVES

The goal of the research was to determine if and to what extent nighttime work zone lighting impacts a motorist's ability to detect objects along the side of the road. To achieve this goal, the following objectives were considered:

- conduct a controlled field study using human subjects,
- analyze data to determine detection distances of various objects,
- assess the impact of nighttime work zone lighting on a motorist's ability to detect objects, and
- develop recommendations for work zone lighting based on the results of the study.

DATA COLLECTION

The study took place on a closed-course located at the Texas A&M University (TAMU) Riverside Campus (Figure 1). This section describes the participants, treatments, and data collection process.



Figure 1. TAMU Riverside Campus.

Participants

Researchers collected data for 30 participants from the Bryan/College Station, Texas, area. Participants varied in gender and represented two age groups: 18 to 34 and 55 and up. Typically, around the age of 55, the deteriorating effects of age on eyesight have set in, whereas at ages 18 to 34, eyesight is less impacted by age-related phenomena. Thus, these two age groups represent the two extremes with regard to eyesight. However, each individual's eyesight within an age group can vary dramatically. Some of the ways age affects eyesight include slowed vision, meaning it will take longer for the eye to focus on objects, visual scanning becomes difficult due to it taking longer to focus, the pupil gets smaller so less light reaches the retina, and near-vision declines. Generally, distance vision is slower to change (3).

Treatments

Participants were asked to identify four objects that were located 2 feet from the edge line of the simulated roadway: a gray visibility target (7 in × 7 in x 0.5 in), a brown box (6.5 in × 12 in × 9.25 in), a tire (75 R15, 27 in diameter), and a construction worker. The gray visibility target, small brown box and tire represented low contrast debris that may be found in a work area (Figure 2). Using three low contrast objects also reduced the learning effect. The construction worker, consistently dressed in blue scrubs, a Class 3 Level 2 vest and no hardhat (Figure 3), represented the worst case scenario of a human in the work zone.



Figure 2. Low Contrast Objects (Target, Box, Tire).



Figure 3. High Contrast Worker.

Three lighting conditions were set up on the course on separate runways: a dark region (no lights), a portable, trailer-mounted light tower, and a portable balloon light. The dark condition provided data regarding detection distances with only the vehicle's headlights and thus was considered the base condition. As discussed previously, balloon lights evenly distribute light over a large area and help reduce glare (Figure 4). In order to produce an intentional glare situation, the portable light tower was aimed down the simulated roadway in the southbound direction (Figure 5). Participants drove both northbound and southbound along the course past both temporary work zone lighting conditions. For the portable light tower this allowed participants to be driving with the direction of the lights (southbound, no glare) and opposite of the direction of the lights (northbound, glare).

Under each temporary work zone lighting condition, there were three possible positions for the objects: position 1, 2, and 3. Figure 6 and Figure 7 show the locations of these three positions with respect to the lights for the balloon light and portable light tower, respectively. Position 2 was located near the light where there was an illuminance level of approximately 54 lux because it is the minimum illuminance level required for general construction and maintenance work, according to the National Cooperative Research Program (NCHRP) Project 5-13 (2). Position 1 and position 3 were placed where the illuminance level was only approximately 2 lux as these locations represented the far reaches of the light where participants would be entering and leaving the lit area.

Since the balloon light provided a more uniformly distributed light, position 1 and position 3 were positioned at equal distances from the light support (60 feet). With the portable light tower, however, the light was angled in such a way that resulted in position 1 being much closer to the portable light tower than position 3 (10 feet and 165 feet, respectively).



Figure 4. Northbound Approach to Balloon Light.



Figure 5. Southbound Approach to Portable Light Tower.

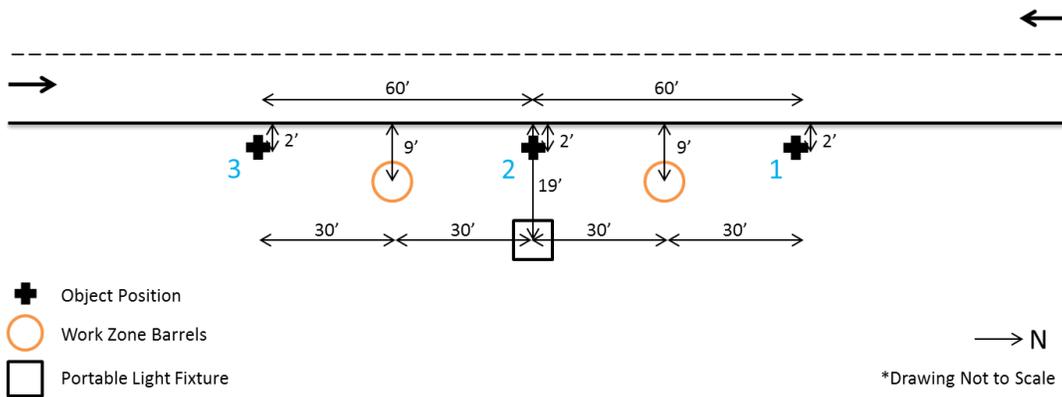


Figure 6. Dimensions and Layout for Balloon Light.

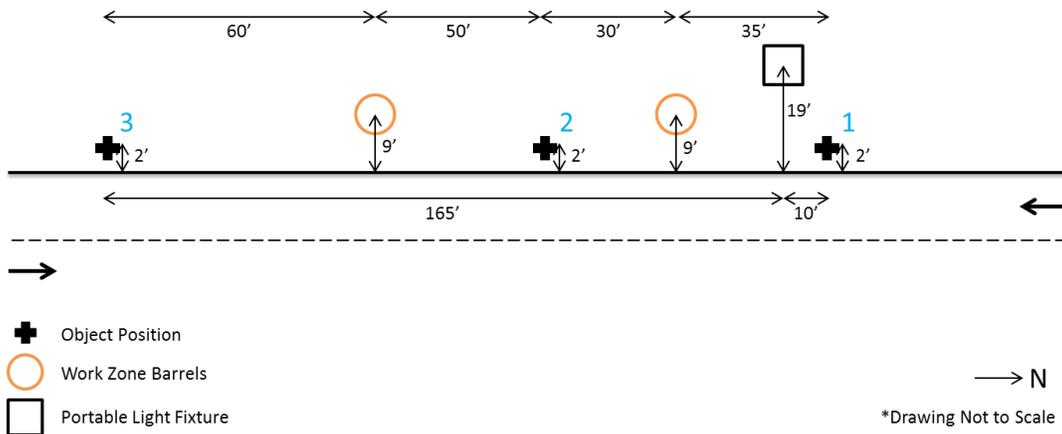


Figure 7. Dimensions and Layout for Portable Light Tower.

Overall, there were 52 treatments used, separated into three treatment orders. Each treatment order consisted of the four base treatments (dark conditions) and 16 different temporary work zone lighting treatments. To reduce learning effects and to keep the duration of the study reasonable, each participant saw only one treatment order.

Vehicles and Instrumentation

The study utilized two state-owned vehicles, both 2009 Ford Explorers, with the headlights aimed according the manufacturer's instructions. A Global Positioning System (GPS) was mounted on the windshield and connected to a laptop with data collection software. A researcher was present in the back seat of the vehicle at all times with two primary goals: 1) safely navigate each subject through the course, and 2) operate the data collection equipment during testing. Using an ASCII tag system in the software, the researchers indicated when the participant began a course run and when the participant identified an object.

Photometric Data

Each night, at the beginning of the study, illuminance measurements were taken at each of the three positions for each lighting condition. The averages and standard deviations of the illuminance values collected each night of the study are shown in Table 6. As previously stated, when the object was placed at the light, the illuminance value should have been approximately 54 lux; however, due to natural conditions that changed from night to night (e.g., wind), the actual values for each position 2 varied. The illuminance value at each position 1 and 3 also varied from the planned 2 lux.

Table 6. Illuminance.

Light Type	Location	Average	Standard Deviation
Portable Light Tower	Position 1	2.93	1.37
	Position 2	49.30	4.46
	Position 3	2.41	0.33
Portable Balloon Light	Position 1	2.09	0.11
	Position 2	65.07	2.30
	Position 3	2.14	0.13

Study Approach

Upon arrival at Riverside Campus, each participant checked in and a briefing took place. A researcher then presented the participants with an explanation of the study, including what objects they were looking for, and asked them to read and sign an informed consent document. Participants then had their visual abilities assessed through three tests: visual acuity, contrast sensitivity, and color blindness. Participants were then informed they would be driving a state-owned vehicle equipped with instrumentation that allowed researchers to measure various

driving data, but operated and drove like a normal car. Each participant was then escorted to the vehicle by a researcher.

Once in the vehicle, the researcher checked that all equipment was powered on and running properly, and went over more detailed directions. Participants were asked to verbally state out loud as soon as they could correctly identify an object. Participants were informed that if they realized they misidentified an object, they should restate the correct object as soon as they noticed. In addition to identifying the objects, participants were asked to rate how easy or hard it was to identify the object correctly on a scale of 1 to 5, where 1 was very easy, 3 was neither easy nor hard, and 5 was very hard. The researcher marked the participant's response on a standard data collection sheet, while also noting any other relevant comments or explanations the participants offered. After reviewing the instructions, the researcher directed the participant toward the course. Participants drove the vehicles at approximately 40 mph.

Two participants, one in each vehicle, drove through the course simultaneously; one after another, with designated points in the course for each vehicle to stop, and allow the other vehicle to complete a run. The study began with the base treatments. The base treatments presented each object without any additional temporary work zone lighting. Participants were asked to detect and identify each object with just the vehicle's headlights, which remained on low beams for the entire study. After the base treatments, the participants were directed toward the first lit treatment. The participants continued through a series of lit treatments, which varied in object, light type, and travel direction. When completed with the 16 lit treatments, the researcher asked the participant final, follow-up questions about the different lighting conditions.

DATA REDUCTION AND ANALYSIS

While a participant drove through the course, the researcher in the vehicle used the ASCII tag system in the GPS software to indicate when the participant began a course run and when the participant identified an object. After the study was completed, all GPS data collected were imported into. In the spreadsheet, data were reduced to the points of interest—any point marked with an ASCII tag.

Utilizing the GPS software, researchers drove through the course once, marking from the start of each lap to each object position under the temporary work zone lights and under the dark condition. These data were reduced as well and used to determine the actual travel distance between the lap start and each position. Detection distances were calculated by subtracting the distance between the start to the identification of the object from the distance between the start to the actual object position.

For analysis, researchers considered one response variable (detection distance) to assess the impact of the temporary work zone lighting scenarios studied. Since the base treatments were all located in the dark (one light type) and did not include multiple positions, researchers used the object variable as the only factor. For the lit treatments, the factors included in the analyses were light type and object position. Researchers did not consider travel direction as a separate factor since they intentionally designed the portable light tower to produce glare in one direction, but not the other. Instead, travel direction was incorporated into the light type factor yielding four

light types: balloon northbound, balloon southbound, light tower northbound, and light tower southbound. For the lit treatments, the three object positions were at, before, and after the temporary work zone lighting.

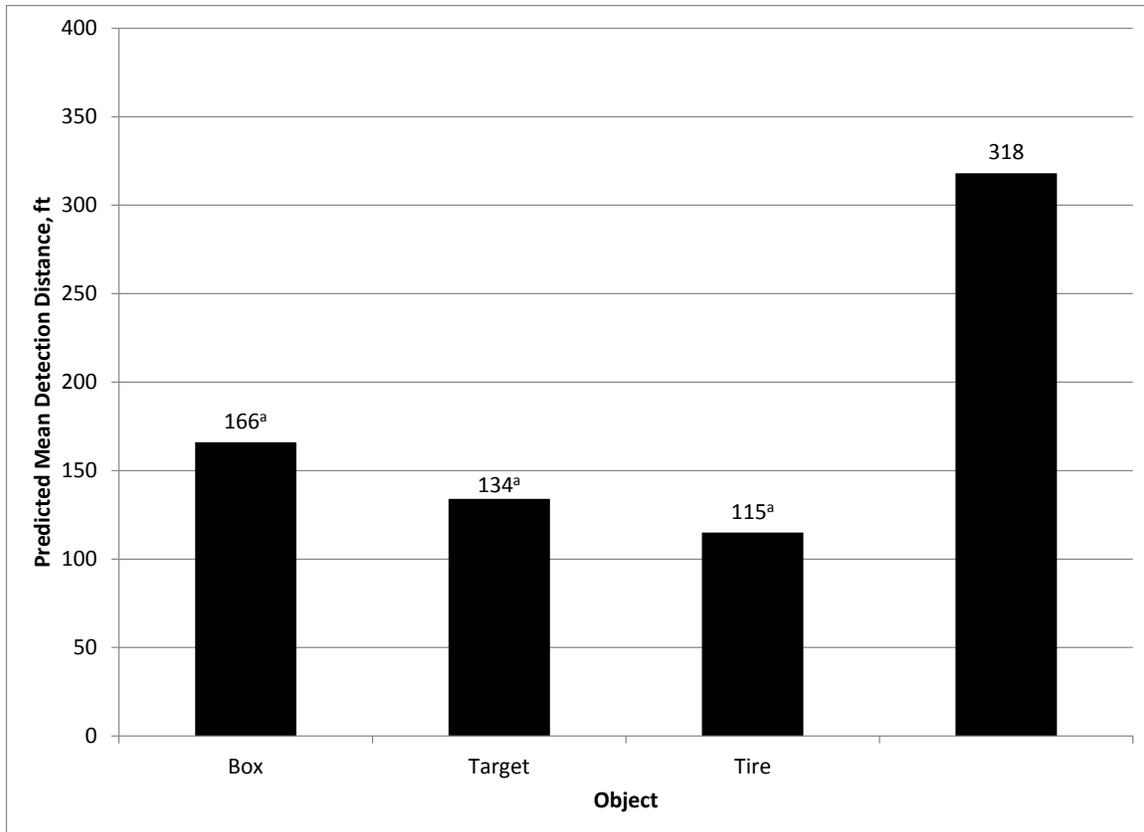
Researchers initially fit a model with all main effects and possible two-way interactions. While researchers did not design the study to investigate the impact of the demographic variables (gender and age), they were considered in the model for completeness. As expected, gender was not found to be a significant factor and thus was removed from the final models. Aware of the fact that older adults typically have shorter detection distances than younger adults due to age-related effects on eyesight, researchers considered age group (18 to 34 and 55 plus) as a covariate factor. This allowed researchers to adjust the results for the potential difference among the age groups, which could influence the response variable, before the start of the experiment. A 5 percent significance level ($\alpha=0.05$) was used for all statistical analyses.

RESULTS

This section describes the results and analyses of the different treatments. Researchers used the predicted values (estimated marginal means) for the mean detection distances to compare different treatments. When there are multiple factors in the model, it is not fair to make comparisons between raw cell means in data because raw cell means do not compensate for other factors in the model. The estimated marginal means are the predicted values of the response variable for each level of a factor that have been adjusted for the other factors in the model.

Base Treatments

Each participant started the study with the base treatments. In these scenarios, the only light surrounding the objects was that contributed by the vehicle headlights. The statistical analysis results showed that the main effect (i.e., object) was statistically significant ($\alpha=0.05$). As shown in Figure 8, the predicted mean detection distances for the box, target, and tire were consistently lower and significantly different than the mean detection distances for the worker. Due to the retroreflective components of the vest, this difference was expected. Since no significant differences were found among the three low contrast objects, the further lighting analyses were separated into a high contrast (worker) and a low contrast (box, target, and tire) group.



^a The box, target, and tire treatments were significantly different from the worker treatment.

Figure 8. Mean Detection Distances for Base Treatments.

Worker Treatments

The statistical analysis results showed that light type and object position, as well as the two-way interaction between these main effects were statistically significant ($\alpha=0.05$) for the worker (high contrast) treatments. Based on these data, researchers further examined the interaction of the two main effect variables.

The balloon light provides an evenly distributed light for the surrounding area. For this reason, it was expected that the travel direction would have little effect on the detection distance. Figure 9 shows the predicted mean detection distances for each position under the balloon light based on travel direction and the predicted mean detection distance for the dark treatment. At each position, the difference in the predicted mean detection distance for each travel direction varied by up to approximately 150 ft (or 2.5 seconds traveling at 40 mph). However, there were no significant differences in the predicted mean detection distances between the two directions, verifying the expectations. Although the contribution from headlights differed with travel direction, the impact was minimal compared to the light distribution from the balloon light. General trends show that the at position, which was under the light (position 2), yielded the longest detection distances. The after and before positions produced similar mean detection distances; however the mean detection distances for the before position were slightly less since the worker was backlit in this position (i.e., negative contrast), so detection relied more heavily

on the headlights. Overall, at each position, the predicted mean detection distances under the balloon light were all longer than in the dark scenario, showing that the balloon light did increase the detection distance of the worker.

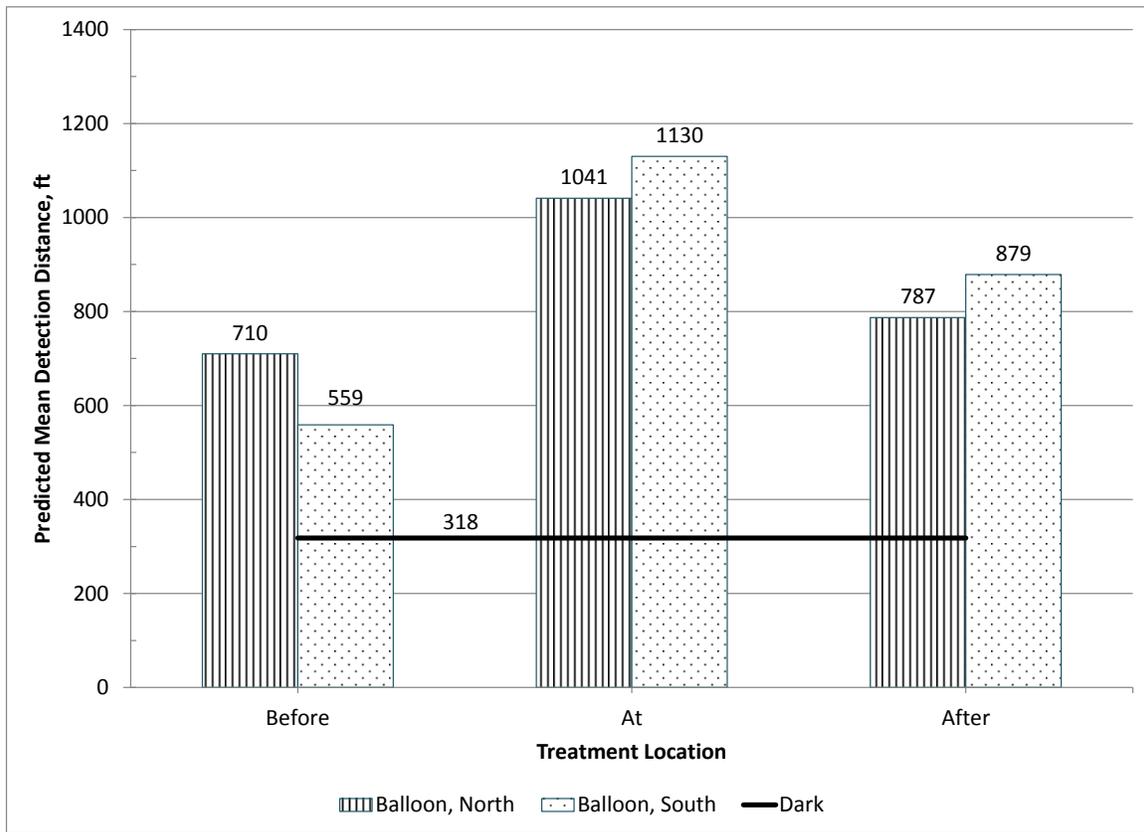


Figure 9. Mean Detection Distances for Worker, Balloon Light Treatments.

As expected, with the light tower travel direction had a larger impact on the predicted mean detection distances (Figure 10). When traveling northbound, participants drove into the light or intentional glare. This glare was not present when traveling southbound as the participants were driving in the same direction as the light. Due to the impact of glare, the detection distances when traveling north were consistently shorter than the detection distances obtained when traveling south (differences of approximately 300 ft or 5 seconds traveling at 40 mph). While these larger differences in the predicted mean detection distances were not found to be statistically significant, the trend does show the impact of glare throughout the simulated work area. Because of the angled nature of the light tower, the predicted mean detection distances at the before were the longest and became shorter as participants progressed through the simulated work area (decreasing by about 470 ft). At each position, the predicted mean detection distances under the light tower were all longer than in the dark scenario, except for light tower in the northbound direction after the light. So while most light tower scenarios increased the detection distance of the worker above the dark condition, at the location immediately following the light that produced glare the predicted mean detection distance was practically the same.

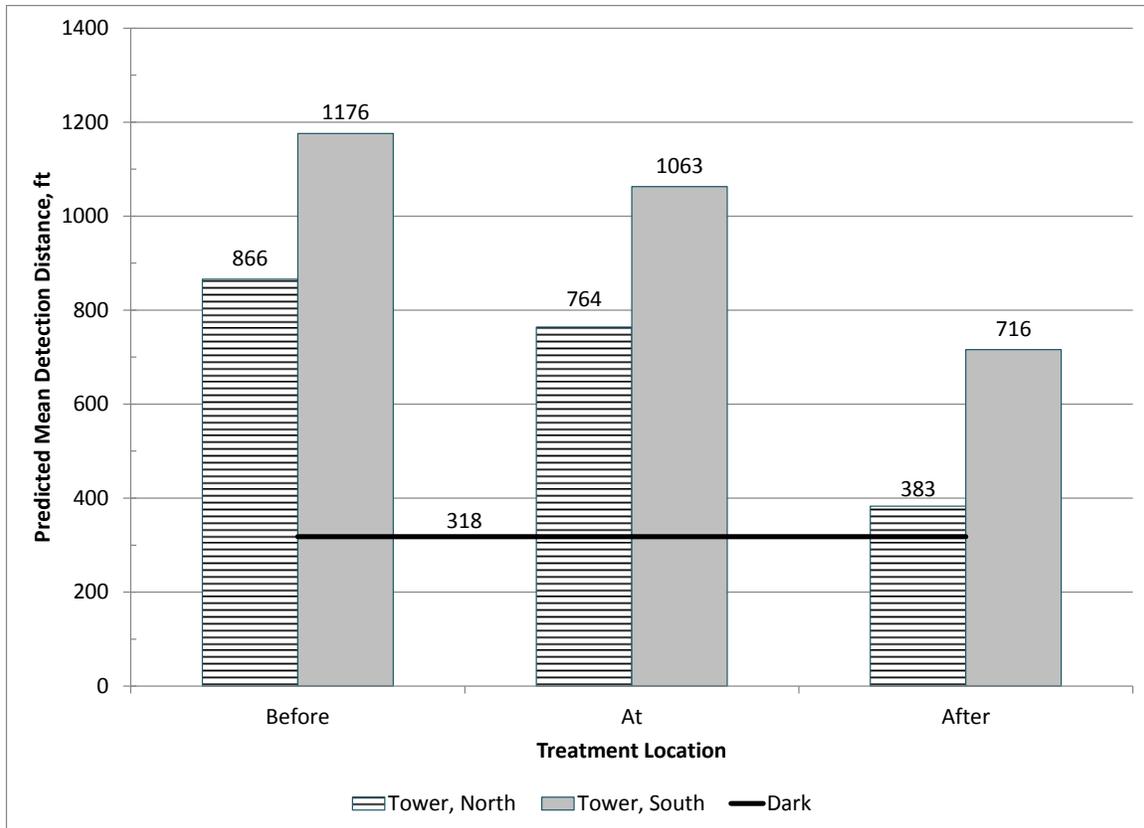


Figure 10. Mean Detection Distances for Worker, Light Tower Treatments.

Traveling north toward the balloon light was a similar situation to traveling south toward the light tower in that for each, the vehicle headlights were directed to the right and the objects were placed to the right. Conversely, traveling south toward the balloon light and north toward the light tower can be compared. For these situations, the objects were to the left with the headlights to the right.

In Figure 11, northbound balloon treatments were compared to southbound light tower treatments. For the at and after positions, the detection distances were practically the same. In the before position, the balloon light resulted in a shorter predicted mean detection distance than the light tower (710 ft compared to 1176 ft; 466 ft difference). For both light conditions, the worker was backlit in the before position. Due to the angle of the light tower, though, researchers observed that the contrast between the worker and the background under the light tower appeared greater than that under the balloon light, which may have contributed to this difference. While a larger difference was found in one position compared to the other positions, there were no significant differences in the predicted mean detection distances between the two light types at any of the object positions.

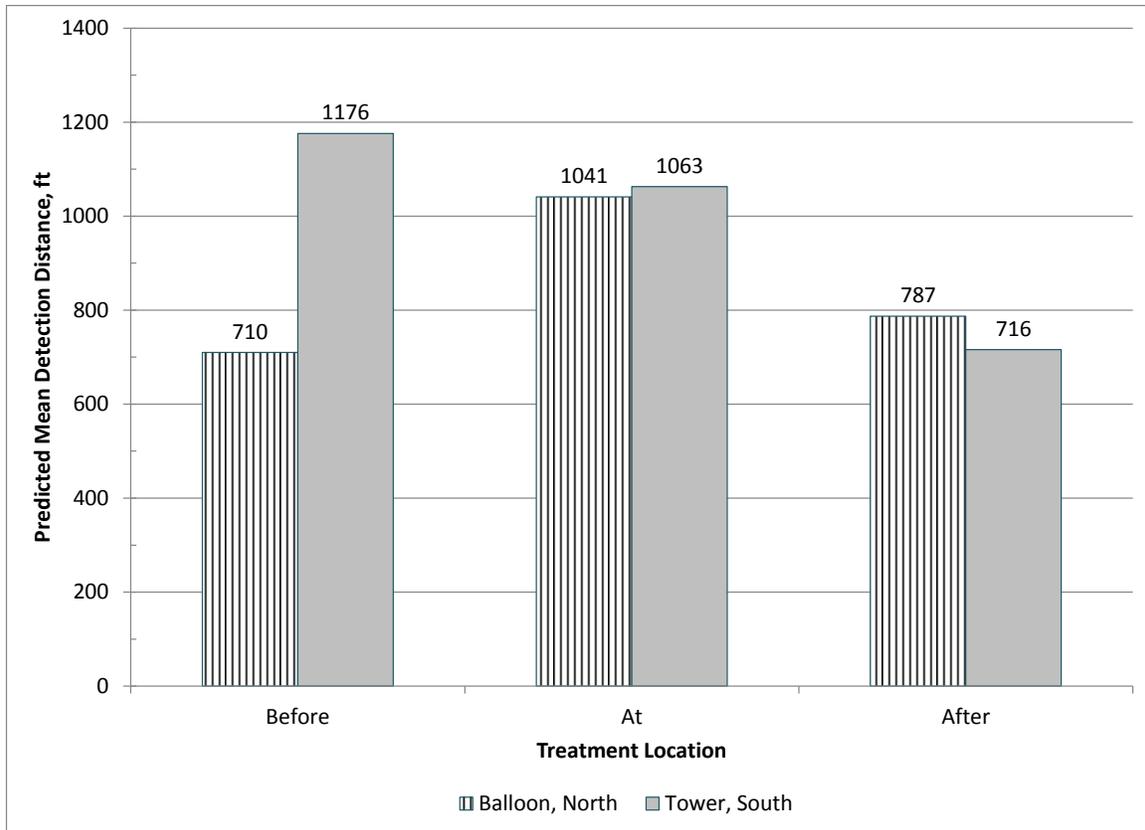


Figure 11. Comparison of Detection Distances for Worker Balloon North and Tower South Treatments.

For the southbound balloon treatments and northbound tower treatments, there were also no significant differences in the predicted mean detection distances between the two light types at any of the worker positions. However, shown in Figure 12 the trends between the positions did differ. For the northbound light tower, the predicted mean detection distances decreased as the participants went toward and past the light tower back into the dark. Again, this shows the impact of glare on the detection of worker. In contrast, for the balloon light the longest predicted mean detection distance was located at the light. Comparing the two light types, the light tower again appears to provide longer detection distances before the light, but when glare occurs the detection distances are less than those with a balloon light (by between 366 and 496 ft).

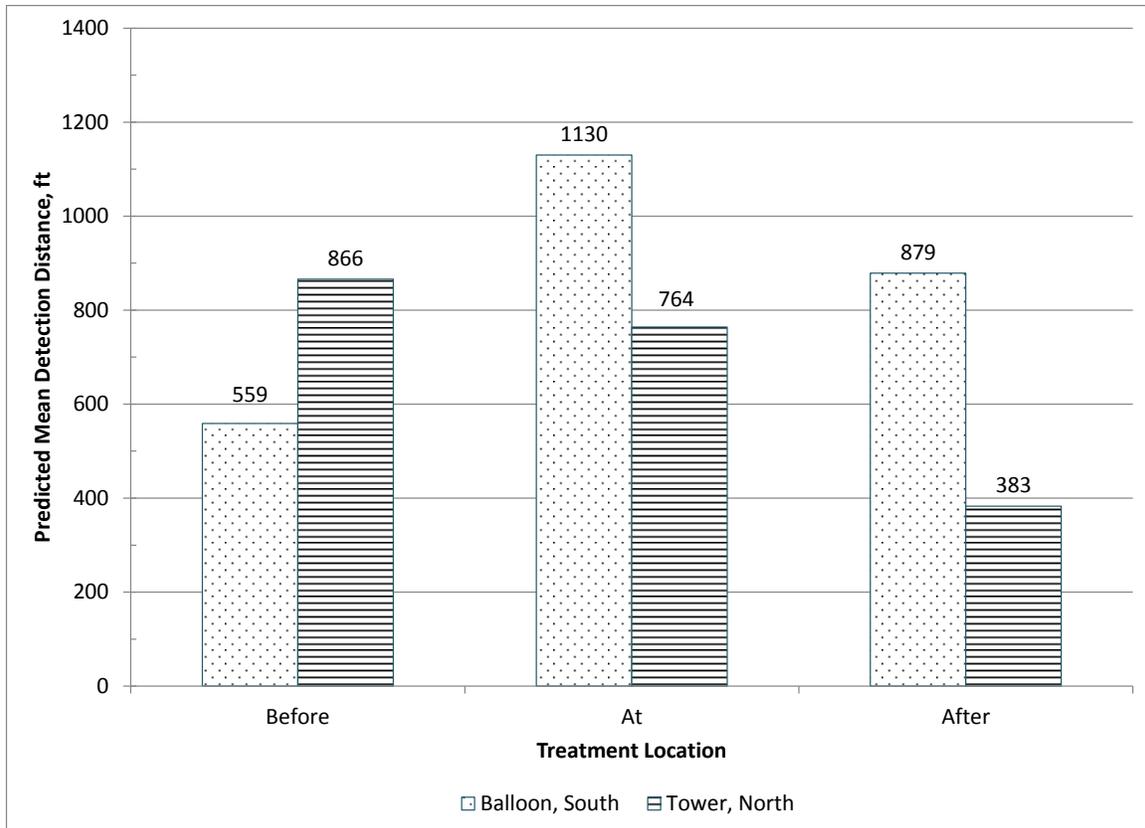


Figure 12. Comparison of Detection Distances for Worker Balloon South and Tower North Treatments.

Low Contrast Treatments

Based on the analysis of the dark treatments, the three low contrast objects had detection distances that were statistically the same, therefore, all of the low contrast treatments were analyzed as one object. Just as with the worker, the statistical analysis results indicated that light type and object position, as well as the two-way interaction between them were statistically significant for the low contrast treatments.

Considering the even distribution of the balloon light, the trend of the predicted mean detection distances for the low contrast objects was similar to that of the worker treatments (Figure 13). At each position, the difference in the predicted mean detection distance for each travel direction varied by up to approximately 70 ft (or 1 second traveling at 40 mph). However, there were no significant differences in the predicted mean detection distances between the two directions. Researchers believe that the before position yielded the shortest detection distance because at this position the low contrast objects were backlit; thus, the only light falling on the face of the objects was from the vehicle headlights. Unexpectedly, this condition yielded predicted mean detection distance at or below the predicted mean detection distance found in the dark scenario.

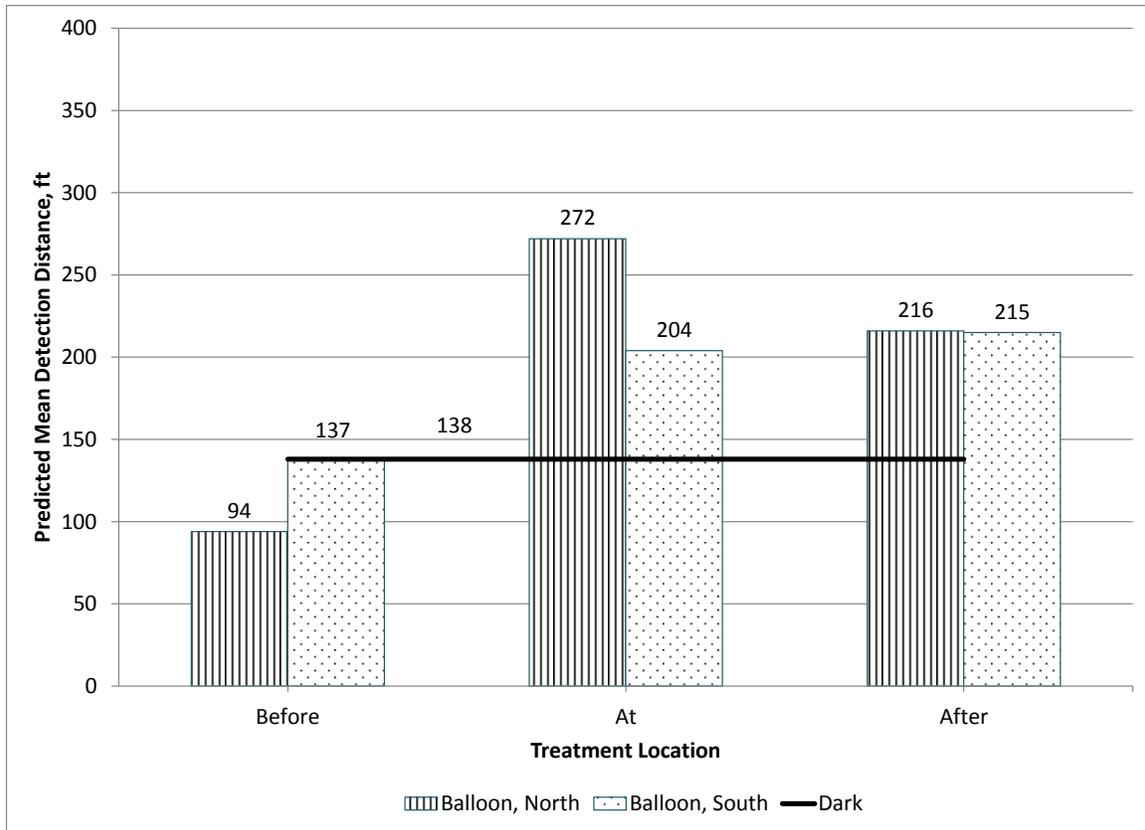


Figure 13. Mean Detection Distances for Low Contrast, Balloon Light Treatments.

Again the light tower travel direction had an impact on the predicted mean detection distance (Figure 14). As with the worker, due to the impact of glare, the predicted mean detection distances when traveling north were shorter than the predicted mean detection distances obtained when traveling south. However with the low contrast objects, the difference in the predicted means by travel direction was statistically significant for the at and after positions; again showing the impact of the glare as participants traveled through the work area. Since the low contrast objects did not include retroreflective components, the longest predicted mean detection distances were actually near the light where the face of the object was continually illuminated by the light. Traveling into the light the predicted mean after the light was only 37 ft (275 ft less than in the southbound direction and approximately 100 ft less than in the dark scenario). So while most light tower scenarios increased the detection distance of the worker above the dark condition (even with some glare), at the location immediately following the light that produced glare the predicted mean detection distance was much less (less than one second traveling at 40 mph).

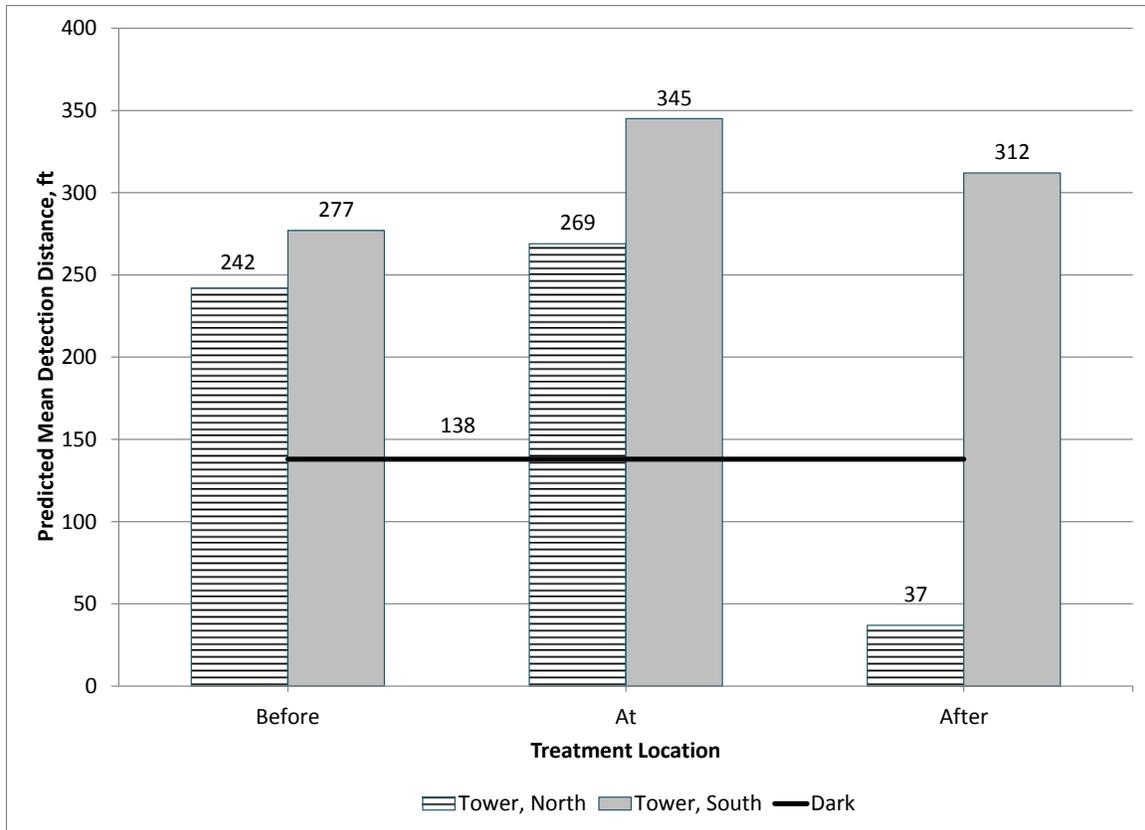


Figure 14. Mean Detection Distances for Low Contrast, Light Tower Treatments.

As was done with the worker treatments, similar work zone lighting scenarios were compared for analysis. Predicted mean detection distances for northbound toward the balloon light and southbound toward the light tower are shown in Figure 15. Unlike for the worker, with the low contrast objects the type of light impacted the detection of the objects. Statistical analysis showed that at every position the light tower resulted in significantly longer predicted mean detection distances than the balloon light (differences between approximately 70 to 180 ft; 1 to 3 seconds). This is not surprising considering that the light tower produced a higher intensity light over a larger area; thus, increasing the contrast between the objects and the background.

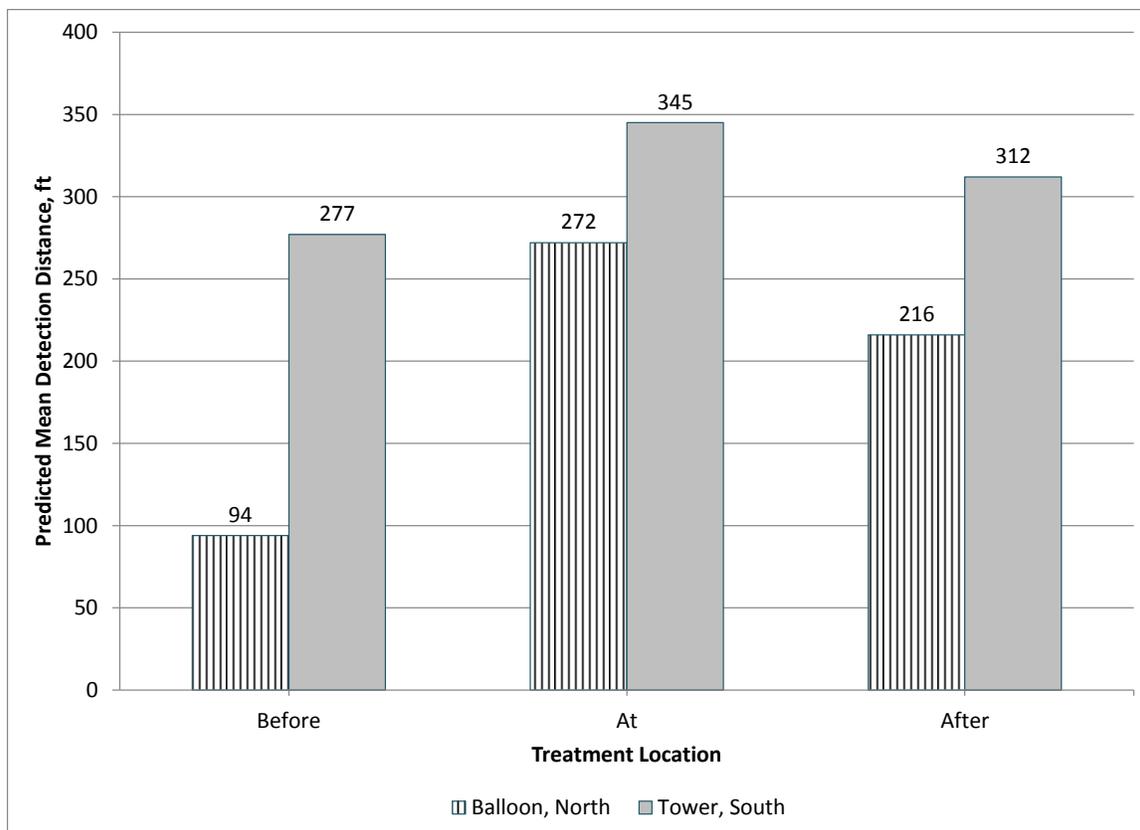


Figure 15. Comparison of Detection Distances for Low Contrast Balloon North and Tower South Treatments.

Predicted mean detection distances for southbound toward the balloon light and northbound toward the light tower are shown in Figure 16. Again, the light tower resulted in longer predicted mean detection distances than the balloon light before and at the light; however, only the difference for the before position was statistically significant. After the light, the opposite effect was found. The predicted mean detection distance going north after the tower (into and past the glare) was only 37 ft. In contrast, the predicted mean detection distance going south after the balloon light was 215 ft (178 ft or 3 seconds). This difference was also found to be statistically significant. These data again show the negative impact of glare on the ability to detect low contrast objects.

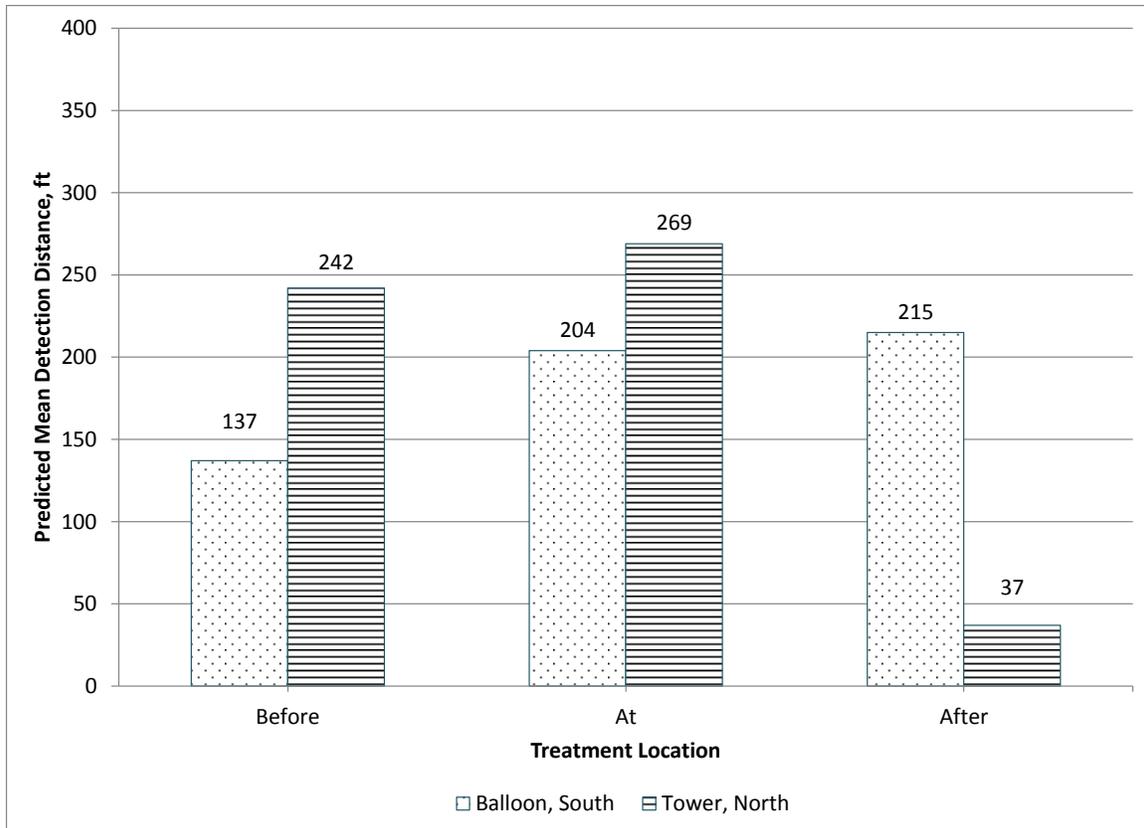


Figure 16. Comparison of Detection Distances for Low Contrast Balloon South and Tower North Treatments.

CONCLUSIONS

Lighting is one of the most important aspects of nighttime construction as it not only affects the workers, but the motorists that pass through the work zone. For this reason, lighting in a nighttime construction zone needs to be considered before work begins, acknowledging the impact of glare on passing motorists and ensuring adequate lighting is provided for workers. Based on the research conducted, both balloon lighting and tower lighting in work zones have benefits and drawbacks. While the balloon light provides consistent detection distances despite travel direction, the light tower allows for longer detection distances in many situations, specifically when objects or workers are under the lights, where most of the work should be taking place. However, glare to motorists traveling in the opposite direction definitely has a degrading impact on motorists' ability to detect objects throughout the work zone.

Despite the glare, portable light towers could still be utilized if different considerations were made when the work zone is set up. Aiming the light tower directly down could potentially decrease the effects of glare, present a greater contrast between objects and surroundings, and allow for a larger illuminated region. However, most light towers have limited aiming abilities. As such, when light towers are used near active travel lanes, personnel need to drive through the work zone in both directions to ensure that glare is not an issue.

Balloon lights are an alternative that appear to remove the issue of glare. However, multiple balloon lights setup accordingly would be needed to produce a larger, brighter illuminated area. Based on this research, increasing the light output, without inducing glare, should increase the detection distance of objects located around the work area.

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