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Evaluation of Roadway High-Mast Tower Lighting

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16. Abstract

This study conducted an evaluation of high-mast roadway lighting, which included a review of Illinois Department of Transportation's high-mast lighting specification and a field experiment. The lighting specification was reviewed for potential cost-saving measures. Recommended changes included the use of an external drive mechanism, a design-by-application mounting ring, and using the industry standard handhole design. The field experiment consisted of two human factors evaluations. In one evaluation, participants were driven along I-57 through five interchanges with various lighting designs and answered questionnaires about the lighting. Results showed that interchanges that were fully lit outperformed partially lit interchanges for perceptions of comfort, safety, and visibility regardless of whether the interchange used conventional lighting or high-mast lighting. When comparing participants' responses between high-mast lighting at full intensity or at a 50% dim level, there was no change in perceptions of comfort, safety, or visibility. In the second evaluation, radar sensors were placed at key locations at each interchange and the speed behavior of traffic was recorded and analyzed. Speed analysis showed that lighting designs using only high-mast lighting had a potential ±safety benefit via reductions in vehicle speed variation. Comparing high-mast lighting at full intensity and at a 50% dim level, the dimmed lighting resulted in a significant reduction in speed for exiting traffic. Furthermore, dimming improved safe speed behavior on ramp segments while not significantly affecting the speed behavior for vehicles traveling through the interchange. Recommendations based on the results include using full interchange lighting designs, using a single light type (conventional or high mast, but not both), using a lower light level, and dimming lighting during times of low traffic volume.

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EXECUTIVE SUMMARY

This research considers high-mast lighting and includes the development of a high-mast tower specification alongside an in situ evaluation of the impact of high-mast lighting compared to conventional lighting. The research team first carried out a literature review, then performed a review of the existing Illinois Department of Transportation (IDOT) high-mast specification, and finally completed an in situ public highway experiment in Illinois to compare the lighting system's performance to a conventional system.

A field evaluation was conducted to examine the performance of existing interchange lighting along I-57. Five interchanges were selected for inclusion based on the type of existing lighting. A human factors study was conducted to obtain subjective evaluations of the lighting at each interchange. Additionally, speed data were collected using radar sensors, and a photometric evaluation was performed using Virginia Tech Transportation Institute's Roadway Lighting Mobile Measurement System.

Some of the most noteworthy results were from the assessment of dim level. Dimming high-mast lighting did not affect participants' perceptions of visibility, safety, comfort, or glare. Dimming was also shown to have a positive impact on ramp speed behavior, as vehicles entering the road were reaching comparable merging speeds with less speed variation under dimmed high-mast lighting, while exiting vehicles were adjusting their speed upstream of the exit ramp and varying their speed less in the ramp area. Results suggest that dimming high mast lighting from high to medium does not detract from public perception of safety, visibility, or comfort.

Speed results showed that, in general, there was a trend where an increase in light level correlated with an increase in speed and speed variation. However, high-mast lighting appeared to give more control over speed variation. Lighting designs that included only high-mast lighting improved safe speed behavior, compared to conventional lighting designs, as speed variation was lower and mean vehicle speeds were closer to the posted mainline speed limits. Partial interchange lighting had a negative impact on ramp speed behavior, as vehicles were not adjusting their speed enough in advance of taking the ramp. Entrance ramp speed behavior was more affected by lighting design and ramp geometry than light level, and, thus, interchanges with shorter entrance ramps may not have been giving drivers enough distance to properly accelerate, even in the presence of sufficient lighting.

Subjective participant survey results found, in general, that participant opinion of safety, comfort, and visibility improved as light levels increased, especially for designs that included high-mast lighting. Interchanges with high-mast lighting at a high light level were rated as providing the best visibility of ramp segments and rated the highest for comfort and safety sentiment. Fully lit interchanges were rated more favorably for comfort, safety, and visibility than partially lit interchanges. Small-object detection results followed the expected performance levels for age and light level, with results suggesting that lighting design choice could be tailored to levels that positively influence the other subjective measures studied. Overall, lighting designs that used only high-mast lighting were rated similarly for discomfort glare as comparable conventional designs while providing slightly more illumination.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

High-mast roadway lighting is a class of roadway lighting installation where the luminaires are mounted at heights greater than 65 ft (~20 m) (Illuminating Engineering Society [IES], 2018). These installations are typically used for lighting large areas such as parking lots, high-lane-count roadways, and interchanges. In a high-mast installation, the luminaires are mounted on a ring at the top of a tower. The light from the luminaires is then projected over the area to be lit.

This research considers high-mast lighting and includes an in situ evaluation of the impact of high-mast lighting compared to conventional lighting and the development of a high-mast tower specification. This was accomplished through conducting a literature review, performing a review of the existing Illinois Department of Transportation (IDOT) high-mast specification, and performing an on-road experiment in Illinois to compare the lighting system's performance to a conventional system.

LITERATURE REVIEW

One of the most significant benefits of high-mast lighting systems is reduced glare. A driver experiences glare when the light sources in the roadway are visible from the driving position. According to Adrian and Bhanji (1991), drivers can experience two types of glare: discomfort glare (also known as psychological glare) and disability glare (or physiological glare). Discomfort glare is the experience of uneasiness in the lighted environment without any reduction in visual performance. Disability glare occurs when light from the glare source is scattered in the eye and casts a veil of light across the observer's retina, reducing visual contrast and, in turn, visual performance. Disability glare depends on the illuminance of the light source and the angle between the line of sight and the glare source. High-mast installations reduce disability glare for drivers by affecting all factors that influence disability glare. In high-mast installations, the luminaires are located not only farther away from the roadway but also higher than conventional luminaires. This increased eccentricity and mounting height increases the angle between the line of observation and the light source and reduces disability glare. Further, the visual cutoff from a vehicle's roof and the A-pillar also reduces the illuminance of the light source at the driver's eye and, as a result, the disability glare, as the high-mast luminaires are farther away in the driver's field of view than conventional luminaires.

In addition to affecting glare, high-mast tower lighting systems illuminate large areas and with a high degree of lighting uniformity. Uniformity is a measure of how evenly lit the roadway is. Roadways that are uniformly lit have fewer dark spots and increase the visual comfort of drivers (Narendran et al., 2016).

In terms of providing guidance to a driver, a high-mast system can provide a visual clue to the direction of the upcoming roadway from a long distance away, as high-mast installations on a continuous roadway are typically a single row of luminaires that delineate the roadway (Van Bommel, 2014).

One of the major disadvantages of high-mast systems is the high cost of installation. The complexity of these high-mast systems along with the large sizes of the poles and mounting bases and the need for harmonic stabilizers in windy locations all contribute to the high system cost.

Typical Pole Configurations

According to the IES (2018), typically poles are mounted in the center of the area with luminaires balanced around the ring, as shown in Figure 1. Additional equipment such as cameras and weather sensors can also be mounted on top of the tower. To maintain the luminaires and other equipment, a lowering device accessed through a handhole in the bottom of the tower is used to raise and lower the mounting ring. These systems have several different attachment and latching methods. A physical latch must be provided for safety in case of system failure. These latch systems can generally be categorized into top-latch or bottom-latch systems. Other systems such as tipping poles have been tested but are not currently in general use.

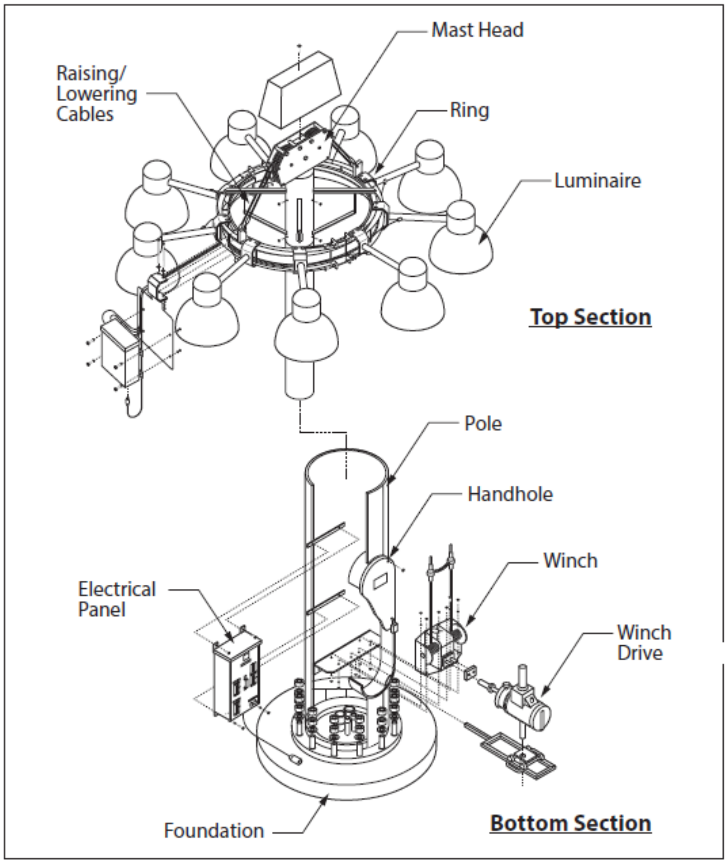

Figure 1. Diagram. Part of high-mast lighting system along with raising/lowering system (non-top latching) (IES, 2018).

Handholes on the high-mast lighting towers are where fatigue cracks have been observed in addition to at the base of the tower (Sherman & Connor, 2018). As a result, the handhole and the base of the tower need to be visually inspected at regular intervals to determine the structural integrity of the pole (Connor et al., 2007). Newer technologies such as fixed poles could potentially remove the need for handholes, thereby eliminating one of the major sources of fatigue cracking in high-mast lighting towers.

High-Mast Lighting: Review of Standards

Several standards exist that govern and advise the use of high-mast lights for roadway lighting applications. Specifically, the U.S. Federal Highway Administration (Lutkevich et al., 2012), the American Association of State Highway and Transportation Officials (AASHTO, 2018), and the IES (2018) all specifically mention high-mast lighting in their official publications. Each document standardizes high-mast lighting from a different perspective while also giving many useful recommendations, and it is important to consult all the documents before implementing high-mast lighting systems.

Guidelines from FHWA Lighting Handbook

The *FHWA Lighting Handbook* (Lutkevich et al., 2012) makes recommendations regarding the use of high-mast lighting at roadway interchanges, mitigating the effects of glare from high-mast lights, and high-mast lighting system layout and geometry. Regarding roadway interchanges, the document states that a partial interchange lighting system consisting of two high-mast towers per ramp should be used for lighting interchanges wherever a complete interchange lighting system is not feasible to implement (Lutkevich et al., 2012). One fixture would be located on the inner ramp curve near the gore, while the other would be located on the outer curve of the ramp midway through the controlling curvature. (Note that IDOT uses a slightly different configuration with the second tower being at the terminal of the crossroad.)

Glare

The *FHWA Lighting Handbook* cites the International Commission on Illumination (CIE) 150:2003 *Guide on the Limitation of the Effects of Obtrusive Light from Outdoor Lighting Installations* (Pollard et al., 2017) that defines limitations for source intensity and spill light for outdoor applications. Source intensity is cited as a general method of evaluating off-site discomfort glare, and the handbook provides a table of source intensity limitations for different environmental zones (Table 1). The document specifically states that this method should be applied where high-wattage sources such as flood lighting or high-mast lights are used.

Table 1. Source Intensity Levels. If the Luminaire Is Public (Road) Lighting then the Environmental Zone 1 Post-Curfew Value May Be Up to 500 cd (Lutkevich et al., 2012)

Light Technical Parameter	Application Conditions	Environmental Zone 1	Environmental Zone 2	Environmental Zone 3	Environmental Zone 4
Luminous intensity emitted by luminaires (*I*)	Pre-curfew:	2500 cd	7500 cd	10000 cd	25000 cd
	Post-curfew:	0 cd	500 cd	1000 cd	2500 cd

Design Process

Regarding system layout and geometry, Lutkevich et al. (2012) states that a lighting calculation process specifically for high-mast lighting must be used. They recommend that the lighting designer develop lighting templates for a variety of high-mast pole arrangements using a range of fixture quantities and distributions. This can be accomplished by using various combinations of individual luminaires clustered on a given pole to create the most effective overall distribution of light through trial and adjustment. By combining efficient templates, the designer can produce optimal light distribution for the given road geometry while considering mounting height, number of luminaires, optics, wattage, light source, and photometric evaluation. The templates will show the pole location with luminance or illuminance levels using contour lines to represent the different levels of luminance or illuminance. The templates should be drafted in the context of the site plan to show approximate pole locations relative to other site features. Once the pole locations and pole distributions have been optimized, a lighting calculation should be performed for the entire interchange (an example of which is shown in Figure 2). Note that high-mast lighting design typically requires many calculations and trial and adjustment cycles to provide an optimized design.

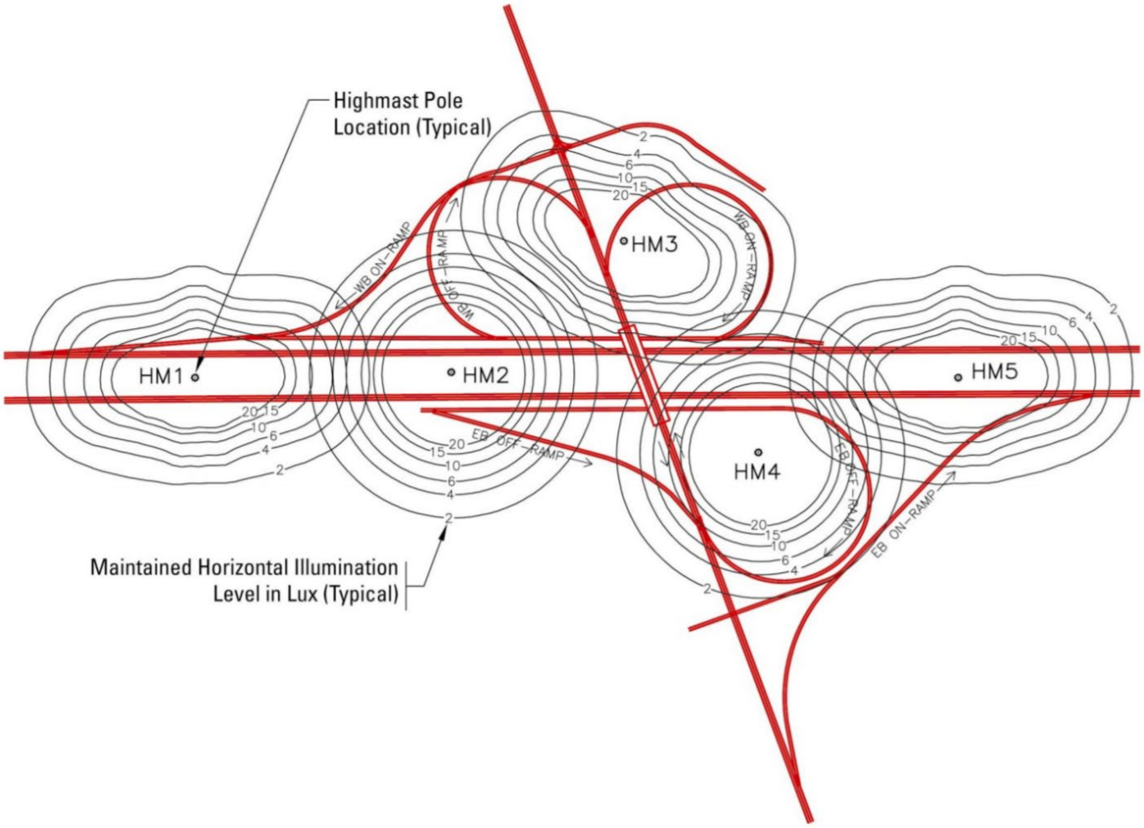

Figure 2. Diagram. High-mast lighting design for an interchange (Lutkevich et al., 2012).

Guidelines from AASHTO's Roadway Lighting Design Guide

The AASHTO guidelines describe the benefits of high-mast lighting as a method of reducing roadside obstacles in the event that a vehicle leaves the roadway, because high-mast lighting requires fewer lighting structures than traditional roadway lighting and the masts are often located away from roadways. Structural supports for high-mast lighting systems should always be placed outside the clear zone, but if they cannot be, they should be protected with a proper traffic barrier (AASHTO, 2018). High-mast lighting supports are considered fixed-base support systems that do not yield or break away on impact, as the large mass of these support systems and the potential safety risks of the systems when they fall to the ground require a fixed-base design.

Maintenance

The AASHTO (2018) *Roadway Lighting Design Guide* recommends that a luminaire pole inspection program be developed to monitor the condition of luminaire poles, with particular emphasis on high structures. AASHTO recommends that periodic maintenance activities include removing debris from around the pole base to reduce the likelihood of trapped moisture that leads to excessive corrosion, checking and tightening hardware (particularly anchor bolts), ensuring all handhole covers are in place and closed properly, and checking for visual signs of wire tampering or vandalism.

Light Trespass

Another issue related to roadway lighting that applies greatly to high-mast lighting and is addressed in the AASHTO guidelines is light trespass. Light trespass is evaluated in terms of maximum vertical illuminance at any point along a plane at a property line. The limits of vertical illuminance are based on the lighting zone (LZ) in which the lighting system is located. The maximum values for this appear in Table 2. In addition to these lighting trespass limits, the fixture brightness of high-mast luminaires is also sometimes cited as an issue. This issue can even affect observers from large distances away where no measurable light can be attributed to the roadway lighting system. This is a perceived brightness issue that arises from the contrast between the luminaire and the dark sky. This issue can generally only be addressed by shielding the luminaire optics from direct view. Shielding bright luminaires cannot always be achieved while maintaining the required lighting levels on the roadway, so the issue needs to be evaluated and addressed on an individual case basis.

Table 2. Vertical Illuminance Maximum Limits for Different Lighting Zones from the *Roadway Lighting Design Guide* (AASHTO, 2018)

Lighting Zone LZ-0	Lighting Zone LZ-1	Lighting Zone LZ-2	Lighting Zone LZ-3	Lighting Zone LZ-4
0.05 fc (0.5 lux)	0.1 fc (1.0 lux)	0.3 fc (3.0 lux)	0.8 fc (8.0 lux)	1.5 fc (15.0 lux)

Guidelines from IES RP-8

The IES RP-8 standards address high-mast lighting more thoroughly than the previously mentioned standards documents, with sections covering lighting calculations, geotechnical and structural engineering, life-cycle costs, raising and lowering systems, obstruction and warning devices, roadway lighting design considerations, and high-mast-specific maintenance (IES, 2018). Regarding lighting calculations, IES RP-8 describes the exact same process of creating templates and optimizing through trial and observation as in the *FHWA Lighting Handbook*. Regarding geotechnical and structural engineering, the document states that it may be necessary to define the shape of the pole support foundation based on soil conditions. Specifically, high-mast lighting will require geotechnical engineers to make recommendations for custom foundations. Custom poles are also usually required for high-mast lighting applications. Where a custom pole and foundation is required, the process should include four steps:

- The structural engineer will assess pole loading and define base reaction forces based on local wind loads and applicable codes.
- A geotechnical engineer will take soil borings and use base reaction forces to establish foundation depth and shape. (Situations with high base reaction forces and poor soils may require pile support or other reinforcement of the solid.)
- The structural engineer will define foundation reinforcing and concrete mix design and will produce an installation drawing.
- The geotechnical engineer will define backfill requirements.

Life-Cycle Costs

Regarding life-cycle costs, the IES (2018) compares the life-cycle costs of conventional and high-mast roadway lighting as an example. Life-cycle costs include the capital (initial) costs as well as operating costs over the estimated life of the system. Operating costs should include power and preventative maintenance costs, which are also calculated over the life of the system (typically 30 years). Because the equipment will most likely not be used again after the 30-year operation, no residual value should be considered. When life-cycle costs are used to compare lighting systems, current operating costs can be used as the basis over the operating period. As costs are most likely to increase over time, inflation may be factored in to provide a more accurate estimate of the total costs. IES RP-8 gives specific examples of calculating the life cycle costs for two different types of roadway lighting. For the davit-style lighting example, the capital cost is calculated as $453,000, the 30-year energy cost is $255,420, and the 30-year maintenance cost is $183,000 for a total life-cycle cost of $891,420. For the high-mast lighting example, the total capital cost is calculated as $434,000, the 30-year energy cost is $345,720, and the 30-year maintenance cost is $18,480 for a total life-cycle cost of $798,200. This example demonstrates that the significant reduction in maintenance costs for high-mast systems can make the potentially higher energy cost negligible and that all costs must be considered in the life-cycle cost estimates.

Raising and Lowering Systems

Regarding raising and lowering systems, the IES RP-8 document states that high-mast luminaires are located on a mounting ring consisting of 3 to 12 luminaires. The ring is attached to cables that allow the luminaires to be lowered to ground level for servicing. There are three main types of latching systems: top-latching units, non-top-latching-units, and bottom-latching units.

In top-latching units, the luminaire ring latches at the top of the pole to hold the ring and luminaires in position at the top of the pole. Once the luminaire ring is attached, the raise/lower cables are no longer under tension. In non-top-latching units, the luminaire ring is suspended by the raise/lower cables under full tension with no latch at the top of the pole. The winch and safety chains in the pole handhole act as the locking device that latches the ring in place at the top of the pole. In bottom-latching units, the support cables are detachable and connected to a lowering winch and cable spool at the bottom of the pole, which is used to raise and lower the ring. Top-latching systems are typically perceived as safer if a failure occurs in the mounting cable because the ring will not fall; however, these systems are more difficult to manage in the event of a failure. Non-top-latching systems are simpler, but the mounting cable is always under tension. For all high-mast systems, the supporting cables run from the winch up the pole and around a series of pulleys on the mast head and connect to the luminaire ring. Workers raise and lower the ring through a large handhole in the pole and operate the winch drive unit. The winch drive unit can be a portable unit (drill-type), or each pole may be equipped with an internal motorized drive unit. Some units can even be remotely activated off-site.

The consensus among manufacturers and regulators is that top-latching high-mast lowering devices are the preferred choice. Companies such as Holophane, Carolina High-Mast, and Stratus offer multiple product options in both varieties, but more options exist for top-latching lowering devices. According to Holophane, top-latch systems prevent wear on the cable, winch, and inaccessible sheaves and bearings, provide a safer environment for the operators, and require only a two-year inspection schedule (Holophane, 2003). The manufacturer also states that the constant loading of non-top-latching systems can wear cables and inaccessible sheaves, shafts, and bearings at the top of the pole, can stretch cables, can unseat the ring from the top of the pole, can put the operator at risk when inside the handhole, and require frequent inspection. Strong winds also expose non-top-latching system weaknesses and can accelerate normal deterioration of cables, while top-latching systems are less likely to fail due to these forces.

Obstruction and Warning Devices

IES RP-8-18 states that high-mast poles may require special considerations for aircraft, including obstruction warning lights mounted on the luminaire ring for daytime and nighttime visibility, and sometimes special paint schemes for daytime visibility. The designer should consult with federal and local airport authorities and check local bylaws to confirm requirements for these features.

Roadway Lighting Design Considerations

IES RP-8-18 recommends caution when using high-mast lighting in urban residential areas or in areas where poles will impact local residents' views. A public involvement process should be considered prior to employing a high-mast system. Due to the high intensity of light emitted from high-mast luminaire clusters, poles in close proximity to bridges and signs may cast sharp shadows onto the roadways. The designer should analyze the design to identify these impacts and mitigate them by locating other light sources in a manner that will illuminate the otherwise shadowed areas. Placement of light poles is a function of speed, traffic volumes, side slope, and horizontal and vertical alignments.

Maintenance

According to IES RP-8-18, preventative maintenance work on the raising and lowering system should not be conducted when there are high wind speeds or during other severe weather conditions. Maintenance should be performed on the raising and lowering systems at regular intervals, and the ring assembly should be lowered and inspected as part of the maintenance work. Examples of possible problems with all high-mast raising and lowering systems include twisting of the support cables, power cable twisting around the support cables, deterioration or damage to the support cables, deterioration or damage where the support cables connect to the luminaire ring assembly, winch cable being too loose or twisted on the winch drum, deterioration or damage of the connection of the luminaire to the support arm and/or the support arm to the luminaire assembly, and deterioration or damage to the winch assembly and/or winch cable. Examples of possible problems with top-latching systems include latching pins breaking (e.g., because the luminaire ring was not level when it was latched) and failure of one or more pins to latch or unlatch. Examples of possible problems with non-top-latching and bottom-latching systems include pendulum motion and possible damage to the cables if the luminaire ring was not fully docked at the top of the pole or the ring has not been lowered and raised regularly. If the ring on a non-latching system is simply left in place, then over time the constant load on the support cables may cause the cables to stretch and the ring to become undocked. Therefore, for a non-latching system, it is critically important to lower and raise the ring at regularly scheduled intervals. It is important to inspect the bases of high-mast poles for signs of cracking or other problems. Binoculars may be used to perform a cursory visual inspection of the outside of the pole above 6.6 feet (2 m). Some high-mast lighting systems utilize a small number of high-wattage lamps per pole (e.g., three 750-watt lamps per pole). In these systems, the failure of one lamp will result in a proportionally greater loss of lighting on the roadway compared to the loss of a single lamp in a conventional lighting system. Therefore, the timely replacement of a single failed lamp in a high-mast lighting system may be more important than it is with a conventional lighting system.

SPECIFICATION REVIEW

During this research, the existing IDOT high-mast lighting specification was reviewed. The goals of this review were to compare the current practices in other jurisdictions to those used by Illinois and to consider ways to reduce the cost of the installed systems. Virginia Tech Transportation Institute (VTTI) personnel performed the review through discussions with vendors, industry experts, and other DOTs. Additionally, WSP—who partnered with VTTI as a consultant on this project—reviewed the documents.

The review underwent several iterations, including consideration of a fixed pole, modification of the IDOT handhole, and remote LED drivers. Cost estimates were assigned to each of these alternative designs as a method to consider the merit of changing the design specification.

Illinois Specification

The current Illinois specification is one of the more complex specifications in use today. In addition to the pole itself, the specification requires the use of a dedicated internally mounted lift motor. The latching mechanism is a bottom latch using a stainless-steel cable. The access handhole is also a large opening in the pole shaft to allow the entire motor system to be installed and removed. The access handhole also requires a full-size door with a piano hinge and several latches for mounting and locking. The specification also requires a six-luminaire ring. Finally, the electrical specifications are included for the internally mounted motor, which uses a worm drive to prevent slippage and the potential for a falling ring but does require a reversing switch and a power supply for the system to function.

During the review, potential areas to reduce costs were identified and considered. These were primarily identified as differences between the IDOT specification and other agencies:

- Illinois uses higher material grades for the base plate and anchor bolts.
    - IDOT uses Fatigue Category 1. New standards show that there is a possibility of using Fatigue Category 2 (lower maximum wind speed), which could be used to lower the material thickness requirements.
    - Note that this change was rejected by IDOT and was not considered further.
- IDOT details the large and complicated handhole opening (12′ × 36″), the grounding pads, and wires between shaft sections for bonding.
    - These options are expensive but do provide access to the motor drive and the control mechanism.
- The specification requires a six-arm mounting ring even if fewer than six luminaires are required for the design.
- The latching mechanism could be top mounted and reduce the requirements for the hoisting cable.
- Most DOTs specify a galvanized raising cable rather than a stainless-steel version.
- An external lowering device (a large drill) could be used rather than a dedicated motor and control mechanism in each tower.
    - For the lowering device with handhole exemption, the driving minimum dimension is at the base of the pole to allow a lowering device winch to be mounted inside.
- The advent of solid-state luminaires can reduce the need for maintenance of the luminaire, thus reducing the need to lower the ring.
    - There is a possibility that a fixed ring can be used with no lowering device.
    - Lamp failures in solid-state lighting typically involve the driver, the driver could be mounted remotely for maintenance without having to lower the lighting system.

These considerations and the possible positive and negative impacts are shown in Table 3.

Alternative Designs

The team identified alternative lighting designs as a method of cost savings. These alternatives included a fixed pole with no lowering capabilities, a fixed pole with remote drivers, typical industry design poles with an exempted handhole (a reduced-size handhole allowable in national standards), a typical pole with the traditional size handhole, and finally the Illinois specification.

Comparison costs were obtained for these designs. Note that these are for comparison only and may differ significantly for a real pole design. The assumption is a six-luminaire pole at 100 ft (30.5 m) in height. The characteristics with respect to the handhole and the exemption of the alternative design are with the comparison costs shown in Table 4.

These estimates indicate that there are significant cost savings in using a fixed pole, but the maintenance of fixed-pole luminaires could be very expensive. The remote driver tower may also provide significant cost savings but maintaining the number of wires in the poles (24 wires for a six-luminaire pole) could be problematic. Using the exempted minimum handhole may result in moderate cost savings. Another source of potential cost savings is using an external lowering device. This would likely reduce the cost per tower by $4,000 to $5,000.

Table 3. Possible Changes to the Tower Design with Impacts Identified

Technology	Positive Impact	Negative Impact
Removal of the lowering system	Reduced cost due to removal of winch, lowering system and latching mechanism Reduced handhole size	Must service the luminaires from a crane and bucket or lower the tower.
Use of external lowering device	Reduced cost for individual towers.	More complicated for the maintenance teams, as an external device must be transported and matched to the tower designs. Power hookups for the lowering device will also be needed.
Design of the mounting ring based on need rather than standard six-point connection	Reduced cost for rings and ensuring the ring meets the needs of the job.	A higher chance of installation error due to the need to pair the correct tower and ring at each installation location.
Lighter and typically smaller luminaires that can be supported by a smaller mounting ring	Reduced wind load and reduced top weight thus reducing the tower material requirements.	N/A
Latching mechanism either removed or switched to top latch	May not be needed if the lowering system is removed. Reduced weight for top latching, reduced cable weight as compared to bottom latching.	If the system is a lowering system, then there is no safety backup if the cable fails.
Hand access hole reduction to standard specification	Possibly reducing the tower wall thickness requirements around the handhole location.	No easy access to wiring in case of failure.
Remote drivers for luminaires (Drivers placed close to the ground rather than in the air)	Reduction in maintenance and requirements to lower luminaires.	Significant voltage drop in cable, requiring larger gauge wires to run from the driver to the luminaire. The voltage must be limited to ensure that the input voltage to the LED luminaires is within their specified operational range and regulatory requirements (e.g., electrical code) Additional energy losses to overcome drop in the wire. Twice as much wire would be required for a luminaire that uses 2 drivers. Assuming a 100-ft high mast tower, with a 1-volt drop at 2 Amps, this would be an additional 2 watts to overcome the loss. (Note high voltages can be used to overcome losses (IDOT uses 240 V or 489V) Additionally, four number 12 wires would be required for each luminaire, significantly increasing cost.

Table 4. Initial Installed Cost Comparisons for Alternative Pole Designs

Design Elements	Fixed Pole	Remote Driver	Industry Minimum Exemption	Industry Minimum Without Exemption	IDOT Spec
Pole Diameter	18.17"	18.17"	19.67"	28"	19.67"
Exemption to Sec. 5.6.6.1			Yes	No	Yes
Lowering device capable			Yes	Yes	Yes
Handhole			Standard reinforcement for high-mast lighting with lowering device	Standard reinforcement for high-mast lighting with lowering device	Custom rim with hinges, clasps, rain shield, etc. for high-mast lighting with lowering device
Price factor			Minimal	High due to much larger size which is driven by the requirements of Sec. 5.6.6.1	Handhole features add over $1K price
Pole - 100'	$9,700	$9,700	$10,400	$19,800	$11,400
Mounting / Lowering Device	$2,000	$2,000	$10,000	$10,000	$10,000
Luminaires (Assuming six, $1,000 per)	$6,000	$6,000	$6,000	$6,000	$6,000
Base	$1,300	$1,300	$1,300	$1,300	$1,300
Handhole	$195	$195	$430	$430	$1,600
Miscellaneous (Remove Junction Boxes, grounding pads etc.)	$750	$750	$2,000	$2,000	$2,000
Wire and Junction Box		$3,500			
Total	$19,945	$23,445	$30,130	$39,530	$32,300

Recommended Specification Changes

The research team believes that a change to a fixed pole and remote drivers has significant drawbacks, so this is not recommended currently. More data on solid-state luminaire maintenance are needed for a reliable cost/benefit analysis.

To reduce costs associated with high-mast lighting, the research team recommends using an external drive mechanism, a design-by-application ring rather than the six-ring application, and a reduced handhole to the industry’s typical design.

An annotated specification performed by members of the research team is attached as an appendix to this report.

CHAPTER 2: FIELD EVALUATION METHODS

A field evaluation was conducted to examine the performance of existing interchange lighting along I-57. Five interchanges were selected for inclusion based on the type of existing lighting. A human factors study was conducted to obtain subjective evaluations of the lighting at each interchange. Additionally, speed data were collected using radar sensors, and a photometric evaluation was performed using VTTI’s Roadway Lighting Mobile Measurement System (RLMMS). These efforts are discussed in detail below.

INTERCHANGES AND LIGHTING DESIGNS

The five interchanges for this study were selected based on their relatively similar geometry, variety of lighting, and proximity to each other (Table 5). Two of the interchanges used conventional lighting, two used high-mast lighting, and one used a combination of high-mast and conventional lighting. Satellite images show the layout of each interchange in Figure 3. For simplicity, each interchange is referred to by its associated exit number. For example, the interchange at I-57 – E 6000 N Rd is referred to as Interchange 318.

Table 5. Interchanges and Associated Lighting

<table>
<tr><th>Interchange</th><th>Exit</th><th>Interstate Lighting</th><th colspan="2">Cross Road Lighting</th></tr>
<tr><td colspan="2">I-57—E 6000 N Rd</td><td>318</td><td>High Mast</td><td>Conventional</td></tr>
<tr><td colspan="2">I-57—E Co Hwy 9</td><td>322</td><td>Conventional</td><td>Conventional</td></tr>
<tr><td colspan="2">I-57—W Wilmington Rd</td><td>327</td><td>Partial High Mast</td><td>No Light</td></tr>
<tr><td colspan="2">I-57—W Monee Manhattan Rd</td><td>335</td><td>Conventional</td><td>Conventional</td></tr>
<tr><td colspan="2">I-57—Lincoln Hwy (US 30)</td><td>340</td><td>High Mast & Conventional</td><td>Conventional</td></tr>
</table>


Interchange 318 Interchange 322 Interchange 327 Interchange 335 Interchange 340

Figure 3. Photo. Satellite images of selected interchanges (Google).

DATA COLLECTION METHODS

The field evaluation consisted of three separate data collection efforts. These efforts included a photometric evaluation, a subjective evaluation, and a speed evaluation.

Photometric Evaluation Methods

A photometric evaluation was conducted at each interchange with VTTI's RLMSS. The details of the evaluation are discussed below.

Equipment

The RLMMS is a rooftop-mounted, modular measurement system that can be mounted to almost any vehicle. The system's conceptual layout is shown in Figure 4. A photo of the deployed system is shown in Figure 5. It includes a four-armed apparatus placed on top of the vehicle with a waterproof Minolta illuminance detector head at the end of each arm. This allows roadway illuminance to be measured at three positions in each lane (left, right, and center) with a redundant measurement at the center position (both front and rear Minolta heads are aligned with the center of the vehicle). These positions correspond to the left track, center of the lane, and the right track and are approximately 32 in. (0.8 m) apart across the lane. Positioned in the center of the four arms is a NovaTel GPS. A fifth Minolta illuminance detector is mounted to the forward windshield of the vehicle to detect vertical illuminance directed toward the driver.

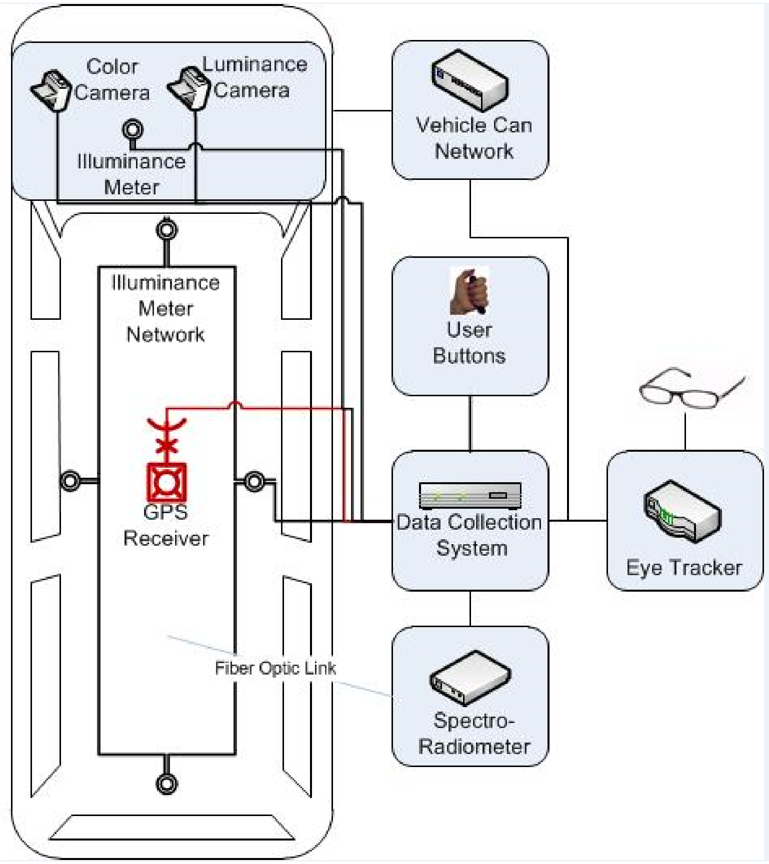

Figure 4. Diagram. VTTI RLMMS (Gibbons et al., 2018).

Figure 5. Photo. Experimental vehicle (2017 Ford Explorer) with RLMMS deployed.

Data Collection

For this process, data collected included:

- Horizontal Illuminance: the amount of light falling onto and spreading over a horizontal surface—in this case, the surface of the experimental vehicle.
- Vertical Illuminance: the amount of light falling onto and spreading over a vertical plane—in this case, the light directed through the windshield toward the driver.

The RLMMS was deployed on the experimental vehicle, which was then driven through each of the five interchanges. The vehicle was driven through both the left and right lanes of the interstate as well as every lane along the exit and entrance ramps. This process was repeated twice at Interchange 318—once at full brightness and once at the 50% dim level. Illuminance data were measured in lux (lx) and linked with the GPS position of the vehicle. All illuminance data in this report has been reported in the metric system unit of lux (one lux is equal to one lumen per square meter) which can be converted to the imperial unit foot candles by multiplying a given lux value by 0.0929 (The Engineering ToolBox, 2004).

Three elements of the photometric data collection efforts deviated from IES LM-50, the standard that guides photometric measurement of roadway lighting installations. For instance, illuminance was captured at 6 ft height rather than at the roadway surface for the left, middle, and right vehicle tracks within each lane. These changes produced more in-lane measurements than IES LM-50 specifies. Furthermore, measurement frequency was 20 hz, which resulted in illuminance data every 4.76 ft (while travelling at 65 mph), giving researchers about three times more data points than IES LM-50 specified. Photometric data collection methods resulted in a more robust data set than the standards specified in IES LM-50.

Data Reduction

RLMMS data were imported into ArcGIS Pro, where the lighting measurements were added, and an interchange ID was created to mark the five study interchanges. For each interchange, RLMMS data were divided by direction of travel and interchange segment. All vehicle tracks traveling in the through lanes were marked as "through." Vehicle tracks that took entrance and exit ramps were marked as such until the point at which the paths overlapped with existing through tracks (typically near the gore point). Additionally, entrance and exit segments were selected based on the time vehicles left surface streets until they had fully merged into the through traffic (Figure 6).

Figure 6. Photo. Interchange segment type selection with symbol indicating the allocation of data.

Lighting measurements also included a 1-mile (1.61 km) buffer segment on either end of the interchange, labeled as the "approach" segment. This was done to capture differences in lighting leading up to an interchange, as this may affect participants' dark adaptation and perceptions of the lighting at the interchange. Figure 7 shows an illuminance heatmap of the entire route. While the lighting at Interchanges 318 through 327 existed in relative isolation, Interchanges 335 and 340 were surrounded by additional roadway lighting along the approach segments.

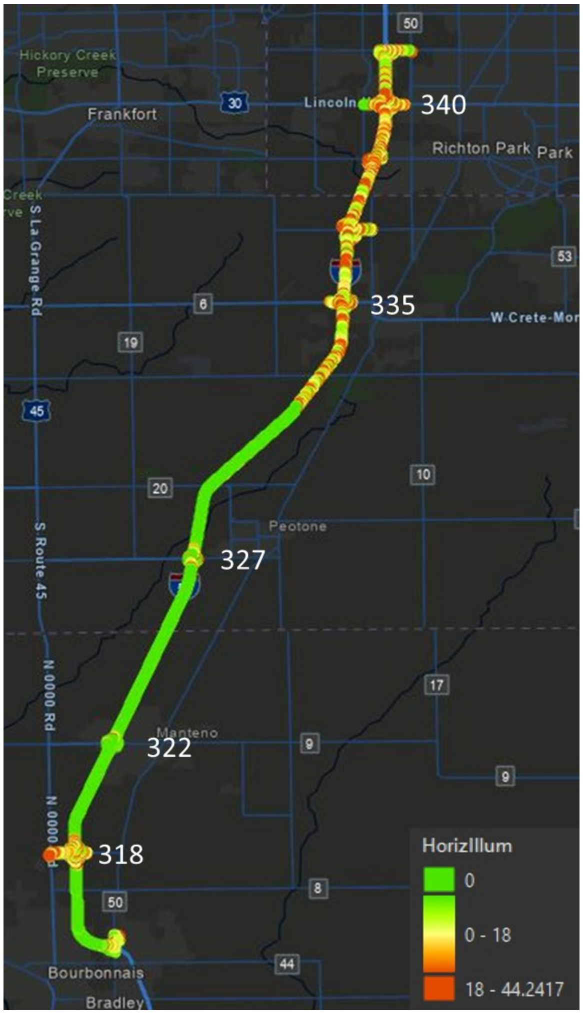

Figure 7. Photo. Illuminance heatmap of the test route on I-57. Green indicates low illuminance values, while yellow and red indicate increasingly higher illuminance values and specify where lighting infrastructure exists.

Quality checking took place to ensure that all interchange and approach data contained reasonable values for horizontal and vertical illuminance measurements. Reduction revealed some negative values were present across all measurement efforts. The negative values ranged between −2 and 0 lx for horizontal illuminance and between −9 and 0 lx for vertical illuminance. Negative values are known to occur in the RLMMS data due to noise in the measurement system. All values equal to or less than zero were removed from the data.

During the data collection process efforts were taken to minimize the influence of opposing vehicle headlights and ambient light on the photometric measurements. For example, horizontal illuminance was measured by vertical facing sensors located on top of the vehicle and all measurements were taken late at night where traffic volumes were significantly reduced. Furthermore, during data reduction outliers were identified and values too large to be attributed to roadway lighting conditions were excluded from the analysis data set.

Horizontal illuminance was captured at three points in each lane; however, the middle-of-vehicle track contained front and rear measurements that were redundant. Both center-of-lane measurements were averaged to form a middle track value. For data analysis, horizontal illuminance was summarized by averaging the left, right, and middle-of-lane vehicle track measurements. Vertical illuminance was captured in the middle of the lane from windshield height.

For interchange segment data, 64,469 out of 65,094 (99.03%) measurement points had horizontal illuminance calculated. Missing data (0.97%) were due to all four horizontal illuminance measurement points being negative. Similarly, vertical illuminance was available for 59,315 out of 65,094 (91.1%) measurement points. A total of 5,779 (8.9%) negative data points were removed from the vertical illuminance data for analysis.

For approach data, 123,391 out of 139,769 (88.2%) measurement points had horizontal illuminance calculated. The missing data (16,378 points, or 11.8%) were due to all four measurements of horizontal illuminance at a given point being negative. Similarly, vertical illuminance was available for 87,653 out of 139,769 (62.7%) measurement points. For vertical illuminance, 52,116 (37.3%) points were negative and were not factored into the analysis.

Subjective Evaluation Methods

A subjective evaluation of the interchange lighting was conducted using drivers recruited from the area around Bourbonnais, Illinois. Participants rode in a vehicle driven by an experimenter and observed the lighting at the five selected interchanges. Participants answered a questionnaire regarding their perceptions of the lighting at each interchange.

Participants

Participants were recruited via ads sent through email or posted on social media. A total of 18 participants took part in the study: nine males and nine females. The age of participants ranged from 18 to 63 with an average age of 38 and a median age of 33. Participants were categorized by age and gender with the younger group defined as 32 or younger, and the older group as 43 or older. A total of four older females, four older males, five younger females, and five younger males made up the participant pool. All participants had a valid driver’s license.

Procedures

Testing was conducted between March 26 and March 30, 2023. Participants were scheduled to meet with experimenters after dark at a location just off I-57 at exit 315. When participants arrived, they were greeted by an experimenter and escorted to a vehicle outside. Participants were instructed to sit in the front passenger seat. The experimenter entered the driver’s seat and then read instructions for the study to the participant. Participants were informed that they would be driven along I-57 and asked to observe the roadway lighting at specific interchanges before filling out a questionnaire. They were told to consider the following while observing the lighting:

- How well the lighting let them see the exit and entrance ramps.
- How comfortable they would feel driving in that type of lighting.
- How safe they would feel driving in that type of lighting.
- If there was too much or too little lighting.
- If glare from the lighting caused any discomfort for them.

Participants were also instructed to look for “targets” near the interchanges and to keep a count of how many they saw. Targets were mounted to existing infrastructure along the interstate including signposts, delineator posts, and light poles (Figure 8). At each interchange, one target was placed along each exit and entrance ramp and along the through lanes for a total of six targets at each interchange (three in each direction). To familiarize participants with what a target looked like, an example target was mounted to the stop sign at the exit of the parking lot, and the experimenter pointed it out to the participant before starting the study.

Figure 8. Photos. A target being mounted (left) and a target mounted to a signpost (right).

Participants were then handed a tablet that they would use to answer the questionnaire. Participants filled out a practice questionnaire in the parking lot to familiarize themselves with how to operate the tablet and the questions that they would be answering.

Once the drive was started, the experimenter would inform the participant each time they were approaching one of the interchanges of interest so they would be prepared to observe the area. Additionally, the questionnaire listed the exit number of the upcoming interchange, which the participant would observe and rate. Participants were instructed to observe the area around the interchange while they were driven through it, and only once they reached the end of the entrance ramp would they fill out the questionnaire. This was done to ensure that participants had an opportunity to observe the entire interchange and did not get distracted by the questionnaire while still in the interchange.

Test Route

The experimenter began the route by entering I-57 North at Interchange 315. They then traveled north through the five selected interchanges and exited at Interchange 342. Note that Interchanges 315 and 342 were not included in the evaluations; they were simply used as the start and end points of the route. The experimenter then got back onto I-57 South and returned to Interchange 315, which concluded the participant’s session. Along the way, the experimenter would take the exit ramp at some interchanges and then use the on-ramp to get back on. At other interchanges, they would stay on the interstate. Experimenters would alternate the order of these actions to balance routes between participants. Participants were assigned one of four orders, as shown in Table 6. Participants who were assigned orders 1 and 2 observed the lighting at Interchange 318 at full brightness, while participants who were assigned orders 3 and 4 observed the lighting at a 50% dim level.

Table 6. Participant Orders

Direction	Interchange	Order 1 (Full Brightness at Interchange 318)	Order 2 (Full Brightness at Interchange 318)	Order 3 (50% Dim at Interchange 318)	Order 4 (50% Dim at Interchange 318)
Northbound	318	Exit	Through	Exit	Through
	322	Through	Exit	Through	Exit
	327	Exit	Through	Exit	Through
	335	Through	Exit	Through	Exit
	340	Exit	Through	Exit	Through
Southbound	340	Through	Exit	Through	Exit
	335	Exit	Through	Exit	Through
	327	Through	Exit	Through	Exit
	322	Exit	Through	Exit	Through
	318	Through	Exit	Through	Exit

Traffic Speed Evaluation Methods

The traffic speed evaluation focused on the speed of traffic at each interchange. Radar sensors were placed at several locations around the interchange to capture the speed of vehicles as they took the exit ramp, traveled straight along the interstate, or entered the interstate from the on-ramp.

Data Collection

To capture vehicle speeds, portable radar towers were deployed at specific locations at each interchange. The radar kits included a radar sensor mounted on top of a 15 ft (4.57 m) tall telescoping pole, a box that housed a computer for recording data, and a sandbag for stability (Figure 9). Each night, after participants had completed their session, a total of five towers were set up at a single interchange: one near the gore point of each exit and entrance ramp, and one along the through lanes. Data were collected for at least 1 hour before the radar kits were collected by the research team. This was repeated for a total of six nights until data had been collected at each of the five interchanges, including twice for the two dim levels at Interchange 318.

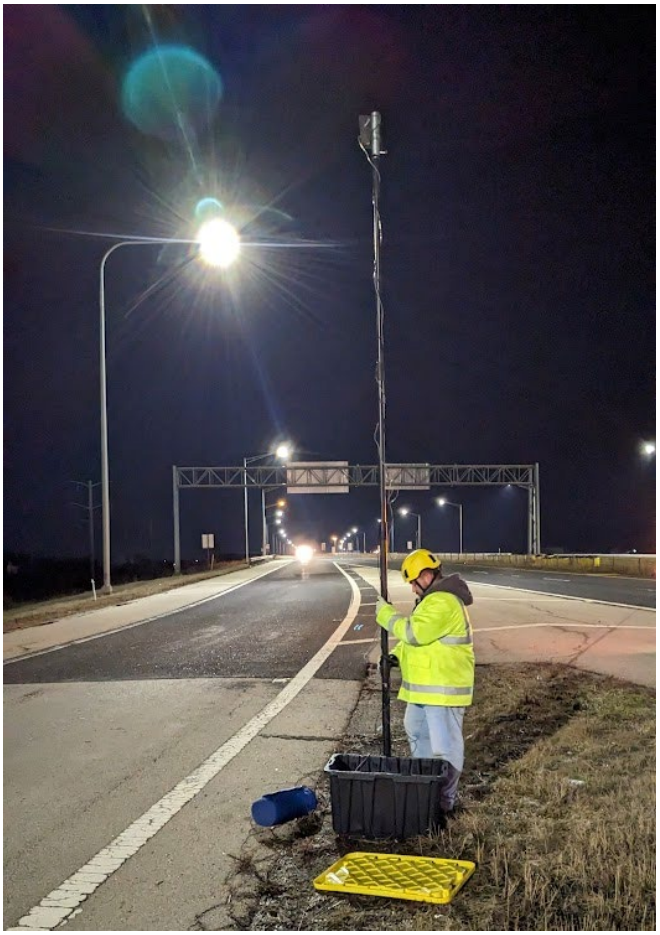

Figure 9. Photo. Radar tower being deployed at an exit ramp.

Data Reduction

Radar data collection resulted in data sets from each of the five kits for all six interchange measurement efforts. Radar kits were set up for measurement periods varying between 1 hour and 6 hours, with most kits measuring for about 2 hours. Overall, there was data from all interchange segments except for the entrance ramp segment at Interchange 340. The data collection effort produced 30 data sets that contained 389,693 unique data points that the research team sought to reduce for use in the traffic speed analysis.

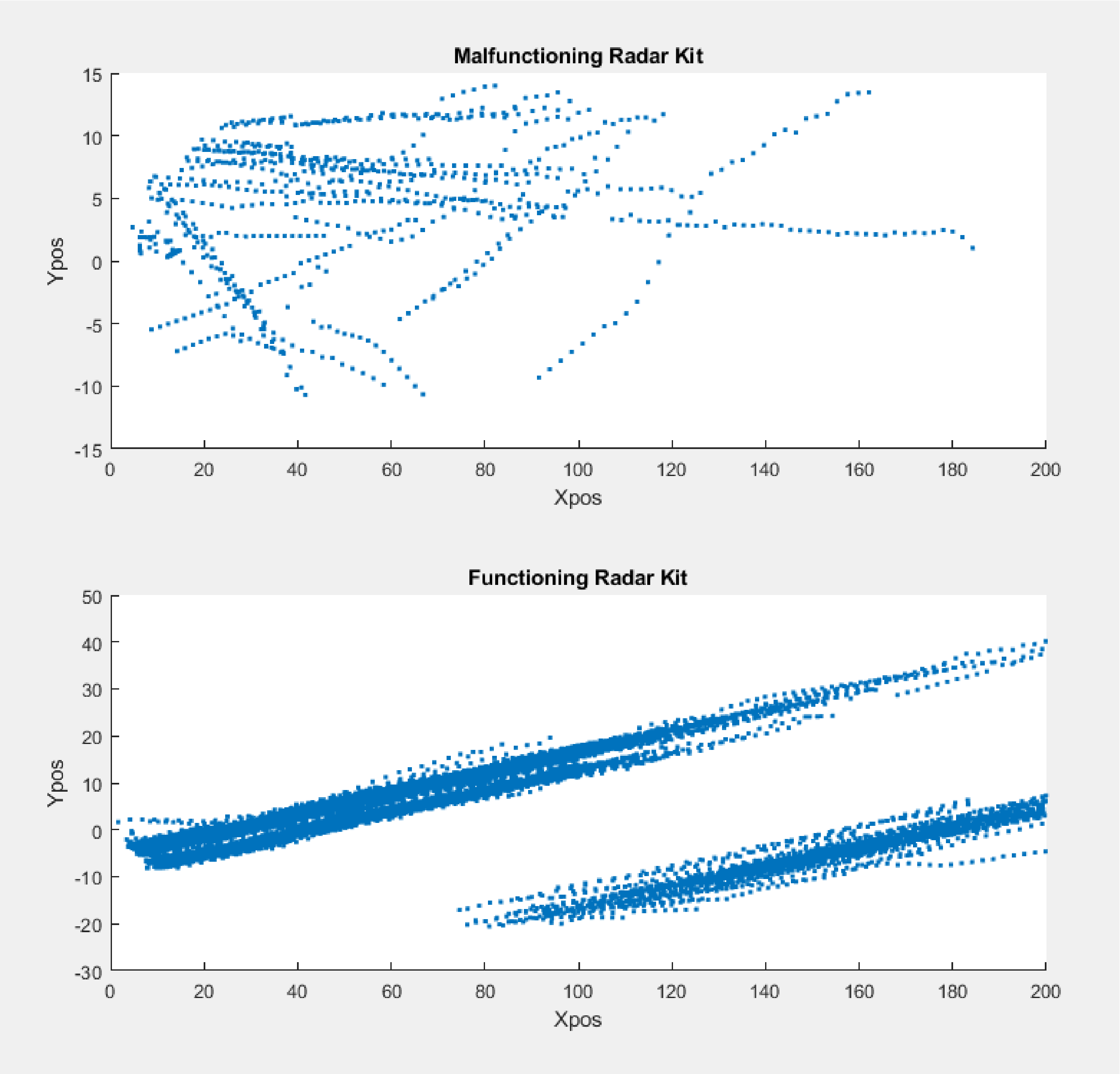

Figure 10. Image. Radar data from a kit that malfunctioned (top) which was not considered for inclusion in analysis. Good radar data from a kit set up to collect vehicles traveling through an interchange (right).

During data reduction, radar results were compiled by interchange and segment. Then, each kit was checked for consistency. Radar kits that produced measurements without a clear indication of vehicle path or lane adherence were excluded from analysis, as shown in the upper panel of Figure 10. Two of the radar kits measuring through traffic were excluded from the final analysis data set. Usable through-traffic measurements, as shown in the bottom panel of Figure 10, were included in the data reduction effort to isolate only the intended direction of travel. The radar kits reliably measured the through lanes adjacent to their placement, and all vehicles traveling in the opposite direction were removed. Reductionists determined which data points to remove by comparing the *x* and *y* position variables and removing the vehicles traveling away from the radar kit. Overall, the radar kits that were positioned to capture through vehicles primarily captured vehicles moving through the interchanges in the adjacent lane.

Data reduction also involved reducing the data collected by radar kits set up to capture vehicles entering and exiting the roadway. The research team found that radar kits that were placed in the gore points of various entrance and exit ramps captured a large percentage (80% to 95%) of vehicles traveling through the interchange in addition to the ramp traffic. This was due to the wide range of the radar kit measurement area, which made it difficult to isolate the capture of ramp traffic in a real-world environment. Thus, the research team reduced the data to separate ramp traffic, through traffic, and unusable data from the entrance and exit radar kits.

To separate vehicles by interchange segment, the radar kit data were read into MATLAB. MATLAB allowed the reductionists to visualize the vehicle tracks and carefully select only vehicles judged to be taking a ramp segment or traveling through the interchange. Figure 11 shows the results of data reduction for a radar kit that measured vehicles entering the roadway. Through-vehicle traffic was extracted from the ramp radar kits using the same methodology. Any data not clearly indicating ramp traffic or adjacent through traffic was excluded and not considered in the analysis. The number of reductionists was minimized to reduce the experimenter-to-experimenter variability when selecting useful radar data.

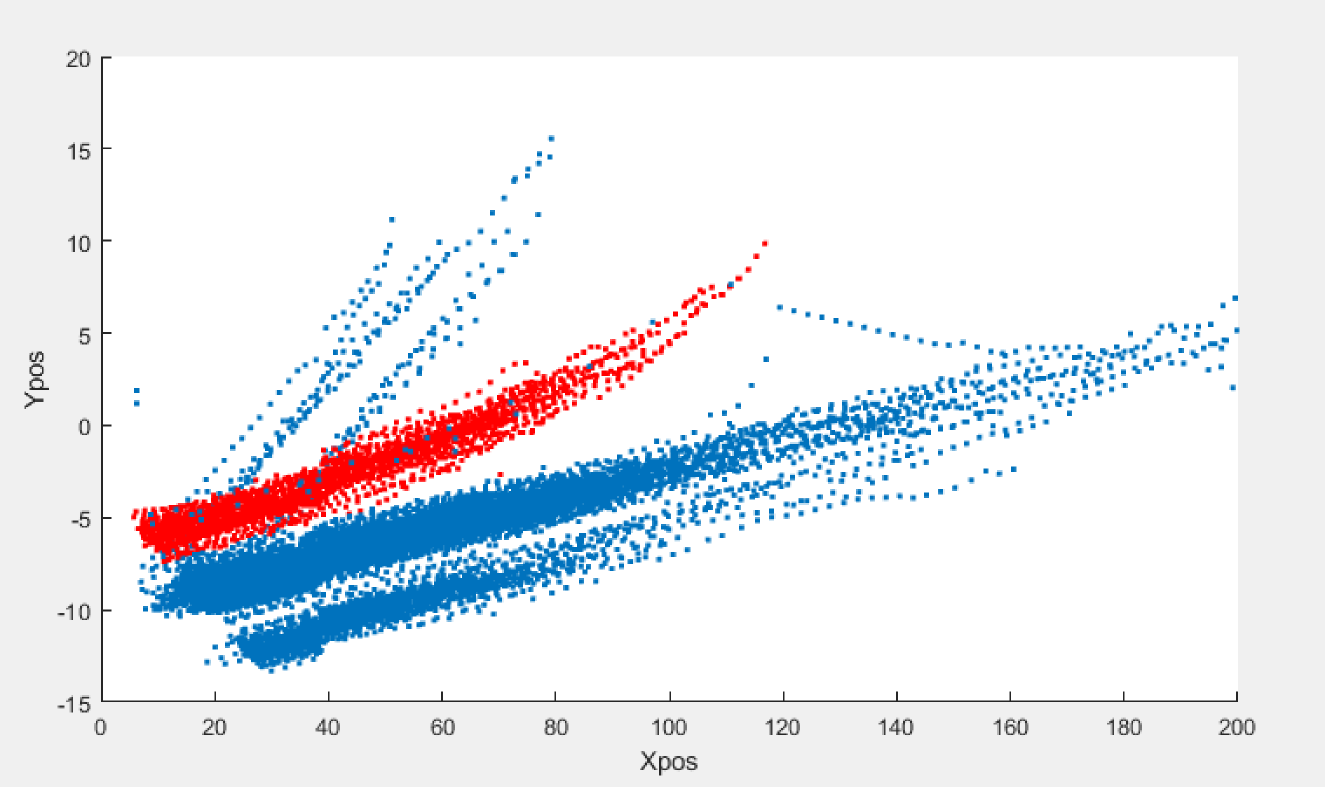

Figure 11. Image. Radar data reduction results for vehicles entering the roadway. Points highlighted in red were selected by reductionists as entering vehicles.

After reduction, the reduced data sets were merged with the raw data to produce the full radar data set, which contained all variables for the ramp and through traffic. The full data set contained vehicle position (*x* and *y*), velocity (*x* and *y*), and object IDs for each object measured by the radar kits.

Radar kit data were further processed to assign a unique vehicle ID to each object. In total, the reduction identified 13,429 unique vehicles across all ramps and through traffic. As vehicles approached the radar kits, they were measured at a rate of 10 Hz (10 cycles per second). The research team used this information to identify vehicles with a low number of measurements, and vehicles with low measurement counts were removed. Some vehicles were measured in excess of 100 times as they traveled through the target interchanges while others were only measured once or twice. To minimize uncertainty in the speed of the object being measured, the research team only included vehicles with a reasonable number of measurements taken on them. The radar kit sensor measurement frequency drove the choice for which vehicle measurements to exclude. All vehicles measured fewer than 10 times (1 second) were excluded from analysis.

After trimming low measurement vehicles, the final data set for analysis included 10,674 unique vehicles. Table 7 gives the distribution of vehicle count by interchange and segment type. The final reduction step involved calculating response measures for analysis. This included vehicle speed, which was averaged across all measurements for each unique vehicle, and standard deviation of speed.

Table 7. Vehicle Count Results of Radar Data Collection by Exit Number and Segment Type

Interchange	Entrance	Exit	Through	Row Total
318 Bright	129	164	2,238	2,531
318 Dim	26	50	1,117	1,193
322	47	36	1,282	1,365
327	135	116	2,344	2,595
335	155	167	1,223	1,545
340	0	319	1,126	1,445
Column Total	492	852	9,330	10,674 (*N*)

To supplement radar kit data, the research team collected speed limit information for all segments at each of the five target interchanges (Table 8). Speed limit was gathered using Google Street View, where the watermark tags indicated that the images were captured in August 2022. Speed limit data collection took place in April 2023. The data were verified as accurate by using experimental videos taken during data collection. Verification was needed due to potential construction efforts and roadway changes between the most recent Google Maps data and the data collection period.

Table 8. Speed Limit Data Collection Results by Interchange, Segment, and Type of Speed Limit

Interchange	Interchange Segment	Speed Limit	Type
318	Entrance	None Posted	Advisory
318	Exit	50	Advisory
318	Through	70	Enforceable
322	Entrance	None Posted	Advisory
322	Exit	50	Advisory
322	Through	70	Enforceable
327	Entrance	None Posted	Advisory
327	Exit	40	Advisory
327	Through	70	Enforceable
335	Entrance	None Posted	Advisory
335	Exit	40	Advisory
335	Through	70	Enforceable
340	Entrance	None Posted	Advisory
340	Exit	40	Advisory
340	Through	55	Enforceable

Reductionists processed the radar data so that vehicle speed could be used for the response variable in statistical modeling. A relative speed variable was created by comparing vehicle speeds to the through segment speed limit. Using relative speed, rather than measured speed, allowed comparison between interchange segments that had different speed limits. Ramp speed limits were only advisory and not enforceable by authorities, which contributed to the research team deciding to use the relative speed limits when comparing entrance and exiting traffic across interchanges. Preliminary data review also found that the through segment speed limit was a primary driving factor for vehicle speed rather than the advisory speed limits. Additionally, the radar kits captured vehicles as they were exiting or entering the through segments and did not capture the full acceleration or deceleration profiles. All analyses comparing light levels and lighting designs used the relative speed as the response variable. Analyses comparing speeds within Interchange 318 used the measured vehicle speeds as the response variable because there was no variation in speed limit.

DATA ANALYSIS

Photometric Evaluation Analysis

The photometric evaluation did not entail statistical analysis. Rather, the results were used to inform the subjective evaluation and traffic speed analyses by categorizing the lighting level of each interchange segment, which was then used as a factor in those analyses.

Subjective Evaluation Analysis

Linear Mixed Modeling

The subjective evaluation consisted of three separate analyses to answer the research questions. The first analysis evaluated differences in participant survey responses as they related to interchange lighting designs. The second analysis evaluated differences in participant survey responses as they related to light level, which were categorized during photometric analysis. The third analysis examined the influence of dimming high-mast lighting within one interchange (Interchange 318). The significance level for all statistical tests was set at $\alpha = 0.05$; *p*-values lower than the significance level were considered statistically significant.

For the lighting design and light level analyses, all models were fit using a linear mixed modeling (LMM) procedure for repeated measures. Each analysis included lighting design or light level and age as fixed effects. Participant-to-participant variation was included as a random effect. Additionally, the models also included the interaction between either lighting design or light level and age to test if lighting design or light level affected participant response within either age group (young, old). All main effects were kept in the model to preserve hierarchy regardless of their significance.

Where the LMMs found a significant result, post hoc analyses were performed to determine which factor levels were significantly different. Pairwise comparisons were conducted using a differences of least-squares means procedure. Comparisons requiring multiple post hoc tests were corrected using Tukey's honest significant difference to keep the familywise error rate at 0.05.

Researchers had the capability to manipulate the roadway lighting levels at Interchange 318, which contained high-mast lighting. This capability facilitated an assessment of the effect of dim level. The dim level was a between-subject variable with each participant driving under either full strength or 50% dimmed high-mast lighting at Interchange 318. All participants drove through Interchange 318 in both directions.

For the dim level analyses, a repeated measures mixed model was built for each of the survey question groupings. The modeling effort used the fixed effects of dim level and age and the random effect of participant. Each model also included the interaction between dim level and age to test if dim level was having an impact on target detection within either age group (young, old). All main effects were kept in the model to preserve hierarchy regardless of their significance.

Overall, researchers performed 21 separate LMM analyses to assess the impact of lighting design, light level, dimming, and age on participant survey response. These analyses are detailed in the results section and discuss each question grouping separately.

Cronbach's Alpha Test

The human factors participant survey effort consisted of 11 questions spanning five dimensions: target detection, safety, comfort, visibility, and discomfort glare. A Cronbach's alpha test was performed to determine if the answers to questions intended to measure the same dimension were in fact correlated so that the answers to each could be combined into a single, more reliable measure. Cronbach's alpha was calculated using Figure 12.

$$\alpha = \frac{N * \overline{c}}{\overline{v} + (N-1) * \overline{c}}$$

Figure 12. Equation. Cronbach's alpha equation.

Safety, comfort, and visibility preference areas each had three questions that were investigated for internal consistency between questionnaire statements. Resulting alpha values were evaluated using Table 9. Researchers set a threshold of acceptable alpha values at 0.7, where values less than 0.7 were not considered to have enough inter-item reliability. Additionally, values over 0.95 would be considered too high and indicate redundancy in the question statements (Habidin et al., 2015). Researchers only considered the standardized Cronbach's alpha values.

Table 9. Rule of Thumb Table for Interpreting Alpha for Likert Scale Questions (Habidin et al., 2015)

Cronbach's Alpha	Internal Consistency
$\alpha \geq 0.9$	Excellent
$0.9 \geq \alpha \geq 0.8$	Good
$0.8 \geq \alpha \geq 0.7$	Acceptable
$0.7 \geq \alpha \geq 0.6$	Questionable
$0.6 \geq \alpha \geq 0.5$	Poor
$0.5 > \alpha$	Unacceptable

Cronbach's alpha assessment found that safety (0.93) and comfort (0.92) questionnaire cohorts had excellent measures of internal consistency, while the visibility (0.29) cohort had an unacceptable level of internal consistency. All cohort groupings for the assessment, sample sizes, and resulting alpha values are shown in Table 10.

Table 10. Cronbach's Alpha Procedure Results

Question Group	Question 1	Question 2	Question 3	Sample Size (*n*)	Variable	Alpha (α)
Comfort	I would feel comfortable driving through the interchange with this type of lighting.	I would feel comfortable taking the exit with this type of lighting.	I would feel comfortable entering the interstate in this type of lighting.	175	Standardized	0.927
Safety	I would feel safe driving through the interchange with this type of lighting.	I would feel safe taking the exit with this type of lighting.	I would feel safe entering the interstate in this type of lighting.	173	Standardized	0.939
Visibility	This lighting allowed me to clearly see the exits and entrances at the interchange.	There is too much light on the road.	There is not enough light on the road.	174	Standardized	0.296

As informed by Cronbach's alpha procedure, the research team created composite Likert scale (Table 12) scores for the safety and comfort questionnaire cohorts by averaging values across the grouped questionnaire statements (Boone & Boone, 2012; Sullivan & Artino, 2013). Subsequent analyses were performed using the new question groupings, as shown in Table 11. Because safety and comfort had excellent Cronbach's alpha values, they were grouped for analysis. However, no combination of visibility cohort questions had an acceptable measure of reliability, and therefore each question was evaluated separately.

Table 11. Survey Questions Asked to Participants and Their Grouping for Analysis

Survey Question	Survey Question Number	Analysis Question Grouping
If you saw any targets at this interchange how many did you see?	1	1
This lighting allowed me to clearly see the exits and entrances at the interchange.	2	2
I would feel comfortable driving through the interchange with this type of lighting.	3	3
I would feel comfortable taking the exit with this type of lighting.	4	3
I would feel comfortable entering the interstate in this type of lighting.	5	3
I would feel safe driving through the interchange with this type of lighting.	6	4
I would feel safe taking the exit with this type of lighting.	7	4
I would feel safe entering the interstate in this type of lighting.	8	4
There is too much light on the road.	9	5
There is not enough light on the road.	10	6
Please rate your level of discomfort glare by using the following rating scale and checking the number that closely matches your perception of discomfort glare in the present condition.	11	7

Table 12. Five-point Likert Scale Used to Assess Participant Sentiment for Question Groups 2, 3, 4, 5, and 6. Scale Was Prompted by the Statement "Please indicate how strongly you agree or disagree with the following statements."

Scale Wording	Scale Number
Strongly Disagree	1
Disagree	2
Neutral	3
Agree	4
Strongly Agree	5

Traffic Speed Evaluation Analysis

The traffic speed evaluation consisted of three separate analyses to answer the research questions. For each analysis, traffic speed was assessed for two measures of driver behavior. The first response measure was participant speed. Analyses that compared factors between interchanges used speed relative to the mainline speed limit as the response variable, due to variation in speed limit. The analysis comparing dim level within Interchange 318 used the measured speeds as the response variable. The second response measure was speed variation. All speed variation analyses used the standard deviation of speed as the response variable. The significance level for all statistical tests was set at α = 0.05; *p*-values lower than the significance level were considered statistically significant.

The first analysis evaluated differences in participant speed behavior between the different interchange lighting designs. The second analysis evaluated differences in participant speed behavior between each of the light levels categorized during photometric evaluation. The third analysis looked at the influence of dimming high-mast lighting within one interchange (Interchange 318). All models were fit using an LMM procedure, and each analysis included interchange segment and lighting design or light level as fixed effects and approach direction as a random effect. Approach direction was included to account for variation in visual complexity, interchange layout, etc. as vehicles drove toward the study interchanges.

Where the LMMs produced a significant result, post hoc analyses were performed to determine which factor levels were significantly different. Pairwise comparisons were conducted using a differences of least-squares means procedure. Comparisons requiring multiple post hoc tests were corrected using Tukey's honest significant difference to keep the familywise error rate at 0.05.

Table 13. Descriptive Statistical Results of Radar Data Collection by Interchange Exit Number and Segment Type. Speeds Are Reported in mph

Interchange	Interchange Segment	Vehicle Count (*n*)	Avg. Speed	Std. Dev. Speed	Min. Speed	Max. Speed
318 Bright	Entrance	129	59.5	1.0	25.5	80.6
318 Bright	Exit	164	59.1	1.9	27.1	80.6
318 Bright	Through	2238	72.7	0.3	30.0	95.1
318 Dim	Entrance	26	58.1	0.6	44.9	69.9
318 Dim	Exit	50	55.2	1.7	36.7	69.8
318 Dim	Through	1117	71.0	0.3	11.1	94.0
322	Entrance	47	57.9	0.9	39.5	80.6
322	Exit	36	56.2	2.3	42.0	87.5
322	Through	1282	69.9	0.5	34.1	94.9
327	Entrance	135	52.5	0.9	31.0	81.4
327	Exit	116	52.3	2.1	29.1	90.0
327	Through	2344	69.3	0.3	19.2	94.9
335	Entrance	155	49.0	1.0	23.0	80.3
335	Exit	167	47.5	2.2	23.1	79.6
335	Through	1223	70.3	0.3	32.6	95.5
340	Entrance	0				
340	Exit	319	48.4	2.7	24.0	89.1
340	Through	1126	63.9	0.8	7.9	95.0

For speed and speed variation analyses, the data were analyzed within interchange segments. The research team expected differences in driver behavior between segment types. For example, drivers traveling through the interchange would be expected to have higher measured speeds than those taking the ramps. Additionally, researchers anticipated a difference in speed variation, as vehicles traveling through the interchange would not need to alter their speed much while those taking ramps would need to accelerate to match the traffic flow speeds or decelerate to safely navigate an exit ramp. A summary of the data is provided in Table 13. The table provides descriptive statistics, which include number of vehicles measured (*n*), arithmetic mean, standard deviation, and minimum and maximum speed values. Formal statistical analysis is presented in the results section.

Overall, researchers performed six separate LMM analyses to assess the impact of lighting design, light level, dimming, and age on participant speed and speed variation. These analyses are detailed in the results section, and the results are discussed by interchange segment.

CHAPTER 3: RESULTS

This section discusses the results of the different evaluation efforts. The dependent and independent variables are listed in Table 14 and Table 15, respectively.

Table 14. Dependent Variables and Description

Dependent Variable	Data Type	Levels / Range	Description
Targets Detected	Discrete	0 to 4	Number of targets detected by participants as they traveled past the interchange. While the maximum number of targets that a participant could see would have been 3, the answer scale ranged from 0 to 4 as to not give away how many targets might be present.
Discomfort Glare Rating	Discrete	0 to 6	Discomfort glare rated by participants as they traveled through the interchange
Preference (Likert Scale)	Discrete	1 to 5	Preference rated on a 5-point Likert scale
Speed (mph)	Continuous	30 to 85 mph	The speed of vehicles measured by radar as they passed through the interchange segments
Relative Speed (mph)	Continuous	−50 to 49 mph	The speed of vehicles relative to the posted mainline speed limit measured by radar as they passed through the interchange
Standard Deviation of Speed (mph)	Continuous	0.0016 to 10 mph	The standard deviation of speed calculated for each vehicle measured by the radar kits

Table 15. Independent Variables and Their Factor Levels

Independent Variable	Effect Type	Levels	Description
Age	Fixed	Young, Old	Age of participants grouped into young and old categories
Dim Level	Fixed	Bright, Dim	The dim level of the lighting at Interchange 318 categorized as “bright” (100% brightness) and “dim” (50% brightness)
Light Level	Fixed	Low, Medium, High	The measured light levels along each roadway segment categorized as Low (0~7 lx), Med (7~12 lx), or High (>12 lx)
Lighting Design	Fixed	Conventional, Conventional Exit Only, High-Mast, High-Mast & Conventional, Partial High-Mast	Each interchange was categorized by the lighting design so that comparisons could be made across types of lighting designs.
Direction	Random	Northbound, Southbound	Included in analyses to account for random differences between the northbound and southbound lanes of each interchange (e.g., visual complexity on approach)
Participant Number	Random	Participants 1 to 18	Included in analyses to account for random differences among participants

PHOTOMETRIC EVALUATION RESULTS

For each interchange, the research team summarized photometric evaluation results by interchange segment, with the interchange at Exit 318 being measured twice: once at full luminaire strength (100%) and once while dimmed (50%). Illuminance measurements were averaged for all points along each segment within a given interchange. The photometric data results are summarized in Table 16.

Due to the frequency of measurements, the RLMMS captured minimum values close to zero for every segment across all interchanges except for two. Uniformity calculations performed by the research team compared the average horizontal illuminance to the minimum value. This resulted in unnaturally high uniformity ratios. As a result, uniformity was not a useful metric in any of the subsequent analyses.

Illuminance by Interchange Segment

Horizontal illuminance data were categorized into low, medium, and high for use as a categorical variable in analysis. Gibbons et al. (2014) presents tabular illuminance ranges categorizing horizontal and vertical values, in lux, into levels ranging from 0 to 7. The results of Gibbons et al. (2014) helped to inform the selection of bin ranges for categorizing illuminance data. Researchers assigned low values to all segments measuring approximately 7 lux or less, medium values to segments measuring between approximately 7 and 12 lux, and high values to segments measuring above approximately 12 lux. In total, five segments were found to be low light level, seven segments were measured at medium light level, and six segments were measured at the high light level.

Table 16. RLMMS Photometric Analysis Results. Illuminance Values Are Reported in lux and Averaged by Segment for All Interchanges

Interchange Number	Lighting Design	Interchange Segment	Light Level	Horizontal Illum (lx)	Vertical Illum (lx)
318	High-Mast Bright	Entrance	Medium	11.02	0.91
318	High-Mast Bright	Exit	High	14.59	1.71
318	High-Mast Bright	Through	Medium	11.11	1.98
318	High-Mast Dim	Entrance	Low	6.84	0.46
318	High-Mast Dim	Exit	Medium	8.79	0.89
318	High-Mast Dim	Through	Low	7.02	1.11
322	Partial High-Mast	Entrance	Low	0.47	0.48
322	Partial High-Mast	Exit	Low	3.05	0.77
322	Partial High-Mast	Through	Low	0.92	0.52
327	Conventional Exit Only	Entrance	Medium	8.79	0.81
327	Conventional Exit Only	Exit	Medium	9.14	0.88
327	Conventional Exit Only	Through	Medium	12.28	0.67
335	Conventional	Entrance	High	16.39	1.04
335	Conventional	Exit	High	15.23	1.64
335	Conventional	Through	Medium	11.76	1.32
340	High-Mast & Conventional	Entrance	High	17.96	1.76
340	High-Mast & Conventional	Exit	High	16.44	1.78
340	High-Mast & Conventional	Through	High	14.57	2.11

Overall, photometric data evaluation found that vertical illuminance levels were, on average, between 0.45 and 2.15 lux for all interchange segments across all interchanges. Horizontal illuminance, on average, ranged between 0.90 and 18 lux across all interchanges and segments.

The average horizontal illuminance for through segments ranged between 0.92 to 14.57 lux across all interchanges. Two through segments were measured at low light level, three at medium light level, and one at high light level. The average horizontal illuminance for entrance ramp segments ranged from 0.45 to 17.96 lux across all interchanges. Two entrance segments were measured at low light level, two at medium light level, and two at high light level. The average horizontal illuminance for exit ramp segments ranged from 3.05 to 16.44 lux. One exit segment was measured at low light level, two at medium light level, and three at high light level.

The average vertical illuminance for through segments varied between 0.52 to 2.11 lux, while average vertical illuminance for entrance ramp segments varied between 0.45 to 1.75 lux, and average vertical illuminance for exit ramp segments ranged from 0.88 to 1.78 lux.

Overall, the highest vertical illuminance was measured at Interchange 340, which used high-mast and conventional lighting, and Interchange 318 at full brightness, which used high-mast lighting. The highest horizontal illuminance measurements occurred at Interchange 340 and at Interchange 335, which used conventional lighting. Across all interchanges and segments, the horizontal illuminance measurements varied considerably, while, in contrast, vertical illuminance was reasonably consistent between interchanges and segments.

Illuminance by Approach Segment

Additionally, researchers were interested in the impact roadway lighting, adjacent commercial lighting, and ambient lighting had on vehicles as they approached the target study interchanges. To address this question, a photometric evaluation considered the lighting conditions participants would have experienced as they approached the target interchanges from both directions. Data were compiled for analysis segments of 1 mile extending north and south of each interchange. Horizontal illuminance and vertical illuminance were calculated for all approach analysis segments and are reported in Table 17.

Evaluation of the photometric approach data found that horizontal and vertical illuminance varied between interchanges and by approach direction within some interchanges. Interchanges 318 and 322 had an average horizontal illuminance on approach between 0.18 and 0.25 lux that was consistent across approach directions. Interchange 327 had an average horizontal illuminance of 0.26 lux when approaching from the north, which was significantly lower than when approaching from the south (1.73 lux). Interchanges 335 and 340 had considerably higher horizontal illumination on approach than Interchanges 318, 322, and 327. At Interchange 335, the average horizontal illuminance was consistent regardless of approach direction (Table 17). However, horizontal illuminance when approaching Interchange 340 from the south (20.35 lux) was 77% higher than when approaching from the north (11.50 lux). Across all interchange and approach segments, the area south of Interchange 340 had the highest horizontal illuminance.

Table 17. Photometric Data Descriptive Statistics for 1 Mile Approach to Each Study Interchange from Northbound and Southbound

Interchange	Dim Level	Approach Direction	Measurement Type	Horizontal Illum (lx)	Vertical Illum (lx)
318	Bright	South	Approach	0.25	0.25
318	Dim	South	Approach	0.22	0.29
318	Bright	North	Approach	0.20	0.32
318	Dim	North	Approach	0.18	0.30
322	Bright	South	Approach	0.20	0.33
322	Bright	North	Approach	0.22	0.25
327	Bright	South	Approach	1.73	0.32
327	Bright	North	Approach	0.26	0.31
335	Bright	South	Approach	13.46	1.13
335	Bright	North	Approach	13.83	1.17
340	Bright	South	Approach	20.35	2.03
340	Bright	North	Approach	11.50	1.52

Vertical illuminance was very consistent across Interchanges 318, 322, and 327. The average vertical illuminance ranged between 0.25 and 0.33 lux across approach direction. Similarly, vertical illuminance was consistent at Interchange 335 regardless of approach direction. However, the approach measurements north (1.13 lux) and south (1.17 lux) of Interchange 335 were significantly higher than for Interchanges 318, 322, and 327. Vehicles approaching Interchange 340 experienced the most vertical illuminance. Vehicles approaching from the north experienced a vertical illuminance of 1.52 lux, while drivers approaching Interchange 340 from the south (2.03 lux) experienced the highest vertical illuminance of any approach segment.

For further analysis, the research team considered the results of the photometric evaluation and concluded that a difference in light level by approach direction could impact the visual conditions and unduly influence driver speed behavior. Visual complexity, as anecdotally assessed by experimenters and checked using satellite images, was not consistent across all interchanges and directions on travel. Therefore, researchers decided to include the influence of direction as a random effect when modeling vehicle speed and vehicle speed variation.

Illuminance Heatmaps by Interchange

Data recorded for the photometric evaluation are presented here visually as illuminance heatmaps for each interchange. These heatmaps are included to help visualize the differences in lighting among the interchanges. Please note that the horizontal and vertical illuminance heatmaps use a different scale. The range of vertical illuminance data was much smaller, so a smaller scale was used to highlight differences.

High-Mast at Interchange 318

Figure 13 shows the illuminance heatmaps for Interchange 318 at full brightness and at the 50% dim level. This interchange used a high-mast lighting design, and there was no lighting in the approach segments. Conventional lighting was present at the cross-street intersections and was included in the results, however, only spill over light from poles located on the cross-street was captured. Interchange 318 was the only interchange examined at two dim levels.

Figure 13. Photo. Horizontal illuminance (left) and vertical illuminance (right) heatmaps for Interchange 318 (High-Mast) while at full brightness (top) and dimmed to 50% (bottom).

Conventional Exit Only at Interchange 322

Figure 14 shows the illuminance heatmap for Interchange 322, which uses conventional lighting only at the gore point of the exit ramps. Conventional lighting was present at the cross-street intersections and was included in the results; however, only spill over light from poles located on the cross-street was captured. This lighting design is referred to as Conventional Exit Only in the results. Interchange 322 did not have any lighting in the approach segments.

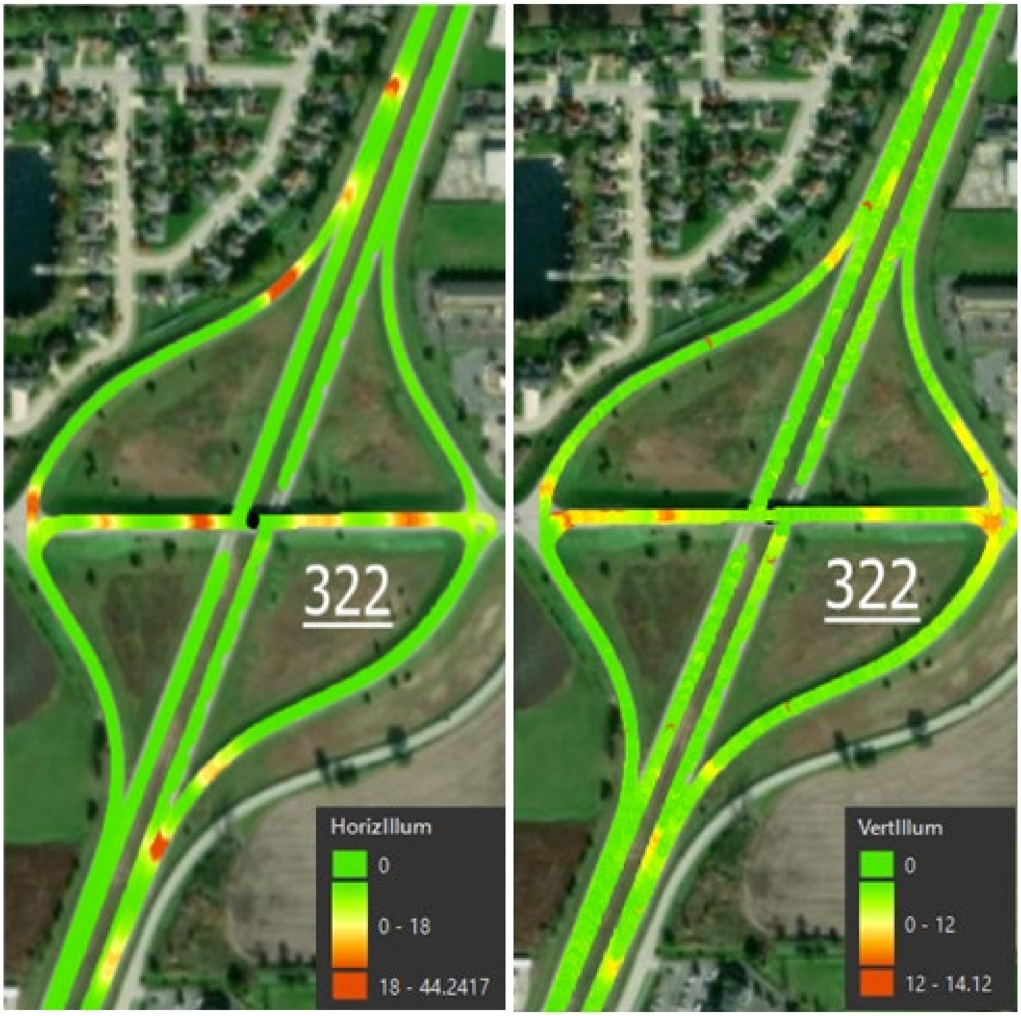

Figure 14. Photo. Horizontal illuminance (left) and vertical illuminance (right) heatmaps for Interchange 322 (conventional exit only).

Partial High-Mast at Interchange 327

Figure 15 shows the illuminance heatmaps for Interchange 327. This interchange used a high-mast lighting design with a total of four towers placed in the median: two just before and after the gore points on either end. Conventional lighting was present at the cross-street intersections and was included in the results. No lighting infrastructure was present for the cross-street section travelling over I-57. This lighting design is referred to as Partial High-Mast in the results. There was no lighting in the approach segments for Interchange 327.

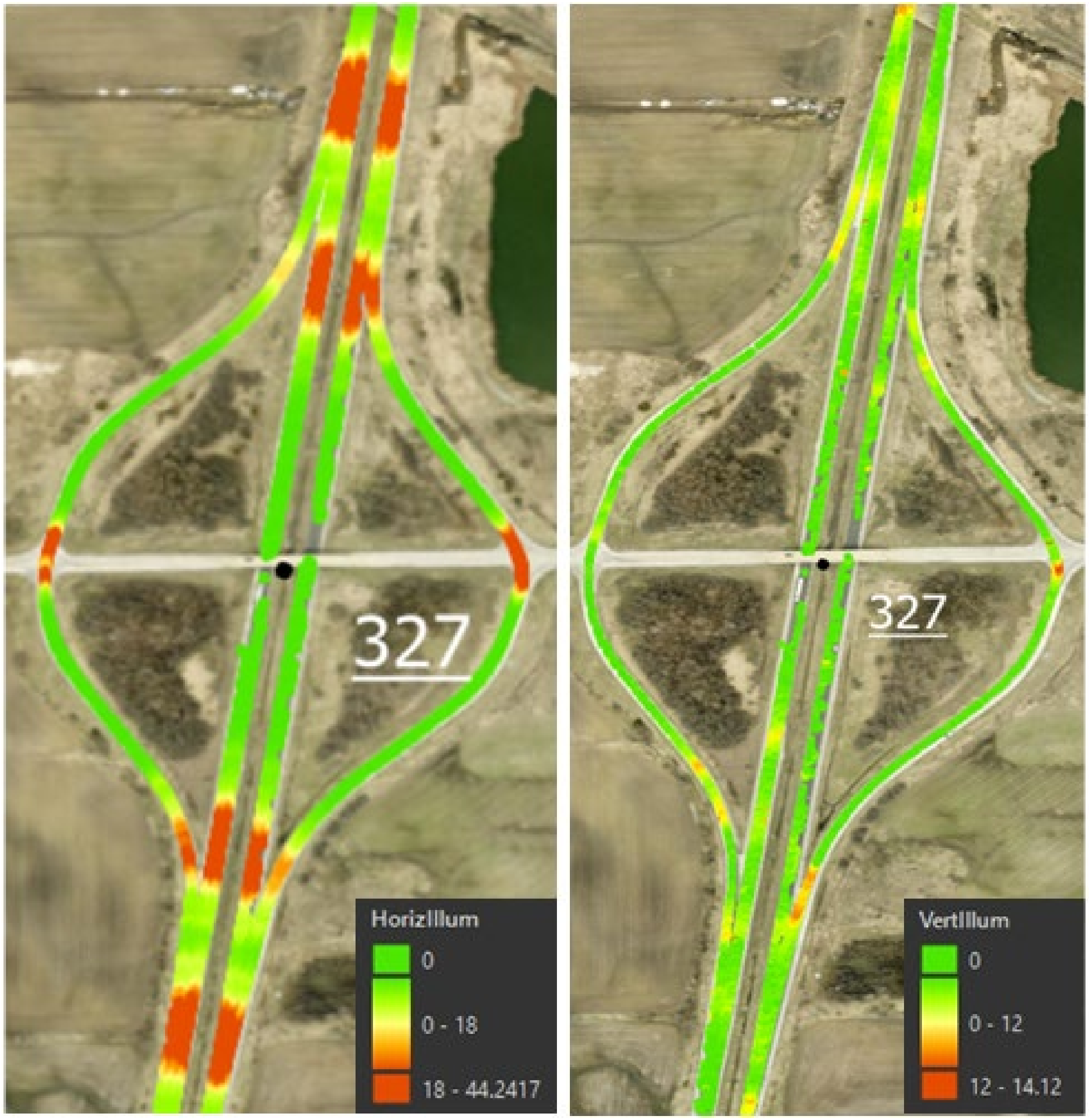

Figure 15. Photo. Horizontal illuminance (left) and vertical illuminance (right) heatmaps for Interchange 327 (partial high mast).

Conventional at Interchange 335

Figure 16 shows the illuminance heatmaps for Interchange 335. This interchange used conventional lighting throughout the interchange and extending into the approach segments. Conventional lighting was present at the cross-street intersections and was included in the results; however, only spill over light from poles located along the cross-street was captured. The high vertical illuminance values found at the end of the northbound exit ramp may be partially attributed to lighting associated with the gas station across the street, as shown in Figure 17.

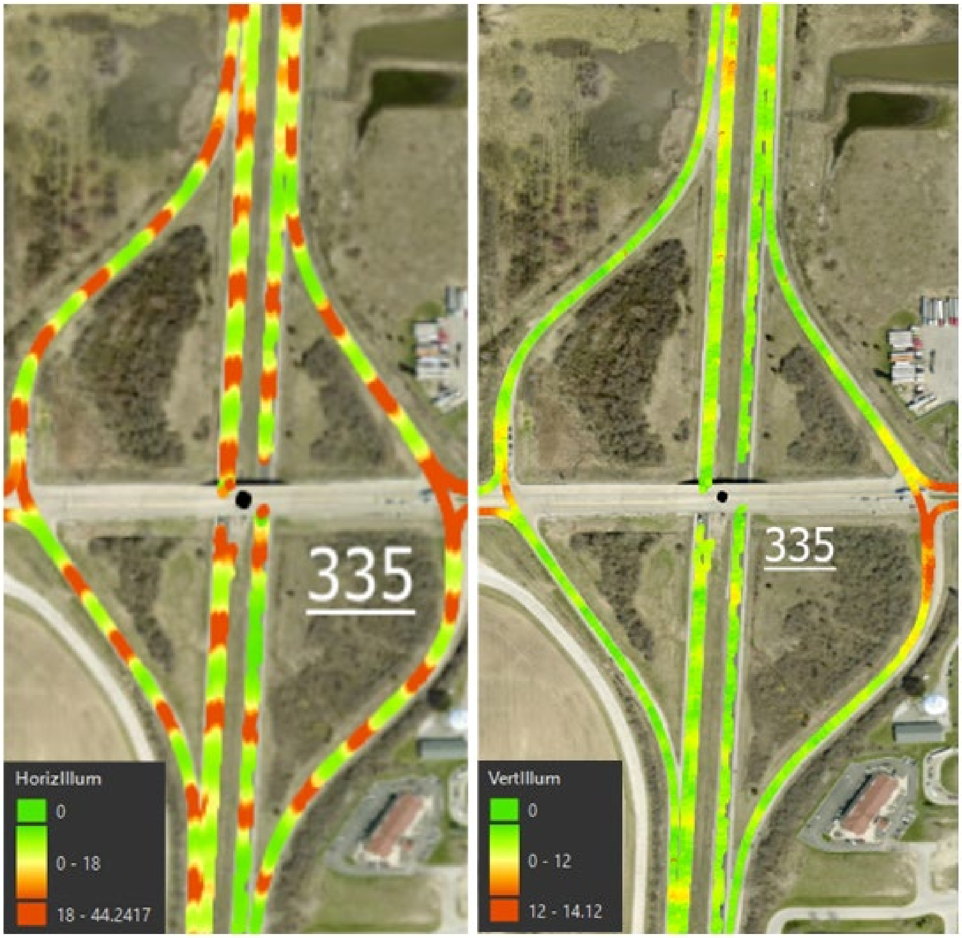

Figure 16. Photo. Horizontal illuminance (left) and vertical illuminance (right) heatmaps for Interchange 335 (conventional).

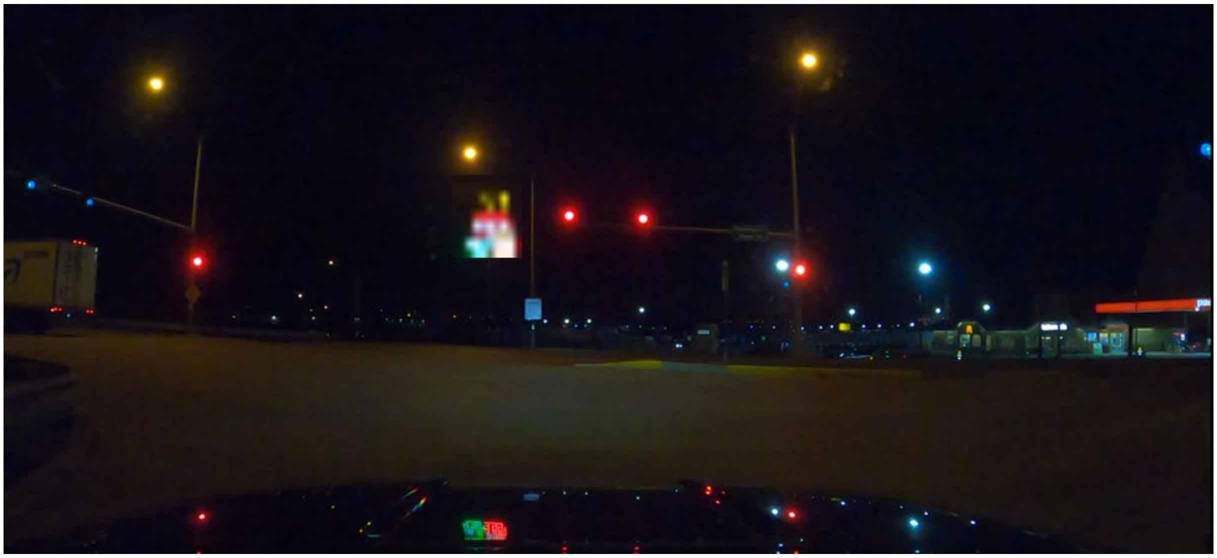

Figure 17. Photo. Sources of vertical illuminance at the end of the northbound exit ramp for Interchange 335 (conventional).

High-Mast & Conventional at Interchange 340

Figure 18 shows the illuminance heatmaps for Interchange 340. This interchange used a combination of conventional and high-mast lighting throughout the interchange. Conventional lighting was present at the cross-street intersections and was included in the results; however, only spill over light from poles located along the cross-street and loops were captured. The conventional lighting also extended into the approach segments on both sides of the interchange; however, a difference in light level was discovered between the approach directions, with vehicles approaching from the north having a lower light level. This is discussed further in later sections of the report.

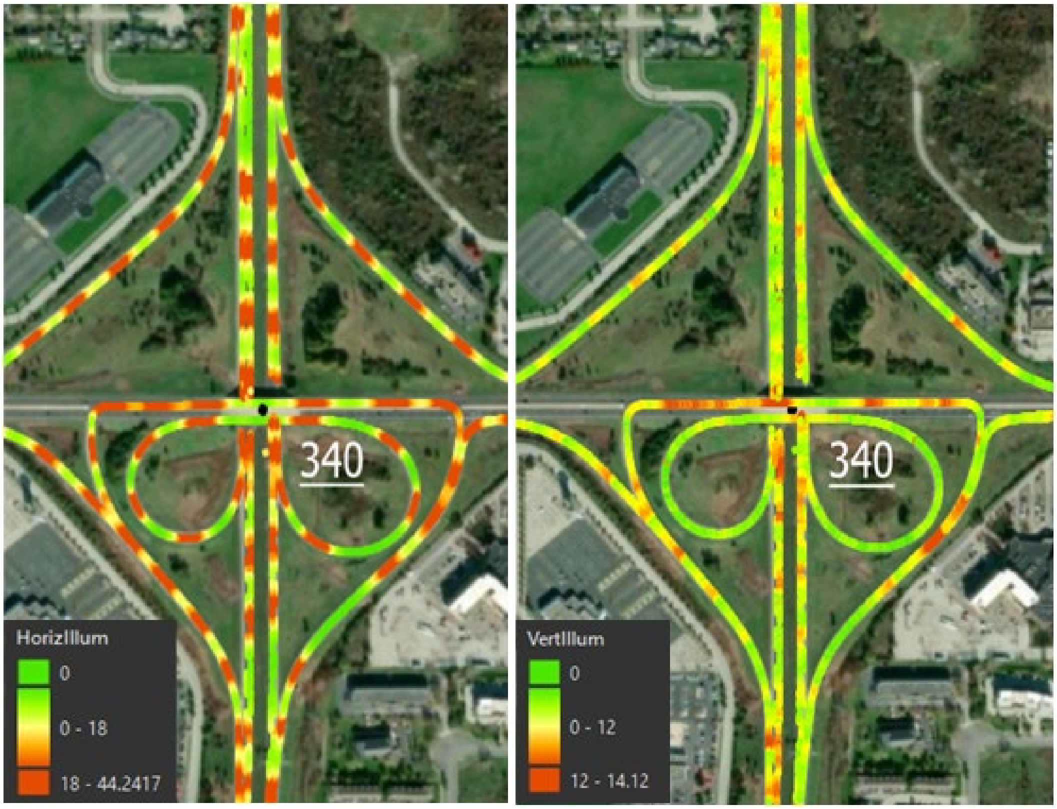

Figure 18. Photo. Horizontal illuminance (left) and vertical illuminance (right) heatmaps for Interchange 340 (high mast and conventional).

SUBJECTIVE EVALUATION RESULTS

The results of the subjective evaluation are discussed below, organized by question and independent variable (i.e., lighting design and lighting level).

Question 1: Target Detection

Lighting Design

The results of the LMM for Question 1 regarding lighting design are summarized in Table 18. The main effects of lighting design and age were not significant, and the two-way interaction involving these two variables was also not significant.

Table 18. Target Detection Task: Type 3 Tests of Fixed Effects for Age, Lighting Design, and the Interaction between Age and Lighting Design

Question Group	Effect	Num DF	Den DF	*F* Value	*p*-Value
Target Detection	Age (A)	1	16.9	2.39	0.1404
	Lighting Design (LD)	4	69.6	1.3	0.2777
	A*LD	4	69.6	1.12	0.3542

Bolded p-values were considered statistically significant.

Light Level

The results of the LMM for Question 1 regarding light level are summarized in Table 19. The main effects of light level and age were not significant, and the two-way interaction involving these two variables was also not significant. The research team did not perform a follow-up analysis for Question 1 because none of the model terms indicated significant effect.

Table 19. Target Detection Task: Type 3 Tests of Fixed Effects for Age, Light Level, and the Interaction between Age and Light Level

Question Group	Effect	Num DF	Den DF	*F* Value	*p*-Value
Target Detection	Age (A)	1	16	2.01	0.175
	Light Level (LL)	2	76.4	0.9	0.4089
	A*LL	2	76.4	1.73	0.1836

Bolded p-values were considered statistically significant.

Question 2: Visibility of Ramps

Lighting Design

The results of the LMM for Question 2 regarding lighting design are summarized in Table 20. The main effect of lighting design was significant, while the main effect of age and the two-way interaction involving lighting design and age was not significant. Post hoc comparisons were performed to determine which lighting designs resulted in significantly different participant perception of visibility of ramp segments.

Table 20. Ramp Visibility Survey: Type 3 Tests of Fixed Effects for Age, Lighting Design, and the Interaction between Age and Lighting Design

Question Group	Effect	Num DF	Den DF	*F* Value	*p*-Value
Visibility of Ramps (Entrance and Exit)	Age (A)	1	16.1	1.56	0.2293
	Lighting Design (LD)	4	84.5	13.19	**<.0001**
	A*LD	4	84.5	0.89	0.4747

Bolded p-values were considered statistically significant.

Least-squares means and post hoc comparison results are presented in Figure 19. After adjusting for multiple tests, several lighting design comparisons were found to result in significantly different participant opinions of ramp visibility. Overall, participants rated ramp visibility as no opinion/neutral or better for all lighting designs. When driving under High-Mast (mean = 4.37), Conventional (mean =

4.03), and High-Mast & Conventional lighting (mean = 4.30), participant ratings ranged from agreed to strongly agreed that these lighting designs allowed them to clearly see the interchange ramp segments. All three lighting designs were rated as providing significantly more ramp visibility than Partial High-Mast (mean = 3.02) or Conventional Exit Only lighting (mean = 3.61). Partial High-Mast lighting was rated 16.2% lower than any other lighting design for ramp visibility, but this rating equated to a neutral opinion by participants.

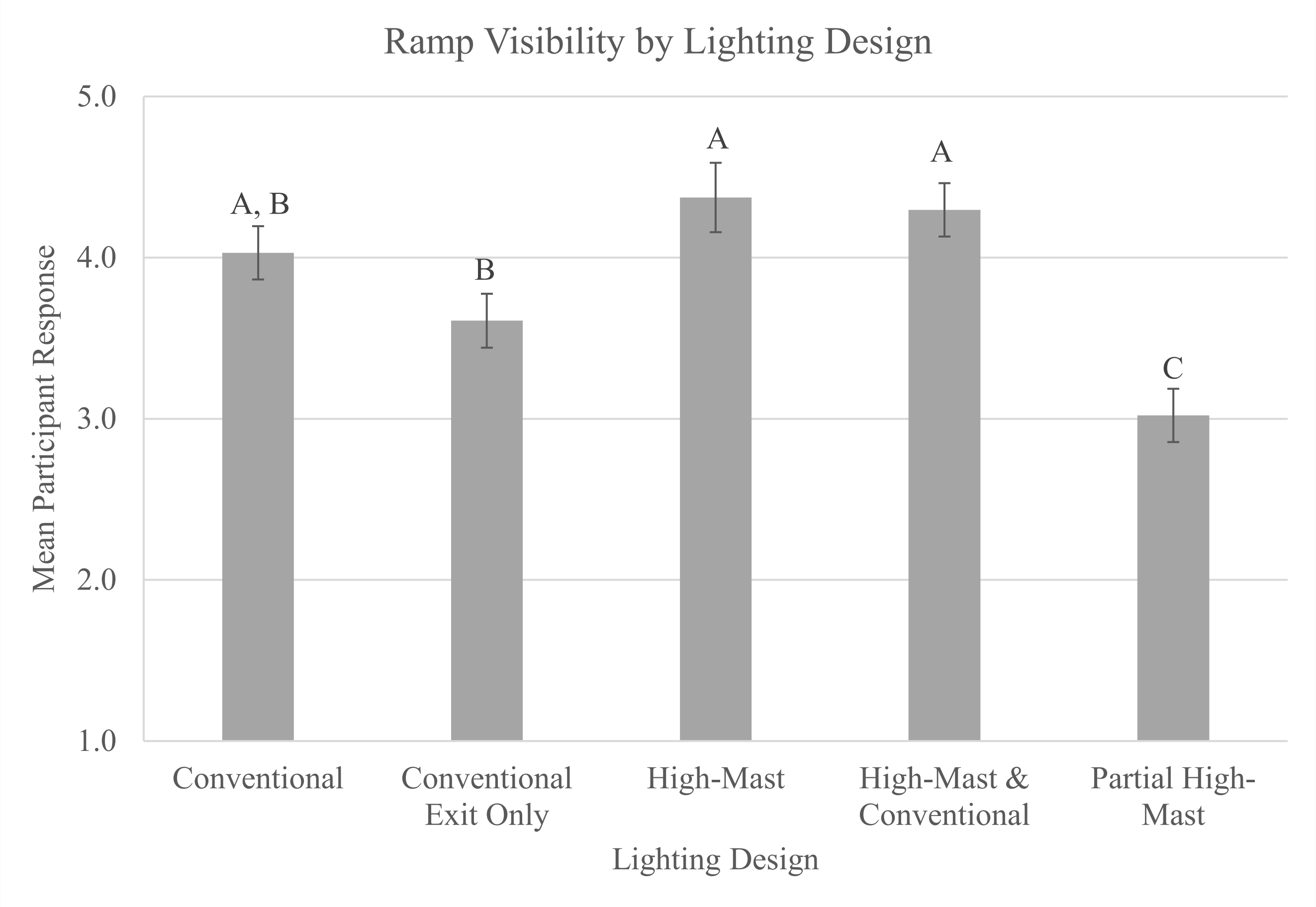

Figure 19. Graph. Ramp visibility survey results by lighting design. Data are reported for mean participant response, and the error bars represent standard error. Uppercase letters indicate post hoc grouping from pairwise comparisons.

Light Level

The results of the LMM for Question 2 regarding light level are summarized in Table 21. Only the main effect of light level was significant. Post hoc comparisons were performed to determine which light level comparisons resulted in significantly different participant opinion about the visibility of ramp segments.

Table 21. Ramp Visibility Survey: Type 3 Tests of Fixed Effects for Age, Light Level, and the Interaction between Age and Light Level

Question Group	Effect	Num DF	Den DF	*F* Value	*p*-Value
Visibility of Ramps (Entrance and Exit)	Age (A)	1	16.3	1.32	0.2672
	Light Level (LL)	2	88.6	7.48	**0.001**
	A*LL	2	88.6	0.98	0.3785

Bolded p-values were considered statistically significant.

Least-squares means and pairwise comparisons for participant ramp visibility rating by lighting level are presented in Figure 20. After adjusting for multiple tests, two light level comparisons were found to result in significantly different ramp visibility sentiment. Overall, across all light levels and ages, participants either felt no opinion/neutral or agreed that the interchange lighting allowed them to clearly see ramp segments. Interchanges measured as having medium light level (mean = 3.54) were rated the lowest by participants. Interchanges with high light level (mean = 4.24) were rated 19.7% higher than the medium light level interchanges. Interchanges with a low light level (mean = 3.79) were not rated significantly different than high or medium.

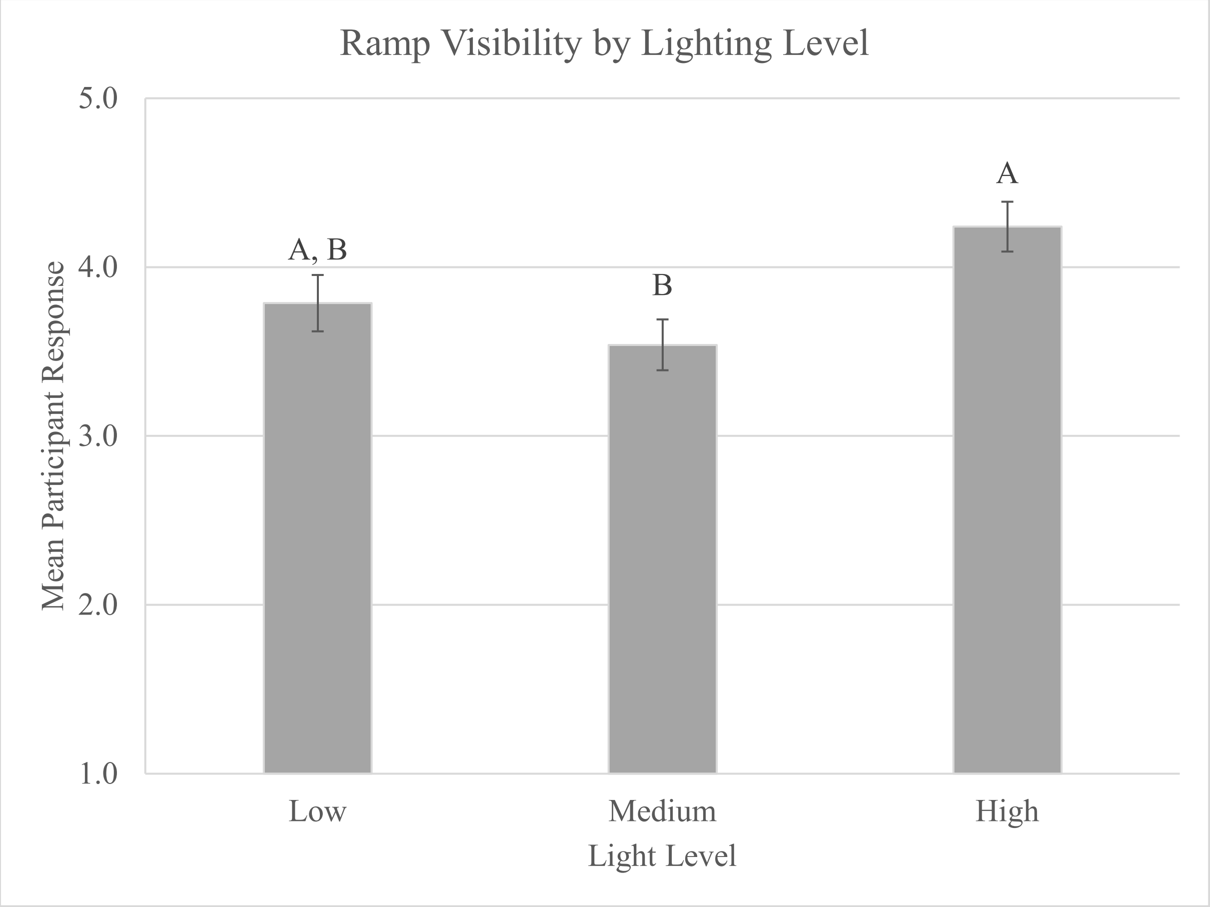

Figure 20. Graph. Ramp visibility survey results by light level. Data are reported for mean participant response, and the error bars represent standard error. Uppercase letters indicate post hoc grouping from pairwise comparisons.

Question 3: Comfort

Lighting Design

The results of the LMM for Question 3 regarding lighting design are summarized in Table 22. Modeling results showed that participant comfort sentiment was significantly different between at least two lighting designs. No significance was found between the age groups or the two-way interaction involving age and lighting design. Follow-up analysis for Question 3 focused on the differences in participant comfort between the factor levels of lighting design.

Table 22. Participant Comfort Survey: Type 3 Tests of Fixed Effects for Age, Lighting Design, and the Interaction between Age and Lighting Design

Question Group	Effect	Num DF	Den DF	*F* Value	*p*-Value
Comfort	Age (A)	1	16.1	0.52	0.4806
	Lighting Design (LD)	4	171	30.29	**<.0001**
	A*LD	4	171	1.89	0.1147

Bolded p-values were considered statistically significant.

Least-squares means and pairwise comparisons for participant comfort rating are presented in Figure 21. After adjusting for multiple tests, several lighting design comparisons were found to result in significantly different participant comfort sentiment. Overall, participants rated their comfort with no opinion/neutral or better for all lighting designs. The Partial High-Mast lighting design was rated the lowest (mean = 2.95) with participant sentiment, on average, being neutral/no opinion. All other lighting designs were rated significantly better for participant comfort. Participant comfort was 49.7% higher under High-Mast lighting (mean = 4.41) compared to Partial High-Mast; this comparison was the largest difference between lighting designs. High-Mast lighting and High-Mast lighting paired with Conventional lighting (mean = 4.28) were rated significantly better for participant comfort than the Conventional Exit Only lighting (mean = 3.76). Participants indicated, on average, that they were most comfortable under High-Mast or High-Mast & Conventional lighting designs.

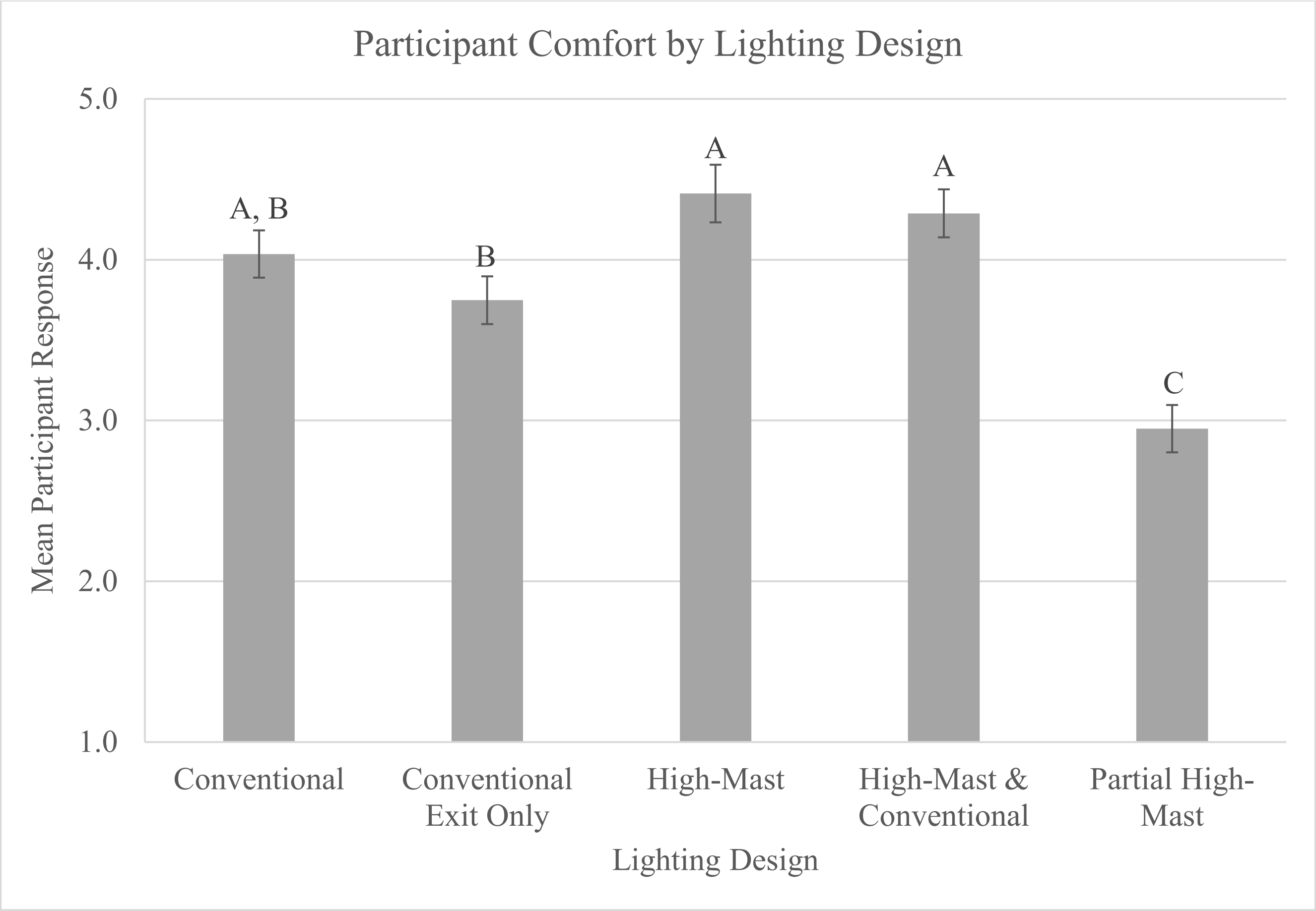

Figure 21. Graph. Participant comfort survey results by lighting design. Data are reported for mean participant response, and the error bars represent standard error. Uppercase letters indicate post hoc grouping from pairwise comparisons.

Light Level

The LMM results for Question 3 regarding light level are summarized in Table 23. Modeling outcomes indicated that at least two light levels resulted in significantly different participant opinion about comfort. Age and the two-way age interaction involving age and light level were not statistically significant. The research team conducted post hoc testing to determine which light levels were producing different participant comfort sentiment.

Table 23. Participant Comfort Survey: Type 3 Tests of Fixed Effects for Age, Light Level, and the Interaction between Age and Light Level

Question Group	Effect	Num DF	Den DF	*F* Value	*p*-Value
Comfort	Age (A)	1	16.2	0.48	0.4984
	Light Level (LL)	2	189	18.99	**<.0001**
	A*LL	2	189	1.8	0.1676

Bolded p-values were considered statistically significant.

Figure 22 shows the least-squares means and pairwise comparisons for participant comfort rating by lighting level. After adjusting for multiple tests, all light level comparisons resulted in significantly different participant comfort ratings. Overall, participants had, on average, a favorable rating of comfort for each light level. Interchanges with high light level (mean = 4.28) were rated 22.3% higher than the medium (mean = 3.50) and 9.6% higher than low (mean = 3.90) horizontal illuminance interchanges. Low light level interchanges were rated significantly higher than medium level interchanges but significantly lower than high light level interchanges.

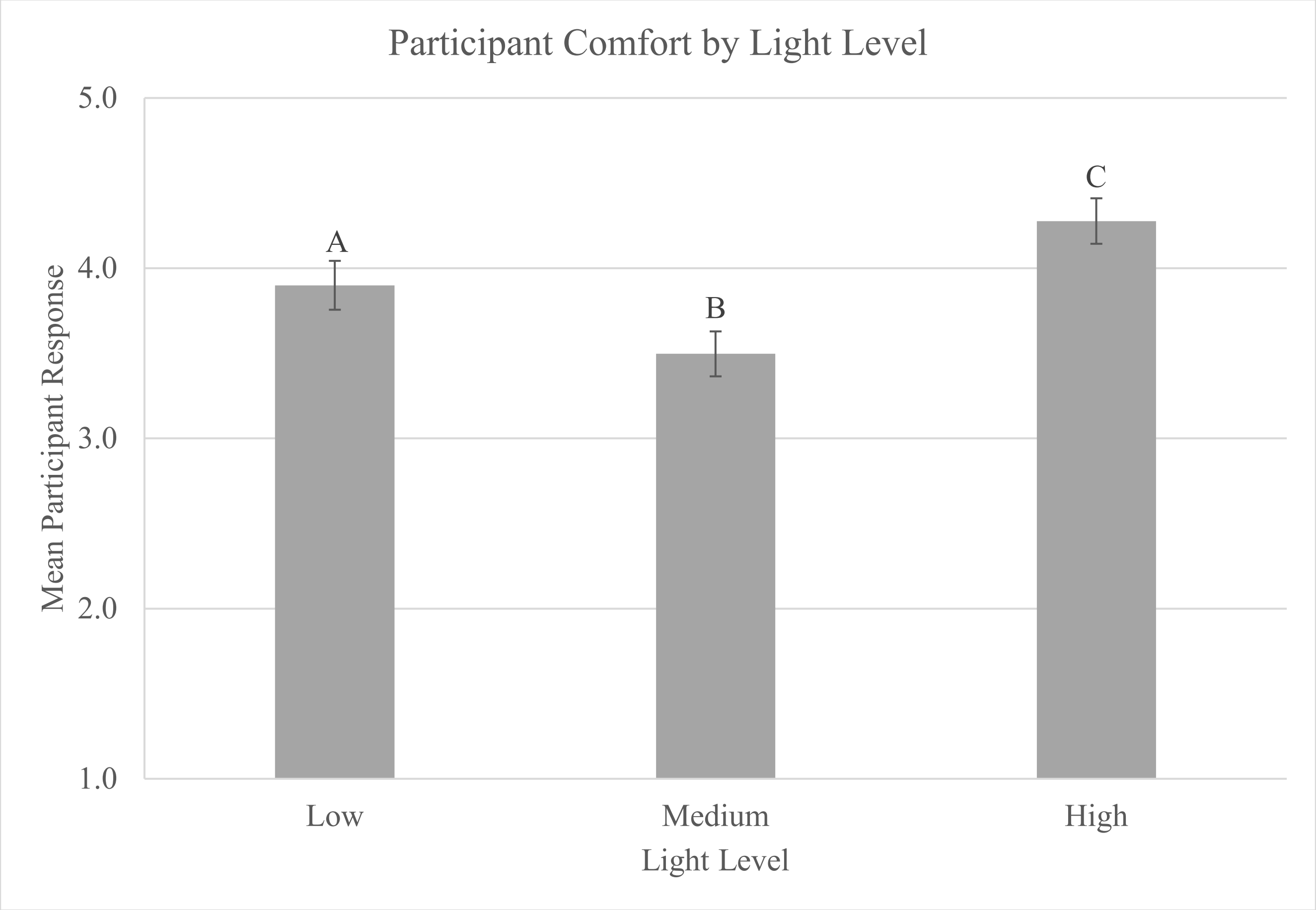

Figure 22. Graph. Participant comfort survey results by light level. Data are reported for mean participant response, and the error bars represent standard error. Uppercase letters indicate post hoc grouping from pairwise comparisons.

Question 4: Safety

Lighting Design

LMM results for Question 4 regarding lighting design are summarized in Table 24. The main effect of lighting design was significant, while age and the interaction involving age and lighting design were not significant. Post hoc testing focused on identifying significant differences in participant safety opinion between the factor levels of lighting design.

Table 24. Participant Safety Survey: Type 3 Tests of Fixed Effects for Age, Lighting Design, and the Interaction between Age and Lighting Design

Question Group	Effect	Num DF	Den DF	*F* Value	*p*-Value
Safety	Age (A)	1	16.2	0.47	0.5013
	Lighting Design (LD)	4	171	21.46	**<.0001**
	A*LD	4	171	1.94	0.1052

Bolded p-values were considered statistically significant.

Figure 23 shows the least-squares means and pairwise comparison results for participant safety rating. After adjusting for multiple tests, several lighting design comparisons were found to result in significantly different participant opinions of safety. Overall, participants rated their feeling of safety with no opinion/neutral or better for all lighting designs. Conventional (mean = 4.18), High-Mast (mean = 4.31), and the combination of High-Mast & Conventional (mean = 4.29) lighting designs all received, on average, high ratings for safety, and pairwise comparisons found no significant difference among them. Conventional, High-Mast, and High-Mast & Conventional lighting designs were rated significantly higher for safety than Conventional Exit Only (mean = 3.68), which was, in turn, rated significantly higher than Partial High-Mast (mean = 3.15) lighting design. Participants' safety opinion for Partial High-Mast lighting was at least 73% lower than all other lighting designs.

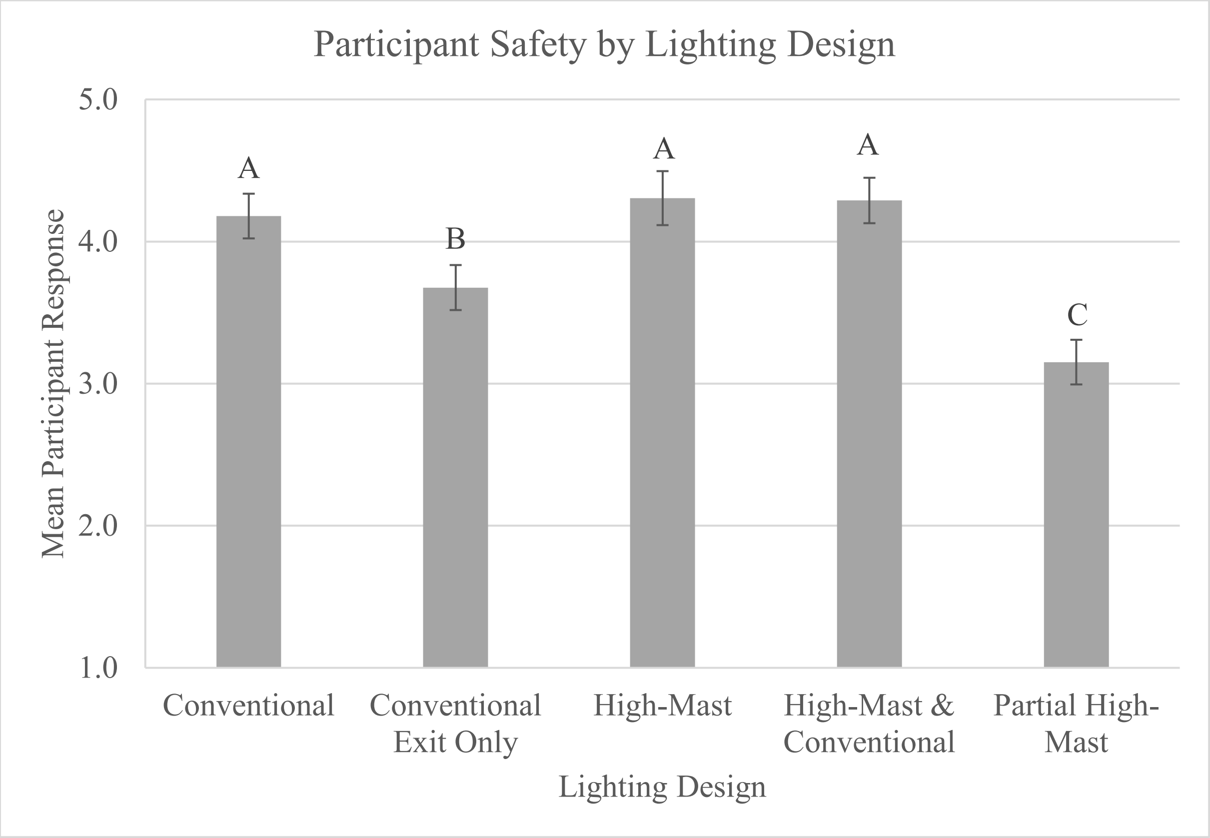

Figure 23. Graph. Participant safety survey results by lighting design. Data are reported for mean participant response, and the error bars represent standard error. Uppercase letters indicate post hoc grouping from pairwise comparisons.

Light Level

The results of the LMM for Question 4 regarding light level are summarized in Table 25. Concerning the main effects, age was not significant, while light level was significant. In addition, the two-way interaction involving age and light level was significant. Follow-up analysis assessed the difference in participant safety perception between light levels and between the factor combinations of age and light level.

Table 25. Participant Safety Survey: Type 3 Tests of Fixed Effects for Age, Light Level, and the Interaction between Age and Light Level

Question Group	Effect	Num DF	Den DF	*F* Value	*p*-Value
Safety	Age (A)	1	16.1	0.16	0.6931
	Light Level (LL)	2	184	17.73	**<.0001**
	A*LL	2	184	3.67	**0.0275**

Bolded p-values were considered statistically significant.

The least-squares means and pairwise comparisons for participant safety rating by lighting level and age are given in Figure 24. After adjusting for multiple tests, several comparisons were found to result in significantly different participant safety sentiments. Overall, participants, on average, responded that they felt safe driving at all light levels.

Pairwise comparisons within age groups indicated that older participants rated high light level interchanges (mean = 4.35) 29.2% better for perception of safety than medium light level interchanges (mean = 3.36) and 13.1% better than low light level interchanges (mean = 3.84). However, safety sentiment for the low light level was not statistically different than medium or high light levels. Young participants gave significantly higher safety ratings for interchanges with high light levels (mean = 4.36) than low (mean = 3.69) or medium (mean = 3.82) light levels. Perception of safety at high light level interchanges for younger participants was 18.1% higher than low and 14.2% higher than medium.

Pairwise comparisons between age groups indicated that both younger and older participants rated safety significantly higher at high light level interchanges when compared to medium light level interchanges. For younger participants, perception of safety increased with light level. However, for older participants, medium light level interchanges were rated lower than low light level interchanges. Increasing light levels from low to high resulted in a larger increase in safety perception for younger (18%) than for older (13%) participants. Across age groups, participants responded, on average, that they either agreed or strongly agreed that they felt safe at those interchanges.

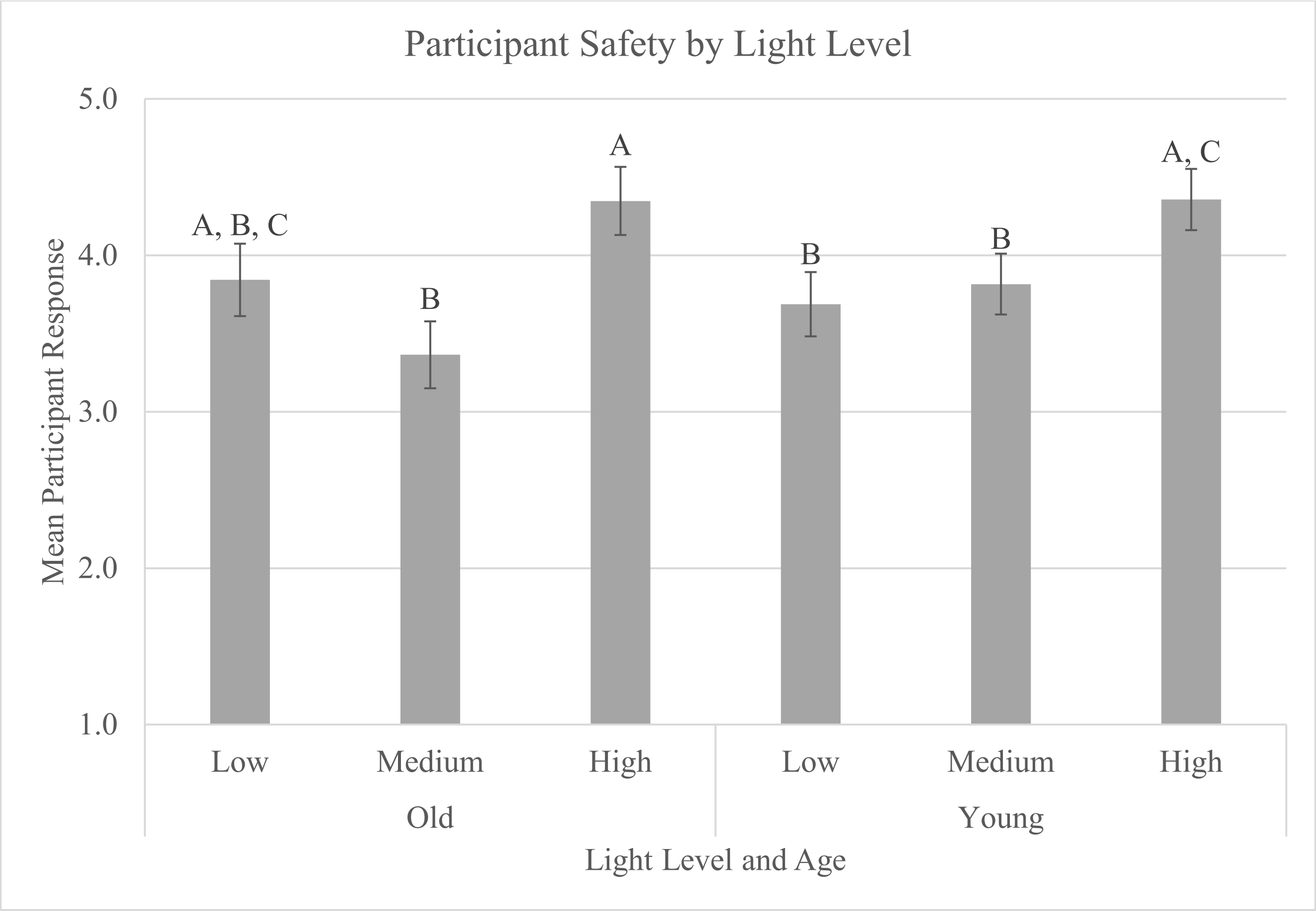

Figure 24. Graph. Participant safety survey results by light level and age. Data are reported for mean participant response, and the error bars represent standard error. Uppercase letters indicate post hoc grouping from pairwise comparisons.

The least-squares means and pairwise comparisons for participant safety rating by lighting level are given in Figure 25. After adjusting for multiple tests, two light level comparisons were found to result in significantly different participant safety ratings. Overall, across all light levels, participants had a positive rating of safety. Safety sentiment was best at interchanges with high light level (mean = 4.35), which were rated 21.2% higher than medium (mean = 3.59) and 15.6% higher than low (mean = 3.90) light level interchanges. Participant safety sentiment was statistically similar for low and medium light level interchanges.

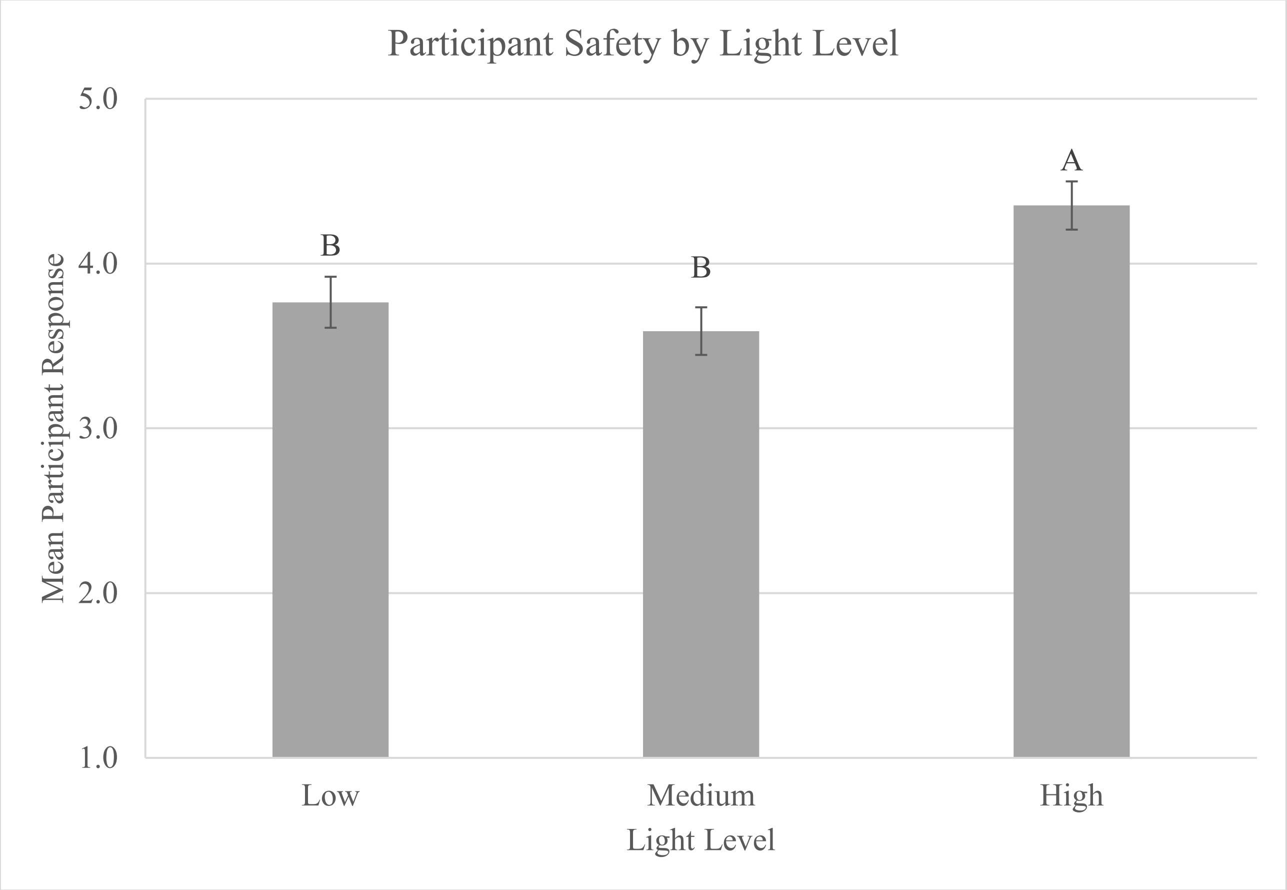

Figure 25. Graph. Participant safety survey results by light level. Data are reported for mean participant response, and the error bars represent standard error. Uppercase letters indicate post hoc grouping from pairwise comparisons.

Question 5: Amount of Roadway Lighting (Too Much)

Lighting Design

The LMM results for Question 5 regarding lighting design are summarized in Table 26. Results showed that the main effect of lighting design was statistically significant. Age and the interaction between lighting design and age were not significant. The research team conducted a follow-up analysis to determine which lighting designs were influencing participant opinion on the amount of lighting (too much).

Table 26. Amount of Roadway Lighting (Too Much) Survey: Type 3 Tests of Fixed Effects for Age, Lighting Design, and the Interaction between Age and Lighting Design

Question Group	Effect	Num DF	Den DF	*F* Value	*p*-Value
Amount of light (too much)	Age (A)	1	16.1	0.54	0.4747
	Lighting Design (LD)	4	80.4	4.62	**0.0021**
	A*LD	4	80.4	0.68	0.6084

Bolded p-values were considered statistically significant.

The least-squares means and pairwise comparison results for participant opinion on the amount of lighting at interchanges (too much) are shown in Figure 26. After adjusting for multiple tests, two lighting design comparisons were found to result in significantly different participant opinions on whether the roadway was overlit. Overall, participants indicated that, on average, they did not think any of the interchanges were overlit. Participant response ranged between disagreeing and strongly disagreeing that the study interchanges had too much lighting. Conventional (mean = 1.94) and High-Mast & Conventional (mean = 1.90) were rated significantly worse than the Partial High-Mast (mean = 1.30) lighting design. While statistically significant, the differences did not result in any practical change in participant opinion.

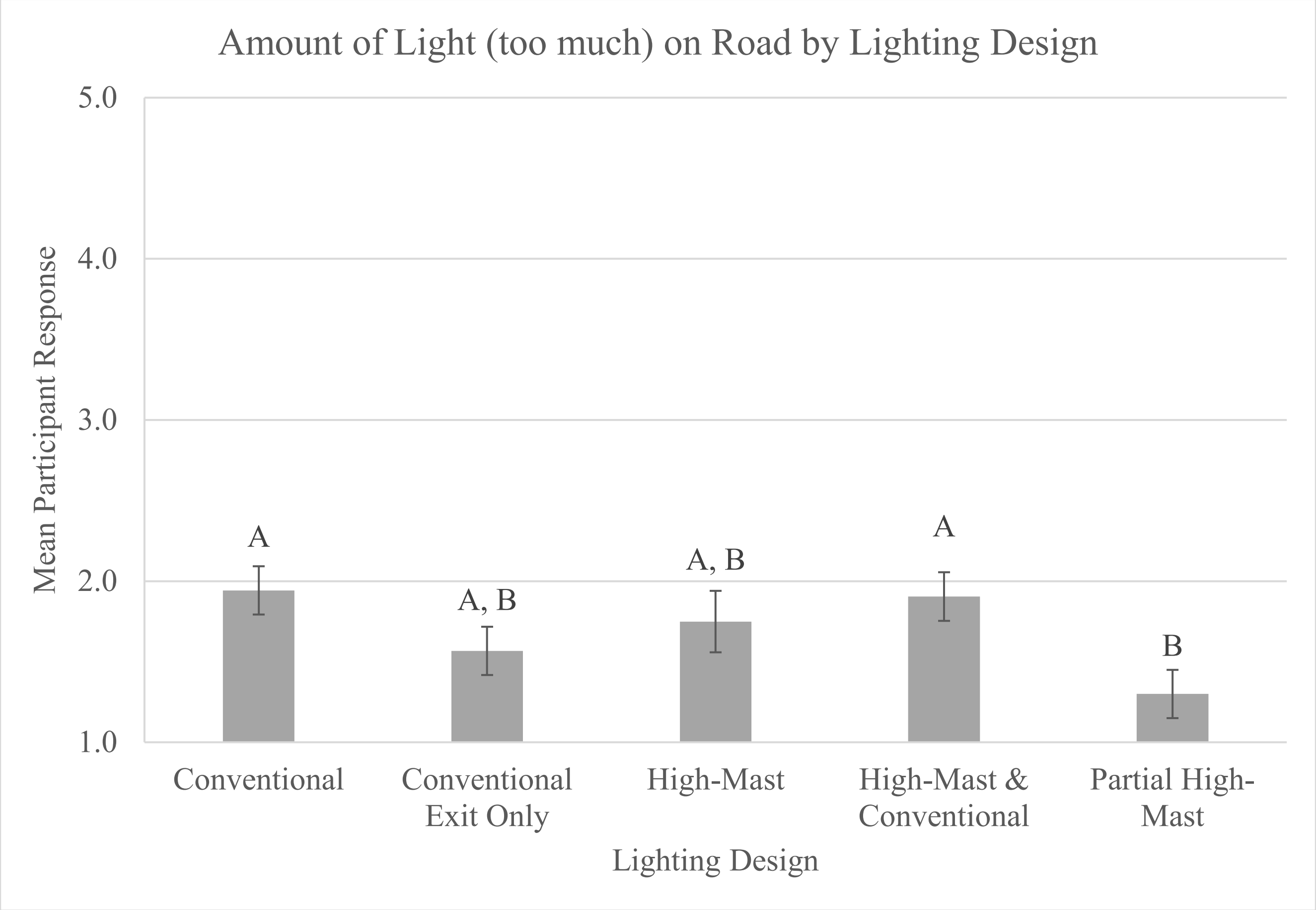

Figure 26. Graph. Amount of roadway lighting (too much) survey results by lighting design. Data are reported for mean participant response, and the error bars represent standard error. Uppercase letters indicate post hoc grouping from pairwise comparisons.

Light Level

LMM results for Question 5 regarding light level are summarized in Table 27. The main effect of light level was statistically significant, while age and the interaction between age and light level were not significant. Follow-up analysis focused on the differences in participant opinion about the amount of light (too much) between the study interchanges.

Table 27. Amount of Roadway Lighting (Too Much) Survey: Type 3 Tests of Fixed Effects for Age, Light Level, and the Interaction between Age and Light Level

Question Group	Effect	Num DF	Den DF	*F* Value	*p*-Value
Amount of light (too much)	Age (A)	1	16.2	0.38	0.544
	Light Level (LL)	2	80.7	7.08	**0.0015**
	A*LL	2	80.7	0.66	0.5212

Bolded p-values were considered statistically significant.

The least-squares means and pairwise comparisons for participant opinion on if the study interchanges were overlit by lighting level are given in Figure 27. After adjusting for multiple tests, two light level comparisons were found to result in significantly different participant ratings. Overall, across all light levels, study participants did not think that the roadway was overlit. For all light levels, participants indicated that, on average, they disagreed or strongly disagreed that there was too much lighting at the study interchanges. Participant ratings for interchanges with a high light level (mean = 1.93) were rated 32.0% worse than medium (mean = 1.46) and 21.3% worse than low (mean = 1.59) light level interchanges. Participant opinion on overlighting at the study interchanges was statistically similar for low and medium light levels. While statistically significant, the differences observed between high, medium, and low light levels did not result in a change in overall participant sentiment.

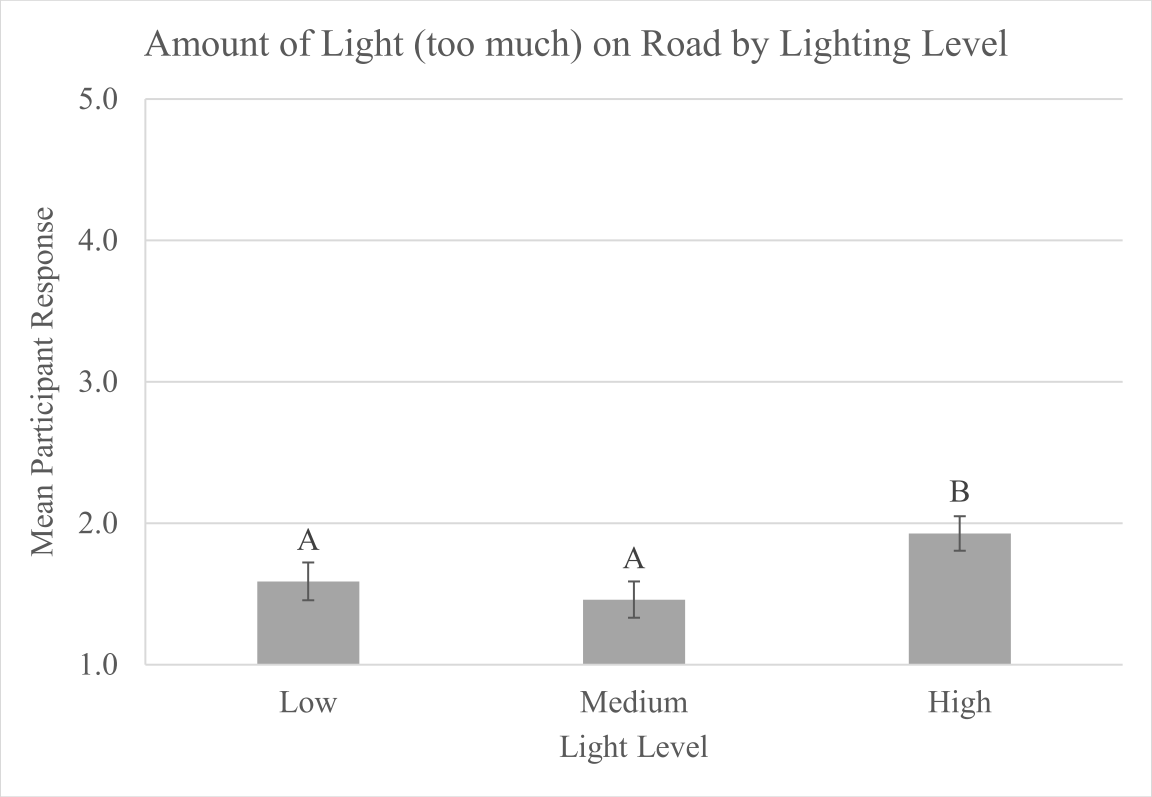

Figure 27. Graph. Amount of roadway lighting (too much) survey results by light level. Data are reported for mean participant response, and the error bars represent standard error. Uppercase letters indicate post hoc grouping from pairwise comparisons.

Question 6: Amount of Roadway Lighting (Too Little)

Lighting Design

LMM results for Question 6 regarding lighting design are summarized in Table 28. Statistical significance was found for lighting design but was not found for age or the interaction between them. A follow-up analysis was conducted to determine which factor levels of lighting design were impacting participant opinion on the amount of lighting (too little).

Table 28. Amount of Roadway Lighting (Too Little) Survey: Type 3 Tests of Fixed Effects for Age, Lighting Design, and the Interaction between Age and Lighting Design

Question Group	Effect	Num DF	Den DF	*F* Value	*p*-Value
Amount of light (too little)	Age (A)	1	16.3	0.06	0.8136
	Lighting Design (LD)	4	77	22.27	**<.0001**
	A*LD	4	77	1.16	0.3359

Bolded p-values were considered statistically significant.

Figure 28 includes the least-squares means and pairwise comparison results for participant opinion on if the study interchanges were underlit. After adjusting for multiple tests, several lighting design comparisons were found to result in significantly different participant opinion on if the roadway was underlit. Overall, participants gave a mixed opinion on whether the study interchanges were underlit. Participants indicated that, on average, they thought three of the interchanges were not underlit. Participants responded that they felt that Conventional (mean = 2.31), High-Mast & Conventional (mean = 2.24), and High-Mast (mean = 2.12) interchanges did not have too little lighting. The previously mentioned lighting designs were rated significantly better than Conventional Exit Only (mean = 3.20) and Partial High-Mast (mean = 4.05) lighting designs. Participant response was, on average, neutral when asked if they thought the Conventional Exit Only lighting design was underlit. Participants, on average, agreed with the statement that the Partial High-Mast lighting design did not provide enough lighting. The Partial High-Mast design was rated significantly worse than all other lighting designs, and all post hoc comparisons involving it were statistically significant.

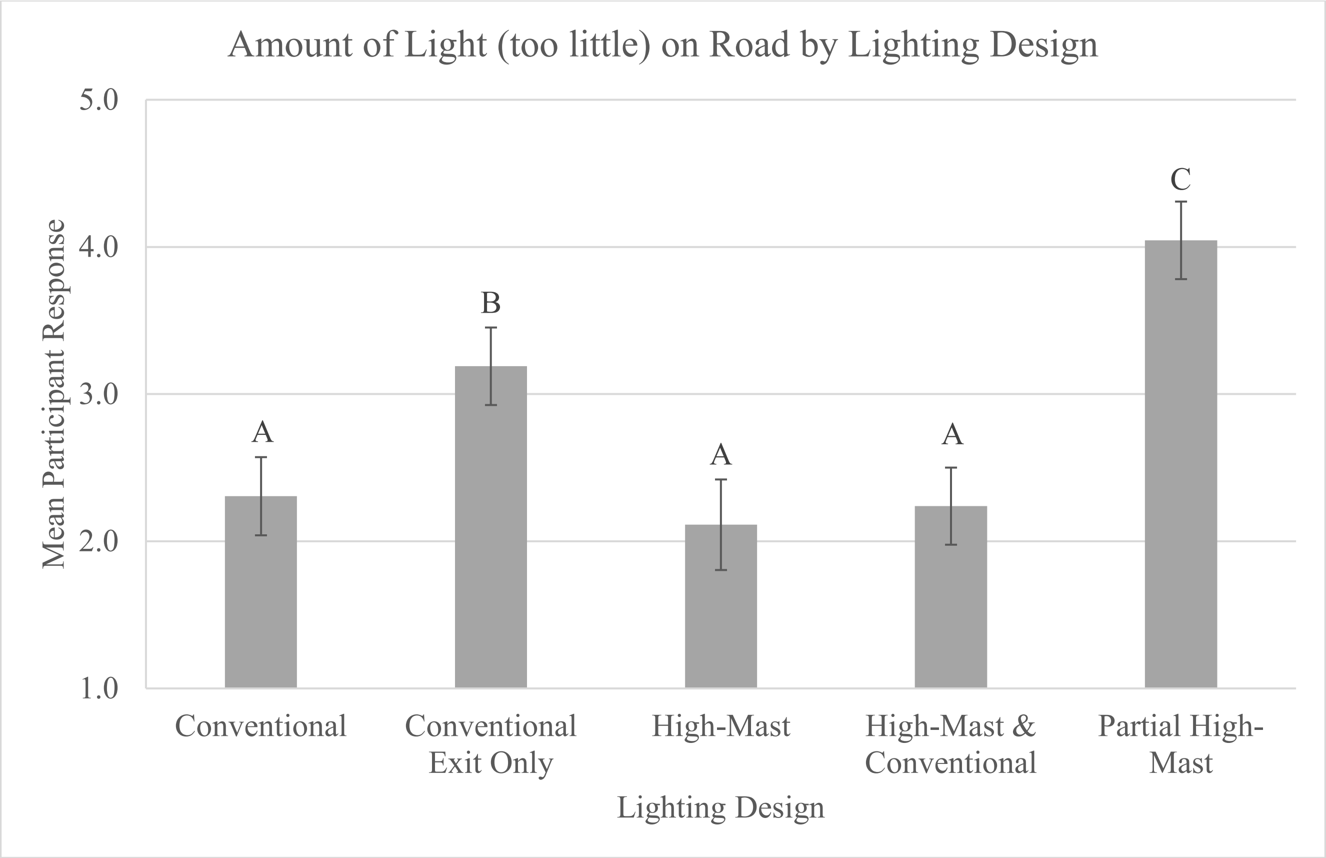

Figure 28. Graph. Amount of roadway lighting (too little) survey results by lighting design. Data are reported for mean participant response, and the error bars represent standard error. Uppercase letters indicate post hoc grouping from pairwise comparisons.

Light Level

The results of the LMM for Question 6 regarding light level are summarized in Table 29. Light level was statistically significant, but age and the interaction between age and light level were not significant. Follow-up analysis focused on the differences in participant opinion about the amount of light (too little) between the study interchanges.

Table 29. Amount of Roadway Lighting (Too Little) Survey: Type 3 Tests of Fixed Effects for Age, Light Level, and the Interaction between Age and Light Level

Question Group	Effect	Num DF	Den DF	*F* Value	*p*-Value
Amount of light (too little)	Age (A)	1	16.1	0.01	0.911
	Light Level (LL)	2	77.7	11.55	**<.0001**
	A*LL	2	77.7	1.15	0.3205

Bolded p-values were considered statistically significant.

The least-squares means and pairwise comparisons for participant opinion on if the study interchanges were underlit by lighting level are given in Figure 29. After adjusting for multiple comparisons, two light level comparisons were found to result in significantly different participant ratings. Overall, across all light levels, survey participants did not think that interchanges with a high level of lighting were underlit; however, participants gave, on average, neutral responses when asked about low and medium light level interchanges. Participant ratings for interchanges with a high light level (mean = 2.20) were rated significantly better than the medium (mean = 3.33) and low (mean = 2.90) light level interchanges. Low and medium light level interchanges were rated similarly but not significantly different than each other.

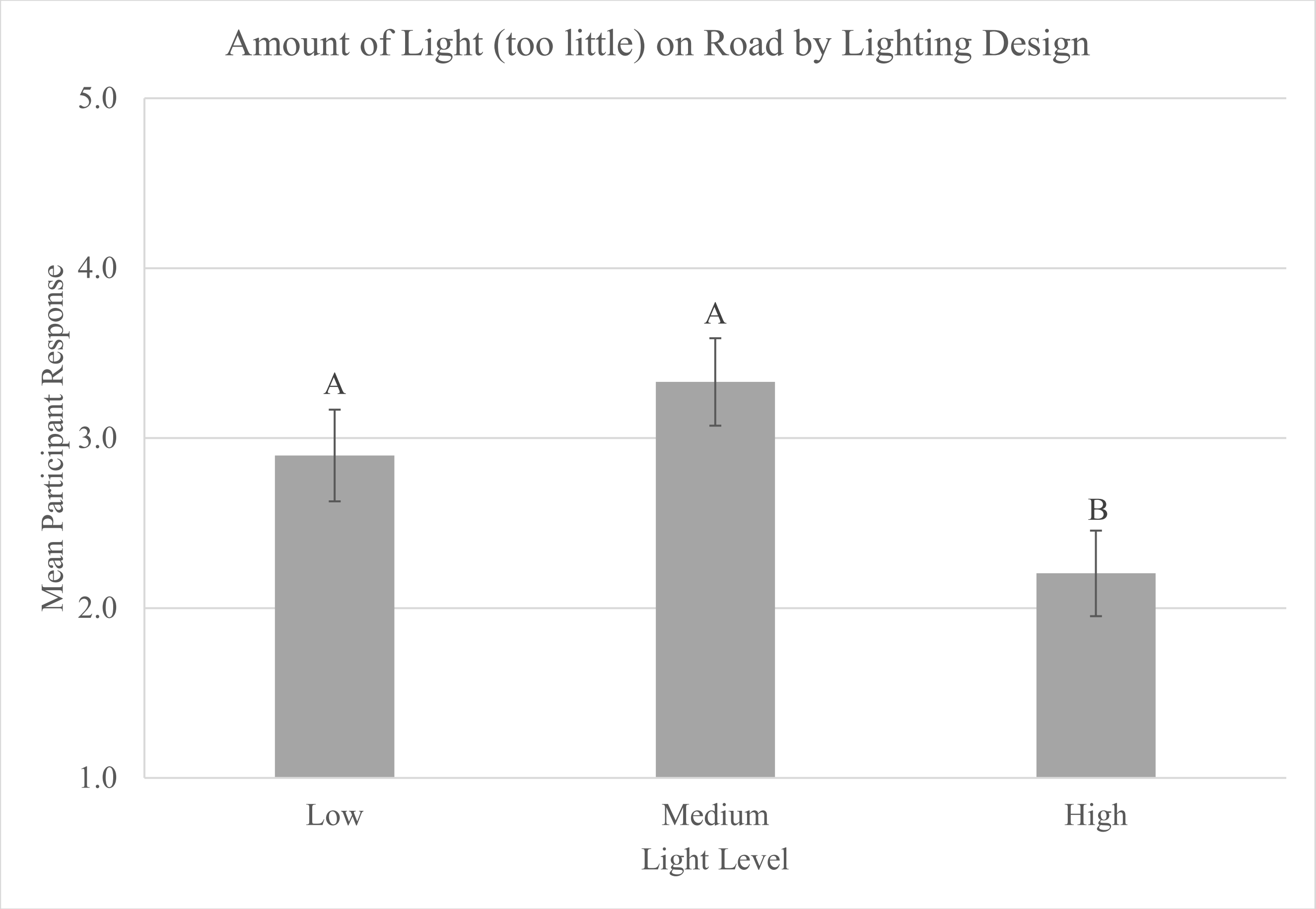

Figure 29. Graph. Amount of roadway lighting (too little) survey results by light level. Data are reported for mean participant response, and the error bars represent standard error. Uppercase letters indicate post hoc grouping from pairwise comparisons.

Question 7: Discomfort Glare

Lighting Design

LMM results for Question 7 regarding lighting design are summarized in Table 30. Modeling found that lighting design was significant, while age and the two-way interaction involving lighting design and age were not significant. Follow-up analysis investigated which lighting designs were resulting in significantly different participant perception of discomfort glare.

Table 30. Discomfort Glare Survey: Type 3 Tests of Fixed Effects for Age, Lighting Design, and the Interaction between Age and Lighting Design

Question Group	Effect	Num DF	Den DF	*F* Value	*p*-Value
Discomfort Glare	Age (A)	1	14.9	1.24	0.2832
	Lighting Design (LD)	4	90.8	4.65	**0.0018**
	A*LD	4	90.8	1.57	0.189

Bolded p-values were considered statistically significant.

Figure 30 shows the least-squares means and pairwise comparison results from the LMM procedure. After adjusting for multiple comparisons, one lighting design was statistically significantly different than the others. Participant rating of discomfort glare for the High-Mast & Conventional lighting design (mean = 2.34) was at least 51% higher than for Conventional Exit Only (mean = 1.56), Conventional (mean = 1.49), and Partial High-Mast (mean = 1.47). High-Mast & Conventional lighting was rated worse for discomfort glare than High-Mast lighting (mean = 1.70). However, the difference was not statistically significant. No other comparisons between lighting design were statistically significant. Overall, participants rated the glare produced by the interchange lighting designs as nonexistent to noticeable, except for High-Mast & Conventional lighting, which was rated as having between noticeable and disagreeable discomfort glare.

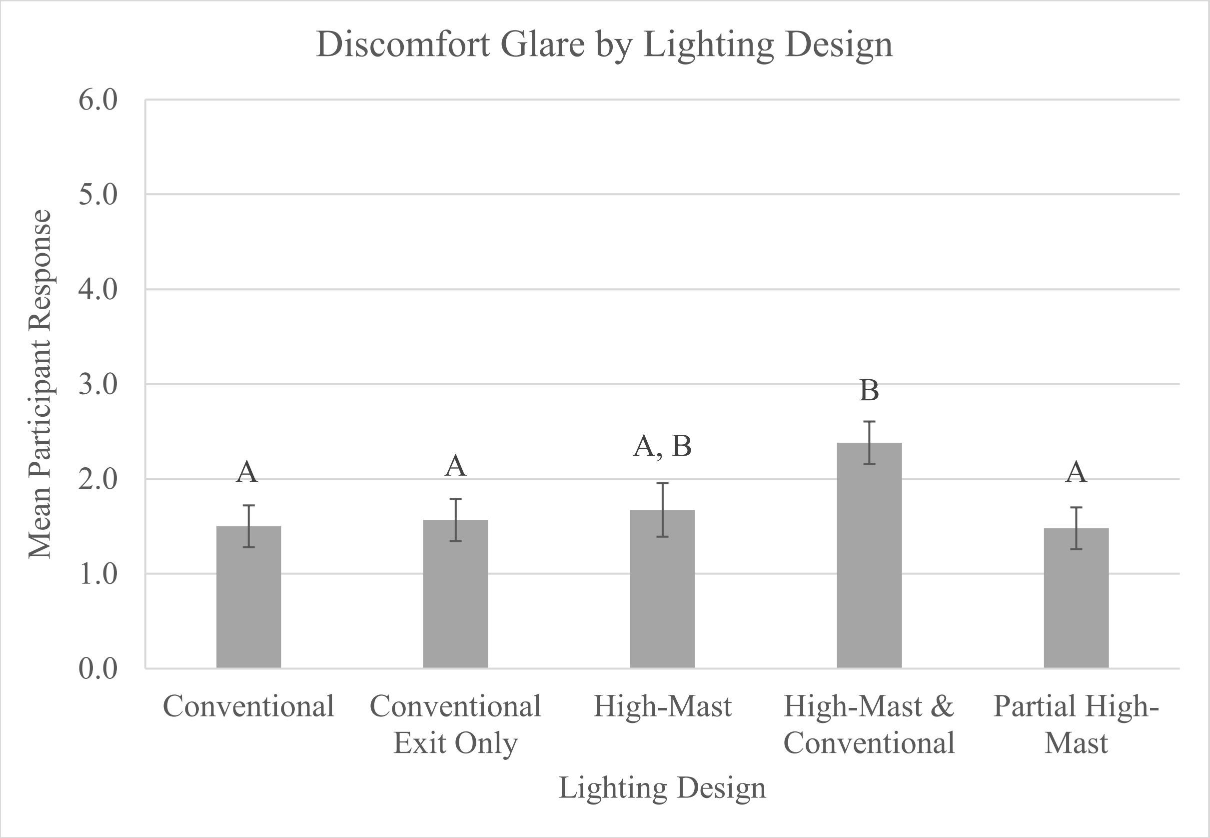

Figure 30. Graph. Discomfort glare survey results by lighting design. Data are reported for mean participant response, and the error bars represent standard error. Uppercase letters indicate post hoc grouping from pairwise comparisons.

Figure 31 includes the survey results for participant glare rating on the *x*-axis and the vertical illumination results from the photometric evaluation on the *y*-axis. Researchers note that as vertical illuminance increases, on average, so did the participant discomfort glare rating. For the two lighting designs with the least amount of lighting infrastructure, Partial High-Mast & Conventional Exit Only, the Partial High-Mast design was rated similarly for discomfort glare while providing 21.7% more vertical illuminance. Also, High-Mast lighting provided 14.3% more vertical illuminance than Conventional lighting and was rated only slightly higher for discomfort glare. The High-Mast & Conventional lighting design was rated as having significantly higher discomfort glare than all other lighting designs while having the highest vertical illuminance. Overall, the High-Mast lighting designs were rated similarly for discomfort glare as comparable conventional lighting designs while providing higher vertical illuminance levels.

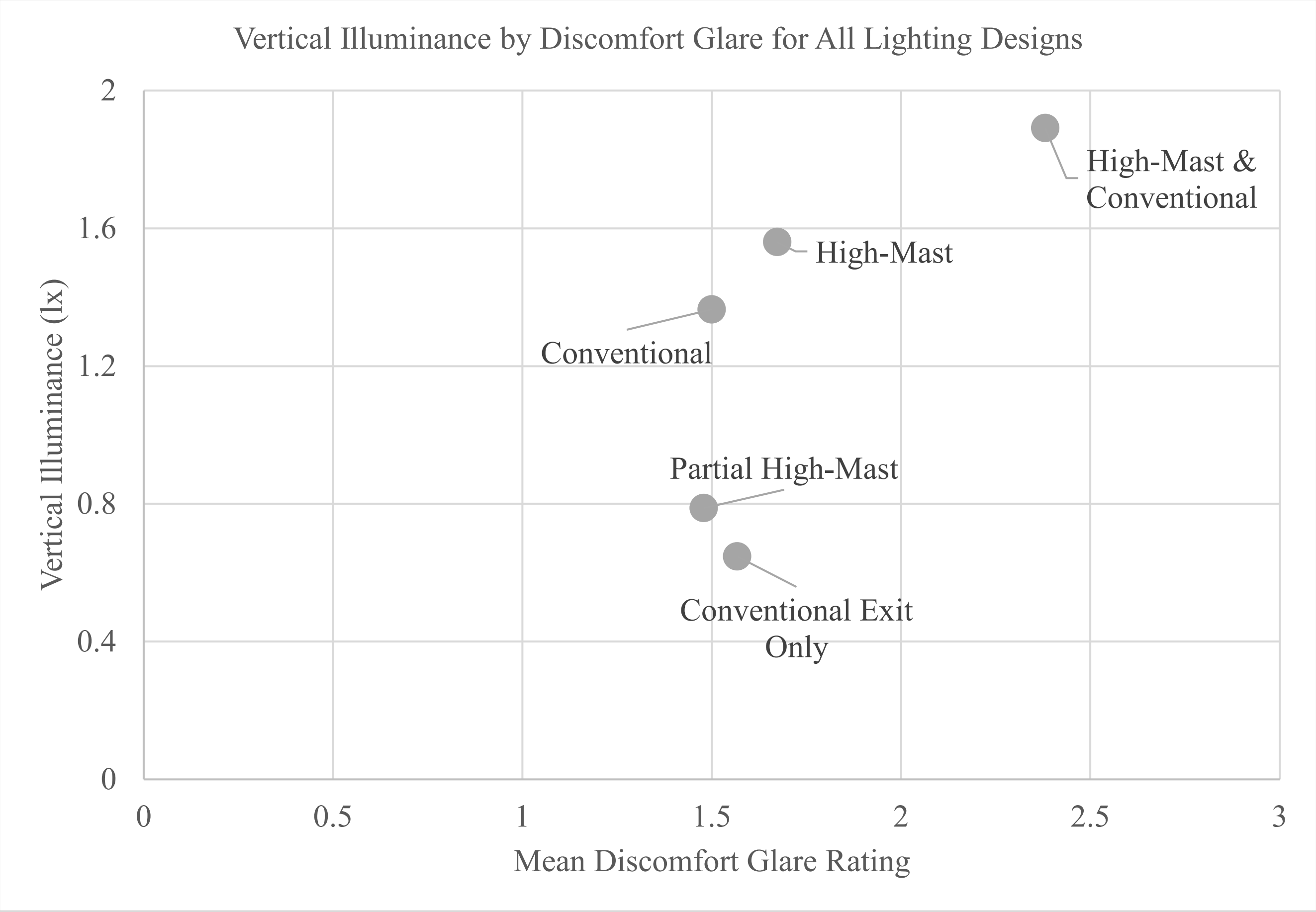

Figure 31. Graph. Participant discomfort glare rating by vertical illuminance for all lighting designs.

Light Level

The results of the LMM for Question 7 regarding light level are summarized in Table 31. Light level and age were not significant, and the two-way interaction involving those variables was also not significant. No post hoc comparisons were performed.

Table 31. Discomfort Glare Survey: Type 3 Tests of Fixed Effects for Age, Light Level, and the Interaction between Age and Light Level

Question Group	Effect	Num DF	Den DF	*F* Value	*p*-Value
Discomfort Glare	Age (A)	1	16	1.67	0.2141
	Light Level (LL)	2	99.1	1.48	0.2317
	A*LL	2	99.1	0.43	0.6489

Bolded p-values were considered statistically significant.

Effect of Dimming at Interchange 318

LMM results for question groupings 1 to 7 are summarized in Table 32. For each question grouping, the chi-square goodness-of-fit tests for the main effects and their interaction are reported. Results showed no significant effect of dim level, age, or their interaction for all question groupings except for the target detection task. For the target detection task (Question 1), the main effect of age was significant. Dim level was not significant, nor was the interaction between age and dim level, though the main effect of dim level was approaching significance. Follow-up analysis focused on the difference in factor levels for age and dim level for Question 1.

Table 32. Type 3 Tests of Fixed Effects for Age, Dim Level, and the Interaction between Age and Dim Level at Interchange 318.

Question Group	Question Area	Effect	Num DF	Den DF	*F* Value	*p*-Value
1	Target Detection	Age (A)	1	14	5.22	**0.0384**
		Dim Level (DL)	1	14	3.4	**0.0866**
		A*DL	1	14	0.66	0.431
2	Visibility of Ramps	A	1	14	2.01	0.1779
		DL	1	14	0.29	0.599
		A*DL	1	14	0.29	0.599
3	Participant Comfort	A	1	14	0.5	0.492
		DL	1	14	0.01	0.9426
		A*DL	1	14	0.5	0.492
4	Participant Safety	A	1	14	0.25	0.6261
		DL	1	14	0	0.9756
		A*DL	1	14	0.2	0.6653
5	Amount of Lighting (Too Much)	A	1	14	0	0.9582
		DL	1	14	0	0.9582
		A*DL	1	14	0.48	0.4997
6	Amount of Lighting (Too Little)	A	1	14	0.37	0.5543
		DL	1	14	0.09	0.7664
		A*DL	1	14	2.29	0.1522
7	Discomfort Glare	A	1	14	0.06	0.8103
		DL	1	14	1.27	0.2795
		A*DL	1	14	0	0.9617

Bolded p-values were considered statistically significant.

The least-squares means results from the LMM procedure for Question 1 are reported in Figure 32. A statistically significant difference in mean targets detected was found between older and younger participants independent of dim level. No statistically significant difference in target detection was found between the full brightness and 50% dim levels, but this test was approaching significance. Furthermore, after adjusting for multiple tests, none of the interaction comparisons between dim level and age were statistically significant.

Results for age and dim level main effects were in line with research expectations. For age, statistically significant results showed that younger participants (mean = 2.3) saw 28% more targets than older participants (mean = 1.78). For dim level, participants saw 23% more targets at full brightness (mean = 2.25) than when the High-Mast lighting was dimmed to 50% (mean = 1.83).

While not statistically significant, results comparing the interaction between age and dim level were in line with research expectations, with one comparison approaching significance. The comparison that was approaching significance (adj. *p*-value = 0.06) compared younger participants at full brightness to older participants under dim lighting. Results found that younger participants driving under full brightness (mean = 2.6), on average, detected 56% more targets than the older participants driving under a 50% dim level (mean = 1.67).

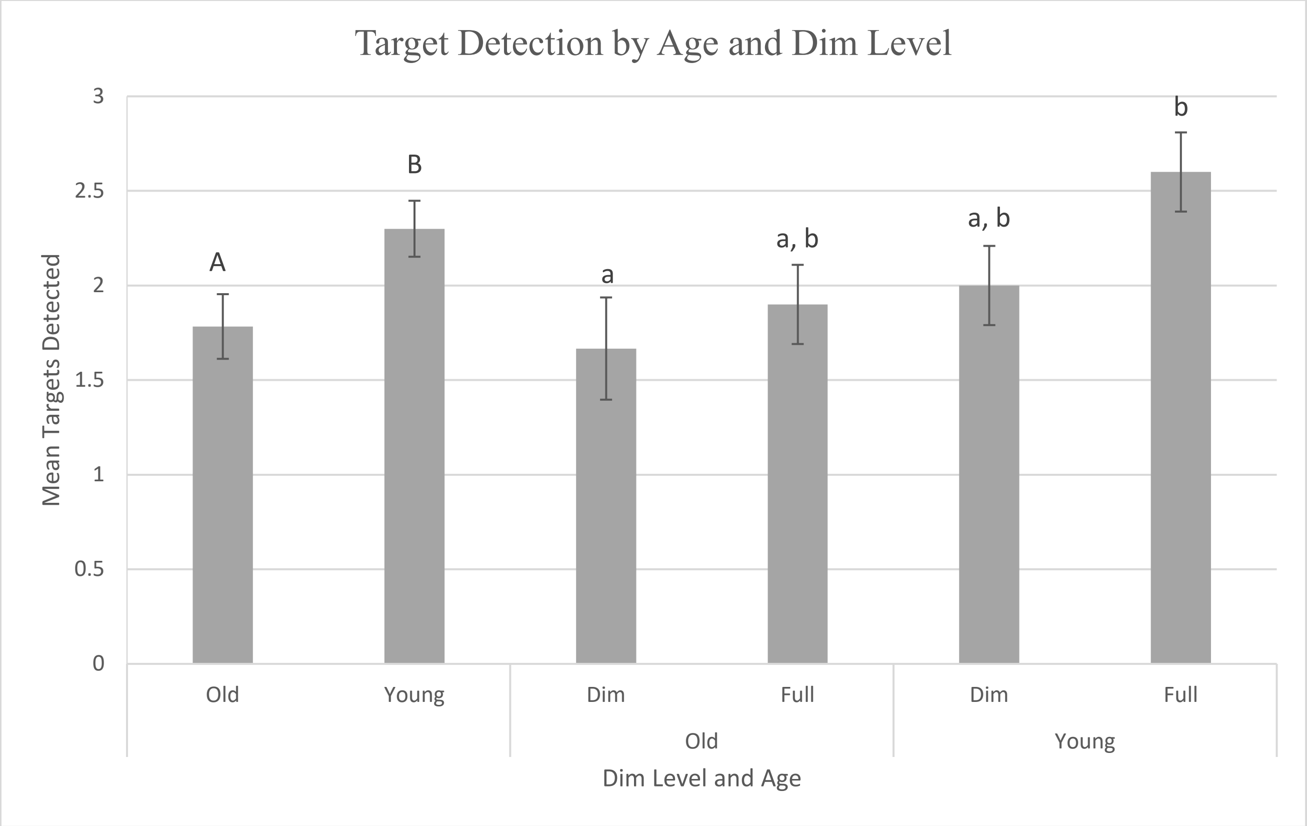

Figure 32. Graph. Target detection task results by age and dim level at Interchange 318. Data are reported for mean targets detected, and the error bars represent standard error. Uppercase letters indicate post hoc grouping from pairwise comparisons for age, and lowercase letters indicate post hoc grouping for the interaction between age and dim level.

TRAFFIC SPEED EVALUATION

Speed

Lighting Design Analysis

Table 33 shows the LMM results for the effect of lighting design and interchange segment on vehicle speed. A statistical difference was found for vehicle speeds between interchange segments and between lighting designs. There was also a statistical difference between at least two of the factor level combinations for the interaction between lighting design and interchange segment. The research team expected a difference in vehicle speeds between interchange segments as through traffic would, on average, be traveling at speeds that were unsafe or at which it would be impossible to navigate ramp segments. Ramp segment speed limits, while not enforceable, varied between 15 to 30 mph slower than mainline enforceable speed limits (Table 8). Thus, pairwise comparisons focused on the difference in vehicle speeds between lighting designs within each interchange segment.

Table 33. Speed: Type 3 Tests of Fixed Effects for Lighting Design, Interchange Segment, and the Interaction between Lighting Design and Interchange Segment

Effect	Num DF	Den DF	*F* Value	*p*-Value
Lighting Design (LD)	4	9424	215.47	**<.0001**
Interchange Segment (IS)	2	9466	1520.95	**<.0001**
LD*IS	7	9465	23.86	**<.0001**

Bolded p-values were considered statistically significant.

Post hoc analysis was informed by conducting a test of the simple effects. Table 34 displays the significance of testing results that assess the differences of the least-squares means within each interchange segment. Testing significance indicates a difference in vehicle speed between at least two combinations of lighting designs within each interchange segment. Results showed that, for vehicles entering the road, vehicles exiting the road, and vehicles traveling through the study interchanges, lighting design was potentially an influence on mean vehicle speeds. A follow-up analysis was conducted to assess how vehicle speed varied between lighting designs. The results of the follow-up analysis are presented separately for through, entering, and exiting vehicle traffic.

Table 34. Speed: Tests of Effect Slices at all Factor Levels of Interchange Segment for the Influence of Lighting Design

Effect	Interchange Segment	Num DF	Den DF	*F* Value	*p*-Value
LD*IS	Entrance	3	9466	40.48	**0.0004**
LD*IS	Exit	4	9464	100.26	**<.0001**
LD*IS	Through	4	9307	226.05	**<.0001**

Bolded p-values were considered statistically significant.

Through Traffic

The least-squares means and pairwise comparisons of mean speed for vehicles traveling through the study interchanges are shown in Figure 33. After adjusting for multiple comparisons, several lighting designs experienced significantly different speed behavior. All speeds are reported relative to the through segment speed limit at each interchange, as shown in Table 8.

Vehicles traveled, on average, faster than the speed limit under two lighting designs: High-Mast and High-Mast & Conventional. When driving through High-Mast & Conventional (8.25 mph) lighting, vehicles traveled significantly faster, relative to the speed limit, than when traveling through all other lighting designs. Vehicles driving through High-Mast (2.87 mph) lighting traveled significantly faster, relative to the speed limit, than Conventional (0.51 mph), Partial High-Mast (-0.77 mph), and Conventional Exit Only (0.21 mph) lighting designs. While these speed differences were statistically significant, the magnitude of speed difference might not represent a practical difference, as the average vehicle speeds under these four lighting designs were close to the posted speed limit.

Table 35. Arithmetic Mean Speed by Direction of Travel for Vehicles at Interchange 340

Interchange	Direction of travel	Relative Speed (mph)
340	Approaching from South	10.04
340	Approaching from North	8.84

The High-Mast & Conventional lighting design was located at Interchange 340, which was the only interchange with a 55-mph mainline speed limit. Researchers further investigated the speed behavior at Interchange 340 because average vehicle speeds, relative to the speed limit, were in the range of being cited by law enforcement. The research team explored speeding behavior by direction of travel to see if vehicles were simply not reducing their speed while traveling from higher speed limit areas or if speeding was prevalent in both directions. Vehicles approaching Interchange 340 from southbound were coming from a 70-mph zone, while vehicles approaching from northbound were in a 55-mph zone. Even though vehicles approaching from the north were coming from an area with a lower speed limit, mean vehicle speeds were still in excess of the speed limit (8.84 mph), as shown in Table 35. Experimental data suggest that more than just the approach speed limit was affecting mainline vehicle speed behavior.

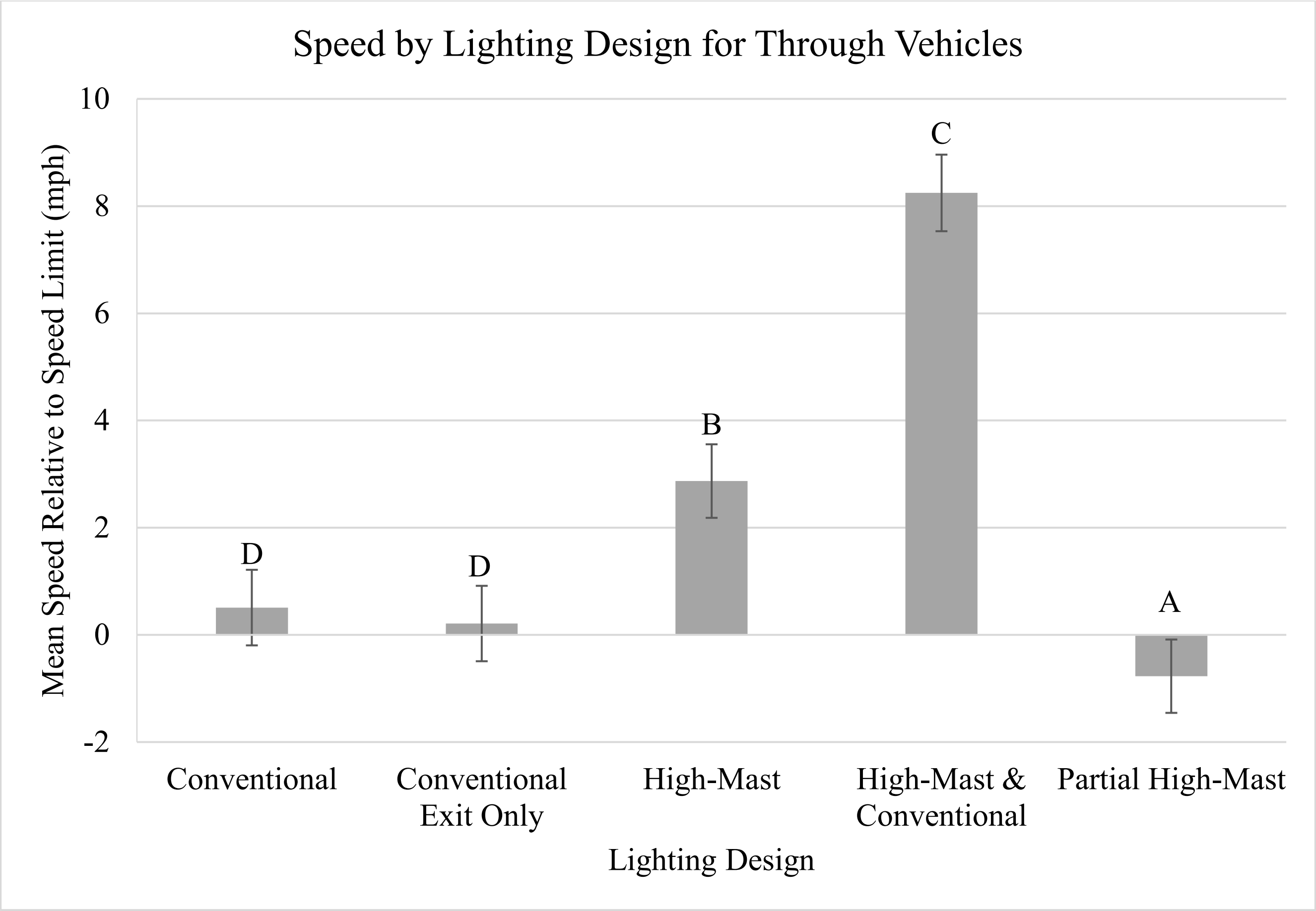

Figure 33. Graph. Speed results by lighting design for vehicles traveling through the target interchanges. Data are reported for mean speed relative to the speed limit, in mph, and the error bars represent standard error. Uppercase letters indicate post hoc grouping from pairwise comparisons.

Exiting Traffic

The least-squares means and pairwise comparisons of mean speed for vehicles taking exit ramps at the study interchanges are shown in Figure 34. After adjusting for multiple tests, several lighting design comparisons were statistically significant. All speeds are reported relative to the mainline speed limit at each interchange. Mainline speed limits are shown in Table 8.

Overall, across all lighting designs, exiting vehicles traveled between 7 and 23 mph slower than the mainline speed limit. Significant difference in mean speed relative to the mainline speed limit was found between all lighting designs except the comparisons between Conventional Exit Only (−13.16 mph) and both High-Mast (−11.3 mph) and Partial High-Mast (−17.57 mph) lighting designs. Vehicles traveling under the Conventional lighting design (−22.67 mph) had a significantly larger reduction in mean speed than all other conditions, while High-Mast & Conventional lighting (−7.30 mph) had a significantly smaller reduction in speed (Figure 34).

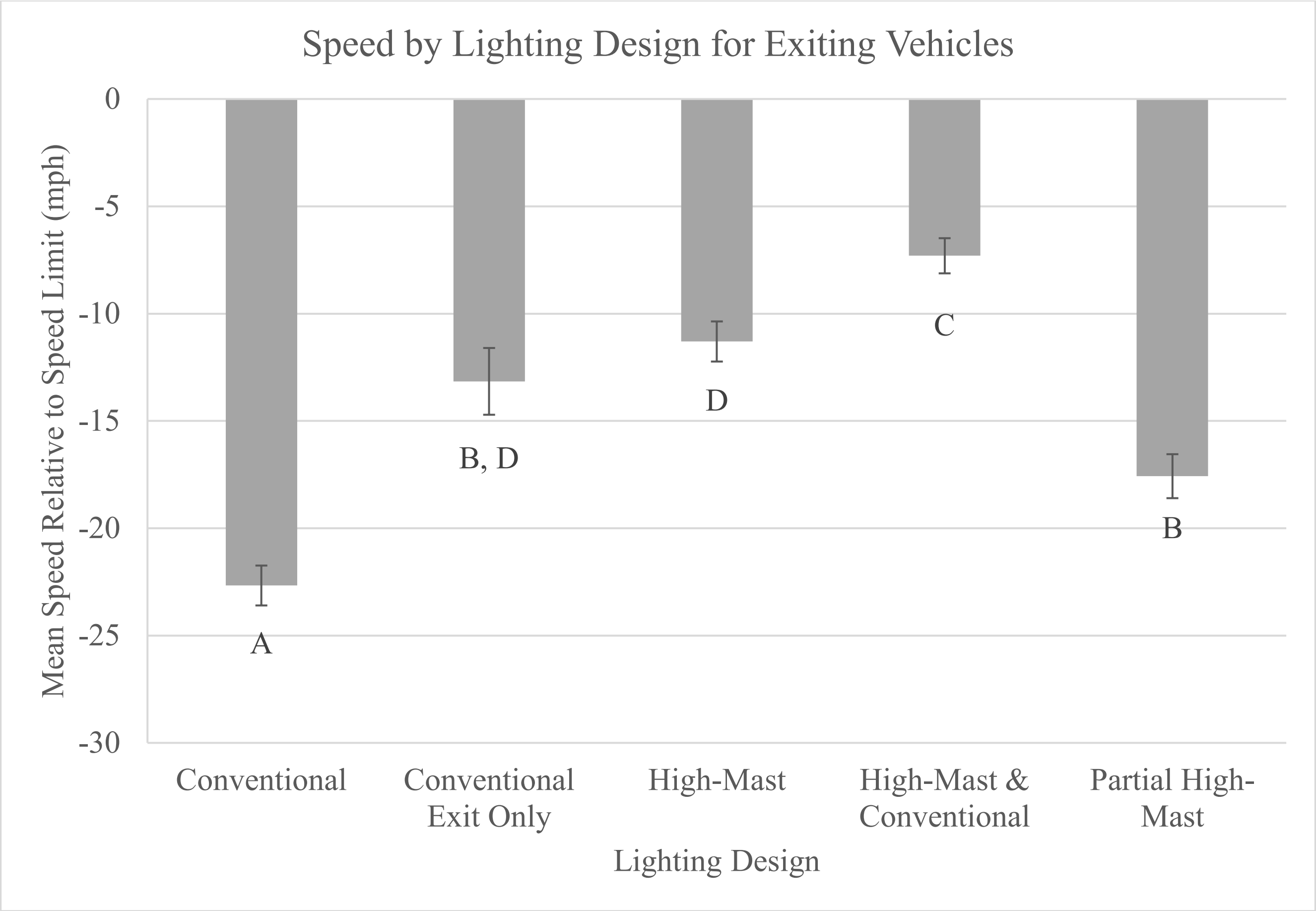

Figure 34. Graph. Speed results by lighting design for vehicles exiting the road at target interchanges. Data are reported for mean speed relative to the speed limit, in mph, and the error bars represent standard error. Uppercase letters indicate post hoc grouping from pairwise comparisons.

Exit ramp speed limits are typically advisory and provide guidance on a recommended safe speed limit. Across the five study interchanges, exit ramp speed limit varied in relation to the mainline speed limit, implying vehicles would need to achieve different reductions in speed to safely navigate exit ramp segments. For example, vehicles taking exits at Interchange 335 (which used conventional lighting) had to reduce their speed 30 mph to match the recommended safe ramp speed, while vehicles taking exits at Interchange 340 only had to reduce their speed by 15 mph. Table 36 summarizes the mean speeds for vehicles taking exit ramps across all interchanges relative to the suggested ramp speed limit. Speed behavior, relative to the ramp speed limit, was consistent for four of the five lighting designs where vehicles were found to take exit ramps at a speed between 6.8 and 8.8 mph more than the recommended speed limit (Table 36). In contrast, vehicles traveling under Partial High-Mast lighting took exit ramp segments at significantly faster speeds. Vehicles driving under the Partial High-Mast lighting design traveled between 43% and 81% faster than all other lighting designs, relative to recommended safe ramp speeds.

Table 36. Mean Speed Relative to the Ramp Speed Limits Posted at Off Ramps for Each Interchange

Interchange Number	Lighting Design	Speed (mph)	Speed Relative to Ramp Speed Limit (mph)
335	Conventional	47.33	7.33
322	Conventional Exit Only	56.84	6.84
318	High-Mast	58.70	8.70
340	High-Mast & Conventional	47.69	7.69
327	Partial High-Mast	52.42	12.4

Entering Traffic

The least-squares means and pairwise comparisons of mean speed for vehicles using entrance ramps at the study interchanges are shown in Figure 35. Due to radar kit failure during data collection, there were no entrance vehicles measured at Interchange 340, which used a combination of High-Mast & Conventional lighting. Therefore, all entrance pairwise comparisons were made between the remaining four lighting designs. After adjusting for multiple tests, several between lighting design differences in vehicle speeds were found. All speeds are reported relative to the mainline speed limit at each interchange. Mainline speed limits are shown in Table 8.

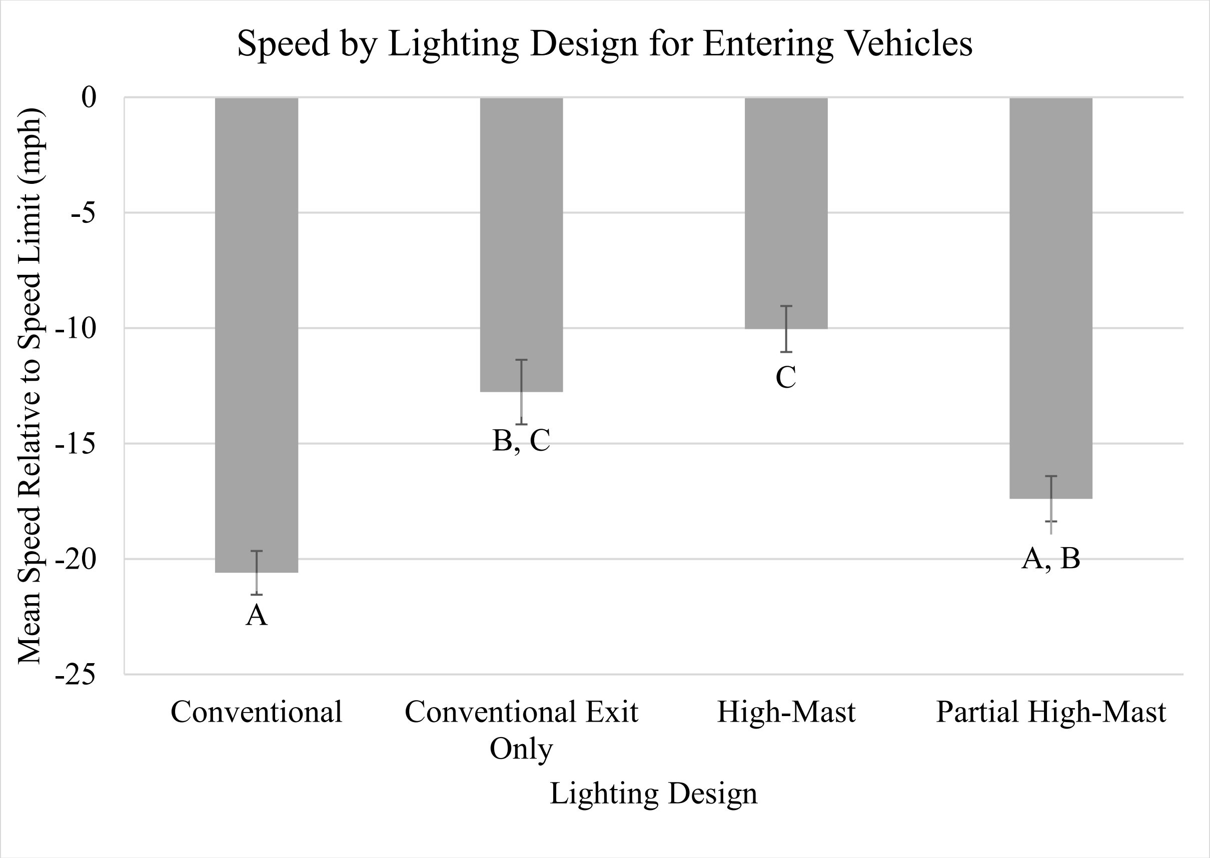

Figure 35. Graph. Speed results by lighting design for vehicles entering the road at target interchanges. Data are reported for mean speed relative to the speed limit, in mph, and the error bars represent standard error. Uppercase letters indicate post hoc grouping from pairwise comparisons.

Overall, across all lighting designs, vehicles entering the roadways traveled between 10 and 21 mph slower than the mainline speed limit. A significant difference in mean speed relative to the mainline speed limit was found between High-Mast lighting (−10.03 mph) and both Conventional (−20.6 mph) and Partial High-Mast (−17.4 mph) lighting designs. Vehicles traveling under High-Mast lighting entered the roadway with significantly less difference (52% to 43%) between their average speed and the mainline speed limit.

Light Level Analysis

The LMM results for the effect of light level and interchange segment on vehicle speed are given in Table 37. Results indicated significant difference between at least two factor levels of interchange segment and light level. Additionally, there was statistical difference between at least two factor level combinations of light level and interchange segment. The research team expected a difference in vehicle speeds between interchange segments as through traffic would, on average, be traveling at speeds that were unsafe or at which it would be impossible to navigate ramp segments. The ramp segment speed limits, while not enforceable, varied between 15 to 20 mph slower than mainline enforceable speed limits. Comparisons between light levels without accounting for the interchange segment where vehicle speed was measured were not of research interest. Therefore, pairwise comparisons focused on the difference in vehicle speeds between light levels within each interchange segment.

Table 37. Speed: Type 3 Tests of Fixed Effects for Light Level, Interchange Segment, and the Interaction between Light Level and Interchange Segment

Effect	Num DF	Den DF	*F* Value	*p*-Value
Light Level (LL)	2	11000	11.71	**<.0001**
Interchange Segment (IS)	2	11000	1311.92	**<.0001**
LL*IS	4	11000	74.64	**<.0001**

Bolded p-values were considered statistically significant.

Researchers began post hoc analysis by conducting a test of the simple effects. The significance of simple effect testing results, which assess the differences of the least-squares means within each interchange segment, are shown in Table 38. Significance, indicated by bolded *p*-values, suggests a difference in mean vehicle speed between at least two light level comparisons within each interchange segment. Results showed that, for vehicles entering the road, vehicles exiting the road, and vehicles traveling through the interchanges, light level was potentially having an influence on mean vehicle speeds. A follow-up analysis was conducted to evaluate which light levels were resulting in differences in vehicle speed. The results of the follow-up analysis are presented separately for through, entering, and exiting vehicle traffic.

Table 38. Speed: Tests of Effect Slices at All Factor Levels of Interchange Segment for the Influence of Light Level

Effect	Interchange Segment	Num DF	Den DF	*F* Value	*p*-Value
LL*IS	Entrance	2	11000	39	**<.0001**
LL*IS	Exit	2	11000	20.66	**<.0001**
LL*IS	Through	2	8846	335.58	**<.0001**

Bolded p-values were considered statistically significant.

Through Traffic

The least-squares means and pairwise comparisons of mean speed for vehicles traveling through the study interchanges are shown in Figure 36. After adjusting for multiple comparisons, statistical difference in speed was found between high to medium and high to low comparisons. All speeds are reported relative to the through segment speed limit at each interchange, as shown in Table 8.

When moving through the study interchanges, vehicles traveled, on average, 8.48 mph faster than the speed limit when the light level was high, which was significantly higher than the posted speed limit. When the through lanes were measured at low or medium light level, vehicles traveled less than 1 mph faster than the speed limit. Furthermore, least-squares means *t* tests showed that vehicle speeds under low and medium light levels were not significantly different than the posted speed limit.

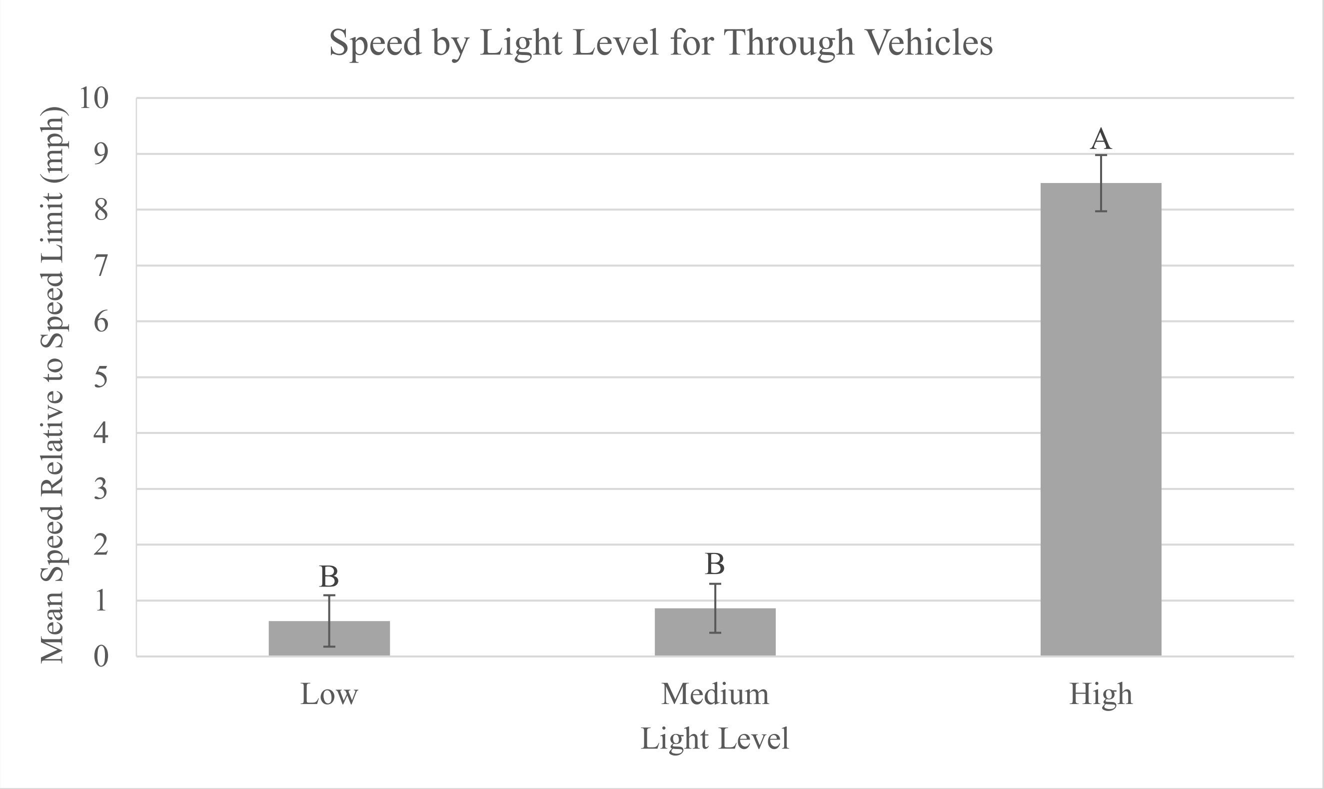

Figure 36. Graph. Speed results by light level for vehicles traveling through the target interchanges. Data are reported for mean speed relative to the speed limit, in mph, and the error bars represent standard error. Uppercase letters indicate post hoc grouping from pairwise comparisons.

Exiting Traffic

Post hoc analysis results for exit ramp speed including least-squares means and pairwise comparisons are shown in Figure 37. Uppercase lettering indicates post hoc grouping. After adjusting for multiple comparisons, one light level comparison was statistically significant. Speeds are reported relative to the mainline speed limit at each interchange, as given in Table 8.

Overall, across all light levels, exiting vehicles, on average, traveled between 12 and 17 mph slower than mainline speed limits. A significant difference in mean speed relative to the mainline speed limit was found between vehicles exiting under medium and high-level lighting. When the light level was high (12.1 mph), vehicle speed was reduced by 28% compared to medium light level (16.9 mph). Speeds at low light level exit ramps were slower than medium and faster than high, but none of the differences were practically or statistically significant.

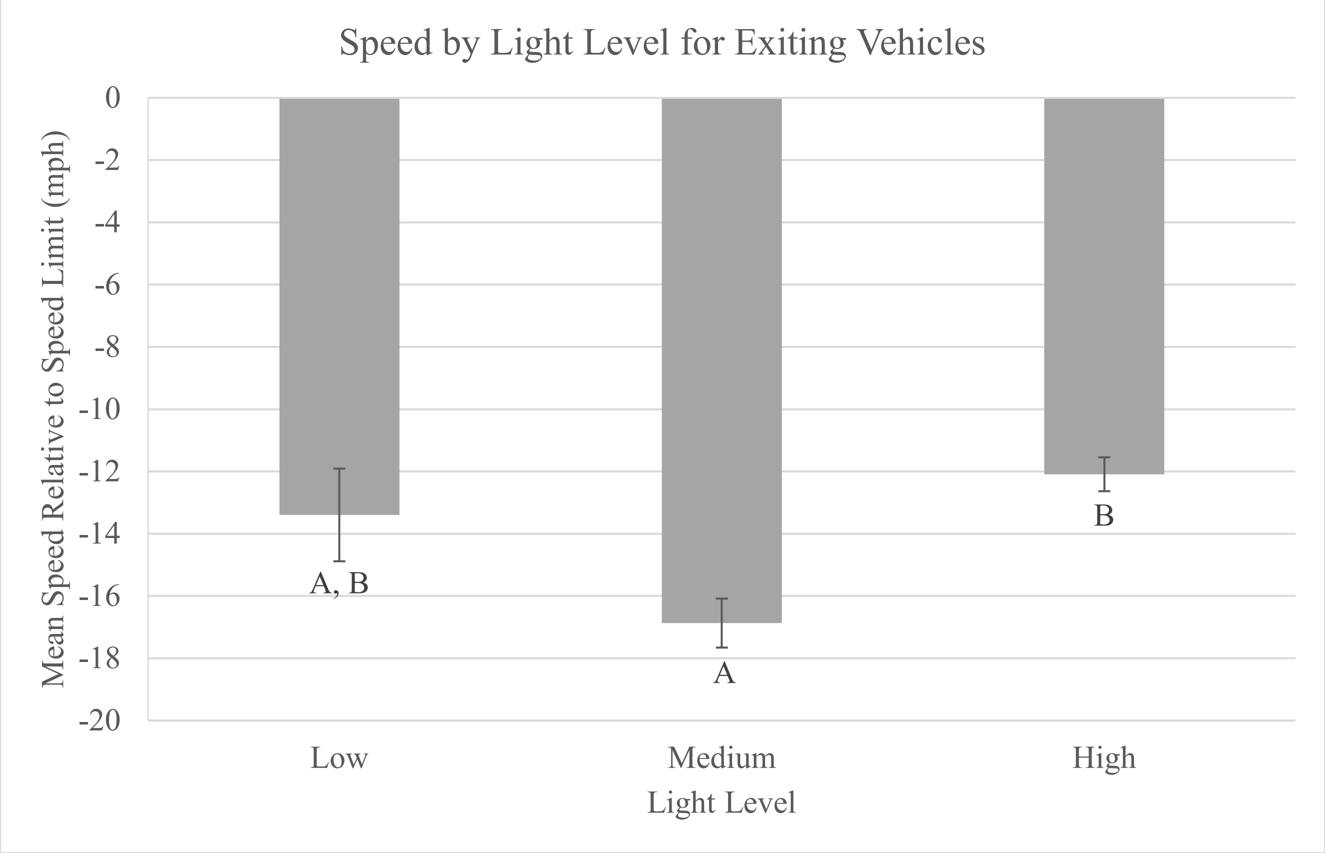

Figure 37. Graph. Speed results by light level for vehicles exiting the road at target interchanges. Data are reported for mean speed relative to the speed limit, in mph, and the error bars represent standard error. Uppercase letters indicate post hoc grouping from pairwise comparisons.

Entering Traffic

Figure 38 shows the LMM results for least-squares means and pairwise comparisons of speed for vehicles taking entrance ramps at the study interchanges. Due to radar kit failure during data collection, there were no entrance vehicles measured under High-Mast & Conventional lighting. After adjusting for multiple comparisons, two between light level differences in vehicle speed were found. All speeds are reported relative to the mainline speed limit at each interchange, as presented in Table 8.

Overall, across all light levels, vehicles entering the interchanges traveled between 12 and 21 mph slower than the mainline speed limit. A significant difference in mean speed relative to the mainline speed limit was found between high light level (−10.03 mph) and both low (−20.6 mph) and High-Mast in the central median (−17.4 mph). Overall, vehicles traveling under high-mast lighting were shown to have significantly closer (52% to 43%) speeds to mainline traffic when compared to medium and low light levels.

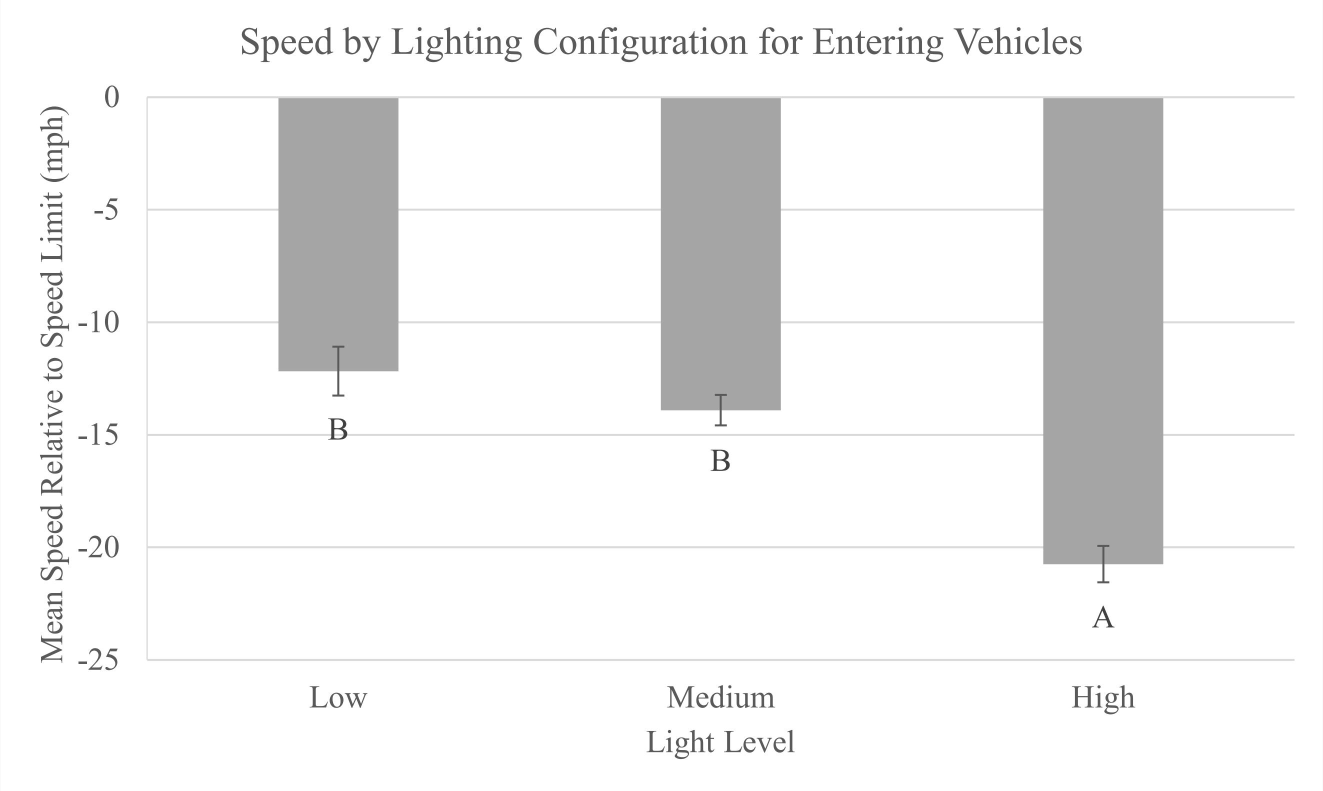

Figure 38. Graph. Speed results by light level for vehicles entering the road at target interchanges. Data are reported for mean speed relative to the speed limit, in mph, and the error bars represent standard error. Uppercase letters indicate post hoc grouping from pairwise comparisons.

Dimming Analysis

Table 39 shows the LMM results for the effect of dim level and interchange segment on vehicle speed at Interchange 318. Statistical differences in vehicle speeds were found between interchange segments and between dim levels. However, there was no statistical difference found between any of the factor level combinations for the interaction between dim level and interchange segment. Researchers expected a difference in vehicle speeds between interchange segments as through traffic would, on average, be traveling at speeds that were unsafe or at which it would be impossible to navigate ramp segments. Therefore, pairwise comparisons focused on the difference in vehicle speeds between dim levels within each interchange segment.

Table 39. Speed: Type 3 Tests of Fixed Effects for Light Level, Interchange Segment, and the Interaction between Light Level and Interchange Segment at Interchange 318

Effect	Num DF	Den DF	*F* Value	*p*-Value
Dim Level (DL)	1	3717	12.93	**0.0003**
Interchange Segment (IS)	2	3593	446.4	**<.0001**
DL*IS	2	3718	2.26	0.104

Bolded p-values were considered statistically significant.

The research team conducted post hoc analysis beginning with a test of the simple effects. Table 40 provides the simple effects testing results that compare the least-squares means for dim level within each interchange segment. Testing significance, indicated by bolded *p*-values, implies a difference in mean vehicle speed between the full brightness and dimmed lighting within a given interchange segment. Results found that, for vehicles entering the road, there was no significant difference in vehicle speed regardless of dim level. Conversely, dim level was found to potentially have an influence on speed for vehicles exiting the road and vehicles traveling through the interchange. Subsequent analysis focused on assessing the vehicle speed difference for full brightness and dimmed high-mast lighting exiting and traveling through Interchange 318.

Table 40. Speed: Tests of Effect Slices at All Factor Levels of Interchange Segment for the Influence of Light Level

Effect	Interchange Segment	Num DF	Den DF	*F* Value	*p*-Value
DL*IS	Entrance	1	3717	0.74	0.3898
DL*IS	Exit	1	3718	12.47	**0.0004**
DL*IS	Through	1	3714	35.56	**<.0001**

Bolded p-values were considered statistically significant.

The least-squares means results from LMM by vehicle speed and dim level for each interchange segment are shown in Figure 39. A significant difference in mean vehicle speed was found between dim levels for exiting and through vehicles. No statistical difference in mean speed between dim levels was found for vehicles entering the roadway at Interchange 318.

Vehicles entering the roadway traveled at similar speeds under bright (59.8 mph) and dim (58.5 mph) levels. Mean speed for vehicles exiting Interchange 318 was significantly faster (7.4%) when the high-mast lighting was at full brightness (58.8 mph) compared to 50% dimmed (54.8 mph). Vehicles heading through Interchange 318 were found to be going statistically significantly faster under full brightness (72.8 mph) than at 50% dim level (71.3 mph), however the difference, while statistically significant, did not represent a practical difference between dim levels. For vehicles traveling through Interchange 318, mean vehicle speed was very close to the speed limit regardless of dim level.

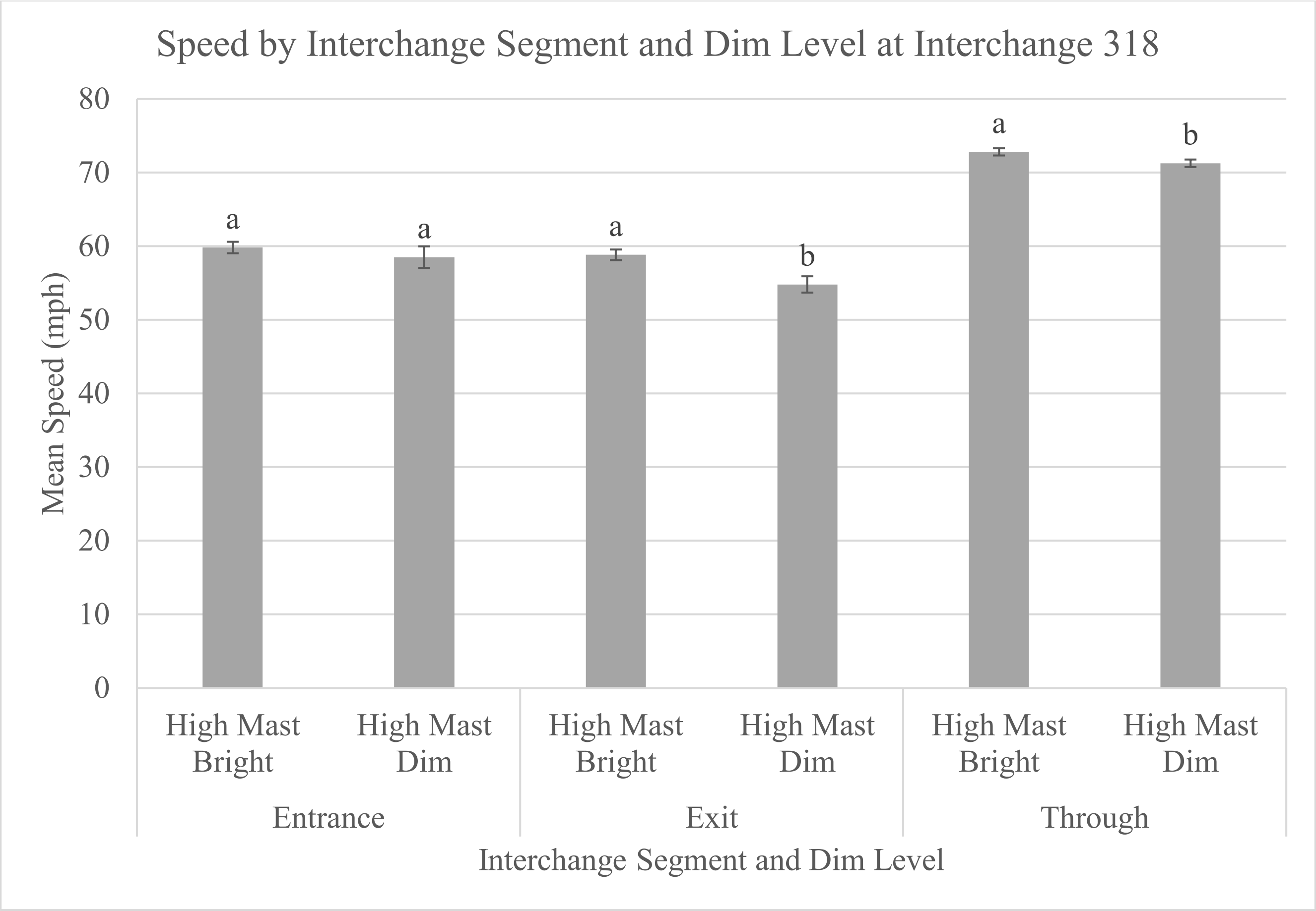

Figure 39. Graph. Speed results by light level and interchange segment. Data are reported for mean speed, in mph, and the error bars represent standard error. Lowercase letters indicate post hoc grouping within interchange segment.

Speed Variation

Lighting Design Analysis

Table 41 shows the LMM results for the effect of lighting design and interchange segment on vehicle speed variation. A statistical difference was found for vehicle speed variation between interchange segments and between lighting designs. There was also a statistical difference in speed variation between at least two of the factor level combinations for the interaction between lighting design and interchange segment. The research team expected a difference in vehicle speed variation between interchange segments, as through traffic would not need to alter speed as much and ramp traffic would be decelerating to enter cross streets or accelerating to match the mainline traffic flow. Therefore, post hoc testing focused on comparing vehicle speed variation between lighting designs within each interchange segment.

Table 41. Speed Variation: Type 3 Tests of Fixed Effects for Lighting Design, Interchange Segment, and the Interaction between Lighting Design and Interchange Segment

Effect	Num DF	Den DF	*F* Value	*p*-Value
Lighting Design (LD)	4	6932	72.71	**<.0001**
Interchange Segment (IS)	2	9464	1579.55	**<.0001**
LD*IS	7	9311	4.94	**<.0001**

Bolded p-values were considered statistically significant.

Post hoc analysis was guided by first conducting a test of the simple effects. Table 42 shows the significance of testing results that evaluate the differences in least-squares means within each interchange segment; *p*-values less than 0.05 indicated a significant difference in vehicle speed variation between at least two lighting designs within each interchange segment. Results suggested that, for vehicles exiting the road and vehicles traveling through the interchanges, lighting design was potentially having an influence on vehicle speed variation. Additional analysis was conducted to assess which lighting designs were experiencing differences in vehicle speed. The results of these analyses are presented separately for through, entering, and exiting vehicle traffic.

Table 42. Speed Variation: Tests of Effect Slices at All Factor Levels of Interchange Segment for the Influence of Lighting Design

Effect	Interchange Segment	Num DF	Den DF	*F* Value	*p*-Value
LD*IS	Entrance	3	9352	1.85	0.1365
LD*IS	Exit	4	9190	41.7	**<.0001**
LD*IS	Through	4	4100	99.15	**<.0001**

Bolded p-values were considered statistically significant.

Through Traffic

Figure 40 gives the least-squares means and pairwise comparisons of speed variation for vehicles traveling through the study interchanges. After adjusting for multiple comparisons, two lighting designs were found to experience significantly larger speed variation.

Speed variation ranged between 0.3 and 0.8 mph for through segments across all interchanges. High-Mast & Conventional lighting (0.785 mph) experienced the largest variation in vehicle speed, which was statistically larger than all other lighting designs. Speed variation at Interchange 322, which used Conventional Exit Only lighting (0.5 mph), had significantly higher speed variation than Conventional (0.31 mph), High-Mast (0.29 mph), and Partial High-Mast (0.30 mph) lighting designs, but lower speed variation than High-Mast & Conventional. The High-Mast & Conventional lighting design saw a 56% to 164% increase in speed variation compared to all other lighting designs, but speed variation for all through segments was relatively low (less than 1 mph) compared to ramp segments.

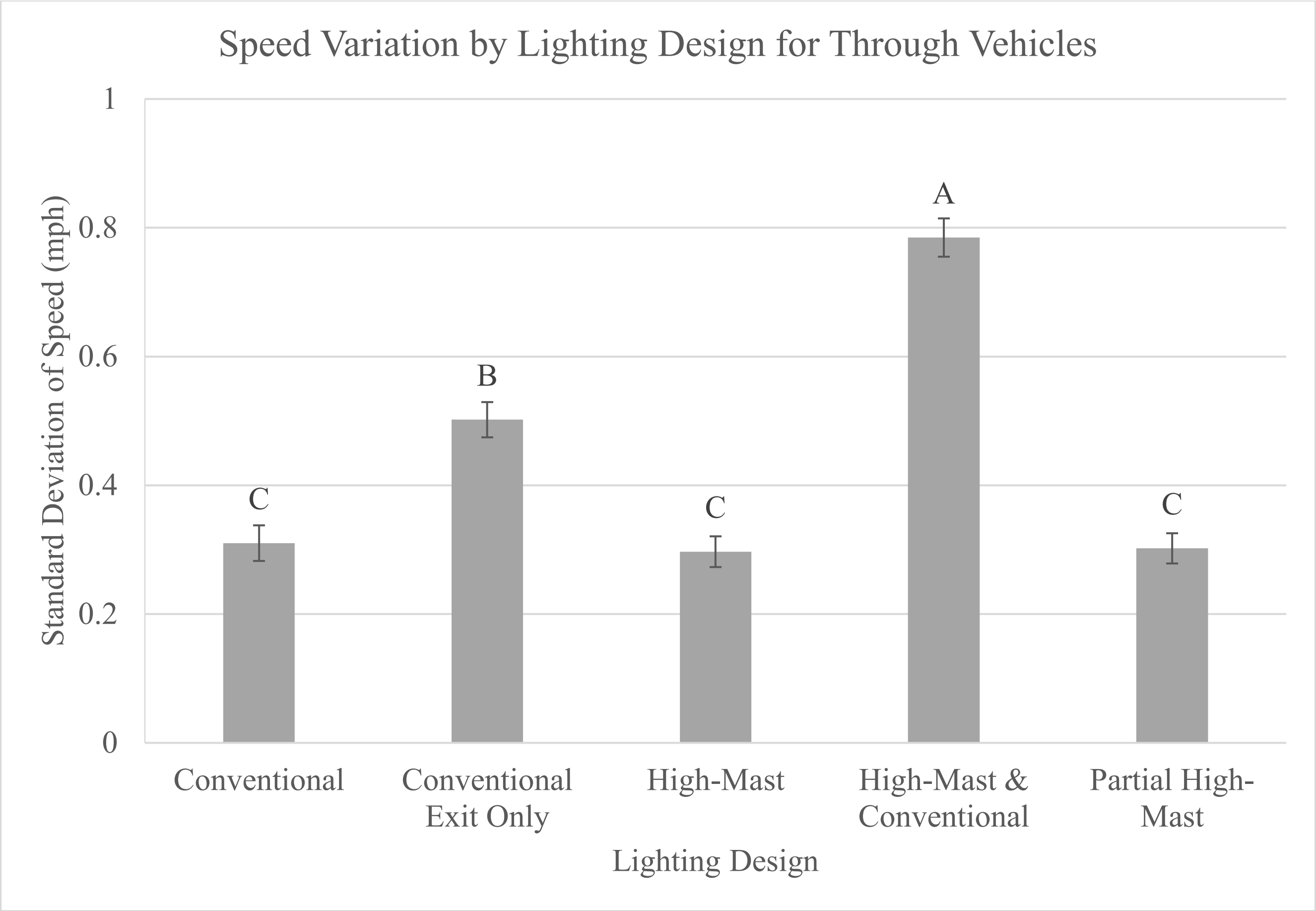

Figure 40. Graph. Speed variation results by lighting design for vehicles traveling through the target interchanges. Data are reported for the standard deviation of speed, in mph, and the error bars represent standard error. Uppercase letters indicate post hoc grouping from pairwise comparisons.

Exiting Traffic

The least-squares means and pairwise comparisons of speed variation for vehicles taking exit ramps are shown in Figure 41. After adjusting for multiple tests, several comparisons indicated that exit vehicle speed variation was different between lighting designs.

Speed variation at exit ramps ranged between 1.9 and 2.8 mph across all interchanges. Exit ramps, on average, saw the most speed variation of any interchange segment. Speed varied at exit ramps across all interchanges by around 2 mph, while entrance speeds varied about 1 mph and through speeds varied by less than 0.5 mph.

Speed variation under High-Mast & Conventional lighting (2.72 mph) was significantly larger than all overlighting designs. Of note, High-Mast & Conventional lighting experienced significantly higher speed variation than High-Mast lighting despite having a smaller difference between mainline and ramp speed limits (Table 8). Vehicles exiting under High-Mast & Conventional lighting varied their speed 44% more than vehicles exiting under High-Mast lighting (1.89 mph). Vehicles exiting at interchanges with Conventional (2.22 mph), Conventional Exit Only (2.26 mph), and Partial High-Mast (2.11 mph) lighting designs had statistically similar speed variation.

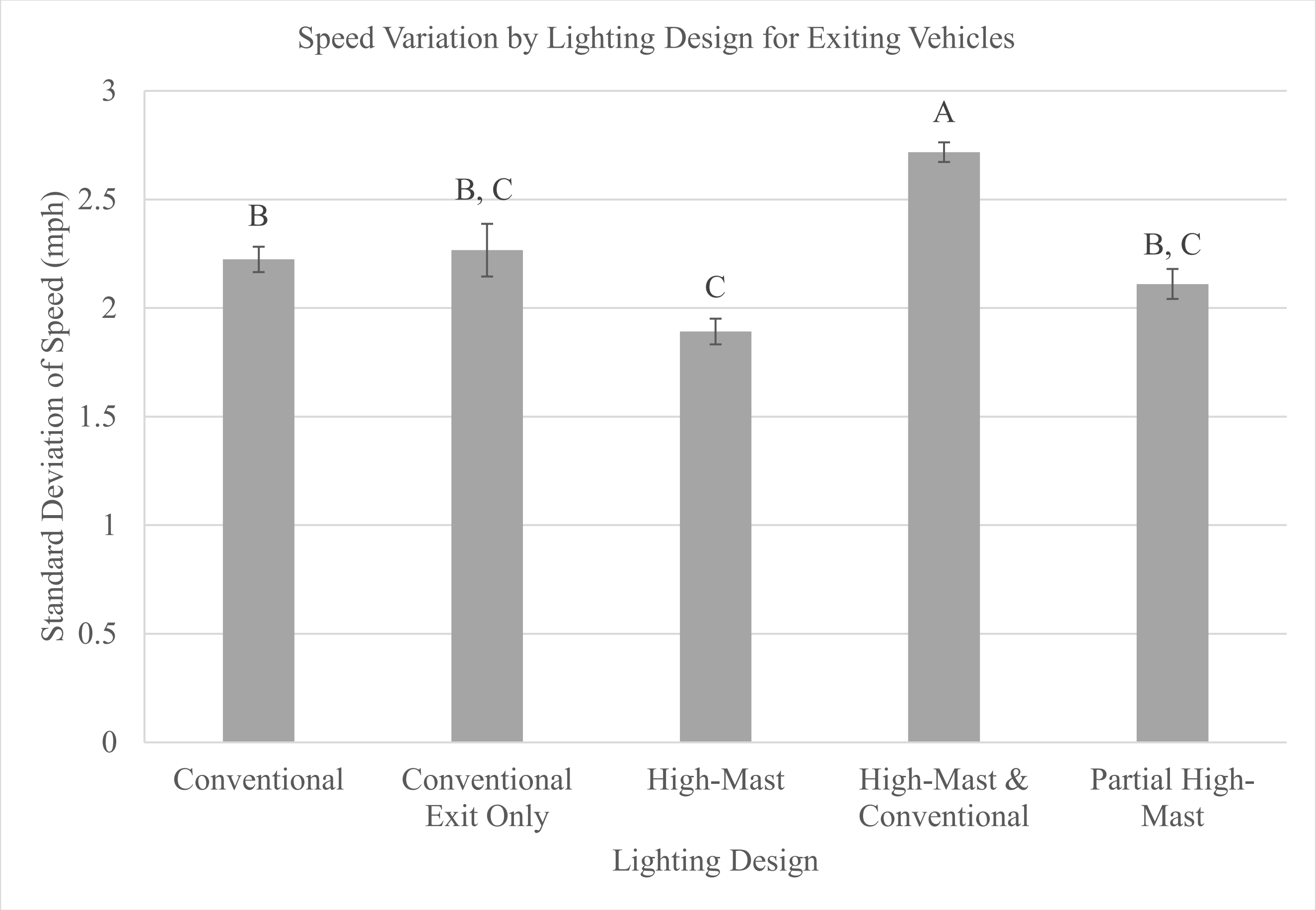

Figure 41. Graph. Speed variation results by lighting design for vehicles exiting the road at target interchanges. Data are reported for the standard deviation of speed, in mph, and the error bars represent standard error. Uppercase letters indicate post hoc grouping from pairwise comparisons.

Entering Traffic

Figure 42 shows the least-squares means and pairwise comparisons of speed variation for vehicles entering mainline traffic at each of the study interchanges. Overall, entrance vehicle speed variation ranged between 0.8 and 1.05 mph across all interchanges. Some variability in speed variation was observed between interchanges, but none of the post hoc comparisons provided practical or statistical significance. Due to radar kit failure during data collection, there were no entrance vehicles measured at Interchange 340, which used a combination of High-Mast & Conventional lighting. Therefore, researchers could not estimate entering traffic speed variation for that lighting design. As vehicles accelerated to meet the flow of traffic, their speed varied more, on average, than through segments but less than vehicles slowing down to exit the roadway.

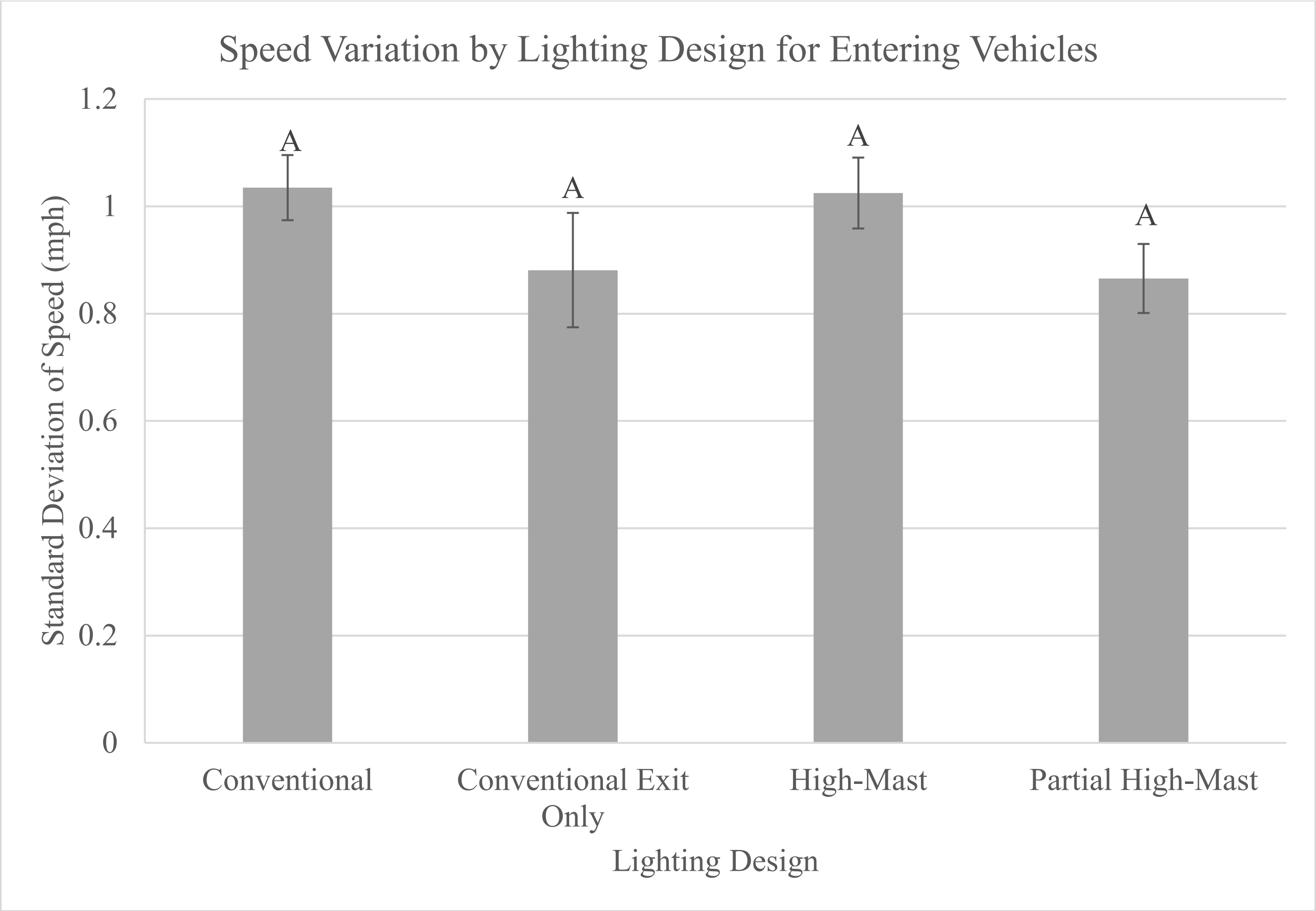

Figure 42. Graph. Speed variation results by lighting design for vehicles entering the road at target interchanges. Data are reported for the standard deviation of speed, in mph, and the error bars represent standard error. Uppercase letters indicate post hoc grouping from pairwise comparisons.

Light Level Analysis

The LMM results for the effect of light level and interchange segment on vehicle speed variation are given in Table 43. A significant difference in speed variation was found between at least two interchange segments and light levels. Additionally, the interaction between interchange segment and light level was significant. The research team expected a difference in vehicle speed variation between interchange segments, as through traffic would not need to alter speed as much and ramp traffic would be decelerating to enter the cross street or accelerating to match the mainline traffic flow. Comparing speed variation by light level without accounting for interchange segment was not of research interest. Therefore, pairwise comparisons focused on the difference in vehicle speeds between light levels within each interchange segment.

Table 43. Speed Variation: Type 3 Tests of Fixed Effects for Light Level, Interchange Segment, and the Interaction between Light Level and Interchange Segment

Effect	Num DF	Den DF	*F* Value	*p*-Value
Light Level (LL)	2	9159	49.91	**<.0001**
Interchange Segment (IS)	2	11000	804.24	**<.0001**
LL*IS	4	8960	8.46	**<.0001**

Bolded p-values were considered statistically significant.

The direction of the follow-up analysis was guided by performing a test of the simple effects. The results of simple effect testing, which assess the differences of the least-squares means within each interchange segment, are shown in Table 44. Significance, indicated by bolded *p*-values, suggests a difference in vehicle speed variation between at least two light level comparisons within each interchange segment. Results found that, for vehicles entering the road, vehicles exiting the road, and vehicles traveling through the interchanges, light level was potentially having an influence on vehicle speed variation. Subsequent analysis evaluated which light levels were resulting in differences in vehicle speed variation. The outcomes of the follow-up analysis are presented separately for through, entering, and exiting vehicle traffic.

Table 44. Speed Variation: Tests of Effect Slices at All Factor Levels of Interchange Segment for the Influence of Light Level

Effect	Interchange Segment	Num DF	Den DF	*F* Value	*p*-Value
LL*IS	Entrance	2	11000	3.69	**0.0249**
LL*IS	Exit	2	9806	19.63	**<.0001**
LL*IS	Through	2	772	182.63	**<.0001**

Bolded p-values were considered statistically significant.

Through Traffic

The least-squares means and pairwise comparisons of speed variation for vehicles traveling through the study interchanges are shown in Figure 43. After adjusting for multiple comparisons, statistical difference in speed variation was found between all light levels. Across all light levels, the speed variation for through vehicles was found, on average, to range between 0.3 and 0.8 mph. Vehicles driving under a high light level (0.77 mph) were found to have the highest speed variation. Speed variation under the high light level increased by 91% compared to low (0.41 mph) and 156% compared to medium (0.30 mph) light levels. Overall, speed variation for vehicles traveling through interchanges was low in magnitude compared to ramp segments.

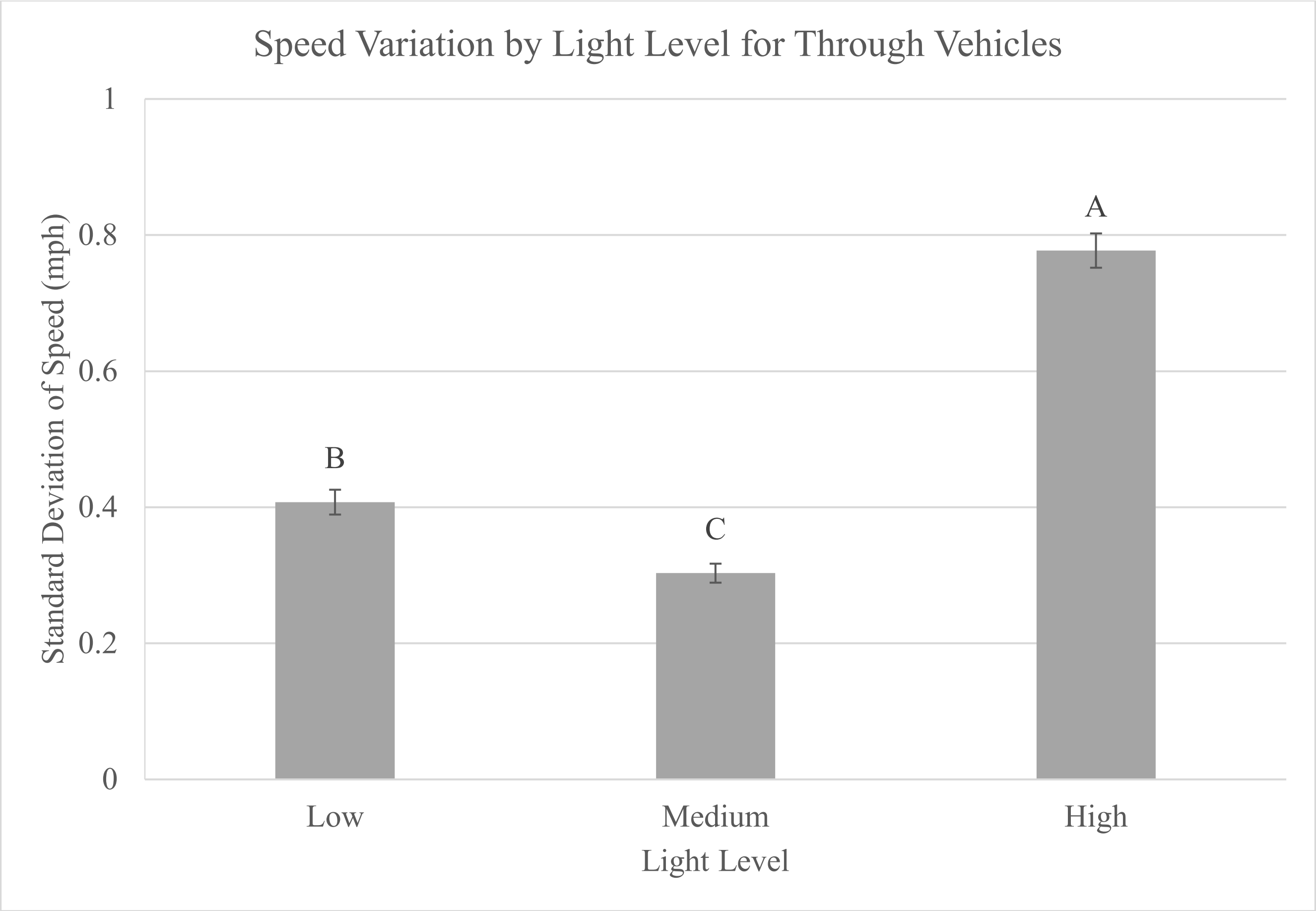

Figure 43. Graph. Speed variation results by light level for vehicles traveling through the target interchanges. Data are reported for the standard deviation of speed, in mph, and the error bars represent standard error. Uppercase letters indicate post hoc grouping from pairwise comparisons.

Exiting Traffic

Post hoc analysis results for exit ramp speed variation, including least-squares means and pairwise comparisons, are shown in Figure 44. After adjusting for multiple comparisons, one light level comparison was statistically significant. A statistical difference in speed variation was found between vehicles exiting under medium and high-level lighting. When the light level was high (2.38 mph), vehicle speed variation increased by 19% compared to medium light level (1.99 mph). Exiting vehicle speed variation at low light level (2.27 mph) was higher than medium and lower than high, but neither of the differences were statistically significant. Compared to vehicles entering the interchange and those traveling through it, exiting vehicles had higher speed variation at every light level.

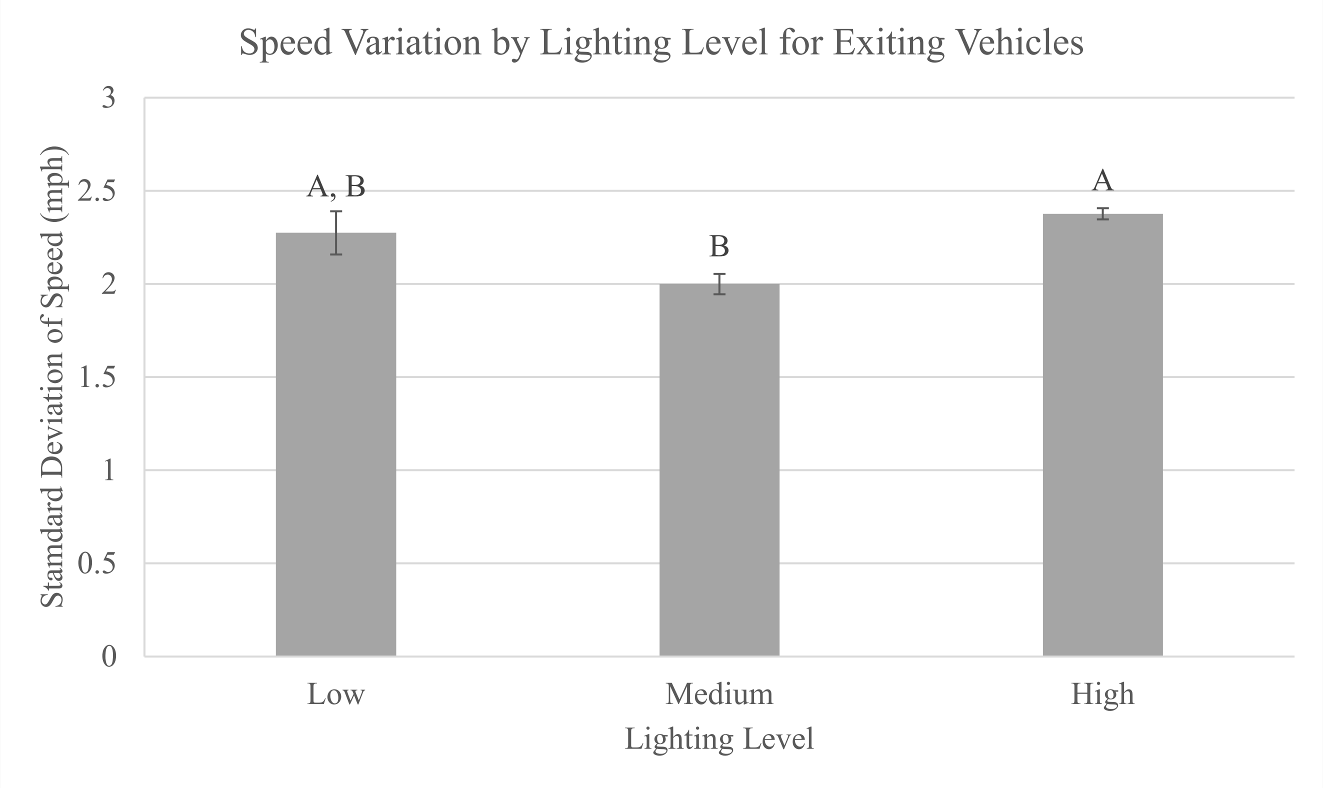

Figure 44. Graph. Speed variation results by light level for vehicles exiting the road at target interchanges. Data are reported for the standard deviation of speed, in mph, and the error bars represent standard error. Uppercase letters indicate post hoc grouping from pairwise comparisons.

Entering Traffic

Figure 45 gives the LMM results for least-squares means and pairwise comparisons of speed variation for vehicles taking entrance ramps at the study interchanges. After adjusting for multiple comparisons, no significant difference was found in entrance speed variation between any of the light levels. Overall, across all light levels, vehicles entering the interchanges were found to, on average, have speed variation between 0.75 and 1.05 mph. While not statistically significant, speed variation for entering vehicles increased by 22.5% at medium (0.94 mph) and 34.5% at high (1.04 mph) compared to low (0.77 mph) light levels.

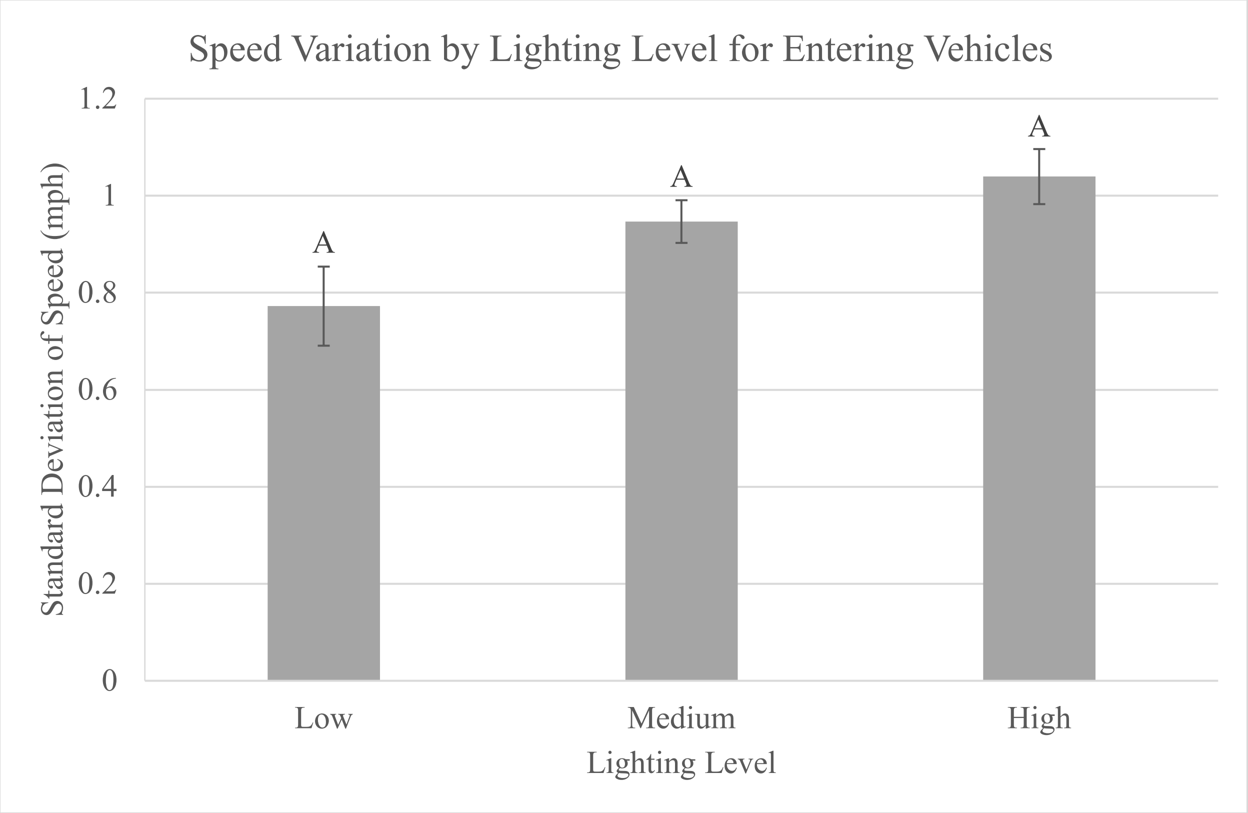

Figure 45. Graph. Speed variation results by light level for vehicles entering the road at target interchanges. Data are reported for the standard deviation of speed, in mph, and the error bars represent standard error. Uppercase letters indicate post hoc grouping from pairwise comparisons.

Dimming Analysis

Table 45 gives the LMM results for the effect of dim level and interchange segment on vehicle speed variation at Interchange 318. Overall, testing revealed a statistical difference in vehicle speed variation between interchange segments and between dim levels. Additionally, there was a statistical difference between at least two of the factor level combinations for the interaction between dim level and interchange segment. Researchers expected a difference in vehicle speed variation between interchange segments, as through traffic would, on average, not need to adjust speed as much while, in contrast, vehicles using the ramps would need to accelerate or decelerate depending on segment. Therefore, pairwise comparisons focused on the difference in vehicle speed variation between dim levels within each interchange segment.

Table 45. Speed Variation: Type 3 Tests of Fixed Effects for Light Level, Interchange Segment, and the Interaction between Light Level and Interchange Segment at Interchange 318

Effect	Num DF	Den DF	*F* Value	*p*-Value
Dim Level (DL)	1	3717	29.43	**<.0001**
Interchange Segment (IS)	2	3674	1037.62	**<.0001**
DL*IS	2	3718	13.86	**<.0001**

Bolded p-values were considered statistically significant.

Researchers conducted a follow-up analysis that began with a test of the simple effects. Table 46 gives the simple effects testing results that compare the least-squares means for light level within each interchange segment. Testing significance, indicated by bolded *p*-values, implies a difference in speed variation between dim levels within a given interchange segment. Results found that, for vehicles entering and exiting the road, dim level was potentially having an impact on vehicle speed variation. Conversely, dim level was not shown to have an influence on speed variation for vehicles traveling through Interchange 318. Further analysis sought to identify the magnitude of differences in speed variation between the full brightness and 50% dim levels.

Table 46. Speed Variation: Tests of Effect Slices at All Factor Levels of Interchange Segment for the Influence of Light Level at Interchange 318

Effect	Interchange Segment	Num DF	Den DF	*F* Value	*p*-Value
DL*IS	Entrance	1	3717	26.46	**<.0001**
DL*IS	Exit	1	3718	4.5	**0.0339**
DL*IS	Through	1	3717	0.39	0.53

Bolded p-values were considered statistically significant.

LMM analysis produced least-squares means estimates for all dim level and interchange segment combinations. These means and pairwise comparison results are shown in Figure 46. Statistical difference in speed variation was found between bright and dim light levels, at Interchange 318, for entering vehicles. No statistical difference in speed variation between dim levels was found for vehicles exiting at, or traveling through, Interchange 318.

Speed variation at Interchange 318 ranged between 0.28 and 1.9 mph across all segments. Vehicles taking exit ramps at Interchange 318 varied their speed the most (1.83 mph), which was significantly more variation than for entering vehicles (0.79 mph) or through traffic (0.28 mph). Speed variation at Interchange 318, by segment, was similar to the trends observed across all interchanges.

Pairwise comparisons revealed that vehicles entering the roadway at Interchange 318 varied their speed 45% more under bright (1.01 mph) high-mast lighting than when dimmed to 50% (0.56 mph). Additionally, vehicles traveling through Interchange 318 were shown to have almost the same speed variation under bright (0.29 mph) and dim (0.28 mph) high-mast lighting. Although speed variation was significantly larger in magnitude for exiting vehicles compared to entering or through traffic, speed variation for exiting vehicles was statistically similar regardless of dim level (bright = 1.90 mph; dim = 1.76 mph).

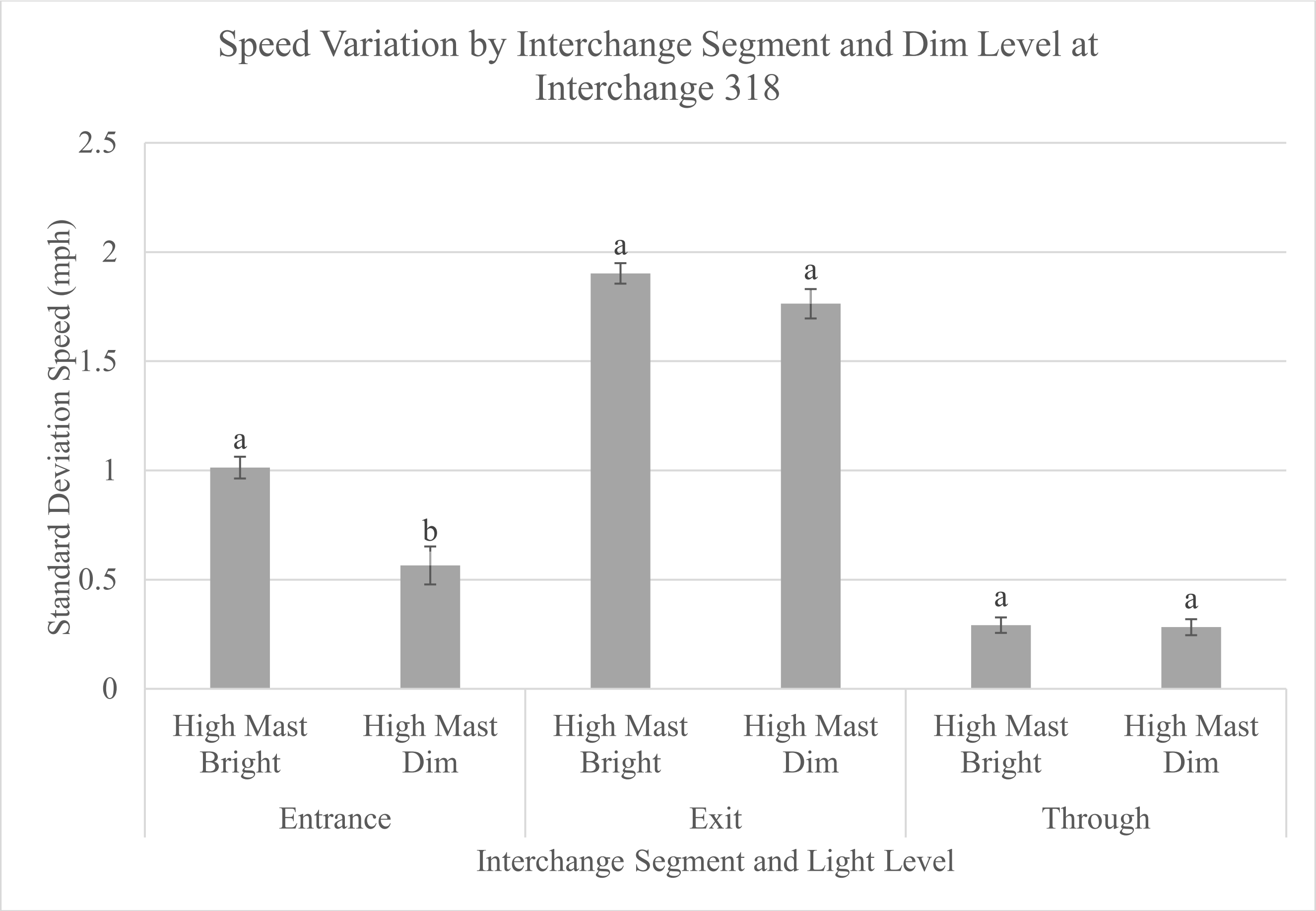

Figure 46. Graph. Speed variation results by light level and interchange segment. Data are reported for the standard deviation of speed, in mph, and the error bars represent standard error. Lowercase letters indicate post hoc grouping from pairwise comparisons within interchange segment.

CHAPTER 4: DISCUSSION

SUBJECTIVE EVALUATION DISCUSSION

Target Detection

No differences were found in target detection between the different lighting designs or light levels. It was difficult to isolate the impact of lighting design, age, and light level on small object detection due to the nature of testing. This may be due to the limited number of targets and reliance on participants' self-reporting, which made the measures less reliable. As a result of testing on live roadways, false detections of non-study targets and reporting bias were possible, as participants did not want to "miss" the detections.

Analysis showed that target detection was reasonably consistent across light levels and lighting designs. Furthermore, older participants, who typically have more difficulty detecting small objects, performed similarly across all interchange lighting designs, but worse than younger participants. In general, results followed the expected performance levels for age and light level, and the lack of significant results could be attributed to the study not having enough power to detect the effect sizes observed.

Results suggest that lighting design choice and light level selection could be tailored to levels that positively influence the other subjective measures studied, such as visibility, comfort, and safety.

Comfort, Safety, and Visibility

For subjective measures of comfort, safety, and visibility, participant response revealed that fully lit interchanges (Conventional, High-Mast, and Conventional & High-Mast) performed best. Among the fully lit interchange lighting designs, those that contained high-mast infrastructure were rated the best concerning safety and comfort sentiment across age groups. Conversely, partially lit interchange lighting designs (Conventional Exit Only, Partial High-Mast) were rated, on average, lower for comfort, safety, and visibility sentiment.

In general, increasing the light level improved participant opinion of safety and comfort across all interchange segments. When accounting for age, the medium light level interchanges were sometimes judged lower for comfort and safety than the low light level interchanges. This could be attributed to the reduced amount of light, compared to high levels, not providing enough visibility for participants to confidently feel safe and comfortable traveling at traffic flow speeds. While at low light level interchanges, participants might adjust their speed to account for the visibility loss, resulting in higher sentiment for comfort and safety.

For the partially lit interchanges, drivers were exposed to a light near the gore points, but then transitioned into darkness. Interestingly, Partial High-Mast lighting was rated significantly worse for comfort, safety, and visibility even though it had a higher horizontal illuminance than the Conventional Exit Only lighting design. This is likely because of inconsistent illumination, due to pole positioning, which placed two high-mast luminaires near each of the gore points, followed by the unlit ramp segments. The transition from light to darkness left participants in a state of transient adaptation, where their eyes were not quite adapted to the bright light of the luminaires or to the darkness of the ramps.

At fully lit interchanges, the pole spacing and light levels were much more consistent. As a result, the interchanges that used high-mast lighting at a high light level were rated as providing the best visibility of ramp segments and rated the highest for comfort and safety sentiment.

When asked whether an interchange had too *much* light, participants disagreed for all interchanges. When asked whether an interchange had too *little* light, participants only agreed for the partially lit interchanges (Conventional Exit Only and Partial High-Mast). Partial High-Mast stood out, as participants strongly disagreed that it had too much lighting and provided agreement sentiment about too little lighting. When grouped by light level, participants disagreed that the high light level interchanges were providing too little light, while medium and low levels received a neutral participant sentiment on whether they were providing too little light. Results suggested that Partial High-Mast lighting was seen as providing too little lighting in its current configuration.

Overall, participant opinion of safety, comfort, and visibility improved as light levels increased, especially for designs that included high-mast lighting. At high light level interchanges, both age groups indicated similar levels of comfort, safety, and visibility for ramp segments.

Discomfort Glare

High-Mast lighting is designed to pull glare out of the driver's eyeline, and this sentiment was reflected in the study data. Results found that lighting designs that used high-mast lighting provided higher illuminance while being rated similarly to conventional lighting designs for discomfort glare. When interchanges were categorized by light level, discomfort glare increased with light level independent of age. However, participant opinion of discomfort glare was overall low.

The High-Mast & Conventional lighting design was rated as significantly more glaring than all other designs. Across age groups, the mean glare rating for High-Mast & Conventional lighting was between "noticeable" glare and "disagreeable" glare. Note that High-Mast & Conventional lighting was only present at Interchange 340, which was the busiest area among all study interchanges in terms of commercial activity, visual complexity, and ramp traffic volume. Furthermore, High-Mast & Conventional lighting was measured as having the highest light levels across all interchange segments. When accounting for age, discomfort glare rating for High-Mast & Conventional lighting was amplified for older participants, who are known to be more susceptible to the impacts of glare. Older participants judged the use of the High-Mast & Conventional lighting design as considerably worse for discomfort glare than all other treatments, with the rating approaching "disagreeable" on average.

Additionally, older participants indicated that Partial High-Mast lighting was producing lower discomfort glare than Conventional Exit Only lighting while being measured at similar vertical illuminance levels. Older participants also experienced the same amount of discomfort glare under

High-Mast lighting as Conventional lighting even though High-Mast lighting was measured at significantly higher values of vertical illuminance.

Overall, the high-mast lighting designs were rated similarly for discomfort glare as comparable conventional lighting designs even though they were measured at higher vertical illuminance levels. Lighting designs that take advantage of high-mast lighting could provide safety benefits for road users who are more sensitive to glare produced by roadway lighting. Participant glare sentiments seem to indicate that participants have a lower glare tolerance for interchange lighting with fewer luminaires, but a higher tolerance for interchanges with more light.

Dimming

When comparing participants' answers between the full brightness and 50% dim levels for High-Mast lighting at Interchange 318, a statistical difference in participant response was only found within one question grouping. There was no difference in participants' perceptions of safety, comfort, or visibility of the ramps between the fully bright and 50% dim levels. Furthermore, there was no indication that dimming the high-mast lighting resulted in too little lighting at Interchange 318 and, conversely, participants did not suggest that the full brightness was overlighting the interchange. Additionally, there was no significant difference in discomfort glare rating between dim levels, as participants rated discomfort glare, on average, as not noticeable for both dim and full brightness. Even though glare sensitivity is known to increase with age, there was no significant difference in discomfort glare rating between younger and older participants when comparing dim levels at Interchange 318.

The only significant difference involving dim level was found in the number of targets detected by older and younger participants. Providing more light facilitated better small-object detection for all participants; however, younger participants saw significantly more targets than older participants. Younger participants detected, on average, 86.6% of targets under full brightness high-mast lighting, while older participants only detected 63.3%. However, as mentioned earlier, target detection relied on self-reporting and therefore may not be a completely reliable measure of visibility.

Results suggest that dimming high-mast lighting was not affecting the participants' perceptions of safety, comfort, visibility, or glare. Thus, lighting designers could take advantage of dimming to reduce ecological impact, CO_2 emissions, and energy cost, among other factors, without detracting from public perception of safety, comfort, visibility, or glare.

This result for dimming is an interesting discussion in that in general the participants favored a higher lighting level feeling that it was safer. However, in the dimming comparisons, the dim level did not show a preference for dimming. This means that although light level is an important criteria, the selection of the intersection configuration and approach to lighting is likely more critical.

SPEED EVALUATION DISCUSSION

Interpretation of the speed behavior data was challenging due to the differences between the five study interchanges. Interchange 340 had a different mainline speed limit than the other interchanges, and ramps among the interchanges had different advisory speeds, different lengths, and different curvatures. Moreover, the difference between the mainline speed limit and ramp advisory speed limits also varied in magnitude, as some interchanges suggested drivers slow by 30 mph to take the exit ramp and some only by 15 mph. Researchers chose to assess mean speed relative to the mainline speed limit to account for some of these differences and produce results that facilitated comparisons between interchanges. Within-interchange comparisons at Interchange 318, which used high-mast lighting, were performed using the measured speeds, in mph.

Through Traffic

Through traffic displayed, overall, relatively consistent speed behavior across all interchange lighting designs, except at Interchange 340, which used a combination of High-Mast & Conventional lighting.

At Interchange 340, vehicles, on average, traveled at speeds well over the limit (8.25 mph over), with the highest speed variation among all interchanges studied. This interchange was the only interchange with a speed limit of 55 mph, which may have contributed to the significant differences in speed behavior. However, data showed that vehicles traveling southbound, from a similar 55 mph zone, through Interchange 340 were also traveling well over the speed limit with comparable speed variation. Even so, the relative speed and speed variation results may be higher here simply because many drivers fail to reduce their speed appropriately.

For the remaining four interchanges, all mean vehicle speeds were within 3 mph of the speed limit, and speed variation was under 0.5 mph for all four lighting designs. These interchanges used Conventional, Conventional Exit Only, High-Mast, and Partial High-Mast lighting designs. Comparisons between fully lit and partially lit lighting designs did show some difference in speed behavior. For fully lit interchanges, which used Conventional lighting and High-Mast lighting, results found higher mean vehicle speeds than their partially lit counterparts (Conventional Exit Only and Partial High-Mast). While speed was higher for fully lit interchanges, speed variation was also lower than for their partially lit parallels. Additionally, lighting designs using high-mast lighting had the lowest speed variation for through traffic.

Peak vehicle speeds and speed variation were found for interchanges with a high light level; however, this result only supports the lighting design comparisons because the only interchange measured at high light level for through segments was Interchange 340.

Overall, Interchange 340 saw vehicle speed behavior significantly different than all other interchanges. Among the remaining four interchanges, Interchange 327 (Partial High-Mast) had the lowest speeds relative to the speed limit for through traffic and the second lowest speed variation, while Interchange 318 (High-Mast) saw the highest speeds and lowest variation. Compared to lighting designs using conventional lighting in some form, including only High-Mast lighting generally resulted in a decrease in speed variation.

Exiting Traffic

Exiting traffic behavior varied between interchanges; however, grouping the interchanges by light level did not reveal as much difference. Comparisons using light level were difficult to interpret, as the speed limit was not consistent between light levels. However, vehicle speeds varied between interchanges, and a significant difference in speed and speed variation was observed between the study interchanges.

Vehicle speed, compared to the recommended ramp speed limit, was similar under four of the lighting designs. The interchanges with Conventional, Conventional Exit Only, High-Mast, and High-Mast & Conventional lighting all had vehicles taking exit ramps at speeds within 9 mph of the recommended ramp speed limit. However, at Interchange 327 (Partial High-Mast), vehicles were measured at, on average, 12.4 mph faster than the ramp speed limit. Vehicles needed to reduce speed from 70 mph to 40 mph to safely navigate the exit ramp at Interchange 327, yet they only reduced their speed by 18 mph before the measurement point. The inconsistent illumination provided by the Partial High-Mast lighting may have contributed to visibility issues preventing drivers from fully decelerating to a safe ramp speed.

Speed variation was the highest for exiting traffic, which researchers expected. Measurements were taken at the ramp gore point, and data captured vehicles decelerating from mainline speeds to take the ramp. Even so, significant difference was found at Interchanges 340 and 318. The High-Mast lighting design at Interchange 318 had the lowest ramp speed variation, while High-Mast & Conventional had the highest. While lighting design is part of the equation, researchers cannot rule out the impact of certain factors not accounted for, such as ramp length. Lighting designs containing conventional lighting had the most speed variation.

Overall, High-Mast lighting improved exit vehicle speed behavior. However, the Partial High-Mast lighting design might not be providing enough light for drivers to properly assess how much they need to reduce their speed, as the exit ramp with that design was measured as low light level and drivers were found to still be traveling at 12.4 mph over the speed limit when passing the gore point.

Entering Traffic

Entering traffic speed varied between interchanges; however, speed variation was similar for all interchanges. Data collection could not account for Interchange 340, and researchers did not gain insight into entrance ramp traffic there.

Overall, vehicle speeds varied by around 1 mph at all interchanges across all light levels. Speed data were taken at the entrance ramp gore point, and most speed variation likely took place as vehicles entered from the cross street and accelerated on portions of the ramp not measured during data collection.

Speed difference was observed between interchanges as vehicles were measured at, on average, 10 to 20 mph under the mainline speed limit. At Interchange 335 (Conventional), vehicles entered the roadway at speeds significantly lower than the speed limit (20.6 mph lower), while High-Mast lighting saw vehicles entering at speeds about 10 mph slower than mainline speed limits. Additionally, at Interchange 327 (Partial High-Mast), drivers were also entering at speeds significantly slower than the mainline speed limit.

When considering light level, the results were the opposite of research expectations. The higher light level entrance ramps measured vehicle speeds that were significantly slower, relative to the mainline speed limit, than low and medium light level entrance ramps. These results suggest that light level alone was not influencing speed at the study interchanges.

Overall, the influence of light level on entrance ramp traffic speeds was not conclusive, and speed behavior looked to be more affected by the lighting design and ramp geometry. Among data collected, the interchange with the longest ramps (Interchange 318) had vehicle speeds closest to the mainline speed limit. Interchanges with shorter entrance ramps may not have been giving drivers enough distance to properly accelerate, even in the presence of sufficient lighting.

Dimming

The different dim level comparisons at Interchange 318 were the only speed evaluations that compared speed behavior at the exact same interchange with the exact same geometry, and these are therefore the most valid speed comparisons.

Dimming the lights to 50% resulted in a significant reduction in speed for exiting vehicles (4 mph reduction) and a non-significant reduction in speed variation. For exit ramps, the suggested safe ramp speed limit was 50 mph, and data showed that vehicles had already reduced their speed from the mainline traffic flow to 54 mph, on average, by the time they passed through the measurement area (ramp gore point). Results suggest that under dim lighting, vehicles were adjusting their speed in advance of the exit ramps.

Speed for vehicles entering I-57 at Interchange 318 was also not significantly affected by dimming the high-mast lighting. While vehicles entered the roadway at around 10 mph slower than the speed limit, on average, they had a significantly higher speed variation under bright high-mast lighting than when dimmed. Dimming high-mast lighting could provide a safety benefit, as roadway users were able to achieve the same speeds, relative to the mainline speed limit, while having less speed variation. Note that is comparison is made at interchange 318 only as it was the only system with dimming capabilities. Other comparisons are at full lighting levels only.

Dimming the lights to 50% did not have a practical impact on the speed or speed variation of vehicles traveling through the high-mast lighting at Interchange 318. Speeds for through vehicles were, on average, only slightly higher than the speed limit, and dimming the lighting did not result in a change in speed variation.

Overall, dimming high-mast lighting fixtures from full brightness to 50% results in insignificant changes in speed behavior for vehicles moving through the interchange. Conversely, positive changes in speed behavior were observed for vehicles entering and exiting the roadway at Interchange 318.

DISCUSSION SUMMARY

Some of the most noteworthy results were from the assessment of dim level. Although in general participants selected higher levels as seeming to be safer, dimming high-mast lighting did not affect participants' perceptions of visibility, safety, comfort, or glare, indicating that the lighting configuration is as important as the lighting level in the feelings of safety. Dimming was also shown to have a positive impact on ramp speed behavior, as vehicles entering the road were reaching comparable merging speeds with less speed variation under dimmed high-mast lighting, while exiting vehicles were adjusting their speed upstream of the exit ramp and varying their speed less in the ramp area. Results suggest that other benefits of dimming, such as savings in energy consumption and maintenance costs, can be achieved without detracting from public perception of safety, visibility, or comfort.

Speed results showed that, in general, there was a trend that an increase in light level correlated with an increase in speed and speed variation. However, high-mast lighting appeared to give more control over speed variation. Lighting designs that included only high-mast lighting improved safe speed behavior, compared to conventional lighting designs, as speed variation was lower and mean vehicle speeds were closer to the posted mainline speed limits. Partial interchange lighting was found to have a negative impact on ramp speed behavior, as vehicles were not adjusting their speed enough in advance of taking the ramp. Entrance ramp speed behavior was more affected by lighting design and ramp geometry than light level. Interchanges with shorter entrance ramps may not have been giving drivers enough distance to properly accelerate, even in the presence of sufficient lighting.

In general, participant opinion of safety, comfort, and visibility improved as light levels increased, especially for designs that included high-mast lighting. Interchanges with high-mast lighting at a high light level were rated as providing the best visibility of ramp segments and rated the highest for comfort and safety sentiment. Furthermore, fully lit interchanges were rated more favorably for comfort, safety, and visibility than partially lit interchanges. This would indicate that a fully lit interchange is more favorable than an interchange that has a high light level. Small-object detection results followed the expected performance levels for age and light level, with results suggesting that lighting design choice could be tailored to levels that positively influence the other subjective measures studied. Overall, as light level increased, the difference in participant sentiment between younger and older participants decreased, except for discomfort glare rating. Lighting designs that used high-mast lighting were rated similarly for discomfort glare as comparable conventional designs while providing similar illumination.

LIMITATIONS

During data collection, reduction, and analysis, the research team identified several characteristics of study design and methodology that affected the interpretation of the results.

- Long-distance recruitment of participants proved challenging, and future subjective participant survey efforts would benefit from more participants to increase the research effort’s power to detect smaller effect sizes.

- Differences in roadway geometry between interchanges were not explicitly accounted for. These differences were included as random effects, as the research team did not have quantitative measures to assess.

- The study only considered interchanges with roadway lighting present. Being able to compare the study subjective and objective results against interchanges without lighting could provide valuable insight into the benefit of high-mast lighting.

- The research effort did not account for some external influences such as cross street illumination or adjacent commercial lighting. Additional research would benefit from formally characterizing visual complexity by approach direction and interchange segment, for inclusion in statistical modeling.

- The scope of speed data collection was limited by the number of radar kits available to the research team. Speed was captured near the gore points of ramp segments, but the full speed profile of each exiting and entering vehicle was not captured. To better understand the impact high-mast lighting was having on speed behavior at ramp segments, taking measurements at different points along ramp segments would be ideal. The study found significant differences in ramp segment speed behavior; nonetheless, measurements at multiple points along the ramp would lend better insight.

CHAPTER 5: CONCLUSIONS

From the human factors–based study, the following conclusions are drawn:

- For the same lighting layout and design, dimming can offer monetary and ecological benefits without compromising public perception of safety, comfort, and visibility.
- Dimming reduced speed variation under high-mast lighting.
- High-mast lighting reduced the impact of discomfort glare, especially for older participants.
- For different lighting designs, Participant sentiment for safety, visibility, and comfort was best for high-mast lighting at high light levels.
- Full interchange lighting offered significant improvements in vehicle speed behavior and participant survey response.
- Lighting designs that included only high-mast lighting improved safe speed behavior, compared to conventional lighting designs.
- The benefits of using high-mast lighting, over conventional, were negated when only used to partially light the interchange.

RECOMMENDATIONS

- The proposed specification changes (Appendix) should be reviewed as a method to reduce costs, including the use of an external lowering device.
- From a driver comfort and feelings of safety standpoint, only full interchange lighting designs should be considered however crash performance statistics should also be investigated.
- When possible and cost effective, a single type of lighting (high-mast or conventional) should be used at an interchange.
- Consider moving to a high-mast-only design using a lower light level. Caution must be used to ensure spill light is controlled. Note that design standard recommendations may have to be adjusted based on this result.
- Dim interchange lighting at times of low traffic volume using a control system.

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APPENDIX: ANNOTATIONS TO IDOT LIGHT TOWER SPECIFICATIONS

The following notes are recommendations for changes in the existing 2016 IDOT Standard Specifications for Road and Bridge Construction as amended through 2021. Specifically, the recommended amendments apply to Section 1069.08 – Light Tower.

Table 47. Recommended Amendments to Section 1069.08—Light Tower of the IDOT Light Tower Specifications

Page	Amendment	Benefit
947	Revise the third paragraph of this Article to read: "The design shall be based upon AASHTO "LRFD Specifications for Structural Supports for Highway Signs, Luminaires and Traffic Signals" in effect on the date of invitation for bids, however the width of reinforced opening requirement in Chapter 5, Section 5.6.6.1 shall not apply. Light Towers shall be designed for ADT > 10,000 Risk Category Typical, and Fatigue Importance Category I."	This amendment results in a significant reduction in the overall weight of the tower, reducing the cost. The four sample poles evaluated indicated a weight reduction from 5065 lbs to 2966 lbs when the additional reinforcing is not required, regardless of the handhole size.
	Revise the first sentence of the fourth paragraph to read: "A minimum combined luminaire weight based on the quantity of luminaires being installed plus a combined hood area and lowering ring weight of 400 lb (181 kg)."	This amendment prevents overdesign of the pole.
949	Revise the first sentence of the third paragraph to read: "The handhole shall have a pocket door with captive, tamper resistant hinges."	This amendment removes the requirement for a full-height piano hinge which is a specialized item that increases cost and potentially lead time.
953	Revise the first two sentences of the fifth paragraph to read: "The ring shall be designed for the quantity of luminaires specified."	This amendment removes the requirement for rings to have a minimum of six tenons, allowing for better optimized designs.
	Revise the first sentence of the sixth paragraph to read: "A continuously welded metal ring with fixed wireway covers shall be furnished."	This amendment removes the requirement for fully enclosed rings using welds which is non-standard and presents an impediment to maintenance that is not required.
956	Revise the first paragraph to read: "The luminaire ring and attached components shall be fabricated of the same type of steel as the tower shaft or Type 201L or Type 304 stainless steel. If it is not fabricated of stainless steel, it shall then be hot-dip galvanized according to AASHTO M 111 or painted in accordance with Article 1069.08 (c)(1)."	This amendment is an extension of the previous amendment, and removes "fully enclosed luminaire ring" from the specification.

Page	Amendment	Benefit
957	Revise subsection (i) to read: "(i) Winch Assembly. Provide lowering device manufacturer supplied winch assembly incorporating a gear reducer having a reduction ratio which will prevent free fall of the luminaire ring upon failure or disengagement of the drive unit. The gear shall limit the travel rate of the ring to 10 to 15 ft (3 to 4.6m) per minute under normal operation. The gear shall be of bronze alloy and keyed to the output shaft. The worm gear shaft and output shaft shall be mounted on antifriction bearings.”	This amendment removes the requirement for a worm gear which gear requires a motor assembly, including starter, reversing switch, and power supply, be provided in lieu of the tested system that the manufacturer has designed, is liable for, and warranties.
	Remove subsection (k) entirely.	This amendment removes the requirement for an internal motor.

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