

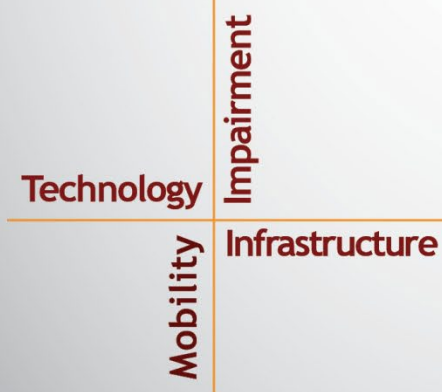
NSTSCCE

National Surface Transportation
Safety Center for Excellence

Initial Investigation of Intersection Lighting

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EXECUTIVE SUMMARY

Nighttime crashes at intersections are a major traffic safety concern in the United States. Although providing lighting at intersections has proved to be a successful intervention against night crashes, current approaches to designing lighting at intersections are relatively simplistic, based on recommending light levels. These light levels stem from research that evaluated the effect of intersection lighting on night crashes, which does not account for the role of a driver's visual performance or the effects of vehicle headlamps. For effective lighting design at intersections, empirical research is required to evaluate the effects of intersection lighting design on a driver's visual performance as well as perceived visibility and glare.

The current study had two goals. The first was to quantify visual performance in three lighting configurations (illuminating the intersection box, approach, or both). The second was to determine what lighting levels within each lighting configuration support the best visual performance. The study involved a target detection task, completed at night on a realistic roadway intersection. Twenty-four participants completed the study, with equal numbers of younger (18–35 years) and older (65+) individuals.

Illuminating the intersection box led to superior visual performance, as indicated by longer target detection distances, fewer missed targets, and more targets identified within a safe stopping distance. For this lighting configuration, visual performance plateaued between an illuminance level of 8 and 12 lux. Visual performance was inferior in lighting configurations in which only the approach to the intersection or both the approach to the intersection and the intersection box were illuminated, and there was not consistent plateauing of visual performance in either condition. Increased performance with box lighting was likely due largely to the rendering of targets involved. Visual performance was reduced among older participants, though age-related differences were consistent across lighting configurations.

These results have important implications for the design of intersection lighting at isolated or rural intersections. Specifically, results indicated that illuminating the intersection box is an effective strategy to increase nighttime visual performance for a wider range of driver ages and could also be an energy-efficient solution.

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LIST OF ABBREVIATIONS AND SYMBOLS

AASHTO	American Association of State Highway and Transportation Officials
CAN	Controller Area Network
CIE	Commission Internationale de l'Éclairage
DAS	data acquisition system
DGPS	differential Global Positioning System
IES	Illuminating Engineering Society
LED	light-emitting diode
LMM	linear mixed model
ND	night-to-day
NHTSA	National Highway Traffic Safety Administration
RVP	relative visual performance
VTI	Virginia Tech Transportation Institute

CHAPTER 1. INTRODUCTION

Crashes at intersections constitute a disproportionate share of the total number of roadway crashes, making them a major safety issue for drivers and vulnerable road users, such as pedestrians and bicyclists. For example, in the United States in 2019, intersection crashes accounted for over 28% of the fatalities.⁽¹⁾ Furthermore, nighttime crashes and fatalities account for approximately 40% of the total crashes and fatalities at intersections.⁽¹⁾ To safely navigate an intersection, drivers should take into consideration a number of factors, such as the presence of other vehicles, pedestrians, bicyclists, signal phases or presence of stop signs, etc. Indeed, intersections are one of the most complex roadway types that drivers encounter. For example, an intersection of two streets with two-way traffic on each has a total of 16 vehicle-to-vehicle conflict points and 16 pedestrian-to-vehicle conflict points as shown in Figure 1.⁽²⁾ Therefore, the ability of drivers to detect hazards (pedestrian, cyclist, fixed object, another vehicle, etc.) at intersections is of paramount importance, especially at night.

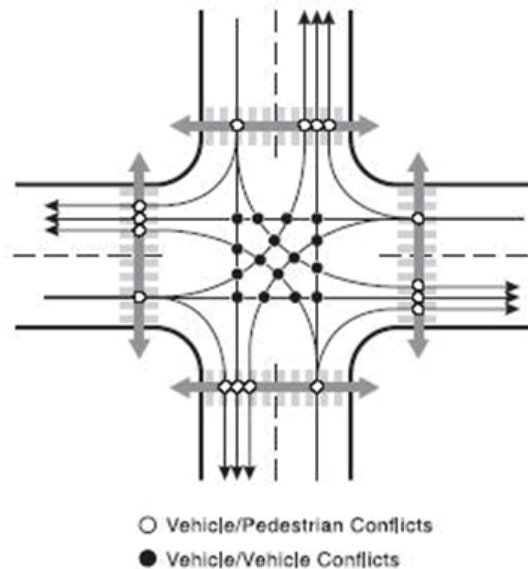


Figure 1. Illustration. Vehicle-pedestrian and vehicle-vehicle conflict points at intersection.

Intersection lighting has received attention as a potential method for reducing the number of nighttime crashes and related fatalities because it increases the amount of visual information available to drivers approaching an intersection and assists in hazard detection. Simply having lighting at intersections appears to reduce the number of nighttime crashes by 13% to 45%,⁽³⁻⁷⁾ and a 1 lux increase in illuminance lowers night-to-day crash ratios and rates by roughly 7% and 9%, respectively.^(8,9) Furthermore, Oya et al.⁽¹⁰⁾ reported that a mean roadway illuminance of 20 lux or more is an effective countermeasure against crashes, and a mean road-surface illuminance of 30 lux results in a statistically significant reduction of nighttime crashes. Minoshima et al.⁽¹¹⁾ used subjective ratings of intersection visibility to assess three intersection lighting designs (approach, corner [or box], and both approach and corner) at three illuminances (5, 10, and 15 lux). They concluded that at illuminances greater than 10 lux, mean ratings of visibility were high in all three lighting designs. While both Oya et al.⁽¹⁰⁾ and Minoshima et al.⁽¹¹⁾ explored two different aspects of driver behavior, both studies indicate that greater than 10 lux of mean

roadway illuminance is required to achieve enhanced perceptions of visibility and a reduction in crashes. This higher illuminance is required for crash reduction because crashes often have multiple causal factors beyond visibility alone.

Intersection lighting has also been given special consideration by both the Illuminating Engineering Society (IES) and the Commission Internationale de l'Éclairage (CIE). These organizations have recommended minimum lighting levels for intersections, with specific levels depending on a number of factors such as roadway classification (only IES), speed, traffic volume, and traffic composition (only CIE). Recommended light levels for intersections, however, differ substantially from those recommended for roadways. IES RP-8 recommends that the lighting level at intersections should be equal to the sum of the lighting levels of each road at the intersection.⁽¹²⁾ The recommended average horizontal illuminance by RP-8 ranges from 8 to 34 lux, based on the pedestrian classification and the functional classification of the roads forming the intersection. CIE's 115:2010 recommends that the lighting level of the intersection should always be higher than the highest lighting level of the roads that form the intersection.⁽¹³⁾ The CIE 115:2010-recommended average horizontal illuminance ranges from 7.5 to 50 lux depending on the lighting classification of the road: C0 (highest light level)–C5 (lowest light level). The CIE's lighting classification of the road depends on a number of factors, such as speed, traffic volume, and traffic composition. Note that these standards provide only recommended luminance and illuminance (light incident on the roadway) levels^(12,13) and do not specify which parts of the intersection should be illuminated. Further, these recommended levels are a result of consensus between researchers and practitioners in the field of roadway illumination who studied the effects of roadway lighting on nighttime crashes. Neither the process of selecting the part of the intersection that is to be illuminated nor the required level of illumination for an intersection is backed by empirical research.

Furthermore, crash data, such as the number of crashes or night-to-day crash ratios, have typically been used to assess the effectiveness of intersection lighting designs, specifically, the part of the intersection that is illuminated and the prevailing illuminance.⁽³⁻⁸⁾ Yet studying the effect of roadway lighting on nighttime crashes or related parameters considers only extreme aspects of driving behavior, ignoring normal driving behaviors, and critical events such as near misses. Studying the relationship between lighting design and crashes might give some insights into the effectiveness of lighting intersection designs in terms of safety. However, such a study would not reveal the full extent of the relationship between lighting design and nighttime visibility, since crashes often have multiple causal factors, making it difficult to understand the specific role of lighting design in contributing to a crash. In addition, standards based on the effect of intersection lighting design on nighttime crashes could lead to over-lighting of intersections, which could make the intersections less safe by introducing glare and reducing visibility. Over-lighting would also result in energy waste without any substantial benefits to visibility or safety. Additionally, using crash metrics and a consensus-based approach to intersection lighting design does not consider the role of human visual response, nor does it account for the potential interactive effects of vehicle headlamps and intersection lighting design on nighttime visibility. Existing standards also do not account for the diverse pedestrian-to-vehicle conflict points at intersections.

To recommend safe lighting standards for intersections, we should understand the relationship between intersection lighting design and nighttime visibility. Intersection lighting design refers

to both the *lighting configuration* (the part of the intersection that should be illuminated (see Figure 7) and the *illuminance* at which the intersection should be maintained. To take into account human visual response, intersection lighting configurations and the illuminance associated with them should be evaluated in terms of driver visual performance. Visual performance plays a critical role in nighttime driving, as it affects the speed and accuracy of performance on the visual component of a task. The detection distance of objects (e.g., pedestrians) is commonly used as a measure of visual performance in nighttime roadway visibility research.⁽¹⁴⁻¹⁹⁾ The presence of lighting and increase in lighting level greatly increases the accuracy and speed with which information can be extracted from the environment, and has been found to increase visual performance.⁽²⁰⁻²⁴⁾ Increase in visual performance of the driver at the intersection due to lighting could assist drivers in hazard detection (e.g., pedestrians, other vehicles, and animals in order to avoid collisions), and making better judgements (e.g., gap acceptance at stop-controlled intersections, yielding to traffic while making left/right turns at signalized intersections, etc.). Previously, Rea et al.⁽²⁵⁾ used photometric software to determine the relative visual performance (RVP) scores for different intersection types, lighting levels, and lighting layouts (continuous vs. localized). They concluded that illuminating intersections would help increase visibility. Further, Bullough et al.⁽³⁾ used a similar photometric simulation approach to understand the relationship between RVP and crash frequency at intersections in Minnesota, and determined that the RVP improvement made by installing roadway lighting could lead to increased safety (i.e., lower crash frequency). These results have not yet been validated in realistic nighttime scenarios. Despite the useful findings of these previous research efforts, intersection lighting design has yet to be evaluated in terms of driver visual performance. For an intersection lighting design to result in increased visual performance, it is important to understand not only the effect of illuminating different parts of an intersection, but also the effect of lighting level and possible interactive influences.

This study had two goals. The first was to evaluate different kinds of lighting configurations to determine which offers the best visual performance. The second was to determine what lighting levels, perhaps specific to each lighting configuration, support the best visual performance. It was hypothesized that (1) intersection lighting configurations would differ in visual performance measurements, since different configurations affect object contrast which, in turn, influences visual performance;^(15,16) and (2) the benefit of increasing illuminance on visual performance will decrease (or plateau) at higher illuminance, consistent with the Adrian's model⁽²⁶⁾ and the RVP model.⁽²⁷⁾ Results from this work were intended to facilitate development of intersection lighting design standards (especially for those intersections located in isolated/rural areas) that increase driver visual performance and consequently reduce nighttime crashes.

CHAPTER 2. METHODS

PARTICIPANTS

Twenty-four participants completed the study and were categorized into two age groups (younger and older), each of which was gender balanced. The younger group comprised participants aged 18–35 years ($M = 30.8$ years, $SD = 2.7$), while members of the older group were all 65 years or older ($M = 68.2$ years, $SD = 1.6$). These age ranges were intended to capture a wide range of driving experiences as well as a broad range of visual capabilities, as human eyes undergo many physiological changes with age resulting in various effects, such as a decrease in visual acuity, a decrease in contrast sensitivity, and an increase in dark adaptation time.⁽²⁸⁻³²⁾

Participants were recruited from the Virginia Tech Transportation Institute (VTTI) participant database and through campus notices posted electronically, and were required to have a valid United States driver's license. Eligible participants completed an initial screening session in which they first provided written, informed consent (all experimental procedures were approved by the Virginia Tech Institutional Review Board). Participants then completed a basic visual acuity test administered by an Early Treatment Diabetic Retinopathy Study chart with an illuminator cabinet. All participants had a minimum corrected visual acuity of at least 6/12 (20/40). Data collection took place in three sessions, on separate days, following the initial screening session. Participants were paid \$30 per hour for their participation in this study.

EXPERIMENTAL DESIGN

A repeated measures experimental design was employed to investigate the effects of target location, intersection lighting configuration, and illuminance on visual performance. Visual performance was measured indirectly, using a target detection distance, while participants drove at night through a realistic roadway intersection under several conditions involving different lighting configurations and illuminances. Targets were placed at multiple locations within and surrounding the intersection. This study was conducted at the intersection on the Virginia Smart Roads Highway at VTTI (Figure 2). The Smart Roads Highway is a 2.2-mile-long, controlled access roadway research facility built to United States highway standards. The intersection is equipped with signal lights, but they were not used for this study in order to eliminate the confounding effect of signal phase timing on intersection approaches. Independent variables and the levels used in the study are summarized in Table 1, with additional details below. In a given experimental session, participants encountered one lighting configuration, all five illuminances, and all target locations within each illuminance. The remaining lighting configurations were encountered in subsequent sessions; this approach was used because changes in lighting configuration were relatively time consuming compared to changes in illuminance and target locations. Presentation orders of both lighting configuration and illuminances were counterbalanced across participants to reduce potential order-related confounding effects. Target location was randomized in a given combination of lighting configuration and illuminance, with blanks (no target presentation or null condition) included as catch trials.

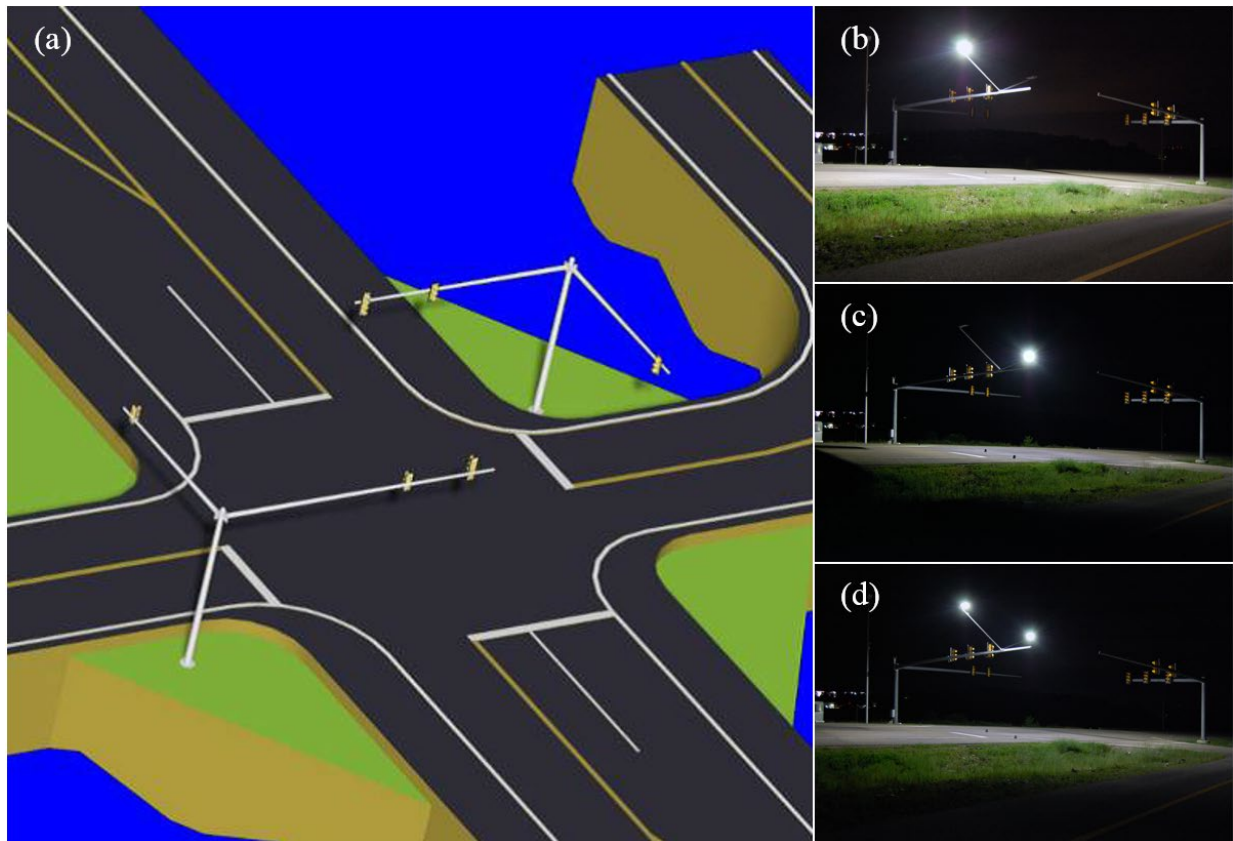


Figure 2. Diagram. Smart Road intersection: (a) The intersection is equipped with signal lights and lane markings associated with a typical signalized intersection. The intersection could also have one of three lighting configurations, which illuminated the Approach (b), the Box (c), or the Approach and the Box (d).

Table 1. Independent variables and their levels used in the experiment.

Independent Variable	Levels
Target Location	Near Right, Near Middle, Near Left, Far Right, and Far Left
Intersection Lighting Configuration	Lighted Approach, Lighted Intersection Box, Both Approach and Box Lighted
Intersection Illuminance	0 (no lighting), 8, 12, 16, and 21 lux

INDEPENDENT VARIABLES

Target Locations

A gray-colored wooden target, 18 × 18 cm (50% reflectance), was used for the detection task. This target was the same as those used in earlier research on nighttime roadway visibility.^(12,14,17,33-37) Five target locations were used (Figure 3) at the entrances and exits to pedestrian crosswalks. Targets were placed on the roadway (see Figure 4–Figure 6). Target locations were selected so that they contrasted against the roadway surface rather than the pavement markers on the roadway. Care was taken during the initial setup to avoid the influence of shadows on target detection.

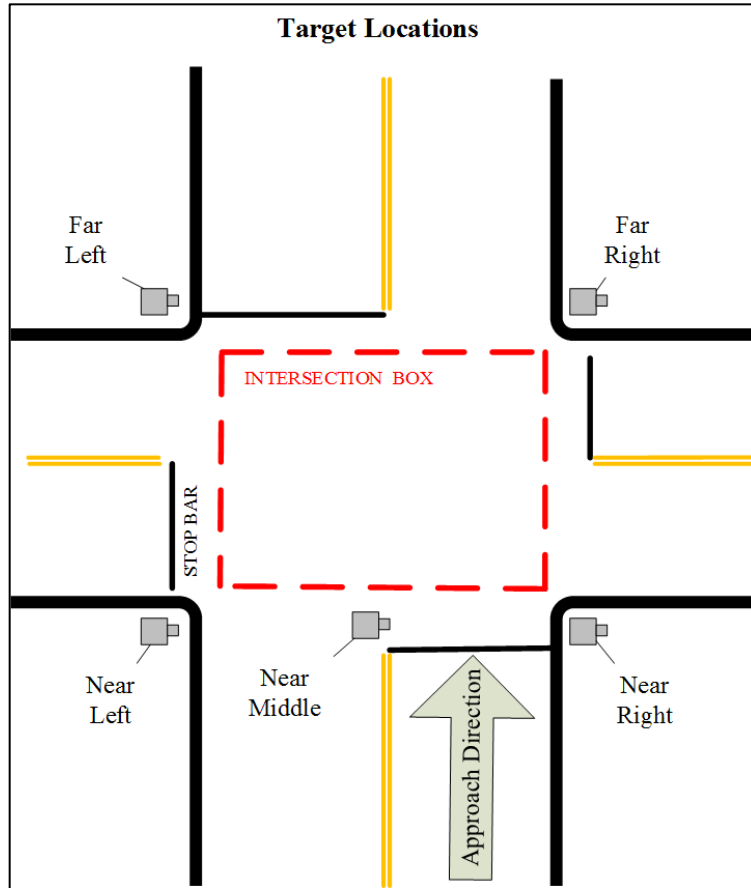


Figure 3. Diagram. Overhead view of the intersection and the five target positions used.



Figure 4. Photo. Targets in Approach lighting configuration.



Figure 5. Photo. Targets in Box lighting configuration.



Figure 6. Photo. Targets in the Both lighting configuration.

Intersection Lighting Configurations

Three different intersection lighting configurations were developed (Figure 2) and classified based on the part of the intersection that was illuminated. In the first configuration (Approach), the approach to the intersection was primarily illuminated (Figure 2b and Figure 7a). In the second configuration (Box), the intersection box was illuminated (Figure 2c and Figure 7b). The third configuration (Approach and Box), both the intersection's approach and box were illuminated (Figure 2d and Figure 7c). In addition to allowing for the assessment of different lighting configurations, these alternatives also made it possible to test the effects of the positive versus negative contrast of the target located at the near-right and near-middle target locations on drivers' visual performance. Specifically, the Approach configuration rendered these targets in positive contrast, since the face of the target was brighter than the background (Figure 8a). The Box configuration rendered these targets in negative contrast, since the background was brighter than the face of the target and appeared in silhouette (Figure 8b). In the Approach and Box configurations, target contrast was dependent on the illuminance. Another reason for selecting these three lighting configurations was to achieve a symmetrical lighting design at the intersection so that the results could be generalized for all approaches. For example, illuminating the area after the intersection would render all the objects in negative contrast for a driver approaching in one direction, while the targets would be rendered in positive contrast for a vehicle approaching from the opposite direction.

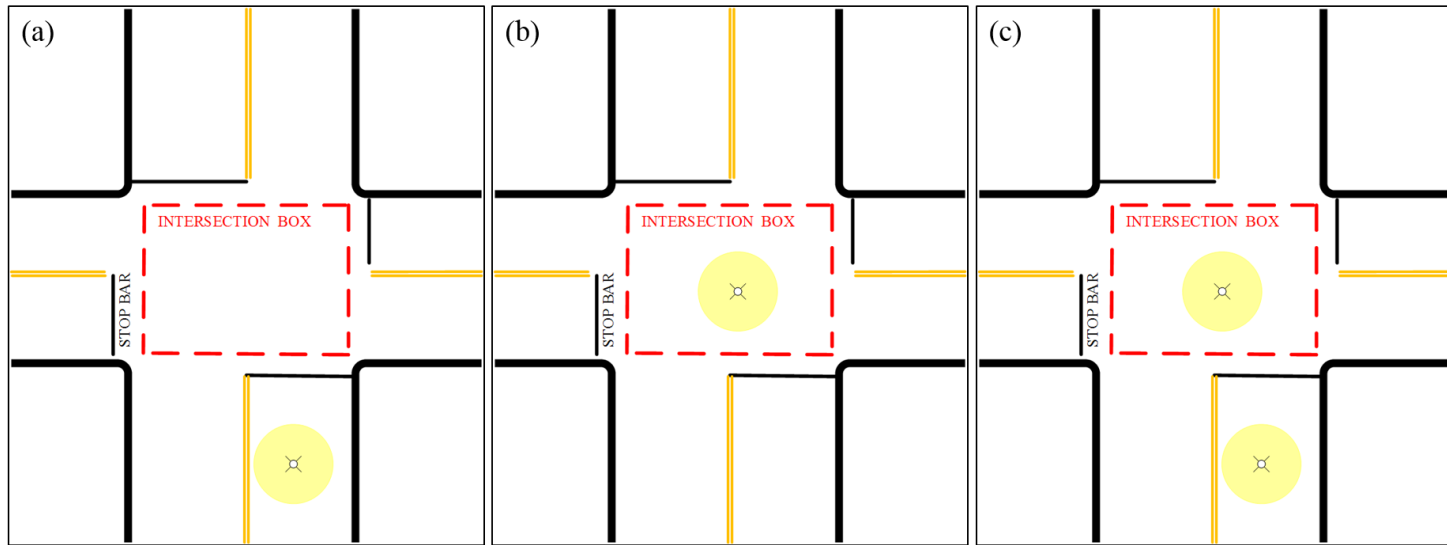


Figure 7. Diagrams. Illustrations of the three intersection lighting configurations: (a) Intersection approach is illuminated, (b) Intersection box is illuminated, (c) Both the box and approach are illuminated.

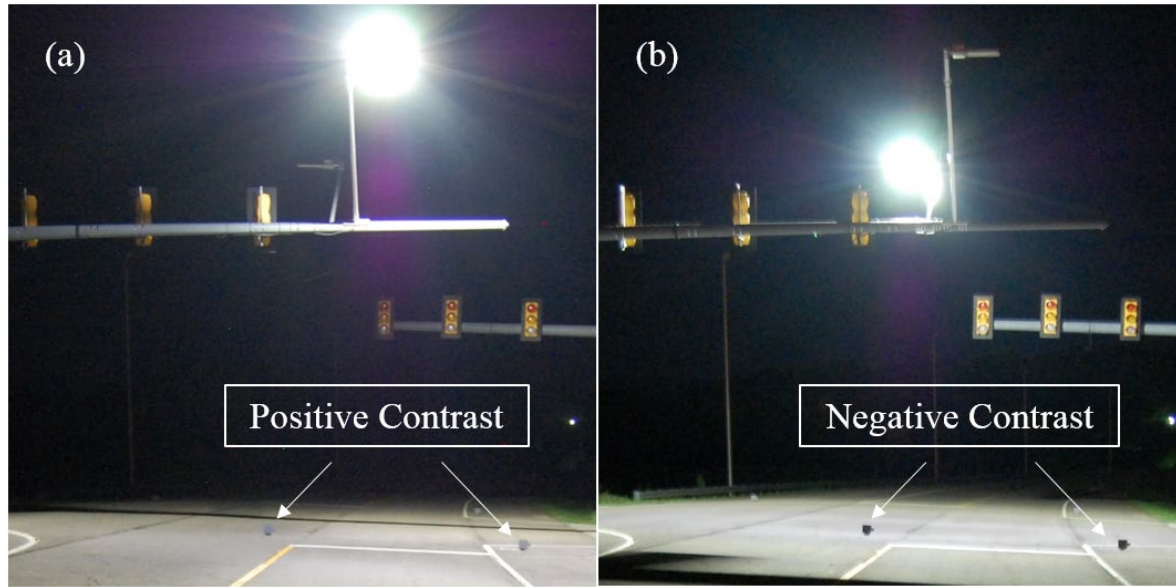


Figure 8. Photographs. Near-right and near-middle target locations in positive and negative contrast in the Approach (a) and Box (b) lighting configurations. Targets were placed on the roadway.

Intersection Illuminance

Two 4000 Kelvin light-emitting diode (LED) luminaires were used for illuminating the intersection, mounted at a height of 8.5 meters. Luminaires used for illuminating the approach and the box were, respectively, type II and type V, and each had different light distribution patterns. Type II luminaires are generally used for illuminating roadways; these are typically mounted near the edge of the roadway and have an elliptical light distribution pattern. Type V luminaires are typically mounted in the center of a four-way intersection and have circular light distributions with the same light intensity in all lateral directions.⁽³⁸⁾

Five different illuminance levels were used, with the intention of spanning a range of recommended values. The specific levels were 0 (no lighting), 8, 12, 16, and 21 lux, and were the horizontal illuminance measured at the near-right target location on the intersection rather than the mean of multiple point or measure values. The two lowest light levels (8 and 12 lux) are also the IES RP-8 recommended average illuminance values at low nighttime pedestrian volume locations, such as rural/suburban areas.⁽¹²⁾ The 16 and 21 lux levels are the IES RP-8 recommended average illuminance values for high and medium pedestrian conflict areas at suburban and urban locations.⁽¹²⁾ Since it was impossible to maintain the same illuminance at every target location under different lighting configurations, only the near-right target location was selected to match illuminance across the lighting configurations. The horizontal illuminance for each target location and the mean horizontal illuminance of the intersection (mean intersection illuminance) are shown in Table 2 for each lighting configuration and illuminance. Mean horizontal illuminance was the average horizontal roadway surface illuminance of the area enclosed by the stop bars at the intersection.

Table 2. Horizontal illuminance at the target locations and mean intersection illuminance used in the study for each lighting configuration and illuminance.

Approach Lighting Configuration						
Illuminance (lux)	Near Right	Near Middle	Near Left	Far Right	Far Left	Mean Intersection Illuminance
8	8.8	6.3	4.4	0.9	0.2	5
12	12.6	9.4	6.4	1.5	0.2	7
16	17.1	12.5	8.6	1.8	0.3	9
21	22.5	16.3	11.6	2.4	0.4	12
Box Lighting Configuration						
8	9.0	9.6	8.3	2.5	2.1	7
12	13.2	14.0	12.2	3.3	3.1	10
16	17.1	18.5	16.1	4.7	4.0	13
21	22.1	24.4	21.4	6.4	5.8	18
Both Lighting Configuration						
8	8.7	7.2	5.8	1.6	1.0	5
12	13.3	11.2	8.9	2.4	1.4	8
16	17.0	15.1	12.8	3.2	2.2	11
21	22.4	19.7	14.8	3.6	2.4	13

EXPERIMENTAL PROCEDURES AND DEPENDENT MEASURE

Participants were scheduled to arrive 15 minutes prior to the start of data collection in each experimental session. Sessions were conducted at night (after civil twilight) and only in clear weather conditions (no rain, snow, fog, etc.). Two participants were scheduled for each experimental session for efficiency (see below). In the first experimental session, after arrival at VTTI, participants initialed the informed consent again, reviewed the activities listed for the session, and were shown sample images of a target they might encounter during the study. A definition of a detection task was provided, along with an example of how they should respond upon seeing a target. In the subsequent two experimental sessions, participants were given the option of reviewing the experimental protocol or not prior to starting the session. At all times during the driving portion of the study, an experimenter was seated in the rear passenger seat of the experimental vehicle.

Two vehicles were used (1999 and 2000 Ford Explorers), each instrumented with a data acquisition system (DAS) connected to the vehicle's Controller Area Network (CAN) and onboard camera systems. The DAS collected kinematic data from the vehicle's CAN system, including vehicle speed, differential Global Positioning System (DGPS) coordinates, four video images (driver's face, forward roadway, left side of roadway, and right side of roadway), audio from the driver, manual button presses, and other input from an in-vehicle experimenter. Low beam headlamps were used during the study and were aimed before each experimental session.

Once in the vehicle, participants were shown the locations of the vehicle's seat adjustment buttons, steering height adjustment buttons, headlamp switch, windshield wiper switch, etc. Participants were then given several minutes to familiarize themselves with the vehicle. Once the participants indicated they were comfortable and all their questions/concerns were addressed, they were asked to drive the vehicle onto the Smart Road. Before entering the Smart Road, participants were informed that the speed limit for the study was 56 km/h (35 mph). Participants were also informed about where to stop and turn. After entering the Smart Road, participants completed two practice "laps" (see Figure 9), in which they practiced the target detection task (under the no lighting configuration). In each lap, the first participant approached the intersection while the second waited at the starting point. After the first participant completed the approach, they were instructed to wait for the second vehicle at the end point with all lights turned off. The second participant then began their approach and arrived at the end point. From there, both participants drove back to the starting point and were instructed to be ready to begin the next lap.

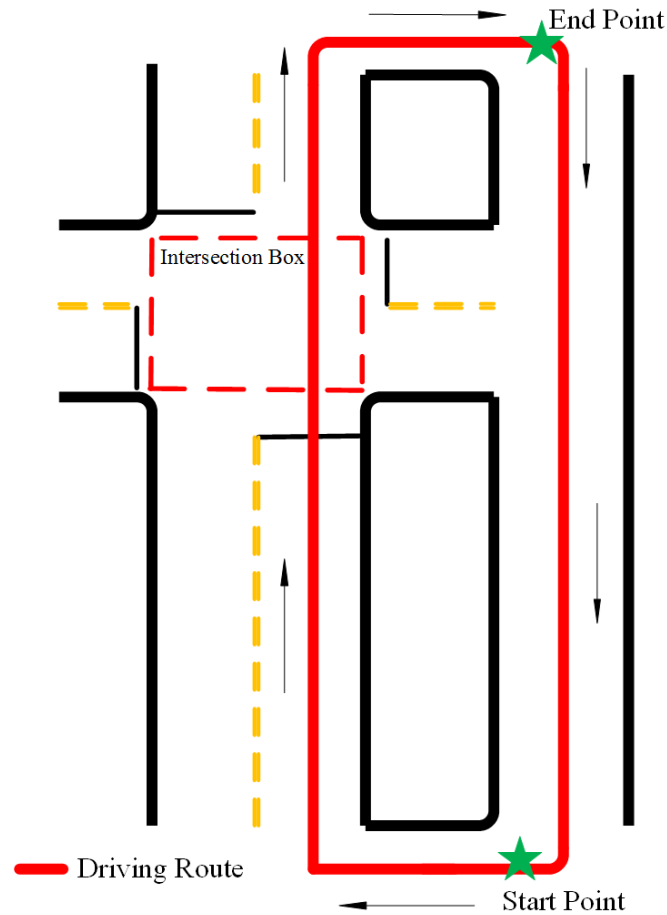


Figure 9. Diagram. Overhead view of the Smart Road intersection. The thick red rectangle shows the start and end points of each lap. Participants completed 30 laps per session.

Subsequently, participants approached the intersection six times for each illuminance condition (five target locations and one catch trial), always driving straight through the intersection. During each approach, participants were asked to verbally indicate when they saw a target by saying the word “target” out loud. Response time was recorded (by the in-vehicle experimenter) via a button press. At the time the vehicle passed the target, the experimenter pressed another button. These button presses were used as indices in the data stream recorded by the DAS, and were subsequently used to determine the exact point of target detection by watching and listening to the DAS-recorded audio-video stream. The DGPS coordinates of each target were prerecorded. The DGPS coordinates at the point of detection between the car and the target were used to calculate the detection distance, which was used as the dependent measure. The accuracy of the detection distances calculated using the DGPS system was about 0.2 m (0.66 ft.). The target was moved (or removed for catch trials) between laps, at a time when the intersection was not visible to participants (i.e., when they were heading to the start point from the end point; see Figure 9). After target presentation was completed for one illuminance condition, an additional six approaches were completed for each of the remaining illuminance conditions. These same procedures were repeated in the second and third sessions for the two other lighting configurations.

DATA REDUCTION

The data reduction process helped to eliminate the time delay between the participant's "target" response and the experimenter's button press. During data reduction, the data stream from the vehicle was processed by adjusting the time stamp from the experimenter's button press to the instant of detection when the participant said "*target*." This post hoc processing was performed using an in-house data analysis and reduction tool, which synchronized all the data (audio, video, kinematic, GPS, etc.) collected from the vehicle's DAS and presented it to the researchers and reductionists. By capturing the coordinates at the instant the participant indicated they detected the target, the time lag due between detection instant and experimenter button press was eliminated. The experimenter button press served only as an index in the data stream to facilitate data reduction.

ANALYSES

A linear mixed model (LMM) analysis was used to assess the (fixed) effects of target location, lighting configuration, and illuminance on detection distance. Age was included as a blocking factor. Based on preliminary analysis of LMM residuals, the detection distance values were square root transformed because the model residuals using untransformed values were not normally distributed. The square root transformation allowed the model residuals to be normally distributed, which satisfied the parametric model assumptions. The level of significance was $p < 0.05$ for all statistical tests. Effect sizes were determined and reported using partial eta-squared (η_p^2). Where relevant, post hoc analyses (pairwise comparisons) were performed using Tukey's honest significant difference for main effects and simple effects testing for interaction effects. Back-transformed means and standard errors are also reported.

To investigate if targets were detected from a "safe" distance under each combination of lighting configuration and illuminance, mean detection distances across the five targets were compared to the stopping sight distance.⁽³⁹⁾ Stopping sight distance is the length of the roadway required for a vehicle traveling at the "design speed" (here, 56 km/h or 35 mph) to come to a stop, and is the distance traveled by the vehicle from the time a driver sees an object to the vehicle coming to a complete stop (sum of distance traveled during brake reaction time and braking distance). For the purpose of recommending the safe stopping distance, a brake reaction time of 2.5 seconds and deceleration rate of 3.4 m/s² is assumed by the American Association of State Highway and Transportation Officials. Based on AASHTO (2001), and given the 56 km/h (35 mph) driving speed used in the current study, if the mean detection distance was greater than 76.2 meters (250 ft.) for a given target location, then the driver would have had enough distance to stop safely after detection. Thus, 76.2 meters was used as a basis for assessing target detection distances.

CHAPTER 3. RESULTS

Overall, there were 1,872 target presentations, including both targets and blanks (no target presentation, or “catch” trials). Of these 1,872 target presentations, there were 312 presentations for each target location (1,560 total target presentations) and 312 blank presentations. Out of the 1,560 target presentations across all participants, there were three false detections. False detections are cases when the participants reported a target when no target was presented (catch trial). This small number was not unexpected, as the experimental design was not a forced-choice paradigm. Rather, participants could, in the majority of cases, eventually see the target since it was always present; it was just a matter of the distance at which they could actually detect the target. This distance was affected by how well a certain lighting design and illuminance affected the targets’ visibility. False detections were excluded from the LMM analysis. A total of 130 targets were missed and were also excluded from the LMM analysis. The percentage of misses depended on the target location and lighting configuration. Participants missed a higher percentage of targets in the Approach lighting configuration (14.2%) than in the Box (3.7%) or Both (6.3%) configurations. In the Approach configuration, the near-left and far-left target locations had the highest percentages of misses (Figure 10).

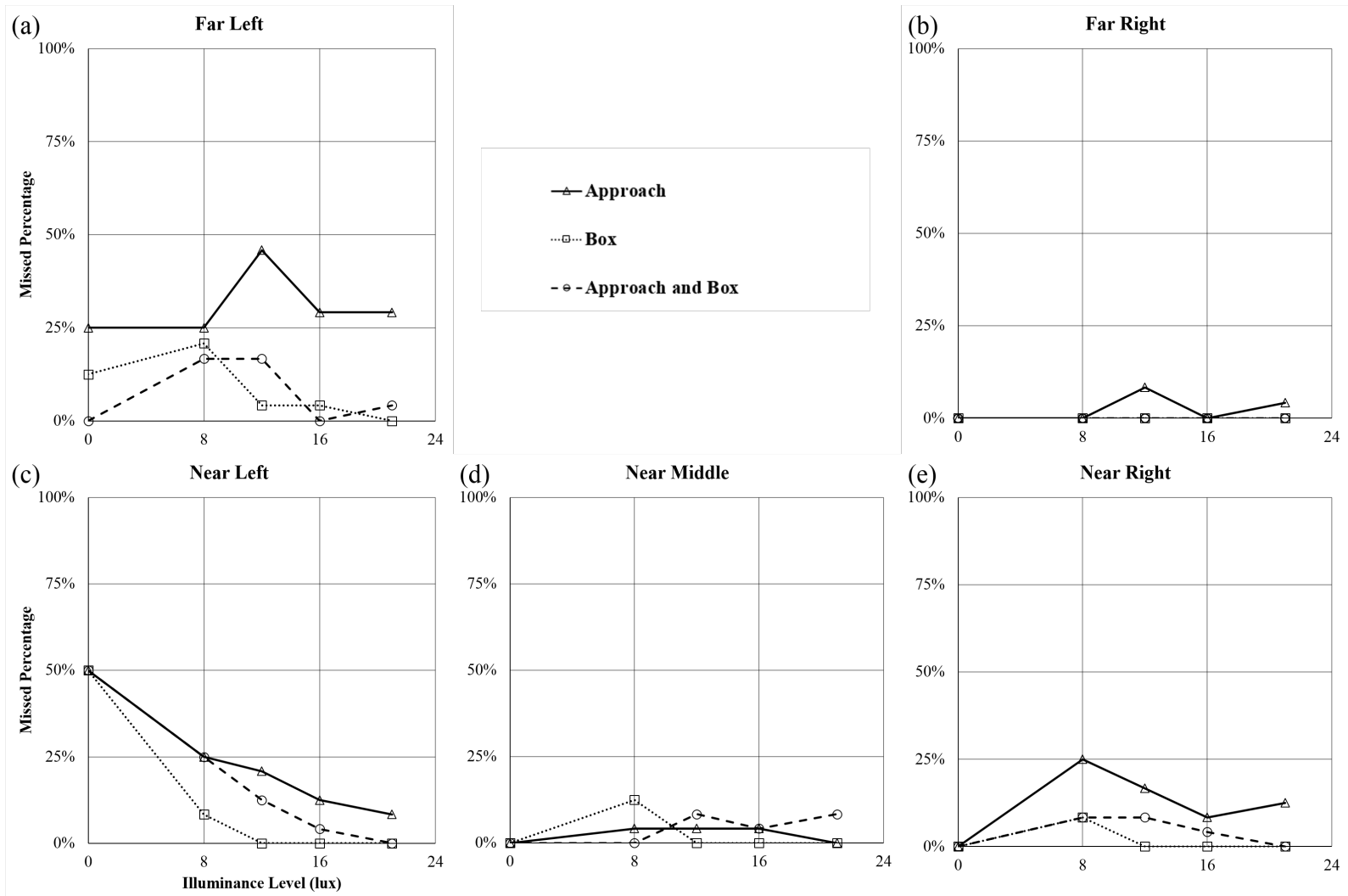


Figure 10. Graphs. Percentage of missed targets by location and lighting configuration.

All LMM results are summarized in Table 3. All main effects were significant, along with several two-way interactions, and the three-way interaction of target location, lighting configuration, and illuminance. Subsequent subsections provide additional details on the results regarding participant age and lighting configuration, followed by the noted three-way interaction effect.

Table 3. Statistical results from LMM analysis of detection distance. Significant effects are highlighted in bold in shaded cells.

Effect	Effect Size (η_p^2)	<i>p</i> value
Age (A)	0.15	0.0324
Target Location (TL)	0.25	<.0001
Lighting Configuration (LC)	0.16	<.0001
Illuminance Level (IL)	0.06	<.0001
A × LC	0.00	0.0417
A × IL	0.00	0.6698
A × TL	0.00	0.4353
LC × IL	0.05	<.0001
TL × LC	0.12	<.0001
TL × IL	0.01	0.3504
A × LC × IL	0.01	0.1727
A × TL × LC	0.00	0.675
A × TL × IL	0.01	0.2071
TL × LC × IL	0.03	0.0221
A × TL × LC × IL	0.01	0.9906

INTERACTIVE EFFECT OF AGE AND LIGHTING CONFIGURATION

Detection distances were longer for the younger age group in all three lighting configurations, though the difference between age groups was inconsistent across the three configurations (Figure 11). Simple effects tests indicated that differences between groups were significant only for the Both and Box configurations, with younger participants having ~32% and ~27% longer detection distances in these configurations, respectively. Simple effects of lighting configurations were also significant in both age groups, with detection distances being longest in the Box configuration and shortest in the Approach configuration.

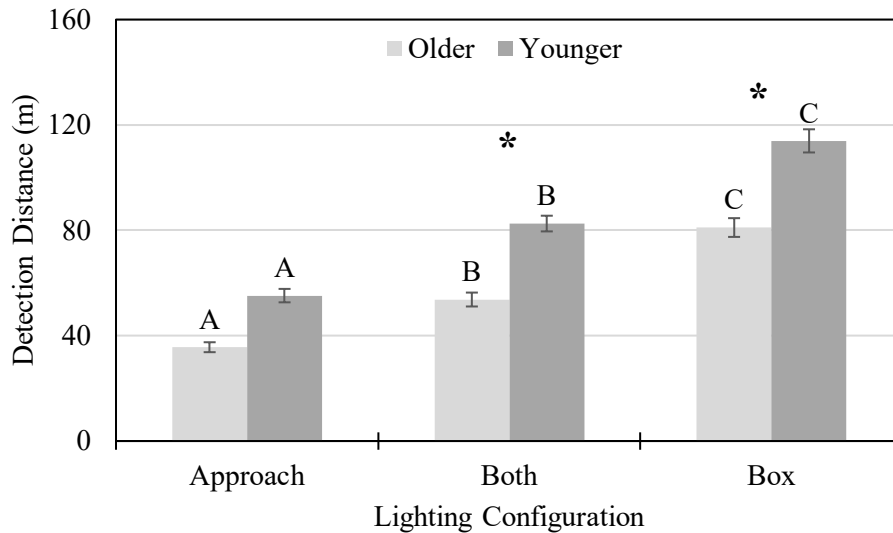


Figure 11. Bar graph. Effects of age and lighting configuration on detection distance. (Values are means of detection distances and error bars indicate standard errors. Uppercase letters represent post hoc groups between lighting configurations in each age group, and the symbol * indicates a significant difference between age groups in each lighting condition.)

INTERACTIVE EFFECT OF TARGET LOCATION, LIGHTING CONFIGURATION, AND ILLUMINANCE

The combined effects of target location, lighting configuration, and illuminance on detection distance are summarized in this section. Two analysis approaches were used to further assess this three-way interaction effect, with an emphasis on two aspects that were considered most practically relevant. The first examined the effect of lighting configuration on detection distance at each illuminance for each target location, and focused on the differences between configurations and the consistency of these differences across illuminance and target locations. The second examined the effect of illuminance on detection distance at each lighting configuration for each target location, and was used to assess plateaus that were evident in detection distances with increasing illuminance.

Effect of Lighting Configuration

Overall, detection distances were longest in the Box lighting configuration and shortest in the Approach configuration ($M_{Box} = 108.04$ m; $M_{Both} = 75.95$ m; $M_{Approach} = 52.32$ m); this pattern of results was consistent for each of the illuminance conditions. From simple effects testing, the effect of lighting configuration was significant at every illuminance for the near-right, near-middle, near-left, and far-left target locations. For the remaining (far-right) target location, differences in detection distances between lighting configurations were only significant at the 12-lux illuminance. These results are illustrated in Figure 12.

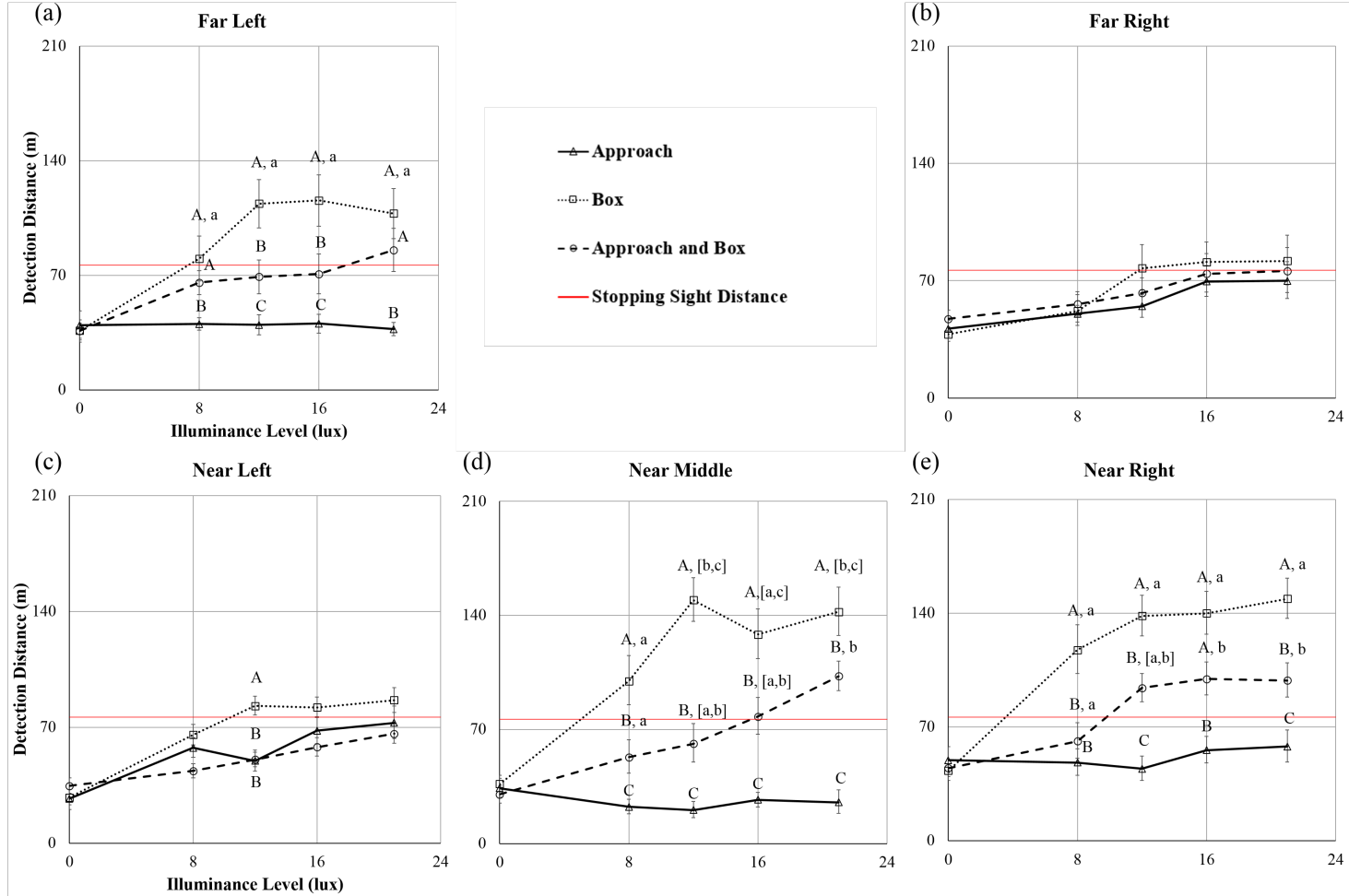


Figure 12. Graphs. Interactive effects of lighting configuration and illuminance at each target location. (Values are means of detection distances and error bars reflect standard errors. Uppercase letters indicate post hoc groupings [from paired comparisons] between lighting configurations at a given illuminance level, while lowercase letters indicate such groupings between illuminances for a given lighting configuration. Horizontal red lines indicate the stopping sight distance at 56 km/h [35 mph].)

Assessment of the post hoc pairwise comparisons revealed the existence of significant differences in detection distances between the lighting configurations at every illuminance and target location. For near-right (Figure 12e), near-middle (Figure 12d), and far-left (Figure 12a) target locations, detection distances in the Box lighting configuration were significantly longer than those in the Both and Approach lighting configurations at every tested illuminance greater than 0 lux. For the near-left target location (Figure 12c), pairwise comparisons were significant between the three lighting configurations only at the 12-lux illuminance. No pairwise comparisons between lighting configurations were significant for the far-right target location (Figure 12b). At every illuminance, the Box lighting configuration had longer detection distances than the Both configuration by approximately 25% to 50% depending on the illuminance, and the Approach configuration by approximately 50% to 60% depending on the illuminance.

To isolate the effect of the intersection lighting configuration on detection distances, the mean detection distances in the no lighting condition (headlamp only) were subtracted from the mean detection distances at each illuminance level in all three lighting configurations. The results showed that the mean detection distances of all targets under the Box lighting configuration were higher than the Approach and Both lighting configurations at all illuminance levels (see Figure 13). In the Box and Both lighting configurations, the mean detection distance with roadway lighting present increased along with the level of illuminance. The increase in the mean detection distance with an increased level of illuminance was the highest in the Box lighting configuration (ranging from 137% to 219% of the mean detection distance in the headlamps-only condition) followed by the Both lighting condition (26% to 101% of the mean detection distance in the no lighting condition). In the Approach lighting configuration, the increase in the detection distance was the lowest (ranging from -14% to 21% of the mean detection distance in the no lighting condition).

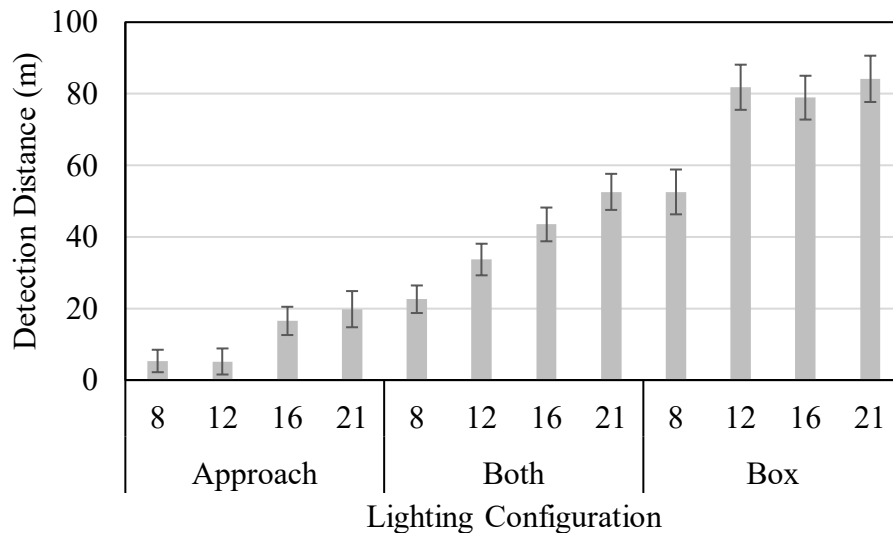


Figure 13. Bar graph. Effect of lighting configuration and illuminance without taking the vehicle’s headlamps into consideration. (Values are means of detection distances in each lighting configuration and illuminance with the mean detection distance in the no-lighting condition subtracted. Error bars represent standard errors.)

Effect of Illuminance

There appeared to be an illuminance at which detection distance plateaued within each lighting configuration and for every target location (see Figure 12). Simple effects testing revealed that illuminance had a significant effect on detection distance for near-right, near-middle, and far-left target locations in the Box and Both lighting configurations. At the near-left target location, illuminance had a significant effect on detection distances in all three lighting configurations. At the far-right target location, illuminance had a significant effect on detection distances in the Approach and Box lighting configurations.

Assessment of post hoc pairwise comparisons confirmed the existence of plateaus in detection distance for several target locations in the different lighting configurations. These plateaus occurred for all targets (in the range of the illuminances evaluated) except the far right, though inconsistently across lighting configurations (Table 4). Four of the five target locations (except the far right) had such a plateau in the Box lighting configuration. In the Approach and Both lighting configurations, only three target locations (near left for Approach, near right and near middle for Both) showed the detection distance plateau, respectively. Furthermore, the mean detection distance at which the plateau occurred was significantly higher and occurred at a lower illuminance in the Box versus the Approach and Box lighting configurations (Figure 12).

Table 4. Illuminance at which a detection distance plateau occurred or was not evident (based on paired comparisons) for each combination of target location and lighting configurations at each location.

Target Location	Lighting Configuration		
	Approach	Box	Both
Near Right	No Plateau	8 lux	12 lux
Near Middle	No Plateau	12 lux	12 lux
Near Left	16 lux	12 lux	No Plateau
Far Right	No Plateau	No Plateau	No Plateau
Far Left	No Plateau	8 lux	No Plateau

COMPARISONS OF MEAN DETECTION DISTANCE TO SAFE STOPPING DISTANCE

Overall, 48.3% of the target locations were detected from a safe distance (based on the value of 76.2 m [250 ft.] as described earlier). In the Box lighting configuration, 90% of target locations were detected from a safe distance, while only 45% and 10% were detected at a safe distance in the Approach and Both configurations, respectively.

In the Box configuration, near-right, near-middle, and far-left target locations had mean detection distances greater than the stopping sight distance for all levels of illuminance except the no lighting condition (Figure 12). For the remaining targets in this same lighting configuration (near left and far right), the mean detection distance was greater than the stopping sight distance for three illuminances: 12, 16, and 21 lux. In the Approach configuration, only the near-left and far-right target locations at the highest illuminance (21 lux) had mean detection distances greater than the stopping sight distance (Figure 12). In the Both lighting configuration,

the following target locations had mean detection distances greater than the stopping sight distance (Figure 12): near right (12, 16, and 21 lux), near middle (16 and 21 lux), far right (16 and 21 lux), and far left (16 and 21 lux).

CHAPTER 4. DISCUSSION

The goals of this study were to determine whether a driver's visual performance, measured using a target detection task, differed between three intersection lighting configurations and to identify the illuminance that offers the best visual performance within each intersection lighting configuration. Three major findings were evident. First, there was a significant difference in visual performance between the three lighting configurations, with the Box lighting configuration having the longest detection distances and the Approach lighting configuration having the shortest detection distances ($M_{Box} = 108.0$ m; $M_{Both} = 75.9$ m; $M_{Approach} = 52.3$ m). Second, the effect of illuminance on visual performance within each lighting configuration was not consistent, but rather was dependent on target location. Third, age-related differences in visual performance measurements were consistent across the conditions investigated, with younger participants having better visual performance (longer detection distances) than older participants.

EFFECT OF LIGHTING CONFIGURATION

Regarding the effects of lighting configuration, three converging lines of evidence indicate that the Box lighting configuration yielded superior visual performance. First, longer detection distances were found with Box lighting than either the Approach or Both configurations, and this was found at every illuminance and target location. Second, 90% of targets were detected from a safe distance under the Box lighting configuration, compared to 45% and 10% in the Box and Approach configurations, respectively. Third, participants missed (failed to detect) fewer targets in the Box lighting configuration (3.7%) than in the Approach (14.2%) and Both (6.3%) configurations.

Superior visual performance in the Box lighting configuration is likely a result of the contrast at which the target's locations were rendered. Generally, the visibility of objects at nighttime depends on their contrast with the relevant background.^(15,40) With respect to intersections, target contrasts are affected by the lighting configuration (part of the intersection illuminated) and the vehicle's headlamps. Those target locations rendered in negative contrast in the Box lighting configuration (i.e., near right and near middle) had significantly longer detection distances than when the same target locations were rendered in positive contrast in the Approach lighting configuration, and this difference was found at every illuminance greater than 0 lux. This finding implies that negative contrast on targets results in better nighttime visual performance than positive contrast. This finding is consistent with work reported by Aulhorn⁽⁴¹⁾ and Hills,⁽¹⁶⁾ who showed that objects in negative contrast (Weber contrast) were detected faster and from farther than those in positive contrast. However, it is important to note that Aulhorn⁽⁴¹⁾ and Hills⁽¹⁶⁾ used positive and negative contrasts of the same magnitude, while in this study the magnitude of the contrasts in which the targets were rendered was not controlled. Furthermore, a model of visibility suggested by Adrian⁽²⁶⁾ contains an adjustment factor for contrast polarity, which makes targets in negative contrast twice as detectable as those in positive contrast. Comparing mean detection distances here in the Approach versus Box lighting configurations for the younger and older participants showed that negatively contrasted targets had detection distances that were 2.8 times higher than positively contrasted targets (range = 1.7 to 4 times depending on age and light level), which is higher than the value suggested by Adrian. However, a more detailed photometric analysis, which is beyond the scope of this paper, is required to accurately

understand the influence of contrast polarity on detection. The result of small targets being detected more easily in negative contrast than in positive contrast has also been reported by Fotios et al.,⁽⁴²⁾ who studied the detection of small obstacles by cyclists with bicycle-mounted lamps and roadway lighting. The contrast polarity (negative/positive) of the near-right and near-middle targets in the Both lighting configuration depended on the illuminance, as both the areas in front of and behind the target locations were illuminated; a photometric analysis is required in the future to accurately determine the contrast on these targets.

Targets can also undergo a change in contrast polarity (negative to positive or vice versa) from the point of view a moving vehicle's driver. For example, near-right and near-middle target locations were originally rendered in negative contrast in the Box lighting configuration, but slowly transitioned into positive contrast as the vehicle moved closer to the target and the headlamps illuminated the face of the target to be brighter than the background. Headlamps, however, only generate a substantial influence at distances less than 100 meters to the target.⁽¹⁵⁾ Our results indicated that the negatively contrasted targets in the Box lighting configuration had mean detection distances greater than 100 meters even at the 8-lux illuminance, whereas the positively contrasted targets in the Approach lighting configuration had mean detection distances well under 100 meters at the highest illuminance of 21 lux. The shorter mean detection distances in the Approach lighting configuration also suggest that the magnitude of positive contrast in which the near-right and near-middle target locations were rendered is not sufficient to be detected by participants and that additional luminance from the headlamps is required to further increase the contrast and facilitate detection. The mean detection distances of the same targets in the Box lighting configuration, however, were typically detected beyond the range of headlamps.

Targets rendered in the same contrast polarity also exhibited different levels of visual performance across the tested lighting configurations. For example, the far-left target location was rendered in positive contrast in all three lighting configurations, yet detection distances in the Box lighting configuration were higher than the other two configurations. The differences between lighting configurations could be attributed to the far-left target being rendered in a higher positive contrast in the Box lighting configuration than in the other two lighting configurations. Further, the far-left target had a higher mean detection distance than the far-right target in the Box lighting configuration, even though both targets were rendered in positive contrast. On further examination of target locations, this phenomenon could be due to the influence of background luminance at these target locations, as viewed by the approaching driver. Specifically, the far-right target seemed to have a higher background luminance, being contrasted against the pavement, whereas the far-left target was contrasted against the darker region beyond the pavement. The darker background, and associated lower background luminance ($L_{bg} = 0.05 \text{ cd/m}^2$), likely caused the far-left target to have a higher contrast compared to the far-right target location where the background luminance was higher ($L_{bg} = 0.11 \text{ cd/m}^2$) (Figure 14).

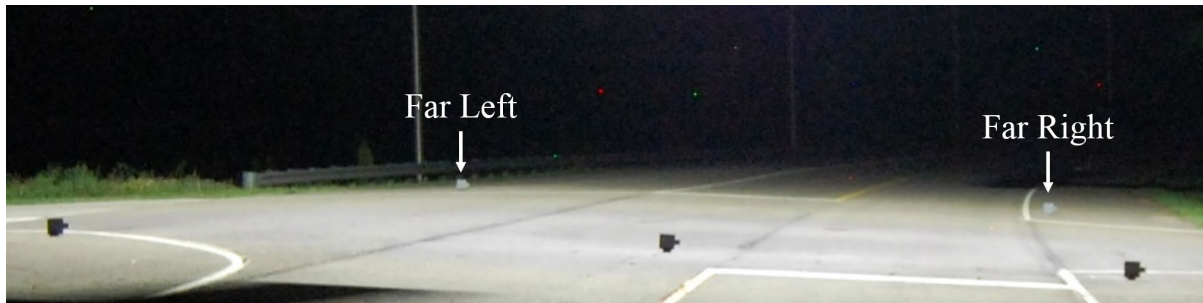


Figure 14. Photo. Intersection, illustrating background luminance values at the far-left and far-right target locations.

EFFECTS OF ILLUMINANCE

Increases in illuminance generally resulted in increased visual performance, consistent with earlier evidence on the effects of illuminance on visual performance.^(20,21,23,24) Of these four noted studies, however, only the one by Terry and Gibbons⁽²³⁾ used target detection distance as measure of visual performance, and only the one by Van Bommel and Tekelenburg⁽²⁴⁾ used pedestrian detection distance as measure of visual performance. Terry and Gibbons⁽²³⁾ evaluated 10 incremental illuminances in a real driving scenario and showed that an increase in illuminance resulted in an increase in detection distance. However, their study did not explore the relationship between illuminance and potential plateaus in visual performance. Van Bommel and Tekelenburg⁽²⁴⁾ studied the effect of three incremental luminance conditions on the detection distances of pedestrians and showed that increase in the luminance resulted in increased detection distance up to a luminance of 3.4 cd/m². The two remaining studies were conducted in laboratories and used reaction time as a measure of visual performance in a stimulus detection task.

Here, the increase in visual performance with increasing illuminance was not consistent across the three evaluated lighting configurations, being highest in the Box configuration. Further, even at the highest illuminance (21 lux), some target locations (near left in Both; near middle, near left, and far left in Approach) had mean detection distances that were shorter than the safe stopping distance in the Approach and Both lighting configurations. However, in the Box lighting configuration all target locations had mean detection distances longer than the safe stopping distance at an illuminance of 12 lux or greater. From this, it can be concluded that the Box lighting configuration illuminates the range of intersection target locations better than the other two lighting configurations, and at a lower illuminance.

Comparison of illuminances under each lighting configuration and target location indicated plateaus in visual performance in some conditions. However, only the Box lighting configuration showed a visual performance plateau for all target locations (except the far-right target), and this plateau was consistently at the 8 or 12 lux illuminances (average intersection illuminance between 7 and 10 lux). The Approach and Both lighting configurations did not show consistent plateauing of visual performance for most of the target locations; for the few target locations where plateaus were evident, illuminances varied between 16 and 21 lux. The lack of evidence of such plateaus in either the Both or Approach lighting configurations suggests that higher illuminances than tested are required to attain maximal visual performance.

The effect of illuminance on intersection visibility in this study did not completely align with results of past studies on intersection visibility. Minoshima et al.⁽¹¹⁾ reported that a mean roadway surface illuminance of 10 lux or higher will increase the visibility of the intersection irrespective of the lighting configuration, clearly in contrast with the present results. Only in the Box lighting configuration were participants able to detect all targets from a safe distance at an average intersection illuminance of 10 lux. In both the Approach and Both lighting configurations, and even at the highest illuminance (12 lux in Approach and 13 lux in Both), none of the targets had mean results that were shorter than the safe distances. This discrepancy could be attributed to the different experimental methodologies used, in that visual performance here was objectively assessed (using detection distance) whereas Minoshima et al.⁽¹¹⁾ used subjective ratings of intersection visibility.

The effect of illuminance on intersection visibility in this study could also translate to lowering the night-to-day (ND) crash ratios at rural intersections. Bullough et al.⁽³⁾ calculated the RVP scores of different kinds of intersections and correlated them to ND crash ratios, showing that rural intersections with a mean intersection illuminance of 10 lux reduce the ND crash ratio by about 2%. Our results, showing a plateauing of visual performance at the 10 lux mean horizontal illuminance, support the results of Bullough et al.⁽³⁾ Edwards⁽⁹⁾ found that intersections with mean illuminance between 5 and 18.42 lux had fewer nighttime crashes than intersections with mean illuminance less than 5 lux. Although the illuminance range recommended by Edwards⁽⁹⁾ does not completely overlap the illuminance range (> 10 lux) where the visual performance plateaued here in the Box lighting configuration, there is, we believe, a strong indication that maintaining the mean illuminance of an intersection at 10 lux or more could result in lowering the number of nighttime crashes.

EFFECTS OF AGE AND HEADLAMPS

Age clearly influenced visual performance, with the older group having shorter detection distances. This was consistent with existing research on detection distances of targets and pedestrians, which also found older drivers to have shorter detection distances.^(14,23) A decrease in visual performance among the older participants is likely a consequence of age-related physiological changes in the eyes that lead to reduced visual acuity and contrast sensitivity.⁽²⁸⁻³²⁾ Interestingly, age-related differences in visual performance existed and were fairly similar in all three intersection lighting configurations. Both age groups had longer detection distances in the Box lighting configuration than either the Approach or Both configurations, indicating that the Box lighting configuration offers better visual performance for a wider range of drivers.

Headlamp beam patterns also affected target detection rates. Targets on the left-hand side of the road had lower detection rates, especially in the no lighting condition (or headlamp only condition). We believe this is because of the headlamp beam patterns, which are tailored to reduce light output to the left lane to reduce glare to oncoming drivers. Targets on the right side of the road, in contrast, had a higher detection rate because of higher light output in that direction. On the left side, the far-left target had a higher detection rate than the near-left target, which we believe could be because of the lower background luminance of the far-left target, which increased its contrast relative to that of the near-left target, as mentioned above.

PRACTICAL IMPLICATIONS

The results of this study have several practical implications. The observed differences in visual performance across the three lighting configurations imply that the part of the intersection that is illuminated plays a critical role in the visibility of targets at that intersection. For instance, illuminating the intersection box enhances the likelihood that targets at a variety of locations (e.g., intersection entry, exit, and the middle of the crosswalk) are visible from at least a minimum safe stopping distance at 56 km/h (35 mph). The Box lighting configuration has an additional benefit in that it requires only one luminaire to illuminate the entire intersection, whereas the other two configurations need at least as many luminaires as there are approaches at the intersection. A plateau in visual performance was also evident for the Box lighting configuration, attained between 8 and 12 lux (mean intersection illuminance between 7 and 10 lux) depending on the target location. With the Box illuminated, increases in the illuminance beyond 12 lux (mean intersection illuminance 10 lux) are thus considered unlikely to substantially increase driver visual performance at an intersection. This mean horizontal illuminance of 10 lux in the Box lighting configuration is lower than existing specifications of 15 lux for “Major/Collector” or 13 lux for “Major/Local” functional classifications by IES’s RP-8, which closely resemble rural intersections in the United States. The Box lighting configuration also increased visual performance benefits to participants in both the younger and older age ranges, suggesting that a single configuration can be of benefit to a wide range of drivers. Use of Box lighting is thus argued to be an effective approach to facilitate the development of intersection lighting design standards that will increase driver visual performance without over-lighting intersections. The need for a single luminaire and the noted performance plateaus further suggest that Box lighting can be used to facilitate potential energy savings. However, this recommendation of illuminating the intersection box would be more suitable for installing lighting at intersections which currently do not have lighting. For intersections that are already illuminated, a cost-benefit analysis should be performed to compare the cost of installing a new lighting design (to illuminate the intersection box) versus the cost of installing new luminaires, along with associated energy costs, to increase the illuminances to provide optimum visibility.

LIMITATIONS AND FUTURE RESEARCH

There are a few limitations of the current work that should be noted. First, there was no traffic (no additional vehicles) on the studied intersection and the signal lights at the intersection were turned off. These simplifications were made to reduce the possible confounding effects related to the presence of traffic and phase of the signal during approaches to the intersection. The presence of additional vehicles would also have introduced more confounding glare effects, which could also have affected the illuminance and target contrasts. The experimental design was intended to isolate visual performance so that intersection lighting configurations and illuminances could be accurately evaluated. Second, pedestrians could not be used as objects for the detection task, as the length of the approach of the intersection used here was not long enough to show differences in the lighting configurations and illuminances. Third, the results of this study are mainly applicable to isolated or rural intersections with a single source of illumination which do not have continuous roadway lighting on any of the intersecting roads. Further, only one intersection approach was illuminated in the Approach and Both lighting configurations. In reality, all the approaches might be illuminated when Approach and Both configurations are used, which could substantially impact the luminance and contrast of objects located at the intersections, and

consequently, their visibility. The presence of luminaires illuminating the approaches will increase object luminance at the intersections; however, the change in object contrast is difficult to predict, as the objects will be illuminated from multiple directions. To address these limitations, future work should test visual performance under more realistic, complex scenarios with continuous lighting, and incorporate objective measures of pedestrian visibility to better determine the effectiveness of intersection lighting configurations.

CHAPTER 5. CONCLUSION

Driver nighttime visual performance at an intersection is clearly influenced by the part of the intersection that is illuminated. The lighting configuration in which the intersection box was illuminated resulted in longer detection distances at every illuminance (other than no lighting). With the Box lighting configuration, visual performance also plateaued between a mean intersection illuminance of 7 and 10 lux; beyond this level, additional increases in illuminance did not result in significant increases in visual performance (for either older or younger drivers). Lighting configurations in which only the intersection approach or both the intersection approach and box were illuminated performed worse than the Box lighting configuration, and did not show any consistent plateauing of visual performance. Younger participants had longer detection distances (by 29.3%), and the influences of lighting configuration and illuminance were generally consistent between the two age groups studied. Results also showed that older drivers could benefit from higher illuminances (> 21 lux at near-right target location or mean intersection illuminance of 12 lux), especially in the Approach and Both lighting configurations. These findings have important implications for intersection lighting design, especially intersections at isolated or rural areas. Our results suggest that illuminating the intersection box can increase visual performance for the nighttime driver and could be an energy-efficient lighting solution.

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