Effects of Intersection Lighting Design on Driver Visual Performance, Perceived Visibility, and Glare

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ABSTRACT

Nighttime intersection crashes account for nearly half of all the intersection crashes, making them a major traffic safety concern. Although providing lighting at intersections has proven to be a successful countermeasure against these crashes, existing approaches to designing lighting at intersections are overly simplified. Current standards are based on recommending lighting levels, but do not account for the role of human vision or vehicle headlamps or the numerous pedestrian-vehicle conflict locations at intersections. For effective intersection lighting design, empirical evidence is required regarding the effects of lighting configuration (part of the intersection illuminated) and lighting levels on nighttime visibility. This research effort had three goals. The first was to identify an intersection lighting design that results in the best nighttime visibility. The second goal was to determine the effect of illuminance on visual performance at intersections. The third goal was to understand the relationships between object luminance, contrast, and visibility. To achieve these goals, three specific configurations were used, that illuminated the intersection approach (Approach), intersection box (Box), and both the intersection approach and box (Both). Each lighting configuration was evaluated under five levels of illumination. Visibility was assessed both objectively (visual performance) and subjectively (perceptions of visibility and glare).

Illuminating the intersection box led to superior visual performance, higher perceived visibility, and lower perceived glare. For this same configuration, plateaus in visual performance and perceived visibility occurred between 8 and 12 lux illuminance levels. A photometric analysis revealed that the Box lighting configuration rendered targets in sufficient positive and negative contrasts to result in higher nighttime visibility. Negatively contrast targets aided visual performance, while for targets rendered in positive contrast visual performance was dependent on the magnitude of the contrast. The relationship between pedestrian contrast and perceived pedestrian visibility was more complex, as pedestrians were often rendered in multiple contrast polarities. These results indicate that Box illumination is an effective strategy to enhance nighttime visual performance and perceptions of visibility while reducing glare, and which may be an energy efficient solution as it requires fewer luminaires.

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Chapter 1 – Introduction

Crashes at intersections constitute a disproportionate share of the total number of roadway crashes making them a major traffic safety issue. For example in the United States, in 2013, intersection crashes constituted over 45% of number of crashes and 25% of the number of fatalities on the roadways (NHTSA, 2014). Furthermore, night crashes and fatalities account for approximately 40% of the total crashes and fatalities at intersections (NHTSA, 2014). Intersections are locations where two roadways cross each other (Figure 1).

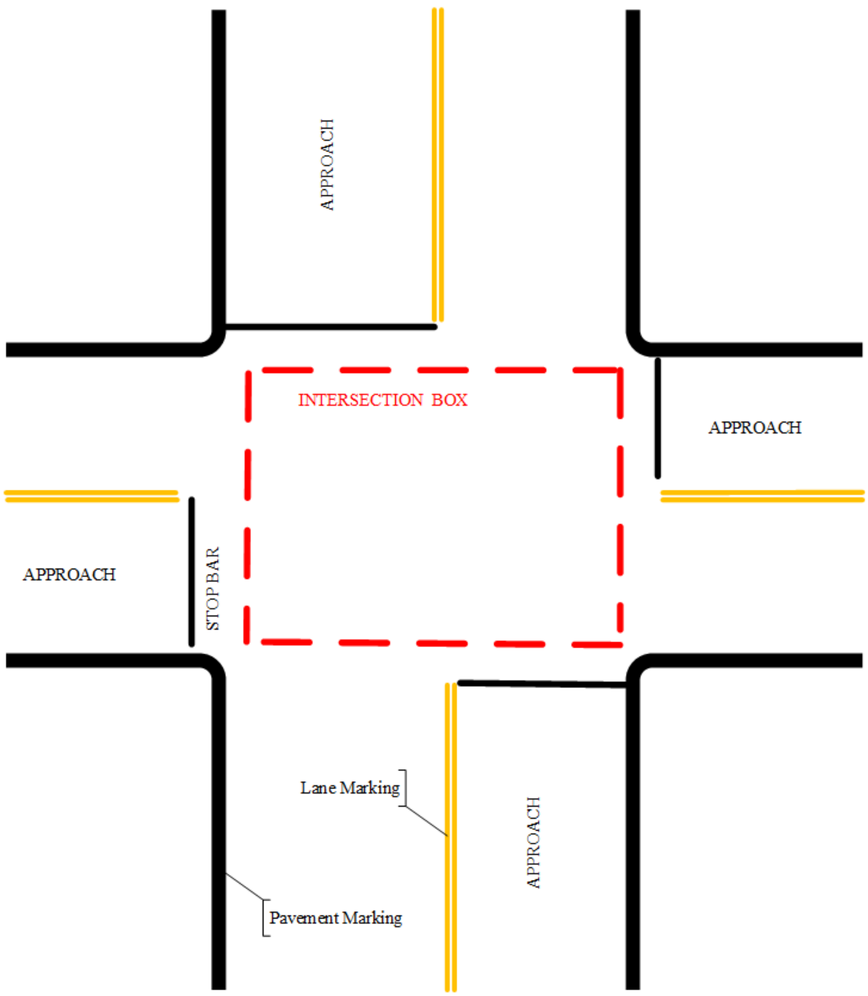

Figure 1. Basic Terminology associated with intersections

1.1 Intersections Lighting Design Standards

Intersections are designated as conflict areas because vehicle flows intersect each other and other road users like pedestrians, bicyclists etc. might be present. Intersections are one of the most complex roadway types that road users encounter. An intersection is a very dynamic environment, wherein drivers need to make judgments based on many extraneous factors such as the presence of others vehicles, pedestrians, bicyclists, signal phases, or presence of stop signs. An intersection with two streets, two-way traffic, no restricted turn lanes, and no signal has 16 vehicle-vehicle conflict points and 16 vehicle-pedestrian conflict points (Turner, Sandt, Toole, Benz, & Petten, 2006).

All the different kinds of users, changes in traffic flows, and geometry of the roads make intersections more prone to collisions. Therefore lighting design of intersections is given special consideration by agencies that recommend lighting standards. Both the Illumination Engineering Society of North America (IESNA) and the Commission Internationale de l'Éclairage (CIE) have recommended minimum lighting values for intersections depending on number of factors like speed, traffic volume, traffic composition etc. These recommended values differ from those recommended for lighting of roadways significantly. IESNA Recommended Practice (RP) – 8 recommends that the lighting level at the intersections should be equal to the sum of the lighting levels of the each road at the intersection (IESNA, 2005). The recommended lighting levels by IESNA RP-8 are illustrated in Table 1.

Table 1. IESNA recommended illuminance levels for intersections (IESNA, 2005)

Illuminance for Intersections				
Functional Classification	**Average maintained illumination at pavement by pedestrian area classification (lux)**			**Uniformity Ratio**
	High	**Medium**	**Low**	
Major/Major	34	26	18	3
Major/Collector	29	22	15	3
Major/Local	26	20	13	3
Collector/Collector	24	18	12	4
Collector/Local	21	16	10	4
Local/Local	18	14	8	6

For intersection lighting design, CIE-115:2010 denotes the 6 lighting classes (C0-C5), C0 class providing highest and C5 the lowest level of illuminance (

Table 3). The lighting class is determined by applying appropriate weighting values for different parameters (Table 2). These weighted values are added, and the sum is subtracted from 6 to determine the C lighting class (CIE, 2010). Threshold Increment is a measure of the loss of visibility caused by disability glare. It is a percentage increment in the contrast of the object to make it visible again in the presence of glare (van Bommel & Boer, 1980):

$$C = 6 - V_{ws}$$

Table 2. Parameters and weight values recommended for intersections (CIE, 2010)

Parameter	Options	Weighting Values for C Lighting Class
Speed	Very High	3
	High	2
	Moderate	1
	Low	0
Traffic Volume	Very High	1
	High	0.5
	Moderate	0
	Low	-0.5
	Very Low	-1
Traffic Composition	Mixed with high % of non-motorized	2
	Mixed	1
	Motorized only	0
Separation of Carriageways	No	1
	Yes	0
Ambient luminance	High	1
	Moderate	0
	Low	-1
Visual guidance/ traffic control	Poor	0.5
	Moderate or Good	0

Table 3. CIE recommended lighting classes and levels for intersections based on illuminance (CIE, 2010)

Lighting Class	Average Illuminance over whole used surface E in lx	Uniformity of Illuminance	Threshold Increment in f_{TI} in %	
			High and Moderate Speed	Low and Very Low Speed
C0	50	0.4	10	15
C1	30	0.4	10	15
C2	20	0.4	10	15
C3	15	0.4	15	20
C4	10	0.4	15	20
C5	7.5	0.4	15	25

The highest illuminance level recommended by CIE-115 is greater than the highest illuminance level recommended by IESNA RP8. Another metric where the standards differ is the uniformity ratio; CIE-115 recommends the same uniformity of 2.5 at all intersection classes whereas IESNA RP8 recommended uniformity increases as the level of illuminance decreases.

Another concern with the IESNA-RP8 standard is that it only takes into account vehicle-vehicle conflict points at intersections. Vehicle-pedestrian conflict points are not considered. IESNA-RP8 only recommends that providing negative contrast will make a pedestrian reasonably visible. The lighting configurations are recommended by the IESNA-RP8 standard for intersections, and all these lighting configurations make the pedestrian visible in negative contrast.

1.2 Effect of Lighting and Lighting Levels on Nighttime Traffic Safety at Intersections

Roadway lighting increases visibility, augments vehicles headlamps, and provides more information about the surrounding area, and thereby can result in fewer number of crashes (Hasson & Lutkevich, 2002). Wortman, Lipinski, Fricke, Grimwade, and Kyle (1972) concluded that lighting could significantly help in reducing the night time accidents at intersections. In an analysis of rural intersections in Illinois, it was found that illumination does have a significant benefit on night time accidents, in that the number of accidents was reduced by about 30% (Wortman & Lipinski, 1974). Walker and Roberts (1976) reported that the accident frequency almost reduced by 49% in a study conducted in Iowa before and after the installation of lighting.

A meta-analysis (Elvik, 1995) of 37 published studies from 1948 to 1989 in 11 different countries indicated a reduction of 65% in night time fatal crashes, a 30% reduction in injury crashes, and a 15% reduction in crashes involving property damage, when lighting was installed on both intersections and road segments (rural, urban and freeway). A study conducted by the Minnesota Local Road Research Board (LRRB) indicated that lighting at rural intersections not only reduces night time crashes, but also is a cost effective countermeasure against crashes (Preston & Schoenecker, 1999). A before and after study conducted in Kentucky by Green, Agent, Barrett, and Pigman (2003) also concluded installation of lighting reduced night time crashes by 45%. A study conducted by Isebrands et al. (2010) on 48 intersections in Minnesota to determine the effectiveness of lighting on nighttime crashes found a 37% reduction in the nighttime crash rate after lighting was installed.

Studies have also shown that increasing the lighting levels at intersections can make them safer and reduce crash rates. Oya *et al*. (2002) reviewed the effect of illuminance in reducing accidents at intersections and found that an average road surface illuminance of 20 lux or higher serves as an effective countermeasure against crashes. Moreover, average road surface illuminance of 30 lux were found to yield statistically significant reductions in crashes.

Only one existing study has examined the effect of intersection lighting design on subjective ratings of visibility. In this work (Minoshima, Oka, Ikehara, & Inukai, 2006), subjective ratings of visibility were obtained from drivers who were exposed to three different intersection lighting layouts (or configurations), each with three levels of illumination (5, 10 and 15 lux). The three intersection layouts were based on the part of the intersection that was illuminated, and used the following three configurations: approach, corner (or box), and both approach and corner. Drivers rated five statements – "danger to pedestrian", "ease of driving", "brightness" and "safety" – on Likert-type scales (1 to 5), and a mean rating higher than 3 (or the "neutral" anchor) was used as a measure of effectiveness of an intersection lighting design. In this study, increases in illuminance levels resulted in higher subjective ratings of visibility. With illuminance levels higher than 10 lux, mean ratings of pedestrian visibility were higher than 3 on the Likert-type scale in all three layouts. Minoshima et al. (2006) also found that ratings (all statements including pedestrian visibility) depended on the illuminance level. At the 15 lux illuminance level, the lighting configuration that illuminated the approach and corner was rated highest, while at the 10 and 5 lux illuminance levels the configuration that illuminated the approach was rated the highest. The authors concluded that the approach lighting layout should be used to maintain a mean roadway surface luminance of 10 lux, but if a higher level of average roadway illuminance is needed then both approach and corner illumination should be used. This study also conducted a survey of intersections where accidents occurred frequently and the optical properties at these intersections were analyzed. The results have indicated that a uniformity ratio of illuminance of 0.4 makes intersections safer.

A study performed at rural intersections in Iowa where lighting levels (illuminance and luminance) were measured, concluded that it was difficult to quantify the effect of lighting on intersection safety (Smadi, Hawkins, & Aldemir-Bektas, 2011). However, the authors noted that the presence of fixed overhead lighting made intersection safer than unlighted ones. More recently, lighting data collected from 100 rural intersections in Virginia showed that for a 1-unit increase in the illuminance the number of night crashes decreased by 7% (Bhagavathula, Gibbons, & Edwards, 2015). For the lighted intersections, the same increase in average horizontal illuminance decreased the number of night crashes by 9%. The largest decrease in the number of night crashes was for unlighted intersections, where for a 1-unit increase in the average horizontal illuminance the night crashes decreased by 21%. These relationships between illuminance and night crashes may only be valid, however, for the tested illuminance ranges (0.28 to 31.6 lux).

1.3 Vision

So far only infrastructure-based factors have been considered, external to the driver's eye. The human visual system, though, is an important component of the driver-infrastructure interface. Vision is critical for safe driving, which is why most of the countries require a vision test before the issuing of a driver's license. The human visual system consists of two main parts, the optical part (the eye) and the image processing part (optic never to visual cortex in the brain). Before discussing vision specifically during nighttime driving, it is important to understand the structure of the human visual system.

The spectrum of electromagnetic waves between 400 and 700 nanometers (nm) is called the visible spectrum or light because the human eyes are sensitive to those wavelengths. The light that is reflected from objects will first enter the eye, goes through cornea (the protective cover over the eye), the pupil (the opening that controls the amount of light entering the eyes), the lens, which focuses the lighting on onto a layer of photosensitive cells on the retina. The retina then converts this light into an electrical signal and sends it to the visual cortex in the brain for processing through the optic nerve. The lens is responsible for focusing objects that at different distances from the eyes, the ciliary muscles in the eye help flatten or round the lens to accommodate in focusing.

The retina, however, is the most interesting part of the human visual system. It consists of a photosensitive layer of cells or receptors which are sensitive to wavelengths of the electromagnetic radiation between 400 and 700 nm. There are four types of photosensitive receptors on the retina which can be classified into two major categories called cones and rods. Each photoreceptor has a different kind of photo pigment which makes them sensitive to four different kinds of spectra. The rods have the same pigment; therefore all the rods have the same spectral sensitivity. The cones on the other hand have three different kinds of photo pigments and consequently have three different kinds of spectral sensitivities; therefore there are three different kinds of cones. The three cone receptors are called short (S), medium (M) and long (L) depending on region in which they have the greatest sensitivity. The three relative spectral response curves of three kinds of cones are shown in the following figure. The response of the S-cone is centered at 437nm, which coincides with blue light. If light activates the S-cone, it is perceived as blue. The M and L-cones overlap each other in a big way; their spectral sensitivities are peaked at 533 and 564 nm. These are more responsive to green to yellowish-green light and a good portion of the tails extend into the region perceived as red color (wavelengths > 600 nm).

1.4 Nighttime Driving – Role of Rods and Cones - Adaptation

Rods and cones play a major role while driving at night. They control the adaptation of the eye so that the capabilities of vision are not affected when the lighting conditions change. Along with eye movement and accommodation, adaptation is one of the continuous adjustments that the eye makes to look at object in the field of view (Boyce, 2009).

The human eye can encounter a wide range of luminances, from 0.000001 cd/m^2 (very dark night) to 10000 cd/m^2 (sunlit beach). Through a process called adaptation, the human eye unconsciously and continuously changes it sensitivity, in order to cope up with this wide range of luminances. Adaptation involves three stages, namely, change in pupil size, neural adaptation and photochemical adaptation (Wördenweber, Wallaschek, Boyce, & Hoffman, 2007).

Change in Pupil Size: As the amount of light entering the eye (retinal illuminance) changes, in response the iris dilates or constricts the pupil. The pupil plays a minor role in the adaptation of the eye. The constriction is faster (approx. 0.3 seconds (s)) than dilation (approx. 1.5 s) (Wördenweber et al., 2007).

Neural Adaptation: This adaptation is extremely fast to the order of a couple of hundred milliseconds. It is brought about the synaptic interactions in the retina. This adaptation is effective over a two to three log units of luminance.

Photochemical Adaptation: When the retinal illuminance changes in the order of two to three log units, neural adaptation is enough to compensate the vision system. However, if there are larger changes, then photochemical adaptation is necessary. This happens when the photo pigments in the four types of photoreceptors of the eye get bleached by the absorption the light. In the dark the pigment is regenerated and gets ready to absorb light again. The sensitivity of the eye is a function of the percentage of the unbleached pigment. When a person in a vehicle moves from a dark area to a lighted area, the pigment gets bleached and then it gets regenerated to re-establish equilibrium. The time take for the pigment to reach equilibrium depends on two factors, the magnitude of the change, the photoreceptors involved and the direction of the change. Small changes can be taken care of by neural adaptation as mentioned above, but for large changes photochemical adaptation is necessary. The time taken for photochemical adaptation ranges from couple of minutes to tens of minutes depending on the type of photoreceptors involved. If change in the light level is within the cones' operational range, the adaptation will take place in a couple minutes, but if it involves the operation of cones to rods then adaptation will take tens of minutes. It is easier to adapt to light than to adapt to dark. It is important to note that the rate of adaptation is not linear with time but it varies asymptotically. When the eye is still adapting, the capabilities of the visual system are severely diminished. Transient adaptation is when the eye is still in the process of adapting, it becomes important when the car moves from a brightly lighted area to a very dark area (Wördenweber et al., 2007).

1.5 Photopic, Scotopic and Mesopic Vision

The state of adaptation of the human eye dictates the spectral sensitivity because at different luminances different photoreceptors (rods and cones) are active. There are three defined states of the spectral sensitivity of the human eye, (i) Photopic Vision, (ii) Scotopic Vision and (iii) Mesopic Vision

Photopic Vision: When the luminance of the operating environment of the human eye is greater than 3 cd/m^2, the state of the adaptation is termed as photopic vision. In this state only activity of the cones is dominant. This results in good color vision and fine resolution of detail (Boyce, 2009).

Scotopic Vision: The state of adaptation of the human visual system is defined as scotopic vision when the luminance of the environment in which it is operating is less than 0.001 cd/m^2. In this state only rods are active. Color cannot be perceived and only shades of grey can be identified (Boyce, 2009).

Mesopic Vision: This is the intermediate state between photopic and scotopic vision. It operates when luminance range is between 0.001cd/m^2 and 3cd/m^2. In this state of adaptation, both rods and cones are said to be active (Boyce, 2009). As the luminance decreases thought the mesopic state, the activity of cones in the fovea decreases which results in decreased absolute sensitivity, without a major change in the spectral sensitivity, until the scotopic state is reached. In the periphery the rods slowly come to dominate with decreasing luminance, this results in deterioration of color vision and resolution of fine detail. The spectral sensitivity shifts to shorter wavelengths.

1.6 Nighttime Driving & Mesopic Vision

Human visual system operates under the mesopic vision while driving at night (Bullough & Rea, 2004; Plainis, Murray, & Charman, 2005). This is so because, any kind of vehicle forward lighting will provide enough light to push the visual system into mesopic state (Boyce, 2009). Scotopic levels are so low that even the presence of moonlight results in mesopic conditions. A field survey of roadway luminances conducted at various roadway intersections concluded that they were in mesopic vision ranges (He, Rea, Bierman, & Bullough, 1997).

Human vision is not clearly understood in the mesopic luminance range even though most of the night driving is performed in these luminance ranges. A study conducted to understand the mesopic spectral sensitivity revealed that as the luminance decreased the contribution of the rods increased even for on axis vision (Várady & Bodrogi, 2006). It is suggested that at mesopic luminance levels eye fixation is not stable and these eye movements will let the peripheral vision be involved, even when the target is placed on-axis. Another study which was looking at the visual performance in nighttime driving conditions also revealed that with decreasing light levels, rods play an increasing role in vision and most of the visual information in nighttime traffic situations is gained from periphery (Eloholma, Ketomäki, Orreveteläinen, & Halonen, 2006).

While driving at night the visual field of the driver changes continuously, this change in the visual field results in the driver being exposed to a wide range of luminance values. The variation in luminance values will result in varying states of adaptation of the drivers’ vision. A study conducted by Plainis et al. (2005) which studied the state of retinal adaptation under road lighting when driving at night. The results suggested that vision is mediated by the cone pathway at higher mesopic range (5 lux) and rod pathway at lower mesopic ranges (0.1 and 0.5 lux). The adaptation rate of the visual system slowed down significantly, resulting in higher reaction times. There was no significant change in the retinal sensitivity.

Retinal sensitivity and speed of recovery decreased in the periphery, this is of critical importance because, most of the visual field used while driving is peripheral (Owsley & McGwin Jr, 1999).

1.7 Visual Performance

One other factor that plays a critical role in nighttime driving, but that has not been utilized in evaluating lighting design, is visual performance. Almost every task performed by a human has a visual component. To complete a task successfully, one must be able to first perform the visual component of the task successfully. Performance on the visual component of the task depends on the visual characteristics of the task (lighting level, contrast, size etc.) and physical characteristics of the task performer (vision system). This performance on the visual component of a task is called visual performance. Lighting affects task performance in a major way. Presence of lighting greatly increases the accuracy and speed with which information can be extracted from the environment (Rea, 2000). Visual performance can be measured by the speed and accuracy of performance on a realistic task (like driving) requiring vision. It is very important to separate visual components of a task from non-visual components to truly measure visual performance. Several models of visual performance have been suggested which mimicked realistic tasks to understand the relationship between visual performance and illumination. They are discussed in briefly in the following section*:*

Blackwell Model: Blackwell developed several models for predicting supra-threshold visual performance (Blackwell, 1959). These models are based detection of discs of several sizes under different levels of illumination. These models used visibility level as a basis of prediction of visual performance. Visibility level is a multiplier and is defined as the ratio of actual contrast to threshold contrast at a certain adaptation luminance. Visibility Level (VL) sets the level of luminance difference the object must reach with respect to its background to be visible. Threshold contrast is the contrast at which an object is just about visible. Blackwell suggested that visual performance can be accurately predicted by relating supra-threshold visual performance (performance at levels greater than threshold levels) to threshold visual performance. Studies later showed that supra-threshold visual performance cannot be accurately predicted from threshold levels (Clear & Berman, 1983). This model, though, is rarely used.

Adrian's Visibility Level Model: Adrian's Model is based on luminance difference of an object from its background (Adrian, 1987). This model takes into consideration factors like object size, contrast, observer age, exposure time, eccentricity angle, adaptation luminance, and distance to object to determine the visibility level (VL). A VL of 1 means that the object is just about detected. VLs between 10 and 20 are considered to safe for traffic conditions at night. A major drawback of this model is that all the data were collected in a laboratory setting and not actually in a driving scenario.

Relative Visual Performance (RVP) Model: It is a model of visual performance developed by Rea and Ouellette (Rea & Ouellette, 1991). It is based on changes in reaction time while detecting visual stimuli of different sizes under different adaptation luminances and luminance contrasts. By using reaction time the effect of non-visual components is minimized and an accurate estimate of visual performance can be estimated. RVP indicates that the human visual system is capable of a high level of visual performance over a wide range of object sizes, illuminance levels and luminance contrasts but at some point one of the above factors become insufficient and visual performance reduces towards a threshold state (Boyce & Rea, 1987). This model suffers from similar drawbacks to Adrian's Model in the sense that all the data for this model have been collected in a laboratory setting and not in a realistic driving task.

Even though all noted models have limited applicability to understand visual performance in a driving setting, they provide valuable directions for measuring visual performance for a realistic night driving task. Visual performance can be accurately measured by measuring the response time of drivers while detecting objects in a driving task. By measuring the time taken by a driver to detect an object the influence on non-visual components of task performance can be kept to a minimum. Therefore reaction time can be used to measure visual performance of drivers in a nighttime driving task.

1.8 Factors Affecting Visual Performance

A lighting engineer's duty is to change the visual characteristics of the task in such way so as to offer excellent visibility, as often it is the only thing under control. A task with good visibility will not always guaranty good visual performance, if the task performers are tired, distracted, have bad vision or untrained. Providing excellent visibility for a task at least ensures there is a potential for good visual performance. Even though good visual performance does not ensure good task performance when it comes to designing lighting at intersections and roadways, it is the only thing that can be changed by altering the lighting configurations and lighting levels. Therefore, studying visual performance of drivers under different lighting configurations and lighting levels can help in determining the best lighting configuration and level that offers best conditions for visibility. The following section summarizes important factors affecting visual performance.

1.8.1 Visual Size

The visual size of an object is defined by the solid angle the object subtends at the eye. Solid angle is obtained by dividing the cross-sectional area of the object by the square of the distance between the object and the eye. Solid angle is measured in steradians (sr.). In general, objects subtending larger visual sizes are detected easily (Boyce, 2009; Johnson, Keltner, & Balestrery, 1978). Night driving research has also shown that, objects with large cross-sectional areas have higher odds of detection from a wide range of distances compared to objects with smaller cross-sections (Gibbons, Edwards, Bhagavathula, Carlson, & Owens, 2012).

1.8.2 Contrast

Contrast or the luminance contrast is defined as the ratio of, luminance difference between the object and the background and the luminance of the background.

$$C = (L_b – L_t)/L_b$$

Where L_b is the luminance of the background, L_t is the luminance of the object and C is the contrast. In general, a higher luminance contrast leads to easier detection and vice versa (Pretto & Chatziastros, 2006). If the luminance of the object is higher than the background, then the object is said to be in positive contrast and if the object has a lower luminance than the background it is said to be in negative contrast. Research has shown that objects when viewed from a moving vehicle undergo a change in the contrast from negative to positive (Gibbons et al., 2015; Gibbons, Edwards, Williams, & Andersen, 2008). At distances greater than 100 m, the object will be under negative contrast. As the object comes within the range of the headlamps (30-100 m) on the vehicle; the contrast on the object changes from negative to positive. At distances greater than 100 m, negative contrast aids in object detection (Gibbons et al., 2008; Hills, 1975) and at shorter distances (30 to 100 m) positive contrast helps in object detection (Gibbons et al., 2008).

1.8.3 Illuminance

Illuminance is the amount of light incident on a unit surface area. It is unit is lux or footcandle (fc), where 1 lux = 10.76 fc. Illuminance on a surface is equal to the luminous intensity on the plane normal to the direction of propagation of light divided by square of the distance between the source and the surface. This is also called inverse square law. Increase in illuminance level greatly increases the accuracy and speed with which information can be extracted from the environment, and has been found to increase visual performance (Boyce, 1973; Eloholma et al., 2006; Rea, 2000; Terry & Gibbons, 2015). Many studies also concluded that increase in illuminance level results in decrease in night crashes at intersections (Bhagavathula et al., 2015; Minoshima et al., 2006; Oya, Ando, & Kanoshima, 2002).

Vertical Illuminance (E_{vert}): Vertical illuminance is the amount of light incident on a vertical plane. Vertical illuminance on an object is defined as the horizontal component of the luminous intensity incident on the object divided by the distance between the light source and object. In roadway lighting, the distance between the light source or the luminaire and the object is given by subtracting the object height (a) from the mounting of the luminaire (h) dividing by the sine of the angle the object makes at the luminaire (Figure 2). For pedestrian visibility, studies have shown that a vertical illuminance level of 20 lux at height of 1.5 m from the road surface resulted in good driver visual performance at nighttime (Edwards & Gibbons, 2008).

$$E_{vert} = \frac{I.\cos\phi}{\left(\frac{(h-a)}{\sin\phi}\right)^2} = \frac{I.\cos\phi.(\sin\phi)^2}{(h-a)^2}$$

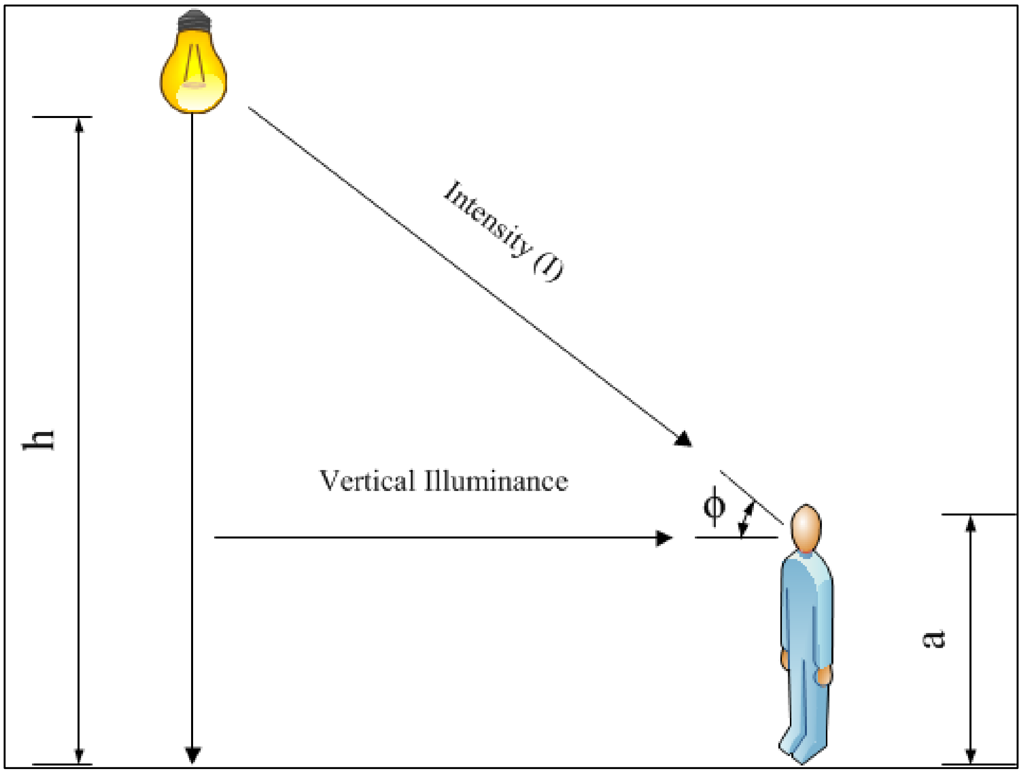

Figure 2. Components of Vertical Illuminance

1.8.4 Luminance

Luminance is the amount of light emitted by a surface in a specific direction per unit area. Its unit if candela per square meter (cd/m^2). It is a measure of brightness of an object when viewed from a given direction. Research has shown that increasing the luminance of the roadway surface makes the objects on the roadway easier to detect (Economopoulos, 1978). Drivers detect objects sooner as the average luminance of the roadway increases (Cuvalci & Ertas, 2000; Gibbons et al., 2015; He et al., 1997; Lewis, 1999).

1.8.5 Age

Age plays an important role in the visual performance of drivers. As a person ages, their vision deteriorates and the following changes occur (Murdoch, 2003):

1. The nearest point at which the eye can focus an object advances. The lens in the eye becomes less flexible as the person ages. This lack of flexibility comes to a point at which the ciliary muscles cannot alter the curvature of the lens to focus on objects close to the eye.
2. Pupil size decreases and the amount of light entering the eye decreases by 2 times.
3. The lens yellows and colors like blue and violet look gray because shorter wavelengths are absorbed.
4. Adaptation time increases. When an older person moves from a high ambient light level to lower ambient light level, their eyes take more time to adapt to the lower light level conditions and might not notice hazards in the area.
5. Sensitivity to glare increases. Glare is caused by luminances in the visual field that are higher than luminance to which the eyes are adapted to. Glare causes discomfort and might also decrease the visual performance.
6. Visual acuity (Sturgis & Osgood, 1982), contrast sensitivity and speed of perception decreases.

As people age, the threshold luminances at which objects are detected increases, indicating that older driver need increased light levels for the same visual performance (Easa et al., 2010; Sturgis & Osgood, 1982). A study conducted by Owens, et al. (2007) showed that, older drivers performance in nighttime pedestrian recognition task was worse than younger and middle aged drivers. Owens and Tyrell (1999), reported in the low luminance settings such as those in nighttime driving conditions, the steering accuracy of older drivers was poorer compared to younger drivers.

1.9 Problem Statement

Installing lighting at intersections has been used a successful countermeasure against night crashes. As discussed previously (Section 1.2), lighting an intersection has reduced night-to-day crash ratios and rates by 13 to 45%, respectively (Bullough, Donnell, & Rea, 2013; Donnell, Porter, & Shankar, 2010; Isebrands et al., 2006; Smadi et al., 2011; Wortman & Lipinski, 1974), and an increase illuminance levels has been associated with respective decreases in night-to-day crash ratios and rates of 7% (Bhagavathula et al., 2015) and 9% (Edwards, 2015).

However, existing recommendations and guidelines for the design of intersection lighting have focused solely on lighting levels and stem from research relating lighting to night crashes at intersections. This has ignored the role of human vision in intersection lighting design as well as the interactive effect of vehicle headlamps and overhead lighting. Furthermore, existing standards (Illumination Engineering Society of North America (IESNA) and the Commission Internationale de l'Éclairage (CIE)) prescribe minimum lighting levels to be maintained within the intersection box (area enclosed within the stop bars at the intersection), which does not account for the multiple pedestrian–vehicle conflict points at intersections. Moreover, 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 night crashes. Both, the process of selecting the part of the intersection that is to be illuminated and the required level of illumination for an intersection are not 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 levels (Bhagavathula et al., 2015; Bullough et al., 2013; Donnell et al., 2010; Isebrands et al., 2006; Smadi et al., 2011; Wortman & Lipinski, 1974). Yet, studying the effect of roadway lighting on night crashes or related parameters only considers an extreme aspect of driving behavior, ignoring normal driving behaviors and critical events such as near misses. 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 night crashes could lead to over-lighting of intersections, which could make the intersections less safe by introducing glare to drivers and reducing visibility; over-lighting would also result in energy wastage without any substantial benefits to visibility. Using crash metrics and a consensus-based approach to intersection lighting design also does not consider the role of human visual response, nor does it account for potential interactive effects of vehicle headlamps and intersection lighting design on nighttime visibility. Existing standards also do not account for the various pedestrian-to-vehicle conflict points at intersections.

To recommend safe lighting standards for intersections, the relationship between intersection lighting design and nighttime visibility needs to be understood. To take into account human visual response, intersection lighting configurations (part of the intersection illuminated) and illuminance levels 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. Moreover, for an intersection lighting design to be effective and accepted it should not only increase a driver’s visual performance but also increase perceived visibility and reduce glare. However, intersection lighting design has yet to be evaluated in terms of drivers’ visual performance or their perceptions of visibility and glare. For an intersection lighting design to enhance nighttime visibility (both objectively and subjectively), it is important to understand not only the effect of illuminating different parts of an intersection but also the effect of illuminance level and possible interactive influences.

1.10 Research Goals

This research effort has three overarching goals, and achieving these was intended to address important existing research gaps in intersection lighting design. These goals were:

1. To assess the effect of intersection lighting design on visibility and to identify one intersection lighting design that would increase visibility. Visibility was assessed using both objective and subjective measures. Visibility was measured objectively using visual performance (detection distance) (Chapter 2), and subjectively by measuring perceptions of visibility and glare (Chapter 3).

2. To determine the illuminance level that offers the best visual performance at intersections within each lighting configuration. This is also the illuminance level at which any additional increase in the illuminance level will not result in a corresponding increase in the visual performance or the visual performance plateaus (see Figure 3; where the visual performance plateau was theoretically observed at approximately 20 lux). By dimming the lights to this illuminance level both increased visibility and energy efficiency could be achieved without compromising on safety. The existence of plateaus was explored in both visual performance (Chapter 2) and perceptions of visibility and glare (Chapter 3).

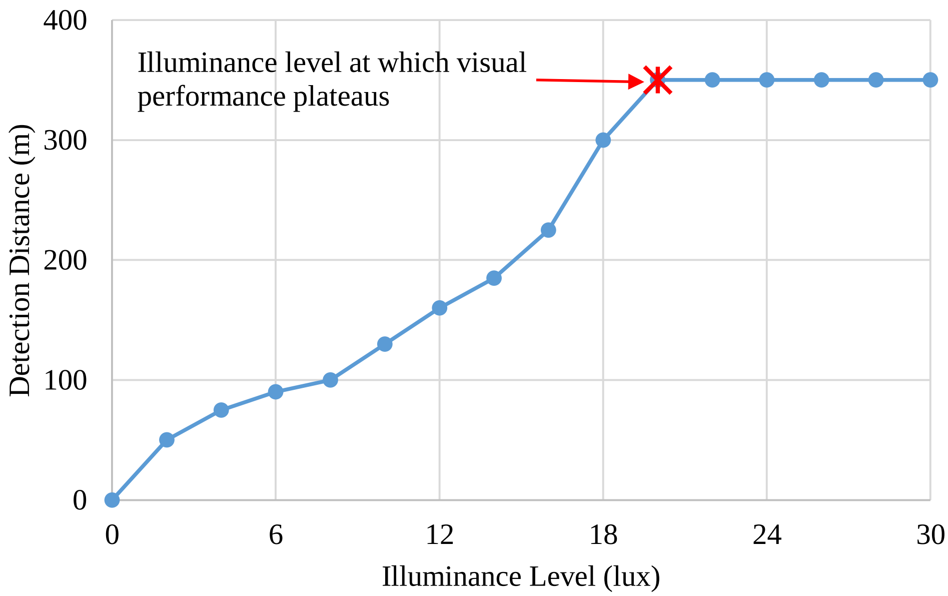

Figure 3. Effect of increasing illuminance level on visual performance. Visual performance is expected to plateau a certain illuminance level and further increase in illuminance will not result in a corresponding increase in visual performance. Theoretical representation.

3. To understand the relationship between object contrast, luminance and visibility at intersections. Photometric analyses of objects have been performed for roadways but not for intersections

(Ekrias, Eloholma, & Halonen, 2008; Gibbons et al., 2015), this analysis help understand the luminance and contrast variance of objects as a vehicle approaches an intersection. This was compared to the contrast at which the objects were detected which helped understand the relationship between contrast and visibility (Chapter 4).

Chapter 2 – Effects of Intersection Lighting Design on Nighttime Visual Performance of Drivers

Abstract – Nighttime crashes at intersections present a major traffic safety issue in the United States. Providing lighting at intersections has been a successful countermeasure to reduce night crashes, yet current approaches to lighting design at intersections are based on recommending lighting levels. These recommended lighting levels stem from research conducted on the effect of intersection lighting on night crashes. This approach does not account for a driver's visual performance or the potential interactive effects of vehicle headlamps and roadway lighting. For effective design lighting at intersection, empirical research is required to evaluate the effects of lighting configuration (part of the intersection illuminated) and lighting levels on nighttime driver visual performance. The current study had two goals. First, to quantify visual performance in three lighting configurations (illuminating the intersection box, approach, or both). Second, 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 8 and 12 lux illuminance level. Visual performance was inferior in lighting configurations in which only the intersection approach or both the intersection approach and box were illuminated performed, and there was not consistent plateauing of visual performance in either condition. Increased performance with box lighting is argued as mainly a result of 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/rural intersections, specifically 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.

2.1 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 like pedestrian, bicyclists etc. For example in the United States, in 2013, intersection crashes constituted over 45% of number of crashes and 25% of the number of fatalities in the United States (NHTSA, 2014). Furthermore, night crashes and fatalities account for approximately 40% of the total crashes and fatalities at intersections (NHTSA, 2014). To safely navigate an intersection, drivers should, ideally, take into consideration a number of factors such as the presence of others 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 (Turner et al., 2006).

Lighting of intersections has received attention as a potential method for reducing the number of night crashes and related fatalities. Simply having lighting at intersections does appear to reduce the number of night crashes, by 13 to 45% (Bullough et al., 2013; Donnell et al., 2010; Isebrands et al., 2006; Smadi et al., 2011; Wortman & Lipinski, 1974), and an increase in illuminance level lowers night-to-day crash ratios and rates by roughly 7% (Bhagavathula et al., 2015) and 9% (Edwards, 2015), respectively. Furthermore, Oya et al. (2002) reported that a mean roadway illuminance of 20 lx or more is an effective countermeasure against crashes and mean road-surface illuminance of 30 lx results in a statistically significant reduction of night crashes. Minoshima et al. (2006) reported that a mean roadway illuminance of 10 lx or more is required to make the intersection more visible to drivers approaching intersections.

Intersection lighting has also been given a special consideration by both the Illumination Engineering Society of North America (IESNA) 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 IESNA), speed, traffic volume, and traffic composition (only CIE). Recommended light levels for intersections, though, differ substantially from those recommended for lighting of roadways. IESNA’s 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 (IESNA, 2005). CIE’s 115:2010 recommends that lighting level of the intersection should always be higher than the highest lighting level of the roads that form the intersection (CIE, 2010). Of note, these standards provide only recommended luminance (or brightness) and illuminance (light incident on the roadway) levels (CIE, 2010; IESNA, 2005) 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 night crashes. Both, the process of selecting the part of the intersection that is to be illuminated and the required level of illumination for an intersection are not 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 levels (Bhagavathula et al., 2015; Bullough et al., 2013; Donnell et al., 2010; Isebrands et al., 2006; Smadi et al., 2011; Wortman & Lipinski, 1974). Yet, studying the effect of roadway lighting on night crashes or related parameters only considers an extreme aspect 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 night crashes could lead to over-lighting of intersections, which could make the intersections less safe by introducing glare to drivers and reducing visibility; over-lighting would also result in energy wastage without any substantial benefits to visibility. Using crash metrics and a consensus-based approach to intersection lighting design also does not consider the role of human visual response, nor does it account for 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* (part of the intersection that should be illuminated) and the *illuminance level* at which the intersection should be maintained. To take into account human visual response, intersection lighting configurations (part of the intersection illuminated) and illuminance levels 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. Detection distance is commonly used a measure of visual performance in nighttime roadway visibility research (Bhagavathula & Gibbons, 2013; Edwards & Gibbons, 2008; Hills, 1975; Janoff, 1993; Shinar, 1985; Zwahlen & Schnell, 1999). 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 (Boyce, 1973; Eloholma et al., 2006; Rea, 2000; Terry & Gibbons, 2015). However, 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 illuminance level and possible interactive influences.

This study had two goals. The first was to evaluate different kinds of lighting configurations to determine the ones that offer the best visual performance. The second was to determine what illuminance 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 (Edwards & Gibbons, 2008; Hills, 1975); and (2) the benefit of increasing illuminance on visual performance will decrease (or plateau) at higher illuminance levels, consistent with the Adrian's (Adrian, 1989) Model and the Relative Visual Performance (RVP) model (Rea & Ouellette, 1991). Results from this work were intended to facilitate development of intersection lighting design standards (especially for those intersections located in isolated/rural areas) that will increase driver visual performance and consequently reduces nighttime crashes.

2.2 Methods

2.2.1 Participants

Twenty-four participants completed the study, and were recruited to form two age groups (younger and older), each of which was gender balanced. The younger group was comprised of 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 since human eyes undergo many physiological changes with age that result in several effects such as a decrease in visual acuity, a decrease in contrast sensitivity, an increase in dark adaptation time (Salvi, Akhtar, & Currie, 2006).

Participants were recruited from the Virginia Tech Transportation Institute 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 this, participants 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 that was administered by an Early Treatment Diabetic Retinopathy Study (ETDRS) chart with an illuminator cabinet. A minimum corrected visual acuity of at least 6/12 (20/40) was required; potential participants who did not meet this criterion were excluded. 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.

2.2.2 Experimental Design

A repeated measures experimental design was employed to investigate the effects of target location, intersection lighting configuration, and illuminance level 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 illuminance levels. Targets were located at multiple locations within and surrounding the intersection. This study was conducted at the intersection on the Virginia Smart Road at the Virginia Tech Transportation Institute (Figure 4). The Smart Road 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 to eliminate the confounding effect of signal phase timing on intersection approaches. Independent variables and the level used in the study are summarized in Table 4, with additional details below. In a given experimental session, participants encountered one lighting configuration, all five illuminance levels, and all target locations within each illuminance level. The remaining lighting configurations were encountered in subsequent sessions; this approach was used since changes in lighting configuration were relatively time consuming compared to changes in illuminance level and target location. Presentation orders of both lighting configuration and illuminance levels were counterbalanced across participants to reduce potential order-related confounding effects. Target location was randomized in a given combination of lighting configuration and illuminance level, with blanks (no target presentation) included as catch trials.

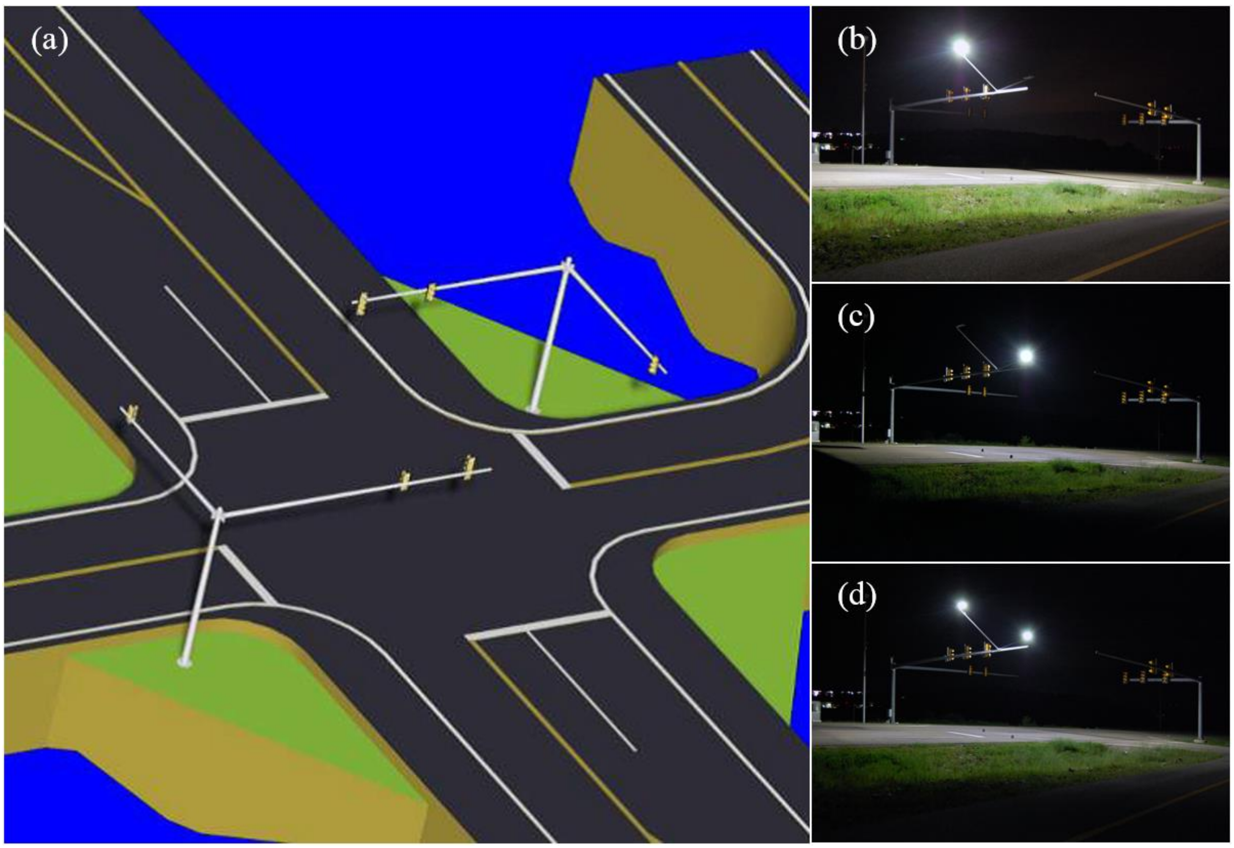

Figure 4. Diagram of the intersection on the Smart Road (a). The intersection is equipped with signal lights and lane markings associated with a typical signalized intersection. The intersection

could also be illuminated by three configurations, which illuminated the Approach (b), the Box (c) or the Approach and the Box (d)

Table 4. 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 Level	0 (no lighting), 8, 12, 16 and 21 lux

2.2.3 Independent Variables

Target Locations: A gray-colored wooden target, 18 x 18 cm, was used for the detection task, the same as targets used in earlier research on nighttime roadway visibility (Bhagavathula & Gibbons, 2013; Bhagavathula, Gibbons, & Edwards, 2012; Gibbons, Flintsch, Williams, Du, & Rakha, 2013; Gibbons et al., 2012; IESNA, 2005; Janoff, 1992; Janoff, 1993; Mayeur, Bremond, & Bastien, 2010). Five target locations were used (Figure 1), to cover several locations within/surrounding the intersection, more specifically the entrances and exits to pedestrian crosswalks. Targets were placed at a distance of 0.3 meters (one feet) from outside the right shoulder of the road at the intersection, so that it was contrasted against the roadway surface and not the pavement marker on the shoulder. Gray color was chosen for targets as it is a neutral color and will be rendered similarly under different lighting configurations and illuminance levels.

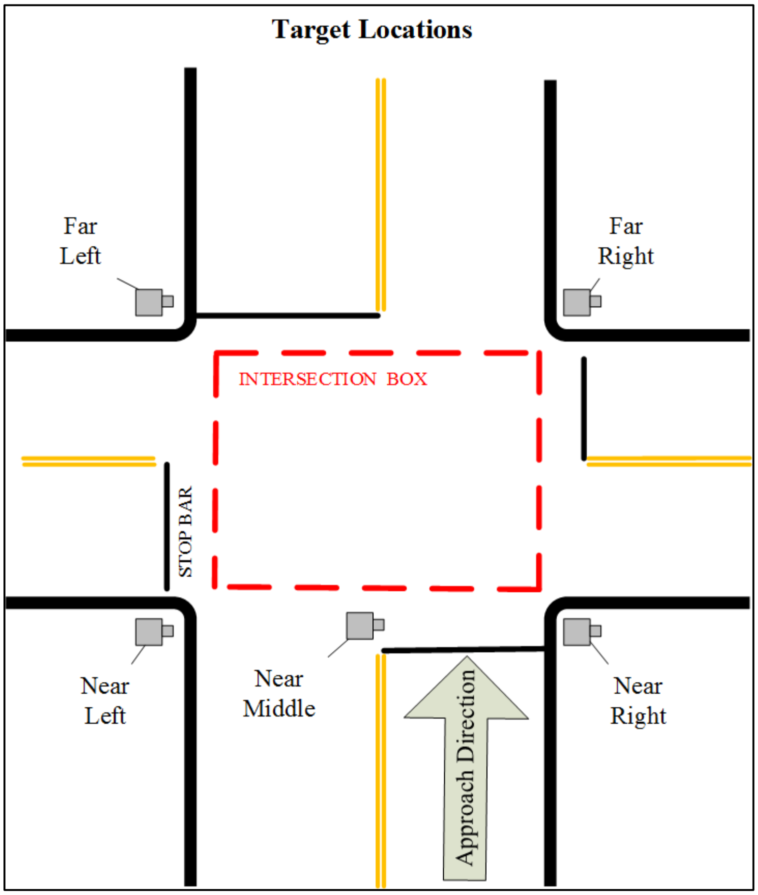

Figure 5. Overhead view of the intersection and the five target positions used.

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 4b and Figure 6a). In the second configuration (Box), the intersection box was illuminated (Figure 4c and Figure 6b). The third configuration (Approach and Box) had both the approach and box of the intersection illuminated (Figure 4d and Figure 6c). As well as assessing different lighting configurations, these alternatives also allowed for testing the effects of the two different kinds of contrast (positive and negative) of the target located at the near right and near middle target locations on the visual performance of drivers. Specifically, the Approach configuration rendered these targets in positive contrast, since the face of the target was brighter than the background (Figure 7a). The Box configuration rendered these targets in negative contrast, since the background was brighter than the face of the target and it appeared in silhouette (Figure 7b). In the Approach and Box configuration, target contrast will depend on the illuminance level.

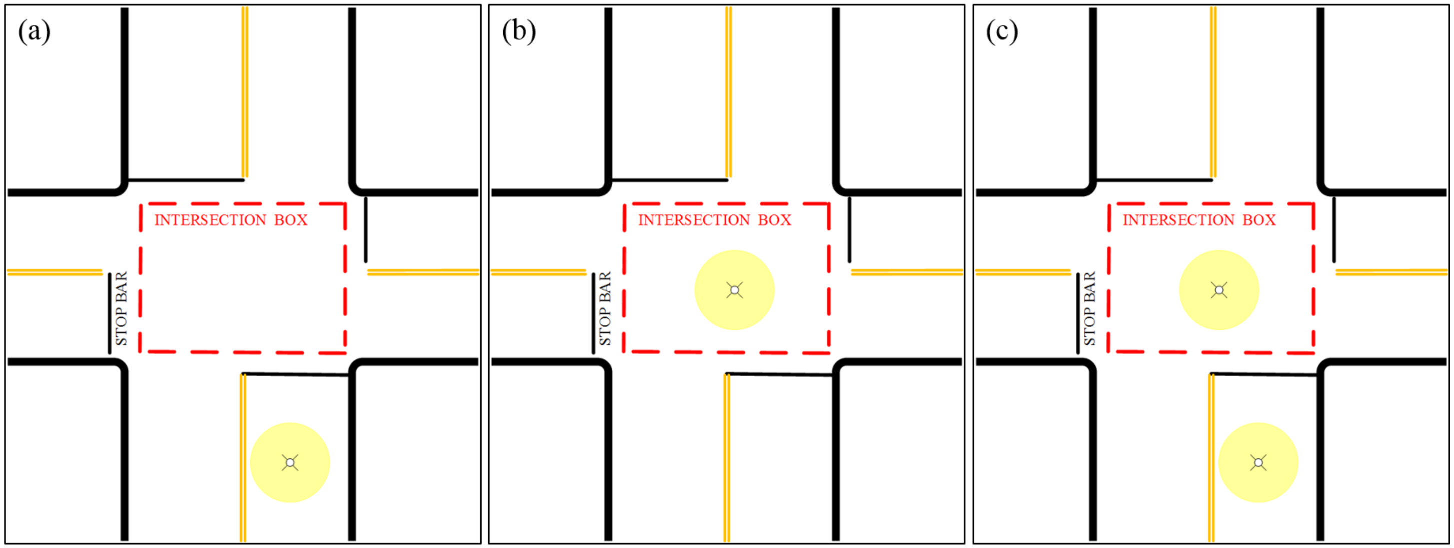

Figure 6. Illustrations of the three intersection lighting configurations: (a) Intersection approach is illuminated, (b) Intersection box is illuminated. (c) Both the box and approach are illuminated.

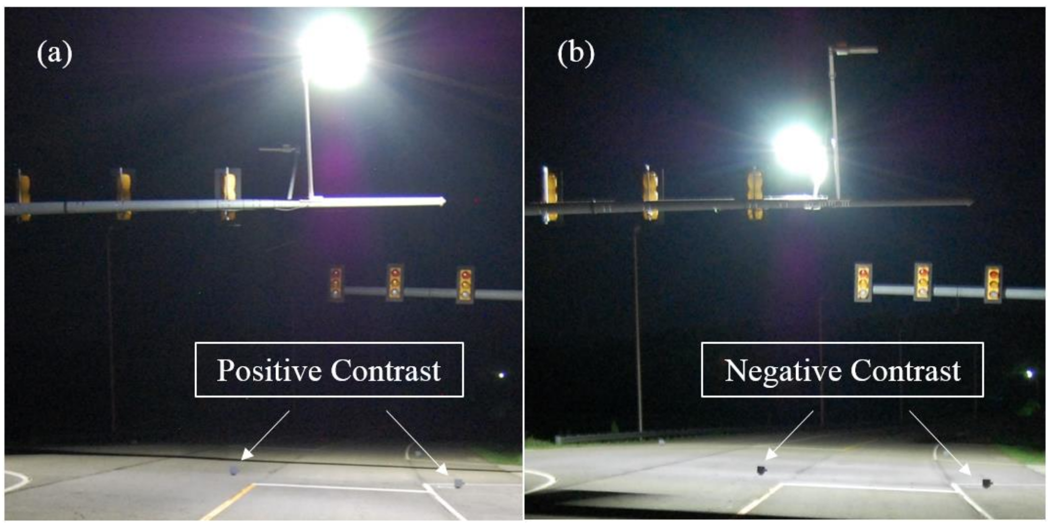

Figure 7. Near right and near middle target locations in positive and negative contrast in the Approach (a) and Box (b) lighting configurations.

Intersection Illuminance Levels: Two 4000 Kelvin light emitting diode (LED) luminaires were used for illuminating the intersection, and were mounted at height of 8.5 m. Luminaires used for illuminating the approach and the box were, respectively, type II and type V, and which had different light distribution patterns. Types II luminaires are 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 a circular light distributions with the same light intensity in all lateral directions (Murdoch, 2003). .

Five different illuminance levels were used, and intended to span a range of recommended values. The specific levels were 0 (no lighting), 8, 12, 16, and 21 lux, and were the horizontal illuminance levels measured at the near right target location on the intersection. The two lowest light levels (8 and 12 lux) are also the IESNA RP-8 recommended average illuminance levels at low nighttime pedestrian volume locations, such as those at rural/sub-urban areas (IESNA, 2005). The 16 and 21 lux levels are the IESNA RP-8 recommended average illuminance levels for high and medium pedestrian conflict areas at sub-urban and urban locations (IESNA, 2005). Since it was impossible to maintain the same illuminance level at every target location under different lighting configurations, only the near right target location was selected to match illuminance levels across the lighting configurations.

2.2.4 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 each experimental session for efficiency (see below). In the first experimental session, after arrival, 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 when they see a target. In the subsequent two experimental sessions, participants were given the choice to review the experimental protocol prior to starting the session. At all times during the driving portion of the study, an experimenter was in the vehicle with the participant. The experimenter was seated in the rear passenger seat of the experimental vehicle.

Two vehicles were used (1999 and 2000 Ford Explorers), which were instrumented with data acquisition systems (DAS) connected to the vehicles' controller area network (CAN) and on-board 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 study and were aimed before each experimental session. The headlamps used were Hella 90 mm Bi-Xenon projector lamps with a single 1-F capacitor-stabilized headlamp input voltage on each vehicle.

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 answered, 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 mi/h). Participants were also informed about where to stop and turn. After entering the Smart Road, participants completed two practice "laps" (see Figure 8), in which they practiced the target detection task (under the no lighting configuration). In each lap, the first participant would approach the intersection while the second would wait at the start 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 participated drove back to the start point and were instructed to be ready to begin the next lap.

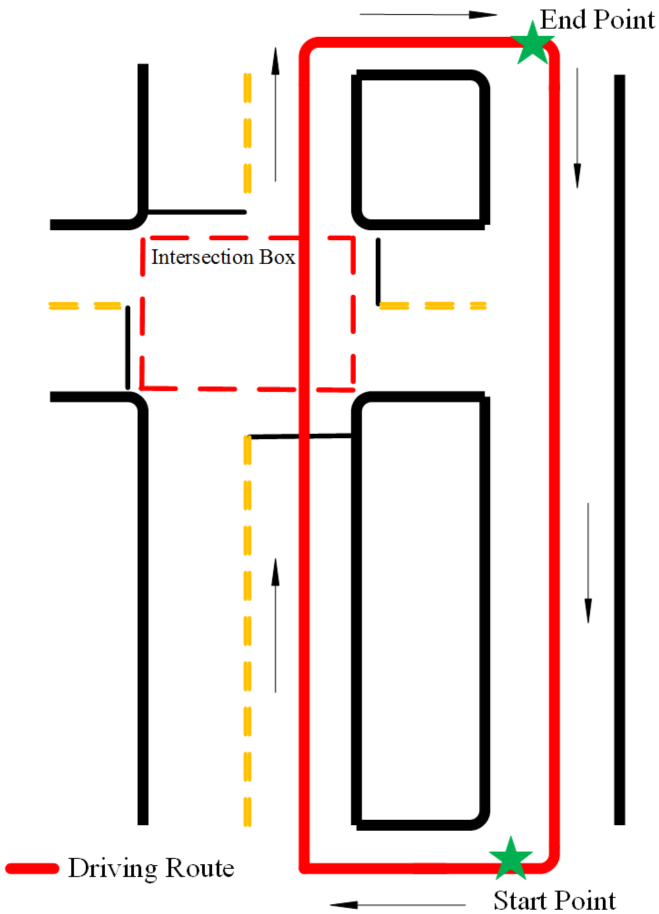

Figure 8. Overhead view of the Smart Road intersection. Participants completed several "laps" through the intersection, as indicated by the thick red rectangle.

Subsequently, participants approached the intersection six times for each illuminance level (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) by a button press in the data stream being recorded by the DAS. At the time the vehicle passed the target, the experimenter pressed another button. These button presses were used subsequently to calculate the detection distance, which was used as the dependent measure (i.e., using the DGPS coordinates at the point of detection between the car and the target). 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 8). After target presentation was completed for one illuminance level, an additional six approaches were completed for each of the remaining illuminance levels. These same procedures were repeated in the second and third sessions for the two other lighting configurations.

2.2.5 Analyses

A linear mixed model (LMM) analysis was used to assess the (fixed) effects of target location, lighting configuration, and illuminance level on detection distance. Age was included as a blocking factor. Based on preliminary analysis of LMM residuals, detection distances were square-root transformed to be more consistent with 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 (HSD) 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 level, mean detection distances across the five target were compared to the stopping sight distance ((AASHTO, 2011). Stopping sight distance is the length of the roadway required for a vehicle travelling at the "design speed" (here, 56km/h or 35 mph) to come to a stop, and is the distance travelled by the vehicle from the time a driver sees an object to the vehicle coming to a complete stop (sum of distance travelled 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/s^2 is assumed by AASHTO. 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.

2.3 Results

Out of 1560 target presentation across all participants, 130 were missed and were excluded from the LMM analysis. The percentage of misses depended on target location and lighting configuration. Participants missed 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, near left and far left target locations had the highest percentages of misses (Figure 9).

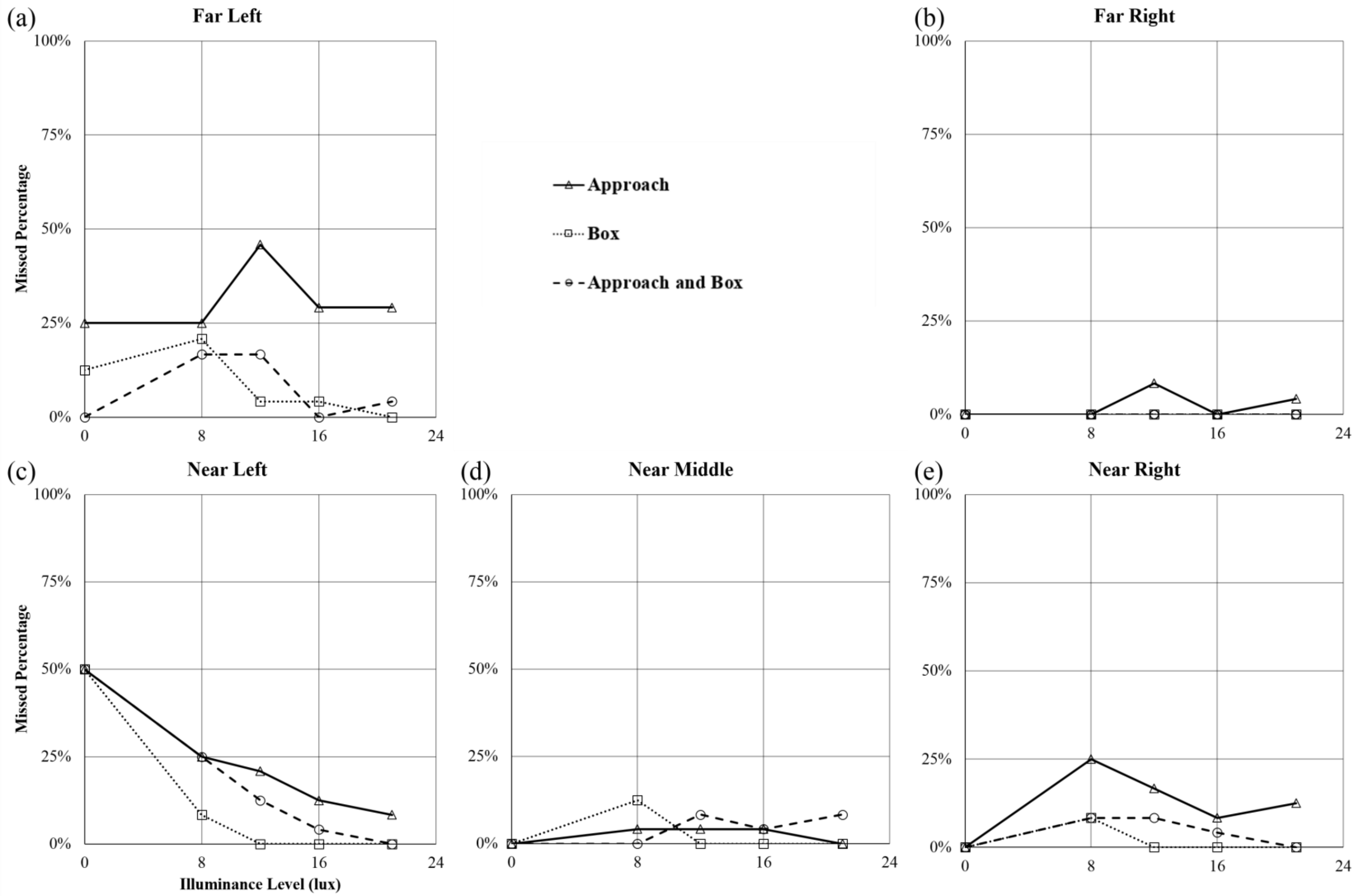

Figure 9. Percentage of missed targets by location and lighting configuration.

All LMM results are summarized in Table 5. All main effects were significant, along with several two-way interactions, and the three-way interaction of target location, lighting configuration and illuminance level. Subsequent subsections provide additional details on the results regarding age and lighting configuration, followed by the noted three-way interaction effect.

Table 5. Statistical results from linear mixed model analysis of detection distance. Significant effects are highlighted using bold text.

Effect	**Effect Size (η_p^2)**	***p* 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 x LC	**0.00**	**0.0417**
A x IL	0.00	0.6698
A x TL	0.00	0.4353
LC X IL	**0.05**	**<.0001**
TL x LC	**0.12**	**<.0001**
TL X IL	0.01	0.3504
A X LC x IL	0.01	0.1727
A x TL x LC	0.00	0.675
A x TL x IL	0.01	0.2071
TL x LC x IL	**0.03**	**0.0221**
A x TL x LC x IL	0.01	0.9906

2.3.1 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 10). 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 distances in these configurations, respectively. Simple effects of lighting configurations were also significant in both age groups, and in which detection distances were longest in the Box configuration and shortest in the Approach configuration

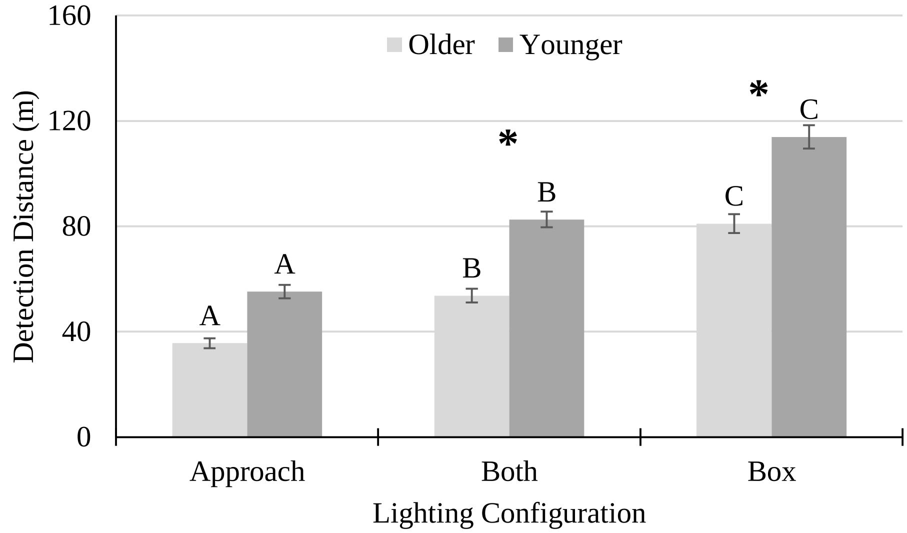

Figure 10. Effects of age and lighting configuration on detection distance. Values are means of detection distances and error bars indicate standard errors. Uppercase letter represent post-hoc groups between lighting configurations in each age group, and the symbol * indicates a significant difference between age groups in each lighting condition.

2.3.2 Interactive Effect of Target Location, Lighting Configuration and Illuminance Level

The combined effects of target location, lighting configuration, and illuminance level on detection distance are summarized in Figure 2. Two analysis approaches were used to further assess this three-way interaction effect, and 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 level for each target location, which focused on the differences between configurations and the consistency of these differences across illuminance levels and target locations. The second examined the effect of illuminance level on detection distance at each lighting configuration for each target location, and which was used to assess plateaus that were evident in detection distances with increasing illuminance levels.

2.3.3 Effect of Lighting Configuration

For every target location, detection distances were longest in the Box lighting configuration and shortest in the Approach configuration; this pattern of results was consistent for each of the illuminance levels. From simple effects testing, the effect of lighting configuration was significant at every illuminance level 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 level.

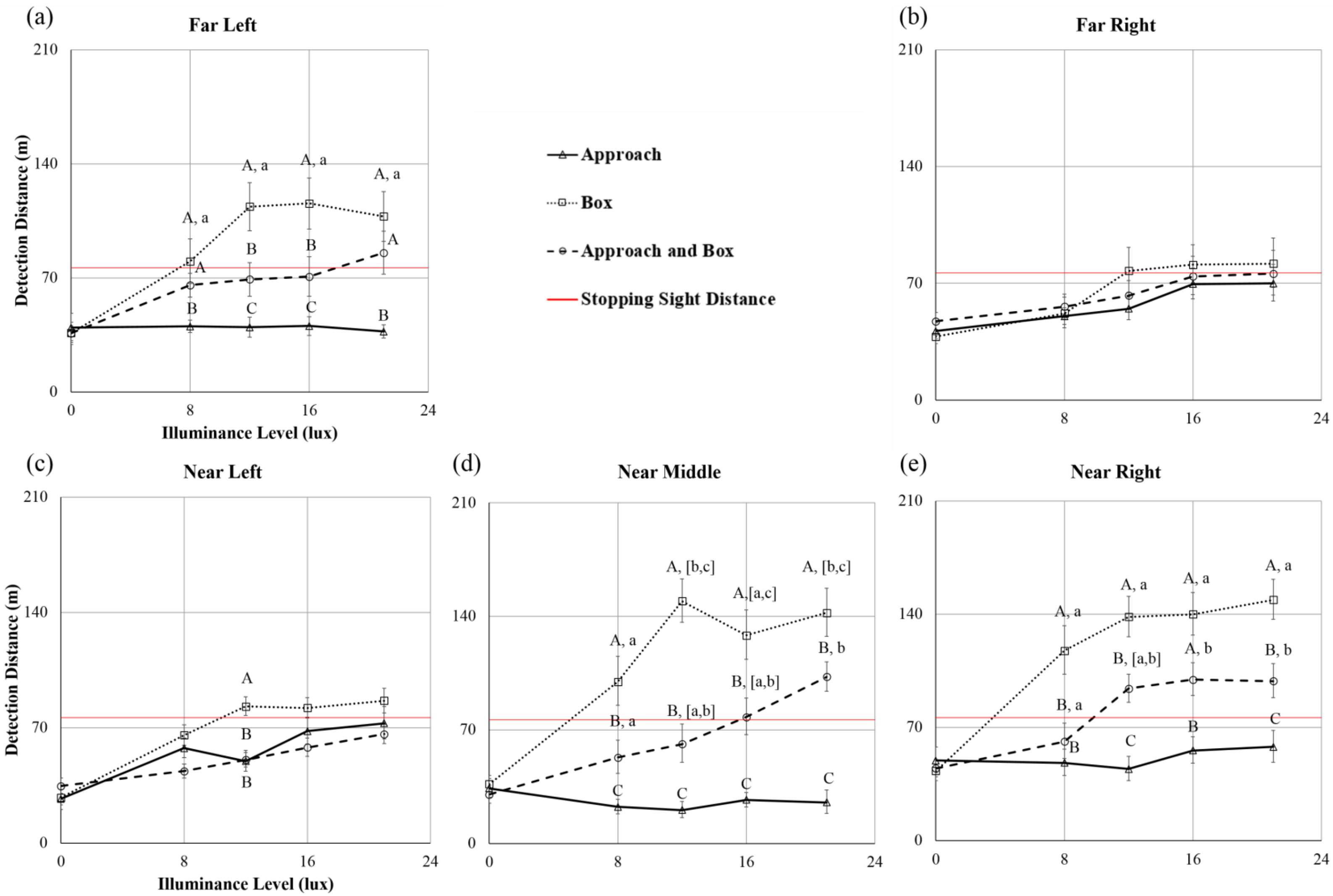

Figure 11. Interactive effects of lighting configuration and illuminance level at each target location. Values are means of detection distances and error bars reflect standard errors. Uppercase letters indicate post-hoc groupings (from paired comparisons) between lighting configurations at a given illuminance level, while lower case letters indicate such groupings between illuminance levels for a given lighting configuration. Horizontal red lines indicate the stopping sight distance at 56 km/h (35 mi/h).

Assessment of the post-hoc pairwise comparisons revealed the existence of significant differences in detection distances between the lighting configurations at every illuminance level and target location. For near right (Figure 11e), near middle (Figure 11d) and far left (Figure 11a) 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 level greater than 0 lux. For the near left target location (Figure 11c), pairwise comparisons were significant between the three lighting configurations only at the 12 lux illuminance level. No pairwise comparisons between lighting configurations were significant for the far right target location (Figure 11b). At every illuminance level, the Box lighting configuration had longer detection distances than the Both configuration by approxmimately 25 to 50% depending on the illuminance level and the Approach configuration by approximately 50 to 60% depending on the illuminance level.

2.3.4 Effect of Illuminance Level

There appeared to be an illuminance level at which detection distance plateaued within each lighting configuration and for every target location (see Figure 11). Simple effects testing revealed that illuminance level 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 level had a significant effect on detection distances in all three lighting configurations. At the far right target location, illuminance level 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 excepting the far right, though inconsistently across lighting configurations (Table 6). Four of the five target locations (except far right) had such a plateau in the Box lighting configuration. In the Approach and Both lighting configurations, only two and one target locations 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 level in the Box vs. the Approach and Box lighting configurations (Figure 11).

Table 6. Illuminance levels at which detection distance plateaus occurred or was not evident (based on paired comparisons) for each combination of target location and lighting configurations at each.

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

2.3.5 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 11). 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 illuminance levels: 12, 16 and 21 lux. In the Approach configuration, only the near left and far right target locations at the highest illuminance level (21 lux) had mean detection distances greater than the stopping sight distance (Figure 11). In the Both lighting configuration, the following target locations had mean detection distances greater than the stopping sight distance (Figure 11): 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).

2.4 Discussion

The goals of this study were to determine whether a driver's visual performance, measured using a target detection task, differs between three intersection lighting configurations and to identify the illuminance level 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. Second, the effect of illuminance level 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 the younger participants having better visual performance (longer detection distances) than older participants.

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 level and target location. Second, 90% of target locations 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 in which the targets locations were rendered. Generally, the visibility of objects at nighttime depends on their contrast with the relevant background (Edwards & Gibbons, 2008; Pretto & Chatziastros, 2006). With respect to intersection, target contrasts are affected by the lighting configuration (part of the intersection illuminated) and the headlamps of the vehicle. 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 level greater than 0 lux. This finding implies that negative contrast on targets results in better nighttime visual performance than positive contrast. Such a result is consistent with work reported by Aulhorn (1964) and Hills (1975), who showed that objects in negative contrast were detected faster and from farther than those in positive contrast. The contrast polarity (negative/positive) of the near right and near targets in the Both lighting configuration depended on the illuminance level, since both the area in front of and behind the target locations were illuminated, and 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 of driver in a moving vehicle. 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 illuminate the face of the target to be brighter than the background. Headlamps, though, only generate a substantial influence at distances less than 100 meters to the target (Edwards & Gibbons, 2008). Our results indicated that the negatively contrasted targets in the Box lighting configuration had mean detection distances > 100 meters even at the 8 lux illuminance level, whereas the positively contrasted targets in the Approach lighting configuration had mean detection distances well under 100 meters at the highest illuminance level 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 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 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, likely caused the far left target to have a higher contrast compared to the far right target location where the background luminance was higher (Figure 12). However, a photometric analysis is again required to confirm this speculation.

Figure 12. Photo of the intersection, illustrating background luminance values at the far left and far right target locations.

The far left target location had a lower number of missed detection than near left target location. This was not expected since both the locations were on the left hand side of the road. This result could be attributed to far left target location having a darker background than the near left target location, by virtue of its position at the intersection. Specifically, the background of the near left target location consisted of the pavement, whereas the background of the far left target location consisted of the area beyond the pavement which was darker than the pavement. The lower contrast on the near left target location could have made it harder for the participants to detect it. Because of the darker background luminance, the far left target location could have had a higher contrast, making it relatively easier to detect in the no lighting condition.

Increases in illuminance level generally resulted in increased visual performance, consistent with earlier evidence on the effects of illuminance level on visual performance (Boyce, 1973; Eloholma et al., 2006; Terry & Gibbons, 2015). Of these three noted studies, though, only the one by Terry and Gibbons (2015) used target detection distance as measure of visual performance, which was evaluated at 10 incremental illuminance levels in a real driving scenario and showed that an increase in illuminance level resulted in an increase in detection distance. However, their study did not explore the relationship between illuminance level and potential plateaus in visual performance. 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 level (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. In the Box lighting configuration, though, all targets locations had mean detection distances longer than the safe stopping distance at an illuminance level of ≥12 lux. 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 level.

Comparison of illuminance levels 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 (excepting the far right target), and this plateau was consistently at the 8 or 12 lux illuminance levels. 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, it varied between 16 and 21 lux. The lack of evidence of such plateaus in either the Both or Approach lighting configurations suggests that higher illuminance levels than tested are required to attain maximal visual performance.

The effect of illuminance levels on intersection visibility in this study did not completely align with earlier results on intersection visibility. Minoshima et al. (2006) 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 illuminance level greater than 12 lux. In both the Approach and Both lighting configurations, and even at highest illuminance level (21 lux), none of the targets had mean results that were shorted that 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. (2006) used subjective ratings of intersection visibility.

Age clearly influenced visual performance, with older group having shorter detection distances, and consistent with existing research on detection distances of targets and pedestrians that also found older drivers to have shorter detection distances (Bhagavathula & Gibbons, 2013; Terry & Gibbons, 2015) . A decrease in visual performance among the older participants is likely consequent to age-related physiological changes in the eyes that leads to reduced visual acuity and contrast sensitivity (Salvi et al., 2006). 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.

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 minimum safe stopping distance at 56 km/h (35 mi/h). Additionally, the longer detection distances in the Box lighting configuration could also be underestimated as the other lighting configurations had higher numbers of missed detections. The higher missed detections indicate that the actual differences in visual performance is likely higher than what is measured using detection distances. 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 they are approaches at the intersection. A plateau in visual performance plateau was also evident for the Box lighting configuration, attained between 8 and 12 lux depending on the target location. With the Box illuminated, increases in the illuminance level beyond 12 lux are thus not likely to substantially increase driver visual performance at an intersection. 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 as 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 used to facilitate potential energy savings. Finally, this study used high-intensity discharge headlamps on the experimental vehicles. This should not have an impact on generalizability of the results, though, as past research has shown that in the presence of overhead lighting the color or the intensity of the headlamps does not substantially affect detection or recognition distances (Gibbons et al., 2015).

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 used 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 additional confounding effects of glare, which could also have affected the illuminance levels and target contrasts. The current experimental design was intended to isolate visual performance so that intersection lighting configurations and illuminance levels 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 illuminance levels. Third, the results of this study are mainly applicable to isolated or rural intersections, which do not have continuous roadway lighting on any of the intersecting roads and which are illuminated by single luminaires. Furthermore, when Approach and Both lighting configurations are used, all the approaches leading to intersection are illuminated. The latter could impact the visibility of objects located at the pedestrian-vehicle conflict locations, since the contrasts in which they are rendered also changes. While the presence of additional luminaires might increase light levels at intersections, the change in object contrasts would hard to determine in advance (without a photometric analysis) since they will be illuminated from multiple directions. Fourth, current findings are applicable to roadway surface paved with asphalt. Use of alternative roadway surfaces such as concrete and darker asphalt mixtures could change the contrast in which targets are rendered and thereby affect their visibility. For example, concrete pavement surfaces are lighter and might need lower levels of illuminance to render a target in the same contrast compared to an asphalt surface. 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.

In conclusion, driver nighttime visual performance at an intersection is clearly influenced 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 level (other than no lighting). With the Box lighting configuration, visual performance also plateaued between 8 and 12 lux (depending on target location); beyond this level additional increases in illuminance level did not result in significant increases in visual performance. 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, and the influences of lighting configuration and illuminance level were generally consistent between the two age groups studied. These findings have important implications for lighting design of intersections, especially those at isolated/rural areas. Our results suggest that illuminating the intersection box can increase visual performance for the nighttime driver and could be an energy efficient solution.

Chapter 3 – Effect of Intersection Lighting Design on Perceived Visibility and Glare

Abstract: A systems level approach to intersection lighting design has shown that illuminating the intersection box increases drivers' nighttime visual performance. However, for an intersection lighting design to be effective and accepted, it should not only maximize visual performance but also enhance perceived visibility and minimize glare. The goals of this study were to assess the effects of intersection lighting design on perceived visibility and glare. Visibility was assessed in three areas: pedestrian, target and intersection. Perceptions of visibility and glare were measured using Likert scales, with participants exposed to multiple lighting designs on a realistic intersection. Twenty-four participants with equal number of younger (18-35 years) and older (65+) drivers completed the study. The lighting design that illuminated the intersection box had the highest levels of perceived target and intersection visibility and the lowest ratings of glare. Although this configuration did not have highest ratings of pedestrian visibility, mean ratings exceeded the "neutral" anchor. For the same lighting configuration, a strong positive correlation was also found between perceived target visibility and earlier results on target detection distances. In this configuration, perceived visibility plateaued at between 8 and 12 lux illuminance levels. Increased levels of perceived visibility in different conditions were likely a result of size and contrast differences and the distribution of the luminaires used. These results indicate that illuminating the intersection box has multiple benefits, in that it not only increases visual performance but also increases perceived visibility and reduces glare while requiring fewer luminaires.

3.1 Introduction

Night crashes at intersections pose a major safety concern in the United States, as they account for about 40% of the total crashes at intersections (NHTSA, 2014). Installing lighting at intersections has been used a successful countermeasure against night crashes. For example, lighting an intersection has reduced night-to-day crash ratios and rates by 13 to 45%, respectively (Bullough et al., 2013; Donnell et al., 2010; Isebrands et al., 2006; Smadi et al., 2011; Wortman & Lipinski, 1974), and an increase illuminance levels has been associated with respective decreases in night-to-day crash ratios and rates of 7% (Bhagavathula et al., 2015) and 9% (Edwards, 2015). As discussed earlier (see Chapter 2), however, existing recommendations and guidelines for the design of intersection lighting have focused solely on lighting levels and stem from research relating lighting to night crashes at intersections. This has ignored the role of human vision in intersection lighting design as well as the interactive effect of vehicle headlamps and overhead lighting. Furthermore, existing standards (Illumination Engineering Society of North America and the Commission Internationale de l'Éclairage) prescribe minimum lighting levels to be maintained within the intersection box (area enclosed within the stop bars at the intersection), which does not account for the multiple pedestrian – vehicle conflict points at intersections.

A new systems level approach to intersection lighting design was introduced in Chapter 2 (intersection lighting design refers to both the part of the intersection illuminated and the recommended illuminance level). In that, three intersection lighting designs were evaluated. This was done on the basis of drivers' nighttime visual performance, by objective measures of detection distances for targets located at the entrances, exits, and middle of pedestrian crosswalks at intersections. The results indicated that the design that illuminated the intersection box offered better visual performance and had fewer number of missed target detections. However, for an intersection lighting design to be effective and accepted it should not only increase a driver's visual performance but also increase perceived visibility and reduce glare. Furthermore, pedestrian visibility is also important, since, as noted, existing intersection lighting designs do not account for pedestrian-vehicle conflict locations. Finally, it is important to know if intersection lighting configuration that resulted in enhanced detection (longer target detection distances) are also perceived as having high visibility and low glare.

Past research on roadway visibility has shown that perceived visibility is associated with nighttime driver visual performance. Gallagher, Koth, and Freedman (1975) showed that a visibility metric based on subjective ratings was a strong predictor of driver visual performance. Janoff et al. (1977) also showed that subjective ratings of visibility can serve as a predictor of nighttime crashes. Janoff (1989) studied the relation between subjective ratings of visibility and a Visibility Index (VI). The VI is a measure of visibility and is dependent on contrast, relative contrast sensitivity, and disability glare. Their results indicated that VI is highly correlated with subjective ratings of visibility and that both the size of the object involved and the contrast affect the relationship between subjective ratings of visibility and VI. An increase in lighting level was also found to be associated with an increase in subjective ratings of visibility. Increase in lighting level has also been associated with increase in the perceived ratings of glare (Alferdinck & Varkevisser, 1991; Schmidt-Clausen & Bindels, 1974; Sivak, Simmons, & Flannagan, 1990; Theeuwes, Alferdinck, & Perel, 2002).

However, only one existing report has examined the effect of intersection lighting design on subjective ratings of visibility. In this work (Minoshima et al., 2006), subjective ratings of visibility were obtained from drivers who were exposed to three different intersection lighting layouts (or configurations) each with three levels of illumination (5, 10 and 15 lux). The three intersection layouts were based on the part of the intersection that was illuminated, and used the following three configurations: approach, corner (or box), and both approach and corner. Drivers rated five statements: "danger to pedestrian", "ease of driving", "brightness" and "safety" on a Likert-type scale (1 to 5) and a mean rating higher than 3 (or "neutral" anchor the Likert-type scale) was used as measure of effectiveness of an intersection lighting design. In this study, increases in illuminance levels resulted in higher subjective ratings of visibility. With illuminance levels higher than 10 lux, mean ratings of pedestrian visibility were higher than 3 on the Likert-type scale in all three layouts. Minoshima et al.)2006) also found that ratings (all statements including pedestrian visibility) depended on the illuminance level. At the 15 lux illuminance level, the lighting configuration that illuminated the approach and corner was rated highest, while at the 10 and 5 lux illuminance levels the configuration that illuminated the approach was rated the highest. The authors concluded that the approach lighting layout should be used to maintain a mean roadway surface luminance of 10 lux, but if a higher level of average roadway illuminance is needed then both approach and corner illumination should be used. However, this study did not measure perceived glare. Furthermore, only mean ratings were presented and no statistical analyses were reported regarding differences between lighting configurations or illuminance levels. The specific age ranges of participants were also not described, other than that an unbalanced sample of "elder" (n=5) and "non-elder" (n=15) individuals were included. Thus, there is need for additional research that considers the perception of glare as well as more formally quantifying differences in perceived visibility with different intersection lighting designs.

This study assessed the effects of different intersection lighting configurations and illuminance levels on perceived visibility and glare. Visibility was assessed here in three areas: pedestrian visibility, target visibility, and intersection visibility. It was hypothesized that: (1) perceived visibility and glare will differ between the three lighting configurations and between ratings of pedestrians and target areas, similar to results reported by Janoff (1989); and (2) increasing illuminance level will result in higher perceived visibility, also as reported by Janoff (1989) and Minoshima et al. (2006) and higher perceived glare as supported by existing research in the area (Alferdinck & Varkevisser, 1991; Schmidt-Clausen & Bindels, 1974; Sivak et al., 1990; Theeuwes et al., 2002). Results from this study were intended to supplement earlier results regarding visual performance (Chapter 2), and to determine whether intersection lighting designs that result in better visual performance also lead to improved visibility and lower glare.

3.2 Methods

This study was performed in conjunction with the work reported earlier (Chapter 2) and used many of the same methods. Therefore, this chapter only provides a summary of the methods used, and the reader is referred to earlier chapter for further details. Twenty-four participants completed the study, and were recruited to form two age groups – younger (M = 30.8 years, SD = 2.7) and older (M = 68.2 years, SD = 1.6) – with same number of male and female participants in each group. The selected age groups were intended to account for a wide range of driving experiences and visual capabilities. All participants had a valid US driver's license and a minimum visual acuity of 6/12 (20/40). Participants' visual acuity was assessed using a basic visual acuity test, which was administered using an Early Treatment Diabetic Retinopathy Study (ETDRS) chart with an illuminator cabinet. Experimental sessions were conducted on three separate nights, after an initial screening session. Participants were compensated $30 per hour for their participation. All experimental protocols were approved by Virginia Tech Institutional Review Board, and all participants provided written informed consent prior to any data collection.

3.2.1 Experimental Design

The effects of intersection lighting configuration and illuminance level on participants' perceptions of pedestrian visibility, target visibility, intersection visibility, and glare were evaluated using a repeated measures factorial design. Participants were exposed to both fixed targets and a simulated pedestrian, under multiple lighting configurations and illuminance levels at a realistic roadway intersection. This intersection was on the Virginia Smart Road, located at the Virginia Tech Transportation Institute. The Smart Road is a controlled access roadway research facility built to United States Federal Highway Administration specifications, and the intersection is fully functional, two-lane, four-way, and signalized (Figure 13a). Participants encountered each of three lighting configurations, in separate data collection sessions on different nights, and five illuminance levels within each lighting configuration. Data collection occurred only on clear nights (no rain, snow or fog) and after civil twilight. The order of presentation of lighting configurations and illuminance levels was counterbalanced to minimize order effects. The locations at which the targets were presented was also randomized, with catch trails included (no target presentation).

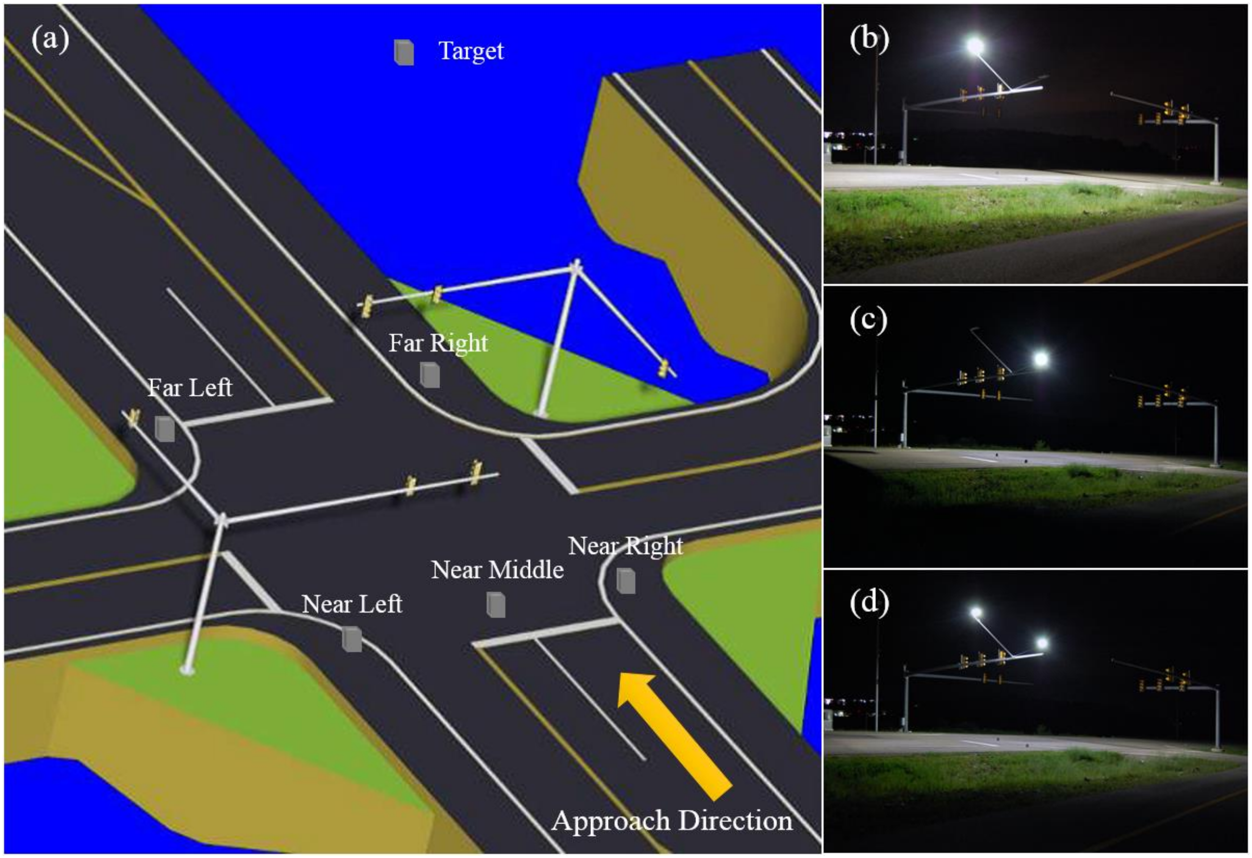

Figure 13. Diagram of the intersection on the Virginia Smart Road with target locations indicated (a). The intersection is equipped with signal lights and lane markings. The intersection could also be illuminated by three separate lighting configurations, which illuminated the intersection approach (b), the intersection box (c), and both the intersection approach and box (d).

Targets:

Targets were used to evaluate roadway visibility; these were of grey color and 18 x 18 cm in size, similar to ones used in earlier work (Bhagavathula & Gibbons, 2013; Bhagavathula et al., 2012; Gibbons et al., 2013; Gibbons et al., 2012; IESNA, 2005; Janoff, 1992; Janoff, 1993; Mayeur et al., 2010). Targets were located 0.3 meters (one foot) outside the right shoulder of the road. Five target locations were used in the study (see Figure 13a), as described earlier, and were located at the entrances, exits, and the middle of the crosswalks located at the intersections.

Pedestrian:

A simulated pedestrian was achieved using a member of the experimental team (stature = 177 cm), and was clothed in gray medical scrubs (Figure 14). A gray color was chosen because it is a neutral color and would be rendered similarly under different lighting configurations and illuminance levels.

Figure 14. Simulated pedestrian, wearing gray medical scrubs

Intersection Lighting Configurations:

Three intersection lighting configurations were used. In the first, or Approach lighting, the approach to the intersection was illuminated (Figure 13b). In the second configuration (Box), the intersection box was illuminated (Figure 13c), while the third configuration (Approach and Box or Both) illuminated both the approach and box (Figure 13d). These lighting configurations also render an object (Target or Pedestrian) located at the near right, near middle and near left target locations in different contrasts for an approaching driver. The Approach configuration rendered objects in these locations in positive contrast, whereas the Box configuration rendered them in negative contrast. Contrasts of the near right, near middle and near left targets in the Both lighting configuration depended on the illuminance level. The remaining two target locations (far right and far left) always appeared in positive contrast, as their face was always brighter than the background by the virtue of their location with respect to the lighting configurations.

Intersection Illuminance Levels:

Illumination was provided by two 4000 Kelvin light emitting diode (LED) luminaires that were mounted at a height of 8.5 m (28 ft.). One luminaire was used to illuminate the intersection approach and the other illuminated the intersection box. The former luminaire had a type II distribution, while the one illuminating the intersection box had a type V distribution. Each lighting configuration was illuminated to five illuminance levels, specifically 0 (no lighting), 8, 12, 16, and 21 lux. These levels corresponded to the horizontal illuminance levels at the pedestrian/near right target location and were selected so that they could be could be obtained in all three lighting configurations. Illuminance levels used were based on the IESNA RP-8 recommended average illuminance levels for pedestrian volumes areas (low, medium and high) at rural, sub-urban, and urban areas (IESNA, 2005).

3.2.2 Experimental Procedure

Experimental procedures are very similar to those used in the noted in the previous chapter (see Chapter 2). Two participants were scheduled for each experimental session, and upon arrival they initialed the informed consent and were provided with an overview of the experimental session by an experimenter in one of the vehicles used (Ford Explorers, model years 1999 and 2000). This overview included a presentation of images of the targets and pedestrian they would be seeing on the road and an explanation of how to provide ratings using questionnaires (described below). Participants performed two separate tasks in each of the three data collection session (see Figure 15). The first was a target detection task, in which participants detected targets and their detection distances were measured (see Chapter 2). The second task was the questionnaire rating, in which participants rated the intersection lighting configuration and the illuminance level with a simulated pedestrian standing at the intersection.

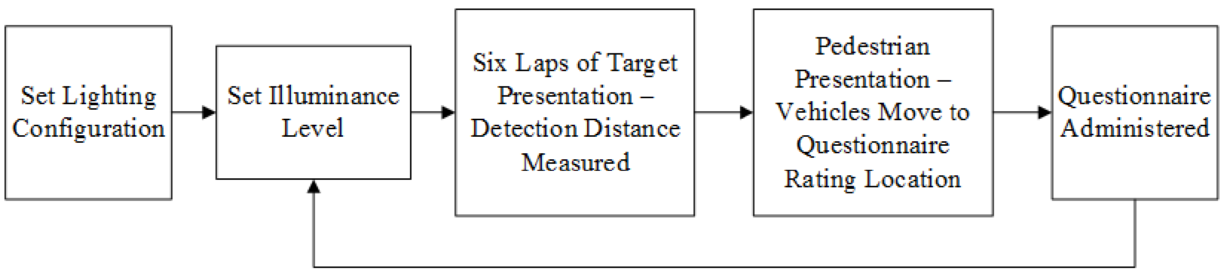

Figure 15. Sequence of events that occurred in each experimental session.

Participants approached the intersection six times for each illuminance level and lighting configuration, during which they performed the noted target detection task. The speed limit for the detection task was 56 km/h (35 mi/h). Before starting the target detection task, participants were asked to remember how that particular combination of lighting configuration and illuminance level affected their perception of target visibility (the questionnaire contained specific statements about target visibility).

Questionnaire rating task was started after completing all target detections for a given illuminance level. Both participants were first asked to drive to the location in the intersection approach marked by a cone (see Figure 16). Both the experimental vehicles were parked next to each other, with the second vehicle's headlamps turned off. This was done for efficiency, allowing both participants, in the two vehicles, to rate the questionnaires in parallel. The cone (Figure 16) was located 76.2 m (250 ft.) from the location of the simulated pedestrian, who stood in the right shoulder at the entrance to the nearest crosswalk and always faced the roadway (Figure 16). This specific distance was used, as it is the stopping sight distance for the "design speed" of 56 km/h (35 mi/h) (AASHTO, 2011), or the distance along the roadway required for a vehicle travelling at the design speed to come to a complete stop.

Once both the experimental vehicles were parked at the cone facing the intersection with the pedestrian, they were administered a questionnaire by the in-vehicle experimenter. Participants rated their level of agreement with several statements, using a custom questionnaire developed for this study (Figure 17). There were a total of 10 statements, assessing four areas – Pedestrian Visibility, Target Visibility, Intersection Visibility, and Glare – with responses obtained using a Likert Scale. Pedestrian Visibility (statements 1 and 7) and Target Visibility (statements 2 and 6) were each assessed using two statements, while Intersection Visibility (statements 4, 9 and 10) and Glare (statements 3, 5 and 8) were assessed with three statements each. After completing the questionnaire, participants travelled back to the starting point and prepared for the next trial, at the next illuminance level. The same protocol was repeated in the second and third data collection sessions, using the other two lighting configurations.

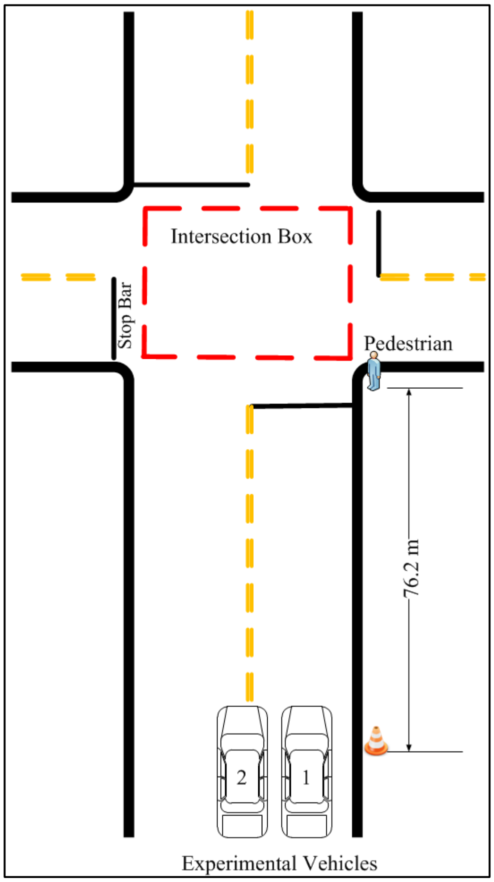

Figure 16. Pedestrian and experimental vehicle locations when the questionnaire was administered

Please indicate how much you agree or disagree with each of the following statements with respect to the current lighting level (please the check the appropriate box)

No	Statement	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
		1	2	3	4	5
1	The pedestrian is clearly visible					
2	All targets were seen from a safe distance					
3	I experienced glare when approaching the intersection					
4	It was easy to drive through the intersection					
5	Glare from the overhead lighting is affecting my ability to see the pedestrian					
6	All targets were clearly visible					
7	I can easily see the pedestrian					
8	Glare from overhead lighting is affecting my ability to detect targets					
9	All the roads leading to the intersection are clearly visible					
10	Intersection is clearly visible					

Figure 17. Likert scale questionnaire used for subjective ratings of pedestrian visibility, target visibility, intersection visibility, and glare

3.2.3 Analyses

Inter-item reliability of the questionnaire responses was assessed using standardized Cronbach's alpha value for each of four assessment areas. Additional analyses were only conducted when Cronbach's alpha was > 0.7, indicating that there was a high level inter-item reliability in the questionnaire statements for a particular assessment area (Nunnally & Bernstein, 1994). Standardized Cronbach's alpha values for each assessment area are shown in Table 7. Given this high level of reliability, composite Likert scores were calculated for each assessment area, as mean ratings across multiple statements in each assessment area. These composite scores were used as the dependent measures.

Table 7. Standardized Cronbach's alpha values for the questionnaire responses in each of the four assessment areas

Assessment Area	Standardized Cronbach's Alpha
Pedestrian Visibility	0.95
Target Visibility	0.94
Intersection Visibility	0.85
Glare	0.78

Separate linear mixed models (LMM) were used to assess the effects of lighting configuration and illuminance levels on composite scores in each of the four assessment areas (pedestrian visibility, target visibility, intersection visibility, and glare). Age group was used as a blocking variable. Preliminary analyses indicated that no main or interactive effects involving gender were significant. Thus, gender was not included in the final models. For all statistical tests, the significance level was established at $p < 0.05$. Where relevant, *post hoc* pairwise comparisons were performed using Tukey's honestly significant difference (HSD) for main effects, and simple effects testing was used to examine significant interaction effects. As in the approach used by Minoshima et al. (2006), a particular lighting configuration and illuminance level was considered effective only when the mean visibility ratings (Pedestrian, Target and Intersection) were > 3 (i.e., "Agree" or "Strongly Agree") and mean Glare ratings were < 3 (i.e., "Disagree" or "Strongly Disagree"). Additionally, Pearson product-moment correlation coefficients were determined separately in each of the three lighting configurations to assess the association between target detection distance (from the visual performance experiment in Chapter 2) and the composite score of perceived target visibility.

3.3 Results

The LMM results of Likert-scale composite scores of pedestrian visibility, target visibility, intersection visibility, and glare are summarized in Table 8. Both lighting configuration and illuminance level had significant main effects on all scores, excepting the effect of illuminance level on glare, for which there was a significant interactive effect. For target visibility and intersection visibility, the interaction between lighting configuration and illuminance level approached significance. Results for each of these assessment areas are presented in more detail in the following sections.

Table 8. Statistical results from linear mixed model analysis of the effects of age, lighting configuration, and illuminance level on composite scores of pedestrian visibility, target visibility, intersection visibility, and glare. Significant effects are highlighted using bold text.

Effect	Pedestrian Visibility	Target Visibility	Intersection Visibility	Glare
Age (A)	$F_{(1,22.4)} = 3.8$, $p = 0.064$	$F_{(1,23)} = 0.1$, $p = 0.752$	$F_{(1,22.7)} = 0.25$, $p = 0.620$	$F_{(1,22.4)} = 0.43$, $p = 0.517$
Lighting Configuration (LC)	**$F_{(2,115)} = 5.63$, $p = 0.005$**	**$F_{(2,118)} = 20.3$, $p < 0.001$**	**$F_{(2,118)} = 14.12$, $p < 0.001$**	$F_{(2,106)} = 1.63$, $p = 0.200$
Illuminance Level (IL)	**$F_{(4,220)} = 82.07$, $p < 0.001$**	**$F_{(4,218)} = 21.42$, $p < 0.001$**	**$F_{(4,218)} = 77.95$, $p < 0.001$**	**$F_{(4,220)} = 14.84$, $p < 0.001$**
A x LC	$F_{(2,115)} = 0.97$, $p = 0.383$	$F_{(2,118)} = 1.35$, $p = 0.263$	$F_{(2,118)} = 0.74$, $p = 0.480$	$F_{(2,106)} = 1.04$, $p = 0.358$
A x IL	**$F_{(4,220)} = 2.43$, $p = 0.048$**	$F_{(4,218)} = 1.15$, $p = 0.332$	$F_{(4,218)} = 0.49$, $p = 0.741$	$F_{(4,220)} = 0.75$, $p = 0.562$
LC x IL	$F_{(8,236)} = 1.49$, $p = 0.163$	$F_{(8,236)} = 1.96$, $p = 0.053$	$F_{(8,236)} = 1.96$, $p = 0.052$	**$F_{(8,238)} = 2.33$, $p = 0.02$**
A x LC x IL	$F_{(8,236)} = 0.73$, $p = 0.666$	$F_{(8,236)} = 1.83$, $p = 0.073$	$F_{(8,236)} = 1.7$, $p = 0.099$	$F_{(8,238)} = 0.62$, $p = 0.762$

3.3.1 Pedestrian Visibility

Subjective ratings of pedestrian visibility were higher for the Approach and Both vs. the Box lighting configuration (Figure 18). The difference between age groups approached significance, with younger participants (M = 3.84, SD = 1.13) providing higher composite scores than older participants (M = 3.14, SD = 1.36).

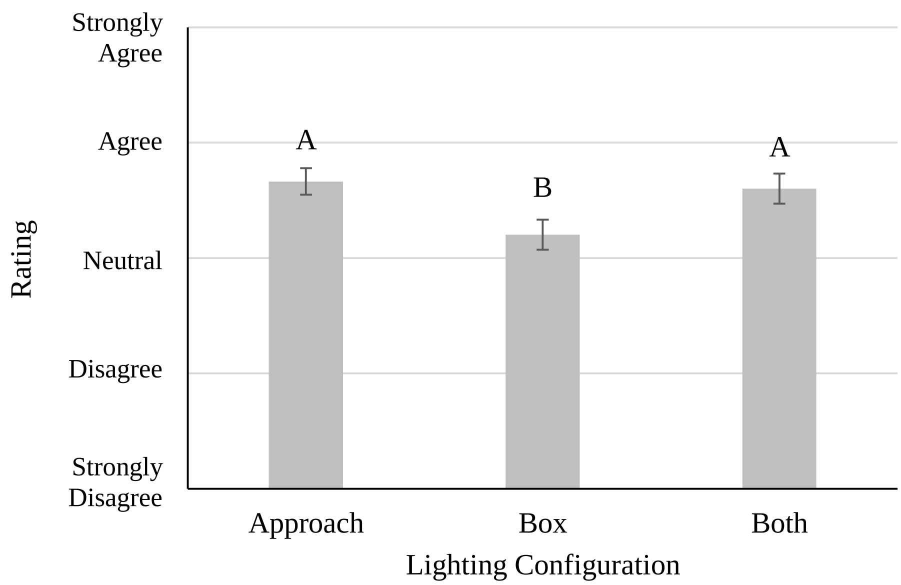

Figure 18. Ratings of pedestrian visibility in the three lighting configurations. Values are means of Likert-scale composite scores, and error bars represent standard errors. Upper case letters indicate groupings based on paired comparisons between lighting configurations.

Analysis of the age x illuminance level interaction revealed no significant differences between age groups at any of the illuminance levels. A pattern was evident, however, in that younger participants gave higher ratings at all illuminance levels greater than zero (Figure 19). Within each age group, increases in illuminance levels were associated with higher ratings. For both groups, ratings appeared to increase for every increment in illuminance level (albeit not significantly). For younger participants, mean Likert-scale composite score exceeded the “neutral” anchor (or the value 3) at the 8 lux illuminance level and this occurred at the 12 lux illuminance level for older participants (Figure 19).

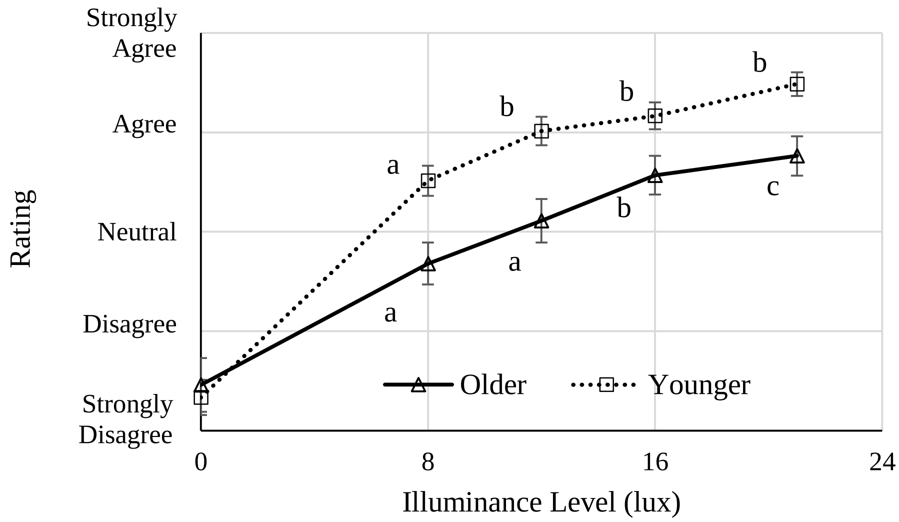

Figure 19. Ratings of pedestrian visibility at each illuminance level for the two age groups. Values are means of Likert-scale composite scores, and error bars represent standard errors. Lower case letters indicate groupings based on paired comparisons between illuminance levels, within each age group. Differences between zero and every other illuminance level were significant but are not denoted here.

3.3.2 Target Visibility

Subjective ratings of target visibility were significantly higher for the Both (*M* = 3.31, *SD* = 1.06) and Box (*M* = 3.7, *SD* = 1.08) vs. the Approach (*M* = 2.6, *SD* = 1) lighting configurations. Ratings in the Box configuration were significantly higher than in the Approach configuration at every illuminance level (Figure 20). Differences between the Approach and Both lighting configurations, however, were inconsistent and dependent on illuminance level. In each lighting configuration, increases in illuminance level were generally associated with increased target visibility ratings, though only a few paired differences were statistically significant. Plateaus with increasing illuminance were evident only in the Box and Both lighting configurations, for which the respective plateaus were attained at the 8 and 12 lux illuminance levels, respectively. For the Box and Both lighting configurations, mean Likert-scale composite score exceeded the “neutral” anchor (or the value 3) at the 8 lux illuminance level, whereas it was never exceeded for the Approach lighting configuration (Figure 20).

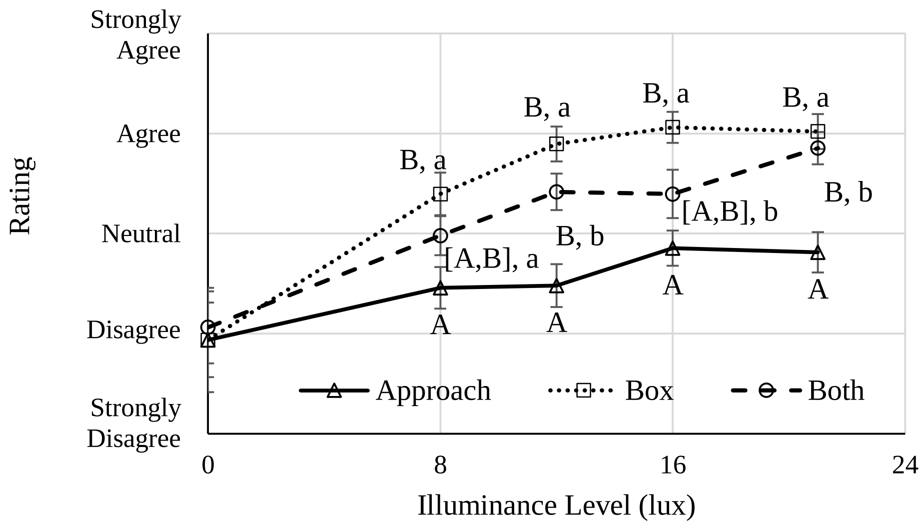

Figure 20. Ratings of target visibility for each combination of illuminance level and lighting configurations. Values are means of Likert-scale composite scores, and error bars represent standard errors. Upper case letters indicate groupings based on paired comparisons between lighting configurations at each illuminance level >0. Lower case letters indicate groupings based on paired comparisons between illuminance levels >0 within each configuration. Differences between zero and every other illuminance level for the Box and Both lighting configurations were significant but are not denoted here.

The associations between target detection distance and composite ratings of target visibility depended on the lighting configuration. The Box ($r_{(24)}$ = 0.43, p = 0.035) and Both ($r_{(24)}$ = 0.50, p = 0.012) lighting configurations exhibited significant positive correlations between detection distance and composite ratings of target visibility (Figure 21). This correlation was not significant, though, in the Approach lighting configuration ($r_{(24)}$ = 0.02; p = 0.931).

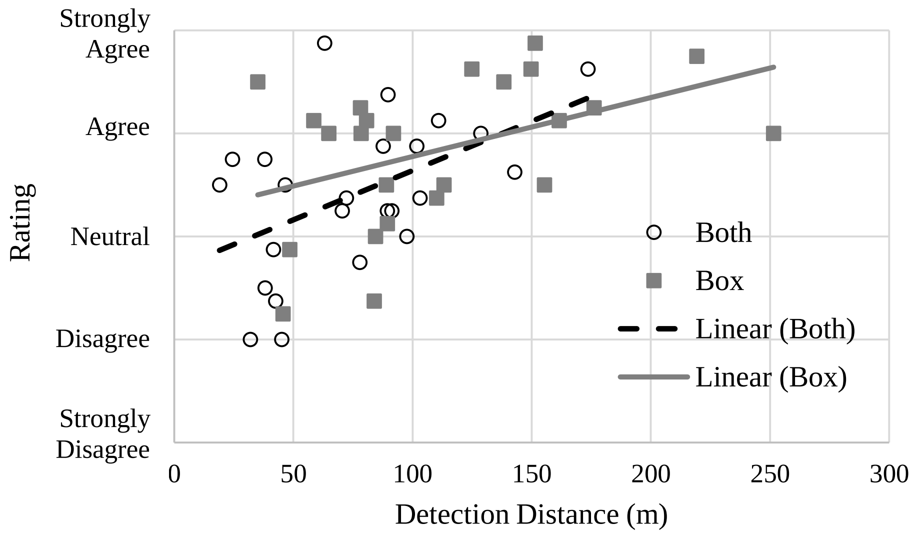

Figure 21. Associations between perceived target visibility (composite scores) and detection distances in the Box and Both lighting configurations.

3.3.3 Intersection Visibility

Subjective ratings of intersection visibility were significantly higher for the Both (M = 3.64, SD = 0.92) and Box (M = 3.94, SD = 0.87) vs. the Approach (M = 3.29, SD = 0.87) lighting configurations. Differences in the ratings of the Approach and Box lighting configuration were significant at every illuminance level >0, being the highest in the Box lighting configuration (Figure 22). In each lighting configuration, increases in illuminance level were associated with increases in ratings of intersection visibility (Figure 22), although paired differences were found only for the Both configuration. Plateaus were evident in Likert-scale composite scores for all the three lighting configurations. For the Approach and Box lighting configurations the plateau in subjective ratings of target visibility occurred at the 8 lux illuminance level and for the Both lighting configuration the plateau occurred at the 12 lux illuminance level. All the three lighting configurations mean Likert composite score exceeded the “neutral” anchor at the 8 lux illuminance level (Figure 22).

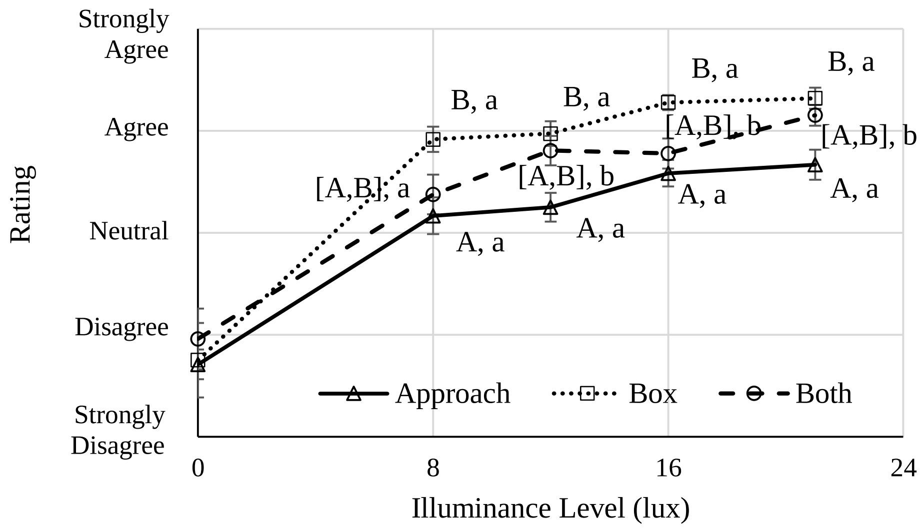

Figure 22. Ratings of intersection visibility at each illuminance level under all the three lighting configurations. Values are means of Likert-scale composite scores, and error bars represent standard errors. Upper case letters indicate groupings based on paired comparisons between lighting configurations at each illuminance level >0. Lower case letters indicate groupings based on paired comparisons between illuminance levels >0. Differences between zero and every other illuminance level were significant but are not denoted here.

3.3.4 Glare

There was a significant main effect of illuminance level, with the ratings at the 0 illuminance level (M = 1.22, SD = 0.39) having the lowest glare ratings vs. all other illuminance levels (8 lux - M = 2.28, SD = 0.91, 12 lux - M = 2.30, SD = 0.86, 16 lux - M = 2.25, SD = 0.81, 21 lux M = 2.13, SD = 0.69). However, there was also a significant lighting configuration x illuminance level interaction, evidence of a differential influence of illuminance level in the three configurations (Figure 23). Glare was reported to be lowest in the Box configuration and higher in the Approach configuration, for all illuminance levels >0, though no pairwise differences were significant. There were also no significant pairwise differences between illuminance levels (>0) within the Approach and Both lighting configurations. For the Box lighting configuration there were no significant differences between any of the illuminance levels including the 0. All the three lighting configurations' mean Likert-scale composite scores were less than the "neutral" anchor (Figure 23).

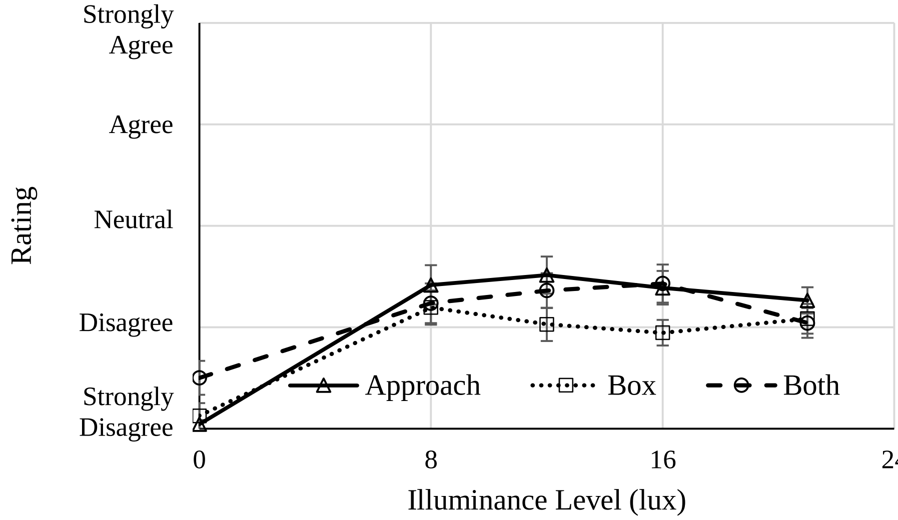

Figure 23. Ratings of glare at each illuminance level under all the three lighting configurations. Values are means of Likert-scale composite scores, and error bars represent standard errors. Note that lower values indicate less perceived glare. Differences between zero and every other illuminance level for the Approach and Both lighting configurations were significant but are not denoted here.

3.4 Discussion

The goals of this work were to assess the effects of intersection lighting configuration and illuminance levels on perceived visibility and glare. Three major findings were evident. First, there were differences in perceived visibility between the three lighting configurations, and the magnitude of these differences depended on the lighting configuration and object size. Second, increases in illuminance level resulted in increased ratings of visibility at some lighting configurations, and there was some evidence of plateaus in these rating with increasing illuminance levels. Third, none of the three lighting configurations were a major source of glare, even at the highest illuminance level.

Perceived visibility depended on the intersection lighting configuration and assessment area. For instance, pedestrian visibility had higher ratings in the Approach lighting configuration, whereas target and intersection visibility were rated higher in the Box lighting configuration. This lack of agreement in the ratings between pedestrian and target visibility may be attributed to the size object involved in each of these assessments. Regarding the former aspect, the pedestrian used here was substantially larger than the targets, and earlier results indicate that larger objects are perceived as being more visible, compared to smaller objects (Janoff, 1989).

Regarding perceived target and intersection visibility, the Box lighting configuration was rated higher than the other two lighting configurations at every illuminance level. These results are consistent with the results regarding visual performance experiment, as assessed by target detection distances

(Chapter 2). Specifically, the Box lighting configuration had longer detection distances at every illuminance level and fewer number of missed target detections, compared to the other two lighting configurations. In the Box and Both lighting configurations, target detection distance and perceived target visibility were positively correlated. In Chapter 2, the longer detection distances in the Box lighting configuration was attributed to the contrast in which the targets were rendered. This conclusion, along with the results regarding perceived target visibility, suggest that the Box lighting configuration renders the targets in adequate contrast (both positive and negative, since target visibility was assessed for all target locations), resulting in both longer detection distances and higher perceived visibility. The fact that the perceived visibility and target detection distances in the Both lighting configuration were lower than in the Box lighting configuration may have resulted because targets in the Both lighting configuration were rendered in lower contrast. However, a photometric analysis is required to substantiate the specific contrast levels (see Chapter 4). In the Approach lighting configuration, all targets were rendered in positive contrast, which may account for the absence of a correlation between target detection distance and perceived visibility in this configuration. Further, positive contrast may also have a differential effect on perceived visibility, depending on the size of the object, since the simulated pedestrian was perceived as more visible than the targets, however, a photometric analysis is required to ascertain this assumption.

The higher ratings of target and intersection visibility in the Box configuration could be attributed to the distribution pattern of the type V luminaire used to illuminate the intersection box. This pattern is more circular and more uniformly illuminates the intersection compared to the type II luminaires. The latter, used for illuminating the approach, has a more oval light distribution pattern, and which does not illuminate all the approaches of the intersection (Figure 24). This could also explain the results in the Both lighting configuration, which had the second highest ratings of both target and intersection visibility, since it included a combination of type II and type V luminaires. This combination increased the area illuminated around the intersection, which could have led to participants getting more visual information from the surroundings, resulting in higher ratings of target and intersection visibility compared to the Approach lighting configuration.

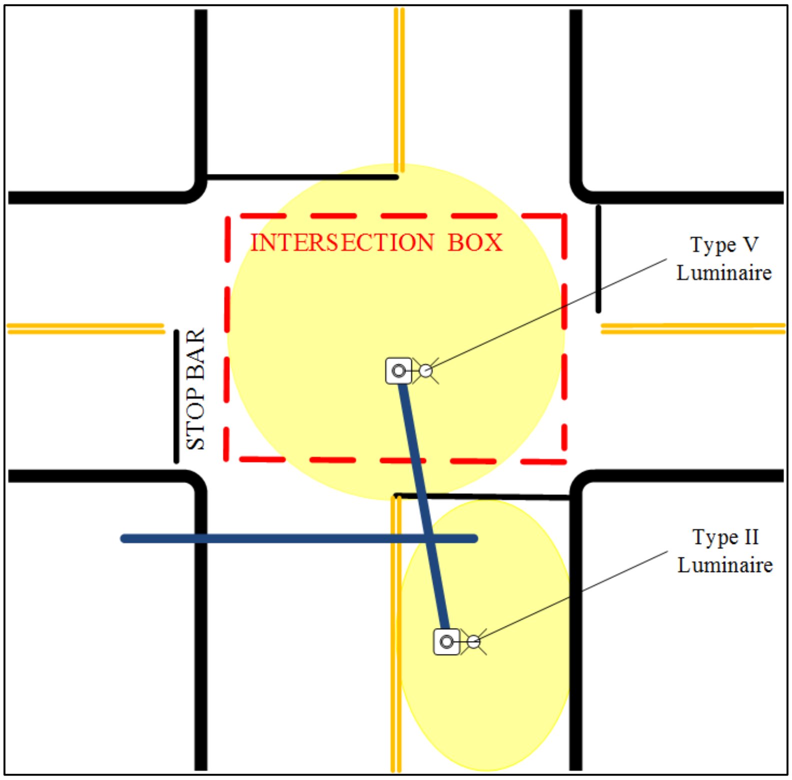

Figure 24. Distributions of type V and type II luminaires used to illuminate the intersection box and approach, respectively.

Ratings of pedestrian visibility exceed the "neutral" anchor (> 3) in all three lighting configurations, albeit at different illuminance levels. For the Approach lighting configuration this occurred at 8 lux, whereas for the Both and Box lighting configurations this threshold was crossed at 12 lux. These pedestrian rating results align with results of Minoshima et al. (2006), which indicated that at an average surface illuminance of 10 lux or higher yielded mean rating higher than 3 regardless of luminaire layout or lighting configuration. However, results here regarding perceptions here of intersection visibility and target visibility did not completely align with those of Minoshima et al. (2006). Mean ratings of intersection visibility here exceeded the "neutral" anchor for all three lighting configurations at an illuminance level lower (8 vs. 10 lux) than what was reported by Minoshima et al. (2006). For target visibility, mean ratings in the Approach lighting configuration never exceeded the "neutral" anchor, even at the highest illuminance level studied (21 lux), whereas in the Box and Both lighting configurations it was exceeded at 8 and 12 lux, respectively. These results indicate that luminaire layout (or lighting configuration) plays and important role in influencing perceived intersection and target visibility, but less of a role in influencing pedestrian visibility.

Increases in illuminance level generally resulted in higher ratings of pedestrian, target, and intersection visibility in all the three lighting configurations. These results are similar to those of Minoshima et al. (2006) and Janoff (1989), who found higher subjective ratings of visibility with increases in illuminance level. Assessments of the effects of illuminance levels within each lighting configuration showed that some plateaus occurred, but such patterns depended on the specific lighting configuration and perceptual measure. For the Box and Both lighting configurations this occurred at 8 and 12 lux illuminance levels, whilst the Approach lighting configuration exhibited a plateau for intersection visibility at the 8 lux illuminance level.

The Box lighting configuration led to the lowest glare ratings amongst the three lighting configurations, though none of the three intersection lighting configurations appeared to be a major source of glare. This result in not agreement existing research and the discrepancy could be attributed to different experimental methodologies used to assess perceived ratings of glare. In this study, the only source of glare were the luminaires used to illuminate the intersection whereas in the other studies the sources of glare were primarily headlamps or simulated headlamps of vehicles which direct substantially more light into driver's eyes (Alferdinck & Varkevisser, 1991; Schmidt-Clausen & Bindels, 1974; Sivak et al., 1990; Theeuwes et al., 2002).

Individual differences also did not appear to be a major source of variability. There were no significant differences found between males and females for any of the rating, and also no significant differences between the two age groups examined except for pedestrian visibility. Regarding the latter, younger participants reported higher levels of pedestrian visibility for all non-zero illuminance levels.

This study has some limitations, as summarized in the prior Chapter 2. For example, the experimental setting was somewhat limited in that there was no additional traffic and the signal lights were turned off at the intersection. These conditions were used to minimize potential confounding effects of glare and signal phase timing that could have affected drivers' perceptions of visibility and glare. Furthermore, when the Approach and Both lighting configurations are used, all the approaches are illuminated, which could affect the perceptions of glare and visibility of objects at the intersections. Thus, the results of this study may be most valid for isolated/rural intersections, which are illuminated by a single source of illumination and none of the approaching roads have continuous lighting. On roads with continuous lighting, additional light from luminaires might substantially affect contrast and subsequently the visibility of objects located at the intersection. Future work on intersection lighting should consider the effects of the presence of multiple vehicles, signal phase, and continuous lighting to more accurately understand the effects of intersection lighting design on visibility and glare.

In conclusion, illuminating different parts of an intersection leads to important differences in perceived visibility and glare, and the patterns of these differences are generally consistent with measures of visual performance (Chapter 2). Illuminating the intersection box yielded the highest ratings of target and intersection visibility and lowest ratings of glare. Even though the Approach lighting configuration had higher ratings of pedestrian visibility than the Box lighting configuration, target visibility ratings in this configuration were lower than the “neutral” anchor at every illuminance level. Moreover, at illuminance levels greater than 8 lux, pedestrian visibility ratings in all three lighting configurations exceeded the “neutral” anchor and did not differ significantly from one another. For the Box lighting configuration, plateaus in perceived visibility differed between assessment areas, occurring at 8 (target and intersection visibility) or 12 lux (pedestrian visibility) illuminance levels. Ratings of the Approach lighting configuration were less consistent, yielding the highest ratings for pedestrian visibility and the lowest ratings of target and intersection visibility. The Box lighting configuration also had lowest ratings of glare, although none of the three lighting configurations were a major source of glare. The Box lighting configuration also requires only one luminaire to illuminate the entire intersection, whereas the Approach and Both lighting configurations require as many luminaires as they are approaches at the minimum, making these latter more expensive. These results have important implications for lighting design of rural/isolated intersections. Specifically, they suggest that illuminating the intersection box is likely to have multiple parallel benefits, with longer detection distances, higher perceived visibility, lower glare, and fewer required luminaires.

Chapter 4 – Intersection Lighting Design Influences Target and Pedestrian Contrast

Abstract – Earlier assessments of three intersection lighting designs (illuminated approach, illuminated box and illuminated approach + box) indicated that the different designs had important influences on visual performance and perceived visibility. However, the source of these differences was not identified, but was speculated to be a result of object contrast. Furthermore, the combined effect of vehicle headlamps and intersection lighting on object contrast has not been reported previously, though such contrast plays an important role in nighttime visibility. The goals of this study were to quantify object luminance and contrast as a function of a vehicle's distance to an intersection using the three lighting designs, and to assess whether contrast influences visual performance and perceived visibility. Both luminance and contrast of roadway visibility targets and a pedestrian were measured at a simulated intersection. Both target and pedestrian contrast and luminance were substantially affected by the intersection lighting configuration, illuminance level, location at the intersection, and the distance of the vehicle from the intersection. Negative contrast on targets was associated with higher visual performance. Within a given contrast polarity, visual performance depended on the magnitude of contrast, with higher contrast associated with higher visual performance. The relationship between pedestrian contrast and perceived visibility was complex, since pedestrians were often rendered in multiple contrasts. The lighting configuration that illuminated the intersection box rendered the targets at contrasts (both positive and negative) that resulted in higher visual performance and higher perceived visibility. Thus, these findings have important implication for lighting design of intersections at isolated/rural areas.

4.1 Introduction

A systems-level approach to evaluating intersection lighting designs was introduced previously (Chapters 2 and 3). Two studies were conducted that evaluated the effect of intersection lighting design on visual performance along with perceived visibility and glare. Intersection lighting design here, recall, refers to both the part of the intersection illuminated (lighting configuration) and the recommended illuminance level. Visual performance was measured using detection distance – the distance at which drivers detected a target located at the intersection. Perceived visibility and glare were measured using composite subjective ratings of pedestrian visibility, target visibility, intersection visibility, and glare. In the visual performance experiment, the lighting configuration which illuminated the intersection box yielded better visual performance (longer detection distances) and fewer missed target detections than the two alternatives tested (Approach and Approach + Box). Visual performance typically plateaued between 8 and 12 lux illuminance levels. While there was no difference between the three lighting configurations in terms of pedestrian visibility, the Box lighting configuration resulted in higher perceived target and intersection visibility and lower perceived glare. Perceived visibility ratings also plateaued between 8 and 12 lux illuminance levels in this lighting configuration.

Although these two experiments helped identify effective intersection lighting designs, they did not reveal *why* one design (i.e., Box configuration) resulted in better visual performance and higher perceived visibility than the rest. Changes in visual performance and perceived visibility between designs could be attributed to the contrast in which the objects (targets and pedestrians) were rendered by the intersection lighting designs. It is important to know how different intersection lighting design affect object contrast, since contrast drives the visibility of an object and object contrast is often directly proportional to its visibility (Adrian, 1989; Gibbons et al., 2015; Gibbons et al., 2008; Pretto & Chatziastros, 2006).

There are two kinds of contrasts relevant to visibility. The first is luminance contrast, which is the ratio of the luminance difference between an object and its background vs. the luminance of its background. The second is color contrast, which is the ratio of the color difference between an object and its background vs. the color of its background. In nighttime driving scenarios, the human visual system is under mesopic vision (Bullough & Rea, 2004; Plainis et al., 2005). However, in this mesopic state of adaptation, rods play a dominant role and luminance contrast drives an object’s visibility more so than color contrast (Eloholma et al., 2006; Várady & Bodrogi, 2006). Therefore luminance contrast measures are most relevant and typically used in nighttime visibility research (Akashi & Rea, 2002; Alferdinck, 2006; Gibbons et al., 2015; Lewis, 1999; Lingard & Rea, 2002).

Luminance contrast, or Weber contrast, is defined as the ratio of the luminance difference between an object and its background relative to the luminance of the background:

$$C = \frac{(L_t - L_b)}{L_b}$$

where *C* is the luminance (Weber) contrast, L_t is the target luminance, and L_b is the background luminance. An object is considered be in *negative contrast* when it is darker than its background and *positive contrast* when it is brighter than its background. Contrast polarity is an interesting phenomenon that was detailed in early work by Aulhorn (1964); cited by Adrian (1989)), who reported that that objects in negative contrast are detected sooner than those in positive contrast for the same difference in luminance. This phenomenon was also reported by Hills (1975), specifically under road lighting conditions; objects in negative contrast were detected from farther away than those in positive contrast. Object size also influences perceived visibility, with larger objects being perceived as being more visible than smaller objects (Janoff, 1989). In the presence of roadway lighting, object contrast also depends on several additional factors, which include target reflectance, vehicle headlamp type, location of the object with respect to the vehicle, and distance between the vehicle and the object (Ekrias et al., 2008; Gibbons et al., 2015). However, the combined effect of intersection lighting design and vehicle headlamps on object contrast has not been previously reported, nor have changes in object contrast as a vehicle approaches an intersection.

This study thus had two goals. The first goal was to assess the change in luminance and contrast of a target and a pedestrian as a vehicle approaches an intersection. This was performed for three intersection lighting designs, as evaluated in the visual performance and the perceived visibility experiments. The second goal was to examine the relationship between target contrast and visual performance, and pedestrian contrast and perceived pedestrian visibility, in the three intersection lighting designs. An object's luminance and contrast might change as vehicle approaches an intersection and the influence of headlamps increases (Ekrias et al., 2008; Gibbons et al., 2015). The location of an object with respect to the location of the luminaire at the intersection was expected to affect target luminance and contrast. Object contrast and size were also expected to influence visual performance and perceived visibility, similar to earlier evidence (Aulhorn, 1964; Hills, 1975; Janoff, 1989). The results of this study were intended to supplement earlier results regarding visual performance and perceived visibility and glare, and to help identify underlying reasons for the superior performance of the Box intersection lighting configuration.

4.2 Methods

Photometric measurements were conducted at the intersection on the Virginia Smart Road at the Virginia Tech Transportation Institute. Photometric measurements included the measurement of luminance of objects and their backgrounds. Targets and a simulated pedestrian were used as objects in this study. The targets were gray in color and 18 cm by 18 cm in size, similar to the ones used in the visual performance experiment (Chapter 2). Targets were located at entrances, exits and the middle of the crosswalks at the intersection. Targets located at the entrances and exits were located at distance of 0.3 meters outside the right shoulder. There were five target locations as described in Chapter 2 (Figure 25). The simulated pedestrian was same as the pedestrian described in the perceived visibility experiment in Chapter 3 (Figure 26). Pedestrian location for photometric measurements was moved slightly to the left of the actual location used in the subjective ratings experiment in interest of saving time and to facilitate capturing of all object locations with a single image. Since this move was lateral, the change in the light levels (luminance and illuminance) was minimal. Gray-colored targets were used, and pedestrian wore gray-colored scrubs, as gray is a neutral color and renders similarly in different lighting configurations and illuminance levels.

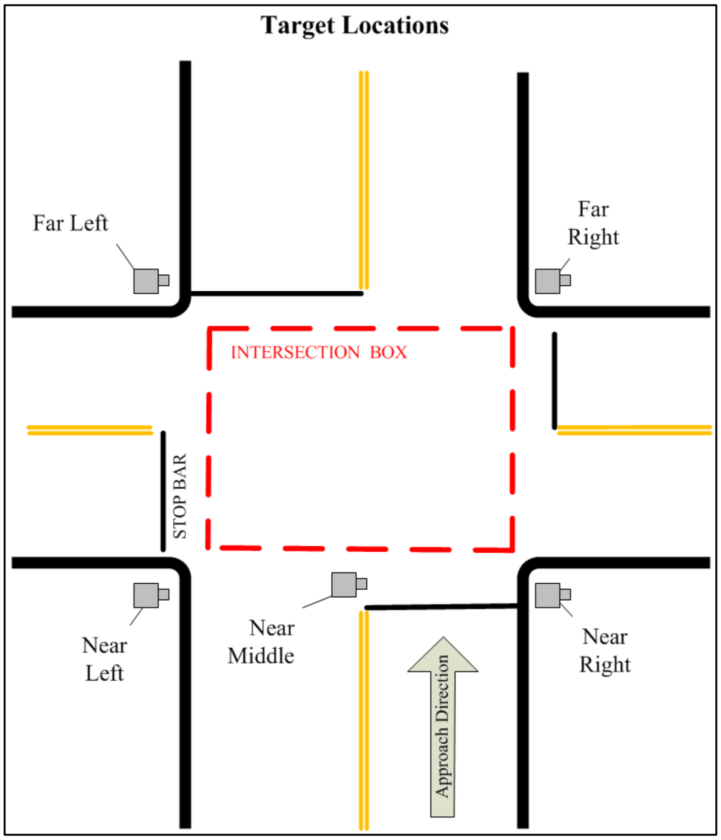

Figure 25. Target locations at the intersection

Figure 26. Pedestrian with grey scrubs

Lighting configurations and illuminance levels were similar to the ones used in the visual performance (Chapter 2) and perceived visibility experiments (Chapter 3). Three lighting configurations were used. In the first lighting configuration, the approach to the intersection was illuminated (Approach, see Figure 27a). In the second, the intersection box was illuminated (Box, see Figure 27b) and in the third, both the approach and the box of the intersection were illuminated (Both, see Figure 27c). The intersection was illuminated by two 4000 Kelvin light emitting diode (LED) luminaires. One was used for illuminating the approach and the other was for illuminating the box. Approach luminaire had a type II distribution and box luminaire had a type V distribution. These luminaires had mounting height of 8.5 meters (28 ft.). Four illuminance levels were used for the photometric measurements, specifically, 8, 12, 16 and 21 lux. These levels were the horizontal illuminance levels measured at the near right target location and were selected based on the IESNA RP-8 minimum recommended levels for low, medium and high pedestrian volumes at rural, sub-urban and urban locations (IESNA, 2005).

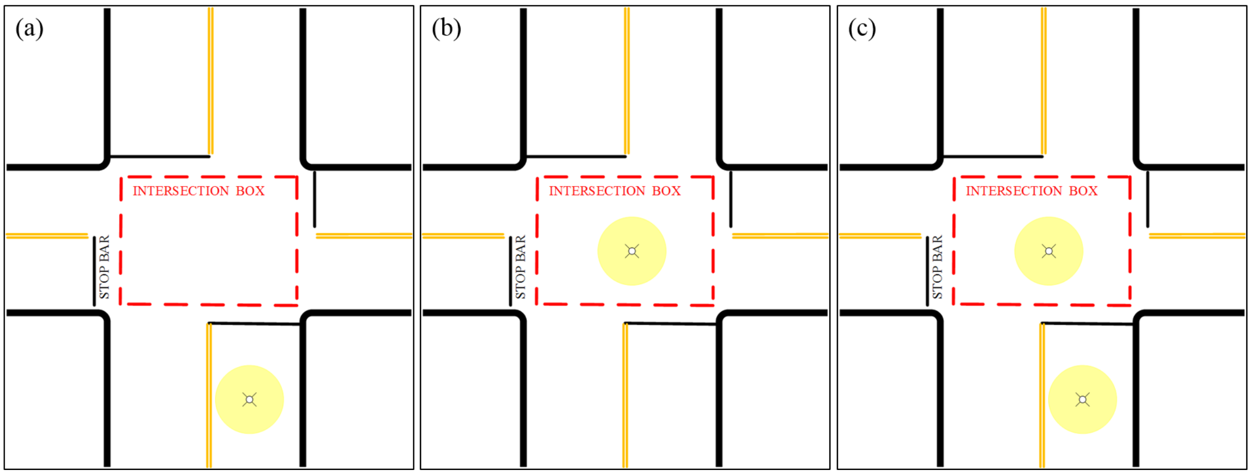

Figure 27. Illustrations of the three intersection lighting designs, (a) Intersection approach is illuminated (b) Intersection box is illuminated. (c) Both the box and approach are illuminated

Luminance and contrast of target and pedestrians were calculated from photometric images taken at 10 distances to the intersection, and in each of the three lighting configurations and four illuminance levels. These distances ranged from 120 to 20 meters to the intersection at 10 meter intervals. The range of distances was selected to capture the luminance and contrast of the objects at the intersection as a vehicle approaches and the headlamps come into influence. The effective range of headlamps varies between 80 to 120 meters depending on the manufacturer (Wördenweber et al., 2007). From a prior study (Terry & Gibbons, 2015) it was evident that the range of the headlamps used in the study was between 80 and 90 meters. The selected ranges thus helped in capturing object luminance and contrast before and after the influence of headlamps. The headlamps mounted on the vehicle were Hella 90 mm Bi-Xenon projector lamps with a single 1-F capacitor-stabilized headlamp input voltage.

Photometric images were captured with a calibrated photometer (ProMetric PM-9913E-1, Radiant Imaging®, Redmond, WA) mounted inside the test vehicle at the driver seat (Figure 28). A 2000 Ford Explorer was used as the test vehicle, one of the two experimental vehicles used in both the visual performance and the perceived visibility experiments. Captured images were analyzed using Radiant Imaging® ProMetric software (ver. 9.1, Radiant Imaging®, Redmond, WA). For calculating the luminance of targets and pedestrians, polygons were traced around the pedestrian and target and the software calculated the mean luminance within the selected polygon. Background luminance was calculated by tracing the same sized polygon around the object location close to its boundaries. The Weber contrast formula was used to calculate the contrast of pedestrians and targets.

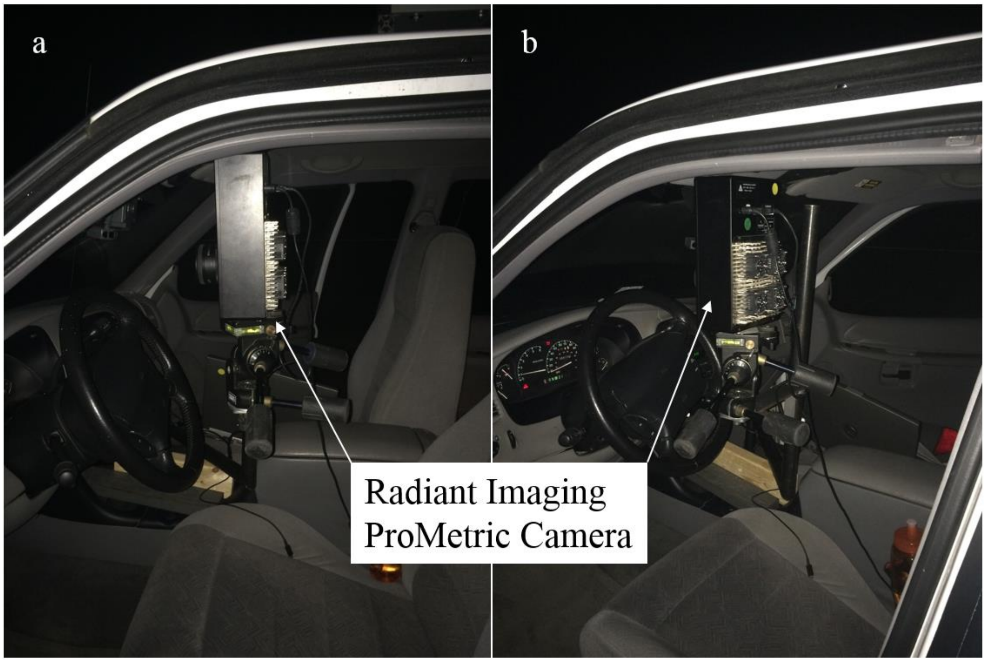

Figure 28. Location of the ProMetric Camera inside the test vehicle at the driver's seat

Detection distances from the visual performance experiment were used to understand the relationship between target contrast and distance to the intersection. In order to simplify and facilitate the ease of understanding, target contrast at the mean detection distance under each lighting configuration and illuminance level were also graphed on the contrast-distance to intersection plots. Contrast and distance to target data were interpolated to get the contrasts at the mean detection distances. Target contrasts beyond 120 meters were not calculated because at those distances the photometer could not resolve the target in sufficient detail. It was not possible to accurately trace a polygon around the target, to calculate the target luminance and the background luminance which are both required to determine the target contrast. For pedestrians, the contrast was calculated at 76.2 meters from the intersections and was graphed on the contrast-distance to intersection plots, this is the distance from where the participants rated pedestrian visibility in the perceived visibility experiment. The change in luminance and object contrast (targets and pedestrians) as the vehicle approaches the intersection along with the contrast at the mean detection distance and pedestrian visibility rating location will help understand the relationship between object contrast, visual performance and perceived visibility at the three intersections lighting configurations.

Two photometric evaluations were conducted. The first focused on the change in target luminance and contrast from the point of view of an approaching vehicle. This was performed for each of the five target locations used in the visual performance experiment. The results of these evaluations were intended to help in understanding the relationship between target contrast, visual performance and perceived visibility. These results could also explain why one intersection lighting configuration performed better than the other. Also in these evaluations, contrasts of the far-right and far-left target locations were compared at each illuminance level under box lighting configuration to understand why the latter had longer detection distances than the former. The second evaluation focused on changes in pedestrian luminance and contrast from the point of view of an approaching vehicle. These evaluations helped understand the relationship between pedestrian contrast and their perceived visibility.

4.3 Results

4.3.1 Target Luminance

Increases in illuminance levels resulted in an increase in the target luminance in all the three lighting configurations (see Figure 29, Figure 30, Figure 31, Figure 32 and Figure 33). However, the rate of increase in the target luminance with distance depended on target location and lighting configuration. For the near right, near middle and near left target location, the Approach lighting configuration had the highest target luminance at every distance to the intersection and the Box lighting configuration had the lowest (Figure 29, Figure 30 and Figure 31). This trend reversed for the far right and far left target locations (Figure 32 and Figure 33).

In general, target luminance measurements increased as the vehicle approached the intersection. Between 120 and 80 meters to the intersection, there were no major changes in the target luminances at any of the target locations. However, for targets on the right shoulders (near right, far right) and the middle (near middle), at distances less than 80 meters to the intersection, there is a rapid increase in the target luminance with decrease in distance to the intersection (Figure 29, Figure 30 and Figure 32). This increase in target luminance was also observed for targets on the left shoulder (near left and far left) but the increase was modest (Figure 31 and Figure 33).

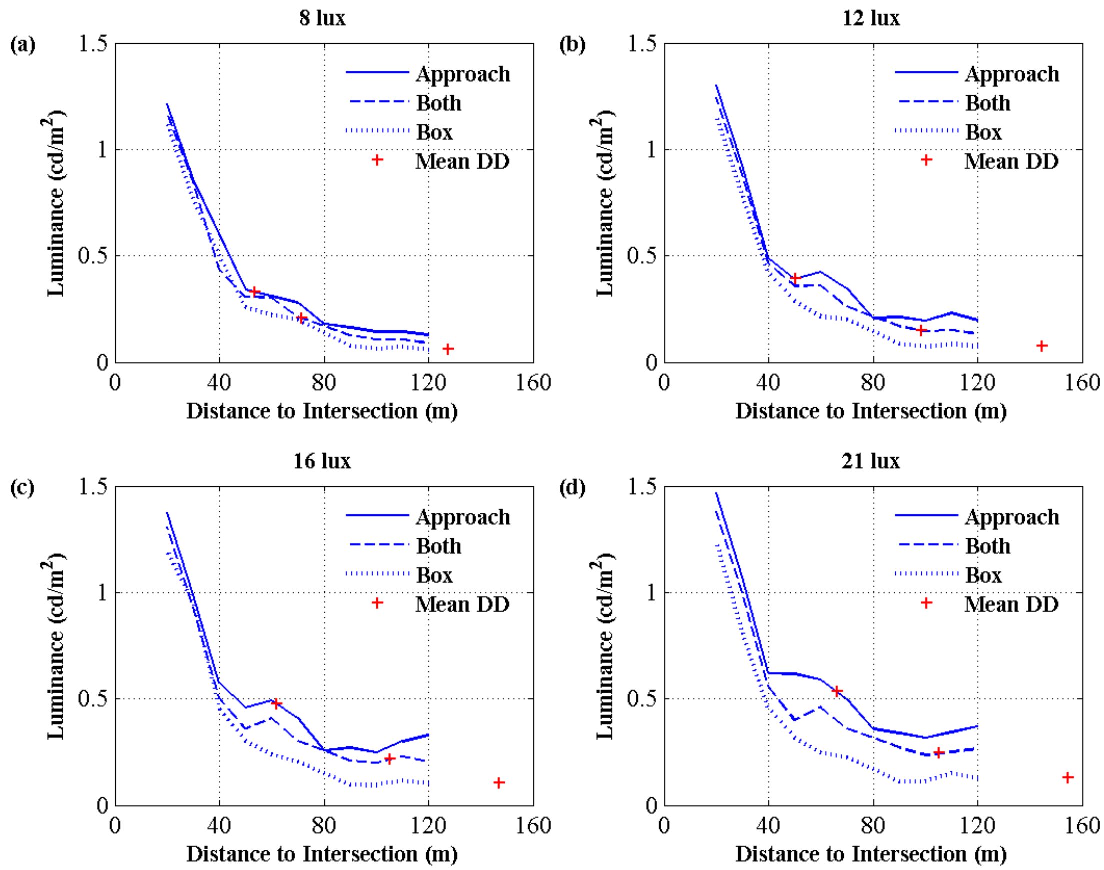

Figure 29. Luminance measurements at the near right target location as a function of the vehicle distance to the intersection in each lighting configuration and illuminance level. The "+" represents the luminance at the mean detection distance.

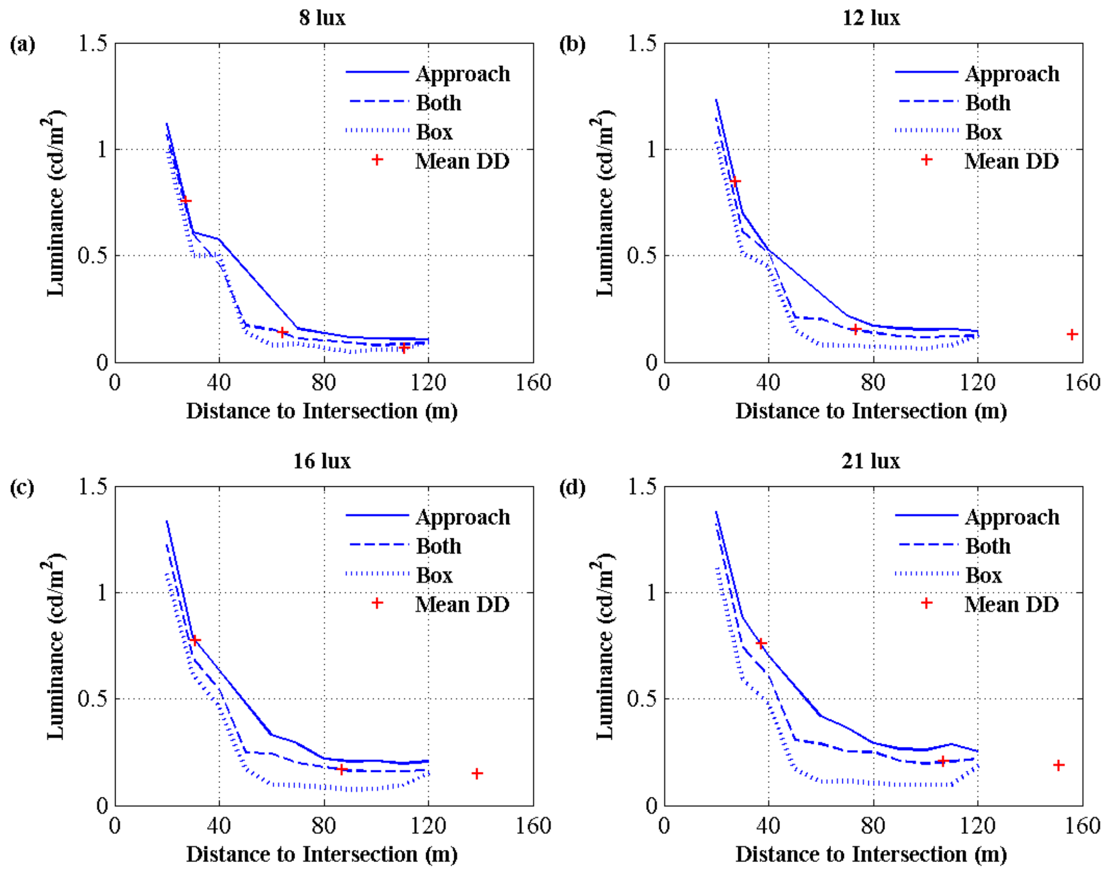

Figure 30. Luminance measurements at the near middle target location as a function of the vehicle distance to the intersection in each lighting configuration and illuminance level. The "+" represents the luminance at the mean detection distance.

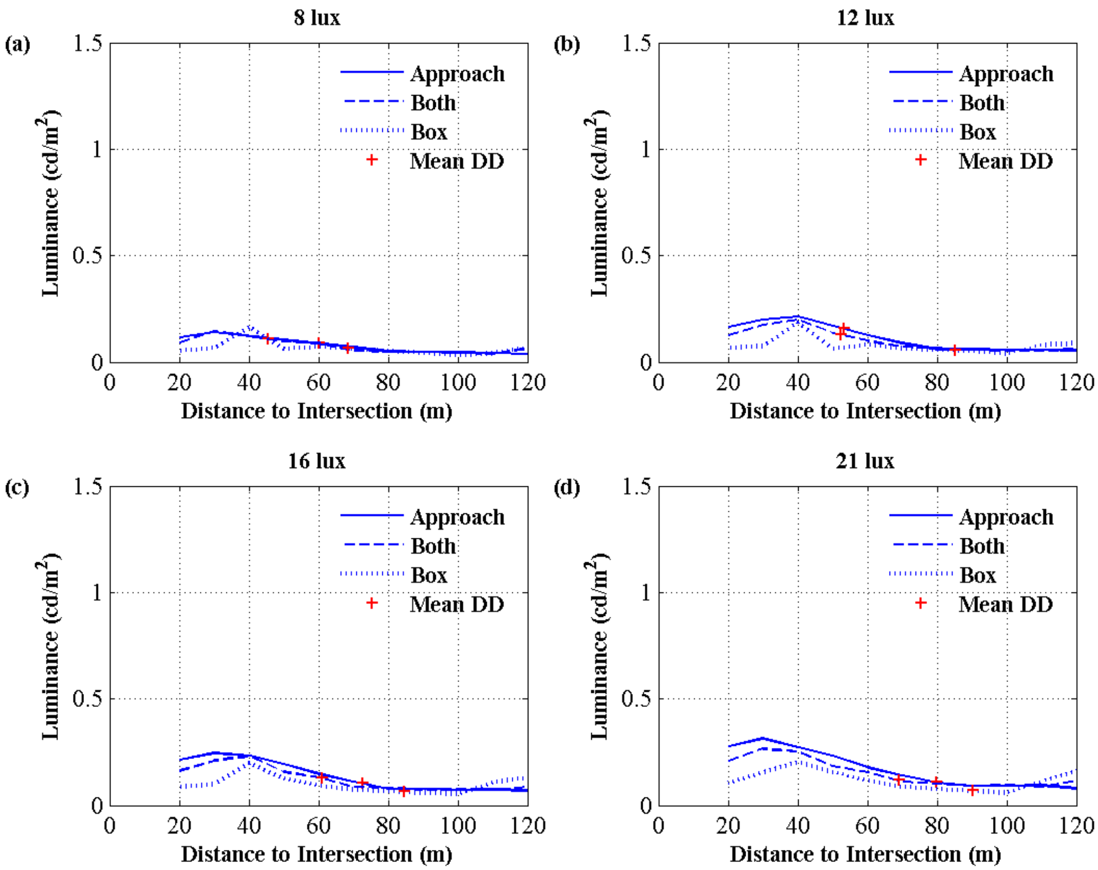

Figure 31. Luminance measurements at the near left target location as a function of the vehicle distance to the intersection in each lighting configuration and illuminance level. The "+" represents the luminance at the mean detection distance.

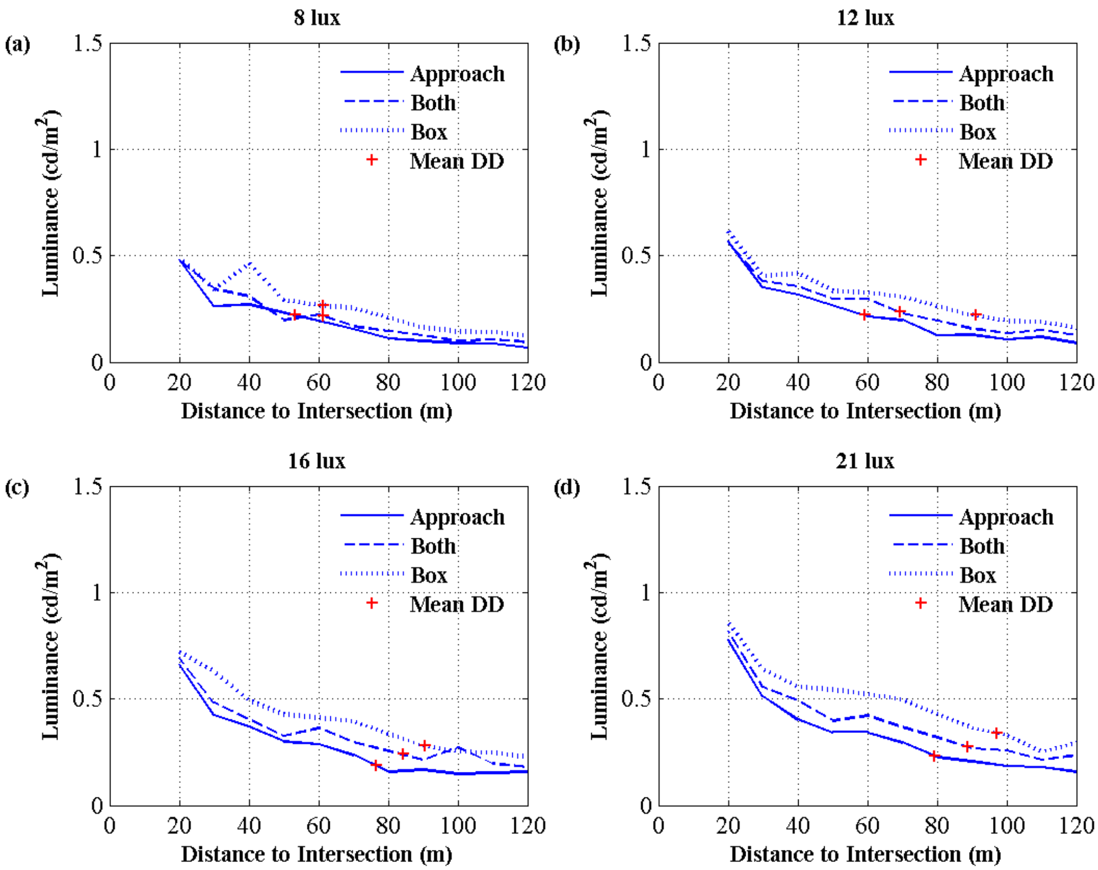

Figure 32. Luminance measurements at the far right target location as a function of the vehicle distance to the intersection in each lighting configuration and illuminance level. The "+" represents the luminance at the mean detection distance.

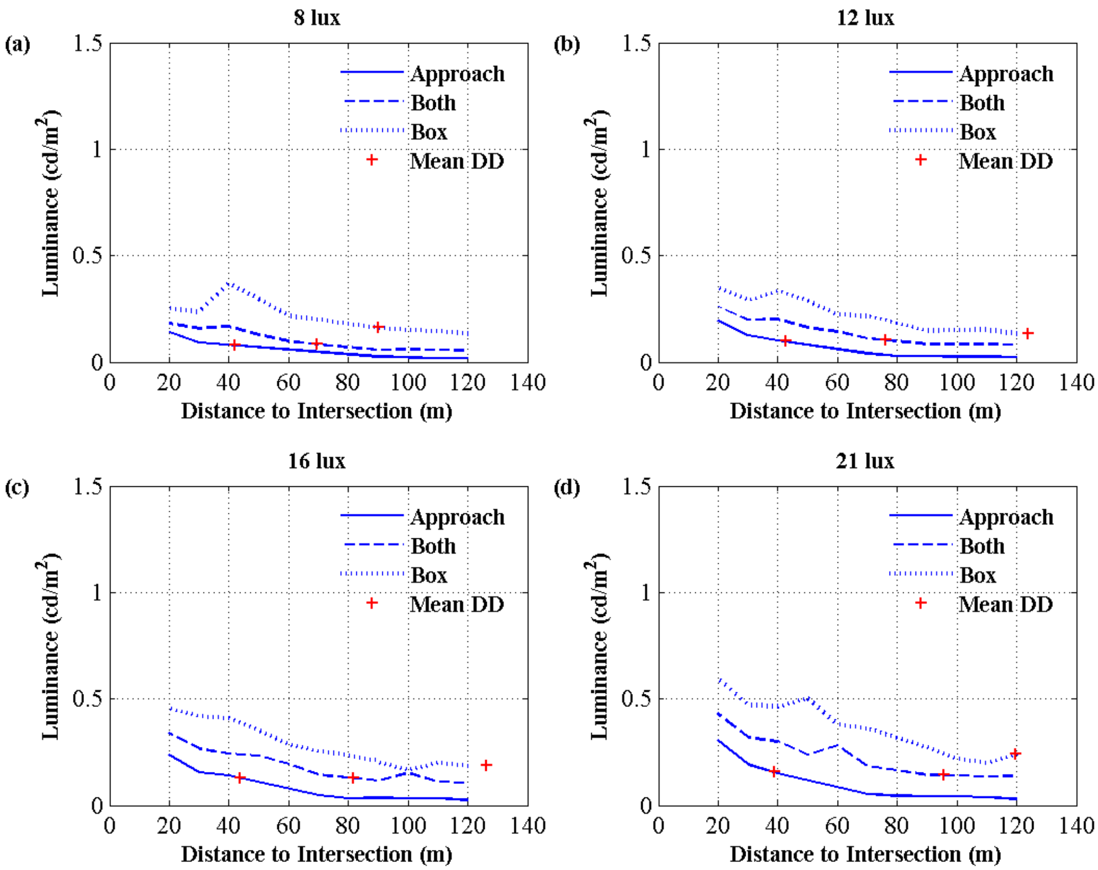

Figure 33. Luminance measurements at the far left target location as a function of the vehicle distance to the intersection in each lighting configuration and illuminance level. The "+" represents the luminance at the mean detection distance.

4.3.2 Target Contrast

Target contrast at the mean detection distance is indicated with "+" sign at each lighting configuration and illuminance level. For the Box lighting configuration, detections happened at distances longer than where the contrast measurements took place, consequently they are marked outside the range at the same level as the last measured contrast without any extrapolation. Target contrast was influenced by lighting configuration, illuminance level and target location.

In the Approach lighting configuration all the target locations were rendered in positive contrast, except the near right target at illuminance levels greater than 8 lux where the target contrast went to negative levels before increasing to positive at distances shorter than 40 meters to the intersection. Target contrast decreased as the vehicle approached the intersection until about 40 meters to the intersection after which it increased. Increase in the target contrast with increase in the illuminance level was only observed for near left and far right target locations.

In the Box lighting configuration the contrast polarity of the targets depended on their location and the distance from the intersection. Near right and near middle target location were rendered in negative contrast and as the vehicle approached the intersection the target contrast changed into positive contrast. The distance at which these targets changed into positive contrast depended on the illuminance level (Figure 34 and Figure 35). The rest of the targets were rendered in positive contrast and as the vehicle approached the intersection the magnitude of the contrast reduced (Figure 36, Figure 37 and Figure 38). In the case of the near left target, the target contrast transitioned from positive to negative contrast between 50 and 60 meters to the intersection (Figure 36). Increase in the illuminance level was also associated with increase in the magnitude of the target contrast.

In the Both lighting configuration also the contrast polarity of the targets depended on their location and the distance from the intersection. Near right and near middle targets started off in positive contrast, it decreased with decrease in distance to the intersection until it went to a negative contrast where it plateaued. As the vehicle got more close to the intersection the contrast polarity again changed to positive. The magnitude and the distance for which the target was rendered in negative contrast depended on the illuminance level (Figure 34 and Figure 35). The rest of the targets were rendered in positive contrast and their contrast decreased as the vehicle got closer to the intersection. For the near left target, the target contrast transitioned from positive to negative contrast between 20 and 60 meters to the intersection depending on the illuminance level (Figure 36). The transition happened at longer distances at higher illuminance levels. The effect of increasing illuminance levels on the magnitude of contrast depended on the target location. Increase in contrast with increase in illuminance level was only observed for near left, far right and far left locations (Figure 36, Figure 37 and Figure 38).

Targets rendered in negative contrast had longer mean detection distances than those rendered in positive contrasts (Figure 34 and Figure 35). Within each contrast polarity, mean detection distance was depended on the magnitude of the contrast. Higher contrasts were associated with longer detection distances (Figure 37 and Figure 38). In the perceived visibility experiments, perceptions of target visibility were assessed as a whole, and results regarding perceptions of individual target visibility were not available for direct comparisons with target contrasts. However, perceptions of target visibility overall were highest in the Box lighting configuration and lowest in the Approach lighting configuration. These perceptions are consistent with the relative levels of target contrasts, with more negative contrast (for near right and near middle targets) and higher levels of positive contrast (for far right and far left targets) associated with higher perceived visibility.

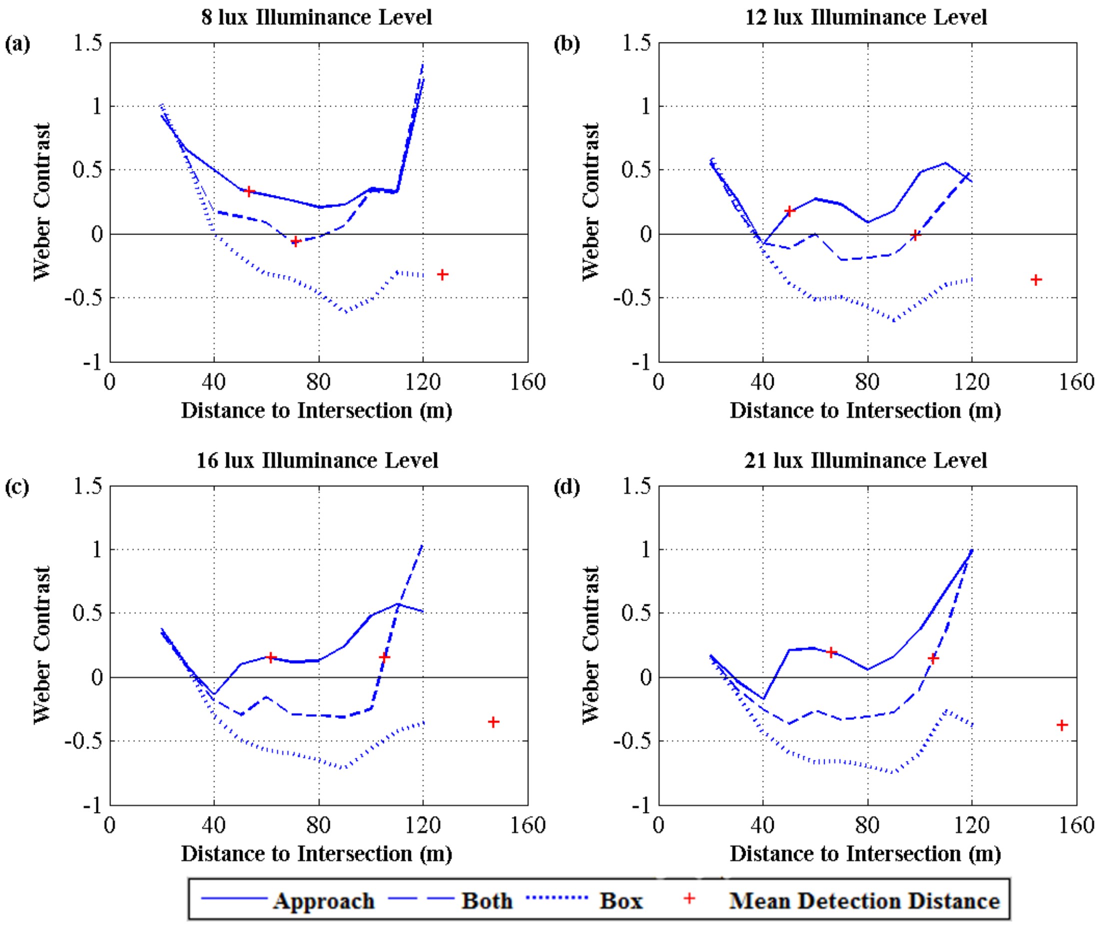

Figure 34. Target contrast at the near right target location as a function of the vehicle distance to the intersection in each lighting configuration and illuminance level. The "+" represents the contrast at the mean detection distance.

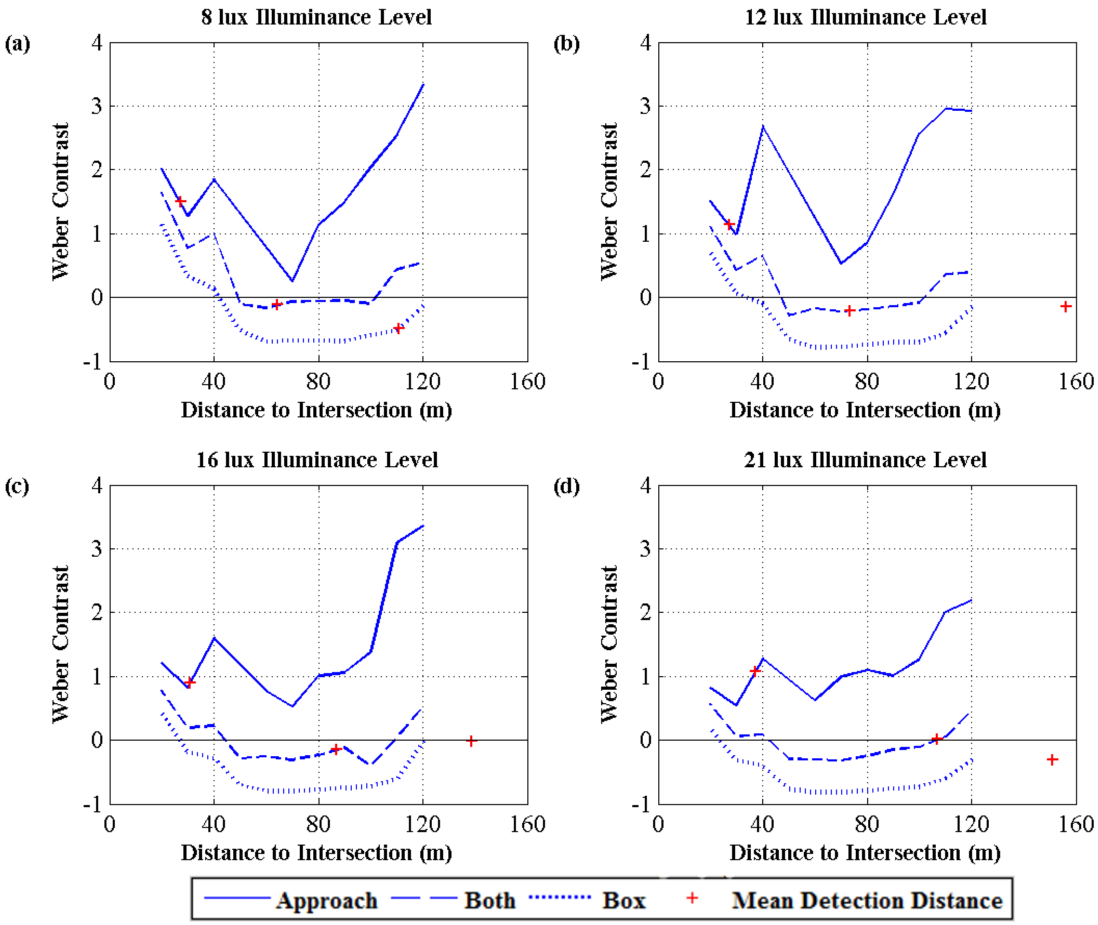

Figure 35. Target contrast at the near right middle target location as a function of the vehicle distance to the intersection in each lighting configuration and illuminance level. The "+" represents the contrast at the mean detection distance.

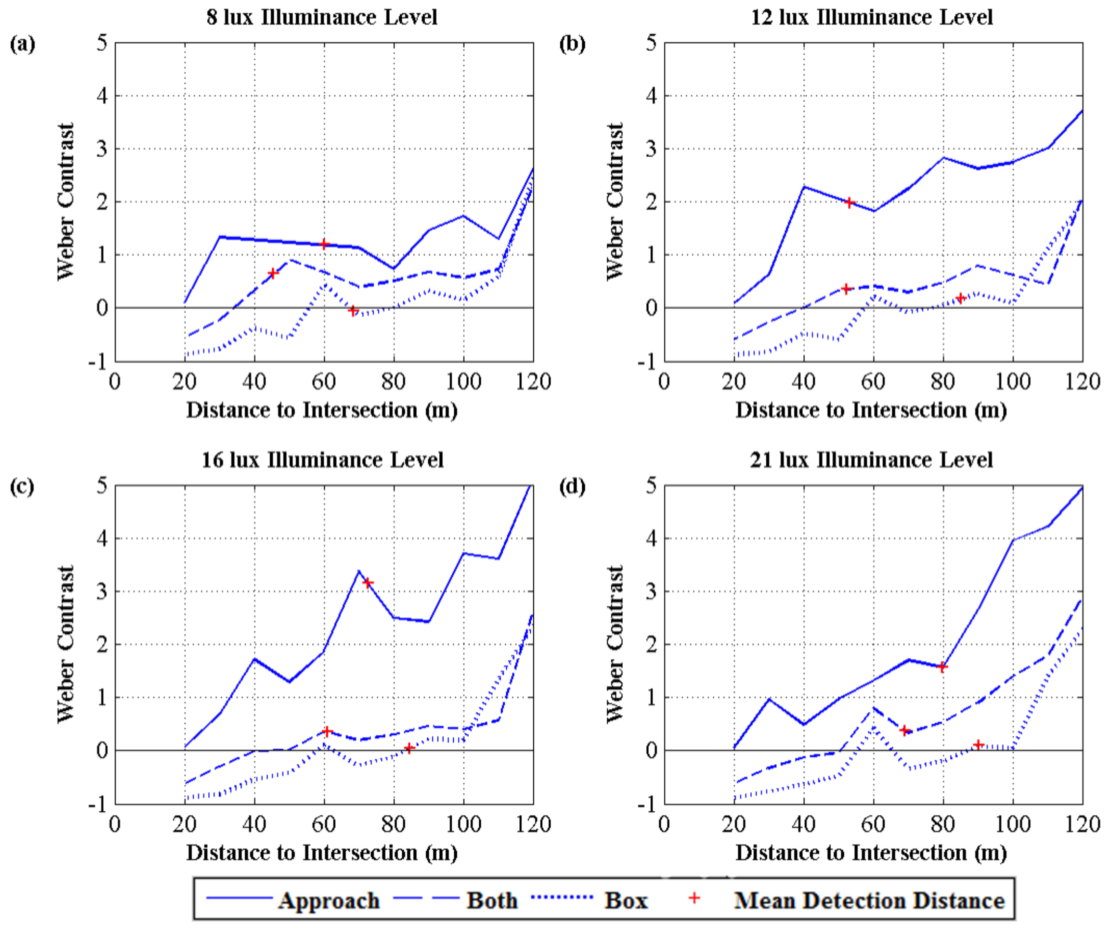

Figure 36. Target contrast at the near left target location as a function of the vehicle distance to the intersection in each lighting configuration and illuminance level. The "+" represents the contrast at the mean detection distance.

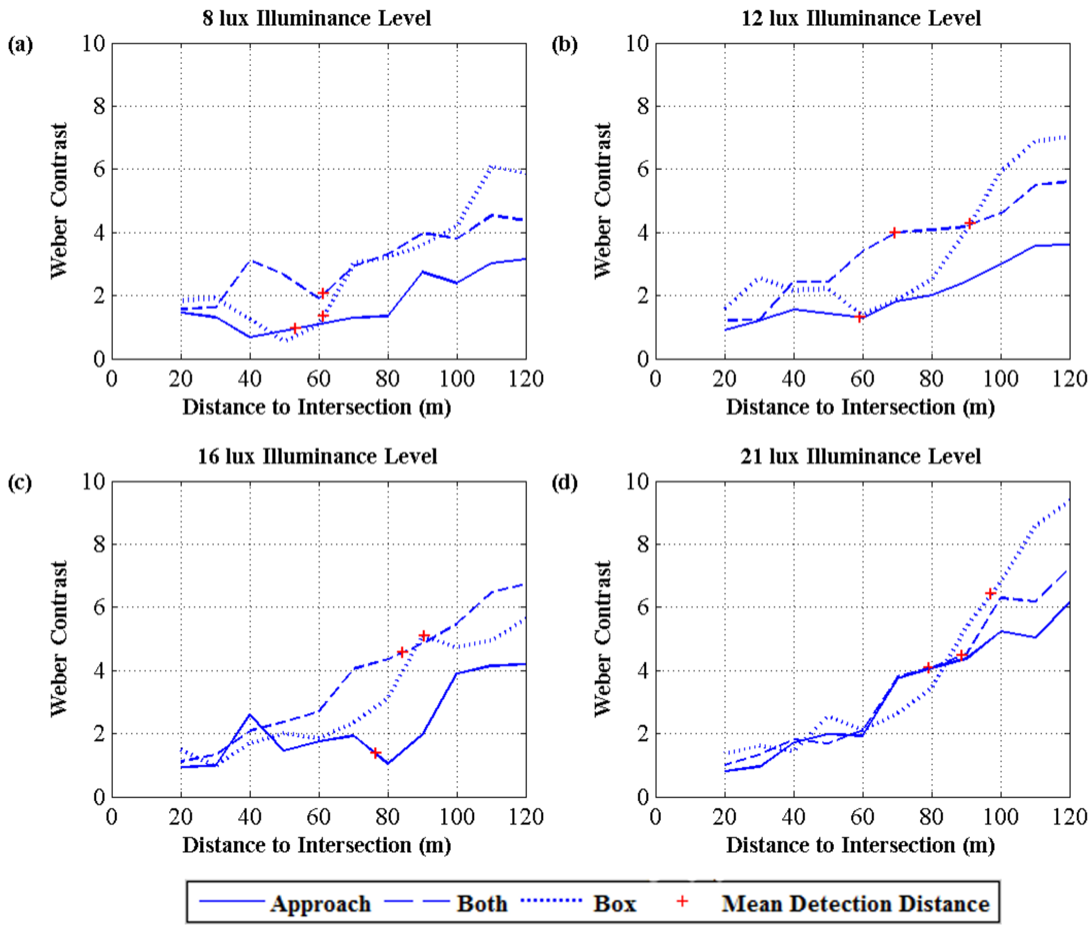

Figure 37. Target contrast at the far right target location as a function of the vehicle distance to the intersection in each lighting configuration and illuminance level. The "+" represents the contrast at the mean detection distance.

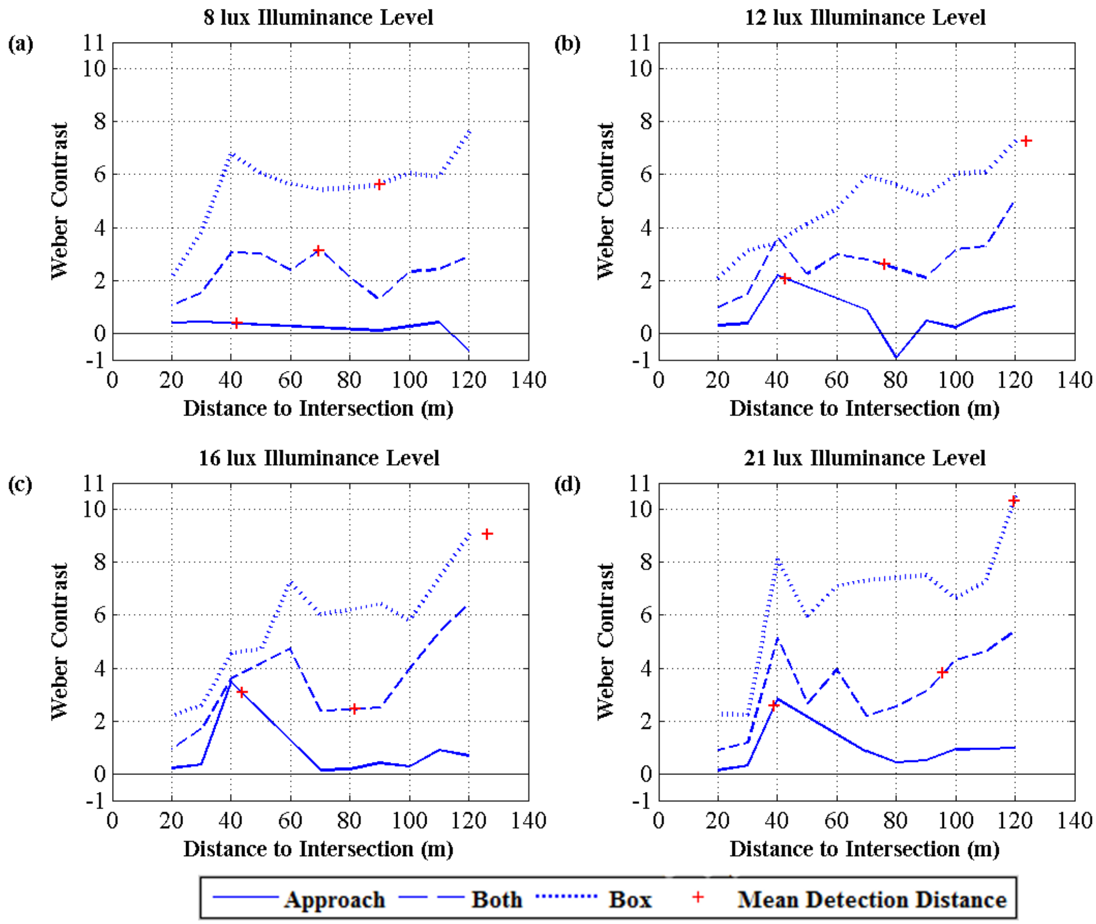

Figure 38. Target contrast at the far left target location as a function of the vehicle distance to the intersection in each lighting configuration and illuminance level. The "+" represents the contrast at the mean detection distance.

4.3.3 Far Right – Far Left Target Contrast Comparison in the Box Lighting Configuration

Both, far right and far left target locations were rendered in positive contrast under the box lighting configuration (Figure 39). At distances less than 100 meters to the intersection, far left target had a higher contrast than far right target at every illuminance level. At the mean detection distance at every illuminance level far left target has a higher contrast than far right target at every illuminance level (Figure 39).

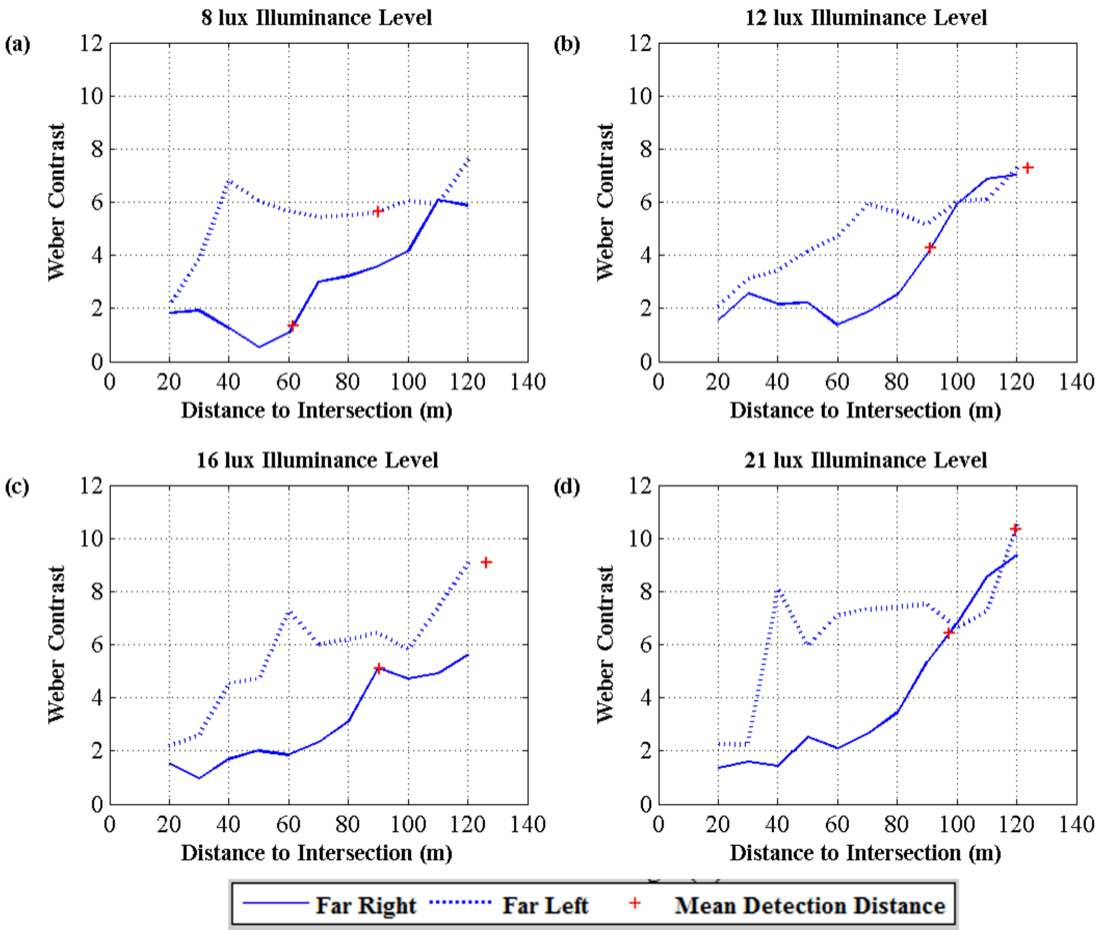

Figure 39. Target contrast at the far right and far left target locations as a function of the vehicle distance to the intersection in the Box lighting configuration. The "+" represents the contrast at the mean detection distance.

4.3.4 Pedestrian Luminance

The luminance of the pedestrian increased as the vehicle approached in all the three lighting configurations (Figure 40). Increase in illuminance level is also associated with an increase in the pedestrian luminance. Also at every distance and illuminance level, pedestrian luminance was highest at the Approach lighting configuration and lowest at the Box lighting configuration (Figure 40).

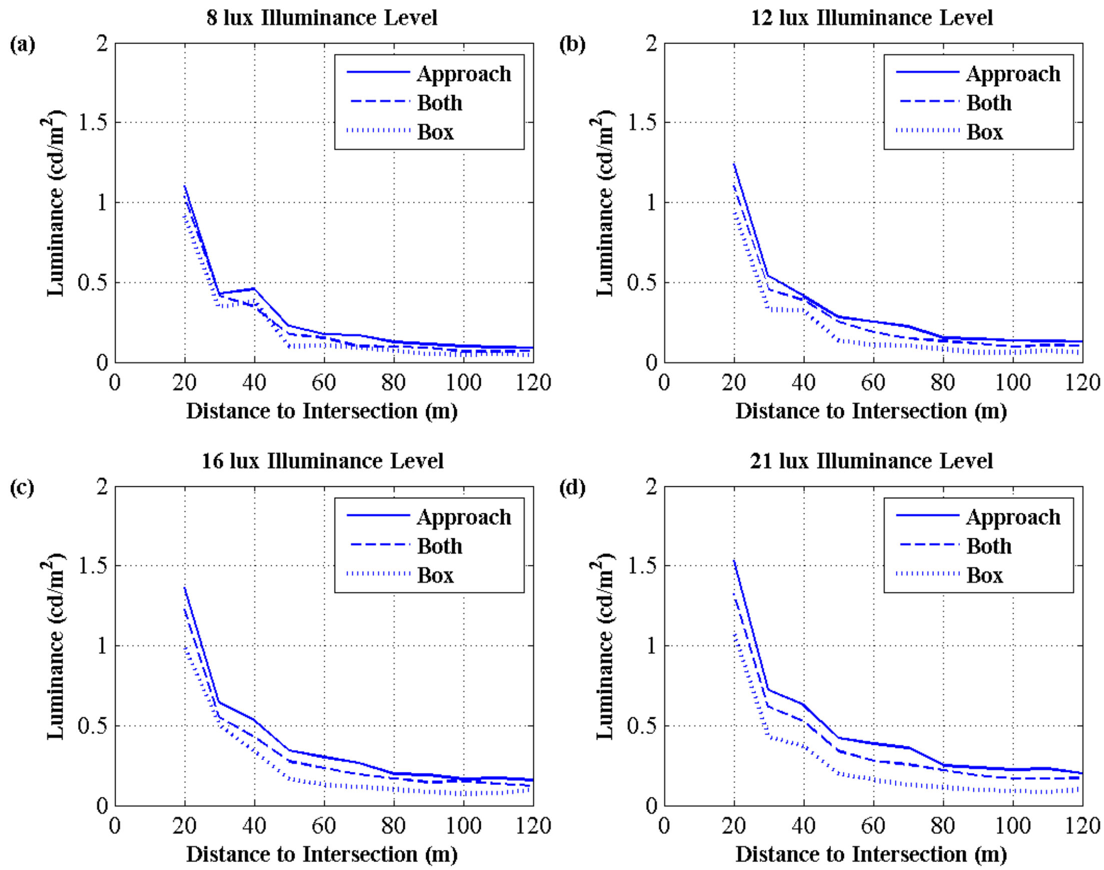

Figure 40. Pedestrian luminance as a function of the vehicle distance to the intersection.

4.3.5 Pedestrian Contrast

Pedestrian contrast varied with the distance to the intersection, lighting configuration and illuminance level (Figure 41). In the Approach lighting configuration, the pedestrian was always rendered in positive contrast and the contrast decreased as vehicle approached the intersection, until about 40 meters. After 40 meters, the contrast sharply decreases at 30 meters to the increases and increase rapids at 20 meters again. This behavior is consistent across all illuminance levels. In the Both lighting configuration, pedestrian contrast starts off at positive contrast and it decreases until 80 meters. From 80 to 50 meters, contrast polarity depended on the illuminance level. At the lower illuminance levels (8 and 12 lux), it went into negative contrast and plateaued. At the higher illuminance levels (16 and 21 lux), the pedestrian was rendered in positive contrast and plateaued. At 40 meters, the contrast increased rapidly at the illuminance levels and then decreased at 30 meters and increased again at 20 meters similar to the contrast behavior in the Approach lighting configuration. In the Box lighting configuration, the pedestrian was rendered in negative contrast at all distances except those greater than 90 meters and at 40 and 20 meters to the intersection respectively. At the questionnaire rating location, the pedestrian was always rendered in positive contrast at the Approach and Both lighting configurations and in negative contrast at the Box lighting configuration (Figure 41).

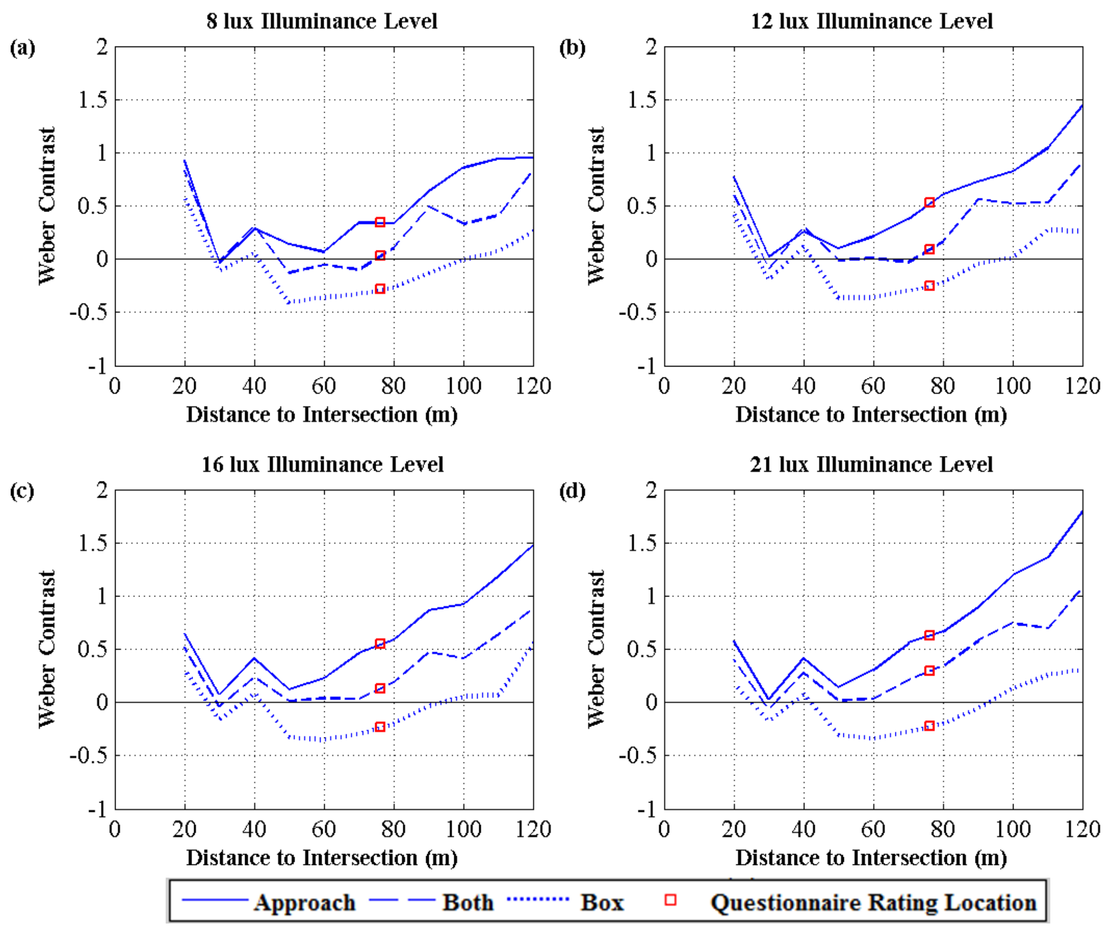

Figure 41. Pedestrian contrast as a function of the vehicle distance to the intersection. The red square represents the contrast of the pedestrian when viewed from the vehicle at the questionnaire rating location (76.2 m from the intersection).

4.4 Discussion

This study had two goals. The first was to assess the change in object luminance and contrast in the three intersection lighting configuration as a vehicle approached the intersection, and the second was to understand the relationship between object contrast and visibility (objective visual performance and perceived visibility). Also evaluated was the effect of contrast magnitude within positively contrasted targets. Four major findings were evident. First, target and pedestrian contrast and luminance were substantially affected by the intersection lighting configuration, illuminance level, location at the intersection, and the distance of the vehicle from the intersection. Second, targets in negative contrast were detected from longer distances than those in positive contrast. Third, within each contrast polarity, visual performance depended on the magnitude of contrast, with higher contrast associated with longer detection distances. Fourth, the relationship between pedestrian contrast and perceived visibility is complex, and a definitive conclusion could not be drawn regarding the effect of pedestrian contrast polarity on perceived pedestrian visibility.

Targets used in this study, placed at several locations within an intersection, underwent important changes in luminance and contrast as a vehicle approached the intersection. In general, target luminances increased as the vehicle got closer, mostly likely because targets entered the effective range of the vehicle headlamps. Increases in target luminance were not uniform, however, with target locations on the right hand side of the road (near right (Figure 29), near middle (Figure 30) and far right (Figure 32)) experiencing a larger increase in luminance compared to those on the left hand side (near left (Figure 31) and far left (Figure 33)). This difference could be attributed to the headlamp beam patterns, which are tailored to reduce luminous intensity in the left lane to reduce glare for oncoming drivers (Boyce, 2009; Wördenweber et al., 2007). Contrasts of targets at the locations used here also decreased until about 80 meters to the intersection. From closer than 80 meters, as the vehicle approached the intersection target contrasts increased as they entered the effective range of the vehicle headlamps and the luminance on the face of the target increased. This trend of increasing contrasts was clearly evident for the near right and near middle target locations (see Figure 34 and Figure 35), again because of the headlamp beam pattern.

Intersection lighting configurations also greatly influenced the magnitude and the polarity of contrast in which a target was rendered, as did the location of the target. In the Box lighting configuration, near right and near middle targets were initially rendered in negative contrast. These changed into positive contrasts as the targets became within the effective range of the vehicle headlamps, which increased the luminance on the face of the target resulting in higher contrast magnitudes (see Figure 34 and Figure 35). When the target transitions from negative to positive contrast or vice versa, it go through a phase of contrast neutrality where the target luminance is same as the background luminance and the target becomes invisible. They become visible again after the target luminance increase on the account of the vehicles headlamps. In the Approach and Both lighting configurations, near right and near middle targets, initially rendered in positive contrasts, also underwent an increase in the magnitude as the vehicle approached the intersection and the targets were in the effective range of the headlamps. The same phenomenon of increases in the contrast magnitude was observed for the far right and far left targets, which were rendered in positive contrast in all the three lighting configurations (see Figure 37 and Figure 38).

Targets rendered in negative contrast had longer detection distances than those rendered in positive contrast as evidenced by the significantly longer mean detection distances of near right and near middle targets in the Box lighting configuration compared to the Approach lighting configuration, where the near right and near middle targets were rendered in positive contrast. Thus negative contrast aided in increasing visual performance, which is in agreement with existing evidence that objects in negative contrast are detected sooner and from farther than objects in positive contrast (Aulhorn, 1964; Hills, 1975). Furthermore, the longest mean detection distances for targets rendered in positive contrast were shorter than mean detection distances of targets rendered in negative contrast (see Figure 42). For a target rendered in positive contrast to be detected at distances comparable to that of a target in negative contrast, the magnitude of the positive contrast required is quite high (Figure 38b-d). For targets rendered in the same contrast polarity, visual performance depended on the magnitude of the contrast. For example, the far left and far right target locations were rendered in positive contrast in the Box lighting configuration, but the former was rendered in higher magnitude of contrast (8 lux – 5.6 vs. 1.3, 12 lux – 7.3 vs. 4.3, 16 lux – 9.1 vs. 5.1 and 21 lux – 10.3 vs. 6.4). Along with a higher contrast for the far left target location, it had a significantly longer mean detection distances (8 lux – 89.9 vs. 60 m, 12 lux – 123.7 vs. 91.1 m, 16 lux – 126.2 vs. 90.5 and 21 lux – 119.5 vs. 97.2 m).

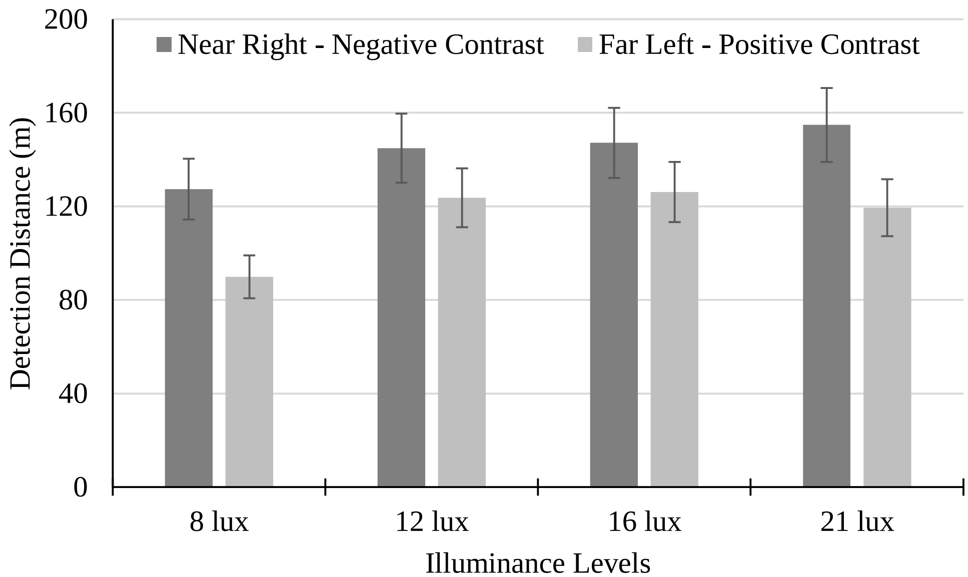

Figure 42. Mean detection distances of near right (negative contrast) and far left (positive contrast) target locations in the Box lighting configuration. Error bars reflect standard errors.

From the luminance measurements it was evident that the impact of headlamps begins from ~80 meters and increases rapidly as the vehicle gets closer to the intersection. Target locations in a lighting configuration with greater than 80 meter detection distances thus had minimal support from headlamp illumination during the target detection task. Such targets were apparently rendered in sufficient contrast (positive or negative) to be detected without headlamp support. Such an assessment was applied to each lighting configuration to determine if individual target locations were rendered in sufficient contrast. There were 20 total conditions (five target locations in each of four illuminance levels) in each lighting configuration.

In the Approach lighting configuration, the mean detection distance for every condition was less than 80 meters, indicating the targets were detected only after they were in the range of headlamps. Approach lighting thus did not render the targets in sufficient positive contrast to facilitate detection. In the Box lighting configuration, a majority of conditions (18 out of 20) had mean detection distances greater than 80 meters, indicating that they were rendered at magnitudes of positive or negative contrasts that facilitated detection beyond the range of headlamps. In the Both lighting configuration, more than half (11 out of 20) of target locations had mean detection distances greater than 80 meters, indicating that headlamps were required to increase contrast and facilitate detection. Thus, in the Box lighting configuration, while negative contrast helped in the detection of near right and near middle target locations, targets rendered in positive contrast had higher magnitudes of contrast compared to the contrasts of similar targets in remaining lighting configurations to facilitate better visual performance. These results are also reinforced by the perceived visibility of targets, where the Box lighting configuration had the highest mean ratings. Overall, intersection lighting configuration with an illuminated box rendered targets at sufficient negative and positive contrast to facilitate better visual performance and higher perceptions of target visibility.

As targets, pedestrians also underwent major changes in luminance and contrast as the vehicle approached the intersection. As the vehicle approached, the intersection (less than 60 meters) the increase in luminance was rapid, as the pedestrian was in the effective range of the headlamps which resulted in a higher rate of increase in the pedestrian luminance. Pedestrian contrasts decreased as the vehicles neared the intersection, until the pedestrian was in the range of headlamps, after which the contrasts increased. The increase in the contrast is likely a result of the increase in luminance on the pedestrian from headlamp illumination.

Perceived pedestrian visibility was highest in the Approach lighting configuration, although there were no statistical differences in the perceived visibility ratings of pedestrians between the three lighting configurations at illuminance levels greater than 8 lux. Differences in the perceptions of pedestrian and target visibility depended on the lighting configuration (and by extension object contrast, since the lighting configuration dictates the contrast in which an object is rendered) and object size. Within the Approach configuration, perceived pedestrian visibility was the highest and perceived target visibility was the lowest across all perceptual ratings. This result could be attributed to the object size since the simulated pedestrian used was substantially larger than the targets, and there is a direct relationship between object size and perceived visibility (Janoff, 1989). However, the photometric measurements from the current study also indicate that contrast polarity has a differential effect on the perceived visibility of objects of different sizes. Negative contrast appears preferable for smaller objects whereas positive contrast is preferable for larger objects (like pedestrians).

Green (2008) also noted that pedestrians might require positive contrast, to help in discerning features like face, hands etc., versus negative contrast where the pedestrian appears as a silhouette and feature determination could be difficult. However, the current photometric assessments of a pedestrian in different intersection lighting configurations has shown that determining pedestrian contrast polarity is complex. Pedestrians were often rendered in multiple contrast polarities (i.e., pedestrian's feet rendered in negative contrast and torso rendered in positive contrast, irrespective of lighting configuration; Figure 43). This difference makes it extremely difficult to determine if perceived pedestrian visibility was dependent on one or the other body region. On the contrary, targets, because of their smaller size, were are not rendered in multiple contrast polarities (see Figure 43), and for these it was easier to relate target contrast with visual performance and perceived visibility. Furthermore, because of the being rendered in multiple contrast polarities, large objects like pedestrians might not go through a phase of contrast neutrality like targets. Further research is recommended to better understand the relationship between pedestrian contrast and perceived visibility.

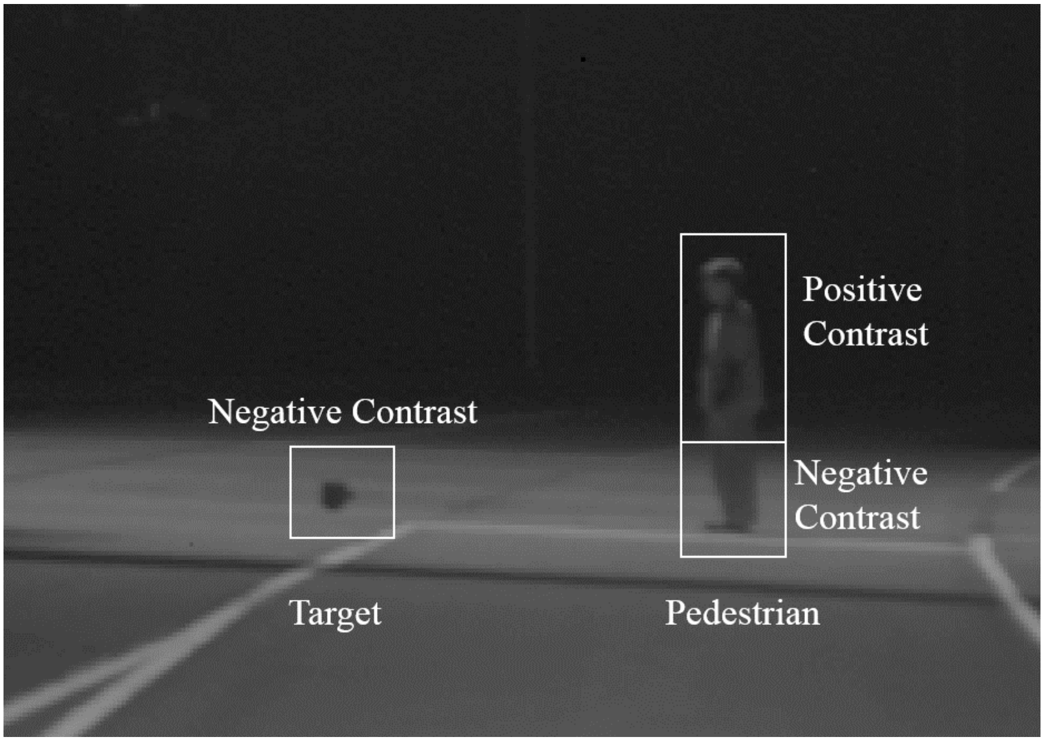

Figure 43. Contrast variance across objects. The pedestrian is rendered in multiple contrasts whereas there is no such variance for the smaller target

This study has a few important limitations that should be noted. First, only grey colored targets and pedestrians were used for measuring luminance and contrast. However, in actual nighttime road scenarios, important objects can have different colors, pedestrians wear different colored clothing, and both targets and pedestrians may not be stationary. Second, this study did not take into account the presence of other vehicles/headlamps or the presence of continuous lighting of the roads leading to an intersection. These factors might introduce additional sources of light, which might affect the luminance and contrast of targets and pedestrians. Third, the luminance and the contrasts of the targets and pedestrians in the study were obtained only for one specific headlamp. In reality, luminances and contrasts of objects could depend on the type and aiming of the headlamps, thought the patterns of object luminance and contrast with distance to the intersection should remain similar to what was observed in the present study. Fourth, in the Approach and Both lighting configurations used here, only one intersection approach was illuminated. In reality, when Approach and Both lighting configurations are used, all the approaches might be illuminated, 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 contrasts are difficult to predict. Therefore, results of this study may only be valid for intersections with a single source of illumination, such as those in isolated/and or rural areas. Finally, the contrasts of targets and pedestrian are applicable to roadway surfaces that are paved with asphalt. The contrasts of the targets and pedestrians would change depending on the surface of the roadway since it determines the background luminance. Roadway surfaces like concrete increase the background luminance which will lower the contrast of the object, conversely, roadway surfaces like newly laid asphalt, reduce the background luminance which could increase the object contrast. While the current work helps to isolate important factors that affect object contrast, future work to better understand the relationships between object contrast, visual performance, and perceived visibility under more diverse conditions.

In summary, intersection lighting design influences the luminance and contrast of targets and pedestrians. Target and pedestrian luminance increased as the vehicle approached the intersection. Object contrast varied not only with distance to the intersection, but also with location of the target within an intersection. Target and pedestrian contrasts were also affected the by vehicle headlamps. Target which underwent transitions from negative to positive contrast or vice versa, went through a phase of contrast neutrality during which they were invisible. Targets rendered in negative contrast had longer mean detection distances than those in positive contrast. The lighting configuration that illuminated the intersection box rendered almost all the target locations in sufficient positive and negative contrast to result in longer detection distances and higher perceived visibility. The relationship between pedestrian contrast and perceived pedestrian visibility was more complex, as pedestrians were rendered in multiple contrast polarities. The current findings have important implications for the lighting design of isolated/rural intersections. Illuminating the intersection box renders the targets located at entrances, exits, and middle of crosswalks in sufficient contrasts (both negative and positive) to ensure higher driver visual performance and perceived visibility compared to lighting designs that just illuminate the approach or both the approach and the box.

Chapter 5 – Conclusions

5.1 Summary of Findings

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 primary goal of this research study was to assess the influences of different lighting configurations and, ideally, identify one configuration that would maximize intersection visibility. The secondary goal of this study is to determine the illuminance level at which visual performance plateaus within each of the lighting configurations that were evaluated, so that appropriate illuminance levels could be identified that address both safety and energy efficiency. In additional to these practical goals, more basic questions were addressed regarding the underlying relationships between object contrast, luminance, and visibility at intersections. Results of this research were intended to help in recommending appropriate lighting configurations and illuminance levels at intersections, especially those intersections that are isolated and/or located in rural areas.

To achieve the aforementioned goals, three lighting configurations were developed and evaluated, and which differed in terms of the parts of the intersection illuminated. Three specific configurations were used, that illuminated the intersection approach (Approach), intersection box (Box), and both the intersection approach and box (Both). Each lighting configuration was evaluated under five levels of illumination. Visibility was assessed both objectively (visual performance) and subjectively (perceptions of visibility and glare). Visual performance was measured using detection distances of small targets located at pedestrian-vehicle conflict points (entrance, middle and exit to crosswalks). Perceived visibility and glare were measured using composite scores from Likert scale ratings. Perceived visibility was assessed in three areas: pedestrian visibility, target visibility, and intersection visibility. Separately, a photometric assessment was conducted, which measured the luminance and contrast of targets and a pedestrian at a range of distances to the intersection, and from the point of view of a driver seated inside a vehicle. The relationship between object contrast and visibility was also assessed in the three intersection lighting configurations and five levels of illumination.

The first analyses revealed that the part of the intersection illuminated played a paramount role in the visual performance of drivers. Box lighting yielded superior visual performance, which was indicated by longer target detection distances, fewer missed target detections, and more target identifications within a safe stopping distance. For this lighting configuration, visual performance plateaued between 8 and 12 lux illuminance levels. The remaining two lighting configurations (Approach and Both) had inferior visual performance and did not show any consistent plateauing of visual performance at any illuminance level. Superior visual performance in the Box configuration was argued to result from the contrasts in which targets were rendered. There were also age-related differences in visual performance, but these differences were consistent across the evaluated lighting configurations. These results indicate that Box illumination is an effective strategy to increase nighttime visual performance for a wider range of driver ages, and it could also be an energy efficient solution as it requires fewer luminaires to illuminate an intersection.

The second analyses showed that illuminating different parts of the intersection resulted in important differences in the perceptions of visibility and glare. These perceptions of visibility were generally consistent with the earlier results regarding visual performance. Box illumination resulted in the highest ratings of target and intersection visibility and the lowest ratings of glare, among the three evaluated lighting configurations. For pedestrian visibility, the Approach lighting configuration had the highest ratings of pedestrian visibility, though this difference was not statistically significant. Moreover, at illuminance levels greater than 8 lux, pedestrian visibility ratings in all three lighting configurations exceeded the "neutral" anchor. For the Box lighting configuration, plateaus in perceived visibility differed between assessment domains, occurring at 8 (target and intersection visibility) or 12 lux (pedestrian visibility) illuminance levels. Ratings of the Approach lighting configuration were less consistent, yielding the highest ratings for pedestrian visibility and the lowest ratings of target and intersection visibility. None of the three lighting configurations was a major source of perceived glare, though the Box lighting configuration yielded the lowest glare ratings. For the Box and Both lighting configurations, a positive correlation was also found between perceived target visibility and target detection distances. These results indicate that illuminating the intersection box has several advantages, in that it increases visual performance, increases perceived visibility, and reduces glare, while also requiring fewer of luminaires.

The third analyses showed that both target and pedestrian contrast and luminance were substantially affected by the intersection lighting configuration, illuminance level, location at the intersection, and the distance of the vehicle from the intersection. In general, as the vehicle gets closer to intersection, object contrast first decreases and then increases as it comes within the range of the vehicle's headlamps. Target locations with the longest detection distances were also identified as being rendered in negative contrast. For targets rendered in positive contrast, the detection distance was largely dependent on the magnitude of the contrast (i.e., higher positive contrast was associated with longer detection distances). The relationship between pedestrian contrast and perceived pedestrian visibility was more complex, as pedestrians were often rendered in multiple contrast polarities. The Box lighting configuration was argued as rendering targets in sufficient positive and negative contrasts to result in longer detection distances and higher perceptions of visibility, compared to the Approach and Both lighting configurations.

5.2 Recommendations

The following recommendation can be made based on the outcomes of this study. For isolated/rural single lane intersections without continuous roadway lighting on any of the approaching roads, and at speed limits up to 56 km/h (35 mi/h), the intersection box should be illuminated with a type V luminaire to a horizontal illuminance level of 12 lux at the entry to the crosswalk. This recommendation is based on the convergence of diverse evidence across the three assessments completed.

5.3 Practical Implications

This research endeavor has several practical implications. First, organizations that recommend lighting standards should adopt a proactive role in recommending lighting standards. Often, the addition of lighting to a road or an intersection is only considered if it meets or exceeds a certain night-today crash ratio, number of night crashes, traffic volume etc. Such an approach, clearly, is more reactive than proactive. A proactive approach, in contrast, should consider lighting as a design factor during the construction of roadways. Furthermore, lighting should be evaluated in terms of the visibility of pedestrians and/or small targets and not based on crash metrics or traffic volume. Failing to do this could lead to over-lighting of intersections, which could actually make the intersections less safe by introducing glare and reducing visibility; over-lighting would also result in energy wastage without any substantial benefits to visibility. Thus, lighting standards for roadways and intersections should be assessed and rigorously evaluated before being recommended. Second, this work presents a novel systems-level approach to evaluating nighttime visibility at intersections, by using both objective measures of visual performance in concert with perceptions of visibility and glare. The major advantages of this approach are that it: (1) considers the joint effects of overhead intersection lighting and vehicle headlamps; (2) considers the role of human visual response, and perceptions of visibility and glare; and (3) accounts for the multiple pedestrian-vehicle conflict locations at intersections, which are currently ignored. Future studies that evaluate intersection lighting design should consider and adopt such a systems-level approach.

5.4 Future Research

There are several possibilities to extend this research. First, pedestrian detection distances were not measured, as was the case for targets, since the length of intersection approach was not long enough to obtain such measures. Future studies in nighttime intersection lighting evaluations should consider objective measures of pedestrian visibility. Second, this research was conducted on an intersection where all the approach roads to the intersection had a single lane and a single speed limit (56 km/h or 35 mi/h). Future work should explore the effects lighting designs on visibility at intersections with multiple lane approaches and with higher speed limits. Moreover, illuminating such intersections could pose additional challenges, since more than one luminaire could be required to provide appropriate illumination and since higher speeds could alter a driver's visual behavior in such a way to have detrimental effects on visibility. Third, nighttime visibility at intersections should also be evaluated for intersections that have continuous roadway lighting present on one of the entry roads. Fourth, future work should explore the effect of illuminating all the intersection approaches on visibility of objects, since object contrast is substantially affected by the presence of multiple light sources. Finally, more research is required to understand the effects of contrast on the visibility of larger objects such as pedestrians. As this work showed, pedestrians are presented in multiple contrasts, making it difficult to determine the effects of such multiple contrasts on perceptions of visibility. Fundamental research to understand the effect of multiple contrasts on visibility can help in the development of effective lighting strategies to illuminate pedestrians and increase their conspicuity.

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Appendix A – Informed Consent Form

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

Informed Consent for Participants of Investigative Projects

Title of Project: Initial Investigation of Intersection Lighting

Investigators: Dr. Ronald Gibbons and Rajaram Bhagavathula

I. The Purpose of this Research/Project

The focus of this study is evaluate alternative intersection lighting designs. We will be testing three different kinds of intersection lighting designs under five different levels of lighting; and how they affect a driver's ability to see. Once this data has been collected, we can determine the effect of different intersection lighting design and lighting levels that are more reliable for night driving. Approximately 40 people will take part in the study.

II. Procedures

During the course of this experiment you will be asked to perform the following tasks:

Visit 1 (approx. 30-45 minutes):

1) Read this Informed Consent Form and sign it if you agree to participate.
2) Show your valid driver's license.
3) Complete vision tests.
4) Complete a W9 tax form for payment purposes.
5) Schedule for return visit to VTTI (if you meet criteria for the study).

Visit 2 (approx. 1.5 hours):

1) Re-read this Informed Consent Form and re-sign it if you agree to participate.
2) Show your valid driver's license.
3) Drive an instrumented vehicle on the Smart Road at night and observe different intersection lighting designs and rate them. Video and audio data of the vehicle interior will be collected during the drive. An experimenter will be with you throughout the study.

Visit 3 (approx. 1.5 hours):

1) Re-read this Informed Consent Form and re-sign it if you agree to participate.
2) Show your valid driver's license.

3) Drive an instrumented vehicle on the Smart Road at night and observe different intersection lighting designs and rate them. Video and audio data of the vehicle interior will be collected during the drive. An experimenter will be with you throughout the study.

Visit 4 (approx. 1.5 hours):

1) Re-read this Informed Consent Form and re-sign it if you agree to participate.
2) Show your valid driver's license.
3) Drive an instrumented vehicle on the Smart Road and observe different intersection lighting designs and rate them. Video and audio data of the vehicle interior will be collected during the drive. An experimenter will be with you throughout the study.

For the Smart Road portion of the study, you will drive an experimental vehicle. You will be asked to notify the experimenter when you can see the different wooden targets and pedestrians located near the road.

It is important for you to understand that we are not evaluating you or your performance in any way. You are helping us to evaluate different intersection lighting designs and their effects on target and pedestrian visibility. The opinions you have will only help us do a better job of identifying factors that may improve intersection lighting design. The information and feedback that you provide is very important to this project. The initial screening session is expected to last approximately 30-45 minutes and the return visit experimental sessions are expected to last approximately 1.5 hours each.

III. Risks

There are risks or discomforts to which you may be exposed in volunteering for this research. They include the following:

For the Smart Road portion of the study, the risks to the participants are similar to that of driving an unfamiliar vehicle at a speed of up to 35 miles per hour in clear weather conditions at night on a road with minimal traffic and off road objects.

While the risk of participation in this study is considered to be no more than that encountered in everyday driving, if you are pregnant you should talk to your physician and discuss this consent form with them before making a decision about participation.

Some studies at VTTI involve an unanticipated event. You may or may not encounter such an event during this study. Please be aware that events such as equipment failure, changes in the test track, stray or wild animals entering the road, and weather changes may require you to respond accordingly.

Finally, due to the length of the study, you may experience fatigue.

The following precautions will be taken to ensure minimal risk to you:

1) Multiple on-road experimenters will be equipped with flashlights and will be instructed to be watching for the presence of deer approaching the test area. Loud noise and the presence of multiple on-road experimenters will be used to keep deer away from the testing area. However, you should also stay alert for deer and other wildlife on the road.
2) An experimenter will monitor your driving and will ask you to stop if he or she feels the risks are too great to continue.
3) You are encouraged to take breaks if you desire, and may withdraw from the study at any time.
4) The experimenter will be present while you are driving. However, as long as you are driving the research vehicle, it remains your responsibility to drive in a safe and legal manner.
5) You will be required to wear the lap and shoulder belt restraint system while in the car. The vehicle is equipped with a driver's side and passenger's side airbag supplemental restraint system, fire extinguisher and first-aid kit. The experimenter will also have a cell phone.
6) There will be other traffic on the Smart Road that is not involved in the study. The other vehicles will be on separate section of the road and you will not encounter them while you are driving. In the event that they need to use the same section of road we are using to exit or enter the road, I will instruct you to pull over on the shoulder while they pass.
7) In the event of a medical emergency, or at your request, VTTI staff will arrange medical transportation to a nearby hospital emergency room. You may elect to undergo examination by medical personnel in the emergency room.
8) All data collection equipment is mounted such that, to the greatest extent possible, it does not pose a hazard to you in any foreseeable case.
9) Testing will be cancelled in the event of poor weather resulting in wet or icy pavement, or poor visibility.
10) On-road experimenters are in contact with in-vehicle experimenters to notify them when objects are in place.
11) All objects are chosen and placed such that impact with them will not harm the driver.
12) On-road experimenters will maintain a safe distance of at least 80 feet from all moving vehicles on the roadway, and will clear the roadway if that distance is breached, or if instructed by in-vehicle experimenters. In the event that you do not detect a pedestrian from a sufficient distance, the pedestrian will automatically clear the roadway if the vehicle enters the pedestrian safety

zone. It should also be noted that pedestrians for this study will be on the shoulder of the road, not in the roadway.

In the event of an accident or injury in an automobile owned or leased by Virginia Tech, the automobile liability coverage for property damage and personal injury is provided. The total policy amount per occurrence is $2,000,000. This coverage (unless the other party was at fault, which would mean all expense would go to the insurer of the other party's vehicle) would apply in case of an accident for all volunteers and would cover medical expenses up to the policy limit. For example, if you were injured in an automobile owned or leased by Virginia Tech, the cost of transportation to the hospital emergency room would be covered by this policy.

Participants in a study are considered volunteers, regardless of whether they receive payment for their participation; under Commonwealth of Virginia law, worker's compensation does not apply to volunteers; therefore, if not in the automobile, the participants are responsible for their own medical insurance for bodily injury. Appropriate health insurance is strongly recommended to cover these types of expenses. For example, if you were injured outside of the automobile owned or leased by Virginia Tech, the cost of transportation to the hospital emergency room would be covered by your insurance.

IV. Benefits of this Project

While there are no direct benefits to you from this research, you may find the experiment interesting. No promise or guarantee of benefits is made to encourage you to participate. Participation in this study will contribute to the improvement of driver safety.

V. Extent of Anonymity and Confidentiality

The data gathered in this experiment will be treated with confidentiality. Shortly after participation, your name will be separated from your data. A coding scheme will be employed to identify the data by participant number only (e.g., Participant No. 1). At no time will the researchers release data identifiable to an individual to anyone other than VTTI staff working on the project without your written consent. De-identified data collected in this project may be used in future VTTI research projects by qualified VTTI researchers who are not part of the original team. All written and digital data associated with this project will be destroyed after seven years.

It is possible that the Institutional Review Board (IRB) may view this study’s collected data for auditing purposes. The IRB is responsible for the oversight of the protection of human subjects involved in research.

VI. Compensation

You will be paid $30.00 per hour for participating. You will be paid at the end of the last visit with a check. If you do not meet the criteria for this study based on the vision tests, you will be paid at the end of the 1st visit with a check for your time. If you choose to withdraw before completing all scheduled experimental tasks, you will be compensated for the portion of time of the study for which you participated. You will not be paid for travel to and from VTTI. If these payments are in excess of $600 dollars in any one calendar year, then by law, Virginia Tech is required to file Form 1099 with the IRS. For any amount less than $600, it is up to you as the participant to report any additional income as Virginia Tech will not file Form 1099 with the IRS.

VII. Freedom to Withdraw

As a participant in this research, you are free to withdraw at any time without penalty. If you choose to withdraw, you will be compensated for the portion of time that you completed. Furthermore, you are free not to answer any question or respond to experimental situations without penalty. If you choose to withdraw while you are driving on the test route, please inform the experimenter of this decision and he/she will provide you with transportation back to the building.

VIII. Approval of Research

Before data can be collected, the research must be approved, as required, by the Institutional Review Board for Research Involving Human Subjects at Virginia Polytechnic Institute and State University and by the Virginia Tech Transportation Institute. You should know that this approval has been obtained. This form is valid for the period listed at the bottom of the page.

IX. Participant's Responsibilities

If you voluntarily agree to participate in this study, you will have the following responsibilities:

1. To follow the experimental procedures as well as you can.
2. To inform the experimenter if you have difficulties of any type.
3. To wear your seat and lap belt.
4. To abstain from any substances that will impair your ability to drive.
5. To obey traffic regulations and maintain safe operation of the vehicle at all times.
6. To adhere to the 35 mph (maximum) speed limit on the Smart Road for this experiment.

X. Participant's Acknowledgements

☐ (Females Only) If I am pregnant, I acknowledge that I have either discussed my participation with my physician, or that I accept any additional risks due to pregnancy.

XI. Participant's Permission

I have read and understand the Informed Consent and conditions of this project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent for participation in this project.

If I participate, I may withdraw at any time without penalty. I agree to abide by the rules of this project.

Participant's Name (Print) Signature Date

Experimenter's Name (Print) Signature Date

Should I have any questions about this research I may contact:

Ron Gibbons 231-1500 RGibbons@vtti.vt.edu

Rajaram Bhagavathula 231-5209 RBhagavathula@vtti.vt.edu

If I should have any questions about the protection of human research participants regarding this study, I may contact:

Dr. David Moore,

Chair Virginia Tech Institutional Review Board for the Protection of Human Subjects

Telephone: (540) 231-4991;

Email: moored@vt.edu;
