An Evaluation of AGi32 Software for Modeling Roadway Illumination

by

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Abstract

Lighting design software like AGi32 is typically used in the scoping and design phases of constructing roadway facilities, however, an alternative purpose exists. AGi32 may be used by Collision Reconstructionists to evaluate illumination at road facilities where the light installation has been changed, reconfigured, or, repaired. To evaluate AGi32 for this purpose, this study sought to evaluate the performance of three modeled environments in AGi32, versus corresponding field measurements collected under a single High Intensity Discharge (HID) luminaire, an out of service luminaire, and a converted Light-Emitting Diode (LED) luminaire. The results of this study concluded that no statistically significant differences existed in any of the tested scenarios between field observations and modelled observations. Furthermore, in consideration of all three scenarios, AGi32 overpredicted field measurements by an average of 0.61 lux (combined average of all three scenarios), with a corresponding average standard deviation of 3.05 lux.

Acknowledgements

This step is one I would not have been able to take without the assistance of many people in my life. I spent a lot of time researching, a lot of time under streetlights in the early morning hours collecting measurements, and a lot of time at my desk, working and learning about this software and about lighting in general. I'd like to thank my employer, CEP Forensic, for providing me with the opportunity to pursue my studies. I would like to thank my fiancée, Marie-Hélène, for enabling me to pursue my master's by supporting my efforts. Lastly, a big thank you to my supervisor Dr. Eric Hildebrand, for sharing with me your passion for transportation engineering, your knowledge, and your patience and persistence in seeing me through to complete my graduate studies. I wish you a happy retirement.

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Chapter 1: Introduction

This chapter introduces the fundamental elements of this study including background information, the key issues this study seeks to address, and it summarizes the scope of the completed study.

1.1 Background

The first documented motor vehicle collision occurred in New York City in 1896, when a "horseless carriage" lost control due to its speed and struck a bicyclist (OldNYTours.com, 2015). Since 1896, collisions have been documented that have occurred between a variety of other vehicles, animals, objects, and of course humans (pedestrians). Unfortunately, collisions between vehicles and vulnerable road users such as pedestrians often result in severe injuries or death, and efforts have been made to advance vehicle technology and safety to aide in reducing the severity and frequency of such collisions.

Alongside motor vehicles, street lighting has also come a long way from its first iterations. The first documented public application of electric street lighting occurred in 1878 in Paris, France, where carbon-arc lamps began to be adopted over their earlier gas-powered models (Eaton, 2022). The historical adoption of electric lighting over gas predecessors is similar to today's adoption of light emitting diode (LED) luminaires, over the earlier high intensity discharge (HID) predecessors. The

motivation for road authorities to change from HID to LED luminaires is due in part largely to the increased public benefits that LEDs provide. These benefits include a reduction of operation/energy costs over the life cycle of the luminaire, decreased maintenance costs, and increased environmental benefit through reduction of "over lighting" and the ability to provide more efficient and optimized lighting layouts. LEDs and optimized lighting designs on roadways ensure a decreased environmental impact is experienced, while maintaining safety and security requirements as defined by various design guidelines. The most commonly referenced guidelines in the North American industry are authored by organizations such as the Transportation Association of Canada (TAC) with the Guide for the Design of Roadway Lighting (TAC, 2006), and the Illuminating Engineering Society of North America (IESNA), with RP-8-21, or the Design of Roadway Facility Lighting (IESNA, 2022).

Contributions to such standards include safety data from organizations such as the National Highway Traffic Safety Administration (NHSA). To better understand the occurrence of pedestrian collisions, NHTSA regularly collects data, enabling organizations like IESNA, TAC, and the National Safety Council (NSC) to complete independent analyses and studies. One such effort recently reported that in 2022, an estimated 7,522 pedestrians died in traffic collisions on public roads in the United States (NSC, 2024). This study further concluded that 39.9% of these collisions occurred at night during dark conditions with artificial lighting present, 34.6% with no lighting present, and 7% during dawn/dusk conditions. Interestingly 76% of these

impacts occurred on open roads, versus 24% occurring at intersections. These findings illustrate that despite an immense leap forward technologically speaking from gas powered lamps and the “horseless carriage” of 1896, vehicles driven at night on roadways under artificially lit conditions continue to strike and kill or injure a large number of pedestrians. The relevance of such an observation is that collision reconstructionists require an understanding of how the human eye perceives and interacts with light, and of basic lighting design principles, to fairly provide professional opinions on such matters.

1.2 Problem Definition

Oftentimes after a collision occurs insurance companies, lawyers, and engineers working in the field of collision reconstruction, are tasked with assisting the injured party to recoup their losses; typically in the form of a financial settlement and/or a medical treatment plan. The role of an engineer is to collect, analyze, interpret, and present physical evidence that was generated from the collision, to assist the triers of fact to assign liability and apportion related damages to the responsible parties. The question of liability for the occurrence of a collision becomes more complicated when claims of inappropriate or deficient lighting conditions are made. This claim is often made when a streetlight is identified to have been non-operational in the area of the collision. Unfortunately claims of this nature can take years to resolve, and oftentimes

engineers/collision reconstructionists are not engaged until a year or two after the incident occurred. Therefore, as a by-product of seeking increased public benefit by re-configuring lighting installations, upgrading from HID to LED luminaires, or simply by repairing a defunct luminaire, reconstructionists are left with little opportunity to obtain relevant illumination measurements and assess lighting levels in the area that the collision took place. Further, safety issues must be considered, as turning off lights at night and/or closing lanes and roadways to perform night-time visibility assessments can be dangerous in high volume traffic facilities, with such efforts often requiring months of logistics and planning and high costs. Therefore, this study sought to evaluate the use of AGi32 in place of completing field work as an alternative method for engineers and collision reconstructionists to assess lighting conditions at the location a collision took place. If proven accurate, it could mean this work can be completed when it is otherwise not possible, or costly to do so, all the while without having to expose personnel to excessive risk.

1.3 Study Goal

The overall goal of this study was to examine if AGi32, an industry-standard lighting design software package, could be used reliably in place of collecting physical lighting measurements in the field. Therefore, the objective of this study was to complete and present the results of a comparative analysis of illumination measurements collected in the field, against the theoretical outputs modelled within AGi32.

1.4 Scope

The completion of this study required a basic understanding of how the human eye perceives and interacts with light, as well as an understanding of basic lighting design principles. Additionally, the use of illumination modelling software was required, so research and training on the use of such software was necessary. Therefore, research and literature reviews were completed into these various subjects; and training modules on streetlighting design provided by AGi32, the selected software, were reviewed.

Various limitations existed due to the limited scope and size of this study. Specifically, only one lighting design software package was evaluated for use. It is recognized that other lighting design software is in use by industry personnel, and so the use of a different software than AGi32 could result in differing outcomes. Furthermore, in managing the size of this study, only a select number of sites that either met safety or specific scenario criteria were considered. These sites were equipped with specific types of luminaires, and/or had luminaires that were converted or repaired from HID to LED. Therefore, the sample size of data that this analysis considered was small. Lastly, the data collection in the field was conducted only during summer months under dry environmental conditions within a specific temperature range. This reduced the variation of field observations due to environmental factors. Therefore, observations during precipitation, in foggy or wet conditions, or with snow or ice on the ground were not considered within the scope of this study.

Chapter 2: Literature Review

The following sections provide a review of research and background required for the completion of this study. It also provides a brief reference to a validation study of AGi32 against requirements as set out by CIE 171:2006, a standard developed by the International Commission on Illumination which specified 33 test cases to be modeled in lighting design programs to validate their efficacy for use (Dau, 2007).

2.1 Fundamentals of Lighting & Human Visual Performance

At its foundation, the primary purpose of roadway illumination is to achieve a level of visibility that provides the ability of motorists, pedestrians, and other users to efficiently observe all significant details of their environment with distinction and certainty (FHWA, 2012). This includes but is not limited to the alignment of the road, the condition of the road, as well as any obstacles either within the roadway or along its sides. Ideally, good design allows for users to see, anticipate, and react to other users and objects around them in a timely manner, such that they can thereby avoid collisions along their desired travel route.

2.1.1 Visibility of Light

To understand how the human eye perceives and responds to light, we first must have a basis of understanding of light itself. Light is visible electromagnetic radiation which

travels in wavelengths of between 380 nanometres (nm) to about 780 nm (TAC, 2006). When this energy is received by the human eye, its characteristics are perceived as light, and its color and brightness is a direct correlation of its respective light source color and wavelength. Figure 2-1 shows the Electromagnetic Spectrum scale:

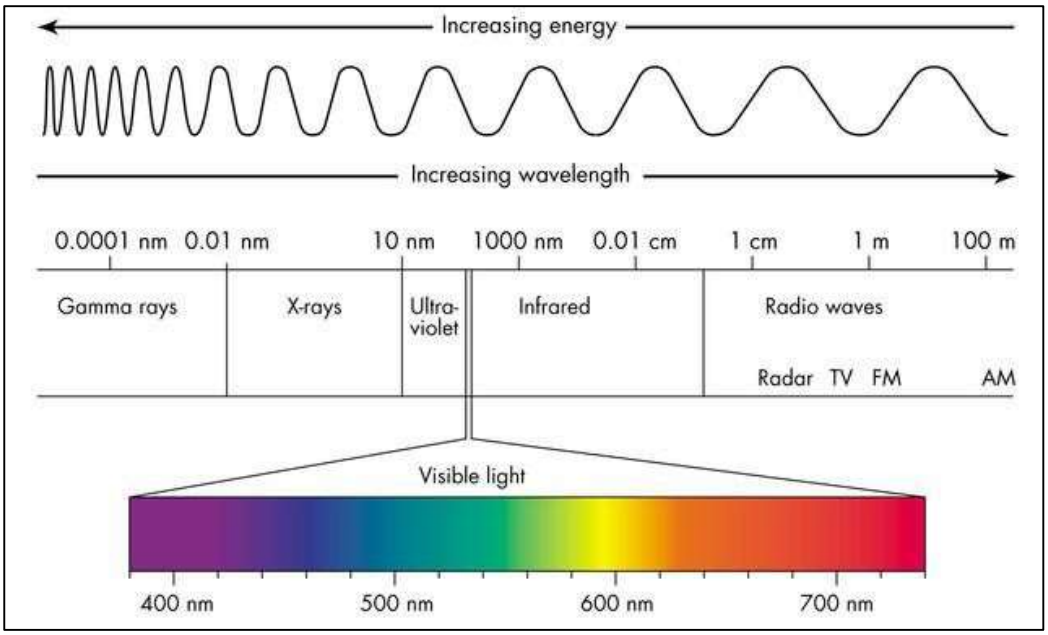


Figure 2-1 The Electromagnetic Spectrum. [source: artofproblemsolving.com, 2022]

From above, the first characteristic of light is its color. The color of light is defined using a Correlated Color Temperature (CCT) scale, represented in degrees Kelvin. This correlation of color scale is set to the Sun as its reference and is based upon how the human eye perceives different colors of the same object, all dependent upon the level of light entering the eye. Figure 2-2 provides an example of the CCT scale:

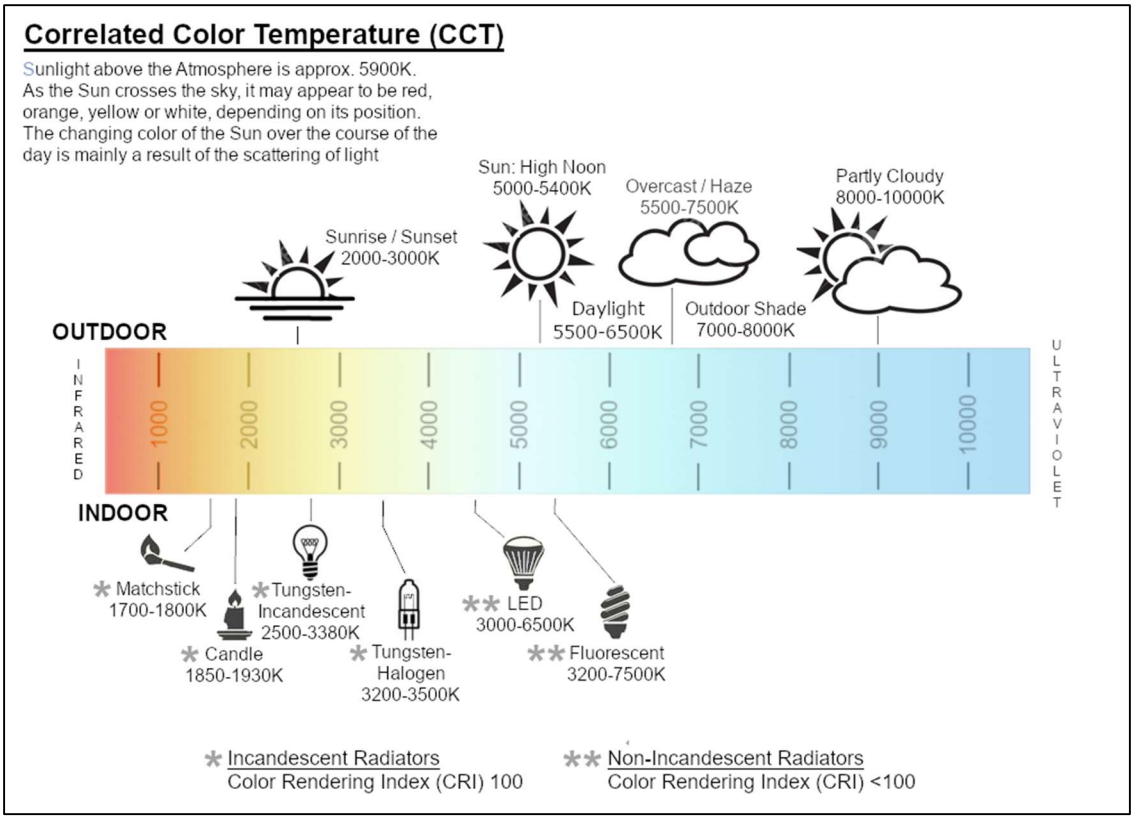


Figure 2-2 Correlated Color Temperature (CCT) Scale. [source: paintingframesplus.com, 2021-2022]

As discussed below, night-time visibility (*i.e.*, performance of the human eye at night) limits the importance of the color of light. Rather, the predominant characteristic of light for nighttime visibility is its Spectral Power Distribution (SPD). The Illuminating Engineering Society of North America (IESNA) defines SPD as:

> "a pictorial representation of the radiant power emitted by a light source at each wavelength or band of wavelengths in the visible region of the electromagnetic spectrum." (ANSI/IES RP-8-21, 2022)

This means that light sources have differing spectral power distributions when operating at different energy levels. In essence, the light source will emit light at differing efficiencies over a range of wavelengths, informing that each light source type has differing effectiveness levels. To illustrate, Figure 2-3 shows the spectral power distributions of traditional lighting sources over the wavelength range of visible electromagnetic radiation.

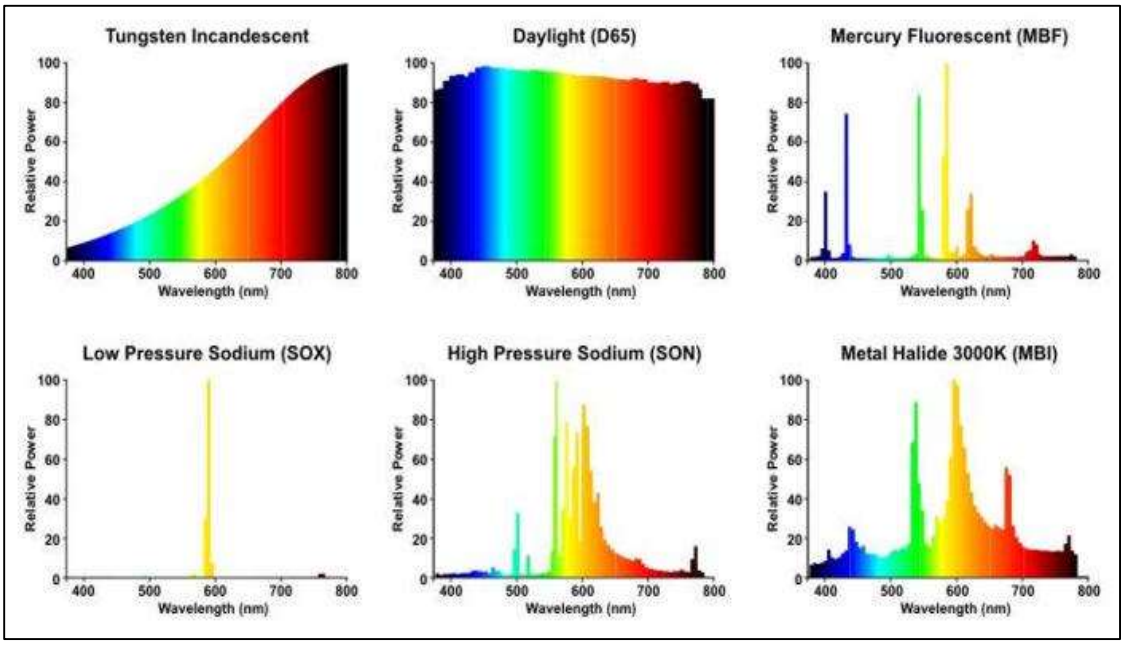


Figure 2-3 Spectral Power Distribution (SPD) Diagrams of Traditional Light Sources. [source: Lamptech.co.uk, 2011]

Based on SPD, it is known that the human eye does not view all wavelengths equally. When set to the same energy expenditure, light will be emitted at the light sources' resultant wavelength, and therefore each type of light source does not match the performance of another at that same energy input. Once received by the eye the

relative brightness of light perceived is either less or more bright than the other, despite the input energy being the same. For this reason, light levels (*i.e.* illuminance and luminance) cannot be measured based upon energy expenditure alone (*e.g.*, wattage) and instead the measurement must be related to the visual performance or 'sensation' experienced by the human eye that light produces.

To measure light, tools have been developed to allow for the determination of illuminance and luminance within any given area. Simply put, illuminance is the amount of light falling onto a surface from a light source, whereas luminance is the amount of light being reflected from the surface. Figure 2-4 illustrates this concept in the context of road lighting.

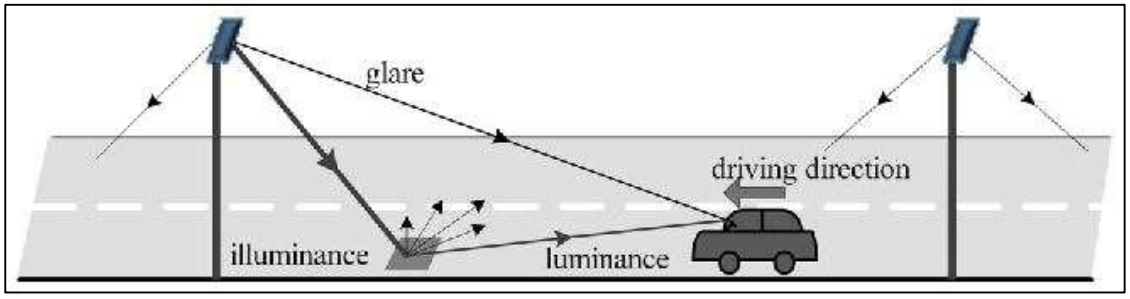


Figure 2-4 Illuminance vs. Luminance in the Context of Road Lighting. [source: Hu X., Keyuan Q., 2013]

As shown, the light falling from the luminaire is illuminating the roadway. The asphalt then reflects the light, diffusing it and the reflected light provides luminance of the roadway surface. Figure 2-4 also introduces glare coming from the light source and observed by the driver, but due to the many issues that glare introduces to design, this

concept will be discussed in more detail later.

To appropriately measure lighting levels in a given subject area, a photometer or 'lux-meter' can be used to evaluate the amount of lux falling from the light source. This measurement is influential on a designs performance if approaching it from the illuminance method. Recognizing, however, that illumination is not exactly what humans see, luminance measurements may also be prudent in good design as it accounts for the reflectance levels of the asphalt and all other objects/surfaces within the lit area. Stated more simply, luminance measurements are more reliable to evaluate what the observer may see, and as such, luminance meters are designed to capture spot measurements of reflected light. The challenge of capturing luminance measurements is that it is highly dependent upon the color and material of the surface from which the light is being reflected. As a result of this variability, design guidelines tend to focus upon illuminance measurements for setting appropriate levels of light to be provisioned for specific facility types (*e.g.,* a pedestrian crossing should have higher lighting levels than a rural road with no pedestrian activity).

2.1.2 The Human Eye

How the human eye can process light and generate signals to the brain for visual performance is related to its anatomy. The eye structure and its relative visual performance is a function and condition of the cornea, iris, pupil, and retina. The retina is the part of the eye that is sensitive to light, and through photoreceptors, much like

those used in measurement equipment, it turns the captured light into signals for the brain.

There are two types of photoreceptors found in the eye known as rods and cones. Cones are located in the center of the retina and are responsible for visual acuity (*i.e.* the ability to discern detail) and are highly sensitive to light and color. Conversely, rods, which are predominantly found in the outer part of the retina, are responsible for peripheral vision. As rods are highly sensitive to low intensity light, it is the rods that contribute to night-time vision. Figure 2-5 illustrates the anatomy of the human eye.

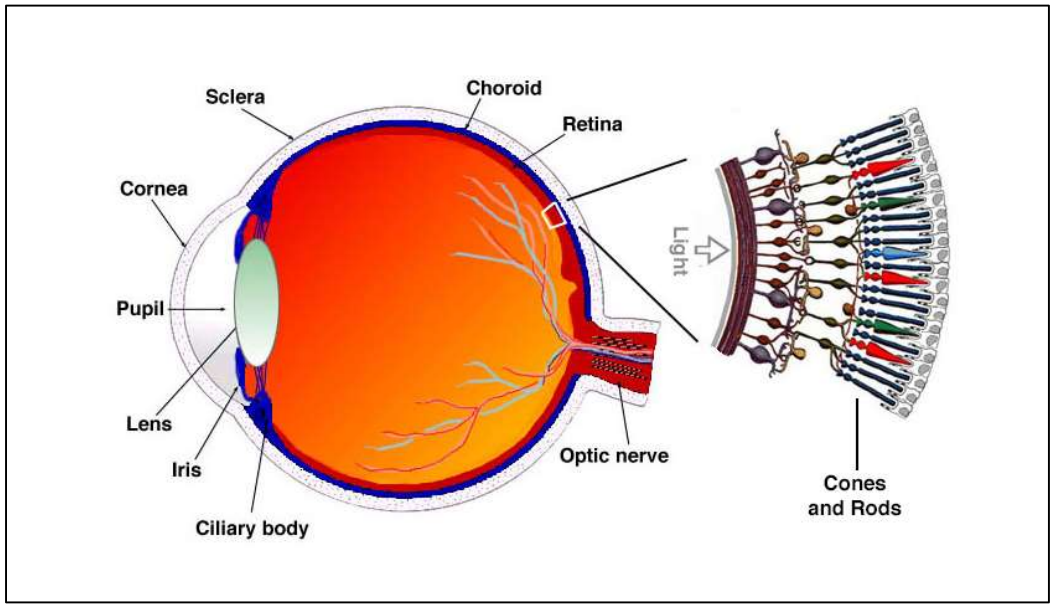


Figure 2-5 The Anatomy of the Human Eye. [source: blueconemonochromacy.org, 2018]

Light enters the eye through the cornea and the iris can expand or contract, altering the size of the pupil to regulate the amount of light allowed into the interior of the eye as a function of the light's brightness. During daytime or in bright areas, the pupil is small as less light is required for visual performance. At night, the pupil can become quite large to allow as much light as may be available into the eye for vision. During the day, vision is conducted primarily through the cones and this is called 'Photopic Vision'. At night, the rods are most prevalent, and this is called 'Scotopic Vision' (TAC, 2006). At twilight, a mix of both rods and cones are engaged and this vision is called 'Mesopic Vision'. It is mesopic vision that lighting designers strive to achieve in provisioning lighting, so they can achieve engagement and resultant benefits from both types of photoreceptors within the eye. In addition to achieving mesopic vision levels of luminance that align with the performance limitations of the human eye, good lighting design should seek to minimize non-uniformities in light levels. In short, introducing bright light to an eye that is adjusted to seeing in the dark with little to no light can be sudden and temporarily reduce visual performance. Conversely, when leaving a well-lit area, the eye can take time to re-adjust to the lack of light available. Therefore, it becomes harder to see until the eye re-adapts and becomes used to the lighting level again. Designers thereby consider uniformity limits to mitigate the frequency with which the eye is required to adjust, and they also attempt to mitigate glare by using luminaires that have proper optical designs (TAC, 2006).

In addition to performance limits, light engineers also seek to address common issues

that the human eye experiences as it ages. As the eye ages its performance degrades due to various factors including the materials of the eye becoming less resilient, distorted, or damaged, or if cataracts or astigmatism develops. These issues can lessen the eyes' ability to perceive light correctly. Further, as eyes age, they can lose their efficiency at adapting to light level fluctuations quickly. This supports the importance of placing light sources with a uniform spacing and limited glare, so these specular effects become less troublesome for drivers.

It is for these reasons that lighting design has evolved from first being tasked with the classic problem solving of "how much light and where", to now include considerations for road user performance and human ability, environmental and energy conservation factors, aesthetics, and economic constraints.

2.2 Approaches & Methodologies of Road Lighting Design

Current practice among road authorities and governments throughout North America consistently try to strike a balance between the economic costs and the associated safety benefits of installing lighting systems along roadways. Due to the primary goal of lighting being to reduce collision rates, facilities with a high confluence of vehicles and pedestrians typically receive priority. Secondary goals to provision street lighting is to reduce crime or improve personal safety. As such it is more likely that areas and roads with an urban classification will receive lighting treatment. Conversely,

additional diligence is taken for rural and suburban areas and the use of a warranting system may be necessary to fairly identify cost-effective locations for lighting treatment. Guidance on lighting warrant analysis is provided commonly in regional manuals as well as in national guides, with most regions deferring warrant considerations to those published within IESNA RP-8 (2022), or the TAC Guide for the Design of Roadway Lighting (2006). Once lighting is determined to be warranted based either on the facilities traffic volumes, pedestrian volumes, collision rates, or some other factor like its proximity to well-lit infrastructure, the next step is to select the desired equipment including luminaires and poles, to then be evaluated through the design process.

2.2.1 Lighting Design Process

The complete lighting design process is best summarized in about 14 steps (Minnesota, 2010). To begin, the facility to be lit is assessed and the minimum lighting levels are determined based on its classifications and traffic volumes. As the spacing and placement of the lights are reliant on the luminaire type, distribution, and performance, the equipment is then selected for the design. With the equipment identified, the engineering analysis (*i.e.*, one of the three design calculation methods) can begin. Once complete, the accuracy of the design must be assessed and often due to issues with uniformity tolerances, glare, over-lighting, or economic constraints, the early

stages of the design process are iterated to find an optimized solution. Therefore, different luminaire and pole combinations are commonly evaluated during this process.

The latter portion of the design process also gives extensive considerations to identifying locations of power sources and checking the physical abilities of the selected equipment. This process can involve laying out the lighting system, its wiring, conduit, and trenching requirements, and then to evaluate the anticipated voltage drops across the system. Once the lighting plan is optimized, it is then that the design can be finalized. The end stages of the design may include identifying salvage and removal requirements, quantities of all items including spare components and inventory requirements, maintenance plans, etc.

2.2.2 Design Calculation Methodologies

As previously noted, the goal of designers is to engage mesopic vision to entice the best visual performance possible by motorists for night-time driving. Studies of mesopic vision have determined that typical luminance levels range for human sight between 0.005 to 5.0 cd/m^2 (Lighting Analysts Inc., 2021). This range informs the luminance levels that a road may require by design, but due to variations in how to properly measure luminance as mentioned previously, this range also infers appropriate illuminance levels. As such, TAC (2006) as well as other national design guides within North America provide various tables denoting minimum lighting

requirements based on the classification of the road for both luminance, and illuminance.

From review of some regional design guidelines, the most desired approach is to use the luminance method. However, there exist certain situations where the luminance method may not be appropriate or practical for use, like on curves in roads, cul-de-sacs, or roundabouts, and therefore the illuminance method is more aptly used. The TAC and IESNA RP-8 guides do specify tables for both luminance and illuminance lighting levels; and so these two methods appear to be specified interchangeably. Lastly, a third commonly used method is the small target visibility (STV) approach; however, this approach is less relied upon due to its complexity and cumbersome nature.

2.2.2.1 Illuminance Method

The illuminance method, summarized simply, is a mathematical function to sum the amount of light (lux), incident on the road surface from each light source within its vicinity. The amount of light available at any given position in the road is dependent on various factors including its distance from the light source to the point of reference, the relative angle at which the light strikes the road surface, and the intensity or strength of the light source.

Of the calculation methods used the simplest is perhaps the illuminance method as at

its most complex, it is a function of the relative distance from the light source, the relative angle of incidence, and the mounting height of the light source. Since designers are likely not as concerned with the area directly beneath a luminaire as they are with the furthest extents of the area to be lit; the cosine law is used to calculate the approximate reduction in illuminance as the distance from the light source increases. The reduction in illuminance and level of lux at any given area is therefore proportional to the mounting height, angle of incidence, and distance away from the light source. This calculation is then repeated for the amount of light sources incident onto the location of the road, and the results are summed.

For calculations of a single light source, manufacturers of luminaires commonly provide Isolux diagrams with a specified conversion factor for the selected mounting height. This makes determining lux values out to common performance distances from the installed location easier to run quickly. However, even quicker than doing this approach by hand, there are many computer programs designed for such purposes which will be reviewed later (TAC , 2006).

2.2.2.2 Luminance Method

The luminance method is similar to the illuminance method in that the result is a summation of all light sources that are incident upon any given point within the road. A key difference between the luminance method and the illuminance method however

is that the luminance method correctly considers the amount of light being re-directed, partially reflected, or even absorbed by the material surfaces all around the location in question. In common design practice however, designers are most concerned with the luminance specific to the pavement, and therefore the luminance method is limited to only consider the pavement surface. The method then applies similar calculations as conducted within the illuminance method but adds a reduction factor known as the reduced coefficient of reflectance (IESNA, 2022).

The output of the luminance method by far is the most requested method based on the reviewed design guides across Canada and the United States. This is due to this method being more comparable to the performance of the human eye, and it is therefore somewhat more meaningful to designers. Luminance being determined to be within the appropriate range of performance of the human eye is important as it can indicate the difference between truly being able to see an object, versus having enough illumination within an area but perhaps not considering if an object or hazard may be masked due to glare. A way that this is negated and controlled is through validating the design, and by ensuring the design conforms to uniformity levels. Another way of controlling this is to use the third calculation method, small target validation, only to check performance levels and possibly evaluate differing designs.

2.2.2.3 Small Target Visibility Method

Small target visibility is a similar calculation as to that of the luminance method; however, it is not done based upon the reflectivity of the roadway surface. Instead, the calculation is performed by placing an array of standardized targets with 50% diffusion along the road surface. Calculations are then done around the three luminance factors (the target luminance, background luminance, and veiling luminance or glare) and the targets assigned a Visibility Level (VL).

This method brings about an interesting concept in respect of the target luminance in comparison to the background luminance. Individually each factor is important as the dressing choice of the target (when assuming it is a pedestrian) often has direct influence on their overall visibility. However, when considered against a background, it may not matter what the pedestrian is wearing if the background luminance is of similar color or in its applicability to nighttime visibility, its shade.

It is well known that black text on a white page is easily legible due to its high level of contrast. Similarly, it would be very difficult to discern white text on a white page. Applying this to nighttime visibility and as the human eye may only be seeing shades through its rods under scotopic vision, or even mesopic vision with light present; designers should consider if veiling luminance is shielding the target from being observed, and additionally consider if there is sufficient contrast present.

Without endeavoring deeply into contrast and the underlying design influences this

may have, STV is predominantly not relied upon. This is due in large part to the complexities of this method, in addition to the overall workload involved in conducting such a design. As work progresses on developing this method perhaps it will become more economically viable and efficient, but this has yet to occur in respect of modern design guides and best practices. In fact, research has shown that STV-based designs are inaccurate beyond the 6th target level within the array spacing (Senadheera S. *et al.*., 2002). This introduces then that these designs are inherently less safe than when employing the illuminance and luminance methods; as at this distance, a driver's perception is reduced in the space that an appropriate response time and reaction becomes critical (Krauss, 2015). Therefore, STV is handy for checking and validating visibility of targets along a roadway at near range; but at distance other methods ought to be relied upon.

2.2.3 Lighting Design Software

In completing designs there are multiple computer software programs designed to assist lighting engineers to create and evaluate designs with efficiency and ease. Issues exist with each program and preferences also play a key factor in selecting a program for use including its functionality, accuracy, user-friendliness, and its output formats and project renderings. It was observed that many road authorities specify which software suite they prefer to be used in carriage of their design work, and this may be for a reason.

A common misconception is that since luminaire manufacturers are the primary producers of such design software, the independence of these software suites are in question. It is opined that manufacturers use their software package to promote their products and make them the most effective for the design (Lighting Analysts Inc., 2021). Therefore, it is recommended that any user of such software have appropriate training and be able to exercise engineering judgement and analysis of each product being used within a given design.

AGi32 appeared to be the most commonly prescribed lighting design software in practice, and further AGi32 has been validated against the requirements of CIE171:2006, by Dau Design and Consulting Inc. (DDCI), based in Calgary, AB. For these reasons, AGi32 was selected for use in this study. The results of the DDCI report indicated that AGi32 performed within all limits prescribed by CIE171:2006 (Dau, 2007). Despite this, the specific use case for AGi32 in this study was not evaluated by DDCI, and so independent validation of this program for use in this manner is required.

2.2.4 Factors Affecting Roadway Illuminance Effectiveness

Apart from a discussion of well-known light loss factors (LLF) used in the carriage of design such as lamp lumen depreciation, ambient temperature, ballast factor, and dirt depreciation, a larger discussion on factors after design is necessary. An effect of

weather, specifically precipitation and water or snow accumulation on the road surface is that it completely modifies any reflectance values of the asphalt that may have been relied upon during the design process. The presence of water can either increase the specular effect of the road surface, or it can act as a dampener and absorb some or all of the appreciable light. The net effect is a drastically non-uniform lighting level as the motorist traverses the facility, which can increase the risk of an incident occurrence.

Second to the effects of precipitation resulting in design lighting levels to vary wildly, the effectiveness of street lighting is being modified by including considerations for over-lighting effects. This includes reducing energy expenditure, mitigating sky glow, and attempting to mitigate disruption to nocturnal wildlife. Modern efforts have seen dimmers or smart lighting systems being installed to reduce the lighting performance (*i.e.* the amount of lux) during off-peak hours. While this does achieve its goal in respect of the overall consideration of the design, it also challenges the original intent of installing street lighting in the first place, which is to increase safety along the roadway for road users. It is therefore considered to be a reduction in the effectiveness of the roadway lighting installation, especially in the event an incident occurs during the period the light is operating at a diminished level. As such, it is important to understand if such systems are in operation at the time an incident occurs.

Chapter 3: Methodology

This chapter summarizes and presents the methodology employed during this study which included site selection, collection of field observations, modelling in AGi32, and statistical analysis.

3.1 Site Selection

Two test sites were identified, and illuminance measurements were collected to evaluate three specific scenarios. The selected locations met specific requirements to minimize complications in completing this analysis in that they had either HID, (specifically High-Pressure Sodium (HPS) luminaires installed), or LED luminaires. Further, these sites were selected such that there were minimal additional light sources present. These restrictions were chosen so that only the streetlights would provide illumination onto the incident ground surfaces to simplify the modeling of the sites later.

The first site provided the ability to perform field measurements under a single 200W HPS luminaire in a controlled environment. Specifically, a luminaire in Reade Street Park, in Moncton New Brunswick was selected as it was simple to model, and this location was not on a roadway with the net advantage being to not be exposed to traffic, and not have extraneous light sources for which to account. Figure 3-1 illustrates the first test site with the tested area between the trees and the yellow line.

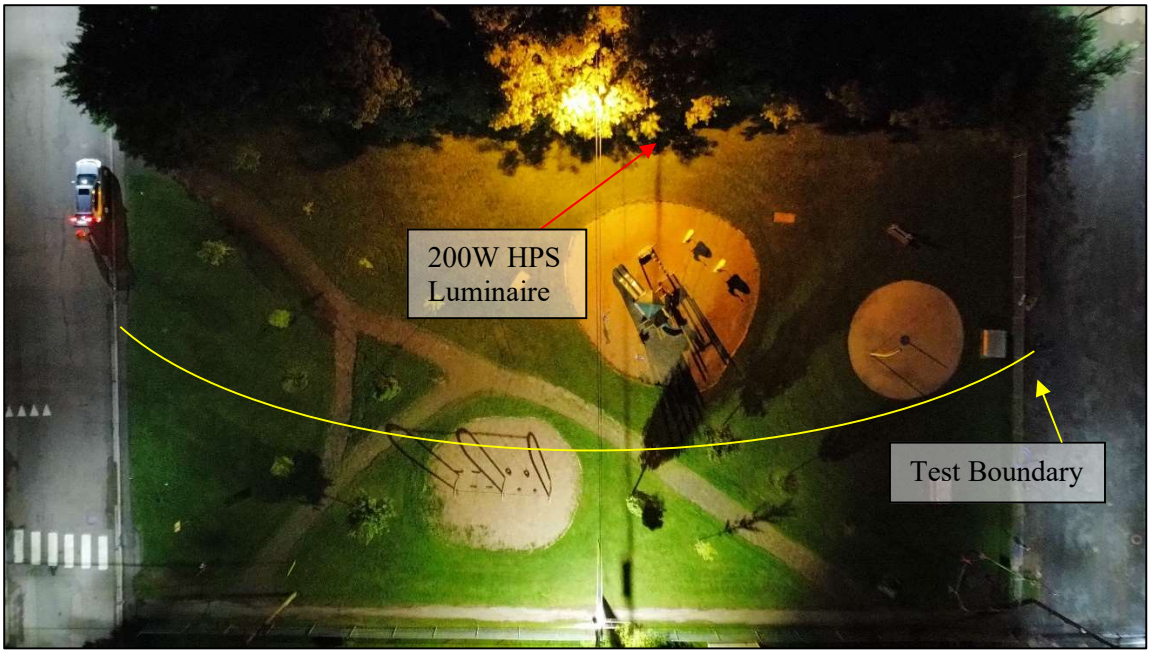


Figure 3-1 Aerial View of Reade Street Park, Moncton, New Brunswick.

The second site was chosen as it gave the opportunity to evaluate AGi32 for two of the intended scenarios including a converted LED luminaire, and an out of service (OOS) luminaire. The specific luminaires evaluated on Dieppe Boulevard at its intersection with Aucoin Street in Dieppe, New Brunswick are illustrated by Figures 3-2 and 3-3.



Figure 3-2 Converted LED Luminaire Between Two HPS Luminaires.

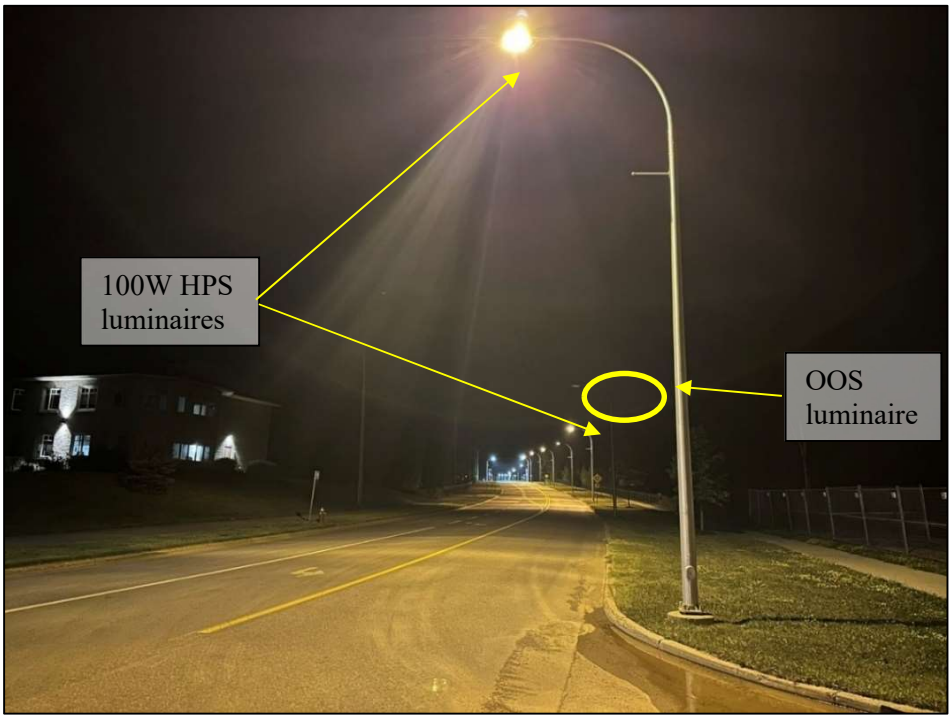


Figure 3-3 Out of Service Luminaire Between Two Operational HPS Luminaires.

3.2 Field Observations

Field observations were completed at both sites under specific conditions which included temperatures of around 20 degrees Celsius, with minimal to no cloud cover, and during dry conditions only. Safety was a primary concern as field work at night under artificial lighting was to be carried out. As such, a safety spotter was used during the collection of field data at site number two given it involved an active roadway. No traffic safety concerns existed for site number one. As previously introduced, the selected sites were identified which both allowed for a simplified exercise to be carried out by not having extraneous light sources, as well as which replicated conditions or issues prevalent to the problem statement, being that a luminaire was non-operational or had been converted to LED. Therefore, both sites selected did not have traffic lights, buildings, or other complex light sources near the test areas, and further each site independently allowed for either a simple validation exercise to be conducted, or for the two complex scenarios to be studied.

3.2.1 Test Site One

As previously introduced, test site one was Reade Street Park in Moncton, New Brunswick. Notably the park was equipped with a 200W HPS area light, mounted via davit-arm to a wooden power pole at a height of approximately 6.5 metres. Observations of this luminaire indicated its lens appeared clean, and it looked to be aimed flat relative to the ground.

Opposite the HPS luminaire across the park was a single LED luminaire mounted at a height of approximately 7 metres. This luminaire was also mounted via davit-arm and appeared to be aimed flat relative to the ground. The ground was flat and level within the park and consisted of grass and gravel surfaces. Metal and plastic child play structures were present in the vicinity of the testing area. Figures 3-1 and 3-4 illustrate the conditions of test site one as well as the single HPS luminaire.



Figure 3-4 200W HPS Area Light Installed in Reade Street Park, Moncton, New Brunswick.

An Extech LT3000 light meter was used to collect field measurements with the sensor held at a height of approximately 1.2 metres to emulate the approximate location of the torso of a pedestrian. The sensor was aimed directly upward to measure illuminance. Measurements were collected at five-meter intervals travelling straight out (longitudinally) from beneath the luminaire, as well as to the left (laterally) away from the luminaire along the tree line. This direction of travel was chosen to minimize the effect of the foliage present beneath the light installation as shown in Figure 3-4. In total, six measurements were captured for test site one related to the HPS luminaire.

3.2.2 Test Site Two

Test site two was located along Dieppe Boulevard at its intersection with Aucoin Street, in Dieppe, New Brunswick. This site was selected as it offered an opportunity to model two of the desired scenarios prevalent to collision reconstruction. Specifically, to one side of the intersection, a converted LED luminaire was bordered by two operational HPS luminaires, and to the opposite side of the intersection, an out of service luminaire was bordered by two operational HPS luminaires. Figure 3-5 shows the two scenario luminaires of interest.



Figure 3-5 Converted LED Luminaire and OOS Luminaire on Dieppe Blvd.

Observations of the luminaires indicated they were all mounted at a height of approximately 9 metres and were aimed relative to the ground. The luminaires appeared clean (*i.e.* minimal light loss factors were present), and were mounted on a combined pole and curved arm assembly. From research and documentation from the City of Dieppe including the design drawing of Dieppe Boulevard, it was identified that the lights installed were likely 100W HPS luminaires, and the LED conversion was likely a 60W luminaire.

In the test area, Dieppe Boulevard was generally flat on level, with grass and asphaltic pavement surfaces. Both sides of the roadway were bordered by pedestrian walking facilities, and in general, the area was very well lit with lighting appearing to be very

uniform along the roadway, less the section where the luminaire was non-operational.

Similar to test site one, an Extech LT3000 light meter was used to collect illuminance measurements with the sensor held at a height of 1.2 meters, aimed directly upward. Measurements were collected travelling longitudinally from the luminaires at varying landmarks including the edges of both pedestrian walking facilities, the curbs on either side of the road, and the painted roadway lines. Laterally measurements were captured beginning directly in-line with an HPS luminaire, and then moving towards the mid-point between the HPS luminaire and the scenario luminaire. This was followed by measurements captured in-line with the scenario luminaire and so on. Overall, forty measurements were captured for the Converted LED test case, and twenty-five measurements were captured for the OOS luminaire test case, for a total of sixty-five observations at test site two.

3.3 Modelling

AGi32 was used to model the two test sites along with their representative features. This was done following the methods employed through the various guides and trainings available for use of the program. Notably for test site one, an aerial drone image included as Figure 3-1 was used as a background image and scaled within the program based on the distance measured between the two luminaires present in the park. Representative luminaires were then selected and added to the model from

AGi32's product library. The luminaires were placed within the model in their respective positions, and mounted and aimed per the field observations. Surfaces matching those present within the park were also added, including grass, gravel, and asphalt. Objects such as play structures, benches, trees, and even vehicles and buildings can also be included within models in AGi32; however, no such objects were added to these models to minimize their relative complexity.

For test site two, the engineering drawing of Dieppe Boulevard was used within the program to install the luminaires in their exact specified positions. Representative luminaires were also selected from AGi32's product library and mounted and aimed per the field observations, and representative surfaces including the asphalt roadway, concrete curbs, grassed boulevards, and concrete and asphalt sidewalks were specified.

Once the models of both sites were built to directly replicate the test sites including their respective luminaires, calculations were applied using AGi32's Full Radiosity Method. This included specifying the measurement height as 1.2 metres, in order to directly replicate the height at which the field measurements were captured.

It is noted that the Full Radiosity calculation method factors in the specified reflectance values of the surfaces selected during the modeling process that directly emulates reflectance values for grass, gravel, asphalt, etc. Also, as a result, the program may calculate unusually high results directly beneath the luminaire as a by-product of reflecting light off of the included pole, producing a phenomenon known as

a calculated ‘hot spot’. Depending upon the type of analysis, hot spots can safely be ignored when they appear directly beneath luminaires as the program does not particularly handle this phenomenon well (Lighting Analysts, 2021). To correct this phenomenon, a scaling factor can be applied with iso-lines displayed to more accurately present data in the rendered environment. Figure 3-6 illustrates what each color iso-line represents in respect of its lighting levels followed by the outputs for each modelled scenario. An example of a ‘hot spot’ is included in Figures 3-7 and 3-8, which are outputs from test site one. Figures 3-9 and 3-10 present the outputs for the converted LED luminaire, and the out of service luminaire.



Figure 3-6 Legend of Iso-line Colors and the Respective Lighting Levels in Lux.

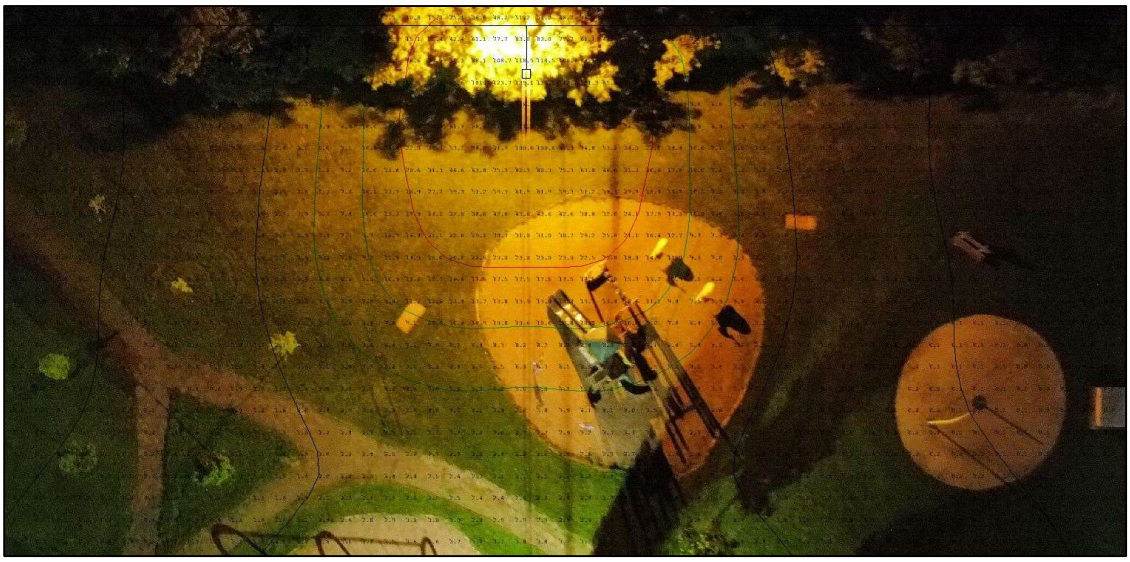


Figure 3-7 AGi32 Output for Modeled Test Site One. Note the iso-lines present.

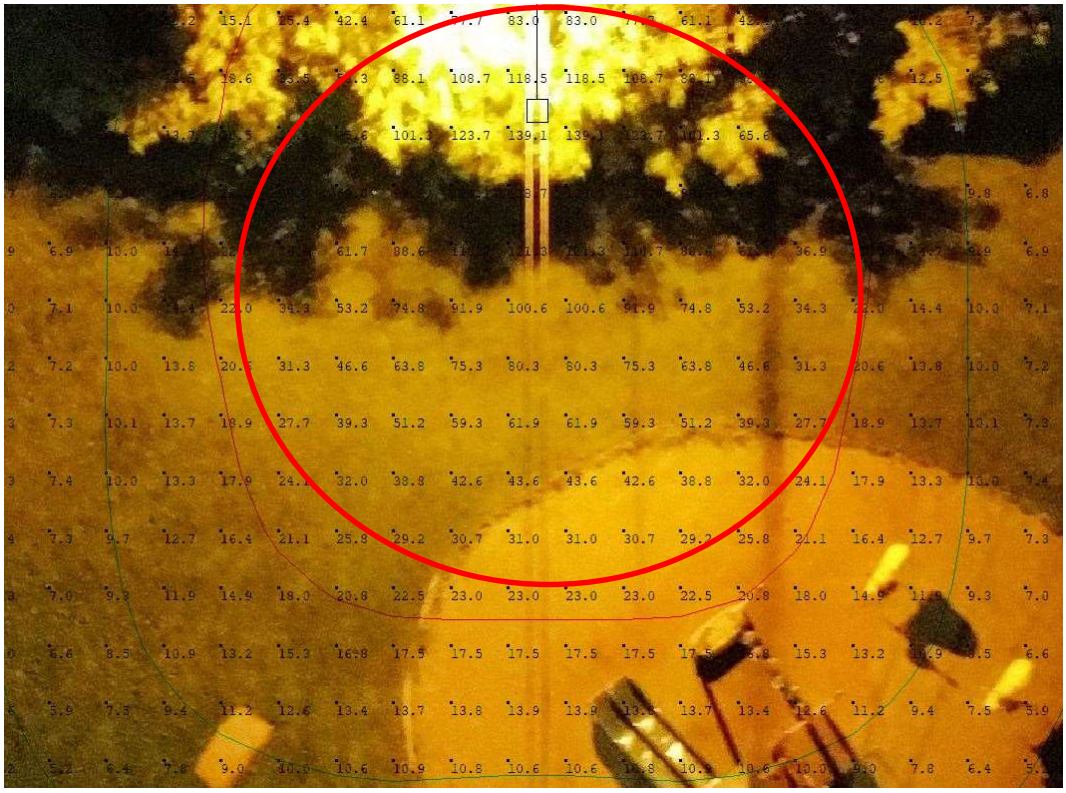


Figure 3-8 Closer View of Modeled Test Site One to Illustrate the Hot Spot (circled in red).

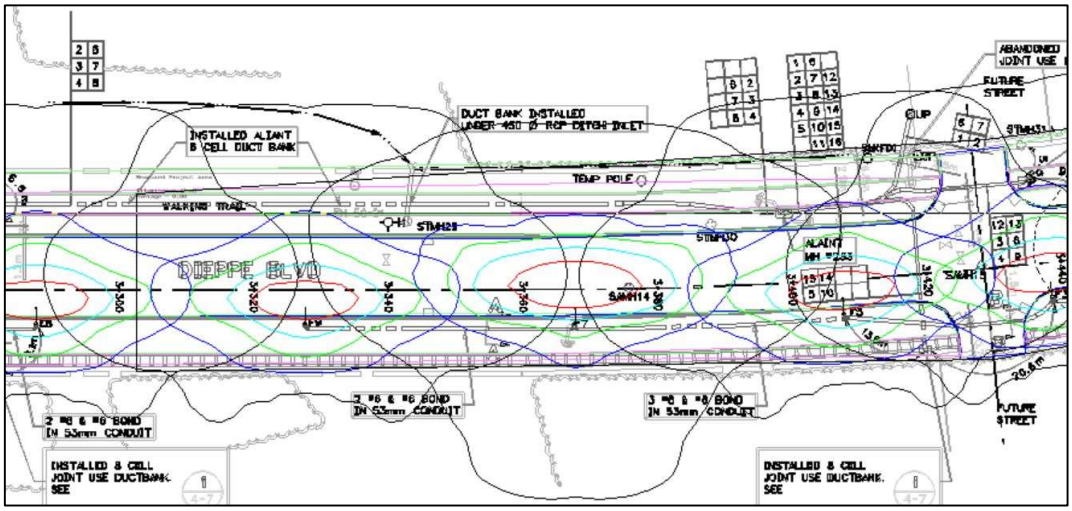


Figure 3-9 AGi32 Output for Modeled Test Site Two; the Converted LED Luminaire.

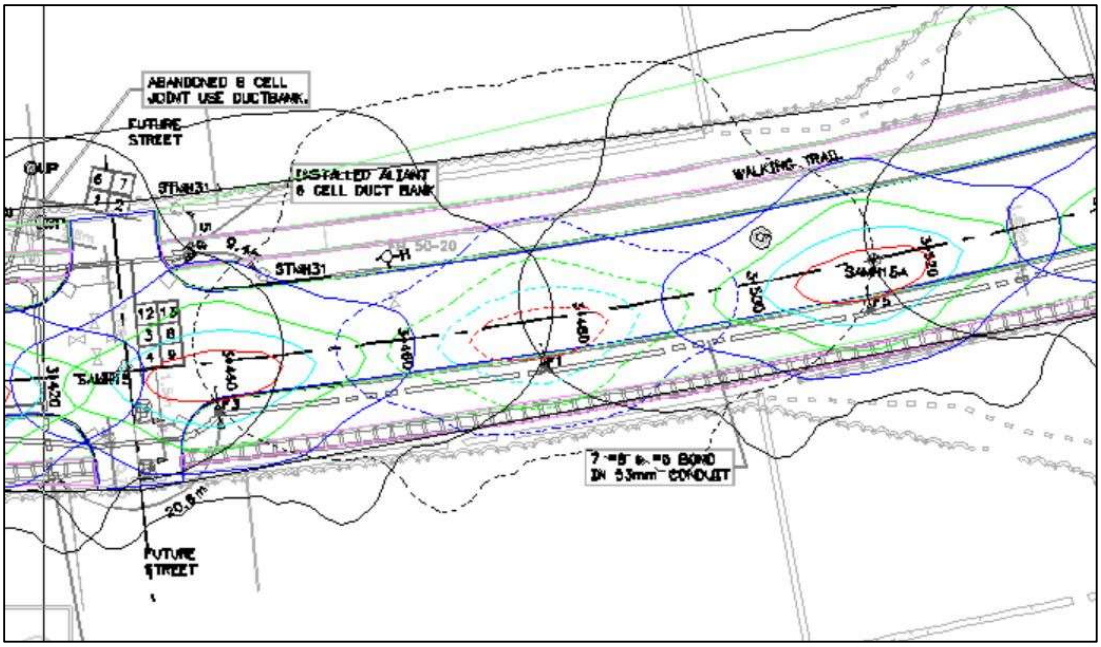


Figure 3-10 AGi32 Output for Modelled Test Site Two; the Out of Service Luminaire. Note the hatched line indicates the luminaire is not functioning within the rendered output.

3.4 Statistical Analysis

Once the field observations were collected and AGi32 modelling was complete, the data were compiled in excel spreadsheets for each evaluated scenario. Excel was then employed to complete statistical analysis of the data. Specifically, paired sample t-tests were run for each scenario to evaluate if there was a statistically significant difference between the field observations and the modelled results of AGi32.

To elaborate briefly, paired sample t-tests were the primary analysis completed to evaluate each scenario as a function of the amount of data collected in this study. Since it would be time-consuming to collect hundreds of field observations and compare

them manually to corresponding modelled outputs of AGi32; a paired t-test was used to test if the null hypothesis was true or could be rejected for the samples of data considered. Specifically, the null hypothesis tested was that the field observations were equal to the modelled results from AGi2 for each lighting scenario tested. The significance of these tests was set at 5%, which is typical of such studies. The p-value, or the probability that the results occurred by chance was then considered. If the p-value was greater than 0.05, then the null hypothesis could not be rejected, meaning the field and modelled data was similar, and no statistically significant difference existed. Conversely, if the p-value calculated was below 0.05, then the null hypothesis must be rejected, as statistically significant differences exist within the data.

Chapter 4: Results

This chapter summarizes the results of the analysis conducted for each scenario evaluated. Notably, Microsoft Excel was employed to carry out these calculations, and as such, the outputs are included within the Appendix.

4.1 Scenario 1: Single HPS Luminaire

Scenario one consisted of evaluating AGi32 against field observations conducted under a single 200W luminaire in Reade Street Park in Moncton. Six field observations and six modelled observations were compared, and the results produced in Tables 1, 2 and Figure A-1, included in the Appendix. It was found that the mean field observation was 9.72 lux, while the mean modelled observation was 11.1 lux. The difference between each corresponding observation was calculated, and the mean difference was then found to be -1.37 lux, with a corresponding standard deviation of 1.58 lux, and mean percent difference of -21.9%. This indicates that in this scenario, AGi32 on average overpredicted field observations by 1.37 lux, (or 21.9%).

Most important, however, were the results of the paired t-test. There was not a significant difference between the field observations versus the modelled observations as the p-value was calculated to be 0.10, or 10%. Recall that the significance of this test was set to 5%. Therefore, the null hypothesis being that the field observations

were equal to the modelled outputs of AGi32 could not be rejected as the p-value was greater than 5%, at a result of 10%, indicating then that these results occurred by chance and not by some anomaly or external factor.

4.2 Scenario 2: Converted LED Luminaire

Scenario two consisted of evaluating AGi32 against field observations collected at a site where a converted LED luminaire was installed between two operational HPS luminaires. 40 field and 40 modeled observations were compared, and the results produced in Tables 3, 4, and Figure A-2 included in the Appendix. It was found that there was no statistically significant difference between the field and modelled observations as the p- value was found to be 0.73. The mean field measurement was determined to be 7.45 lux, with the mean modelled measurement to be 7.20 lux. On average, AGi32 underpredicted field measurements by 0.25 lux, with a corresponding standard deviation of 4.53 lux. The average percent difference was found to be 23%, with a corresponding standard deviation of 37.4%.

4.3 Scenario 3: Out of Service Luminaire

Scenario three consisted of evaluating AGi32 at a site where an out of service luminaire was in place between two operational HPS luminaires. 25 field and modeled observations were compared, and the results produced in Tables 5, 6, and Figure A-3

included in the Appendix. It was found that there was no statistically significant difference between the field and modelled observations based on the results of the paired t-test. Specifically, the p-value was found to be 0.25.

The mean field observation was 3.76 lux, the mean modelled observation was 4.47 lux, and the respective mean difference was found to be -0.71 lux. The corresponding standard deviation was 3.04 lux. The average percent difference was -5.8%, and the percent difference standard deviation was 57.1%. Therefore, the results show that AGi32 on average predicted illuminance levels that were 0.71 lux above field observations, with a standard deviation of 3.04 lux.

Chapter 5: Discussion

This chapter applies the presented results above, to the intended purpose of this study. First, the accuracy of measurements between field and theoretical modelling are discussed, and the sources of error from both collection of the field measurements and the use of AGi32 are explored. Lastly, the results of this study are discussed in the context of collision reconstruction engineering.

5.1 Accuracy of Field vs. Predicted Measurements

The accuracy of measurements captured in the field versus the values predicted by modeling in AGi32 were compared in this study and found to contain no statistically significant differences. This was dependent upon a thorough modeling of the test sites including appropriate application of selected luminaires, surface materials, and geographical elevations and curvatures. Therefore, while the results of this study show the ability to model lighting scenarios is theoretically viable, a slight degree of error must be accepted based on the calculated results for each scenario.

Interestingly a slight degree of error must be accepted even without the use of AGi32 when performing illumination studies for the purpose of visibility testing in collision reconstruction. For example, the light meter employed in this study which is a regular tool used by many collision reconstructionists has a specified error range of +/- 5% as reported by the manufacturer. Therefore, while this is a highly accurate tool, it is still

nevertheless a fact that some error cannot be avoided. To apply this acceptance of error then to the intended purpose of this study means that while field measurements are arguably the best method available to quantify illumination within a given area, the results show that modeling light levels when done correctly can serve as a next best scenario when field measurements may not be possible.

5.2 Sources of Error

The sources of error prevalent to this study can be categorized by three primary sources, human, environmental, and technological.

To explain, human error when performing field measurements is introduced predominantly through the use of the light meter. Specifically, sources of error include not having the photometer (the sensor) attached to the light meter at exactly the same height, or possibly not aimed directly upward for each measurement captured. Furthermore, readings from the light meter were recorded while the light meter, due to its sensitivity level, was consistently fluctuating. The meter would settle about a consistent range of values during any given observation; however, a reading was required and so an individual value read. This variability of the meter would likely fall within the manufacturer specified +/- 5% as previously noted; however, it is important to reiterate this point as it is possible if measurements are taken without monitoring the meter appropriately, then error could be introduced. This issue appears to be more

prevalent when measuring areas with low levels of lighting. In reference to the data appended to this report, some %-differences between the field and modelled outputs were in the range of as much as 184%. These results appeared mostly when lighting levels were between 0 and 3 lux, indicating that the sensitivity of the instrument and subtle errors in measurement can result in significant percent differences and variances, which unfavorably skew results. As such, reporting the results of this study in percentages is not representative of the accuracy and capabilities of AGi32 as compared to reporting the results as the mean difference and its corresponding standard deviation.

Environmental conditions also contribute to possible error. As presented in chapter two, weather conditions, temperature, air density, and moisture affect how light travels from its source. Therefore, if light conditions are not measured in the field during similar conditions as to a given incident, there may be a substantive difference between the time of the incident and the time the engineer is collecting light measurements. Further research may be necessary to evaluate this aspect of lighting analysis; however for the purposes of this study, this error was reduced by taking light measurements during typical summer evenings of 15 to 25 degrees Celsius, with no precipitation and minimal cloud cover. Similarly, surfaces within the models developed for this study matched the conditions as to when field measurements were completed. Specifically, all surfaces programmed into the model were ‘dry’. Notably AGi32 does allow for environmental conditions to be programmed into models as

well, with the inclusion of the ability to modify the radiosity of a given surface to match its wet condition.

Technological sources of error in the constraints of this study are introduced mostly by the use of a modelling software program. While the results of this study show that AGi32 can model lighting levels accurately when compared to field measurements, it is important to note that appropriate selection of representative luminaires, ground surfaces, and geography is required. If any one of these selections cannot be made with good reasoning, the accuracy of the program's output can be misled as a result. For example, if a luminaire used in the model is over-powered, under-powered, mis-aimed, or not positioned at the correct mounting height to match what was present in the field, it will influence the predicted lighting levels. Similarly, if roadway elevations, presence of objects, or even the height at which the field measurements were taken differ between the field and the program, then differences between the real-world measurements and the programs results will exist.

5.3 Applicability to Collision Reconstruction

Based on the results of this study, AGi32 is shown to be a viable tool for use in collision reconstruction. However, its use should only be employed for the express purpose of quantifying the amount of illumination present within a given area. AGi32 ought not to be used in place of a traditional visibility assessment conducted in the

field with representative lighting and environmental conditions.

In reference to chapter two, the human eye relies upon various components and environmental factors to enable visibility. Specifically at night lighting engineers strive to achieve mesopic vision, which engages both types of photoreceptors within the eye. While this is their goal, environmental conditions, lighting factors, and vehicle headlights can modify if mesopic vision is achieved. As such, other visibility elements such as light color (temperature), contrast, and conspicuity of the target (pedestrian), ought to be considered. It is recommended that in a situation where a luminaire has been repaired, converted, or reconfigured, that AGi32 be used to determine what illumination levels were present at the time an incident occurred. Once determined, it is recommended the engineer place a target dressed similarly to the pedestrian involved in a given case within a safe and physically representative location under a similar luminaire and environmental conditions to match the AGi32 determined illumination levels. At this point a traditional visibility assessment can be conducted. In summary, AGi32 can be used to help identify representative lighting conditions to enable additional visibility testing to be completed at an exemplar site if the original location is unsafe, or has been modified.

Chapter 6: Recommendations & Conclusions

This study concludes that AGi32 can be applied for use in collision reconstruction.

The three scenarios tested in this study evaluated AGi32's modelling capabilities against a simple HPS luminaire, as well as against two specific scenarios where a luminaire had been converted to LED, and when a luminaire was reported to be non-operational. While the results varied slightly across each scenario, it is noted that in all cases there was no significant statistical difference between measurements captured in the field and the outputs of AGi32. Further, across all three scenarios AGi32 overpredicted field measurements by an average of 0.61 lux (combined average of all three scenarios), with a corresponding average standard deviation of 3.05 lux. In conclusion, AGi32 performed well for the tested scenarios. It is notable that as light levels lessen, the error seems to worsen as a function of the sensitivities of taking readings in low light conditions (between 0 and 3 lux). As such, extra care is recommended to mitigate measurement error in low light.

6.1 Recommendations

For reasons as discussed in chapter four, it is reiterated that AGi32 ought not be used in place of a traditional visibility assessment. Rather, AGi32 can be used to identify representative light levels, which can then be used to help identify an exemplar location for a visibility assessment to take place.

6.2 Future Research

Throughout this study it was identified that streetlighting is dependent upon various

factors inclusive of product type, installation, and maintenance. Additional efforts ought to be made to deepen the amount of data evaluated to increase the level of certainty of the results previously presented. Most notably lighting conditions and the performance of AGi32 should be further explored for more complex lighting scenarios, including during precipitation, at sites with challenging roadway alignments, and in cases where poor maintenance or performance of lighting issues are present (*i.e.,* increased dependency upon light loss factors is needed).

A concept to rapidly deepen the amount of data available for validating AGi32 for such use is to seek a research partnership with a municipal government who regularly employs the use of AGi32 within their lighting network. This would reduce the need to independently model each test site and would further enable researchers to evaluate adverse lighting conditions when they occur. Further, the AGi32 illumination outputs may be able to be provided with some defining elements included like specifying the height the calculations were computed, to enable researchers to collect large amounts of field measurements under similar conditions as the models. This would also serve to eliminate some sources of error from the modeling itself as it is likely the road authority would use the luminaires installed on their streets within their models, with accurate mounting heights and accounting for aim points. This reduction in error along with an enabled larger sample size would be beneficial to prove AGi32's additional purpose. Lastly, the inclusion of different sensors and light meters for making

observations at each site may serve to validate the efficacy of a particular type of light meter for use for this purpose.

6.3 Research Limitations

The limitations of this study are such that the exact products implemented within each model were not used. Rather, representative luminaires based on observations made in the field and through discussions with owners of lighting installations was necessary. Specifically, the City of Dieppe and NB Power were consulted on the two test locations, and information was provided as best as could be ascertained by the parties. With this in mind, representative systems were modelled; however, there is recognition that these are not the exact systems installed at either test site. Despite this, AGi32 proved to perform with representative lighting levels as measured in the field.

Therefore, should future studies be conducted if not through partnership with involved agencies, at least having sufficient documentation from the engineering firms or municipalities involved in the design of the lighting facility will likely be of benefit like it was in this study.

Further restrictions of this study included managing its scope overall. Specifically, there were aspects of lighting design that were researched, but not included within the analysis and testing conducted due to their complexity and magnitude in respect of this study overall. Namely this included evaluating uniformity along a section of

luminaires, as well as in evaluating respective max/min ratios for considerations of glare. These aspects would be pertinent to address in future studies as AGi32 likely can be used to evaluate such issues as well.

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Appendix

Illuminance Field and Modeled Data & Calculation Outputs

Table 1 – Scenario 1: Single HPS Luminaire Data

Scenario 1: Single HPS Luminaire					
Luminaire	Description	Field Measurement (lux)	Modeled Measurement (lux)	Difference (lux)	% Difference
HPS 1	5 m straight	20	23	-3	-15.0
HPS1	10 m straight	10.3	10.6	-0.3	-2.9
HPS1	15 m straight	1	2.1	-1.1	-110.0
HPS1	5 m left	19	22.5	-3.5	-18.4
HPS1	10 m left	6	6.9	-0.9	-15.0
HPS 1	15 m left	2	1.4	0.6	30.0
Average		**9.72**	**11.1**	-1.37	-21.9
Standard Deviation		**8.27**	**9.64**	**1.58**	**46.7**

Table 2 – Scenario 1: Single HPS Luminaire Paired T-Test Output

	Field Measurement (lux)	*Modelled Measurement (lux)*
Mean	9.72	11.1
Variance	68.3	92.9
Observations	6	6
Pearson Correlation	1.00	
Hypothesized Mean Difference	0	
df	5	
t Stat	-2.12	
P(T<=t) one-tail	0.04	
t Critical one-tail	2.02	
P(T<=t) two-tail	0.09	
t Critical two-tail	2.57	

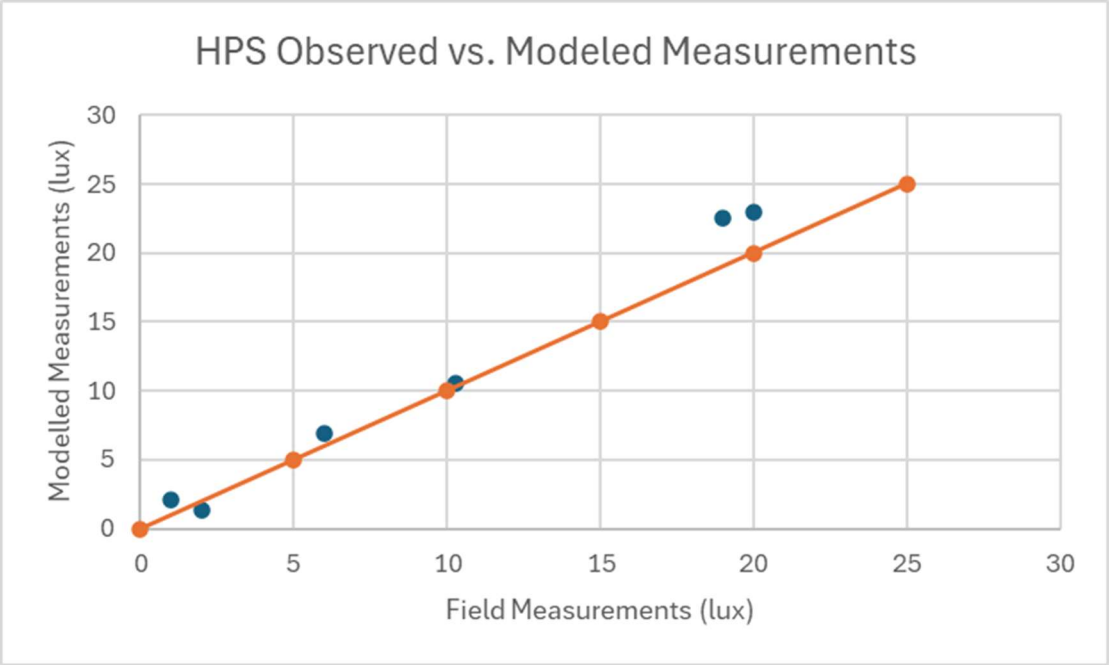


Figure A-1 HPS Field vs. Modelled Observations

Table 3 – Scenario 2: Converted LED Luminaire Data

Scenario 2: LED Luminaire Between Two HPS Luminaires					
Luminaire	Description	Field Measurement (lux)	Modeled Measurement (lux)	Difference (lux)	% Difference
HPS1	Sidewalk Far Side	5.31	2.7	2.61	49.2
HPS1	Sidewalk Near Side	8.29	6.43	1.86	22.4
HPS1	Curb Near Side	20.92	26.12	-5.2	-24.9
HPS1	White Line	18.93	17.16	1.77	9.4
HPS1	Centre Line	11.17	7.91	3.26	29.2
HPS1	Curb Far Side	4.54	4.19	0.35	7.7
HPS1	Walking Trail Near Side	2.09	2.11	-0.02	-1.0
HPS1	Walking Trail Far Side	1.54	1	0.54	35.1
Between HPS1 & LED	Sidewalk Far Side	0.62	0.38	0.24	38.7
Between HPS1 & LED	Sidewalk Near Side	0.92	0.56	0.36	39.1
Between HPS1 & LED	Curb Near Side	5.03	5.1	-0.07	-1.4
Between HPS1 & LED	White Line	8.72	6.45	2.27	26.0
Between HPS1 & LED	Centre Line	8.56	5.12	3.44	40.2
Between HPS1 & LED	Curb Far Side	6.48	2.26	4.22	65.1
Between HPS1 & LED	Walking Trail Near Side	3.57	0.99	2.58	72.3
Between HPS1 & LED	Walking Trail Far Side	2.11	0.68	1.43	67.8
LED	Sidewalk Far Side	1.48	2.46	-0.98	-66.2
LED	Sidewalk Near Side	3.56	3.03	0.53	14.9
LED	Curb Near Side	23.35	26.08	-2.73	-11.7
LED	White Line	29.47	50.82	-21.35	-72.4
LED	Centre Line	16.09	18.15	-2.06	-12.8
LED	Curb Far Side	7.45	5.22	2.23	29.9
LED	Walking Trail Near Side	6.08	1.58	4.5	74.0
LED	Walking Trail Far Side	2.88	1.22	1.66	57.6
Between LED and HPS 2	Sidewalk Far Side	0.62	0.29	0.33	53.2
Between LED and HPS 2	Sidewalk Near Side	0.97	0.54	0.43	44.3
Between LED and HPS 2	Curb Near Side	4.3	4.29	0.01	0.2
Between LED and HPS 2	White Line	9.66	6.07	3.59	37.2
Between LED and HPS 2	Centre Line	9.78	4.01	5.77	59.0
Between LED and HPS 2	Curb Far Side	5	2.48	2.52	50.4
Between LED and HPS 2	Walking Trail Near Side	3.45	1.13	2.32	67.2
Between LED and HPS 2	Walking Trail Far Side	2.3	0.61	1.69	73.5
HPS2	Sidewalk Far Side	4.04	3.53	0.51	12.6
HPS2	Sidewalk Near Side	7.05	7.03	0.02	0.3
HPS2	Curb Near Side	17.3	29.41	-12.11	-70.0
HPS2	White Line	14.78	14.79	-0.01	-0.1
HPS2	Centre Line	9.06	8.67	0.39	4.3
HPS2	Curb Far Side	6.28	4.56	1.72	27.4
HPS2	Walking Trail Near Side	2.67	1.86	0.81	30.3
HPS2	Walking Trail Far Side	1.61	0.92	0.69	42.9
Average		**7.45**	**7.20**	**0.25**	**23.0**
Standard Deviation		**6.82**	**10.3**	**4.53**	**37.4**

Table 4 – Scenario 2: Converted LED Luminaire Paired T-Test Output

	Field Measurement (lux)	*Modelled Observations (lux)*
Mean	7.45	7.2
Variance	46.51	105.2
Observations	40.00	40.0
Pearson Correlation	0.94	
Hypothesized Mean Difference	0.00	
df	39.00	
t Stat	0.35	
P(T<=t) one-tail	0.36	
t Critical one-tail	1.68	
P(T<=t) two-tail	0.73	
t Critical two-tail	2.02	

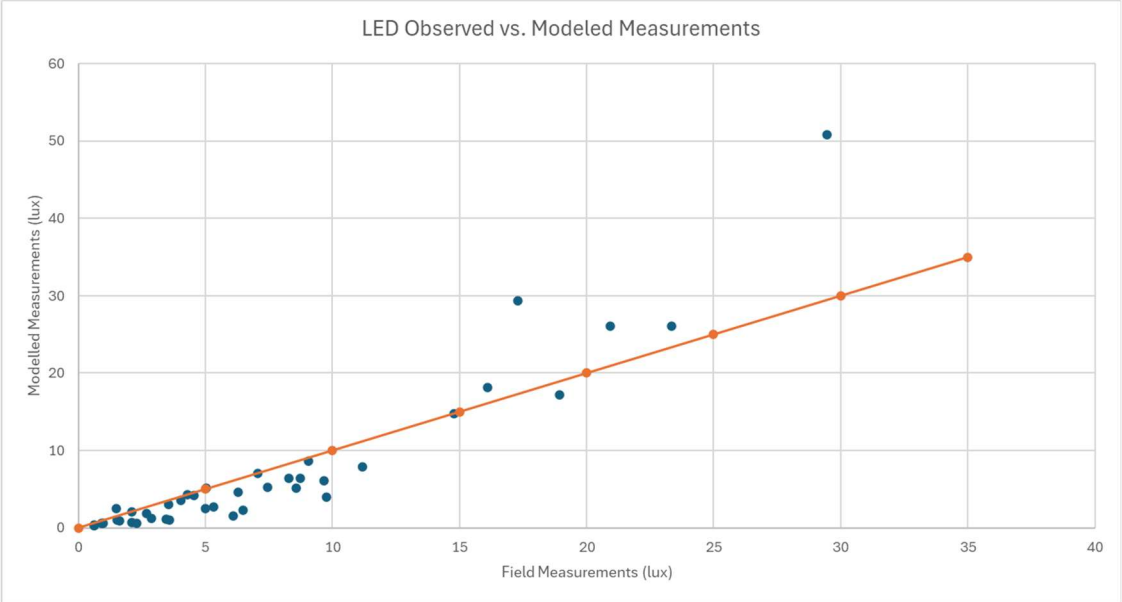


Figure A-2: LED Field vs. Modelled Observations

Table 5 – Scenario 3: OOS Luminaire Data

Scenario 3: OOS HPS Installation between HPS					
Luminaire	Description	Field Measurement (lux)	Modeled Measurement (lux)	Difference (lux)	% Difference
HPS1	Sidewalk Far Side	4	3.4	0.6	14.8
HPS1	Sidewalk Near Side	6	5.3	0.7	11.3
HPS1	Curb Near Side	12.4	21.3	-8.9	-71.5
HPS1	Centre Line	10.6	11.0	-0.4	-3.3
HPS1	Curb Far Side	1.9	3.8	-2.0	-107.6
Between HPS1 & OOS	Sidewalk Far Side	0.5	0.4	0.1	21.3
Between HPS1 & OOS	Sidewalk Near Side	0.6	0.6	0.0	0.0
Between HPS1 & OOS	Curb Near Side	1.2	3.5	-2.3	-184.4
Between HPS1 & OOS	Centre Line	1.9	1.9	-0.1	-2.7
Between HPS1 & OOS	Curb Far Side	1.3	0.8	0.5	38.2
OOS	Sidewalk Far Side	0.1	0.1	0.0	30.0
OOS	Sidewalk Near Side	0.1	0.1	0.0	30.0
OOS	Curb Near Side	0.2	0.1	0.0	13.3
OOS	Centre Line	0.2	0.2	0.1	26.1
OOS	Curb Far Side	0.3	0.1	0.1	48.1
Between OOS and HPS 2	Sidewalk Far Side	0.6	0.3	0.3	50.8
Between OOS and HPS 2	Sidewalk Near Side	0.4	0.6	-0.2	-43.9
Between OOS and HPS 2	Curb Near Side	3.2	3.2	0.0	-0.9
Between OOS and HPS 2	Centre Line	5.4	2.5	2.9	53.5
Between OOS and HPS 2	Curb Far Side	3.4	1.1	2.3	68.0
HPS2	Sidewalk Far Side	3.2	3.7	-0.4	-13.7
HPS2	Sidewalk Near Side	5.9	6.2	-0.2	-4.1
HPS2	Curb Near Side	14.2	25.5	-11.3	-79.0
HPS2	Centre Line	13.7	12.1	1.6	11.5
HPS2	Curb Far Side	2.6	4.0	-1.3	-51.0
Average		**3.76**	**4.47**	**-0.71**	**-5.8**
Standard Deviation		**4.43**	**6.54**	**3.04**	**57.1**

Table 6 – Scenario 3: OOS Luminaire Paired T-Test Output

	Field Measurement (lux)	*Modeled Measurement (lux)*
Mean	3.76	4.47
Variance	19.6	42.8
Observations	25.0	25.0
Pearson Correlation	0.92	
Hypothesized Mean Difference	0.0	
df	24.0	
t Stat	-1.17	
P(T<=t) one-tail	0.13	
t Critical one-tail	1.71	
P(T<=t) two-tail	0.25	
t Critical two-tail	2.06	

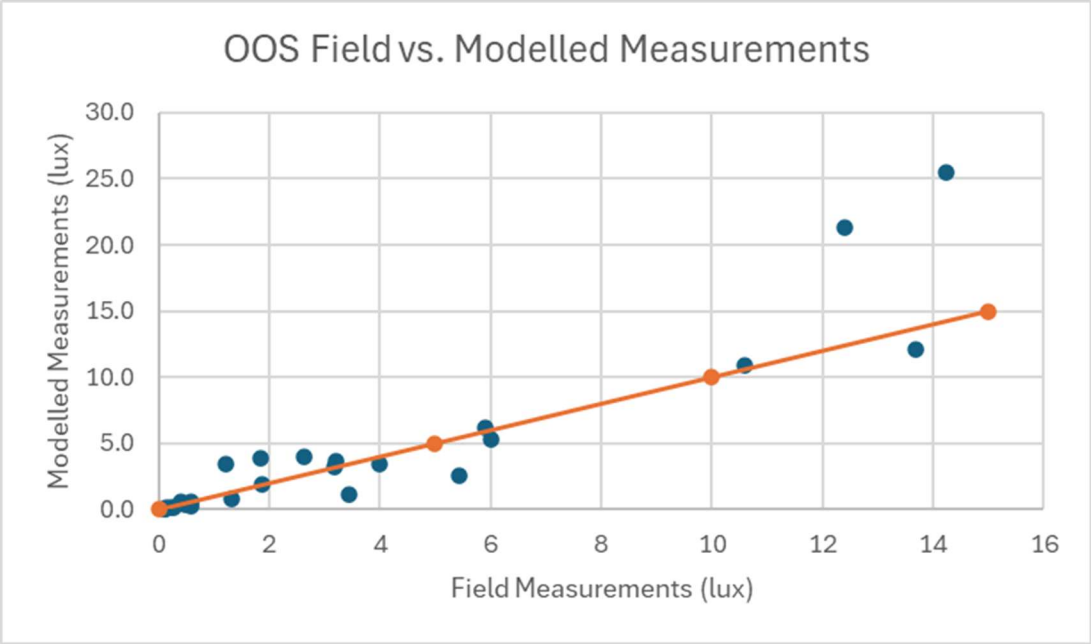


Figure A-3 OOS Field vs. Modelled Observations

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