

# Enhanced Light Crosswalk Illumination

## Final Report

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**Xiaowei (Tom) Shi, Ph.D.**

Principal Investigator (PI), Assistant Professor, University of Wisconsin-Milwaukee

**Xiao Qin, P.E., Ph.D.**

Co-PI, Professor, University of Wisconsin-Milwaukee

**Xiaopeng Li, P.E., Ph.D.**

Co-PI, Professor, University of Wisconsin-Madison

**Brian Scharles Sr.**

Co-PI, Director of Product Innovation, Traffic and Parking Control Co., Inc. (TAPCO)

**Muhammad Fahad**

Ph.D. Student, University of Wisconsin-Milwaukee

**University of Wisconsin-Milwaukee**

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| <b>16. Abstract</b><br><p>This study evaluated the effectiveness of enhanced crosswalk illumination in improving nighttime pedestrian visibility, driver recognition, and pedestrian detection distance. Field tests were conducted at two study sites in Madison and Milwaukee, Wisconsin, representing different roadway geometries and lighting conditions. The experiments compared baseline conditions with multiple enhanced lighting configurations.</p> <p>During each test, an instrumented probe vehicle was driven toward the crosswalk while an electric skateboard-mounted mannequin was used to simulate pedestrian crossing events in a controlled and repeatable manner. The probe vehicle was equipped with a high-resolution GPS system, forward- and rear-facing cameras, and brake pedal logging devices to capture vehicle trajectory, driver response, and braking behavior. Additional lighting data were collected via illuminance measurements, and an eye-tracking-based recognition method was used to determine when the driver first recognized the simulated pedestrian and to estimate the corresponding detection distance.</p> <p>The results indicate that enhanced crosswalk illumination improved driver visual recognition and increased pedestrian detection distance at both sites. At the Madison site, the enhanced lighting system reduced driver reaction time from 0.71 s to 0.67 s and increased detection distance from 212 ft to 275 ft. At the Milwaukee site, driver reaction time decreased from 0.92 s to 0.69 s, while detection distance increased from 242 ft to 261 ft. Overall, blue-light-based enhanced crosswalk lighting increased the average distance at which drivers detected pedestrians by approximately 40 ft relative to the existing baseline condition (no enhanced crosswalk lighting), and by approximately 26 ft relative to conventionally recommended 4000 K white lighting.</p> <p>These findings demonstrate the potential of enhanced crosswalk illumination to improve nighttime pedestrian safety and provide practical guidance for the Wisconsin Department of Transportation and local agencies in selecting lighting spectrum, mounting height, lateral placement, and roadway-specific design configurations.</p> |                                                             |                                           |                                                                                                                                                                                       |  |
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## Table of Contents

|                                                               |           |
|---------------------------------------------------------------|-----------|
| <b>DISCLAIMER .....</b>                                       | <b>1</b>  |
| <b>LIST OF FIGURES.....</b>                                   | <b>6</b>  |
| <b>LIST OF TABLES.....</b>                                    | <b>8</b>  |
| <b>LIST OF ACRONYMS.....</b>                                  | <b>10</b> |
| <b>EXECUTIVE SUMMARY .....</b>                                | <b>11</b> |
| <b>INTRODUCTION .....</b>                                     | <b>15</b> |
| BACKGROUND .....                                              | 15        |
| PROBLEM STATEMENT.....                                        | 15        |
| REPORT ORGANIZATION.....                                      | 16        |
| <b>1. LITERATURE REVIEW .....</b>                             | <b>18</b> |
| 1.1 LIGHTING PARAMETERS AND PERFORMANCE METRICS .....         | 21        |
| 1.2 AGENCY GUIDELINES AND DESIGN STANDARDS .....              | 21        |
| 1.3 LABORATORY AND FIELD EVALUATIONS .....                    | 22        |
| 1.4 IMPLICATIONS FOR ENHANCED CROSSWALK LIGHTING DESIGN ..... | 22        |
| 1.5 SECTION SUMMARY .....                                     | 23        |
| <b>2. DESIGN AND BUILD ENHANCED LIGHT SYSTEMS.....</b>        | <b>24</b> |
| 2.1 DESIGN CRITERIA FROM THE LITERATURE REVIEW .....          | 24        |
| 2.2 SYSTEM PLATFORM: SAFEWALK™ CROSSWALK ILLUMINATOR .....    | 24        |
| 2.3 SPECTRAL CONFIGURATIONS.....                              | 27        |
| 2.4 INSTALLATION GEOMETRY AND DESIGN FACTOR .....             | 28        |
| 2.5 PROTOTYPE DEMONSTRATION AND TASK 2 COMPLETION.....        | 29        |
| <b>3. DRIVER RECOGNITION AND REACTION TIME TESTING .....</b>  | <b>30</b> |
| 3.1 FIELD TESTING OVERVIEW.....                               | 30        |

|                                                                                        |           |
|----------------------------------------------------------------------------------------|-----------|
| 3.2 EXPERIMENTAL APPROACH PROCEDURE .....                                              | 33        |
| 3.3 FIELD EQUIPMENT AND INSTRUMENTATION.....                                           | 34        |
| 3.4 NIGHTTIME FIELD TESTING SETUP .....                                                | 35        |
| 3.5 EXPERIMENTAL FACTORS AND FIELD CONDITIONS .....                                    | 36        |
| 3.6 FIELD DATA RECORD AND QUALITY CONTROL.....                                         | 38        |
| 3.7 SECTION SUMMARY .....                                                              | 38        |
| <b>4. DEMONSTRATION OF ENHANCED LIGHTING SYSTEMS .....</b>                             | <b>40</b> |
| 4.1 DEMONSTRATION SETUP .....                                                          | 40        |
| 4.2 TEST VEHICLE AND FIELD DATA COLLECTION.....                                        | 41        |
| 4.3 LIGHTING AND VISIBILITY OBSERVATION .....                                          | 42        |
| 4.4 SECTION SUMMARY .....                                                              | 43        |
| <b>5. OPTIMAL LIGHTING SPECIFICATIONS .....</b>                                        | <b>44</b> |
| 5.1 ANALYSIS FRAMEWORK .....                                                           | 44        |
| 5.1.1 Data Processing Workflow and Trajectory Mapping .....                            | 44        |
| 5.1.2 Driver Response.....                                                             | 47        |
| 5.1.3 Video Clip Extraction and Synchronization .....                                  | 47        |
| 5.1.4 Deep Learning Algorithm: Face Landmark Localization and Eye Onset Detection..... | 48        |
| 5.1.5 Performance Measures .....                                                       | 52        |
| 5.2 RESULT FOR MILWAUKEE.....                                                          | 54        |
| 5.2.1 Spectrum Comparison.....                                                         | 54        |
| 5.2.2 Lateral Distance Comparison.....                                                 | 55        |
| 5.2.3 Mounting Height Comparison .....                                                 | 56        |
| 5.2.4 Combined Configuration Analysis.....                                             | 56        |
| 5.2.5 Mannequin Type Analysis.....                                                     | 57        |
| 5.2.6 Spill Control Effects on Driver Response .....                                   | 58        |

|                                                                                   |           |
|-----------------------------------------------------------------------------------|-----------|
| 5.2.7 Obstruction Effects on Driver Response.....                                 | 59        |
| 5.3 RESULT FOR MADISON .....                                                      | 60        |
| 5.3.1 Spectrum Comparison.....                                                    | 60        |
| 5.3.2 Mounting Height Comparison .....                                            | 62        |
| 5.3.3 Combined Configuration Analysis.....                                        | 62        |
| 5.3.4 Mannequin Type Analysis.....                                                | 63        |
| 5.3.5 Spill Control Effects on Driver Response .....                              | 64        |
| 5.3.6 Obstruction Effects on Driver Response.....                                 | 65        |
| 5.4 SUMMARY FOR OPTIMAL CONFIGURATION .....                                       | 66        |
| 5.4.1 Cross-Site Spectrum Comparison.....                                         | 66        |
| 5.4.2 Clothing Condition Effects on Driver Response .....                         | 67        |
| 5.4.3 Eye Tracking Physiological Metrics.....                                     | 68        |
| 5.4.4 Baseline Versus Enhanced Lighting Results.....                              | 69        |
| 5.4.5 Interpretation of Driver Recognition Results .....                          | 70        |
| 5.4.6 Basis for Optimal Lighting Specification Development.....                   | 71        |
| 5.4.7 Final Recommended Specifications .....                                      | 71        |
| 5.5 SECTION SUMMARY .....                                                         | 72        |
| <b>6. DESIGN GUIDELINES FOR CROSSWALKS.....</b>                                   | <b>74</b> |
| 6.1 DESIGN GUIDELINE PRINCIPLES .....                                             | 74        |
| 6.2 VARIABLES USED IN THE IMPLEMENTATION FRAMEWORK .....                          | 76        |
| 6.3 STATISTICAL FOUNDATION FOR GENERALIZATION AND PLANNING-LEVEL ESTIMATION ..... | 76        |
| 6.3.1 Model Performance .....                                                     | 78        |
| 6.4 ROADWAY GEOMETRY AND FIXTURE PLACEMENT FRAMEWORK .....                        | 79        |
| 6.5 REACTION TIME AND DETECTION DISTANCE ESTIMATION.....                          | 80        |
| 6.6 STOPPING SIGHT DISTANCE CHECK.....                                            | 81        |

|                                                                  |           |
|------------------------------------------------------------------|-----------|
| 6.7 SOLAR BATTERY SIZING FRAMEWORK .....                         | 85        |
| 6.8 PHOTOMETRIC, GLARE, ADA, AND MAINTENANCE CHECKS .....        | 86        |
| 6.9 RECOMMENDED GENERALIZED DESIGN PROCEDURE .....               | 87        |
| 6.10 SECTION SUMMARY .....                                       | 88        |
| <b>7. IMPLEMENTATION RECOMMENDATIONS FOR WISDOT REVIEW .....</b> | <b>90</b> |
| 7.1 FINAL STUDY FINDINGS.....                                    | 90        |
| 7.2 RECOMMENDED CONFIGURATION FOR WISDOT CONSIDERATION .....     | 91        |
| 7.3 CONSOLIDATED DESIGN SUMMARY FOR DESIGNERS .....              | 91        |
| <b>REFERENCES .....</b>                                          | <b>93</b> |
| <b>APPENDIX .....</b>                                            | <b>95</b> |

## List of Figures

|                                                                                                                                                                       |    |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 1. SafeWalk™ enhanced crosswalk illumination system deployed at a midblock crosswalk.....                                                                      | 26 |
| Figure 2. SafeWalk™ smart crosswalk illuminator specification sheet. ....                                                                                             | 26 |
| Figure 3. Prototype spectral configurations assembled for testing.. ....                                                                                              | 28 |
| Figure 4. Rendered appearance of the seven tested spectral configurations. ....                                                                                       | 28 |
| Figure 5. Madison field experiment layout, roadway map reference, and baseline nighttime illuminance measurement at Williamson Street and South Dickinson Street..... | 32 |
| Figure 6. Milwaukee field experiment layout and roadway map reference on N Maryland Avenue near the University of Wisconsin Milwaukee campus.. ....                   | 33 |
| Figure 7. Field hardware and instrumentation used during nighttime crosswalk lighting experiments.. ....                                                              | 35 |
| Figure 8. Nighttime field testing setup during enhanced crosswalk lighting experiments....                                                                            | 36 |
| Figure 9. Madison nighttime illuminance measurements during field setup.....                                                                                          | 37 |
| Figure 10. Enhanced crosswalk lighting demonstration at the Madison and Milwaukee field sites.. ....                                                                  | 41 |
| Figure 11. Test vehicle and roadway view during the Milwaukee demonstration. ....                                                                                     | 42 |
| Figure 12. Mannequin crossing system used during Milwaukee nighttime testing. ....                                                                                    | 43 |
| Figure 13. GPS trajectory mapping for the Madison field experiment. ....                                                                                              | 45 |
| Figure 14. GPS data structure and key fields used for vehicle trajectory processing.....                                                                              | 45 |
| Figure 15. Deep learning eye onset detection pipeline. ....                                                                                                           | 51 |
| Figure 16. Conceptual top-view illustration of the two primary performance measures: reaction time and detection distance. ....                                       | 53 |
| Figure 17. Milwaukee spectrum performance comparison based on reaction time and detection distance. ....                                                              | 54 |
| Figure 18. Milwaukee lateral distance performance comparison based on reaction time and detection distance. ....                                                      | 56 |

|                                                                                                                                             |    |
|---------------------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 19. Milwaukee mounting height performance comparison based on reaction time and detection distance. ....                             | 56 |
| Figure 20. Milwaukee combined configuration comparison for spectrum, lateral distance, and mounting height. ....                            | 57 |
| Figure 21. Milwaukee driver response results by mannequin type.. ....                                                                       | 58 |
| Figure 22. Milwaukee driver response results by spill control condition.....                                                                | 59 |
| Figure 23. Milwaukee obstruction effects on driver response.....                                                                            | 60 |
| Figure 24. Madison spectrum performance comparison based on reaction time and detection distance. ....                                      | 61 |
| Figure 25. Madison mounting height performance comparison based on reaction time and detection distance.....                                | 62 |
| Figure 26. Madison combined configuration comparison for spectrum and mounting height. ....                                                 | 63 |
| Figure 27. Madison driver response results by mannequin type. ....                                                                          | 64 |
| Figure 28. Madison spill control effects on driver response.....                                                                            | 65 |
| Figure 29. Madison obstruction condition effects on driver response.....                                                                    | 66 |
| Figure 30. Site specific spectrum decision results for Milwaukee and Madison. ....                                                          | 67 |
| Figure 31. Clothing condition effects on driver response by lighting spectrum.....                                                          | 68 |
| Figure 32. Roadway geometry scaling used to generalize mounting height and lateral placement across roadway widths.....                     | 80 |
| Figure 33. Stopping sight distance adequacy across general roadway types.....                                                               | 84 |
| Figure 34. SafeWalk™ system installation and field deployment configuration used during nighttime field testing at the Milwaukee site. .... | 96 |
| Figure 35. Additional field installation view showing lateral placement and beam aiming during nighttime field testing.....                 | 97 |

## List of Tables

|                                                                                                                                                         |    |
|---------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| Table ES-1. Summary of the recommended enhanced crosswalk lighting configuration.....                                                                   | 13 |
| Table 1. Summary of color temperature studies and agency guidance .....                                                                                 | 20 |
| Table 2. Complete technical specifications of the SafeWalk™ enhanced crosswalk illuminator .....                                                        | 25 |
| Table 3. Seven spectral configurations were developed for Task 2 field testing, with selection rationale linked to the literature review findings. .... | 27 |
| Table 4. Experimental factors and field-testing conditions. ....                                                                                        | 36 |
| Table 5. Processed field dataset variables. ....                                                                                                        | 46 |
| Table 6. Driver response event timestamps recorded for each trial.....                                                                                  | 47 |
| Table 7. Video clips extracted for each trial. ....                                                                                                     | 48 |
| Table 8. Milwaukee spectrum reaction time (RT) and detection distance (DD) values.....                                                                  | 55 |
| Table 9. Recommended enhanced lighting configuration for Milwaukee.....                                                                                 | 56 |
| Table 10. Madison spectrum reaction time (RT) and detection distance (DD) values.....                                                                   | 61 |
| Table 11. Recommended enhanced lighting configuration for Madison.....                                                                                  | 62 |
| Table 12. Eye tracking physiological metrics comparing baseline and enhanced lighting conditions.....                                                   | 68 |
| Table 13. Baseline and enhanced lighting comparison by study site. ....                                                                                 | 70 |
| Table 14. Final recommended lighting specifications by application context. ....                                                                        | 71 |
| Table 15. Variables used in the roadway generalization framework. (*: Response Variables) .....                                                         | 76 |
| Table 16. Blue Baseline only OLS regression model outputs for the reaction time and detection distance .....                                            | 78 |
| Table 17. Assumed Values for Generalized Roadway Screening .....                                                                                        | 83 |
| Table 18. Required design checks before installation .....                                                                                              | 87 |

|                                                                                               |    |
|-----------------------------------------------------------------------------------------------|----|
| Table 19. Generalized design procedure.....                                                   | 88 |
| Table 20. Recommended enhanced crosswalk lighting configuration for WisDOT consideration..... | 91 |
| Table 21. Consolidated build specification for designers.....                                 | 92 |

## List of Acronyms

| Acronym | Definition                                                         |
|---------|--------------------------------------------------------------------|
| AASHTO  | American Association of State Highway and Transportation Officials |
| ADA     | Americans with Disabilities Act                                    |
| ANSI    | American National Standards Institute                              |
| CCT     | Correlated Color Temperature                                       |
| CNN     | Convolutional Neural Network                                       |
| CW      | Cool White                                                         |
| DC      | Direct Current                                                     |
| DD      | Detection Distance                                                 |
| DOD     | Depth of Discharge (battery sizing)                                |
| DOT     | Department of Transportation                                       |
| FHWA    | Federal Highway Administration                                     |
| GPS     | Global Positioning System                                          |
| HAWK    | High-Intensity Activated Crosswalk (beacon)                        |
| IDOT    | Illinois Department of Transportation                              |
| IES     | Illuminating Engineering Society                                   |
| IIHS    | Insurance Institute for Highway Safety                             |
| IPIT    | Institute for Physical Infrastructure and Transportation           |
| LED     | Light-Emitting Diode                                               |
| LOR     | Light Output Ratio                                                 |
| MDPI    | Multidisciplinary Digital Publishing Institute                     |
| OLS     | Ordinary Least Squares                                             |
| PI      | Principal Investigator                                             |
| POC     | Project Oversight Committee (WisDOT)                               |
| PSH     | Peak Sun Hours (solar sizing)                                      |
| RGB     | Red, Green, Blue (LED color channels)                              |
| RRFB    | Rectangular Rapid Flashing Beacon                                  |
| RT      | Reaction Time                                                      |
| SSD     | Stopping Sight Distance                                            |
| TAPCO   | Traffic and Parking Control Co., Inc.                              |
| USDOT   | United States Department of Transportation                         |
| UTC     | University Transportation Center                                   |
| VTRC    | Virginia Transportation Research Council                           |
| WisDOT  | Wisconsin Department of Transportation                             |

## **Executive Summary**

This report presents the final findings of the Enhanced Light Crosswalk Illumination project, a WisDOT-sponsored study evaluating how enhanced crosswalk illumination can improve nighttime pedestrian visibility, driver recognition, reaction time, and pedestrian detection distance. The primary safety issue addressed in this project is that pedestrians can be difficult for drivers to detect at night, particularly under low ambient lighting, visually complex backgrounds, dark clothing conditions, adverse weather, winter conditions, or roadway geometries that reduce the driver's available recognition and response time.

In this project, the team first conducted a comprehensive literature review and assessment of current practices for crosswalk and pedestrian illumination standards, policies, and best practices. Based on the literature review, the team designed and built an enhanced light system prototype with adjustable specifications, including lighting spectrum or color, lighting patterns, mounting height, illuminance level, and equipment position. The prototype was then used in controlled nighttime field testing at two crossing areas with different roadway configurations and lighting conditions to evaluate driver recognition, reaction time, detection distance, and braking response under baseline and enhanced lighting conditions. The field results were further analyzed to determine optimal lighting specifications, including recommended lighting patterns, equipment positions, illuminance levels, light spectrum, mounting height, and lateral placement. These findings were synthesized into preliminary design guidelines for pedestrian crosswalks for WisDOT consideration.

The following sections summarize the key findings from each major project component, including the literature review, field testing, optimal lighting specification analysis, and design guideline development.

The literature review showed that color temperature alone is not sufficient to determine effective crosswalk lighting performance. Nighttime pedestrian visibility depends on the combined effects of vertical illuminance, pedestrian-background contrast, beam spread, fixture placement, roadway context, and driver visual adaptation. These findings informed the field-testing design and supported the evaluation of multiple lighting configurations and site conditions.

Field tests were conducted at two study sites in Madison and Milwaukee, Wisconsin, representing different roadway geometries and lighting conditions. The Madison site represented

a wider roadway context with RRFB (Rectangular Rapid Flashing Beacon) equipment, while the Milwaukee site represented a two-lane crosswalk location without RRFB equipment. A total of 104 experimental rounds were completed in Madison, and 177 experimental rounds were completed in Milwaukee. The testing program included multiple lighting spectra, mounting height conditions, obstruction conditions, clothing conditions, weather conditions, ambient lighting conditions, and other site conditions. At the Milwaukee site, additional trials were conducted to study the influence of different lateral distances between the system and the crosswalk and to evaluate visibility under different pedestrian appearance conditions using different mannequin clothing colors.

During each test, an instrumented probe vehicle was driven toward the crosswalk while a mannequin mounted on an electric skateboard was used to simulate pedestrian crossing events in a controlled and repeatable manner. Data were collected using synchronized roadway video, driver-facing infrared video, GPS and speed records, brake event timing, lux measurements, and a deep learning-based eye-tracking algorithm. The algorithm analyzed driver eye movements from the infrared video to identify the first recognition moment. This recognition timestamp was then synchronized with vehicle GPS, speed, and braking data to calculate reaction time, detection distance, reaction distance, and stopping margin.

The field results show that enhanced crosswalk illumination improved driver response and pedestrian detection performance compared with the baseline condition, defined as the existing nighttime crosswalk lighting condition at each site with the SafeWalk™ enhanced illumination system turned off. In Madison, the baseline condition produced a driver reaction time of 0.71 s and a pedestrian detection distance of 212 ft. Under the blue-light-based enhanced lighting condition, reaction time decreased to 0.67 s, while detection distance increased to 275 ft, meaning drivers detected the pedestrian 63 ft sooner than under the baseline condition. In Milwaukee, the baseline condition produced a reaction time of 0.92 s and a pedestrian detection distance of 242 ft. Under the blue-light-based enhanced lighting condition, reaction time decreased to 0.69 s, while detection distance increased to approximately 261 ft, meaning drivers detected the pedestrian 19 ft sooner than under the baseline condition. Overall, these results indicate that the enhanced lighting system increased the distance at which drivers recognized the pedestrian target and reduced the time required to respond, providing a larger available stopping margin under nighttime conditions.

The field findings were generalized into broader roadway design guidance using a statistical model. This analysis considered roadway width, crosswalk context, stopping sight distance (SSD), mounting height, lateral placement, photometric performance, and practical installation feasibility. Note that the recommended configurations should be treated as planning and engineering review starting points rather than fixed standards for all crosswalks. Final application at other Wisconsin roadway locations should be confirmed through site-specific engineering review, including photometric verification, obstruction review, ADA and clear zone review, maintenance review, winter performance considerations, and stopping sight distance checks.

The main value of this project is that it converts field-measured driver response into practical guidance for enhanced crosswalk lighting design. The findings can help WisDOT and local agencies identify suitable lighting configurations, review site conditions, plan pilot deployments, and support future updates to crosswalk lighting guidance. The results also link lighting design with pedestrian visibility, driver recognition, roadway generalization, and field feasibility, making the findings useful for both the tested sites and broader Wisconsin roadway contexts.

Table ES-1 below distills the recommended build configuration for the most common residential roadway contexts. Full design tables, geometry scaling, and step-by-step procedures are provided in Table 14, Table 17, Table 19, Table 20, and Sections 6 and 7.

**Table ES-1. Summary of the recommended enhanced crosswalk lighting configuration (references indicate where full details are provided).**

| <b>Design Element</b> | <b>Recommended Configuration (generalized; most common residential roadway contexts)</b>                                                                                                                         |
|-----------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Lighting spectrum     | Blue Baseline (blue-shifted LED; controller channels Red 129.0, Green 420.75, Blue 741 on the 0–750 scale); Ice Blue (Red 80, Green 520, Blue 750) for narrow two-lane residential contexts (Table 14, Table 20) |
| Vertical illuminance  | At least 20 lux at the pedestrian plane (design target); approximately 21 lux was measured under the enhanced condition in the field (Sections 2.1 and 3.5)                                                      |
| Mounting height       | Scale with roadway width: approximately 12.5 ft for a two-lane residential road up to approximately 15 ft for a 40 ft four-lane residential road (Table 17, Section 6)                                           |
| Lateral placement     | Scale with roadway width: 9.5ft from the crosswalk for the residential scenarios above. For broader generalized roadway screening, scale lateral placement with roadway width using (Table 17, Section 6)        |

|                  |                                                                                                                                         |
|------------------|-----------------------------------------------------------------------------------------------------------------------------------------|
| Spill control    | None required; review glare and light trespass during site-specific design (Section 5.4, Table 14)                                      |
| Power source     | Solar power with battery storage, subject to site feasibility review (Table 14)                                                         |
| Safety screening | Predicted detection distance must exceed the required stopping sight distance for the approach speed (Section 7.1, Table 18, Figure 33) |

It is worth noting that the baseline condition in this report refers to the existing nighttime roadway lighting without enhanced crosswalk lighting installed; it does not refer to 4000 K street lighting. For agencies considering upgrades from existing white-light systems, the spectrum comparisons in Sections 5.2.1 and 5.3.1 (Figures 17 and 24) evaluate the neutral-white configurations (4000 K through 6500 K) alongside the blue-shifted configurations; the blue-shifted configurations provided the strongest overall performance at both sites, indicating an additional benefit beyond conventional white lighting. Using the project field dataset, the enhanced lighting increased mean detection distance relative to the 4000 K condition by 19.2 ft at Milwaukee (237.2 ft to 256.4 ft) and by 33.2 ft at Madison (241.8 ft to 275.0 ft), and an average of approximately 26 ft with reaction times comparable to 4000 K (see Tables 8 and 10 in Sections 5.2.1 and 5.3.1).

## **Introduction**

### **Background**

Pedestrian safety remains one of the persistent challenges in Wisconsin transportation. Pedestrians account for a substantial share of traffic fatalities, and nighttime or low-light conditions create a disproportionate safety risk because drivers have less time and distance to detect, recognize, and respond to pedestrians [1, 17]. This visibility problem becomes more serious when ambient lighting is low, pedestrians wear dark clothing, roadside backgrounds reduce contrast, weather affects visibility, or roadway geometry limits drivers' line of sight.

Existing crosswalk treatments address this problem only partially. Rectangular Rapid Flashing Beacons (RRFB) can improve driver yielding behavior, but they do not directly illuminate the pedestrian as a recognizable human figure. High-intensity activated crosswalk (HAWK) signals provide stronger traffic control, but they require greater infrastructure investment and are not feasible at every uncontrolled crossing. Conventional roadway lighting improves general ambient visibility, but it is usually designed for roadway and pavement illumination rather than targeted pedestrian conspicuity. In-pavement lighting can help mark the crosswalk boundary, but it provides limited vertical illumination of the pedestrian's body and face [1, 16].

Enhanced crosswalk lighting provides a practical approach for addressing this gap. In this study, enhanced crosswalk lighting refers to targeted LED illumination installed on a side-mounted pole to improve pedestrian visibility through adequate vertical illuminance, pedestrian background contrast, controlled beam distribution, and appropriate fixture placement. Its effectiveness depends not only on light spectrum, but also on mounting height, lateral placement, beam direction, roadway context, ambient lighting, obstruction conditions, weather, and driver visual adaptation.

### **Problem Statement**

The core problem addressed by this project is the absence of field-validated, Wisconsin-specific design guidance for enhanced crosswalk lighting. Although prior research and agency guidance show that lighting can improve pedestrian visibility, agencies still need clearer evidence on how specific lighting configurations affect driver reaction time, detection distance, and practical installation feasibility under real roadway conditions [2, 4, 7, 8, 9, 10, 12, 14].

Three specific gaps motivated the study. First, there is spectrum uncertainty. Existing guidance generally favors neutral white LED lighting for pedestrian facilities, often within the

3000 K to 4000 K range [3, 5, 6, 16]. However, modern lighting systems can provide neutral white, cool white, and blue-shifted spectra. It is not clear from existing guidance whether neutral white, cooler white, or blue-shifted lighting produces better driver reaction time, detection distance, and visual comfort at Wisconsin crosswalks. Second, there is geometric uncertainty. Mounting height, fixture angle, beam coverage, and vertical illuminance directly affect pedestrian visibility, glare exposure, and crosswalk coverage. A configuration that works on a narrow residential street may not transfer directly to a wider arterial roadway. Without field evidence, agencies cannot confidently determine which combinations of height, lateral offset, and beam direction are most effective for different crosswalk contexts. Third, there is a transfer gap. Field testing is necessarily limited to specific sites, but WisDOT and local agencies need guidance that can support decisions across different roadway widths, speeds, lighting environments, and pedestrian crossing contexts. A structured method is needed to translate tested configurations into roadway-scaled planning guidance while checking whether the resulting recommendations provide adequate stopping sight distance.

Without evidence on these gaps, agencies cannot confidently specify enhanced crosswalk lighting for new installations, evaluate proposed lighting systems, or develop consistent guidance for future deployment. This project was designed to address these gaps through controlled field measurement, driver response analysis, statistical modeling, and roadway-scaled design guidance.

## **Report Organization**

The remainder of this report is organized as follows. Section 1 presents the literature review and summarizes current knowledge on pedestrian visibility, crosswalk illumination, lighting spectrum, mounting geometry, and glare control. Section 2 describes the enhanced lighting system design and prototype configuration. Section 3 focuses on the field-testing methodology, final experimental design, data collection process, field equipment, experimental conditions, and data quality overview. Section 4 documents the enhanced lighting demonstrations conducted at the Madison and Milwaukee field sites. Section 5 presents the analysis framework, Milwaukee results, Madison results, and optimal lighting configuration summary. Section 6 provides roadway-scaled design guidance, stopping sight distance checks, glare control considerations, solar battery sizing, and implementation considerations for different crosswalk contexts. Section 7 presents

implementation recommendations for WisDOT review and summarizes the final study findings, a practical deployment pathway, limitations, future validation needs, and final conclusions.

## 1. Literature Review

Improving crosswalk lighting has become important because current systems like RRFBs and in-pavement lights do not keep pedestrians clearly visible at night or during winter conditions, and they do not account for the effects of color temperature on visibility and driver response. Research over the past decade has increasingly focused on how lighting characteristics, particularly color temperature, vertical and horizontal illuminance, and beam geometry influence pedestrian detection and driver response. Modern LED systems now enable precise optical control, tunable color output, and improved energy efficiency, creating opportunities to systematically evaluate lighting parameters that directly affect safety outcomes. Accordingly, this project emphasizes the scientific assessment of crosswalk lighting configurations with varying color temperatures to quantify their impact on pedestrian visibility, driver recognition distance, and overall nighttime safety performance.

The research team conducted a comprehensive review of national and international literature drawn from peer-reviewed journals, transportation research databases, and agency technical reports, including those from the Federal Highway Administration (FHWA), their guidelines, professional standards, state Departments of Transportation (DOTs), and academic institutions [1, 3, 5, 7, 9, 16]. The objective was to synthesize current evidence on how color temperature, illuminance, and optical distribution influence pedestrian detection and driver response at crosswalks. More than 90 publications were screened, and approximately 20 were identified as directly relevant to pedestrian illumination and safety. Emphasis was placed on studies published within the past five years to ensure alignment with modern LED lighting capabilities, evolving design standards, and contemporary human-factors research.

A preliminary analysis revealed notable variation in terminology, methodology, and measurement criteria among studies. Terms such as roadway lighting, pedestrian illumination, crosswalk visibility, and adaptive lighting systems were often used interchangeably, although they generally referred to related performance concepts such as color temperature, illuminance, and visual contrast. The research team cataloged detailed information on lighting configurations, experimental settings, sensor technologies, and evaluation procedures used to quantify pedestrian visibility under diverse environmental conditions. Particular attention was given to studies that examined the interaction between color temperature, vertical illuminance, and beam geometry

under adverse weather and low light conditions [4-8]. Table 1 summarizes the principal lighting parameters, evaluation methods, and performance outcomes reported across these studies, identifying those most applicable to developing enhanced crosswalk lighting systems for this project.

**Table 1. Summary of color temperature studies and agency guidance**

| Study                         | Year, Venue         | Setting                 | 2200K | 3000K | 3500K | 4000K | 5000K | 6000K | 6500K | Recommendation                                                                            |
|-------------------------------|---------------------|-------------------------|-------|-------|-------|-------|-------|-------|-------|-------------------------------------------------------------------------------------------|
| SALUSLux [8]                  | 2025, USDOT UTC     | Controlled test track   | X     |       |       | X     | X     |       |       | Use 4000K as the baseline; 3000K is acceptable; 2700K is not preferred.                   |
| City of Alexandria [9]        | 2024, Alexandria    | Field deployment        |       | X     |       | X     | X     |       |       | Prefer 4000–4100K; if 3000K, increase illuminance.                                        |
| Narrow Beam Illuminator [4]   | 2022, Virginia Tech | Lab + testbed           |       | X     |       | X     |       |       |       | Use 4000K with CW (cool white) illuminator; medium to high lux.                           |
| Rain and Fog Assessment [10]  | 2022, Virginia Tech | Fog chamber             |       |       | X     |       |       | X     |       | Prioritize brightness or contrast; color temperature had no consistent advantage.         |
| Midblock Visibility [2]       | 2023, MDPI          | Simulation + field      |       |       |       | X     |       |       |       | Target 10 lx vertical; use CW + positive contrast.                                        |
| Roadway Lighting IDOT [7]     | 2021, IDOT          | Field                   |       |       |       | X     |       |       |       | Use 4000K LEDs; 10 lx vertical + CW at midblock.                                          |
| VTRC Intersection Review [11] | 2020, VTRC          | Review + testing        |       | X     |       | X     |       |       |       | Agencies favor 3000-4000K LEDs; 4000K is the standard color temperature.                  |
| Maine DOT Guidelines [5]      | 2023, Maine DOT     | Guidelines + lab review |       | X     |       | X     |       |       |       | The standard is 4000K; allow $\geq 3000\text{K}$ if necessary for environmental concerns. |
| IIHS Yielding Study [12]      | 2024, IIHS          | Urban sites             |       |       |       | X     |       |       |       | Strongest results with CW + RRFB (not color temperature -driven).                         |
| FHWA Handbook 2023 [16]       | 2023, FHWA          | National guideline      | X     |       |       | X     | X     |       |       | Recommend 3000-4000K, favor 4000K; avoid extremes (2200K & 5000K).                        |

## **1.1 Lighting Parameters and Performance Metrics**

Studies consistently identify color temperature and illuminance as primary parameters influencing pedestrian detection and nighttime visibility [5, 6, 11]. The reviewed literature spans color temperatures from approximately 2,200 K to 6,500 K [1, 5]. Across field, laboratory, and simulation studies, a mid-range white light around 4000 K to 4,500 K is generally favored for balance visual clarity, color rendering, and comfort [11]. The FHWA's Pedestrian Lighting Primer [1] highlights color temperature as a key design consideration, recommending neutral white light near 4,000 K to maintain color accuracy in pedestrian zones.

Similarly, a field study tested color temperature between 1,600 K and 5,400 K at multiple illuminance levels, showing significant effects of both color temperature and ambient temperature on perceived visibility and comfort [14]. A Michigan crosswalk-lighting evaluation comparing 3,000 K and 4,000 K systems reported higher user preference for the latter, especially in urban midblock crossings [19]. Analysts and manufacturers converge on the view that neutral white light (~4,000–4,500 K) offers the optimal trade-off, while very warm ( $\leq 2,700$  K) or cool ( $\geq 6,000$  K) sources may compromise visibility due to poor color fidelity or increased glare [5, 6].

## **1.2 Agency Guidelines and Design Standards**

Several U.S. agencies and DOTs have developed guidelines that reinforce these findings. The Maine DOT Crosswalk Lighting Guide [5] identifies  $\approx 4,000$  K as the typical standard for new LED installations, allowing warmer tones only when environmental restrictions apply. The Illinois DOT Center of Transportation [7] study Roadway Lighting's Effect on Pedestrian Safety at Intersections and Midblock Crosswalks recommends designs emphasizing vertical illuminance and contrast rather than relying solely on color temperature. The Virginia Transportation Research Council likewise notes agency preference for LEDs between 3,000 K and 4,000 K, considering this range most effective for accurate pedestrian rendering [11].

The FHWA Lighting Handbook recommends 3,000–4,000 K for pedestrian facilities, explicitly discouraging extremes such as 2,200 K and 6,000 K due to either poor color discrimination or excessive short-wavelength glare [16]. A nighttime crosswalk study further indicates that while contrast and vertical illumination are dominant factors in pedestrian detection, mid-range color temperature systems paired with active illumination devices such as Rectangular Rapid Flashing Beacons (RRFBs) achieve the strongest results [12, 13].

### **1.3 Laboratory and Field Evaluations**

Controlled and field evaluations have demonstrated that higher color temperatures generally increase detection distance but may introduce glare and visual discomfort [14], particularly above 5,000 K, where short-wavelength output rises. For instance, the SALUSLux test-track experiments established 4,000 K as the baseline, with 3,000 K acceptable under limited conditions, while discouraging temperatures below 2,700 K and those higher than 5,000 K for safety performance [8]. A Virginia Tech fog-chamber study compared 3,500 K and 6,000 K lighting and concluded that while brightness dominated detection under low visibility, color temperature had no consistent advantage in fog conditions [10].

Other simulation and field studies confirm that achieving sufficient vertical illuminance (typically 10 lx at pedestrian height) combined with positive contrast yields better results than manipulating color temperature alone. A 2023 MDPI study supports this by showing that 4,000 K lighting at or above 10 lx vertical illuminance maximized pedestrian detection rates in driver simulations [2]. Overall, integrating moderate color temperature light with adequate brightness and uniformity remains the consensus design strategy.

### **1.4 Implications for Enhanced Crosswalk Lighting Design**

Based on the reviewed evidence, neutral white light around 4,000 K is widely recognized as a practical reference point for crosswalk illumination [3, 5, 11]. Warmer tones can enhance comfort in residential areas or sensitive environmental contexts, but they may reduce object contrast [3, 5]. Cooler tones can improve apparent sharpness and detection distance, but they can also increase glare and perceived visual harshness [11]. Therefore, the recommended approach is to test multiple configurations, including 4,000 K, 5,000 K, 6,500 K, and wavelength-shifted blue light (RGB mode), to quantify performance trade-offs across different environmental and visual contexts.

Agency recommendations emphasize that color temperature should be evaluated together with illuminance, beam angle, mounting height, glare control, and driver adaptation effects. Uniformity ratios, glare indices, and driver adaptation effects should also guide specification development. The integration of modular and dimmable LED systems allows for precise adjustment of these parameters during field testing and calibration [3]. These findings form the empirical foundation for the color-temperature experiments summarized in Table 1.

## 1.5 Section Summary

The literature confirms that lighting characteristics, especially color temperature, vertical illuminance, and beam geometry, directly influence pedestrian detection distance, driver reaction time, and perceived visibility. Based on the reviewed studies, several key findings inform this project's objectives and experimental framework:

There is broad agreement that a mid-range neutral white light around 4,000 K offers the best balance of brightness, contrast, and comfort for both drivers and pedestrians.

Vertical illuminance is a stronger determinant of pedestrian visibility than color temperature alone; maintaining levels near 10 lux at pedestrian height significantly improves detection performance. Very warm tones ( $\leq 2,700$  K) reduce color fidelity and object contrast, while very cool tones ( $\geq 6,000$  K) increase glare and driver discomfort, making them less suitable for crosswalk applications. Agency guidelines from FHWA, Maine DOT, and Illinois DOT consistently recommend the 3,000 to 4,000 K range for pedestrian facilities, discouraging extremes due to visual or environmental drawbacks. Modern LED systems with tunable color temperature and dimmable output provide the flexibility needed to optimize visibility while maintaining energy efficiency and system longevity. Studies show that combining appropriate color temperature with uniform horizontal and vertical illumination yields the greatest improvement in pedestrian recognition and driver response times.

Together, these findings support testing across a representative range of correlated color temperatures and controlled illuminance levels to quantify performance trade-offs. The literature review validates the feasibility and value of developing enhanced crosswalk lighting systems that can vary in color temperature and brightness. The main challenge identified is balancing visibility gains with potential glare and comfort trade-offs, emphasizing the need for empirical testing under diverse lighting and weather conditions. It also highlights the need to evaluate not only brightness or visibility, but also driver recognition, reaction time, detection distance, and glare risk under realistic field conditions.

## **2. Design and Build Enhanced Light Systems**

Section 2 translated the Section 1 literature review findings into a field-ready enhanced pedestrian crosswalk lighting system. The design work was carried out in collaboration with TAPCO, the Wisconsin-based traffic safety products manufacturer and industry partner on this project. The result was a modular, adjustable prototype built on TAPCO's SafeWalk™ Crosswalk Illuminator platform, configured to support various lighting colors, changeable mounting height, adjustable beam direction, different vertical illuminance levels, and different crosswalk coverage conditions. This section documents the design criteria, system specifications, spectral configurations, field-measured illuminance performance, and the prototype demonstration in the lab environment completed as part of Task 2.

### **2.1 Design Criteria from the Literature Review**

The Section 1 literature review established four binding criteria for the Task 2 system design. First, the system must cover the color temperature range from 4000 K through 6500 K plus blue-shifted RGB configurations, because the literature does not resolve which part of this range produces optimal driver response in real nighttime Wisconsin conditions. Second, the system must achieve at least 20 lux vertical illuminances at the pedestrian plane for two- to four-lane coverage, consistent with FHWA guidance and the MDPI simulation study. Third, the system must support independent adjustment of mounting height, beam direction, crosswalk coverage, vertical illuminance levels, and lateral placement so that installation geometry effects can be measured separately from spectrum effects. Fourth, the system must be operationally reliable in Wisconsin winter conditions without requiring specialized maintenance between testing sessions.

The literature review also showed that enhanced crosswalk lighting should improve pedestrian visibility without creating excessive glare for approaching drivers. Therefore, the prototype configuration considered lighting color, mounting height, beam angle, vertical illuminance level, and crosswalk lighting coverage. These factors were included so that the system could be evaluated later under nighttime field conditions for pedestrian visibility and driver visual comfort.

### **2.2 System Platform: SafeWalk™ Crosswalk Illuminator**

The enhanced lighting system is built on TAPCO's SafeWalk™ Crosswalk Illuminator (SafeWalk 2.0), a purpose-built LED crosswalk lighting product designed for uncontrolled midblock and intersection crossings. The unit houses modular LED arrays in an IP66-rated

aluminum and polycarbonate enclosure with an adjustable aluminum pivot bracket for precise beam aiming. Individual LEDs operate at approximately 13.35 V DC, 150 mA, and 2.0 W each, producing approximately 122 lumens per watt. Photometric testing using an EVERFINE Goniophotometer System recorded a maximum luminous intensity of approximately 820 cd/klm with a beam spread of approximately 25° vertical × 24° horizontal and a Type IV crosswalk distribution. Table 2 presents the complete technical specifications as documented in the SafeWalk 2.0 datasheet and test report.

**Table 2. Complete technical specifications of the SafeWalk™ enhanced crosswalk illuminator**

| Parameter             | Specification                                      | Design Relevance                                             |
|-----------------------|----------------------------------------------------|--------------------------------------------------------------|
| Input power           | 12 V DC                                            | Supplied via SafeWalk™ controller; standard low-voltage DC.  |
| Current draw          | Up to 625 mA per lane or 150 mA per LED            | SafeWalk 2.0 datasheet and test report.                      |
| Power consumption     | ≈ 2.0 W per LED (≈ 122 lm/W)                       | Energy-efficient LED modules.                                |
| Illuminance target    | ≥ 20 lux vertical (two- to four-lane coverage)     | Meets and exceeds FHWA pedestrian-lighting recommendation.   |
| Photometric type      | Type IV distribution, 25° V × 24° H beam spread    | Controlled crosswalk-center targeting; limits light spill.   |
| Maximum intensity     | ≈ 820 cd/klm; downward LOR ≈ 24.5%                 | Measured by EVERFINE Goniophotometer (attached test report). |
| Light distance        | Up to 20 ft per illuminator                        | Sufficient for midblock crosswalk coverage.                  |
| Brightness levels     | 3 selectable levels via soft-start circuit         | Allows site-specific calibration and adaptive control.       |
| Mounting height       | 12–15 ft nominal range                             | Compatible with existing poles and brackets.                 |
| Optical pattern       | Outward (crosswalk center) + Flood (approach area) | Dual-beam pattern for uniform pedestrian coverage.           |
| Housing enclosure     | Aluminum + polycarbonate, IP66                     | Corrosion- and weather-resistant; retrofit-ready.            |
| Operating temperature | –40°F to 176°F (–40°C to 80°C)                     | Year-round operation under Wisconsin winter conditions.      |
| Wind rating           | Up to 120 mph                                      | Structural safety margin for pole-mount installation.        |
| Dimensions            | 4.5 in W × 3.5 in H × 4.5 in D (with bracket)      | Compact installs without pole replacement.                   |

Figure 1 illustrates the SafeWalk™ enhanced crosswalk illumination system deployed at a midblock crosswalk.

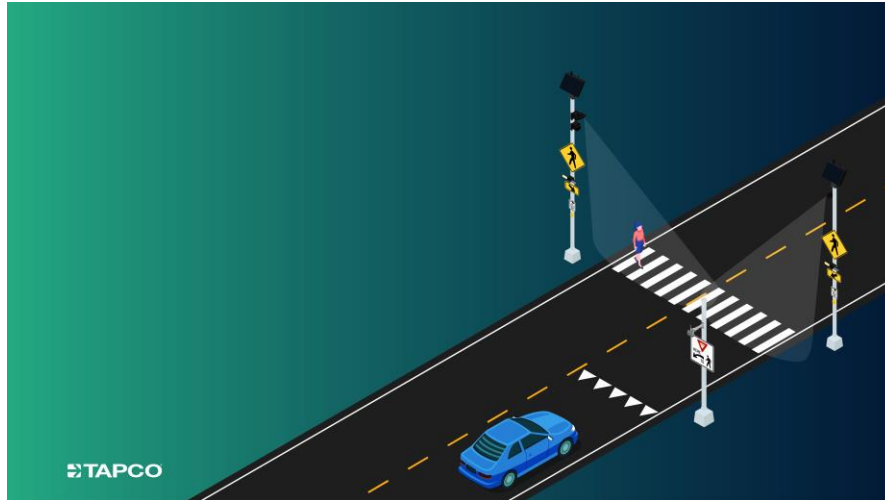


**Figure 1. SafeWalk™ enhanced crosswalk illumination system deployed at a midblock crosswalk. The overhead LED array is mounted on an existing pole bracket, aimed to illuminate the pedestrian figure with a Type IV downward distribution**

Figure 2 presents the SafeWalk™ smart crosswalk illuminator specification sheet used to confirm the system’s photometric characteristics.

Safe travels.

**SAFEWALK®**  
SMART CROSSWALK ILLUMINATOR

| SPECIFICATIONS                       |                                                                                                              |
|--------------------------------------|--------------------------------------------------------------------------------------------------------------|
| <b>POWER</b>                         | 12VDC                                                                                                        |
| <b>POWER CONSUMPTION</b>             | Up to 625mA                                                                                                  |
| <b>ACTIVATION</b>                    | In unison with system activation                                                                             |
| <b>FEATURES</b>                      | Soft start                                                                                                   |
| <b>LIGHT LEVELS</b>                  | 3 levels per lane configuration                                                                              |
| <b>DISPLAY LIGHTS</b>                | 5 LEDs, 4000K                                                                                                |
| <b>BEAM LIGHT</b>                    | Projects outward illuminating the middle of the crosswalk                                                    |
| <b>FLOOD LIGHT</b>                   | Illuminates the approach area of the crosswalk                                                               |
| <b>ILLUMINANCE</b>                   | Set designed to light a (2) two-lane and (4) four-lane crosswalk at a 20 LUX minimum per FHWA recommendation |
| <b>LIGHT DISTANCE</b>                | Up to 20 feet per illuminator                                                                                |
| <b>INSTALLATION HEIGHT</b>           | 12 feet to 15 feet                                                                                           |
| <b>HOUSING</b>                       | Aluminum and weather resistant polycarbonate                                                                 |
| <b>BRACKET</b>                       | Adjustable aluminum                                                                                          |
| <b>ENCLOSURE</b>                     | IP 66                                                                                                        |
| <b>OPERATING TEMPERATURE RANGE</b>   | -40°F to 176°F (-40°C to 80°C)                                                                               |
| <b>WIND RATING</b>                   | Up to 120mph*                                                                                                |
| <b>DIMENSIONS WITH PIVOT BRACKET</b> | 4.5" W x 3.5" H x 4.5" D                                                                                     |

\*Dependent upon pole size and system arrangement

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1029-02008 10/10/25

**Figure 2. SafeWalk™ smart crosswalk illuminator specification sheet. Photometric data confirms the Type IV beam pattern and ≈820 cd/klm peak intensity used to verify the 20-lux design target.**

## 2.3 Spectral Configurations

The prototype was built to support seven distinct spectral configurations. The first three 4000 K, 5000 K, and 6500 K use the standard white LED channels at increasing correlated color temperatures and represent the range most commonly evaluated in the literature. The remaining four Blue Baseline, Ice Blue, Sky Blue, and Pure Royal Blue use the RGB LED channels at varying intensities to produce blue-shifted output. This spectral range was selected because the literature identifies blue-shifted light as a potential high-conspicuity option for nighttime pedestrian detection, while also flagging short-wavelength glare as a potential discomfort risk. The seven configurations cover the full decision space identified in Section 1: the neutral-white agency-recommended range, and the blue-shifted range not yet evaluated in Wisconsin field conditions. Table 3 presents the seven spectral lighting conditions developed for field testing and summarizes the design rationale for each configuration.

**Table 3. Seven spectral configurations were developed for Task 2 field testing, with selection rationale linked to the literature review findings.**

| Configuration   | Type               | Design Rationale                                                                   |
|-----------------|--------------------|------------------------------------------------------------------------------------|
| 4000 K          | Neutral white      | FHWA/agency recommended baseline; highest literature consensus.                    |
| 5000 K          | Cool white         | One step above agency standard; tests detection vs. comfort trade-off.             |
| 6500 K          | Daylight white     | Upper white-light boundary; high blue content but continuous spectrum.             |
| Blue Baseline   | Blue-shifted LED   | Reference RGB configuration; blue channel at low intensity.                        |
| Ice Blue        | Blue-shifted LED   | Blue channel + partial white mix; highest measured luminance among blue configs.   |
| Sky Blue        | Blue-shifted LED   | Mid-intensity blue-shifted; tested as intermediate between Baseline and Ice Blue.  |
| Pure Royal Blue | Saturated blue LED | Maximum blue saturation; highest spectral purity; evaluated for conspicuity limit. |

SafeWalk™ controller RGB channel settings were used for the blue-shifted configurations on the controller's 0-750 channel intensity scale, where 750 represents the maximum channel value. The settings were as follows: Blue Baseline: Red 129.0, Green 420.75, Blue 741; Ice Blue: Red 80, Green 520, Blue 750; Sky Blue: Red 200, Green 480, Blue 750; and Pure Royal Blue: Red 20, Green 50, Blue 750. The white-light configurations, including 4000 K, 5000 K, and 6500 K, used the standard white LED channels and did not require RGB channel settings.

Figure 3 shows the prototype spectral configurations assembled for field testing.



Figure 1 lighting modules 4000 K



Figure 2 lighting modules 5000 K



Figure 3 lighting modules 6500 K



Figure 4 lighting modules RGB, Blue Light

Figure 3. Prototype spectral configurations assembled for testing. Left to right: 4000 K, 5000 K, 6500 K (white-light group); Blue Baseline, Ice Blue, Sky Blue, Pure Royal Blue (blue-shifted group). The white-light configurations produced approximately twice the measured vertical illuminances of the blue-shifted group.

|        |        |        |               |          |          |                 |
|--------|--------|--------|---------------|----------|----------|-----------------|
| 4000 K | 5000 K | 6500 K | Blue Baseline | Ice Blue | Sky Blue | Pure Royal Blue |
|--------|--------|--------|---------------|----------|----------|-----------------|

Figure 4. Rendered appearance of the seven tested spectral configurations, generated from the exact CCT values and RGB channel settings listed in Table 3.

The colors shown in Figure 4 are screen-based renderings generated from the CCT values for the white-light group and the RGB channel intensities for the blue-shifted group. These renderings are intended to illustrate the relative visual appearance of the tested configurations. Actual field appearance depends on fixture output, measured illuminance, pavement reflectance, surrounding ambient lighting, driver viewing angle, and nighttime visibility conditions.

## 2.4 Installation Geometry and Design Factor

The enhanced lighting prototype was designed so that the geometric and optical parameters governing vertical illuminance and pedestrian contrast, the quantities most directly tied to nighttime conspicuity in the lighting literature, could be specified and adjusted independently of the lighting spectrum. The system's controllable design factors are mounting height, beam coverage across the crossing, beam aiming angle, and the flood-light operating mode that reproduces a streetlight turning on and off at the approach. Mounting height and aiming angle set the vertical illuminance delivered to the pedestrian's body and face; beam coverage governs the

uniformity of illumination across the crossing and waiting area; and the flood-light mode reproduces the presence or absence of ambient street lighting so the system can be evaluated under both background conditions.

Lateral offset is part of the same installation geometry, but it is governed by site conditions rather than selected for visual performance. The usable position is constrained by the available pole locations, sidewalk and curb clearance, utility conflicts, and roadway width. It is therefore established for each site from the roadway geometry and confirmed through photometric and pole-feasibility review, using the roadway-scaled procedure developed in Section 6. During field testing, lateral offset was varied to map this installation envelope and to quantify its effect on illumination angle and coverage.

## **2.5 Prototype Demonstration and Task 2 Completion**

The enhanced lighting system was assembled and tested at the researcher's laboratory at the University of Wisconsin-Milwaukee for photometric consistency before field deployment. A live prototype was demonstrated at the Southeast Wisconsin Transportation Symposium 2025, where transportation engineers, researchers, and agency representatives evaluated the live setup. Participants expressed particular interest in the RGB blue-light prototype for its potential to increase pedestrian conspicuity and driver awareness under low-light conditions. Supplemental field installation photographs showing the SafeWalk™ deployment configuration are provided in Appendix A.

### **3. Driver Recognition and Reaction Time Testing**

This section presents the methods used to conduct driver recognition and reaction time testing under nighttime crosswalk conditions. The purpose of this testing was to evaluate how different lighting system configurations affected a driver's ability to visually recognize a pedestrian target, respond through braking, and maintain sufficient stopping distance. The section describes the study sites, experimental setup, probe vehicle instrumentation, mannequin crossing system, lighting configurations, data synchronization process, trajectory mapping procedure, and performance measures used for the field evaluation.

The evaluation focuses on two primary measures: reaction time and detection distance. Reaction time is defined as the time between the driver's first visual recognition of the pedestrian target and the initial brake pedal response. Detection distance is defined as the distance between the probe vehicle and the crosswalk at the moment of first visual recognition. Together, these measures provide a direct basis for assessing how enhanced crosswalk illumination influences driver recognition, braking response, and the available stopping distance under nighttime conditions. These two measures were selected as the primary evaluation criteria because, taken together, they describe both how early a pedestrian becomes visible to the driver (detection distance) and how quickly the driver can act on that information (reaction time); a lighting configuration provides the greatest safety benefit when it improves both, since earlier detection and faster response jointly increase the distance available to stop.

The results from this section provide the empirical basis for the optimal lighting specifications in Section 5, and the design guidance in Section 6.

#### **3.1 Field Testing Overview**

Nighttime field testing was completed at two Wisconsin study sites: Madison and Milwaukee. The two sites were selected to represent different roadway contexts, crossing environments, lighting conditions, and RRFB. Madison represented a wider urban roadway context with existing RRFB equipment, while Milwaukee represented a two-lane campus roadway context without a push button or rectangular rapid flashing beacon.

The Madison study site was located at the Williamson Street and South Dickinson Street intersection in Madison, Wisconsin, with approximate geographic coordinates of 43.08323, -89.35769. This site represented a four-lane urban roadway context with existing rectangular rapid flashing beacons and pedestrian push buttons. The test vehicle approached the marked crosswalk

along the planned roadway approach shown in Figure 5, while the mannequin crossing movement was conducted at the marked crosswalk using an electric skateboard controlled remotely by the research team. The crossing environment included a wider roadway, marked crosswalks, active RRFB equipment, nearby urban land uses, and a more visually complex nighttime background than the Milwaukee site. The existing nighttime lighting condition was documented using field lux measurements collected near the crosswalk and along the vehicle approach path. Under baseline conditions, the recorded lighting level was approximately 0.5 lux, as shown in Figure 5(a). Madison testing included multiple lighting spectra and mounting height conditions. Lateral placement was not independently varied at Madison. Therefore, Madison does not provide a direct field comparison for lateral placement. The roadway scaled lateral placement procedure is discussed in Section 6, Section 6.4, Roadway Geometry Scaling Model. During each trial, the instrumented test vehicle followed the predefined approach path toward the marked crosswalk. The mannequin mounted on an electric skateboard was moved across the crosswalk using a remote control. When the driver visually recognized the mannequin, the driver pressed the brake pedal, and the brake event timestamp was synchronized with roadway video, driver-facing video, GPS trajectory, and speed data. Figure 5(a) shows the Madison field experiment layout, including the enhanced streetlight installation, crosswalk illuminator setup, mannequin mounted on an electric skateboard, lux meter location, vehicle approach path, and roadway map reference used for testing and data collection. Figure 5(a) shows the Madison field experiment layout and roadway map reference used during nighttime field testing and Figure 5(b) lux measurement collected before enhanced lighting.



**Figure 5. Madison field experiment layout, roadway map reference, and baseline nighttime illuminance measurement at Williamson Street and South Dickinson Street. (a) Field experiment layout and test site map showing the crosswalk location, mannequin crossing setup, lux meter location, vehicle approach path, and surrounding roadway context. (b) Baseline nighttime lux measurement collected before enhanced lighting, added flood light, or streetlight simulation was applied**

The Milwaukee study site was located at the marked crosswalk on N Maryland Avenue near the University of Wisconsin-Milwaukee campus, with approximate geographic coordinates of 43.076467, -87.882851. This site represented a two-lane urban campus roadway context with marked crosswalk striping, pedestrian crossing signs, surrounding academic buildings, sidewalks, and regular pedestrian activity. The site did not include a push button or rectangular rapid flashing beacon. The test vehicle approached the marked crosswalk along the planned N Maryland Avenue approach shown in Figure 6, while the mannequin mounted on an electric skateboard was moved across the crosswalk using a remote control. The existing nighttime lighting condition was documented using field lux measurements collected near the crosswalk and along the vehicle approach path. Under baseline conditions, the recorded lighting level was approximately 13 lux. Milwaukee testing included multiple lighting spectra, three mounting heights, and three lateral placement conditions. Therefore, this site provided the primary field basis for documenting how lateral placement, mounting height, beam direction, pedestrian visibility, glare exposure, and driver response measurements varied across installation geometries. Figure 6 shows the Milwaukee field experiment layout, including the enhanced streetlight installation, crosswalk illuminator setup, mannequin mounted on an electric skateboard, lux meter location, vehicle approach path, and roadway map reference used for testing and data collection.

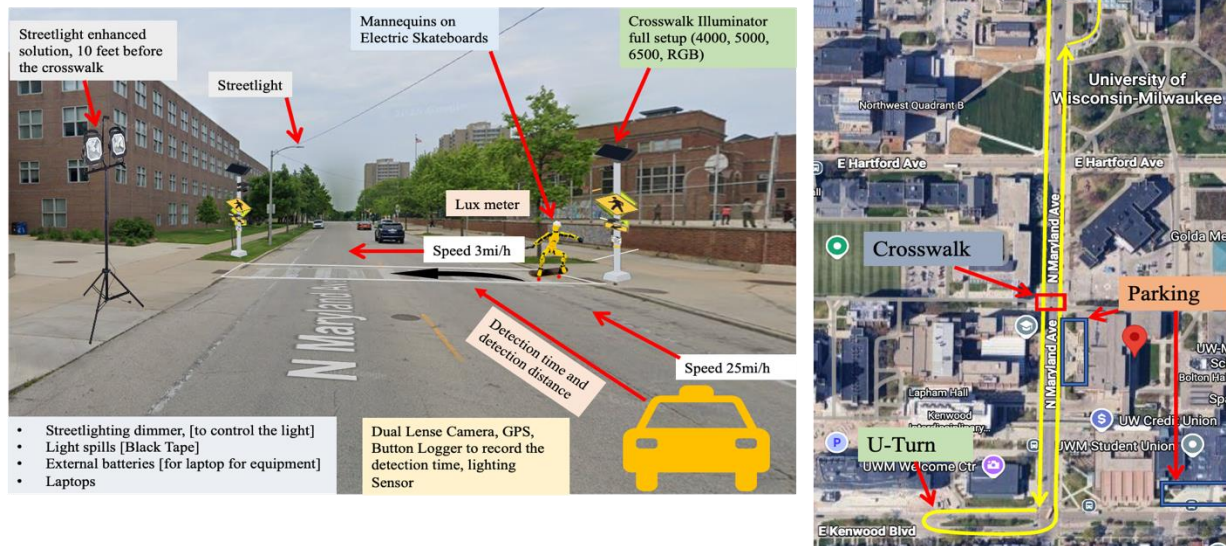


**Figure 6. Milwaukee field experiment layout and roadway map reference on N Maryland Avenue near the University of Wisconsin Milwaukee campus. The figure shows the enhanced streetlight solution, crosswalk illuminator setup, mannequin crossing system, lux meter location, vehicle approach path, and test site map used during nighttime field testing.**

Project records confirm that 104 experimental rounds were completed at Madison, and 177 experimental rounds were completed at Milwaukee. Each lighting and geometry setting was tested twice whenever field conditions allowed. These totals represent completed field rounds. The final analysis used the subset of trials that passed data quality checks, including synchronization, video quality, GPS completeness, brake event matching, and eye onset review.

### 3.2 Experimental Approach Procedure

During each trial, the instrumented test vehicle entered the study roadway and followed the predefined approach path toward the marked crosswalk. The vehicle was driven at the target approach speed for the corresponding experimental setting. The vehicle approach path was kept consistent across repeated trials so that the driver response data, GPS trajectory, and roadway video could be compared across lighting configurations.

At the same time, the mannequin mounted on an electric skateboard was controlled remotely and moved across the crosswalk to simulate a pedestrian crossing event. This method allowed the research team to repeat the pedestrian crossing movement; the exact initiation timing relative to the approaching vehicle was intentionally naturalistic, as described later in this section.

The roadway-facing camera recorded the forward view of the crosswalk, the mannequin movement, the lighting condition, and the vehicle approach. The driver-facing camera recorded

the driver's face and eye movement during the approach. When the driver visually recognized the mannequin, the driver pressed the brake pedal. The brake pedal logger recorded the braking timestamp, which was later synchronized with the roadway video, driver-facing video, GPS trajectory, and speed record. The enhanced crosswalk lighting remained continuously illuminated throughout each trial; it was not dynamically triggered by pedestrian or vehicle detection during the experiments. Trial timing was coordinated through a simple and deliberately naturalistic protocol. The test vehicle was equipped with a flashing marker light, and the driver announced by radio when the vehicle was about to enter the study roadway; this entry time was logged by the field team. A trained team member controlling the skateboard-mounted mannequin platform watched for the approaching flashing marker light and initiated the crossing after the vehicle entered the study approach. The driver was intentionally not told when the crossing would begin or from which side of the roadway the mannequin would enter, so the vehicle-to-crosswalk distance at the moment the mannequin entered the roadway was deliberately not fixed. This design choice was made to preserve genuine, unrehearsed detection behavior: the driver reacted only when the mannequin was actually seen, pressing the brake pedal at that moment, so the recorded reaction time and detection distance reflect natural driver response rather than an anticipated, scripted event. The flashing-light cue kept crossing initiation consistently tied to each vehicle approach, while the crossing position and movement path across the crosswalk remained the same for every trial.

### **3.3 Field Equipment and Instrumentation**

The field testing used an integrated data collection system to record roadway conditions, driver response, vehicle movement, pedestrian target movement, and lighting measurements. The main field equipment included the enhanced crosswalk lighting unit, temporary mounting pole, mannequin mounted on an electric skateboard, lux meter, roadway facing camera, driver facing camera, onboard GPS system, speed recording system, brake event logger, batteries, laptops, communication equipment, satellite phone, traffic control cone, skateboard controller, and test vehicles. Figure 7 shows the main hardware and field instrumentation used during the nighttime driver recognition and reaction time experiments. The equipment included the mannequin crossing system, crosswalk illuminator, camera system, driver reaction recording device, lighting measurement equipment, skateboard controller, test vehicles, communication equipment, satellite phone, and GPS equipment.



**Figure 7. Field hardware and instrumentation used during nighttime crosswalk lighting experiments. (a) Mannequin mounted on an electric skateboard. (b) Temporary pole with crosswalk illuminator. (c) Camera system used to record the driver and roadway view. (d) Foot switch and reaction logging equipment used to record driver brake response. (e) Lux measurement meter used to document baseline and enhanced lighting levels. (f) Skateboard controller used to remotely control mannequin crossing movement. (g) Sedan test vehicles used for field data collection. (h) Van test vehicle used for obstruction and field testing scenarios. (i) Traffic control cone used for field setup and safety marking. (j) Satellite phone used for field communication and safety support. (k) GPS equipment used to record vehicle position, speed, heading, and timestamp.**

The roadway-facing camera documented the crosswalk scene, lighting conditions, mannequin movement, and vehicle approach. The driver-facing camera documented the driver's eye movement and facial behavior. The GPS equipment recorded vehicle position, speed, heading, and timestamp. The foot switch and reaction logger recorded the timestamp of brake pedal activation. The lux meter was used to record lighting levels near the crosswalk and pedestrian target area. The skateboard controller allowed the field team to move the mannequin across the crosswalk in a controlled and repeatable manner.

### 3.4 Nighttime Field Testing Setup

The field equipment described in Section 3.3 was deployed under nighttime roadway conditions during the Madison and Milwaukee experiments. The nighttime setup included the instrumented test vehicle, enhanced crosswalk lighting unit, mannequin mounted on an electric skateboard, temporary field control devices, traffic cone placement, roadway observation area, and field team coordination. These field photos document how the planned experimental setup was implemented during actual testing. Figure 8 shows representative nighttime field testing photos from the Madison and Milwaukee sites. The images document the vehicle approach, enhanced crosswalk lighting, mannequin crossing system, roadway surface condition, traffic cone placement, and real roadway testing environment.



**Figure 8. Nighttime field testing setup during enhanced crosswalk lighting experiments. (a) Madison field testing setup showing the instrumented test vehicle approaching the illuminated crosswalk under wet nighttime roadway conditions. (b) Milwaukee field testing setup showing the approaching test vehicle, mannequin mounted on an electric skateboard, enhanced crosswalk lighting, and field team coordination.**

### 3.5 Experimental Factors and Field Conditions

The field experiment was designed to evaluate how lighting spectrum, installation geometry, pedestrian visibility condition, roadway context, and environmental condition influence driver recognition and reaction time. The tested factors were selected to represent practical nighttime crosswalk conditions in Wisconsin. Table 4 summarizes the experimental factors and field-testing conditions used in the Madison and Milwaukee experiments. Multiple mannequins representing different heights and body types were used in the field testing, including adult (man and woman) and child mannequins, so that driver recognition could be evaluated across different pedestrian statures (see Sections 5.2.5 and 5.3.4). Milwaukee included Adult and Child mannequin labels. Madison included Man, Woman, and Child labels.

**Table 4. Experimental factors and field-testing conditions.**

| Test Factor           | Levels or Measures                                                               | Purpose                                                                                                               |
|-----------------------|----------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------|
| Lighting condition    | Baseline no enhanced lighting and enhanced crosswalk lighting                    | Compare standard nighttime visibility with enhanced illumination.                                                     |
| Lighting spectrum     | 4000 K, 5000 K, 6500 K, Ice Blue, Pure Royal Blue, Sky Blue, Blue Baseline       | Evaluate how neutral white and blue shifted spectra affect driver recognition, reaction time, and detection distance. |
| Mounting height       | Milwaukee: 7.5 ft, 10 ft, 12.5 ft. Madison: 10.0 ft, 12.5 ft, 15.0 ft            | Determine how fixture height affects beam spread, pedestrian illumination, glare exposure, and driver response.       |
| Lateral distance      | Milwaukee: 0 ft, 9.5 ft, 16.5 ft. Madison: not independently varied              | Evaluate how lateral offset affects illumination angle, pedestrian background contrast, visibility, and glare.        |
| Obstruction condition | Parked vehicle obstruction, including van or small vehicle depending on the site | Test pedestrian recognition when the pedestrian or crosswalk area is partially blocked.                               |

|                       |                                                                                                                |                                                                              |
|-----------------------|----------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------|
| Pedestrian target     | Adult and child mannequin                                                                                      | Evaluate driver recognition for different pedestrian target sizes.           |
| Clothing condition    | Dark blue and white clothing at Milwaukee. White clothing at Madison                                           | Evaluate the effect of clothing contrast on nighttime pedestrian visibility. |
| Spill control         | Narrowed lighting spread, crosswalk only lighting, and no control                                              | Examine whether limiting light spill changes visibility and driver response. |
| Weather condition     | Normal nighttime condition and light rain condition                                                            | Evaluate performance under realistic Wisconsin nighttime weather variation.  |
| RRFB condition        | Madison included the RRFB-related condition. Milwaukee did not include RRFB in the same way                    | Account for the presence or absence of flashing warning treatment.           |
| Streetlight condition | Madison is relatively dark with and without streetlight. Milwaukee is relatively brighter with street lighting | Represent differences in ambient lighting and background complexity.         |

This table distinguishes between factors that were directly varied at both sites and factors that were site-specific. Figure 9 shows representative Madison nighttime illuminance measurements collected during the field setup. The photos are included to document measured lux levels under three lighting conditions, not to compare lighting color or spectrum. The sequence shows the baseline condition, the enhanced crosswalk lighting condition, and the enhanced lighting condition with additional floodlight support.



**Figure 9. Madison nighttime illuminance measurements during field setup. (a) Baseline condition without enhanced crosswalk lighting, showing approximately 0.5 lux. (b) Enhanced crosswalk lighting condition, showing approximately 21 lux. (c) Enhanced lighting with additional floodlight support is used to simulate streetlight conditions, showing approximately 40 lux.**

Figure 9 documents the increase in measured illuminance at the Madison site. The baseline condition was approximately 0.5 lux. After enhanced crosswalk lighting was applied, the measured illuminance increased to approximately 21 lux. With additional floodlight support, the measured illuminance increased to approximately 40 lux. This figure is used only to document field lux conditions and should not be interpreted as a lighting color comparison.

Milwaukee provides a stronger empirical basis for lateral distance comparison because lateral placement was independently varied at that site. Madison provides useful evidence for lighting spectrum and mounting height in a wider roadway context, but lateral placement was not independently varied. Therefore, Madison's lateral placement is addressed later through roadway-scaled design guidance rather than direct field comparison.

### **3.6 Field Data Record and Quality Control**

The field testing produced roadway-facing video, driver-facing infrared video, GPS trajectory records, vehicle speed records, brake event timestamps, lux measurements, and field observation records for each test round. These records documented the vehicle approach, mannequin crossing movement, lighting condition, driver response, and vehicle position during the nighttime experiments.

Data quality control was applied to confirm that each field record contained the required information for later analysis. Each test round was reviewed for video availability, GPS completeness, speed record availability, brake event timestamp availability, lux measurement documentation, and general field note consistency. Rounds with missing records, unclear video, incomplete GPS data, or unreliable timing information were flagged before analysis and excluded from the final analysis dataset.

The detailed analysis framework used to synchronize these data sources, identify driver recognition timing, calculate reaction time, and calculate detection distance is presented in Section 5.

### **3.7 Section Summary**

This section focused on the field-testing procedure used to collect driver recognition and reaction time data at the Madison and Milwaukee study sites. The testing process included the vehicle approach procedure, mannequin crossing operation, lighting condition setup, field equipment, roadway facing video, driver facing infrared video, GPS and speed records, brake event timestamps, lux measurements, and field notes.

The section also summarized the field data records and quality control process used to confirm that each test round contained the required information for later analysis. GPS trajectory records were collected to document the vehicle approach path and support later detection distance calculation.

The detailed analysis framework for reaction time calculation and detection distance calculation is presented in Section 5.1.

## **4. Demonstration of Enhanced Lighting Systems**

This section focuses on the field demonstration of the enhanced light system under real nighttime roadway conditions. The purpose of the demonstration was to show how the lighting equipment, temporary mounting system, instrumented probe vehicle, mannequin crossing platform, roadway observation setup, and field data collection process were deployed and operated during field testing.

### **4.1 Demonstration Setup**

The enhanced crosswalk lighting demonstrations were conducted at the same field sites used for driver recognition and reaction time testing. Demonstrations were completed at both the Madison and Milwaukee study locations so that WisDOT Project Oversight Committee (POC) members could observe the system under real nighttime roadway conditions. The POC is composed of WisDOT staff and served as the project's advisory and review body, providing technical direction, reviewing project deliverables, and evaluating the demonstrated system for potential statewide application. The purpose of the demonstrations was to show how the enhanced lighting system operated in the field, how the crosswalk and pedestrian target were illuminated, how the instrumented vehicle approached the crossing, and how the field team coordinated the mannequin crossing system and supporting measurement equipment.

At the Madison site, the demonstration was conducted at the Williamson Street and South Dickinson Street intersection. This location represented a wider urban roadway context with RRFB equipment, including rectangular rapid flashing beacons and pedestrian push buttons. The Madison demonstration allowed POC members and project participants to observe the enhanced lighting system in a visually complex nighttime environment with a wider roadway, marked crosswalk, existing warning devices, wet roadway surface conditions, and surrounding urban activity.

At the Milwaukee site, the demonstration was conducted at the marked crosswalk on N Maryland Avenue near the University of Wisconsin-Milwaukee campus. This location represented a two-lane campus roadway context without a push button or rectangular rapid flashing beacon. The Milwaukee demonstration allowed POC members and project participants to observe the enhanced lighting system in a narrower roadway setting with marked crosswalk striping, pedestrian crossing signs, campus buildings, sidewalks, the mannequin crossing system, and regular nighttime pedestrian activity.

For both demonstrations, the field setup included the enhanced crosswalk lighting unit, temporary mounting pole, mannequin mounted on an electric skateboard, instrumented test vehicle, roadway facing video, driver facing video, GPS and speed recording, brake event logging, lux measurement equipment, batteries, communication equipment, and field coordination materials. The demonstration setup was temporary and adjustable so that lighting spectrum, beam direction, mounting condition, field visibility, and measurement workflow could be observed without requiring permanent installation.

Figure 10 presents representative demonstration photos from both the Madison and Milwaukee field sites. The Madison images document the system demonstration and POC participation at the wider urban roadway site, while the Milwaukee images document the lighting deployment, vehicle approach, crosswalk illumination pattern, and POC observation at the campus roadway site.



**Figure 10. Enhanced crosswalk lighting demonstration at the Madison and Milwaukee field sites. (a) Madison demonstration showing the instrumented test vehicle approaching the illuminated crosswalk under nighttime field conditions. (b) Madison demonstration showing POC members and project participants during the field demonstration. (c) Milwaukee demonstration showing the instrumented test vehicle approaching the illuminated crosswalk under nighttime field conditions. (d) Milwaukee demonstration showing enhanced lighting coverage across the crosswalk. (e) Milwaukee demonstration showing POC members and project participants observing the enhanced lighting system and mannequin crossing setup.**

## 4.2 Test Vehicle and Field Data Collection

The test vehicle was used to collect synchronized driver response and vehicle movement data during each demonstration round. The vehicle approach was recorded together with driver-facing video, roadway video, GPS, speed records, and brake event timing. These data streams were used to document the vehicle approach, driver recognition process, braking response, and vehicle position relative to the crosswalk.

The roadway view was also recorded to document the crosswalk scene, lighting conditions, mannequin movement, vehicle approach, and surrounding roadway context. Together, the vehicle-based and roadway-based data provided a complete record of each experimental round and supported later synchronization, quality control, and calculation of reaction time and detection distance. Figure 11 shows the vehicle approach and roadway view used to document the demonstration from the driver response and field observation perspectives.



**Figure 11. Test vehicle and roadway view during the Milwaukee demonstration. (a) Test vehicle approaching the illuminated crosswalk. (b) Vehicle approach with the pedestrian target near the crosswalk. (c) Roadway view showing enhanced lighting during vehicle approach.**

### 4.3 Lighting and Visibility Observation

The demonstration allowed the research team and WisDOT POC members to observe how the enhanced lighting system changed the nighttime visibility of the crosswalk and pedestrian target. Field observations focused on light spread across the marked crosswalk, pedestrian body visibility, beam direction, glare exposure, and consistency of illumination across the crossing area.

The mannequin mounted on an electric skateboard was used to simulate pedestrian crossing events in a controlled and repeatable manner. This allowed the team to observe the pedestrian target under different lighting conditions while maintaining a consistent crossing path and field setup. Lux measurements were also collected to document the lighting environment and support later comparisons between configurations. Figure 12 shows the mannequin crossing system and enhanced lighting coverage used to observe pedestrian target visibility during nighttime testing.

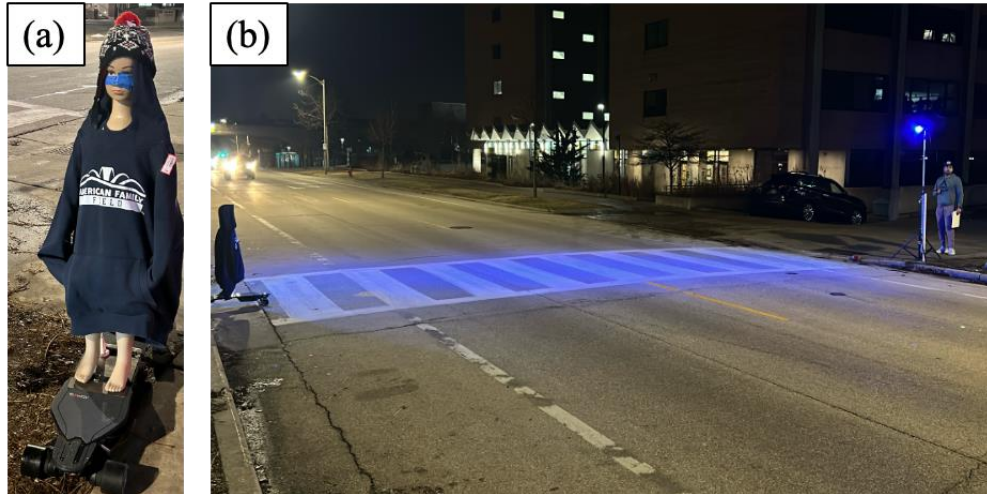


**Figure 12. Mannequin crossing system used during Milwaukee nighttime testing. (a) Close view of the mannequin mounted on an electric skateboard. (b) Mannequin positioned at the crosswalk under enhanced lighting.**

#### **4.4 Section Summary**

This section documented the enhanced crosswalk lighting demonstrations conducted at the same Madison and Milwaukee sites used for field testing. The demonstrations allowed WisDOT POC members and some people from the public to observe the system under real nighttime roadway conditions.

The Madison demonstration showed the system in a wider urban roadway environment with existing RRFB equipment. The Milwaukee demonstration showed the system in a narrower campus roadway environment without a push button or RRFB equipment. Together, the demonstrations confirmed that the temporary lighting setup, mannequin crossing system, test vehicle operation, field measurement process, and site coordination procedure could be deployed across different roadway contexts.

These demonstration activities supported the later development of optimal lighting specifications and design guidance by documenting practical deployment conditions, field visibility, equipment arrangement, and implementation considerations.

## **5. Optimal Lighting Specifications**

This section presents the analysis framework, field results, and optimal lighting specifications for enhanced crosswalk illumination. Section 5.1 defines the analysis framework used to process each field test round, including data sources, synchronization, eye onset detection, reaction time, detection distance, and valid round selection. Section 5.2 presents the Milwaukee results, including the lighting spectrum, lateral distance, mounting height, combined configuration, mannequin type, spill control, and obstruction analyses. Section 5.3 presents the Madison results using the same site-specific interpretation approach. Finally, Section 5.4 synthesizes the Milwaukee and Madison findings, including the cross-site spectrum comparison, clothing condition effects, and eye tracking physiological metrics, into an optimal configuration summary that supports the generalized design guidance developed in Section 6.

### **5.1 Analysis Framework**

#### **5.1.1 Data Processing Workflow and Trajectory Mapping**

This section describes the analysis framework used to convert field testing records into reaction time, detection distance, and lighting performance measures. The field-testing procedure and equipment setup were documented in Section 3. The analysis used GPS records, speed records, brake pedal logs, roadway video, driver-facing infrared video, lux measurements, and eye onset detection results.

The field data collection system included multiple synchronized data sources. Roadway video recorded the forward view of the crosswalk, the lighting condition, the vehicle approach, and the mannequin crossing event. The driver's face and eye movement were video recorded during the approach. The onboard GPS system recorded vehicle position, speed, orientation, and time. The brake pedal logger recorded the timestamp when the driver pressed the brake pedal after visually recognizing the mannequin. These data streams were later synchronized using timestamp matching so that driver recognition, braking response, vehicle location, and roadway scene could be aligned for each trial.

The GPS data were collected from the onboard vehicle sensor system during each approach. The GPS record included local timestamp, latitude, longitude, height, north velocity, east velocity, up velocity, roll, pitch, azimuth, and associated uncertainty fields. The GPS sampling rate was 125 Hz, corresponding to a time interval of 0.008 s between consecutive measurements.

This high-frequency sampling allowed the research team to identify the vehicle position closest to the brake event and eye onset timestamps.

Figure 13 illustrates the collected GPS trajectory plotted on the roadway map for the Madison field experiment. The trajectory map was used to verify the vehicle approach path, crosswalk reference location, and spatial consistency of the GPS data before computing detection distance.

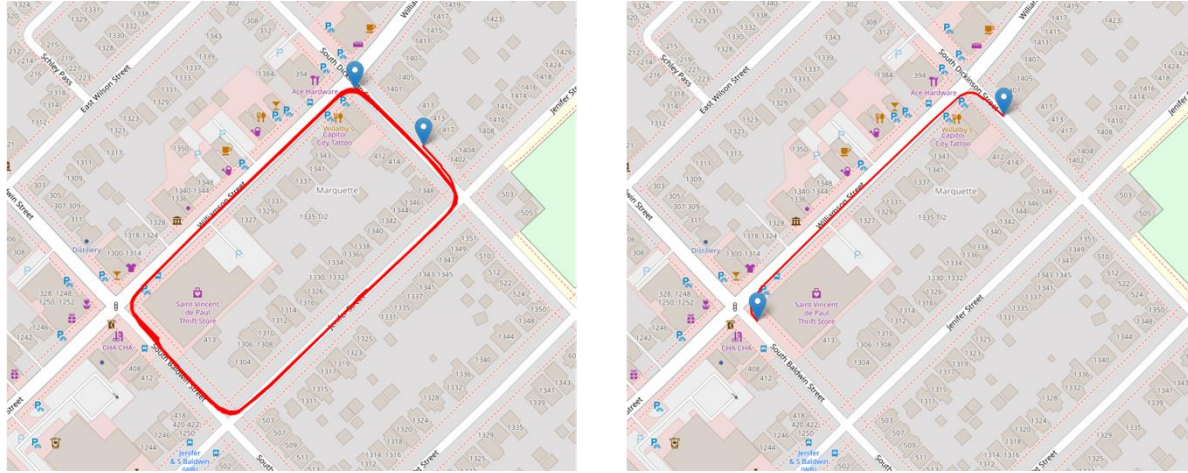


**Figure 13. GPS trajectory mapping for the Madison field experiment. The vehicle trajectory was overlaid on the roadway map to verify the approach path, trial segment, and crosswalk reference location.**

Figure 14 summarizes the GPS data file structure used in the processing workflow. The GPS file contained vehicle position, velocity, orientation, and uncertainty fields, which were used to support trajectory extraction and distance calculations.

| madison_time             | _latitude | _longitude | _height  | _north_velocity | _east_velocity | _up_velocity | _roll | _pitch | _azimuth |
|--------------------------|-----------|------------|----------|-----------------|----------------|--------------|-------|--------|----------|
| '2025-11-24 21:22:23.920 | 43.0854   | -89.3602   | 263.9714 | 0.000635033     | -0.002862566   | 0.002803673  | -6.7  | -4.05  | 134.329  |
| '2025-11-24 21:22:23.928 | 43.0854   | -89.3602   | 263.9713 | -0.000273679    | -0.002074625   | 0.001499556  | -6.7  | -4.04  | 134.329  |
| '2025-11-24 21:22:23.936 | 43.0854   | -89.3602   | 263.9712 | 0.000209431     | -0.002596933   | 0.004320498  | -6.7  | -4.05  | 134.329  |
| '2025-11-24 21:22:23.944 | 43.0854   | -89.3602   | 263.9711 | 0.000637699     | -0.003836488   | 0.004984604  | -6.7  | -4.05  | 134.328  |
| '2025-11-24 21:22:23.952 | 43.0854   | -89.3602   | 263.971  | 0.00012515      | -0.003243338   | 0.002466161  | -6.7  | -4.05  | 134.328  |
| '2025-11-24 21:22:23.960 | 43.0854   | -89.3602   | 263.9709 | -0.000106238    | -0.003133895   | 0.002347488  | -6.7  | -4.05  | 134.328  |
| '2025-11-24 21:22:23.968 | 43.0854   | -89.3602   | 263.9709 | 0.001072635     | -0.004077424   | 0.004579089  | -6.7  | -4.05  | 134.328  |
| '2025-11-24 21:22:23.976 | 43.0854   | -89.3602   | 263.9708 | 0.000368799     | -0.003897461   | 0.003876024  | -6.7  | -4.04  | 134.328  |
| '2025-11-24 21:22:23.984 | 43.0854   | -89.3602   | 263.9707 | -0.001569448    | -0.003535125   | 0.002624014  | -6.7  | -4.05  | 134.328  |
| '2025-11-24 21:22:23.992 | 43.0854   | -89.3602   | 263.9706 | -0.001296947    | -0.004089223   | 0.003706596  | -6.7  | -4.05  | 134.328  |

**Figure 14. GPS data structure and key fields used for vehicle trajectory processing.**

For each experiment  $i$ , the vehicle trajectory segment was extracted from the full GPS record using the trial start time. A one-minute trajectory segment was selected for each trial:

$$T_{iA} = x[t], t \in \{t_{iA}^{start}, \dots, t_{iA}^{start} + 60s\} \quad (1)$$

$T_{iA}$  represents the extracted trajectory for trial  $A$  of experiment  $i$ ,  $x[t]$  represents the GPS-based vehicle position at time  $t$ , and  $t_{iA}^{start}$  is the start time of the trial.

The brake pedal timestamp was then matched with the synchronized GPS and video records. The closest GPS timestamp to the brake or reaction event was identified as:

$$t'_{iA} = \arg \min_{t \in \{t_{iA}^{start}, \dots, t_{iA}^{start} + 60s\}} |t - t_{react}| \quad (2)$$

where  $t_{react}$  is the synchronized reaction event timestamp obtained from the brake event record and driver video review. The corresponding vehicle position was then obtained from the GPS trajectory as:  $x[t'_{iA}]$ . The crosswalk reference location,  $x_c$ , was identified from the site map and field reference point. Detection distance was calculated as the distance between the vehicle position at the synchronized reaction timestamp and the crosswalk reference location:

$$d = \|x[t'_{iA}] - x_c\| \quad (3)$$

All distance measures in this framework were referenced to a fixed crosswalk reference location identified from the site map and field reference point; detection distance therefore represents the vehicle-to-crosswalk distance at the synchronized recognition timestamp, not the vehicle-to-pedestrian distance. No dynamic crosswalk trigger was used during the experiments: the enhanced lighting remained continuously on, and the mannequin crossing was initiated when the skateboard operator sighted the flashing marker light of the approaching test vehicle (Section 3.2); the vehicle-to-crosswalk distance at crossing initiation was intentionally not fixed, preserving naturalistic detection behavior. Because every distance is measured to the fixed crosswalk reference location rather than to the moving pedestrian, this reference basis is unaffected by the naturalistic initiation timing and applies wherever detection distance, reaction distance, or stopping margin is reported in this report.

Table 5 summarizes the main variables included in the processed field dataset.

**Table 5. Processed field dataset variables.**

| Variable Group           | Variables                                                                             | Purpose                                                    |
|--------------------------|---------------------------------------------------------------------------------------|------------------------------------------------------------|
| Trial information        | Site, date, experiment ID, trial ID, start time                                       | Identifies each experimental round                         |
| Repeated trial structure | First trial and second trial for each setting                                         | Supports consistency checking across repeated observations |
| Field condition          | Lighting spectrum, mounting height, lateral placement, obstruction, clothing, weather | Documents the tested field condition                       |
| Vehicle trajectory       | Timestamp, latitude, longitude, height, velocity, roll, pitch, azimuth                | Records vehicle position and movement                      |
| Video data               | Roadway video, driver facing video, extracted event clips                             | Documents the roadway scene and driver response            |

|                   |                                                                       |                                                |
|-------------------|-----------------------------------------------------------------------|------------------------------------------------|
| Brake event data  | Brake pedal timestamp                                                 | Identifies the physical braking response       |
| Eye tracking data | Eye onset timestamp, gaze movement, face detection status             | Identifies the first driver recognition moment |
| Derived measures  | Reaction time, detection distance, reaction distance, stopping margin | Creates analysis ready performance measures    |

This processing workflow ensured that each valid trial had a consistent temporal and spatial structure before analysis. The trajectory plots provided a visual check of the GPS data, while the synchronized video and brake event records supported accurate identification of driver recognition and braking response timing.

### 5.1.2 Driver Response

Driver response was defined as a sequence linking visual recognition, cognitive processing, and physical braking. The driver recognition moment was the estimated time when the driver first visually responded to the pedestrian target. The brake response moment was the time when the brake pedal was pressed. Reaction time was defined as the time difference between these two moments. Detection distance was defined as the distance from the vehicle to the crosswalk at the driver recognition moment. Table 6 defines the event timestamps recorded for each trial and used in these calculations.

**Table 6. Driver response event timestamps recorded for each trial.**

| Timestamp         | Meaning                                                                                      |
|-------------------|----------------------------------------------------------------------------------------------|
| $(t_{detect})$    | Moment when the driver's eyes first move toward or visually recognize the pedestrian hazard. |
| $(t_{brake})$     | Moment when the driver presses the brake pedal.                                              |
| $(t_{crosswalk})$ | Crosswalk reference location based on GPS and field location data.                           |

Reaction time was calculated as:

$$Reaction\ Time = t_{brake} - t_{detect} \quad (4)$$

A shorter reaction time indicates that the driver responded more quickly after visually detecting the pedestrian. However, reaction time alone is not sufficient to evaluate lighting performance. A driver may react quickly only after detecting the pedestrian late. For that reason, detection distance was also used as a primary visibility metric.

### 5.1.3 Video Clip Extraction and Synchronization

Each trial was centered on the brake pedal event. For each brake event, a fixed 3.5-second video clip was extracted from the original field videos, starting 3.0 seconds before the brake pedal activation and ending 0.5 seconds after it. The 3.0-second pre-event window was selected to

provide sufficient temporal coverage for the driver's visual recognition and response process before braking, while the 0.5-second post-event window preserved immediate context after the braking action. The extraction window was defined as:

$$\text{Clip Start Time} = \text{Pedal Time} - 3.0 \text{ seconds} \quad (5)$$

$$\text{Clip End Time} = \text{Pedal Time} + 0.5 \text{ seconds} \quad (6)$$

$$\text{Clip Duration} = 3.5 \text{ seconds} \quad (7)$$

Two synchronized clips were extracted for each valid trial in Table 7.

**Table 7. Video clips extracted for each trial.**

| Clip   | Source               | Purpose                                                                                                    |
|--------|----------------------|------------------------------------------------------------------------------------------------------------|
| Clip A | Forward camera       | roadway Shows the crosswalk, pedestrian target, roadway context, lighting condition, and vehicle approach. |
| Clip B | Driver facing camera | infrared Shows the driver's face, eye movement, gaze direction, blink events, and head pose.               |

The brake pedal timestamp from the field record was matched to the on-screen display timestamp in the video. This allowed the roadway view, driver view, GPS record, speed record, and brake event to be aligned around the same event.

This synchronization process ensured that each trial had a consistent temporal structure. The driver's visual behavior could be analyzed before braking, while the roadway scene could be reviewed to confirm the pedestrian target, lighting conditions, obstructions, and approach context.

#### 5.1.4 Deep Learning Algorithm: Face Landmark Localization and Eye Onset Detection

The driver's visual response was estimated from the driver-facing infrared video using a deep learning-based face landmark localization and eye onset detection pipeline. The purpose of this pipeline was to identify the first moment when the driver visually responded to the pedestrian hazard. This timestamp was defined as the eye onset time,  $t_{detect}$ , and was used with the brake pedal timestamp to calculate driver reaction time.

For each video frame, the algorithm localized the driver's facial landmarks and extracted eye region features. The face geometry model produced a dense set of  $K = 68$  facial landmark coordinates for each frame:

$$L_t = f_{CNN}(I_t) = \{(x_k, y_k)\}_{k=1}^K \quad (8)$$

where  $f_{CNN}$  is the trained face landmark localization model,  $I_t$  is the video frame at time  $t$ ,  $(x_k, y_k)$  represents the two-dimensional pixel coordinate of the  $k$ -th landmark, and  $K = 68$  is the total number of detected facial landmarks.

The left and right eye regions were then extracted from the landmark set. Let  $\Omega_L$  and  $\Omega_R$  denote the landmark index sets corresponding to the left and right eye regions. Each eye region contains six contour landmarks. The estimated center of the left eye region at frame  $t$  was calculated as:

$$p_{L,t} = \frac{1}{|\Omega_L|} \sum_{k \in \Omega_L} (x_k, y_k) \quad (9)$$

Similarly, the right eye center was calculated as:

$$p_{R,t} = \frac{1}{|\Omega_R|} \sum_{k \in \Omega_R} (x_k, y_k) \quad (10)$$

where  $p_{L,t}$  and  $p_{R,t}$  are the estimated left and right eye centers at frame  $t$ , and  $|\Omega_L| = |\Omega_R| = 6$ .

The mean bilateral eye position was then compared with the head reference point to estimate gaze displacement. The head reference point,  $c_{head,t}$ , was defined using the inter ocular geometry of the detected face. The frame level gaze vector was calculated as:

$$g_t = \frac{p_{L,t} + p_{R,t}}{2} - c_{head,t} \quad (11)$$

where  $g_t \in \mathbb{R}^2$  represents the horizontal and vertical gaze displacement relative to the driver's head position. This vector was used to identify gaze shifts toward the pedestrian hazard.

Eye onset was defined as the first frame after the pedestrian became visible in which the gaze vector entered the crosswalk detection zone and the inter frame gaze displacement exceeded a saccadic movement threshold. The eye onset frame was identified as:

$$t_{detect} = \min\{t \geq t_{appear} : \|g_t - g_{zone}\| < \delta \wedge \|g_t - g_{t-1}\| > \theta\} \quad (12)$$

where  $t_{appear}$  is the pedestrian appearance trigger frame,  $g_{zone}$  is the calibrated gaze location corresponding to the crosswalk detection zone,  $\delta$  is the detection zone radius, and  $\theta$  is the saccadic velocity threshold.

After the eye onset frame was identified, the corresponding time was converted from frame index to seconds using the camera frame rate:

$$T_{detect} = \frac{t_{detect}}{fps} \quad (13)$$

where  $fps = 30$  frames per second, giving a temporal resolution of approximately:

$$\frac{1}{30} \approx 0.033 \text{ seconds} \quad (14)$$

Reaction time was calculated as the time between visual detection and brake activation:

$$RT = T_{brake} - T_{detect} \quad (15)$$

In the extracted 3.5 second event clips, the brake event was fixed at 3.0 seconds from the start of the clip. Therefore, reaction time can also be expressed as:

$$RT = 3.0 - T_{detect} \quad (16)$$

This definition is consistent with the event clip structure described in Section 3.5.

Detection distance was then calculated using the GPS synchronized vehicle trajectory. The vehicle position at the eye onset time was compared with the crosswalk reference location:

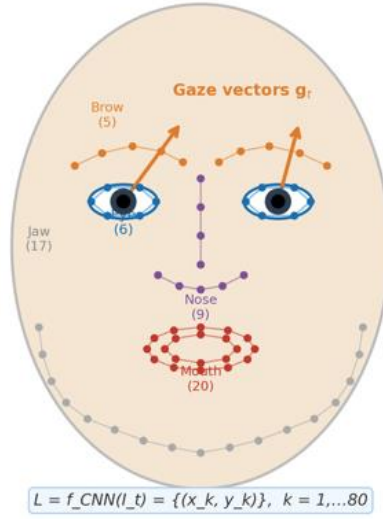
$$DD = \| P_{veh}(t_{detect}) - P_{crosswalk} \| \quad (17)$$

where  $P_{veh}(t_{detect})$  is the GPS derived vehicle position at the eye onset frame and  $P_{crosswalk}$  is the GPS location of the crosswalk reference point.

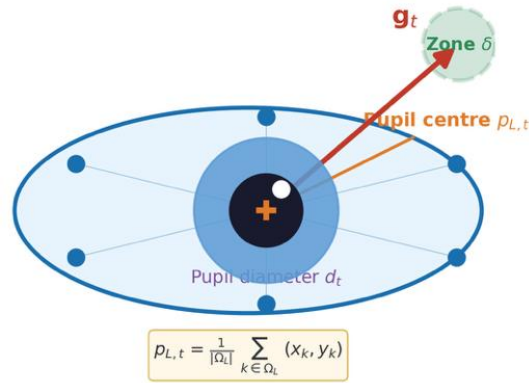
The algorithm also computed frame level visual attention variables, including iris center, gaze direction, eye velocity, saccade indicators, fixation indicators, blink state, eye aspect ratio, pupil diameter, head yaw, head pitch, head roll, and face detection status. These variables were used to separate meaningful gaze shifts from noise caused by blinking, temporary face detection loss, head movement, infrared video variation, glare, reflection, or partial occlusion.

The final  $t_{detect}$  value was accepted only when the detected eye onset was consistent with the driver-facing video, the forward roadway video, and the brake event timestamp. This quality control step helped ensure that reaction time represented the driver's response to the pedestrian hazard rather than unrelated eye movement.

The pipeline achieved a face detection success rate of 92.1 percent across Milwaukee enhanced lighting trials. This indicates that the driver facing infrared video provided sufficient facial visibility for most valid trials, while still requiring quality control review for frames affected by occlusion, glare, head movement, or video noise. Figure 15 illustrates how the driver-facing video was converted into an eye onset timestamp by combining face landmark localization, pupil center estimation, gaze vector tracking, and frame-level onset detection.



(a) CNN-based face landmark localization



(b) Eye region detail showing pupil center estimation, gaze vector  $g_t$ ,

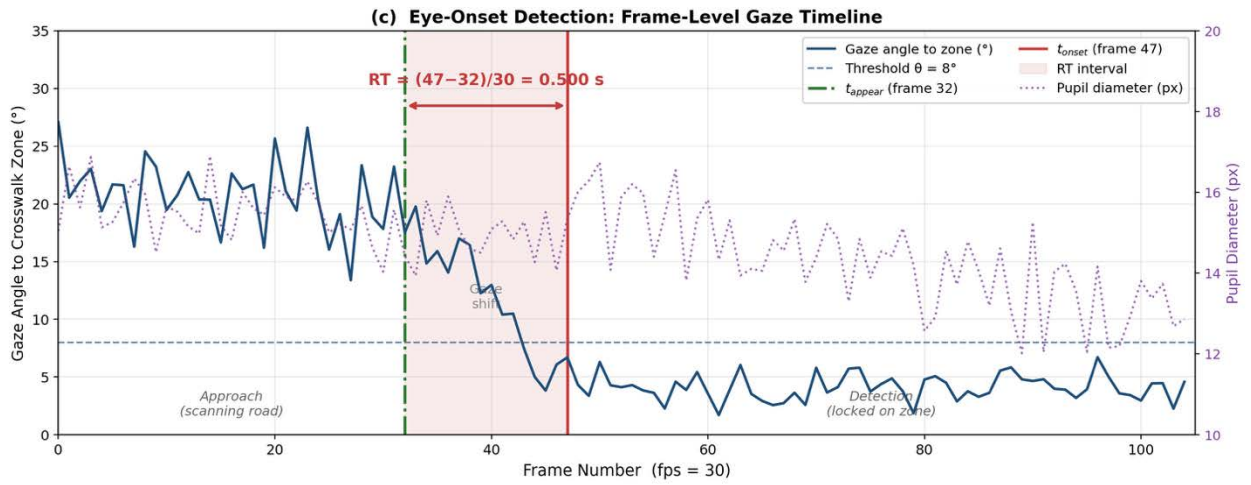


**Figure 15. Deep learning eye onset detection pipeline. (a) CNN-based face landmark localization used to identify facial geometry and eye regions. (b) Eye region detail showing pupil center estimation, gaze vector  $g_t$ , and the calibrated**

crosswalk detection zone. (c) Frame-level gaze timeline showing pedestrian appearance, detected eye onset, reaction time interval, and pupil diameter trend.

### 5.1.5 Performance Measures

#### (1) Reaction Time Calculation

Reaction time represents the time between the driver's first visual detection of the pedestrian and the moment the brake pedal was pressed. In the extracted clip, the brake event was fixed at 3.0 seconds from the start of the clip. Therefore, reaction time was calculated using the detected eye onset time within the clip:

$$\text{Reaction Time} = 3.0 - t_{\text{detect}} \quad (18)$$

where  $t_{\text{detect}}$  is the eye onset time in seconds from the start of the 3.5-second clip.

A shorter reaction time indicates that the driver required less time to respond after visually detecting the pedestrian. In this study, reaction time was interpreted together with detection distance because both measures are needed to understand safety performance. A lighting configuration is more favorable when it supports both earlier pedestrian detection and faster braking response.

#### (2) Detection Distance Calculation

Detection distance was defined as the distance between the vehicle and the crosswalk at the moment when the driver first visually detected the pedestrian. This is the main visibility metric because it indicates how far away the pedestrian could be recognized by the driver.

Detection distance was calculated as:

$$\text{Detection Distance} = \text{Brake Distance} + \text{Reaction Distance} \quad (19)$$

where:

$$\text{Reaction Distance} = \text{Speed} \times \text{Reaction Time} \quad (20)$$

Brake distance represents the distance from the vehicle to the crosswalk at the moment the brake pedal was pressed. This value was obtained from the GPS and vehicle approach data. Reaction distance represents the distance traveled between visual detection and brake activation. Since the vehicle was still moving during this interval, the reaction distance was calculated from the vehicle speed and the reaction time.

A larger detection distance indicates that the pedestrian was visible and recognizable from farther away. This is generally favorable because it gives the driver more time and distance to understand the hazard and complete a braking response.

### (3) Optimization Logic

Two primary performance measures were used to evaluate the lighting configurations: reaction time and detection distance. Reaction time measures the time between the driver's visual detection of the pedestrian and the brake pedal response. A shorter reaction time indicates a faster driver response after the pedestrian has been recognized. Detection distance measures the distance between the vehicle and the crosswalk at the moment of visual pedestrian detection. A longer detection distance gives the driver more time and space to recognize the pedestrian and respond safely.

Both measures were considered together. A configuration with short reaction time but limited detection distance may not provide the best overall safety benefit. Similarly, a configuration with a long detection distance but a slower reaction time may not be optimal. The specification is the configuration that provides the strongest combined performance while remaining practical for installation and reliable for nighttime operation.

Figure 16 illustrates these two performance measures from a top view.

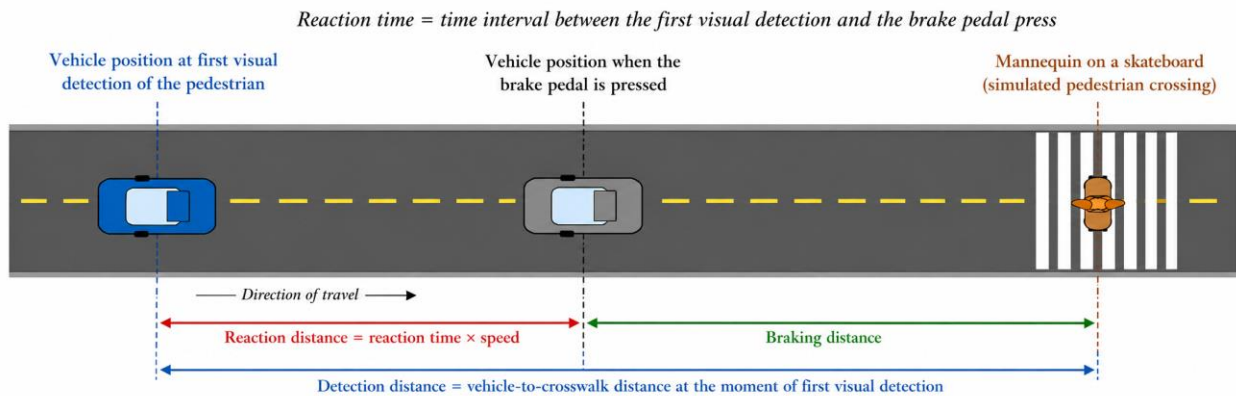


**Figure 16. Conceptual top-view illustration of the two primary performance measures: reaction time and detection distance.**

The approaching vehicle first visually detects the mannequin on the skateboard entering the crosswalk and then presses the brake pedal; reaction time is the interval between these two moments, and detection distance is the vehicle-to-crosswalk distance at the moment of first detection.

## 5.2 Result for Milwaukee

The Milwaukee site provided the strongest basis for evaluating the combined effect of lighting spectrum, mounting height, and lateral placement because all three factors were available for comparison at this site. The results show that the preferred configuration should not be selected from one raw metric alone. Reaction time, detection distance, sample size, field setup, and installation feasibility must be interpreted together.

### 5.2.1 Spectrum Comparison

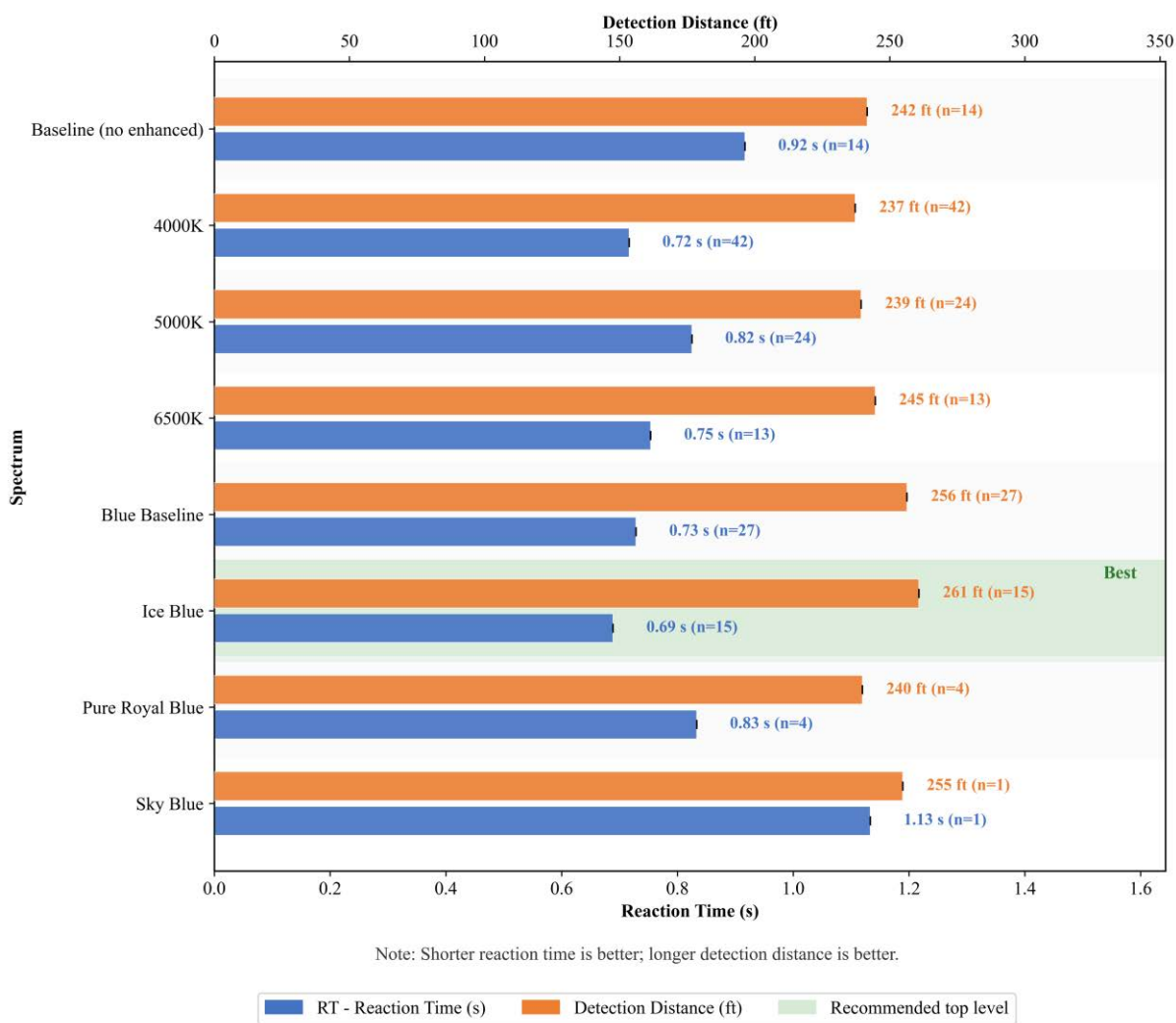


Figure 17. Milwaukee spectrum performance comparison based on reaction time and detection distance.

Figure 17 compares Milwaukee spectrum performance using reaction time and detection distance. The spectrum comparison showed that Ice Blue provided the strongest overall performance for the Milwaukee site. Although some spectra yielded longer raw detection

distances, Ice Blue produced one of the fastest reaction times while maintaining a practical detection distance. The lower horizontal axis shows mean reaction time in seconds, where shorter bars indicate better performance; the upper horizontal axis (0, 50, 100, ...) shows mean detection distance in feet, where longer bars indicate better performance. The 4000 K (conventional white) and Ice Blue conditions are the key comparison pair discussed in the text.

To quantify the comparison against conventional white lighting requested during review, Table 8 reports the mean reaction time (RT) and detection distance (DD) for every tested condition at the Milwaukee site, including the baseline (no enhanced) condition. Relative to the conventionally recommended 4000 K condition, the generalized primary spectrum (Blue Baseline) increased mean detection distance by 19.2 ft (from 237.2 ft to 256.4 ft) with a comparable reaction time (0.72 s versus 0.73 s), and the Milwaukee site-specific configuration (Ice Blue) reached 260.8 ft at 0.69 s.

**Table 8. Milwaukee spectrum reaction time (RT) and detection distance (DD) values.**

| <b>Spectrum</b>        | <b>RT (s)</b> | <b>DD (ft)</b> |
|------------------------|---------------|----------------|
| Baseline (no enhanced) | 0.92          | 242            |
| 4000K                  | 0.72          | 237.2          |
| 5000K                  | 0.82          | 239.4          |
| 6500K                  | 0.75          | 244.6          |
| Blue Baseline          | 0.73          | 256.4          |
| Ice Blue               | 0.69          | 260.8          |
| Pure Royal Blue        | 0.83          | 239.9          |
| Sky Blue               | 1.13          | 254.8          |

The Ice Blue row is the Milwaukee site-specific configuration mentioned in Table 13 (0.69 s, 261 ft); Blue Baseline is the generalized primary spectrum, selected through the cross-site spectrum comparison in Section 5.4.1 and recommended in Sections 6 and 7.

### **5.2.2 Lateral Distance Comparison**

Figure 18 compares Milwaukee lateral placement performance using reaction time and detection distance. The lateral placement comparison showed that 9.5 ft provided the strongest overall placement result. This placement produced the most favorable combined performance across reaction time and detection distance.

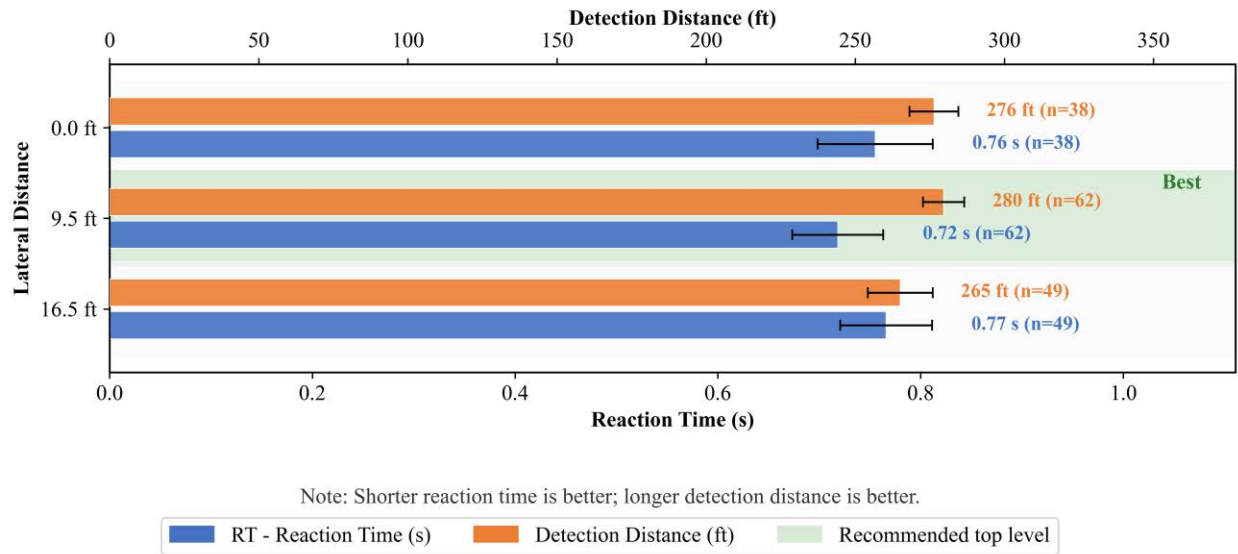


**Figure 18. Milwaukee lateral distance performance comparison based on reaction time and detection distance.**

### 5.2.3 Mounting Height Comparison

Figure 19 compares Milwaukee mounting height performance using reaction time and detection distance. The mounting height comparison showed that 12.5 ft provided the strongest overall height result.

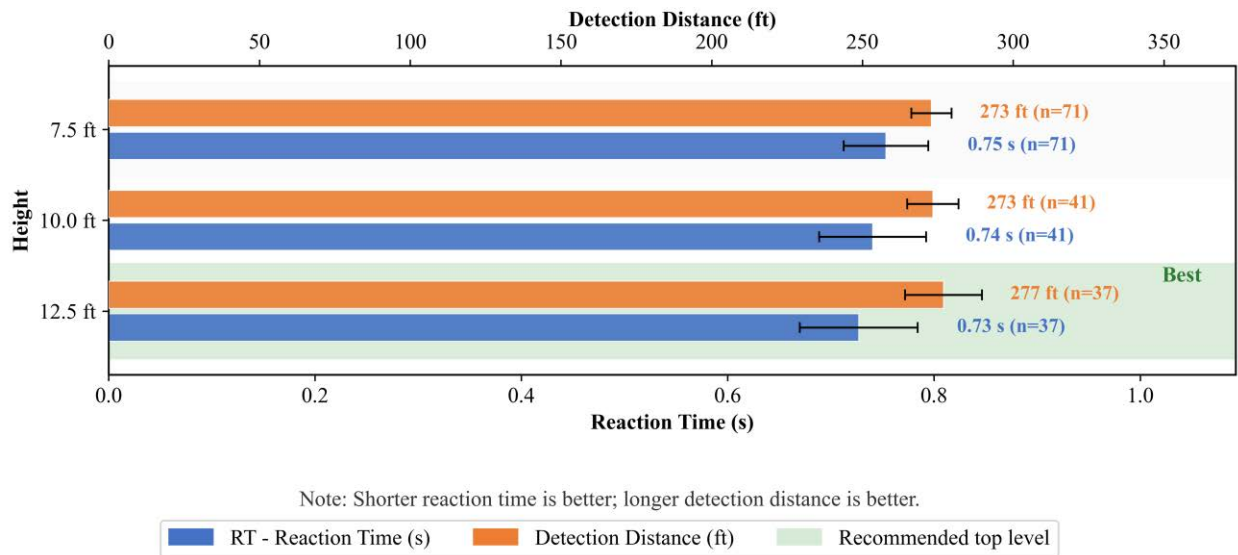


**Figure 19. Milwaukee mounting height performance comparison based on reaction time and detection distance.**

### 5.2.4 Combined Configuration Analysis

Table 9 summarizes the recommended enhanced lighting configuration for Milwaukee.

**Table 9. Recommended enhanced lighting configuration for Milwaukee.**

| Site      | Spectrum | Mounting Height | Lateral Distance | Spill Control    |
|-----------|----------|-----------------|------------------|------------------|
| Milwaukee | Ice Blue | 12.5 ft         | 9.5 ft           | No spill control |

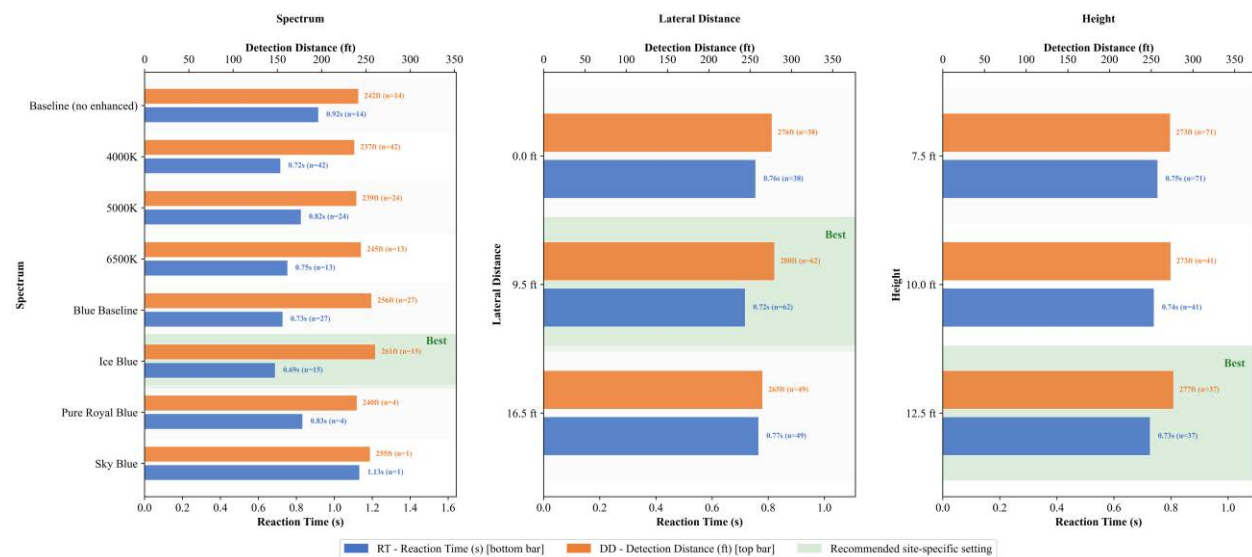


**Figure 20. Milwaukee combined configuration comparison for spectrum, lateral distance, and mounting height.**

Figure 20 presents the combined configuration comparison for lighting spectrum, lateral distance, and mounting height. As shown in Table 9 and Figure 20, the Milwaukee configuration consisted of Ice Blue lighting, a mounting height of 12.5 ft, and a lateral distance of 9.5 ft. This configuration should be interpreted as the Milwaukee field-supported design basis. It does not mean Ice Blue was the highest value for every raw metric. Rather, Ice Blue at 12.5 ft height and 9.5 ft lateral distance provided the strongest overall performance after considering reaction time, detection distance, uneven sample size, field condition variation, and practical installation needs.

### 5.2.5 Mannequin Type Analysis

Milwaukee mannequin-type records included Adult and Child labels in the field test dataset. These categories are reported separately to compare whether the mannequin type affected driver reaction time and detection distance at the Milwaukee site.

### Milwaukee Mannequin-Type Response and Detection Results

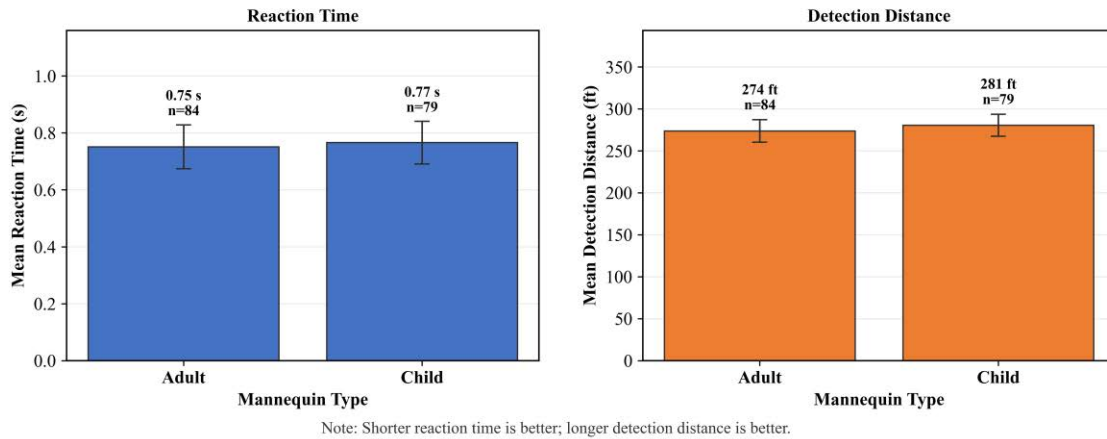


**Figure 21. Milwaukee driver response results by mannequin type. (a) Mean reaction time. (b) Mean detection distance. Error bars show variation, and n shows the number of valid test rounds for each mannequin type.**

Figure 21 shows that driver response at Milwaukee was similar for the adult and child mannequins. The child mannequin had a higher mean reaction time than the adult mannequin. The child mannequin also had a higher mean detection distance.

In the Milwaukee dataset, “Adult” refers to a single adult mannequin category recorded in the field logs; it is not the combination of the separate “Man” and “Woman” categories. The observed differences between the adult and child mannequins were small relative to the overlapping error bars shown in Figure 21, and given the limited per-category sample sizes they should not be interpreted as statistically significant; formal hypothesis testing (for example, a two-sample t-test) is recommended once additional trials are available.

#### 5.2.6 Spill Control Effects on Driver Response

Figure 22 compares the Milwaukee spill control conditions using detection distance and reaction time. The purpose is to evaluate whether limiting light spill to the crosswalk area improved driver recognition performance.

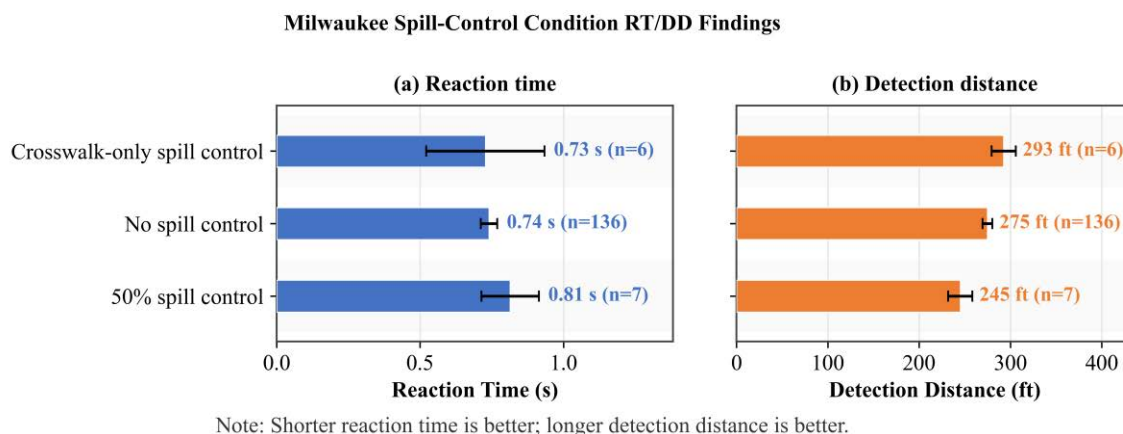


**Figure 22. Milwaukee driver response results by spill control condition. (a) Detection distance. (b) Reaction time. Error bars show variation across valid observations.**

Figure 22 shows that the crosswalk-only spill control condition produced the longest detection distance and the lowest reaction time among the tested spill control settings. The no spill control condition showed slightly shorter detection distance and slightly higher reaction time. The 50 percent spill control condition produced the shortest detection distance and the highest reaction time. These findings suggest that focusing the lighting on the crosswalk area improved driver recognition performance at the Milwaukee site. As with the Madison spill-control comparison (Section 5.3.5), spill control was not a primary focus of this project and the number of trials per spill-control condition was limited; these Milwaukee findings are therefore also presented for reference only and did not inform the final lighting configuration recommendations.

### 5.2.7 Obstruction Effects on Driver Response

Figure 23 compares Milwaukee driver response under clear and small vehicle parked obstruction conditions. This analysis shows how a parked vehicle near the crosswalk affected pedestrian recognition distance and reaction time.

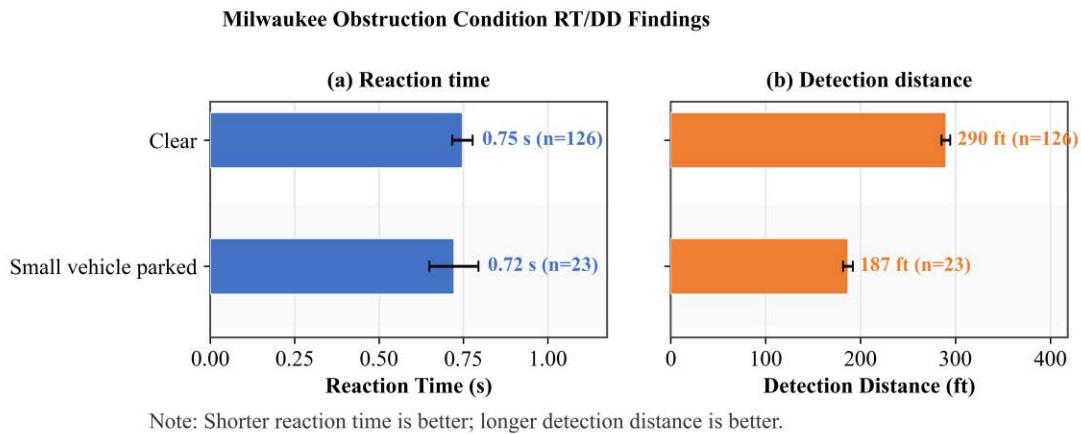


**Figure 23. Milwaukee obstruction effects on driver response. (a) Detection distance. (b) Reaction time. Error bars show variation across valid observations.**

Figure 23 shows that the clear condition produced a much longer detection distance than the small vehicle parked condition. This indicates that the parked vehicle reduced the distance at which drivers recognized the pedestrian target. Reaction time was similar between the two conditions, with only a small difference. The main obstruction effect was therefore a reduction in detection distance at the Milwaukee site.

### 5.3 Result for Madison

The Madison site provided evidence for lighting spectrum and mounting height performance in a wider roadway context with greater ambient and background complexity. Unlike Milwaukee, lateral distance was not independently varied at Madison. Therefore, Madison results should be interpreted mainly for the spectrum and mounting height.

#### 5.3.1 Spectrum Comparison

Figure 24 showed that Blue Baseline provided the strongest overall balanced performance. Blue Baseline produced a short reaction time and a higher detection distance combination. Blue Baseline was selected as the most reliable and balanced Madison spectrum.

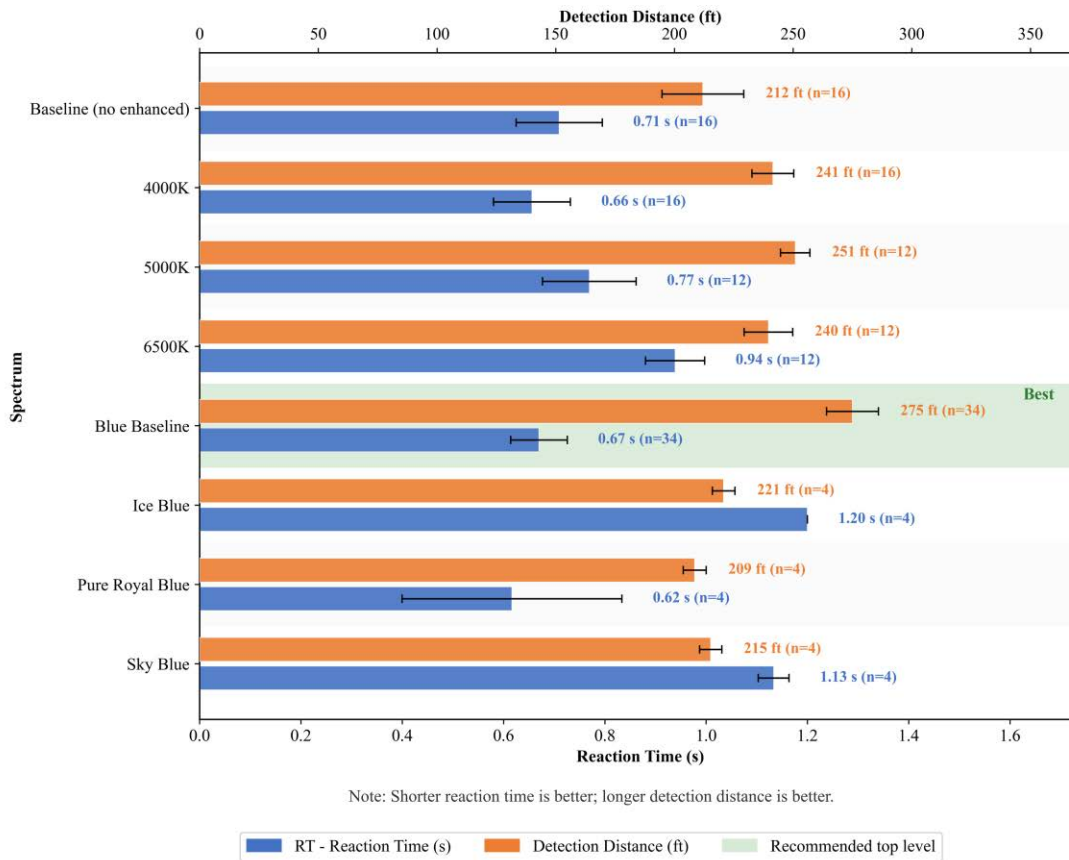


**Figure 24. Madison spectrum performance comparison based on reaction time and detection distance.**

To provide the same white-light comparison for the Madison site, Table 10 reports the mean reaction time (RT) and detection distance (DD) for every tested condition, including the baseline (no enhanced) condition. Relative to the 4000 K condition, the recommended Blue Baseline spectrum increased mean detection distance by 33.2 ft (from 241.8 ft to 275.0 ft) with reaction time essentially unchanged (0.66 s versus 0.67 s).

**Table 10. Madison spectrum reaction time (RT) and detection distance (DD) values.**

| Spectrum               | RT (s) | DD (ft) |
|------------------------|--------|---------|
| Baseline (no enhanced) | 0.71   | 212     |
| 4000K                  | 0.66   | 241.8   |
| 5000K                  | 0.77   | 251.3   |
| 6500K                  | 0.94   | 240.0   |
| Blue Baseline          | 0.67   | 275.0   |
| Ice Blue               | 1.20   | 221.3   |
| Pure Royal Blue        | 0.62   | 209.1   |
| Sky Blue               | 1.13   | 215.9   |

Note: values are means from the project field dataset. The Blue Baseline row is the Madison site-specific configuration and the generalized primary spectrum selected through the cross-site

spectrum comparison in Section 5.4.1 and recommended in Sections 6 and 7, mentioned in Table 13 (0.67 s, 275 ft).

### 5.3.2 Mounting Height Comparison

Figure 25 showed that 15.0 ft provided the strongest overall height basis. Although the 10.0 ft condition showed a similar reaction time and slightly longer detection distance in one comparison, the 15.0 ft height was selected because it provided a strong balance of performance and practical suitability for the wider Madison roadway setting. 12.5 ft height showed weaker performance in this comparison.

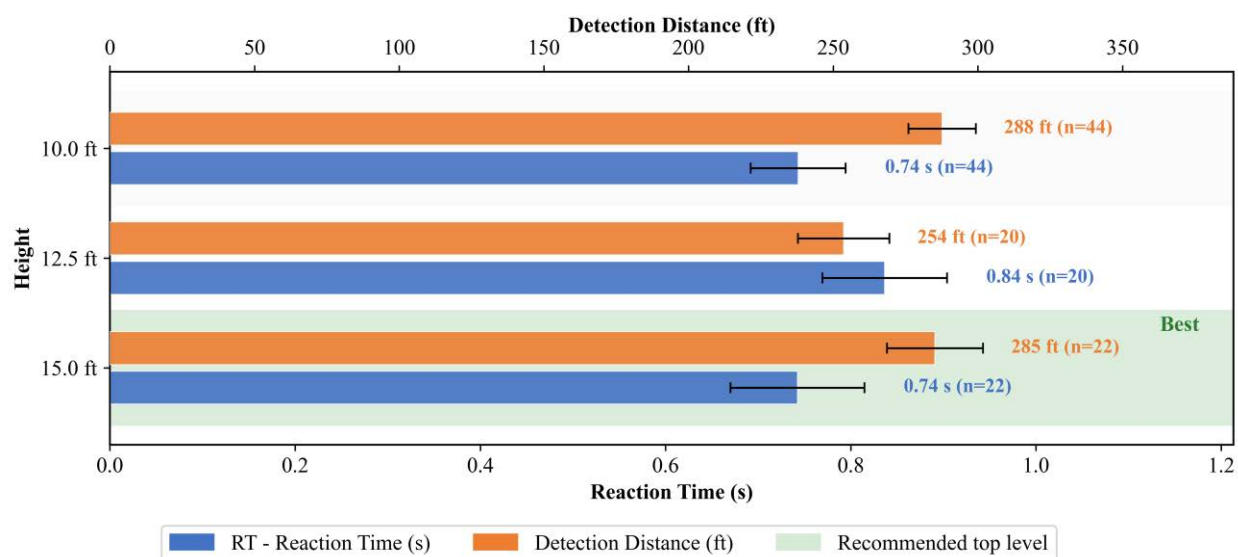


Figure 25. Madison mounting height performance comparison based on reaction time and detection distance.

### 5.3.3 Combined Configuration Analysis

Table 11 summarizes the recommended enhanced lighting configuration for Madison.

Table 11. Recommended enhanced lighting configuration for Madison.

| Site    | Spectrum      | Mounting Height | Lateral Distance         | Spill Control    |
|---------|---------------|-----------------|--------------------------|------------------|
| Madison | Blue Baseline | 15.0 ft         | Not independently varied | No spill control |

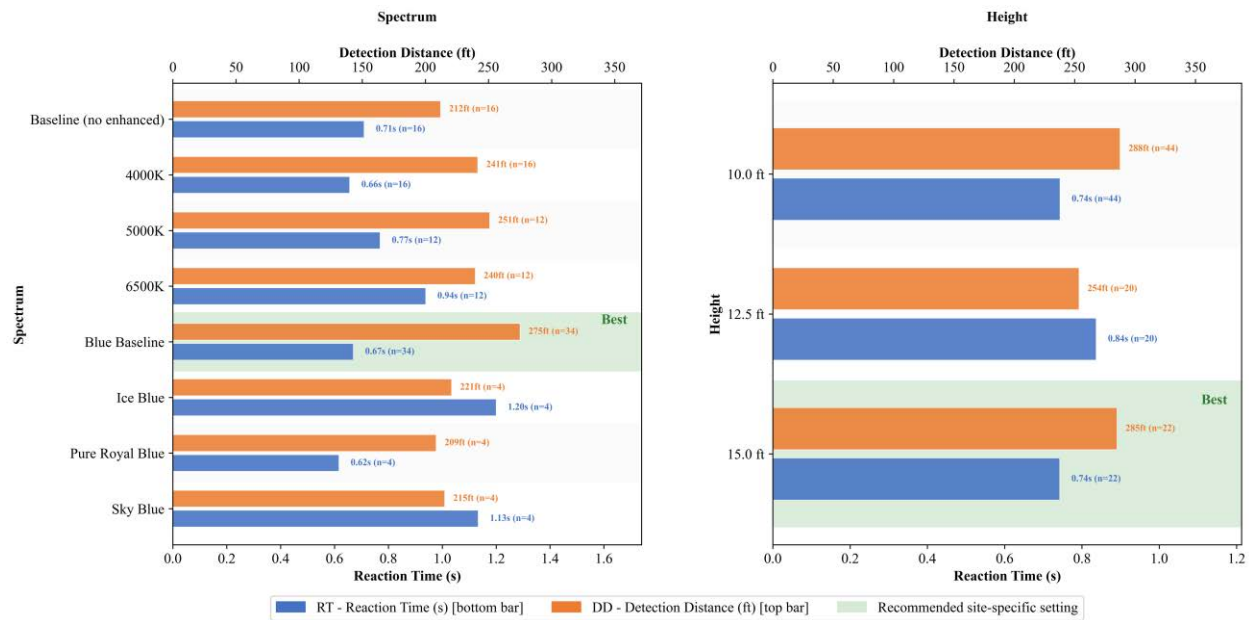


**Figure 26. Madison combined configuration comparison for spectrum and mounting height.**

Figure 26 presents the combined configuration comparison for the spectrum and mounting height. As shown in Figure 26 and Table 11, the Madison configuration consisted of Blue Baseline lighting and a mounting height of 15.0 ft. This configuration should be interpreted as the Madison field-supported design basis. Because lateral distance was not independently tested at Madison, the report should not assign a fixed Madison lateral placement from the field data alone.

### 5.3.4 Mannequin Type Analysis

In the Madison field test, mannequin categories were initially recorded as Man, Woman, and Child across multiple rounds. During testing, windy field conditions made one mannequin difficult to control and caused damage, so the experiment continued using the woman mannequin. Those subsequent records were labeled as adult in the dataset. Therefore, the final Madison dataset includes Man, Woman, Adult, and Child labels. These categories are reported separately for transparency; however, Adult should be understood as a renamed field-test label for the woman mannequin used after the wind-related mannequin issue, not as an additional fourth mannequin

type.

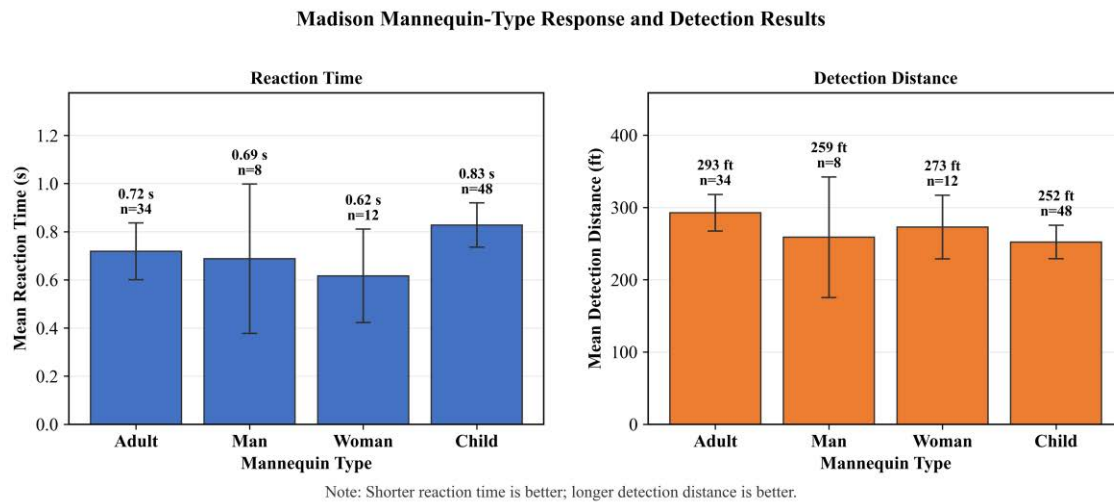
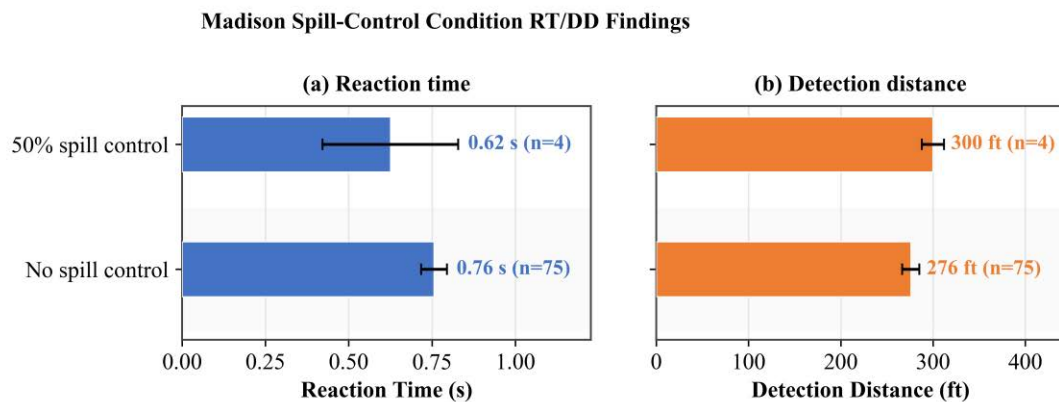


**Figure 27. Madison driver response results by mannequin type. (a) Mean reaction time. (b) Mean detection distance. Error bars show variation, and n shows the number of valid test rounds for each mannequin type**

Figure 27 shows that driver response varied by mannequin type at the Madison site. The child mannequin had the highest mean reaction time and the shortest mean detection distance, which indicates that drivers recognized the child mannequin later than the other mannequin types. The adult mannequin had the longest mean detection distance, while the woman mannequin had the lowest mean reaction time.

### 5.3.5 Spill Control Effects on Driver Response

Figure 28 compares the spill control conditions using detection distance and reaction time. This analysis evaluates whether reducing spill light and focusing illumination toward the crosswalk affected driver recognition performance. Unlike the Milwaukee spill-control comparison in Figure 22, the crosswalk-only condition is not shown here because that condition was not included in the Madison spill-control test plan; only the no-spill-control and 50 percent spill-control conditions were tested at the Madison site.



Note: Crosswalk-only spill-control trials were not available in the Madison dataset.

**Figure 28. Madison spill control effects on driver response. (a) Detection distance. (b) Reaction time. Error bars show variation across valid observations**

Figure 28 shows that the 50 percent spill control condition produced a longer detection distance and lower reaction time than the no spill control condition. This suggests that partial spill control may have enhanced driver recognition performance by directing more usable light toward the crosswalk area while minimizing unnecessary light spread. However, since spill control is not a primary focus of this project and the number of trials conducted under this condition was limited (fewer than 5 trials), these findings are presented for reference only and do not inform the final lighting configuration recommendations. A more rigorous quantitative study would be needed to draw conclusions about the effect of spill control on driver detection performance.

### 5.3.6 Obstruction Effects on Driver Response

Figure 29 compares Madison driver response under clear, small vehicle parked, and van parked obstruction conditions. This analysis shows how different obstruction conditions were associated with detection distance and reaction time during the Madison field testing.

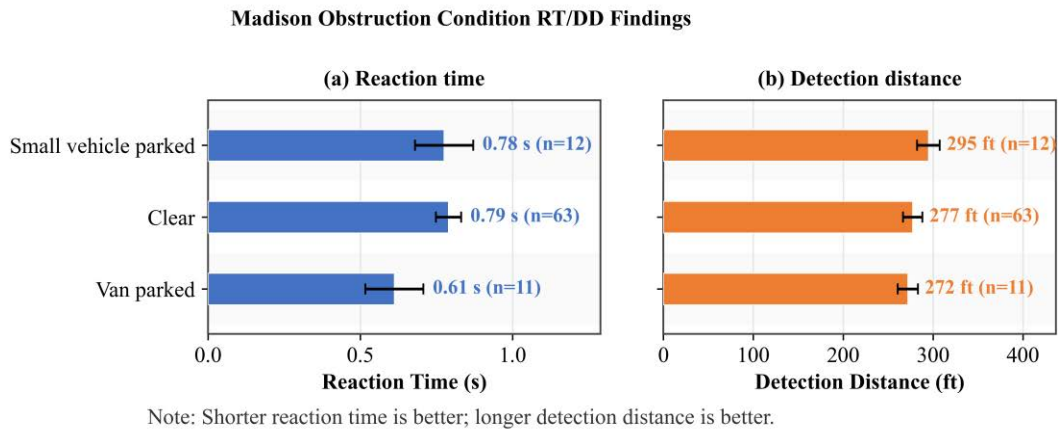


**Figure 29. Madison obstruction condition effects on driver response. (a) Detection distance. (b) Reaction time.**

Figure 29 shows that driver response varied across the Madison obstruction conditions. The small vehicle parked condition produced the longest detection distance, while the clear condition produced the shortest detection distance. Reaction time was similar for the clear and small vehicle parked conditions, while the van parked condition showed a lower reaction time. There is a possibility that drivers may have approached the larger parked vehicle with greater caution, which could have increased their visual attention toward the crosswalk area before reaching the pedestrian target. These results suggest that obstruction effects at Madison should be interpreted together with the specific field condition, lighting setup, and driver approach context.

## 5.4 Summary for Optimal Configuration

### 5.4.1 Cross-Site Spectrum Comparison

Figure 30 shows that the spectrum differed by site context. For Milwaukee, Ice Blue produced the highest site-specific spectrum ranking, supporting it as the strongest Milwaukee field condition. For Madison, Blue Baseline produced the highest spectrum ranking, supporting it as the strongest spectrum for the wider Madison roadway context. These results justify a context-based interpretation: Ice Blue remains a Milwaukee site-supported option, while Blue Baseline is carried forward as the generalized spectrum recommendation because it performed strongest in the wider Madison roadway environment.

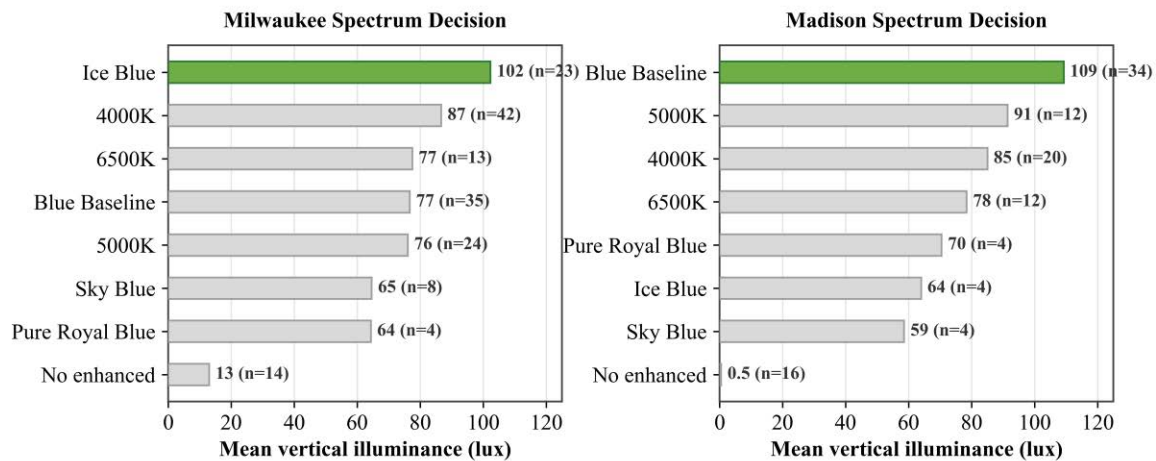


Figure 30. Site specific spectrum decision results for Milwaukee and Madison. (a) Milwaukee spectrum decision ranking based on mean vertical illuminance, showing Ice Blue as the strongest site-specific spectrum for the Milwaukee field context. (b) Madison spectrum decision ranking based on mean vertical illuminance, showing Blue Baseline as the strongest spectrum for the Madison field context.

## 5.4.2 Clothing Condition Effects on Driver Response

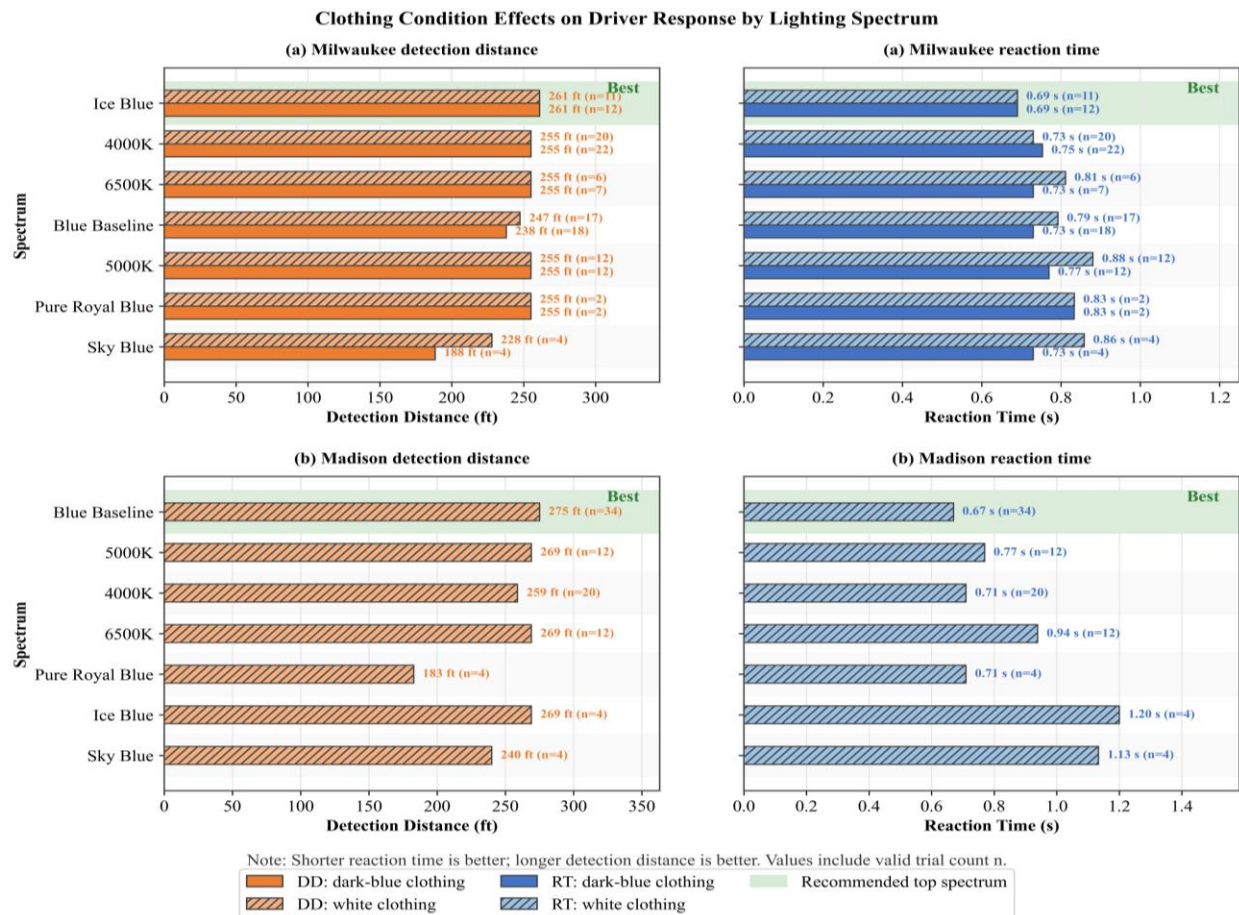


**Figure 31. Clothing condition effects on driver response by lighting spectrum. (a) Milwaukee results for dark blue and white clothing. (b) Madison results for white clothing.**

Figure 31 compares clothing condition effects on detection distance and reaction time for Milwaukee and Madison. In Milwaukee, Ice Blue showed the strongest clothing-based performance for both dark blue and white clothing. In Madison, Blue Baseline showed the strongest performance for the white clothing condition. These results support Ice Blue for the Milwaukee clothing condition analysis and Blue Baseline for the Madison clothing condition analysis.

### 5.4.3 Eye Tracking Physiological Metrics

Beyond reaction time and detection distance, the driver facing infrared video enabled the extraction of physiological eye tracking metrics. These metrics provide additional information about driver attention, visual load, and comfort under baseline and enhanced lighting conditions.

Table 12 included pupil diameter, contrast ratio, glare index, visual comfort score, blink rate, pupil asymmetry, eye aspect ratio, and saccade velocity (the speed of the rapid eye movements a driver makes when shifting gaze between points; it characterizes visual scanning behavior under each lighting condition rather than being inherently better when faster or slower). These measures were used to characterize how enhanced lighting changed the driver's visual environment.

**Table 12. Eye tracking physiological metrics comparing baseline and enhanced lighting conditions**

| Metric               | N   | Baseline Mean | Enhanced Mean | p value | Cohen's d | Interpretation                                                         |
|----------------------|-----|---------------|---------------|---------|-----------|------------------------------------------------------------------------|
| Pupil diameter       | 163 | 5.31 mm       | 4.87 mm       | < 0.001 | 1.903     | Baseline pupils were larger; enhanced lighting caused constriction.    |
| Contrast ratio       | 163 | 0.72          | 0.88          | < 0.001 | 1.179     | Higher contrast ratio under enhanced lighting.                         |
| Glare index          | 163 | 0.18          | 0.31          | < 0.001 | 1.164     | Glare index increased under enhanced lighting and should be monitored. |
| Visual comfort score | 163 | 3.82          | 3.41          | 0.002   | 0.638     | Slight comfort reduction under enhanced lighting.                      |
| Blink rate           | 163 | 0.31 blinks/s | 0.22 blinks/s | < 0.001 | 0.817     | Reduced blink rate under enhanced lighting.                            |
| Pupil asymmetry      | 163 | 0.08          | 0.13          | < 0.001 | 1.179     | Greater asymmetry under enhanced lighting; possible glare indicator.   |
| Eye aspect ratio     | 163 | 0.284         | 0.298         | 0.041   | 0.312     | Slightly higher eye aspect ratio under enhanced lighting.              |
| Saccade velocity     | 163 | 142.3 °/s     | 168.7 °/s     | < 0.001 | 0.751     | Faster saccades under enhanced lighting.                               |

The physiological metrics show that enhanced lighting changed the driver’s visual environment in several ways. Improved contrast and faster saccade response support the visibility benefit of enhanced lighting. At the same time, increased glare index and pupil asymmetry show why glare review remains important in final design. These results support the need to evaluate enhanced lighting using both visibility and comfort-related measures.

#### 5.4.4 Baseline Versus Enhanced Lighting Results

In addition to pooled descriptive statistics, baseline-versus-enhanced comparisons were used to summarize the improvement achieved by the recommended enhanced lighting conditions at each site. These comparisons are appropriate for executive interpretation because they compare the baseline condition with the site-specific enhanced lighting condition.

Figure 26 (the Madison combined configuration comparison for spectrum and mounting height) is repeated below before the summary comparison in Table 13.

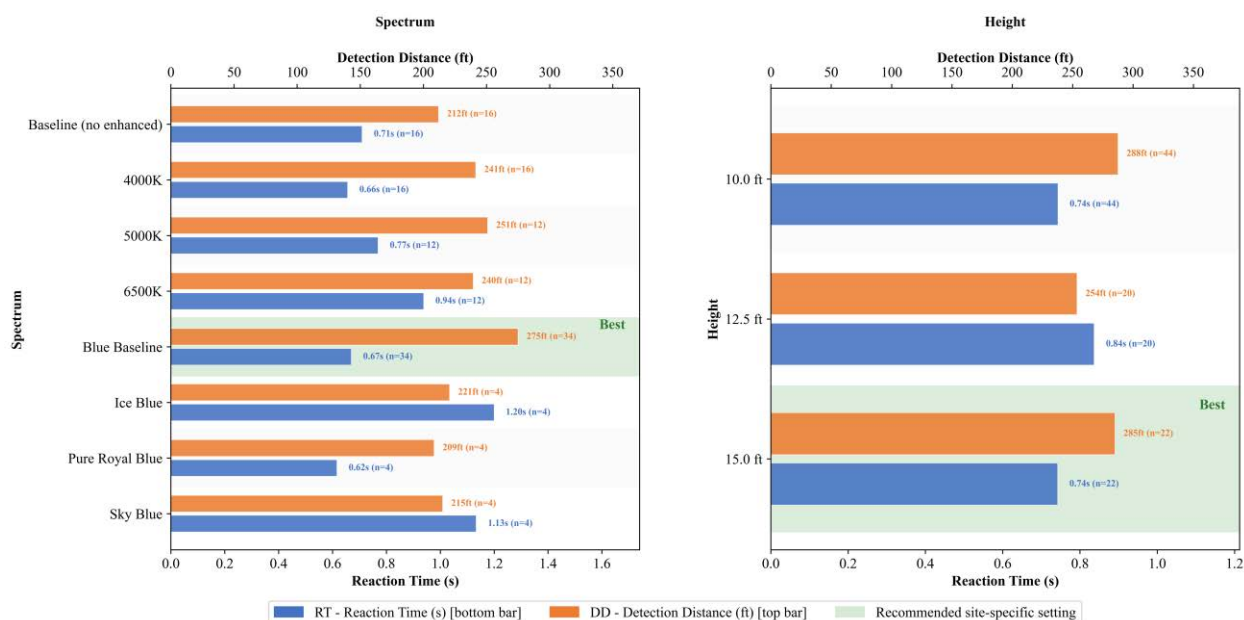


**Figure 26 (repeated). Madison combined configuration comparison for spectrum and mounting height.**

Throughout this report, “baseline” refers to the existing nighttime roadway lighting condition with no enhanced crosswalk lighting installed (labeled “Baseline, no enhancement” in Table 13); it does not refer to the 4000 K configuration. The 4000 K condition, the conventionally recommended white-light configuration prior to this study, is shown in the spectrum comparison figures (Figures 17 and 24) and can be read alongside Table 13 to compare all enhanced options against both reference points.

**Table 13. Baseline and enhanced lighting comparison by study site.**

| Site      | Condition                        | Reaction Time (s) | Detection Distance (ft) | Interpretation                                          |
|-----------|----------------------------------|-------------------|-------------------------|---------------------------------------------------------|
| Madison   | Baseline, no enhancement         | 0.71              | 212                     | Baseline condition used for comparison.                 |
| Madison   | Enhanced lighting, Blue Baseline | 0.67              | 275                     | Reduced reaction time and increased detection distance. |
| Milwaukee | Baseline, no enhancement         | 0.92              | 242                     | Baseline condition used for comparison.                 |
| Milwaukee | Enhanced lighting, Ice Blue      | 0.69              | 261                     | Reduced reaction time and increased detection distance. |

As shown in Table 13, in Madison, reaction time decreased from 0.71 s under the baseline condition to 0.67 s under the Blue Baseline enhanced lighting condition. Detection distance increased from 212 ft to 275 ft. This indicates that the enhanced lighting condition improved both visual recognition distance and driver response time. In Milwaukee, reaction time decreased from 0.92 s under the baseline condition to 0.69 s under the Ice Blue enhanced lighting condition. Detection distance increased from 242 ft to 261 ft. This indicates that the enhanced lighting condition improved driver response timing and pedestrian detection distance in the two-lane residential context. These findings support the effectiveness of enhanced crosswalk lighting under field conditions. Here, “enhanced crosswalk lighting” refers to the site-specific blue-spectrum configurations (Blue Baseline at Madison and Ice Blue at Milwaukee); the spectrum comparisons in Figures 17 and 24 additionally show the further improvements obtained when using blue-spectrum lighting relative to conventional white-light configurations.

#### **5.4.5 Interpretation of Driver Recognition Results**

The results show that enhanced crosswalk lighting improved driver response performance at both field sites when the enhanced configurations were compared with baseline conditions. Both sites showed reduced reaction time and increased detection distance under the enhanced lighting condition.

The results also show that the lighting configuration is site-dependent. Milwaukee favored Ice Blue at 12.5 ft mounting height and 9.5 ft lateral distance. Madison favored Blue Baseline at 15.0 ft mounting height. This difference is reasonable because the two sites differed in roadway width, ambient lighting, background complexity, RRFB condition, and available installation geometry.

A key finding from this section is that the lighting spectrum should not be evaluated alone. The same spectrum can perform differently depending on mounting height, lateral placement, roadway context, and existing lighting. Similarly, the best mounting height depends on crosswalk width, beam spread, pedestrian location, driver approach path, and glare control. Therefore, final design guidance must consider the combined lighting system rather than a single lighting factor.

#### 5.4.6 Basis for Optimal Lighting Specification Development

The optimal lighting specifications were developed using three sources of evidence. First, the field testing results measured driver reaction time and detection distance under different lighting spectra, mounting heights, and lateral placements. These results provided the primary performance evidence for identifying the strongest configurations. Second, the Milwaukee and Madison field sites represented different roadway contexts. Milwaukee represented a two-lane residential roadway condition, while Madison represented a wider roadway condition with greater visual and background complexity. Because these roadway contexts were different, the optimal configurations were evaluated separately before identifying the spectrum most suitable for broader design guidance. Third, the enhanced lighting system developed in Section 2 provided the practical hardware basis for the specifications.

#### 5.4.7 Final Recommended Specifications

The final recommended lighting specifications were established based on driver reaction time, detection distance, roadway context, and practical deployment considerations. The recommendations also considered installation feasibility, glare control, and solar-powered operation. Table 14 summarizes the final field-supported specification bases for different application contexts.

**Table 14. Final recommended lighting specifications by application context.**

| Application Context         | Spectrum      | Mounting Height      | Lateral Distance        | Spill Control    | Power Source    |
|-----------------------------|---------------|----------------------|-------------------------|------------------|-----------------|
| Milwaukee-type roadway      | Ice Blue      | 12.5 ft              | 9.5 ft                  | No spill control | Solar + Battery |
| Madison-type roadway        | Blue Baseline | 15.0 ft              | Site-specific placement | No spill control | Solar + Battery |
| Generalized design guidance | Blue Baseline | Refined in Section 6 | Refined in Section 6    | No spill control | Solar + Battery |

Design illuminance for Table 14: all listed configurations are based on the SafeWalk™ prototype design target of at least 20 lux vertical illuminance at the pedestrian plane (Section 2.1). Under field conditions, the enhanced lighting measured approximately 21 lux at the crosswalk, compared

with approximately 0.5 lux under the unlit Madison baseline and approximately 13 lux under the ambient Milwaukee baseline (Sections 3.1 and 3.5). These illuminance levels apply to each spectrum listed above and are the design values required for the procedures in Sections 6 and 7.

For roadway environments similar to the Milwaukee study site, Ice Blue lighting mounted at 12.5 ft with a 9.5 ft lateral offset provided the strongest overall balance of visibility and driver response performance. For roadway environments similar to the Madison study site, Blue Baseline lighting mounted at 15.0 ft provided the strongest field-supported result. For generalized implementation, Blue Baseline is recommended as the primary spectrum because it demonstrated superior performance in the wider roadway context and greater transferability across roadway applications. No spill control was retained in the recommended specifications because the enhanced lighting conditions provided favorable visibility performance without requiring additional spill-control treatment in the tested field settings. In addition, although the 50 percent spill-control condition showed favorable results at the Madison site (Section 5.3.5), the number of spill-control trials was very limited (fewer than five), so that finding was not considered definitive enough to justify requiring spill-control treatment in the recommended specifications. However, glare and light trespass should still be reviewed during site-specific implementation. Solar power with battery storage is recommended to support flexible deployment where grid access may be limited or costly. Final solar panel sizing, battery capacity, mounting height, lateral placement, and hardware deployment details should be refined through the roadway-specific design process presented in Section 6.

## **5.5 Section Summary**

This section developed field-supported optimal lighting specifications for enhanced crosswalk illumination. The analysis considered reaction time, detection distance, lighting spectrum, mounting height, lateral placement review, site context, sample size balance, glare control, and practical installation feasibility. For two-lane residential or lower speed roadway contexts similar to Milwaukee, the site-specific recommended specification is Ice Blue lighting at a 12.5 ft mounting height and 9.5 ft lateral distance, with no spill control. For wider roadway contexts similar to Madison, the recommended field-supported specification is Blue Baseline lighting at a 15.0 ft mounting height, with lateral placement determined through site-specific review, and no spill control. The generalized mounting height, lateral placement, pole layout,

stopping sight distance review, and solar battery installation requirements are further developed in Section 6.

## **6. Design Guidelines for Crosswalks**

This section develops a planning-level design framework for applying enhanced crosswalk illumination to roadway contexts beyond the Madison and Milwaukee test-sites. The purpose of this section is not to establish a fixed statewide design standard; rather, it is to provide a structured method for transferring field-supported lighting findings into practical installation guidance for future crosswalk applications.

The results in Section 5 identified Blue Baseline as the preferred spectrum for generalized implementation. Therefore, the framework in this section recommends Blue Baseline for future crosswalk applications across a range of roadway contexts. The design process focuses on how the installation geometry should be adjusted for different roadway widths, approach speeds, ambient lighting conditions, pole locations, and pedestrian visibility needs while maintaining the recommended Blue Baseline spectrum.

The generalized design framework includes five major steps. First, the roadway context is described using roadway width, number of lanes, approach speed, ambient lighting conditions, and pedestrian crossing environment. Second, Blue Baseline is applied as the recommended spectrum. Third, mounting height and lateral placement are estimated using roadway geometry and the closest field reference site. Fourth, predicted reaction time and detection distance are estimated using a Blue Baseline-only planning-level model. Fifth, the predicted detection distance is compared with stopping sight distance, and the design is reviewed for photometric coverage, glare, ADA and clear-zone constraints, utility conflicts, solar-battery feasibility, maintenance access, and nighttime field verification.

Because the field data were collected from a limited number of sites and conditions, the results should be interpreted as planning-level guidance rather than final design values. Final implementation at any future location should be confirmed through site-specific engineering review.

### **6.1 Design Guideline Principles**

The design guidance in this section is based on several principles intended to support safe, practical, and transferable implementation of enhanced crosswalk lighting.

First, Blue Baseline is recommended as the generalized spectrum for future crosswalk lighting applications. However, lighting spectrum should not be considered independently of illumination performance. Adequate vertical illuminance, pedestrian-background contrast, and

coverage of the crossing and waiting areas remain essential for pedestrian visibility. The recommended spectrum is most effective when combined with appropriate lighting levels and fixture placement.

Second, installation geometry should be adapted to the roadway context. Recommendations derived from the Milwaukee and Madison field sites should be transferred to other locations by scaling mounting height and lateral placement according to roadway width and crosswalk geometry. Mounting height, lateral placement, beam aiming, and pole location influence pedestrian visibility, vertical illuminance, and glare exposure. Therefore, illumination angle, crossing distance, pole placement feasibility, and crosswalk coverage should be reviewed before final design approval.

Third, glare, visual comfort, and pedestrian-background contrast should be evaluated during design. Although blue-shifted lighting may improve visual attention and pedestrian conspicuity, the installation should be reviewed to minimize driver discomfort glare, excessive brightness, and unwanted contrast effects created by surrounding ambient lighting conditions.

Fourth, detection distance should be checked against stopping sight distance (SSD is the total distance a driver needs to perceive a hazard, react, and brake to a complete stop before reaching it; see Section 6). The lighting design should provide drivers with sufficient distance to detect and respond to a pedestrian before reaching the crosswalk. If the predicted detection distance does not exceed the required stopping sight distance, the design should receive additional engineering review and may require adjustments to fixture placement, mounting height, beam aiming, or supplemental illumination.

Fifth, adaptive operation should be considered wherever appropriate. Motion activation, dimming, or other adaptive control strategies may reduce energy consumption and light pollution while maintaining pedestrian visibility when a pedestrian is present or approaching the crossing.

Finally, planning-level model outputs should support engineering review rather than replace them. Site-specific factors such as ambient lighting, roadway width, speed environment, pedestrian activity, vulnerable user presence, utility conflicts, ADA clearance requirements, solar access, winter maintenance needs, and constructability constraints should be documented before final design approval. Final implementation should also consider pole foundation feasibility, solar-battery placement, maintenance access, drainage, snow storage, utility clearance, and nighttime field verification after installation.

## 6.2 Variables Used in the Implementation Framework

The generalized design framework uses both field-measured variables and roadway design variables, which are given in Table 15. RT and DD are the important response variables, while other variables like the  $W$ ,  $H$ ,  $X$ ,  $V$ ,  $I$  are contextual variables that can be used to predict the RT and DD. Stopping sight distance (SSD) is a verification variable to determine if the recommendation is safe and if refinements are necessary. Variables including  $E$ ,  $P$  and  $C$  are battery and solar specific variables necessary to power the crosswalk with clean solar energy without intervention.

**Table 15. Variables used in the roadway generalization framework. (\*: Response Variables)**

| Symbol      | Description                                          | Unit        |
|-------------|------------------------------------------------------|-------------|
| * RT        | Driver Reaction Time                                 | s           |
| * DD        | Pedestrian Detection Distance                        | ft          |
| $W$         | Target roadway or crossing width                     | ft          |
| $W_0$       | Base roadway width from the reference field site     | ft          |
| $H$         | Recommended mounting height for the target site      | ft          |
| $H_0$       | Base mounting height from the reference field site   | ft          |
| $X$         | Recommended lateral placement for the target site    | ft          |
| $X_0$       | Base lateral placement from the reference field site | ft          |
| SSD         | Required stopping sight distance                     | ft          |
| $V$         | Vehicle approach speed                               | mph         |
| $I$         | Lighting intensity                                   | categorical |
| $C$         | Roadway context category                             | categorical |
| $k_w$       | Scaling factor                                       | -           |
| $E_d$       | Daily energy demand of crosswalk light               | kWh         |
| $C_b$       | Required battery capacity for installation           | kWh         |
| $P_{solar}$ | Required solar capacity for installation             | kW          |

## 6.3 Statistical Foundation for Generalization and Planning-Level Estimation

The roadway generalization framework builds upon the field-testing, lighting-performance evaluation, and site-specific findings presented in the earlier sections and serves as a key step toward the development of the design guidelines as proposed in Task 6. The purpose of this section is to provide a statistical basis for identifying which roadway, lighting, environmental, and pedestrian-related factors are associated with changes in driver response. The two response measures considered in this framework are driver reaction time and pedestrian detection distance.

An Ordinary Least Squares (OLS) regression model was used as the statistical foundation for the planning-level estimation framework [4]. This approach combines the available field observations into one dataset and estimates the average relationship between the response variable

and the predictor variables. The model is not intended to replace field verification or detailed photometric analysis. Instead, it is used as an engineering screening tool to identify influential factors and support comparison of alternative lighting and roadway configurations.

The general form of the OLS regression model is:

$$Y_i = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \dots + \beta_p X_{pi} + \epsilon_i \quad (21)$$

where  $Y_i$  is the response variable for observation  $i$ ,  $X_{1i}, X_{2i}, \dots, X_{pi}$  are the predictor variables.  $\beta_0$  is the intercept,  $\beta_1, \beta_2, \dots, \beta_p$  are the estimated regression coefficients, and  $\epsilon_i$  is the residual error term. In this study,  $Y_i$  represents either reaction time or detection distance, depending on the model being estimated.

Because reaction time and detection distance represent different driver-response outcomes, two separate regression models were estimated. The reaction time model is expressed as:

$$RT_i = \gamma_0 + \gamma_H H_i + \gamma_X X_i + \gamma_W W_i + \gamma_V V_i + \gamma_I I_i + \gamma_P P_i + \epsilon_i^{RT} \quad (22)$$

The detection-distance model is expressed as:

$$DD_i = \delta_0 + \delta_h H_i + \delta_X X_i + \delta_W W_i + \delta_V V_i + \delta_I I_i + \delta_P P_i + \epsilon_i^{DD} \quad (23)$$

where  $RT_i$  is reaction time,  $DD_i$  is pedestrian detection distance,  $H_i$  is the mounting height,  $X_i$  is the lateral distance from crosswalk,  $W_i$  is the roadway width,  $V_i$  is the vehicle speed,  $I_i$  represents the ambient lighting intensity,  $P_i$  represents mannequin type. Categorical variables, such as mannequin type, and ambient light condition (low, medium or high), are represented using indicator variables relative to reference categories.

The OLS model was selected because it provides a transparent and interpretable method for estimating average relationships across the available field observations. The regression coefficients indicate the estimated change in the response variable associated with a one-unit change in a predictor, while holding the other variables constant. For example, a positive coefficient in the detection-distance model indicates that the predictor is associated with an increase in detection distance, while a negative coefficient indicates that the predictor is associated with a decrease in detection distance. For reaction time, lower values are generally more desirable because they indicate faster driver response.

The model results are evaluated using coefficient estimates, statistical significance ( $R^2$ ), residual standard error, and F-statistic. The  $R^2$  value indicates the proportion of variation in the response variable explained by the predictors. The residual standard error provides a measure of

the typical prediction error in the response variable units. A larger F-statistic, together with a small model p-value, indicates that the predictors collectively explain more variation.

The regression model should be interpreted as an exploratory and planning-level screening tool rather than a universal prediction equation. The dataset is limited, and some variables may be partially confounded with site-specific conditions, roadway geometry, lighting setup, or testing conditions. Therefore, the regression results are used to support the roadway generalization effort and provide a quantitative foundation for the design-guideline development process in Task 6. The findings help identify influential factors, compare roadway-lighting alternatives, and establish planning-level expectations for driver response under different conditions.

### 6.3.1 Model Performance

Table 16 presents the Blue Baseline OLS regression results for reaction time and detection distance. The reaction-time model produced an  $R^2$  value of 0.208. Mounting height and relative ambient lighting showed statistically significant associations with reaction time, but the overall model F-statistic was 1.10, indicating limited overall explanatory strength. Therefore, the reaction-time model should be used only as a supporting screening measure.

The detection-distance model showed stronger performance, with an  $R^2$  value of 0.451. Vehicle speed was positively and significantly associated with detection distance, while other variables did not show strong independent statistical effects in this model. The child pedestrian coefficient was negative, which is directionally reasonable because a smaller pedestrian target may be harder to detect, but this effect was not statistically significant.

**Table 16. Blue Baseline only OLS regression model outputs for the reaction time and detection distance**

| Independent Variables                                                                                         | Dependent Variable |                    |
|---------------------------------------------------------------------------------------------------------------|--------------------|--------------------|
|                                                                                                               | Reaction Time      | Detection Distance |
| Mounting height                                                                                               | 0.038*             | 1.452              |
| Lateral distance from crosswalk                                                                               | -0.004             | -1.271             |
| Road width                                                                                                    | -.001              | 1.395              |
| Vehicle speed                                                                                                 | 0.012              | 7.244**            |
| # Pedestrian class: Child vs Adult                                                                            | 0.106              | -34.568            |
| # Ambient lighting: High vs Medium                                                                            | 0.065**            | 3.457              |
| Constant                                                                                                      | 0.032              | 1.758              |
| $R^2$                                                                                                         | 0.208              | 0.451              |
| Residual Standard Error                                                                                       | 0.205              | 55.232             |
| F-statistic                                                                                                   | 1.10               | 2.267*             |
| # Only use when the required class is the second in (i) vs (ii); * $p < 0.1$ ; ** $p < 0.05$ ; *** $p < 0.01$ |                    |                    |

Overall, the detection-distance model provides more useful planning-level information than the reaction-time model because predicted detection distance can be compared directly with stopping sight distance. However, the model is based on a small sample size and should be used only for preliminary screening. Final design decisions should still rely on site-specific photometric verification, glare assessment, stopping sight distance review, ADA and clear-zone review, pole and utility feasibility, maintenance review, and nighttime field validation.

The OLS models should not be interpreted as universal prediction equations. Instead, they provide a practical engineering screening method for comparing design alternatives and identifying which lighting and roadway variables may require additional review.

#### 6.4 Roadway Geometry and Fixture Placement Framework

The field conditions from Madison and Milwaukee cannot be transferred directly to every roadway because roadway width, pole location, crossing distance, and beam angle all influence lighting coverage. Therefore, mounting height and lateral placement were generalized using a roadway-width scaling approach. This framework provides a practical way to estimate fixture placement for roadways wider or narrower than the original field sites.

The roadway width scaling factor is:

$$k_w = \frac{W}{W_0} \quad (24)$$

where  $W$  is the target roadway width and  $W_0$  is the base roadway width of the blue baseline test site.

The generalized mounting height is estimated as:

$$H = H_0 \cdot (k_w)^\alpha \quad (25)$$

The generalized lateral placement is estimated as:

$$X = X_0 \cdot (k_w)^\beta \quad (26)$$

where  $H_0$  and  $X_0$  are the reference mounting height and lateral placement from the base field condition (Madison/Milwaukee), and  $\alpha$  and  $\beta$  are scaling exponents. The scaling exponents used in this study are:  $\alpha = 0.50$ ,  $\beta = 0.75$ .

The square root style of height scaling prevents the mounting height from increasing too aggressively as roadway width increases. A stronger scaling value is used for lateral placement because wider roads generally require greater side offset or pole placement adjustments to maintain adequate crosswalk illumination.

Final placement values should still be reviewed for field feasibility, including pole availability, sidewalk clearance, utilities, solar access, photometric coverage, glare, and installation constraints.

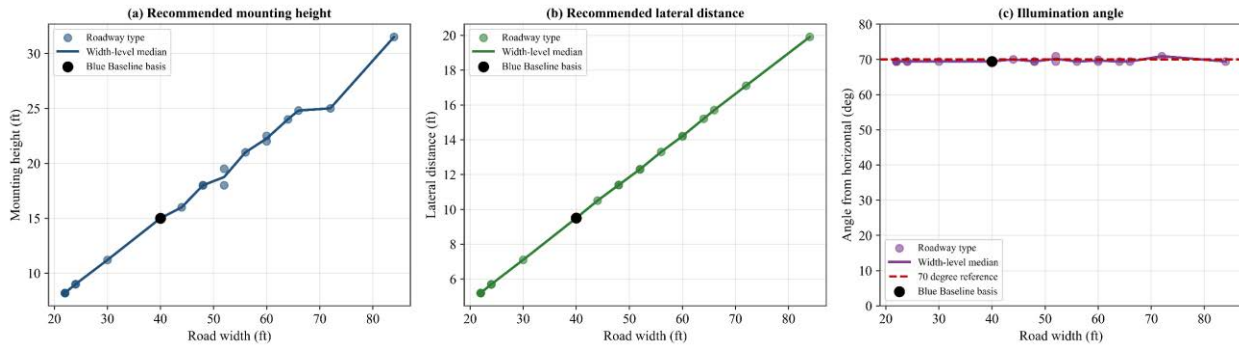


**Figure 32. Roadway geometry scaling used to generalize mounting height and lateral placement across roadway widths. Panel (a) shows recommended mounting height, panel (b) shows recommended lateral placement, and panel (c) shows illumination angle relative to roadway width.**

Figure 32 shows the roadway geometry scaling results for mounting height, lateral placement, and illumination angles. The best Blue-baseline field condition is used as the wider-road reference condition. For example, for a four-lane roadway with a 44 ft roadway width, based on the scaling framework, the generalized mounting height is 16.0 ft and the lateral distance is approximately 11.0 ft; however, this value is also influenced by the planned pole arrangement, and site-specific pole placement needs. Therefore, the lateral placement should be interpreted as a site-adapted design value rather than a direct formula-only output.

## 6.5 Reaction Time and Detection Distance Estimation

After roadway geometry scaling, expected driver response performance is estimated using a planning-level prediction framework. The purpose of this framework is not to replace full field testing or detailed photometric simulation. Instead, it provides an engineering screening method to compare roadway lighting configurations and estimate whether a proposed design is likely to provide sufficient detection distance and acceptable driver reaction performance.

The estimation framework is based on the Ordinary Least Squares regression models developed from field observations. Similar regression-based approaches are commonly used in transportation studies to examine the relationship between safety or driver-response outcomes and explanatory variables such as roadway geometry, traffic conditions, and environmental factors. In

this study, the response variables are reaction time and detection distance, while the explanatory variables include mounting height, lateral distance from crosswalk, roadway width, vehicle speed, lighting condition, pedestrian type (adult or child), and street-lighting condition.

Because reaction time and detection distance represent different driver-response outcomes, two separate regression equations are used. The estimated reaction time is expressed as:

$$\widehat{RT}_i = \gamma_0 + \gamma_H H_i + \gamma_X X_i + \gamma_W W_i + \gamma_V V_i + \gamma_I I_i + \gamma_D D_i + \gamma_{SL} SL_i \quad (27)$$

The estimated detection distance is expressed as:

$$\widehat{DD}_i = \delta_0 + \delta_h H_i + \delta_X X_i + \delta_W W_i + \delta_V V_i + \delta_I I_i + \delta_D D_i + \delta_{SL} SL_i \quad (28)$$

where  $\widehat{RT}_i$  and  $\widehat{DD}_i$  are the predicted reaction time and detection distance respectively for design condition  $i$ . The variable  $H_i$  represents mounting height,  $X_i$  represents lateral distance of the light from crosswalk,  $W_i$  represents mannequin type, and  $SL_i$  represents street-lighting condition. Categorical variables are represented using binary indicator values (0 or 1).

The coefficients ( $\gamma$ ) are obtained from the OLS reaction-time model, while the coefficients ( $\delta$ ) are obtained from the OLS detection-distance model. These coefficient values are reported in Table 16. Each coefficient represents the estimated change in the response variable associated with a one-unit change in the corresponding predictor, while holding the other variables constant. For categorical predictors, the coefficient represents the estimated difference from the reference category.

In this framework, lower predicted reaction time and greater predicted detection distance indicate better expected driver response performance. A lighting configuration that increases detection distance while reducing reaction time would be considered more favorable because drivers would recognize the pedestrian target earlier and respond more quickly.

The model results should be interpreted with caution. The pooled OLS model provides a planning-level estimate based on the available field observations, but it is not a universal prediction equation. The model is most appropriate for comparing design alternatives, identifying configurations that may require additional review, and supporting early-stage design decisions. Final design recommendations should still be verified using site-specific photometric analysis, glare review, stopping sight distance evaluation, installation feasibility checks, field observation, and engineering judgment.

## 6.6 Stopping Sight Distance Check

The generalized lighting design must be checked against stopping sight distance requirements to evaluate whether the predicted detection distance provides enough distance for a driver to perceive, react, and stop safely. This check is used as a planning-level safety screen. A lighting configuration is considered adequate only when the predicted detection distance is greater than the required stopping sight distance for the roadway condition being evaluated.

The roadway SSD is calculated as:

$$SSD = 1.47Vt_r + \frac{V^2}{30(f \pm G)} \quad (29)$$

where  $SSD$  is the stopping sight distance in feet,  $v$  is vehicle speed in miles per hour,  $t_r$  is perception-reaction time in seconds,  $f$  is the braking friction factor, and  $G$  is roadway grade expressed as a decimal. The term  $1.47vt_r$  represents the perception-reaction distance, while the second term represents the braking distance. For design-level screening, a perception-reaction time of 2.5 seconds is commonly used in AASHTO-based SSD calculations [18].

The lighting configuration is considered adequate when:

$$\widehat{DD} \geq SSD \quad (30)$$

The Margin,  $M = \widehat{DD} - SSD$  where  $M > 0$  indicates that predicted detection distance exceeds the required SSD. If  $M \leq 0$ , additional engineering review is required.

The SSD screening results in Figure 33 compare the predicted detection distance from the Blue Baseline planning-level model with the required stopping sight distance for each representative roadway scenario. Required SSD was calculated using the AASHTO stopping sight distance equation with a 2.5-second perception-reaction time, zero roadway grade, and a uniform dry-pavement friction coefficient of 0.35. Predicted detection distances were estimated using the generalized Blue Baseline detection-distance model and the assumed roadway width, approach speed, mounting height, and lateral placement values summarized in Table 17.

Table 17 summarizes the planning-level assumptions used for the generalized roadway screening scenarios. The roadway width and approach speed values represent typical screening conditions for each roadway context, while the recommended mounting heights and lateral placements were calculated using the roadway-width scaling equations described above, with the Madison field condition used as the reference geometry. These values are intended as planning-level starting points for fixture placement and are not substitutes for site-specific design measurements. Stopping sight distance (SSD) was calculated using Eq. 29 with a 2.5-second

perception-reaction time, zero roadway grade, and a uniform dry-pavement friction coefficient of approximately 0.35. Predicted detection distances assume the recommended Blue Baseline spectrum, high-intensity lighting, and adult pedestrian targets. These assumptions provide a consistent basis for comparing representative roadway contexts; final design values should be verified through site-specific measurements, photometric review, glare assessment, ADA and clear-zone review, utility review, and nighttime field verification.

**Table 17. Assumed Values for Generalized Roadway Screening**

| <b>Roadway Scenario</b>    | <b>Assumed Road Width (ft)</b> | <b>Assumed Speed (mph)</b> | <b>Spectrum</b> | <b>Recommended Mounting Height (ft)</b> | <b>Recommended Lateral Placement (ft)</b> |
|----------------------------|--------------------------------|----------------------------|-----------------|-----------------------------------------|-------------------------------------------|
| School Zone 2-Lane         | 22                             | 15                         | Blue Baseline   | 10.6                                    | 5.6                                       |
| School Zone 4-Lane         | 44                             | 20                         | Blue Baseline   | 15.0                                    | 9.5                                       |
| Residential 2-Lane         | 22                             | 25                         | Blue Baseline   | 10.6                                    | 5.6                                       |
| Residential 4-Lane         | 40                             | 30                         | Blue Baseline   | 14.3                                    | 8.8                                       |
| Downtown 2-Lane            | 30                             | 20                         | Blue Baseline   | 12.4                                    | 7.1                                       |
| Downtown 4-Lane            | 52                             | 25                         | Blue Baseline   | 16.3                                    | 10.8                                      |
| Suburban 2-Lane            | 24                             | 35                         | Blue Baseline   | 11.1                                    | 6.0                                       |
| Suburban 4-Lane, No Median | 52                             | 45                         | Blue Baseline   | 16.3                                    | 10.8                                      |
| Suburban 4-Lane, Median    | 60                             | 45                         | Blue Baseline   | 17.5                                    | 12.0                                      |
| Urban 2-Lane               | 24                             | 30                         | Blue Baseline   | 11.1                                    | 6.0                                       |
| Urban 4-Lane, No Median    | 48                             | 35                         | Blue Baseline   | 15.7                                    | 10.1                                      |
| Urban 4-Lane, Median       | 56                             | 35                         | Blue Baseline   | 16.9                                    | 11.4                                      |
| Urban 6-Lane, No Median    | 66                             | 40                         | Blue Baseline   | 18.4                                    | 12.9                                      |
| Urban 6-Lane, Median       | 72                             | 40                         | Blue Baseline   | 19.2                                    | 13.7                                      |
| Rural 2-Lane               | 22                             | 45                         | Blue Baseline   | 10.6                                    | 5.6                                       |
| Rural 4-Lane               | 48                             | 55                         | Blue Baseline   | 15.7                                    | 10.1                                      |
| High-Speed Interchange     | 64                             | 45                         | Blue Baseline   | 18.1                                    | 12.6                                      |
| High-Speed 4-              | 60                             | 55                         | Blue            | 17.5                                    | 12.0                                      |

| Roadway Scenario          | Assumed Road Width (ft) | Assumed Speed (mph) | Spectrum      | Recommended Mounting Height (ft) | Recommended Lateral Placement (ft) |
|---------------------------|-------------------------|---------------------|---------------|----------------------------------|------------------------------------|
| Lane Divided              |                         |                     | Baseline      |                                  |                                    |
| High-Speed 6-Lane Divided | 84                      | 65                  | Blue Baseline | 20.7                             | 15.4                               |

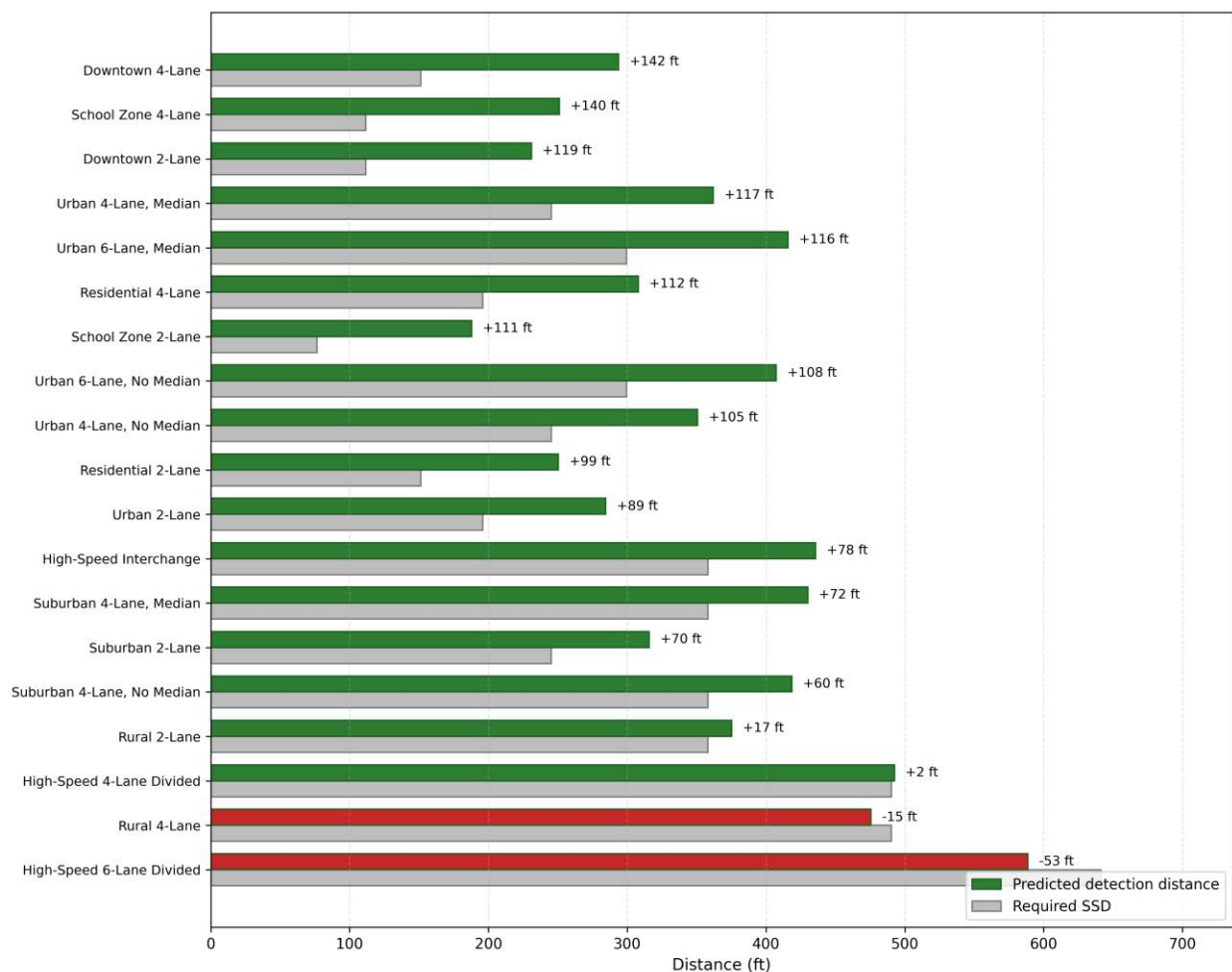


**Figure 33. Stopping sight distance adequacy across general roadway types. Green bars indicate roadway types where predicted detection distance exceeds the required SSD, while red bars indicate roadway types requiring additional design review.**

Figure 33 shows that most low- and moderate-speed roadway scenarios produced positive detection-distance margins, with predicted detection distance exceeding the required SSD. School-zone, residential, downtown, urban, and several suburban scenarios therefore appear suitable for further planning-level consideration under the recommended Blue Baseline implementation, provided that appropriate mounting height and lateral placement are used.

However, the results also show that higher-speed and wider roadway contexts require additional review. The high-speed 4-lane divided scenario barely satisfied the SSD check,

indicating only a limited safety margin and a need for further engineering verification. The rural 4-lane and high-speed 6-lane divided scenarios did not satisfy the SSD screening check, meaning the predicted detection distance was lower than the required SSD under the assumed speed and geometry conditions. These cases should not be advanced without design revision, such as increasing mounting height, modifying lateral placement, improving beam aiming, adding supplemental illumination, or considering additional traffic-control treatments.

Figure 33 should be interpreted as a planning-level screening comparison rather than final design validation. Scenarios with marginal or negative SSD margins require site-specific engineering review, including photometric, glare, SSD, ADA, clear-zone, utility, maintenance, and nighttime field checks.

### 6.7 Solar Battery Sizing Framework

The enhanced crosswalk lighting system is planned to operate using solar power with battery storage. Therefore, the design must verify that the system can provide reliable nighttime operation, especially during Wisconsin winter conditions when available sunlight is reduced, and snow cover may affect solar charging.

For demonstrations or deployments that use a multi-pole lighting layout, solar and battery sizing should be evaluated for each pole location. The review should consider panel exposure, battery enclosure placement, controller access, pole loading, maintenance access, and site constraints. The center pavement or median pole requires special attention because it may have different snow storage, drainage, utility, and maintenance constraints compared with the roadway-edge poles.

The daily energy demand for each lighting unit is estimated as:

$$E_d = P_{load} \cdot T_{op} \quad (31)$$

where:

- $E_d$  = daily energy demand (watt-hours per day, Wh/day)
- $P_{load}$  = lighting system power demand (watts, W)
- $T_{op}$  = nightly operating time (hours per day, h/day)

The required battery capacity is:

$$C_b = \frac{E_d \cdot N_a}{DOD \cdot \eta_b} \quad (32)$$

where:

- $C_b$  = required battery energy capacity (watt-hours, Wh, or kilowatt-hours, kWh)
- $E_d$  = daily energy demand (Wh/day)
- $N_a$  = required number of autonomy days (days). The autonomy period represents the number of days the system should operate without sufficient solar charging.
- $DOD$  = allowable battery depth of discharge (decimal fraction)
- $\eta_b$  = battery efficiency (decimal fraction)

The required solar panel power is:

$$P_{solar} = \frac{E_d}{PSH \cdot \eta_s} \quad (33)$$

where:

- $P_{solar}$  = required solar panel rated power (watts peak, W)
- $E_d$  = daily energy demand (Wh/day)
- $PSH$  = available peak sun-hours (hours per day, h/day)
- $\eta_s$  = overall solar efficiency, including charging, wiring, controller, and panel losses (decimal fraction)

For winter operation, a correction factor should be applied:

$$P_{solar,winter} = P_{solar} \cdot K_w \quad (34)$$

where keeping the factor  $K_w > 1$  accounts for reduced sunlight, snow cover, lower solar angles, panel soiling, and additional charging losses during winter.

The final solar panel size should be selected by comparing the calculated winter-adjusted panel requirement with commercially available panel sizes. The selected panel should be equal to or larger than the calculated  $P_{solar,winter}$  while still being practical for pole mounting, wind loading, orientation, maintenance access, and site appearance. Similarly, the battery should be selected with sufficient usable capacity (Wh, kWh, or Ah at the specified system voltage) to satisfy the autonomy requirement without exceeding the allowable depth of discharge.

Before installation, the final design should be checked for solar access, panel orientation, battery enclosure location, controller compatibility, pole loading, snow clearance, maintenance access, and electrical safety. These checks are especially important for the center pole because it may be more difficult to access and may be exposed to different roadway, drainage, and snow-removal conditions than the edge poles.

## 6.8 Photometric, Glare, ADA, and Maintenance Checks

The generalized design values developed in the previous sections provide recommended starting values for mounting height, lateral placement, Blue Baseline implementation, and solar-battery sizing. However, these values must be confirmed through engineering review before installation. The purpose of this final check is to ensure that the proposed design is not only statistically and geometrically reasonable, but also practical, safe, maintainable, and compatible with site constraints.

Table 18 summarizes the required design checks that should be completed before installation. These checks address photometric coverage, pedestrian visibility, glare, ADA accessibility, clear-zone requirements, utility conflicts, solar access, battery maintenance, and site-specific constraints. The table is intended to function as a final engineering review checklist before the design is approved for field deployment.

**Table 18. Required design checks before installation**

| <b>Check</b>                          | <b>Purpose</b>                                                                                                                                      |
|---------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------|
| Photometric coverage                  | Confirm crosswalk and pedestrian waiting area illumination                                                                                          |
| Vertical illumination                 | Confirm light reaches pedestrian body, not only pavement                                                                                            |
| Glare review                          | Confirm source brightness does not create driver discomfort                                                                                         |
| Beam direction                        | Aim fixtures toward pedestrian conflict areas                                                                                                       |
| ADA clearance                         | Avoid obstruction of accessible pedestrian routes                                                                                                   |
| Clear-zone review                     | Avoid roadside hazards where applicable                                                                                                             |
| Utility review                        | Check underground and overhead utility conflicts                                                                                                    |
| Solar access                          | Confirm adequate sunlight for panel charging                                                                                                        |
| Battery maintenance                   | Confirm safe access for inspection and replacement                                                                                                  |
| Electrical/code review                | Confirm wiring, grounding, controller, battery enclosure, and overcurrent protection meet applicable electrical code and permitting requirements    |
| Center pavement or median pole review | Confirm that the center pole does not conflict with pedestrian refuge space, median width, utilities, drainage, snow storage, or maintenance access |
| Winter durability                     | Account for snow, salt, freezing temperature, and plow operations                                                                                   |

These checks are necessary because the generalized model provides recommended starting values rather than final construction designs. Final design approval should be based on field layout, photometric verification, glare and visibility review, ADA and clear-zone review, solar-battery feasibility, electrical code passes, and maintenance access.

## 6.9 Recommended Generalized Design Procedure

The recommended generalized design procedure provides a step-by-step process for applying the enhanced lighting system to a new crosswalk location. The procedure connects the

Blue Baseline implementation framework, roadway geometry scaling, reaction-time and detection-distance screening, stopping sight distance review, solar-battery sizing, and final engineering review into one implementation workflow.

Table 19 summarizes the recommended sequence of design actions. The procedure begins with collecting roadway and site information, then selecting the appropriate reference condition, applying roadway geometry scaling, estimating reaction time and detection distance, and checking whether the predicted detection distance is sufficient relative to stopping sight distance. The later steps focus on pole layout, solar-battery feasibility, photometric review, glare review, ADA compliance, maintenance access, and nighttime field verification.

**Table 19. Generalized design procedure**

| <b>Step</b> | <b>Design Action</b>                                                                                                                                           |
|-------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1           | Identify roadway width, number of lanes, speed environment, crosswalk geometry, pedestrian activity, and safety need                                           |
| 2           | Use Blue Baseline as the recommended generalized spectrum                                                                                                      |
| 3           | Select the reference field context, using Milwaukee for two lane residential settings and Madison for wider roadway settings                                   |
| 4           | Apply roadway geometry scaling to estimate mounting height and lateral placement                                                                               |
| 5           | Predict reaction time and detection distance using the Blue Baseline OLS regression model                                                                      |
| 6           | Check whether predicted detection distance exceeds required stopping sight distance                                                                            |
| 7           | Select pole layout based on coverage need, glare control, installation feasibility, power requirements, and center pavement or median pole feasibility         |
| 8           | Confirm solar panel exposure, battery capacity, and winter operating reliability                                                                               |
| 9           | Review photometric coverage, vertical illumination, glare, ADA clearance, utilities, clear zone, center pavement or median constraints, and maintenance access |
| 10          | Finalize fixture aiming, pole spacing, battery enclosure, solar panel position, and installation drawings                                                      |
| 11          | Conduct nighttime field verification after installation                                                                                                        |

This procedure is intended to support planning-level design and early-stage screening of Blue Baseline enhanced crosswalk lighting applications. It should not be used as a substitute for final engineering design. Before installation, the recommended design must still be verified through site-specific analysis, field review, construction feasibility assessment, electrical/code review, and nighttime performance verification.

## 6.10 Section Summary

This section presented a planning-level framework for applying the enhanced crosswalk lighting findings beyond the Madison and Milwaukee field test sites. The framework uses field-

supported reference configurations to guide roadway width-scaling for different road contexts, while avoiding direct transfer of site-specific dimensions without engineering review.

The framework combines field-supported Blue Baseline implementation, roadway geometry scaling, driver-response estimation, stopping sight distance screening, solar-battery sizing, and engineering review. Because the field data were collected from a limited number of roadway environments, the recommendations are intended as starting points for design review rather than fixed design standards.

An Ordinary Least Squares regression model was used to estimate reaction time and detection distance for planning-level screening. The detection-distance model provided stronger explanatory value than the reaction-time model because predicted detection distance can be compared with the required stopping sight distance. The model should not be interpreted as a universal prediction equation.

Mounting height and lateral placement were generalized using roadway-width scaling based on the closest field reference condition. These values provide practical starting points, but final fixture placement must still be checked for photometric coverage, glare, pole availability, utilities, ADA clearance, solar access, maintenance access, and constructability.

Predicted detection distance was compared with required stopping sight distance as a safety screening check. The results indicate that low-speed and moderate-speed roadway contexts are more likely to satisfy the screening check, while rural and high-speed conditions require additional review because stopping sight distance increases substantially with speed.

The section also presented a solar-battery sizing framework to estimate daily energy demand, required battery capacity, solar panel size, and winter-adjusted solar capacity. Final implementation should consider snow storage, maintenance access, drainage, pole loading, solar exposure, and nighttime field verification.

## **7. Implementation Recommendations for WisDOT Review**

This section provides the final researcher recommendations for WisDOT review based on the literature review, lighting system development, driver recognition and reaction time testing, demonstration planning, optimal lighting specification analysis, and design guideline framework developed in the previous sections. The purpose of this section is to translate the study findings into practical implementation recommendations that can support future enhanced crosswalk lighting applications in Wisconsin.

The recommendations in this section should be treated as a field-supported implementation framework. Each candidate location should still be reviewed using site-specific engineering judgment, photometric analysis, glare review, ADA review, utility review, solar feasibility review, maintenance review, and nighttime field verification.

### **7.1 Final Study Findings**

The study produced the following major findings.

First, blue-spectrum enhanced crosswalk lighting improved driver recognition conditions compared with baseline lighting (the existing condition with no enhanced crosswalk lighting installed) at the tested sites. The results showed that targeted lighting can improve pedestrian visibility when the lighting spectrum, mounting height, lateral placement, and beam direction are selected together.

Second, the lighting spectrum influenced driver response and detection distance, but the spectrum alone was not sufficient to define the optimal design. A spectrum must be combined with adequate vertical illumination, pedestrian contrast, crosswalk coverage, glare control, and appropriate mounting geometry.

Third, the field results showed different site-specific spectrum outcomes. Ice Blue performed best for the Milwaukee type two lane residential context, while Blue Baseline performed best for the wider Madison roadway context. Based on a comprehensive assessment of field performance and other relevant factors, the Blue Baseline configuration is recommended as the primary generalized lighting spectrum for broader roadway applications.

Fourth, roadway geometry is critical when transferring recommendations from one site to another. Mounting height and lateral placement should not be copied directly from one field site to another without reviewing roadway width, crossing distance, pole placement, illumination angle, glare exposure, and pedestrian waiting area coverage. A roadway-width scaling approach

was introduced in this report to help translate field-tested configurations to other roadway contexts while preserving the intended illumination coverage and driver visibility performance.

Fifth, stopping sight distance should be used as a safety screening check. Predicted detection distance should exceed the required stopping sight distance for the approach speed. Locations where the predicted detection distance does not exceed the required stopping sight distance should receive additional engineering review before implementation.

## 7.2 Recommended Configuration for WisDOT Consideration

For general WisDOT consideration, the recommended enhanced crosswalk lighting configuration is summarized in Table 20.

**Table 20. Recommended enhanced crosswalk lighting configuration for WisDOT consideration**

| <b>Design Element</b> | <b>Recommended Direction</b>                                                                    |
|-----------------------|-------------------------------------------------------------------------------------------------|
| Primary spectrum      | Blue Baseline                                                                                   |
| Mounting height       | Scale with roadway width and verify through photometric review                                  |
| Lateral placement     | Scale with roadway width and adjust based on site layout, pole feasibility, glare, and coverage |
| Power source          | Solar power with battery storage, subject to site feasibility review                            |
| Safety screening      | Predicted detection distance should exceed required stopping sight distance                     |

WisDOT should treat these recommendations as an implementation framework rather than a fixed standard. Each deployment should include roadway geometry review, stopping sight distance screening, photometric verification, glare review, ADA review, utility review, solar battery review, winter maintenance review, and nighttime field verification before final acceptance.

## 7.3 Consolidated Design Summary for Designers

This section consolidates the final build recommendations in one place so that a designer can obtain the complete specification from this section alone. It brings together the lighting specifications (Table 14), the roadway geometry scaling values (Table 17), the design checks (Table 18), the recommended configuration (Table 20), and the field-verified illuminance levels (Sections 2.1 and 3.5).

For a specific roadway, first identify the roadway scenario in Table 17 to obtain the recommended mounting height and lateral placement, then apply the specifications in Table 21 below and complete the design checks in Table 18 and the step-by-step procedure in Table 19 and Section 6.

**Table 21. Consolidated build specification for designers, with the report source for each design element.**

| <b>Design Element</b>           | <b>Specification</b>                                                                                                                                                                                                                                                     | <b>Source in Report</b>            |
|---------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------|
| Lighting spectrum               | Blue Baseline (blue-shifted LED; controller channels Red 129.0, Green 420.75, Blue 741 on the 0–750 scale). Use Ice Blue (Red 80, Green 520, Blue 750) for narrow two-lane residential contexts.                                                                         | Table 3, Table 14, Table 20        |
| Light source and color settings | SafeWalk™ RGB LED channels set to the Blue Baseline configuration: Red 129.0, Green 420.75, Blue 741 on the 0–750 channel intensity scale (for Ice Blue: Red 80, Green 520, Blue 750). Full channel settings for all tested spectra are given in the note under Table 3. | Sections 2.2–2.3, Table 2, Table 3 |
| Vertical illuminance            | At least 20 lux at the pedestrian plane (design target); approximately 21 lux measured in the field under the enhanced condition.                                                                                                                                        | Sections 2.1 and 3.5               |
| Mounting height                 | Scale with roadway width: for example 10.6 ft (22 ft road) up to 19.2 ft (72 ft road); see the full scenario table for each roadway type.                                                                                                                                | Table 17, Section 6                |
| Lateral placement               | Scale with roadway width: for example 5.6 ft (22 ft road) up to 13.7 ft (72 ft road); verify pole feasibility, glare, and coverage on site.                                                                                                                              | Table 17, Section 6                |
| Spill control                   | None required; review glare and light trespass during site-specific design.                                                                                                                                                                                              | Section 5.4, Table 14              |
| Power source                    | Solar power with battery storage, subject to site feasibility review (panel exposure, battery capacity, winter performance).                                                                                                                                             | Table 14, Section 6                |
| Safety screening                | Predicted detection distance must exceed the required stopping sight distance for the approach speed.                                                                                                                                                                    | Section 7.1, Table 18, Figure 33   |
| Design verification             | Photometric verification, glare review, ADA and clear-zone review, utility review, winter maintenance review, and nighttime field verification.                                                                                                                          | Table 18, Table 19                 |

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## **Appendix**

Figures 34 and 35 present additional SafeWalk™ installation and field deployment photographs from the nighttime field testing described in Sections 3 and 4, showing the mounting arrangement, lateral placement, and beam aiming used at the test sites.

Floodlight Summary:

Report based on lamp delivering 1000 lumens.

|                                    |                        |
|------------------------------------|------------------------|
| Maximum Intensity                  | 820.6 cd per klm.      |
| (Luminaire orientation as tested.) | 0.0 degrees vertical   |
|                                    | 0.0 degrees horizontal |

|             |                |               |
|-------------|----------------|---------------|
| Beam Spread | At 10% of Imax | 49.5V x 46.2H |
|             | At 50% of Imax | 25.3V x 23.9H |
|             | At 90% of Imax | 10.0V x 8.5H  |

|           |                |                       |
|-----------|----------------|-----------------------|
| Beam Flux | Total          | 245.1 lumens per klm. |
|           | To 10% of Imax | 153.6 lumens per klm. |
|           | To 50% of Imax | 80.7 lumens per klm.  |
|           | To 90% of Imax | 14.3 lumens per klm.  |

|              |        |
|--------------|--------|
| Upward LOR   | 0.0 %  |
| Downward LOR | 24.5 % |

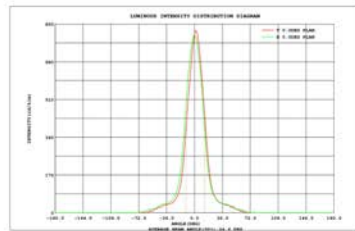
|                                          |        |
|------------------------------------------|--------|
| Luminaire Efficiency(Light Output Ratio) | 24.5 % |
|------------------------------------------|--------|

|                      |                                                  |
|----------------------|--------------------------------------------------|
| C Range: 0 - 180DEG  | γ Range: 0 - 180DEG                              |
| C Interval: 30.0DEG  | γ Interval: 1.0DEG                               |
| Test Speed: HIGH     | Test System:EVERFINE GO-2000B_V1 SYSTEM V2.0.402 |
| Temperature:25.3DEG  | Humidity:65.0%                                   |
| Operators:qiu        | Test Distance:8.100m [K=1.0000]                  |
| Test Date:2025-07-02 | Remarks:                                         |

Figure 34. SafeWalk™ system installation and field deployment configuration used during nighttime field testing.

## LUMINAIRE PHOTOMETRIC TEST REPORT

|                                                                               |                |                  |
|-------------------------------------------------------------------------------|----------------|------------------|
| Test:U:13.351V I:0.1498A P:2.0000W PF:1.0000 Freq:50.00Hz Lamp Flux:1000x1 lm |                |                  |
| NAME: Safewalk2                                                               | TYPE:          | WEIGHT:          |
| SPEC.:                                                                        | DIM.:          | SERIAL No.:      |
| MFR.: Germain                                                                 | SUR.:85mm*60mm | Shielding Angle: |



| DATA OF LAMP      |      | Eff:122.47lm/W     |          |
|-------------------|------|--------------------|----------|
| MODEL             |      | Imax(cd/klm)       | 820.6    |
| NOMINAL POWER(W)  |      | AVAILABILITY (%)   | 15.4     |
| RATED VOLTAGE (V) |      | Avai. FLUX(lm/klm) | 154.0    |
| NOMINAL FLUX(lm)  | 1000 | LOR (%)            | 24.5     |
| LAMPS INSIDE      | 1    | TOTAL FLUX(lm/klm) | 244.9    |
| TEST VOLTAGE (V)  |      | θ @50%(H,V)        | 24,25DEG |

|                |     | AREA FLUX DIAGRAM |      |      |      |      |      |      |      |                  |      |      |      |      |      |      |      | UNIT:lm/klm |      |      |      | φ t | φ a |
|----------------|-----|-------------------|------|------|------|------|------|------|------|------------------|------|------|------|------|------|------|------|-------------|------|------|------|-----|-----|
| VERTICAL (DEG) | 45  | 0.12              | 0.13 | 0.16 | 0.19 | 0.23 | 0.25 | 0.26 | 0.27 | 0.28             | 0.28 | 0.27 | 0.25 | 0.24 | 0.22 | 0.17 | 0.13 | 0.10        | 0.08 | 3.63 | 0.00 |     |     |
|                | 40  | 0.13              | 0.16 | 0.20 | 0.23 | 0.25 | 0.26 | 0.28 | 0.29 | 0.30             | 0.30 | 0.29 | 0.27 | 0.26 | 0.24 | 0.22 | 0.18 | 0.13        | 0.10 | 4.08 | 0.00 |     |     |
|                | 35  | 0.15              | 0.18 | 0.22 | 0.24 | 0.26 | 0.29 | 0.32 | 0.34 | 0.36             | 0.35 | 0.33 | 0.30 | 0.27 | 0.25 | 0.23 | 0.21 | 0.16        | 0.11 | 4.56 | 0.00 |     |     |
|                | 30  | 0.16              | 0.19 | 0.22 | 0.25 | 0.29 | 0.35 | 0.41 | 0.46 | 0.48             | 0.47 | 0.42 | 0.36 | 0.31 | 0.27 | 0.24 | 0.21 | 0.19        | 0.13 | 5.41 | 0.00 |     |     |
|                | 25  | 0.17              | 0.20 | 0.23 | 0.28 | 0.34 | 0.45 | 0.60 | 0.74 | 0.80             | 0.75 | 0.63 | 0.48 | 0.37 | 0.30 | 0.25 | 0.22 | 0.19        | 0.15 | 7.16 | 2.67 |     |     |
|                | 20  | 0.18              | 0.21 | 0.25 | 0.31 | 0.42 | 0.63 | 0.98 | 1.37 | 1.57             | 1.44 | 1.08 | 0.73 | 0.48 | 0.34 | 0.27 | 0.23 | 0.19        | 0.16 | 10.8 | 7.44 |     |     |
|                | 15  | 0.19              | 0.22 | 0.27 | 0.35 | 0.52 | 0.92 | 1.65 | 2.60 | 3.11             | 2.80 | 1.92 | 1.11 | 0.62 | 0.40 | 0.29 | 0.24 | 0.20        | 0.16 | 17.6 | 14.7 |     |     |
|                | 10  | 0.19              | 0.23 | 0.29 | 0.40 | 0.66 | 1.31 | 2.54 | 4.05 | 4.84             | 4.35 | 3.03 | 1.64 | 0.81 | 0.46 | 0.31 | 0.25 | 0.21        | 0.16 | 25.7 | 23.1 |     |     |
|                | 5   | 0.19              | 0.23 | 0.30 | 0.43 | 0.77 | 1.69 | 3.30 | 5.00 | 5.92             | 5.34 | 3.84 | 2.16 | 0.99 | 0.51 | 0.33 | 0.25 | 0.21        | 0.16 | 31.6 | 29.1 |     |     |
|                | 0   | 0.19              | 0.23 | 0.30 | 0.43 | 0.77 | 1.69 | 3.30 | 5.00 | 5.92             | 5.34 | 3.84 | 2.16 | 0.99 | 0.51 | 0.33 | 0.25 | 0.21        | 0.16 | 31.6 | 29.1 |     |     |
|                | -5  | 0.19              | 0.23 | 0.29 | 0.40 | 0.66 | 1.31 | 2.54 | 4.05 | 4.84             | 4.35 | 3.03 | 1.64 | 0.81 | 0.46 | 0.31 | 0.25 | 0.21        | 0.16 | 25.7 | 23.1 |     |     |
|                | -10 | 0.19              | 0.22 | 0.27 | 0.35 | 0.52 | 0.92 | 1.65 | 2.60 | 3.11             | 2.80 | 1.92 | 1.11 | 0.62 | 0.40 | 0.29 | 0.24 | 0.20        | 0.16 | 17.6 | 14.7 |     |     |
|                | -15 | 0.18              | 0.21 | 0.25 | 0.31 | 0.42 | 0.63 | 0.98 | 1.37 | 1.57             | 1.44 | 1.08 | 0.73 | 0.48 | 0.34 | 0.27 | 0.23 | 0.19        | 0.16 | 10.8 | 7.44 |     |     |
|                | -20 | 0.17              | 0.20 | 0.23 | 0.28 | 0.34 | 0.45 | 0.60 | 0.74 | 0.80             | 0.75 | 0.63 | 0.48 | 0.37 | 0.30 | 0.25 | 0.22 | 0.19        | 0.15 | 7.16 | 2.67 |     |     |
|                | -25 | 0.16              | 0.19 | 0.22 | 0.25 | 0.29 | 0.35 | 0.41 | 0.46 | 0.48             | 0.47 | 0.42 | 0.36 | 0.31 | 0.27 | 0.24 | 0.21 | 0.19        | 0.13 | 5.41 | 0.00 |     |     |
|                | -30 | 0.15              | 0.18 | 0.22 | 0.24 | 0.26 | 0.29 | 0.32 | 0.34 | 0.36             | 0.35 | 0.33 | 0.30 | 0.27 | 0.25 | 0.23 | 0.21 | 0.16        | 0.11 | 4.56 | 0.00 |     |     |
|                | -35 | 0.13              | 0.16 | 0.20 | 0.23 | 0.25 | 0.26 | 0.28 | 0.29 | 0.30             | 0.30 | 0.29 | 0.27 | 0.26 | 0.24 | 0.22 | 0.18 | 0.13        | 0.10 | 4.08 | 0.00 |     |     |
|                | -40 | 0.12              | 0.13 | 0.16 | 0.19 | 0.23 | 0.25 | 0.26 | 0.27 | 0.28             | 0.28 | 0.27 | 0.25 | 0.24 | 0.22 | 0.17 | 0.13 | 0.10        | 0.08 | 3.63 | 0.00 |     |     |
|                | -45 | 0.12              | 0.13 | 0.16 | 0.19 | 0.23 | 0.25 | 0.26 | 0.27 | 0.28             | 0.28 | 0.27 | 0.25 | 0.24 | 0.22 | 0.17 | 0.13 | 0.10        | 0.08 | 3.63 | 0.00 |     |     |
|                |     | -45               | -40  | -35  | -30  | -25  | -20  | -15  | -10  | HORIZONTAL (DEG) |      |      |      | 10   | 15   | 20   | 25   | 30          | 35   | 40   | 45   |     |     |
| φ t            |     | 2.96              | 3.52 | 4.24 | 5.34 | 7.49 | 12.3 | 20.7 | 30.3 | 35.3             | 32.2 | 23.6 | 14.6 | 8.71 | 5.97 | 4.63 | 3.82 | 3.17        | 2.41 | 221  | ---  |     |     |
| φ a            |     | 0.00              | 0.00 | 0.00 | 0.00 | 2.84 | 8.62 | 17.5 | 27.3 | 32.4             | 29.1 | 20.4 | 11.1 | 4.40 | 0.30 | 0.00 | 0.00 | 0.00        | 0.00 | ---  | 154  |     |     |

one-half-peak spread: U:12.7,D:12.7 , L:11.8,R:12.3

NEMA Beam Type: Type 4

C Range: 0 - 180DEG  
C Interval: 30.0DEG  
Test Speed: HIGH  
Temperature:25.3DEG  
Operators:qiu  
Test Date:2025-07-02

γ Range: 0 - 180DEG  
γ Interval: 1.0DEG  
Test System:EVERFINE GO-2000B\_V1 SYSTEM V2.0.402  
Humidity:65.0%  
Test Distance:8.100m [K=1.0000]  
Remarks:

Figure 35. Additional field installation view showing lateral placement and beam aiming during nighttime field testing.