Human-Centered Simulation of Intersection Lighting: A Parametric Study of Design Tradeoffs

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***Abstract*—Pedestrian safety in urban environments remains a critical public health issue, with nighttime conditions substantially increasing crash risk for vulnerable road users. Yet intersection lighting design remains constrained by roadway-centric standards and static workflows, offering limited support for evaluating tradeoffs among multidirectional pedestrian visibility, glare, and light trespass—and environmentally sensitive designs are often presumed, without evidence, to compromise safety. We introduce SALUSLux, an open-source, programmable simulation toolkit for pedestrian-centered intersection lighting analysis, and apply it to a parametric study of 2,304 configurations on a standard four-way intersection. Results reveal three findings with direct implications for practice and standards. First, spatial geometry and luminaire properties interact so strongly that they cannot be optimized independently—a luminaire that performs well in one configuration can fail in another, making joint design-space exploration essential. Second, semi-cylindrical illuminance was the most difficult metric to satisfy across all scenarios and should be elevated to a required standard for intersection crosswalks; horizontal illuminance—the dominant metric in current practice—provided little additional information once other criteria were met, and overreliance on it risks encouraging excessive lighting that increases glare without improving pedestrian safety. Third, warm-color 2,700K lighting fully satisfies all pedestrian visibility thresholds when paired with appropriate spatial configuration, directly contradicting the assumed safety-sustainability tradeoff. Together, these findings provide an evidence base for intersection-specific lighting criteria that existing tools cannot deliver.**

***Index Terms*—Intersection lighting, light pollution, light trespass, lighting design tradeoffs, open-source software, pedestrian visibility, photometric analysis, SALUSLux**

List of Abbreviations:

AASHTO	American Association of State Highway and Transportation Officials
ANSI	American National Standards Institute
BIM	Building Information Modeling
CAD	Computer-Aided Design
CCT	Correlated Color Temperature
CIE	International Commission on Illumination
CSV	Comma-Separated Values
DOT	Department of Transportation
FHWA	Federal Highway Administration
GR	Glare Rating
IES	Illuminating Engineering Society
IoT	Internet of Things
LED	Light Emitting Diode
LPI	Leading Pedestrian Interval
NCHRP	National Cooperative Highway Research Program
USDOT	United States Department of Transportation
VLR	Veiling Luminance Ratio
VTTI	Virginia Tech Transportation Institute

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This invited paper is an extension of a conference paper [1] at the 2025 IEEE International Smart Cities Conference (ISC2), held from October 6-9, 2025, in Patras, Greece. This paper has been extended by adding a new analysis section exploring two real-world contextual factors—orientation-dependent light trespass analysis across multiple pole angles and the integration of leading pedestrian intervals with lighting performance—alongside new background, methodology detail, refined parametric analysis, and discussion for the expanded parametric study.

I. Introduction

Pedestrian safety remains a persistent and urgent challenge in transportation systems, particularly for vulnerable road users navigating urban environments. A large share of pedestrian crashes and fatalities occur in low-light conditions, where visibility is reduced and detection distances shorten. Empirical studies consistently show that pedestrian crash risk is substantially higher in darkness than in daylight [2], [3], and the night-to-day crash ratio is widely recognized as a key indicator used to assess pedestrian lighting needs [4]. Sanders et al. found that 75% of U.S. pedestrian fatalities occur in darkness, and that nearly 90% of the increase in pedestrian fatalities from 2009 to 2018 was concentrated in nighttime conditions—a trend driven largely by roadway design factors including the absence or inadequacy of lighting [5]. These findings motivate roadway lighting as a critical design lever for intersection safety—settings where pedestrians must negotiate complex driver trajectories, turning movements, and occlusions. Lighting is also one of the most actionable interventions available to agencies because it can be deployed, upgraded, and managed without requiring reconstruction of the roadway. Prior meta-analyses have reported sizable safety benefits associated with public lighting, including reductions in nighttime fatal, injury, and property-damage-only accidents following new or improved lighting installations [6], [7].

However, “more light” is not universally “better light.” Beyond safety, modern streetlighting must balance additional societal and technological objectives. Over-lighting contributes to light pollution, a key consequence of which is skyglow, which has been associated with circadian disruption and broader health and ecological impacts [8]–[10]. Color temperature choices further complicate this trade space: cooler, higher correlated color temperature (CCT) light emitting diodes (LEDs) can improve certain visibility-related outcomes but may increase blue-light scattering and environmental impacts, while warmer CCTs reduce blue content but can reduce detection distances under some conditions [4], [11]. Recent pedestrian-focused research confirms that CCT has measurable effects on perceived safety, recognition, and comfort from the pedestrian’s perspective—not just the driver’s—and that the optimal CCT for pedestrian-scale environments may differ from that traditionally recommended for roadway contexts [12]. Streetlighting conditions may also interact with emerging roadway technologies. For example, overly reflective materials and certain lighting environments have been reported to create challenges for sensing and perception systems in modern vehicles, raising the possibility that lighting design must increasingly consider compatibility with automated or assisted driving systems [13]. At the human level, lighting affects not only objective crash risk but also perceived safety and nighttime mobility: women in particular report feeling less safe in poorly lit areas [14], and experimental evidence confirms that brighter street lighting leads people to feel meaningfully safer outdoors, with a majority willing to pay for LED upgrades to improve their perceived security [15], [16].

Beyond these over-lighting concerns, the nature of crash risk itself further complicates the picture. Crash risk is influenced by many coupled factors—traffic volume, pedestrian activity, intersection geometry, operating speeds, and driver workload—such that illumination levels alone do not fully explain safety outcomes. Even within the lighting domain, design decisions that improve one safety-relevant attribute may degrade another. For example, a design that increases light levels on the pavement may still fail to illuminate the pedestrian’s body in a way that supports detection, recognition, and intent inference by approaching drivers. Meanwhile, the rapid transition to LED streetlighting has introduced new challenges related to directional emission patterns, high luminance “hot spots,” and discomfort or disability glare, particularly when bright diode arrays are visible in the line of sight [17], [18]. Recent experimental work confirms that discomfort glare from LED luminaires in pedestrian-scale outdoor environments is a measurable and consistent phenomenon, yet existing glare metrics remain poorly calibrated for pedestrian applications—underscoring the need for evaluation tools that explicitly incorporate pedestrian-relevant glare assessment [19]. These issues are especially salient at intersections where pedestrians and drivers often face luminaires at low angles during crossing and turning.

Together, these concerns place streetlighting squarely within a multi-objective design regime spanning safety, sustainability, human comfort, and technology compatibility. These challenges are arising at a moment when cities are rapidly upgrading lighting infrastructure and adding networked controls. Contemporary LED luminaires increasingly support dimming, scheduling, monitoring, and integration with communications modules (e.g., through upgraded photocell sockets and plug-in controllers), enabling adaptive lighting policies at the corridor or intersection scale. Yet the cost and operational complexity of these systems can be substantial [20], and ownership structures (utility-owned vs. municipally owned vs. shared) can limit the extent to which agencies can implement responsive strategies. As a result, practitioners need practical ways to evaluate lighting strategies before installation—quantifying whether a proposed design meets pedestrian lighting guidance (e.g., ANSI/IES RP-8-18 and related recommendations) while limiting glare and light pollution and supporting feasible operational policies [4], [21].

A central barrier is that rigorous lighting evaluation is often difficult to operationalize and reproduce. Many lighting analyses rely on proprietary software, ad hoc workflows, or isolated scenario studies that are challenging to extend, audit, and integrate into open, data-driven urban analytics pipelines (discussed in depth in Section II). The interactive, manual workflows of tools such as DIALux [22] and ReLux [23] are well suited to evaluating a handful of candidate designs, but they cannot support the systematic exploration of large design spaces, sensitivity analyses across hundreds or thousands of parameter combinations, or integration into automated optimization and policy studies. This means that practitioners and researchers have had no practical pathway to understand how intersection lighting performance varies across the full range of plausible design choices, how design parameters interact with one another, or how robust a given design is to changes in geometry, luminaire properties, or operational constraints. These are not peripheral questions—they are central to the development of evidence-based lighting standards and to the selection of designs that perform reliably across real-world conditions.

At the same time, the lighting research literature provides clear guidance on what should be evaluated. Recommended practice and guidance documents emphasize not only horizontal illuminance but also vertical and semi-cylindrical illuminance for pedestrian visibility, luminance for perceived brightness, and glare metrics such as veiling luminance ratio and related indices [4], [21], [24]. Empirical and simulation-based studies—including foundational work by the Virginia Tech Transportation Institute (VTTI) and others—have explored how pole placement, luminaire beam distribution, mounting height, and power influence pedestrian visibility [11], [25]–[27]. These studies have also shown that high-performing configurations for pedestrian visibility (e.g., certain forward-aimed or approach-focused layouts) can still create tradeoffs in glare, comfort, energy use, and light trespass—making it difficult to generalize results across intersection geometries and design constraints. Importantly, the three dominant layout archetypes most commonly studied in this literature—the box, staggered, and turbine configurations—were developed primarily for midblock crosswalk contexts, and their applicability and limitations for full intersection streetlight design remain poorly characterized [28]. Critically, however, these studies evaluate a small number of manually configured scenarios at a single location; none provides a systematic, large-scale exploration of how intersection lighting performance varies across the full combinatorial space of geometric and photometric parameters, nor do they jointly evaluate pedestrian safety, glare, sustainability, and light trespass as coupled objectives. What has been missing is a computational pipeline capable of evaluating these tradeoffs simultaneously, at scale, and in a reproducible way.

This paper addresses these challenges by introducing SALUSLux, an open-source streetlighting analysis and design software and framework that supports reproducible, scalable, scenario-based evaluation of intersection lighting [Redacted Link/Citation to Open-Source Software for Double Blind Review]. SALUSLux is designed to bridge three persistent gaps in practice and research: (i) the need for an accessible and auditable computational toolchain for lighting analysis; (ii) the need to jointly evaluate pedestrian safety-relevant photometric outcomes, sustainability, and comfort impacts; and (iii) the need to explore design spaces—not just single candidate layouts—so practitioners can understand sensitivity to geometry, luminaire properties, and operational constraints. SALUSLux operationalizes this evaluation by combining standard photometric inputs (e.g., manufacturer-provided photometric distributions), physically grounded modeling assumptions, and widely used performance metrics to compute illuminance, luminance, and glare outcomes under candidate designs.

To demonstrate SALUSLux's utility for design exploration, we apply it to a parametric study of a standard four-way intersection and evaluate 2,304 lighting scenarios that vary both geometric and photometric design choices. This large-scale simulation experiment illustrates how decisions such as pole spacing, pole offset, mounting height, and luminaire distribution, in conjunction with key contextual factors such as surrounding light trespass and leading pedestrian intervals (LPIs)—reshape key pedestrian safety and sustainability metrics (i.e., illuminance, luminance, glare, and CCT), and reveals how these metrics often conflict. The analysis provides a transparent and repeatable pathway from candidate lighting designs to quantifiable performance evidence, enabling agencies and researchers to more systematically reason about tradeoffs and robustness across plausible operating conditions.

To summarize, the main *contributions* of this paper are:

1) An open-source, reproducible streetlighting software framework (SALUSLux) that integrates photometric inputs, intersection geometry, and physically grounded assumptions to compute pedestrian-relevant lighting metrics at scale—enabling a class of large-scale, multi-parameter analysis that is not achievable with existing commercial tools;
2) A multi-objective evaluation approach that treats pedestrian safety, visual comfort, sustainability outcomes, and contextual factors as coupled design criteria, aligned with established guidance and glare assessment methods [4], [21], [24]—making explicit the tradeoffs between these objectives that point-based compliance tools obscure;
3) A large parametric intersection case study (2,304 scenarios) that produces novel scientific findings regarding geometry-luminaire interaction effects, the adequacy of existing photometric metrics for intersection contexts, and the feasibility of environmentally sensitive designs—thereby motivating design-space exploration rather than one-off evaluation;
4) Building on the baseline intersection study [1], we introduce two new application scenarios that extend the practical scope of SALUSLux: a light trespass analysis, which evaluates spillover illuminance onto adjacent properties, and a delayed activation scenario, which models adaptive lighting systems where luminaires reach full output after a time lag—both of which reflect real operational conditions not addressed in prior work.

Through these contributions, this paper demonstrates that computational methods can reconcile pedestrian safety and sustainability objectives, and provides an evidence base to support intersection-specific lighting criteria and policies that existing tools and isolated scenario studies cannot deliver.

II. Background

This section provides the minimum technical and scholarly context needed to interpret the modeling choices and evaluation metrics implemented in SALUSLux. In Section II-A, we summarize the pedestrian-safety context that motivates intersection lighting analysis. In Section II-B, we define the core photometric quantities used throughout this paper. Illuminance serves as a measure of pedestrian visibility, luminance as a measure of contrast, CCT as a measure of sustainability (e.g., ecology, DarkSky principles), and glare as a measure of comfort. In Section II-C, we review the standards and guidance that inform common design targets. In Section II-D, we synthesize prior findings on intersection lighting configurations and the safety-sustainability trade space that motivates multi-objective evaluation. And in Section II-E, we review the limitations of IES file handling software in existing lighting software, as well as their manual workflows. Together, these five subsections establish the evidence base for why intersection lighting demands a multi-objective, design-space approach rather than the single-scenario, single-metric evaluations that currently dominate practice. Together, these five subsections establish the evidence base for why intersection lighting demands a multi-objective, design-space approach rather than the single-scenario, single-metric evaluations that currently dominate practice.

A. Pedestrian Nighttime Risk at Intersections

Pedestrian safety has become an increasingly urgent issue in the United States, with recent reporting indicating thousands of annual fatalities and persistent inequities in exposure and risk [29]. Across multiple datasets, the majority of severe pedestrian outcomes occur after dark, and elevated risk persists for hours into the evening [30], [31]. Although many countermeasures affect nighttime risk—vehicle speeds, turning behavior, crosswalk design, signal timing, and pedestrian volumes—lighting is a uniquely scalable intervention because it can be upgraded and controlled independently of major roadway reconstruction. Evidence reviews and meta-analyses support the safety relevance of lighting improvements [6], [7]. However, the design of effective pedestrian lighting requires more than raising overall brightness. The lighting literature emphasizes that visibility and comfort depend on how light is distributed in three dimensions and how the scene is perceived [4], [21], motivating the photometric metrics described next.

B. Photometric Quantities for Pedestrian Lighting Evaluation

Intersection lighting design is commonly evaluated through a combination of illuminance, luminance, and glare metrics. Each captures a distinct aspect of the visual environment and together they describe both visibility-related performance and potential negative externalities [4], [21].

1) Illuminance: Illuminance measures the amount of luminous flux incident on a surface and is reported in lux (lm/m^2). For roadway environments, illuminance is frequently used to assess whether pedestrian facilities (e.g., crosswalks, waiting areas, sidewalks, corners) receive sufficient light to support detection and recognition [4]. Because pedestrians are three-dimensional targets, pedestrian lighting guidance commonly distinguishes among:

- Horizontal illuminance, which characterizes light incident on the ground plane and is often used for pavement and roadway checks;
- Vertical illuminance, which characterizes light incident on a vertical plane and more directly relates to the visibility of a pedestrian's body from a driver's perspective;
- Semi-cylindrical illuminance, which approximates illumination around the human form (rather than on a single plane) and has been used to represent facial visibility and body contour recognition in pedestrian contexts.

In practice, these measures can yield different conclusions for the same design: a layout that raises horizontal illuminance at the crosswalk may still provide insufficient vertical or semi-cylindrical illumination for pedestrians approaching from certain directions.

2) Luminance: Luminance describes the intensity of light reflected from a surface in a given direction and is typically reported in candelas per square meter (cd/m^2). Luminance is closely tied to perceived brightness because it accounts for both incident illumination and surface reflectance. In road environments, reflected luminance from pavement and markings can meaningfully shape contrast patterns and perceived scene brightness, complementing direct illuminance from luminaires [4], [21]. The widespread transition to LED streetlighting has increased the prominence of luminance considerations because LED luminaires can produce high-intensity regions and strong spatial gradients, particularly when optical distributions concentrate light in narrow zones [17].

3) Glare: Glare refers to excessive brightness that can reduce visibility or create discomfort. It is commonly discussed as nuisance glare (bothersome), discomfort glare (visual strain), or disability glare (visibility impairment and delayed recovery) [17], [18]. Glare is a central concern for LEDs because high-luminance diode arrays can be visible within the field of view, particularly at low angles typical of pedestrian and driver sightlines near intersections.

Standards bodies have developed operational measures of glare. The Illuminating Engineering Society (IES) assesses glare in roadway lighting using the Veiling Luminance Ratio (VLR), which evaluates how a bright source can reduce the contrast needed to perceive detail in the surrounding environment [21]. The International Commission on Illumination (CIE) also established a glare rating framework for outdoor lighting, where higher values indicate more glare [24]. While no single glare metric perfectly captures perceived discomfort across contexts, these measures provide practical proxies for comparing candidate designs and identifying layouts likely to introduce visual discomfort or impairment.

4) Color Temperature and Spectral Considerations: CCT affects both visual performance and environmental impact because short-wavelength ("blue") content scatters more readily and contributes disproportionately to skyglow and ecological disruption [8], [9]. At the same time, controlled studies have reported CCT-dependent differences in pedestrian detection distances under some conditions, with tradeoffs between visibility performance and light-pollution impacts across warmer and cooler LEDs [4], [11]. For this reason, pedestrian lighting guidance often treats CCT as a design dimension that must be selected alongside geometry and luminous intensity, rather than as a purely aesthetic choice [4].

C. Standards, Guidance, and Design Targets

Most roadway lighting practice is anchored in standards and guidance that specify performance targets as a function of roadway class, pedestrian activity, and context. In North America, a central reference is ANSI/IES RP-8-18, which provides recommended practice for roadway and parking facility lighting and is widely used to inform municipal and agency design criteria [21]. Complementary guidance is available through transportation design references such as the AASHTO Roadway Lighting Design Guide [32], the Transportation Association of Canada Guide for the Design of Roadway Lighting [33], and historical warranting references such as NCHRP Report 152 [34]. These documents motivate the use of illuminance, luminance, and glare metrics and the evaluation of pedestrian zones beyond the roadway centerline.

Recent pedestrian-focused lighting guidance has been consolidated through work led by VTTI and partners for the

Federal Highway Administration (FHWA). The Pedestrian Lighting Primer synthesizes prior research and provides recommended evaluation approaches and design targets for crosswalks and adjacent pedestrian facilities [4]. Supporting reports further discuss safety benefits and best practices for intersection lighting and provide study-backed recommendations for configurations and performance thresholds [11], [26]. Across these documents, a consistent theme is that pedestrian visibility at intersections is better represented by vertical and semi-cylindrical illuminance (in addition to horizontal measures), and that high-performing designs must be evaluated for glare and other unintended consequences, such as light trespass.

Because standards and guidance are expressed in terms of target photometric outcomes rather than specific layouts, computational tools are needed to translate a candidate configuration (e.g., pole placement, luminaire type, mounting height, aiming) into predicted performance over the crosswalk and adjacent pedestrian space. We would like to note that the choice of North American standards in this paper reflects the context of the case study—a four-lane by four-lane by four-lane U.S. arterial intersection—and is not a limitation of the SALUSLux framework itself. The framework is designed to accommodate any applicable standard: a practitioner modeling a European intersection would supply thresholds from EN 13201-2:2015 (Road Lighting — Performance Requirements [35]) or the internationally recognized CIE 115:2010 (Lighting of Roads for Motor and Pedestrian Traffic [36]), while a practitioner in Asia or elsewhere might apply the corresponding regional guidance. In every case, the photometric simulation engine and evaluation pipeline remain unchanged; only the performance thresholds supplied by the user differ.

D. Prior Work on Lighting Configurations and Design Sensitivities

A substantial body of work has examined how streetlight geometry and photometric distributions influence pedestrian visibility, most prominently for crosswalk contexts. Studies that combine field measurements and simulation have shown that performance is highly sensitive to coupled design choices, including pole spacing, offset, mounting height, power, and beam distribution type [4], [11], [25]. Notably, strong performance for one approach direction does not guarantee robust performance across all relevant viewpoints at an intersection, particularly where turning movements introduce additional driver sightlines.

Recent synthesis and simulation efforts have highlighted a small set of recurring layout archetypes that are often discussed for crosswalk illumination and have been evaluated for their applicability at intersections. These include dynamic (or box) configurations, in which four poles are positioned at each corner of the intersection aiming inward, and turbine configurations, in which four poles are installed forward of the intersection, oriented to light pedestrians in the approach path of oncoming vehicles. While box configurations offer symmetry, they often fail to effectively illuminate pedestrians from the perspective of approaching drivers. They may also inadequately light vehicle turning paths. The turbine configuration has been found effective for frontal pedestrian visibility but tends to perform poorly for illuminating sidewalk approaches or pedestrians crossing from side angles.

VTTI's work, using manufacturer-provided photometric distributions in simulation, indicates that certain forward-aimed configurations can improve vertical illuminance on pedestrians in the approach path of drivers, particularly when paired with appropriate beam distributions and mounting heights [11], [26]. However, these same choices can underperform for other pedestrian locations (e.g., sidewalk approaches or lateral crossing directions) and may elevate glare or increase spill light depending on the optical distribution and intensity required [4], [17]. In other words, prior work motivates the need to evaluate intersection lighting as a multi-objective design problem rather than a single-metric compliance exercise.

This trade space has become more consequential with LED adoption. The directional nature of LEDs can increase spatial non-uniformity and sharp cutoffs between illuminated and dark regions [37], and high-luminance diode arrays can increase discomfort glare under certain viewing geometries [17], [18]. Meanwhile, increasing brightness to recover pedestrian visibility can exacerbate light pollution and associated health and ecological impacts [8], [9].

E. Software Workflows, Reproducibility, and the Need for Programmatic Design-space Evaluation

Despite the importance of lighting design, the analytical workflows available to practitioners remain difficult to operationalize for reproducible, large-scale evaluation. In practice, street lighting layouts are often developed using a combination of computer-aided design (CAD)/building information modeling (BIM) and photometric simulation tools. Geometry and documentation may be produced in platforms such as ArchiCAD [38] and Revit [39], while lighting calculations and visualizations are commonly performed in software packages such as DIALux [22] and ReLux [23]. These tools are effective for producing renderings, compliance checks, and project documentation for a small number of candidate designs.

However, their predominant workflows are interactive and manual, which makes it cumbersome to systematically explore large design spaces, conduct sensitivity analyses, or integrate lighting evaluation into automated optimization, policy studies, or future Internet of Things (IoT) control that accounts for changing environmental conditions. Moreover, interoperability constraints can limit seamless, programmatic ingestion and comparison of luminaire photometry at scale using standard photometric file formats and repeatable scripts. These capabilities are increasingly important for research reproducibility and for embedding lighting analytics into broader smart-city and IoT-enabled decision pipelines. This gap is especially limiting for intersection lighting, where performance is highly sensitive to coupled choices such as pole placement, mounting height, offsets, and luminaire distribution type, and where optimizing one objective can degrade another.

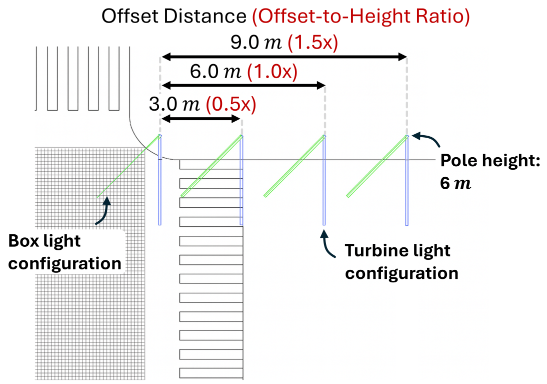


Fig. 1: Illustration of the mounting offset distance and mounting offset-to-pole height (or, "offset-to-height") ratio for box and turbine luminaire configurations, shown for a pole height of 6 m.

III. Methodology

To evaluate the effectiveness of street lighting configurations using standard configuration and photometric data, we developed SALUSLux—a Python-based simulation toolkit tailored for pedestrian-centric lighting analysis. SALUSLux was created to address major limitations in existing commercial lighting design tools such as DIALux and ReLux. These tools are widely used for architectural visualization and lighting simulation but have two key drawbacks:

1) Limited compatibility with standard photometric file formats: While the IES maintains an accessible, plaintext format for photometric data (ANSI/IES LM-63-19), many commercial tools restrict its use—accepting only proprietary formats (e.g., Unified Luminaire Data in DIALux) unless users upgrade to paid versions. Most lighting manufacturers continue to distribute photometric data primarily in the IES format, making this a substantial barrier for accessibility and transparency.
2) Emphasis on manual rendering over programmatic control: Mainstream tools prioritize 3D modeling via graphical user interfaces, making it difficult to systematically vary lighting parameters such as pole height, spacing, distribution type, and color temperature. This approach is impractical for simulating large numbers of design alternatives or optimizing for multiple, interacting criteria such as illuminance, glare, and environmental sustainability.

To overcome these constraints, SALUSLux was built using Python and designed to support parametric, reproducible, and large-scale lighting simulation. It allows researchers and practitioners to load standard IES files, define streetlight configurations programmatically, and simulate lighting behavior across a wide range of design parameters. These include pole height, mounting offset (i.e., the distance that a street light pole is mounted away from the intersection corner, as see in Figure 1), orientation, luminaire distribution type, power, and color temperature—enabling scalable analysis that would be time-prohibitive using traditional tools.

We begin by defining a modular set of functions within SALUSLux, each corresponding to key calculations required in professional lighting design. The remainder of this section outlines the structure of the software and key modeling assumptions. While this paper focuses on a four-way urban intersection as an illustrative case study, the functions are fully generalizable to support a broad range of outdoor lighting scenarios and configurations grounded in photometric physics. The toolkit itself is designed to be geographically agnostic: it computes lighting physics in exactly the same way regardless of whether the evaluation criteria come from North America, Europe, Asia, or elsewhere. For this paper, we model a typical four-lane by four-lane U.S. intersection and therefore reference the ANSI and FHWA standards most commonly applied in built environments [4], [21]. Users applying SALUSLux to other contexts would substitute the appropriate regional standards for international applications, without any modification to the underlying simulation framework. Figure 2 provides a high-level overview of the simulation methodology to accompany the more detailed Algorithm 1.

A. *Parsing an IES File*

The first module parses IES photometric files, which are the most widely used format for sharing standardized light distribution data. The IES file format, defined by ANSI/IES LM-63-19 [40], encodes the luminous intensity distribution of a light fixture measured at various angles, which are published by manufacturers. They include metadata and candela values that enable lighting simulation. While the format is plaintext, parsing IES data requires structure handling given the inconsistencies in manufacturer implementation.

1) Metadata Extraction: The parser begins by reading the IES file line-by-line to extract relevant metadata encoded in fixed positions defined by the ANSI/IES LM-63 standard. This includes the number of lamps, lumens per lamp, candela multiplier, ballast factor, power, and the physical dimensions of the luminaire.

However, not all practically useful attributes are captured within the file itself. Most notably, the LM-63 standard does not include a dedicated field for luminaire distribution type (e.g., Type II, III, IV, V)—a classification that directly characterizes how light is directed onto the roadway. In practice, manufacturers often encode this information in the file name rather than within the file body, an informal convention that varies across vendors and is not guaranteed to be present or consistently formatted. To address this limitation, the parser uses regular expressions and heuristic pattern matching to infer the distribution type from the file name where possible. When no distribution type can be identified, the attribute is flagged as unknown and the user is notified, ensuring that downstream analyses remain transparent about the completeness of the parsed data.

2) Luminous Intensity Distribution: IES files define angular grids over which luminous intensity is measured. These typi-

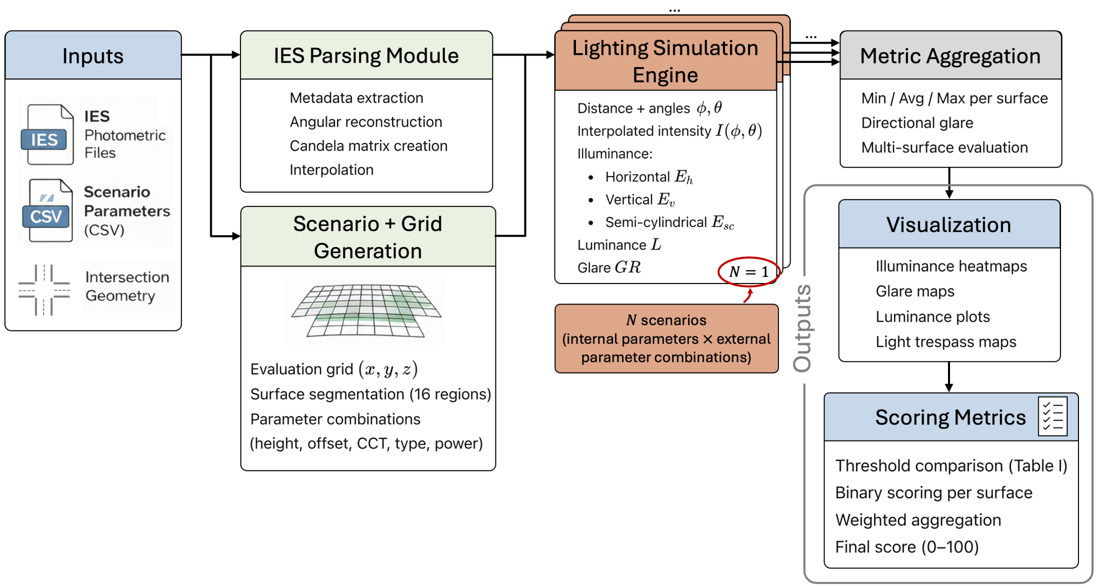
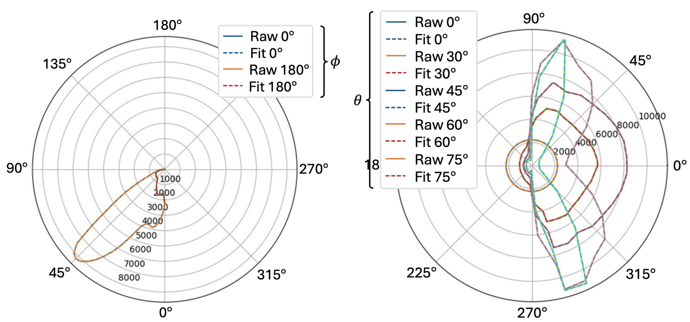


Fig. 2: Overview of the SALUSLux simulation methodology, illustrating the flow of data from IES file parsing and scenario generation through parametric lighting simulation, metric aggregation, scoring, and visualization.



(a) (b)

Fig. 3: A pair of polar from an IES file, with (a) a plot of candela values at each vertical angle (i.e., a side view of light), and (b) a plot of candela values at each horizontal angles (i.e., a top view of light). Each plot is shown together with their interpolations.

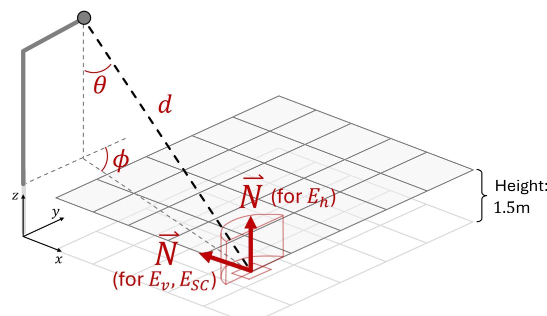


Fig. 4: Basic illumination geometry assigns a normal vector $\vec{N}$ at each point to compute the lux received from a street light based on position and orientation.

cally include a set of horizontal angles $\mathbf{H} = [h_1, h_2, \ldots, h_{n_H}]$ and vertical angles $\mathbf{V} = [v_1, v_2, \ldots, v_{n_V}]$, where n_H and n_V are the number of horizontal and vertical angles discretized, respectively. The IES format may only list a partial angular sweep—such as a quarter or half of the full 360° horizontal and 180° vertical sphere—depending on luminaire symmetry.

To construct a complete luminous intensity distribution, SALUSLux mirrors (e.g., if $\mathbf{H} = [a, b, c]$, $\mathbf{H}_{\text{reversed}} = [c, b, a]$) and concatenates the angles to generate the full set of angles, $\mathbf{H}_{\text{full}}$. Quarter-angle horizontal distributions are mirrored using:

$$\mathbf{H}_{\text{full}} = [\mathbf{H}, 180^\circ \cdot \mathbf{1} - \mathbf{H}_{\text{reversed}}, 180^\circ \cdot \mathbf{1} + \mathbf{H}, 360^\circ - \mathbf{H}_{\text{reversed}}] \quad (1)$$

and half-angle horizontal distributions are completed using

$$\mathbf{H}_{\text{full}} = [\mathbf{H}, 360^\circ \cdot \mathbf{1} - \mathbf{H}_{\text{reversed}}] \quad (2)$$

where $\mathbf{1}$ is a vector of ones of length n_H. For example, given $\mathbf{H} = [0^\circ, 5^\circ, \ldots, 180^\circ]$, then $\mathbf{H}_{\text{reversed}} = [180^\circ, 175^\circ, \ldots, 0^\circ]$ and $360^\circ \cdot \mathbf{1} - \mathbf{H}_{\text{reversed}} = [180^\circ, 185^\circ, \ldots, 360^\circ]$. If an IES file is of the form V90–H180 (Vertical angles from 0°–90° and horizontal angles from 0°–180°), this function turns it into V180–H360. Vertical angles are mirrored similarly to span the full hemisphere. This reconstruction enables a complete representation of light output in all directions.

3) Candela Matrix Construction: Luminous intensity values—measured in candelas—are then parsed and structured into a 2D matrix $\mathbf{C}$, where each element, $C_{ij} = I(h_i, v_j)$ for $i = 1, 2, ..., n_H$ and $j = 1, 2, ..., n_V$, represents the intensity at a given horizontal and vertical angle pair. This matrix forms the core dataset used in subsequent illumination calculations.

4) Angular Interpolation: Because intensity values are only specified at discrete angle pairs, interpolation is required to compute luminous intensity at arbitrary directions. SALUSLux employs bilinear interpolation using SciPy's

`RegularGridInterpolator` [41], allowing smooth estimation of $I(h_i, v_j)$ from the discrete dataset. This is critical for accurate modeling of lighting performance across spatially continuous environments. At any horizontal and vertical angle, we can find the luminous intensity by:

$$I(\phi, \theta) = \text{interp}(\phi, \theta; \mathbf{H}, \mathbf{V}, \mathbf{C}) \tag{3}$$

Here, θ is the vertical angle between the light ray and the surface normal at the point of interest, ϕ is the horizontal angle in the luminaire's polar coordinate system. If the IES file includes a non-unity candela multiplier, γ, all values in the matrix $\mathbf{C}$ are scaled accordingly:

$$\mathbf{C}_{\text{scaled}} = \mathbf{C} \cdot \gamma \tag{4}$$

B. Generating Evaluation Grid Points

The function `generate_unified_grid` creates a mesh of evaluation points covering the rectangular area defined by the user:

$$x_{\text{min}} \leq x \leq x_{\text{max}} \quad \text{and} \quad y_{\text{min}} \leq y \leq y_{\text{max}} \tag{5}$$

The calculation grid is generated by dividing each surface of the intersection into a uniform array of points at a user-specified resolution. The height z is set to $z = 0$ to represent ground level, and the function computes the (x, y, z) coordinates of each point across all 16 surfaces of the intersection.

Unlike existing lighting software, SALUSLux allows the user to set the grid resolution freely. In standard road lighting practice, grid spacing is typically prescribed by the applicable standard. For example, EN 13201-3:2015 specifies that the transverse calculation spacing shall not exceed 1.5 m per lane, and that the longitudinal spacing shall be no greater than $S/2$, where S is the luminaire spacing interval—a scale-dependent rule that produces increasingly sparse grids as the area grows [35]. Similarly, ANSI/IES RP-8-22 defines grid point placement relative to lane width and pole spacing for roadway illuminance calculations [42]. To the best of our knowledge, SALUSLux is the first toolkit that decouples grid resolution from these fixed prescriptions, allowing researchers and practitioners to increase or reduce resolution as needed to align with the requirements of a specific standard, match available computational resources, or support higher-fidelity analyses. In our baseline case study, we set 22 × 22 points per surface, yielding point spacings of approximately 0.3 m × 0.164 m for crosswalk areas, 0.164 m × 0.164 m for sidewalk-corner areas, and 0.3 m × 0.3 m for the middle of intersection areas.

C. Computing Illumination

Illuminance (measured in lux) quantifies the amount of light incident on a surface. Illuminance influences visibility, facial recognition, and perceived safety in urban environments. This module implements two widely used lighting metrics: traditional planar illuminance (generalized both horizontally, E_h, and vertically, E_v), and semi-cylindrical illuminance, E_{sc}.

Algorithm 1 SALUSLux Intersection Simulation Process (From IES files parsing to accumulating and visualizing results)

procedure INTERSECTSIMULATION(`scenario_params`)
  Load IES photometric data for all luminaires
  Initialize evaluation grid across 16 surface regions
  for all grid points (x, y, z) **do**
    for all light sources L **do**
      Compute distance d and angles (ϕ, θ)
      Retrieve luminous intensity $I(\phi, \theta)$ via interpolation
      Compute horizontal illuminance E_h
      for all vertical directions $\vec{N}_v$ **do**
        Compute vertical illuminance E_v
      end for
      Compute semi-cylindrical illuminance E_{sc} (E_v mean)
    end for
    Compute luminance L
    Compute worst-case glare rating GR_{any}
    Compute directional glare rating GR_{dir} (8 cardinal views)
  end for
  Aggregate metrics per surface: `min`, `avg`, `max`
  Export results to CSV and generate visualizations
end procedure

1) Planar Illuminance: The function `compute_illuminance` calculates the illuminance E at each grid point based on the luminous intensity $I(\phi, \theta)$ from each source emitted by a luminaire located at (x_L, y_L, z_L) (Equation 3). The computation follows the standard photometric formula:

$$E(\vec{N}) = \frac{I(\phi, \theta) \cos\theta}{d^2} \tag{6}$$

where d is the distance between the source and the point:

$$d = [(x - x_L)^2 + (y - y_L)^2 + (z - z_L)^2]^{\frac{1}{2}} \tag{7}$$

and

$$\cos(\theta) = \frac{\vec{N}(-\vec{L})}{|\vec{L}|} \tag{8}$$

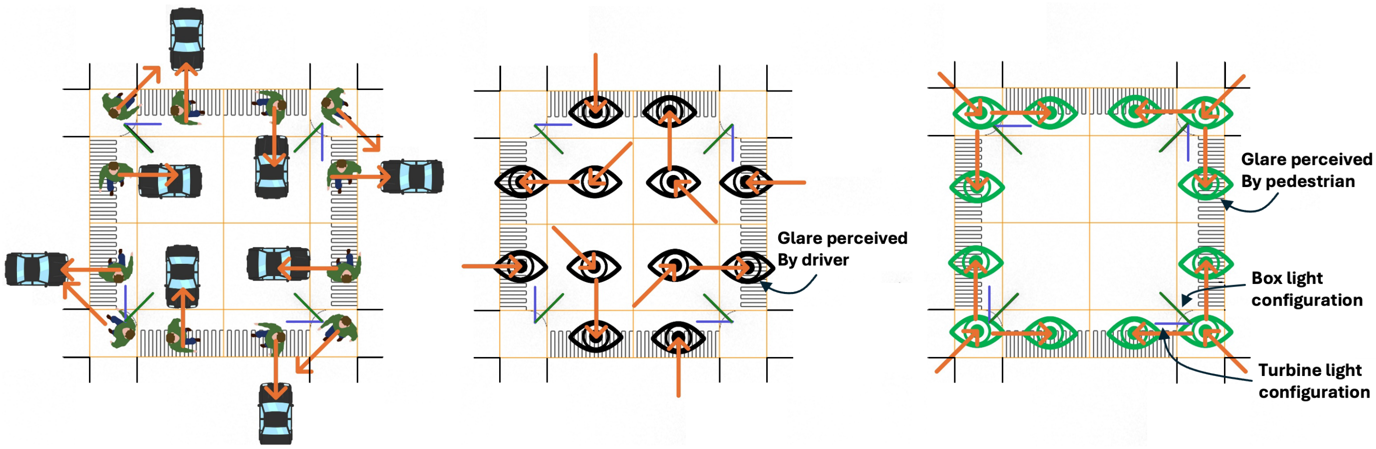
where $\overrightarrow{N}$ is the surface normal and $\overrightarrow{L}$ is the vector from light source to point, where the normal conventionally points outward from the surface (e.g., upward for E_h as seen in Figure 4). By default (although adjustable), illuminance is calculated at a height, $z = 1.5$ m, above the ground, following common lighting standards [4]. This height represents a compromise between pedestrian face visibility and a driver's line of sight, making it an effective proxy for evaluating how well a person can be seen in typical nighttime conditions.

2) Semi-Cylindrical Illumination: SALUSLux also supports the calculation of semi-cylindrical illuminance E_{sc}, which assesses pedestrian visibility from multiple angles. This is important in urban environments where observers—such as drivers—approach from a range of directions. `compute_illuminance_sc` estimates E_{sc} by averaging illuminance at a point from horizontal incident angles:

$$E_{sc}(\vec{N}) = \frac{1}{n} \sum_{i=1}^{n} E(\vec{D}_i) \tag{9}$$

where $\vec{D}_i$ is a set of rotated $\vec{N}$:

$$\vec{D}_i = \begin{bmatrix} \cos\alpha_i & -\sin\alpha_i \\ \sin\alpha_i & \cos\alpha_i \end{bmatrix} \begin{bmatrix} N_x \\ N_y \end{bmatrix} \tag{10}$$



(a) (b) (c)

Fig. 5: Illustration of the set of normal vectors for the calculation of (a) E_v and E_{sc}, (b) glare rating for drivers, GR, and (c) glare rating for pedestrians, GR_{ped}.

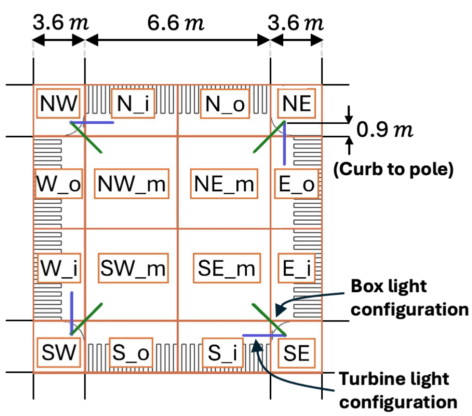


Fig. 6: Key intersection dimensions used in the case study, with surfaces labeled by cardinal directions (North: N, East: E, South: S, West: W) and suffixes _i (incoming), _o (outgoing), and _m (middle); the 45° box setup is shown in green and the 90° turbine setup in blue.

Here, N_x is the component of $\vec{N}$ in the x-direction and N_y is the component in the y-direction. By default, the angle set includes $\alpha_i = \{90°, -60°, -45°, -30°, 0°, 30°, 45°, 60°, 90°\}$, simulating light from various lateral directions. In our study we reduce this set to five representative angles, $\alpha_i = \{-90°, -45°, 0°, 45°, 90°\}$.

D. Computing Luminance

SALUSLux calculates luminance, a photometric quantity closely relating to how bright a surface appears to an observer. While illuminance measures how much light strikes a surface, luminance quantifies how much of the light is reflected.

Formally, luminance L is defined as the radiant intensity per unit projected area per unit solid angle:

$$L = \frac{d^2\Phi}{dA d\omega \cos(\theta)} \tag{11}$$

where $d^2\Phi$ is the differential luminous flux reflected from the surface, dA is the differential surface area, and $d\omega$ is the differential solid angle subtended by the observer's view. Since luminance depends on the reflective behavior of the surface, we adopt a Lambertian reflectance model. This assumes that surfaces (e.g., asphalt) reflect light uniformly in all directions, rather than like a mirror. To derive a practical expression for luminance under Lambertian reflection, the total flux Φ is obtained by integrating over the hemisphere and converting the integral into spherical coordinates:

$$\Phi = \int_0^{2\pi} \int_0^{\pi/2} L \cos(\theta) \sin(\theta) \, d\theta \, d\phi. \tag{12}$$

The azimuthal integral over ϕ gives a factor of 2π, while the polar integral simplifies to:

$$\int_0^{\pi/2} \cos(\theta) \sin(\theta) \, d\theta = \frac{1}{2} \tag{13}$$

Combining and solving for L gives $L = \frac{\Phi}{\pi}$. By substitution $\Phi = E\rho$, $L = \frac{E\rho}{\pi}$. This luminance value is used to assess glare. For typical asphalt road surfaces, a reflectance factor of 20% is the default [43].

E. Computing Glare Rating

Glare is a critical factor during the night, as excessive brightness can reduce visibility, cause discomfort, and obscure important pedestrian features. SALUSLux includes a `compute_glare_rating` function that implements the glare rating, GR, defined by the CIE standard [24]. The glare rating at a specific observer viewpoint and for a set of luminaires is computed as:

$$GR(\vec{N}) = 24 + 27 \log_{10} \left(\frac{L_{VL}}{L_{VE}^{0.9}} \right) \tag{14}$$

TABLE I: Lighting performance thresholds for safety and comfort.

Metric	Threshold	Threshold motivation
E_h	$> 24\ lux$	Based on the intersection road hierarchy, major-major requires 18–34 lux and collector-collector requires 12–24 lux [21]
E_v	$> 40\ lux$	30–40 lux vertical average across the center of crosswalk measured at < 2-m increments [4]
E_{sc}	$> 40\ lux$	Crosswalk lighting level of 40 vertical lux [4] and a ratio of $E_{sc}/E_v > 1$ is beneficial for facial recognition [44]
L	$> 2\ cd/m^2$	For high pedestrian activity (over 100 pedestrians per hour) [4]
GR (driver & pedestrian)	< 30	Glare is noticeable at $GR = 30$ [24]

L_{VL} is the veiling luminance on an observer's eye, which is also vertical illuminance at the observer's eye within the angular field q_i of 1.5° to 60° from the viewing direction:

$$L_{VL} = 10 \sum_i \frac{E_i(\vec{N_{q_i}})}{q_i^2} \tag{15}$$

and L_{VE} is environmental veiling luminance modeled as $L_{VE} = 0.035 L_{\text{average}}$. Here, L_{average} is the average luminance L within a default proximity of within a 1.8-m radius.

F. Intersection Simulation Setup

A key contribution is the development of the `intersect_simulation` function, which integrates all previously discussed components for evaluating pedestrian safety. While this function is demonstrated using a four-way intersection as a representative case, the underlying framework is fully generalizable, enabling the analysis of any street or lighting configuration. This intersection is a four-lane by four-lane intersection, representing a typical major-major road arterial intersection. While this configuration serves as the baseline case study, the framework is fully generalizable to any road classification or intersection geometry by redefining the input surface layout.

The simulation operates by systematically evaluating lighting performance across different configurations and design parameters, computing key metrics including: vertical and semi-cylindrical illuminance (E_v, and E_{sc}, respectively), luminance (L), and glare rating (GR). These metrics are computed across varying combinations of mounting height, pole offset, orientation, distribution type, color temperature, and power. The full process is outlined in Algorithm 1, which captures how each lighting scenario is simulated and assessed.

To evaluate pedestrian visibility, both vertical and semi-cylindrical illuminance are computed with directional vectors aligned to represent realistic observation angles. Specifically, for E_v, the normal vector is oriented along the direction of vehicle travel, simulating how a driver approaching or leaving an intersection would perceive a pedestrian. For E_{sc}, the simulation includes lateral views to account for turning movements—such as vehicles making left or right turns—which require side-angle visibility of pedestrians. These views are illustrated in Figure 5.

When computing GR, observer viewpoints are defined to match typical lines of sight for both pedestrians and drivers. The simulation assumes worst-case glare directions, capturing the most intense luminance observed along likely viewing paths. This ensures that the GR values are both conservative and relevant for design evaluation. These conventions also ensure consistency with the glare heatmaps presented later in the results section, so that the visualizations accurately reflect the modeled observer conditions. By automating the simulation across thousands of scenarios, this framework supports comprehensive evaluation of how intersection lighting design impacts pedestrian safety, visual comfort, and sustainability tradeoffs.

For each simulation scenario, SALUSLux generates a standardized set of visualization outputs, including: horizontal illuminance, vertical illuminance, semi-cylindrical illuminance, glare from any light source (general), glare experienced by drivers, glare experienced by pedestrians, and light trespass.

TABLE II: Maximum scores awarded to scenarios meeting criteria (before final normalization, which scales scores between 0-100).

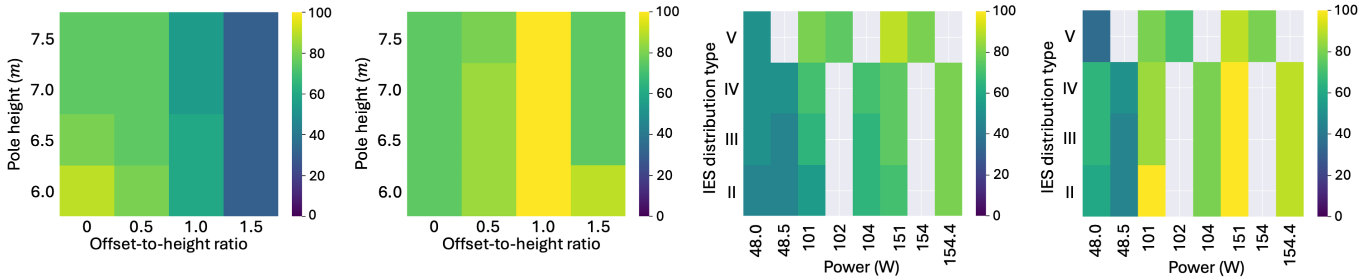
Area	E_h	E_v	E_{sc}	L	GR	GR_{ped}	Sum
NW_m	1	N/A	N/A	1	1	N/A	3
NE_m	1	N/A	N/A	1	1	N/A	3
SW_m	1	N/A	N/A	1	1	N/A	3
SE_m	1	N/A	N/A	1	1	N/A	3
NW	1	1	1	1	N/A	1	5
N_i	1	1	1	1	1	1	6
N_o	1	1	1	1	1	1	6
NE	1	1	1	1	N/A	1	5
E_i	1	1	1	1	1	1	6
E_o	1	1	1	1	1	1	6
SE	1	1	1	1	N/A	1	5
S_i	1	1	1	1	1	1	6
S_o	1	1	1	1	1	1	6
SW	1	1	1	1	N/A	1	5
W_i	1	1	1	1	1	1	6
W_o	1	1	1	1	1	1	6
Sum	16	12	12	16	12	12	80

TABLE III: Scenarios with 45° configuration and perfect scores.

Scenario	Height	Config.	Ratio	CCT	IES Type	Power	Score
372	6 m	45	1	4,000 K	II	151 W	100
378	6 m	45	1	4,000 K	III	151 W	100
384	6 m	45	1	4,000 K	IV	151 W	100
390	6 m	45	1	3,000 K	II	151 W	100
414	6 m	45	1	2,700 K	II	151 W	100

IV. Case Study: Exploring Internal and External Design Variation

To demonstrate the capabilities of SALUSLux and highlight its gains over existing software, we conducted a case study of a four-way intersection, simulating a wide range of lighting design scenarios. The parameters explored in this study fall into two categories: external parameters, which describe the



(a) (b) (c) (d)

Fig. 7: Heatmaps for finding the best scores for external variation for (a) 90°, (b) 45°, (c) internal variation for 90°, and (d) 45° configurations.

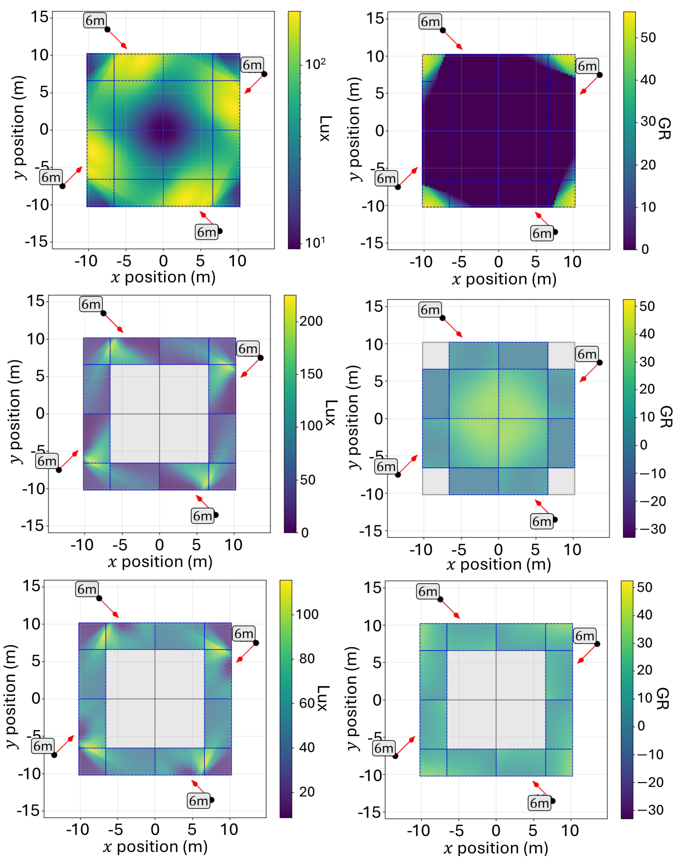


Fig. 8: Lighting performance of scenario 414, featuring a 45° configuration with an offset-to-height ratio of 1 and a 150W, 2700K LED achieving a final score of 100. Left column (top to bottom): horizontal (E_h), vertical (E_v), and semi-cylindrical (E_{sc}) illuminance. Right column (top to bottom): maximum glare rating, glare rating from the driver's perspective, and glare rating from the pedestrian's perspective.

physical layout and placement of the lighting system, and internal parameters, which define the properties of the luminaires themselves. The overall layout and surface designations used in the analysis are shown in Figure 6. A total of 2,304 lighting scenarios were evaluated (32 external configurations and 72 internal configurations), as described below.

A. Simulation Parameters and Setup

For external variation, we evaluated two light configurations: diagonal (45°) (box configuration) and perpendicular (90°) (turbine configuration). For each configuration, four pole offsets were tested (`offset_to _height`, as shown in Figure 1), defined as the ratio of the horizontal offset distance from the crosswalk corner to the pole height (×0, ×0.5, ×1, and ×1.5). Note that the luminaire is also offset from the pole by a fixed distance. Each configuration was tested at four different pole heights (6 m, 6.5 m, 7 m, and 7.5 m). The set of 4 heights was then multiplied by 4 values of the offset ratio of horizontal offset to pole height (16 offsets in total)

For internal variation, lighting properties were varied across two luminaire brands, referred to as Manufacturer 1 and Manufacturer 2, four IES distribution types (Type II, III, IV, and V), three power levels (50 W, 100 W, and 150 W), and three color temperatures (2,700 K, 3,000 K, and 4,000 K). While power values are nominal values, consumption may differ based on manufacturer specifications (e.g., a 100-W LED may consume 104.5-W). These parameters were picked based on market availability, incorporating 32 IES photometric files split between the two lighting manufacturers.

B. Representative Scoring

To evaluate and rank all lighting scenarios, we draw on performance thresholds for each metric drawn from the literature (Table I). In Table I, major-major refers to an intersection where two major roads (arterial) cross, and collector-collector refers to an intersection where two collector roads meet.

For every surface (Figure 6) where a metric meets or exceeds its threshold, a binary score of 1 is assigned; surfaces where the metric falls below the threshold receive a score of 0. Certain metrics are marked as "not applicable" (N/A) on surfaces where the measurement is irrelevant—notably, the four middle sidewalk areas (NW_m, NE_m, SW_m, SE_m), where metrics like vertical and semi-cylindrical illuminance cannot be meaningfully calculated due to the absence of a pedestrian. These scoring exclusions are summarized in Table II. After accounting for these cases, there are 80 applicable metric-surface combinations per scenario. The sum of all binary scores is then normalized to a scale of 0–100, where

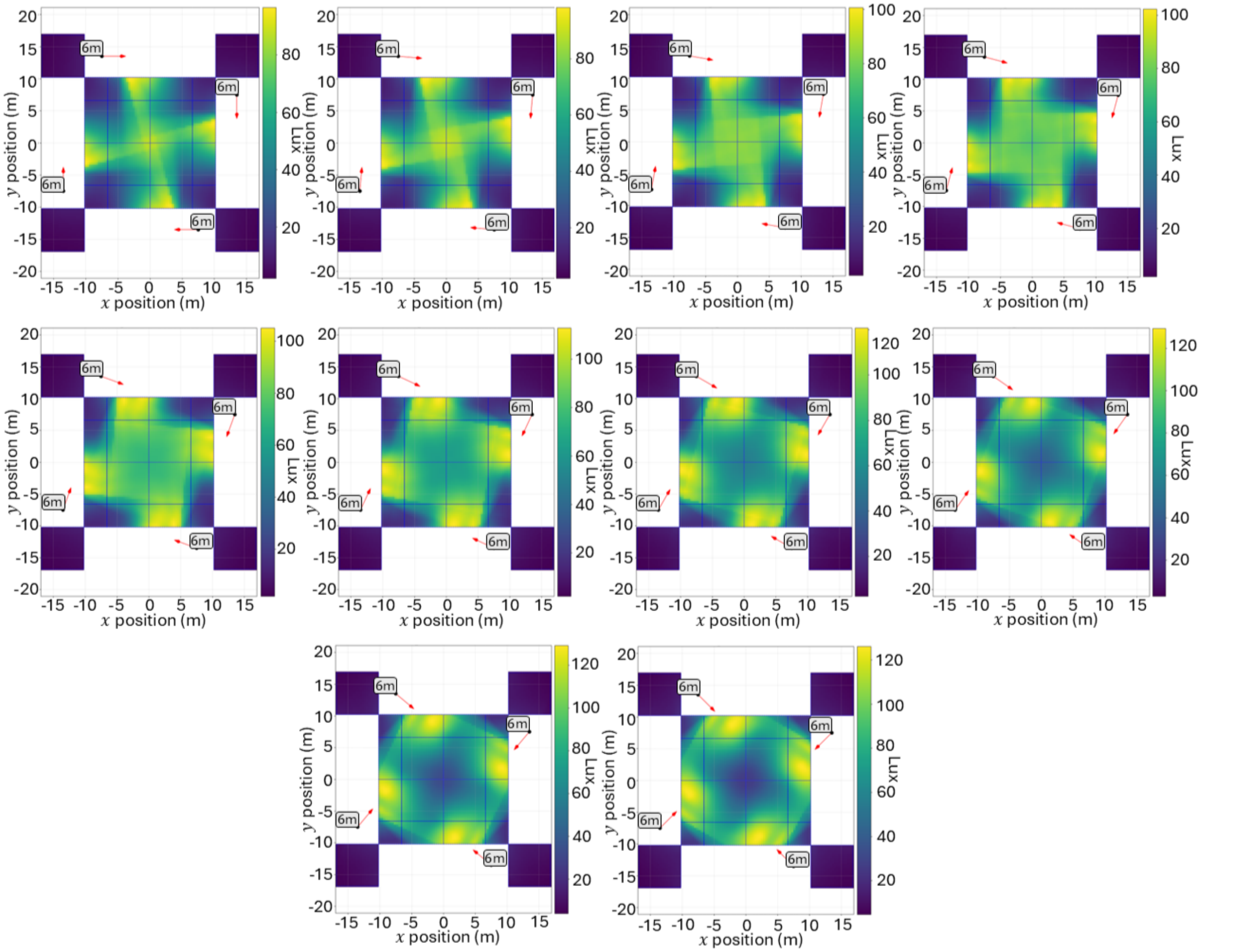


Fig. 9: Heatmaps of horizontal illuminance with four adjacent areas to assess light trespass. From left to right: (Top) 90°, 85°, 80°, 75°; (Middle) 70°, 65°, 60°, 55°; (Bottom) 50°, 45°.

a score of 100 represents a perfect result across all applicable metric-surface combinations. This allows the scoring system to remain consistent even if users consider additional constraints not already considered as thresholds in Table I. The scores awarded to each scenario can be adjusted by the user to prioritize different objectives (e.g., pedestrian safety, light pollution minimization). The preference values selected for this case study are illustrative.

C. Exploring Internal and External Variation

We began by identifying the highest-scoring configurations for the 90° and 45° setups, which are standrad configurations in practice. SALUSLux supports design exploration between these box and turbine setups. Interestingly, pole height exhibited a reverse effect on performance in the 90° configuration—higher poles led to lower scores—while it had minimal impact on the 45°. Similarly, increasing the horizontal offset (`offset_to_z`) generally degraded lighting performance in the 90° configuration. These effects are illustrated in Figure 7.

For the 90° turbine configuration, the top-performing scenarios featured an IES Type V distribution paired with an LED luminaire consuming approximately 151 W. In contrast, the 45° configuration achieved perfect scores using Type II, III, or IV distributions with the same power. Type II, in particular, performed well even at slightly lower powers around 101 W. Notably, a 2700 K color temperature—aligned with DarkSky best practices—still yielded a perfect full score when combined with a Type II distribution and 150 W power level. This scenario represents an ideal balance between pedestrian safety and light pollution mitigation, as visualized in Figure 8.

The three power levels evaluated (50 W, 100 W, and 150 W) represent the commercially available options from the manufacturers' catalogs for the selected luminaire models and are not intended to imply that 150 W is the expected or recommended choice for this intersection type. While energy consumption is not analyzed as a standalone parameter in this study, it is fully within SALUSLux's existing capabilities to incorporate power as a design constraint (or other constraints).

Just as the scoring framework in Table I applies thresholds for photometric performance metrics, a maximum power threshold can be applied in the same way to support multi-criteria decision making that jointly considers safety, comfort, and energy use. Users who wish to restrict results to lower-power configurations can do so directly from the heatmaps in Figure 7, where well-performing designs at 100 W and below are readily identifiable. More broadly, the power levels and luminaire models used here are illustrative; designers are free to update the luminaire catalog with any commercially available selection to reflect their specific project constraints or sustainability objectives.

V. Case Study: Contextual Factors

While scenario 414 (along with other top-scoring designs shown in Table III) satisfy all performance criteria, two key real-world contextual conditions remain unaccounted for.

First, box-style configurations—especially those with pole offsets—can effectively illuminate pedestrians approaching a crosswalk from the incoming direction. However, the light distribution is still constrained by right-of-way boundaries, such as the edges of the street and sidewalks. In the 45° box configuration using a Type II luminaire, some of the emitted light extends beyond the defined evaluation surfaces and reaches adjacent buildings. This effect is known as light trespass. Second, many cities use LPIs, a "head-start" signal strategy that allows pedestrians to begin crossing before vehicles receive a green light. LPIs change when—and where—pedestrians are visible relative to moving traffic. These two contextual considerations—light trespass and LPIs—are explored in this section to demonstrate how SALUSLux can support future standardization in both areas.

A. Light Trespass

1) Current Trespass Standards: Light trespass is typically regulated using fixed maximum vertical illuminance limits measured at property lines or residential windows. Many cities adopt values directly from the IES Model Lighting Ordinance (MLO), which prescribes uniform caps ranging from 0.5 lux to 8 lux depending on the environmental lighting zone [45], regardless of roadway geometry or pedestrian activity. For example, Chicago's municipal code limits light trespass to 0.5 lux of vertical illuminance for most types of streets, and requires that a light shield be placed to cut off light trespass at approximately one mounting height behind the pole [46]. New Mexico, United States, enforces the Night Sky Protection Act, which requires all outdoor lighting fixtures to be shielded, with the exception of those lower than 150 W for incandescent fixtures and 70 W for other sources [47].

2) Intersection Light Trespass: Based on the best design scenario that we previously found, the beam spread from placing the light at a non-90° angle could trespass on private property. In this section, the scenario from the previous case study is modified to have multiple angles between 45° and 90° (at increments of 5 degrees). Aside from the configuration (i.e., turning the pole orientations), we keep all other variables fixed to remain consistent with the previous scenario. As a reminder, the pole height is 6 m, the offset is 6 m, and the luminaire IES file is `Copper ARCH-M-PA2-150-727-U-T2R.ies`.

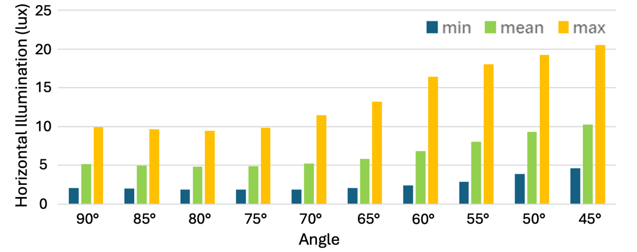
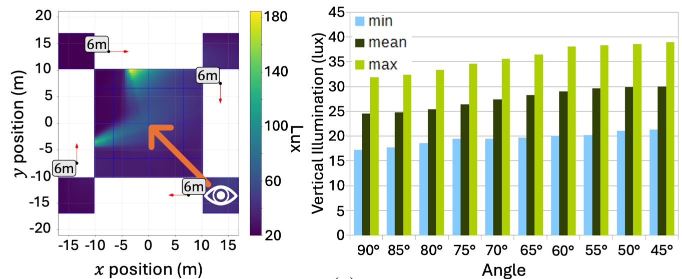
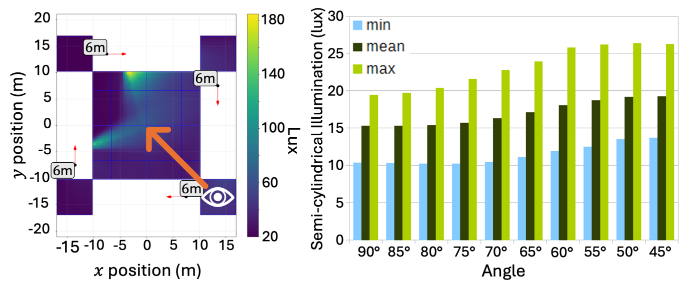


Fig. 10: Horizontal illumination on the adjacent land of the right of way for each turning angle.



(a)



(b)

Fig. 11: (a) Vertical and (b) semi-cylindrical illumination on the land adjacent to the right of way for each turning angle.

We first set up the study for horizontal illuminance, then later for vertical and semi-cylindrical illuminance. Representative calculation surfaces are defined as seen in Figure 9. As hypothesized, there is an increase in horizontal light trespassing in the corner lands as the light turns from 90° to 45°, with a maximum of 20 lux for the 45°, illustrated in Figure 10.

For vertical and semi-cylindrical illuminance, we selected a representative direction of a person standing on the southeast (SE) area looking to the northwest (NW) direction (Figure 6). The maximum reading is still at 45°, with 39 lux vertical and 26 lux in the semi-cylindrical directions, shown in Figure 11. We note that this level of trespass is also not ideal for the 90° angle, meaning that the problem of trespass would still exist even if we returned to the traditional design. Moreover, if one observes from different directions, light trespass is found to be able to hit minimum 0 lux.

Although existing standards aim to reduce nuisance glare and protect residential areas, they rely on static point measurements and often assume a one-size-fits-all solution. As a result, they overlook intersection-specific factors such as crosswalk placement, pedestrian approach angles, and the directional light distribution of luminaires. Our preliminary light-trespass studies suggest that SALUSLux can support the development of intersection-specific trespass standards that are integrated into lighting design and distinct from right-of-way segment standards.

B. Leading Pedestrians Intervals to Improve Safety

Independent of lighting infrastructure, research has shown that the implementation of an LPI significantly enhances safety by reducing vehicle-pedestrian conflicts by approximately 42% [48]. While LPI is traditionally viewed as a head-start mechanism to establish right-of-way, its role in nighttime visibility is critical. At night, LPI increases visibility by allowing pedestrians to move from the relatively dark curb into the lighting area of the intersection before vehicles are permitted to turn.

Generally, an LPI lets pedestrians start crossing 3 s to 7 s before vehicles get a green light [49]. As shown in Figure 12, this is already a solid practice because peak semi-cyllindrical illumination for incoming traffic happens around 2 s to 3 s for our case study, while semi-cylindrical illumination on the outgoing side stays relatively steady. For pedestrians coming from the outgoing side, who could face conflicts with turning vehicles, it is ideal to give them enough time to reach the peak illuminance on the other side, which is about 7 s (Figure 12). As for illuminance, though we established our metrics in Table I, we pick the non-satisfactory lighting condition (Lumec RoadScape LED ComfortEdge 50 W Type II) to best illustrate that even with an intersection design that deviates from our recommendations in Section IV, even the most dangerous intersections can still gain benefits from LPI. Therefore, at a walking speed of 1.4 m/s, SALUSLux indicates that an LPI of 3 s to 7 s is ideal. The amount of semi-cylindrical illumination for the LPI design could also be lower—as this is a concern of turning conflict—and even at an absolute minimum of 0.6 lux, basic facial recognition is possible at a distance of 4 m [44].

VI. Discussion

This study demonstrates that pedestrian-centered intersection lighting performance is governed not by any single design parameter, but by strong interaction effects between spatial geometry (external configuration) and luminaire properties (internal characteristics). By simulating more than 2,000 multidirectional lighting scenarios, the results reveal how common assumptions embedded in current practice—particularly the use of static thresholds and roadway-centric metrics—can obscure meaningful performance differences at intersections. The findings have direct implications for lighting design practice, policy, and standards development, particularly as cities seek solutions that balance safety, energy efficiency, and environmental responsibility.

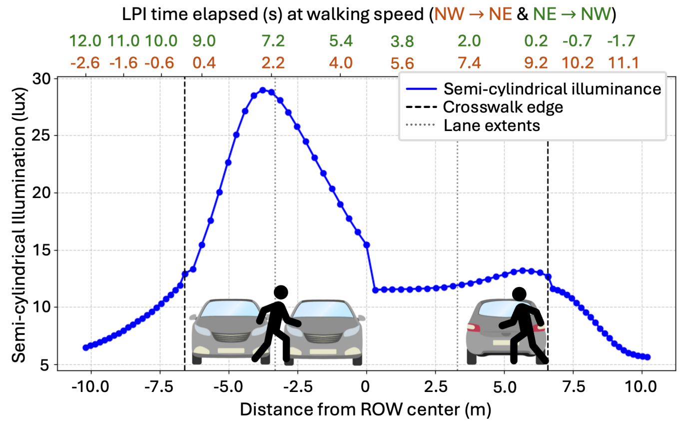


Fig. 12: Pedestrian position and semi-cylindrical illuminance along the crossing.

A. Geometry-Luminaire Interaction Effects at Intersections

A central finding of this work is that external geometry substantially modulates how luminaire properties translate into real-world performance. The 90° turbine configuration exhibited pronounced sensitivity to both pole height and horizontal offset. As mounting height increased or poles were placed farther from the intersection corner, overall performance consistently declined. This behavior likely reflects a reduction in near-field illuminance and increased glare potential as light is projected from higher elevations and less favorable angles, diminishing pedestrian visibility in the crosswalk approach zone.

In contrast, the 45° box configuration proved substantially more robust. Performance remained relatively stable across variations in pole height and offset, suggesting that this geometry distributes light more effectively across pedestrian-facing directions. Intuitively, the 45° orientation better serves the multi-directional viewing conditions that characterize intersections, including pedestrians approaching from different angles and drivers executing turning maneuvers. These results underscore that intersection lighting should not be treated as a simple extension of roadway lighting geometry; instead, the spatial logic of intersections demands distinct design considerations.

B. Implications of Luminaire Distribution, Power, and Color Temperature

Across geometric configurations, the simulations revealed that luminaire distribution type plays a critical role in achieving balanced performance. Among existing options, the IES Type II distribution consistently offered the strongest overall performance, particularly when paired with moderate-to-high power LED luminaires. In the 45° configuration, multiple distribution types (Type II, III, and IV) were capable of achieving top scores at higher powers, but Type II stood out for its efficiency, achieving equivalent performance at lower power levels.

Importantly, the results challenge the widespread assumption that higher color temperatures are necessary to ensure pedestrian safety. Environmentally sensitive designs using

2,700K luminaires—aligned with DarkSky best practices—were able to meet or exceed all performance thresholds when combined with appropriate distribution and power levels. This finding directly contradicts the perceived tradeoff between pedestrian safety and sustainability. In the context of intersections, warm-color lighting does not inherently compromise visibility or glare control when spatial and photometric factors are properly aligned.

At the same time, these findings should not be overgeneralized to continuous roadway segments. While lower mounting heights and intersection-focused distributions perform well in localized contexts, such configurations may be insufficient for extended roadways without additional luminaires. This distinction reinforces the need to decouple intersection lighting criteria from roadway lighting criteria, enabling context-specific solutions rather than one-size-fits-all standards.

C. Rethinking Performance Metrics for Intersection Lighting

Among all evaluated criteria, semi-cylindrical illuminance emerged as the most difficult metric to satisfy consistently. This result is significant. Unlike vertical illuminance, which evaluates light incident on a single plane, semi-cylindrical illuminance captures visibility from multiple directions simultaneously, better reflecting how pedestrians are perceived by drivers approaching from oblique angles. At intersections—where turning vehicles encounter pedestrians from the side—this three-dimensional visibility is critical.

The results reinforce growing evidence that semi-cylindrical illuminance should be prioritized as a required metric for crosswalk lighting at intersections. Conversely, horizontal illuminance offered limited additional insight once other metrics were satisfied. Overreliance on horizontal illuminance risks encouraging excessive lighting levels, which may increase glare and light pollution without improving pedestrian safety. These findings suggest that future lighting standards should shift emphasis toward metrics directly tied to human perception and comfort rather than default roadway-centric measures.

D. Toward Orientation-Aware Light Trespass Standards

The analysis of light trespass further highlights limitations in current regulatory approaches. Existing standards typically rely on fixed vertical illuminance caps applied uniformly across all directions. However, the simulations show that perceived trespass is inherently orientation-dependent. Light projected toward building façades and windows has a far greater impact on occupants than light emitted in directions that do not intersect occupied spaces.

This opens the door to two key advancements. First, trespass limits should be weighted by orientation rather than applied uniformly. Directions aligned with nearby windows should carry the greatest weight, while higher light levels may be acceptable in directions that improve pedestrian safety without affecting building interiors. Second, trespass assessment should transition from vertical illuminance to semi-cylindrical illuminance, which better captures observation from multiple directions. Together, these shifts would allow regulations to better align environmental protection with safety outcomes.

E. Adoption and Extensibility

To support reproducibility and community extension, SALUSLux is released as an open-source Python package under the permissive Apache 2.0 license. This positioning enables SALUSLux to function as a backend for custom tools and evaluation pipelines, and it also creates a pathway for future integration with IoT-enabled sensing and control—e.g., using measured environmental conditions that affect surface reflectance (such as wet pavement) to inform simulation inputs or adaptive lighting strategies.

F. Recommendations

Based on the findings of this study, we propose the following recommendations for future research, practice, and standards development:

- Future work should incorporate variability in surface reflectance and operating conditions (e.g., wet pavement, concrete versus asphalt, textured surfaces, weather, and pedestrian clothing), potentially informed by real-time or near–real-time data from IoT-enabled environmental and infrastructure sensors, to better predict luminance and visibility under real-world conditions.
- Future extensions to SALUSLux should move beyond the standard glare rating formulation by incorporating empirically grounded models of perceived glare that account for factors such as age, visual adaptation, and competing stimuli in complex nighttime environments.
- Standards bodies and luminaire manufacturers should consider developing an intersection-specific photometric distribution combining Type II and Type IV that targets pedestrian activity zones and turning-vehicle approach angles more efficiently than current roadway-centric IES distributions, reducing wasted light, energy use, and spill while preserving glare control and DarkSky objectives.

VII. Conclusion

This study highlights the critical role of street lighting in enhancing pedestrian safety. Through the development and application of SALUSLux, we demonstrated the feasibility of evaluating thousands of lighting configurations using standard IES photometric data without reliance on proprietary software or fixed graphical workflows.. In a case study involving a four-way intersection, SALUSLux simulated 2,304 scenarios, revealing that a 2700K Type II luminaire in a 45° turbine configuration achieved an optimal balance between pedestrian visibility with DarkSky principles.

Beyond identifying high-performing configurations, the results expose a more fundamental limitation: existing IES distribution types are not optimized for intersection lighting. In many cases, only a portion of the luminaire's beam meaningfully contributes to pedestrian illumination, while the remainder is directed along roadway segments where it provides limited safety benefit and increases the risk of light trespass.

This inefficiency motivates the development of intersection-specific photometric distributions—such as the proposed hybrid approach and the conceptual Type VII distribution that combines Type II and Type IV—that reallocate luminous intensity toward pedestrian conflict zones.

By offering an open-source, extensible Python framework, SALUSLux enables researchers, designers, and agencies to move beyond static compliance checks toward context-aware, performance-driven lighting design. The framework can readily incorporate additional evaluation surfaces, regulatory constraints, adaptive controls, or integration with traffic operations and smart-city systems. More broadly, this work illustrates how computational methods can reconcile pedestrian safety objectives with sustainability goals, supporting evidence-based lighting policies that respond to the spatial and perceptual realities of urban intersections.

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CRediT Authorship Statement

[Redacted for Double Blind Review]: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing - original draft; [Redacted for Double Blind Review]: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Visualization, Writing - original draft, Writing - review and editing; [Redacted for Double Blind Review]: Conceptualization, Investigation.

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