

Reflected solar glare from building facades: A critical review of assessment methodologies

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ABSTRACT

The increasing prevalence of high-rise buildings with reflective facades in urban environments has intensified reflected sunlight glare, leading to visual discomfort, health risks, and property damage. Despite these growing concerns, standardized regulations and evaluation methods for building facades remain lacking. This paper comprehensively reviews existing research on glare evaluation for reflected sunlight from building facades, identifying trends, limitations, and future directions. Studies are categorized into measurement, simulation, and integrated approaches. Although measurement-based studies using field surveys and high dynamic range imaging offer empirical insights, they often lack standardized quantitative evaluation or human perception-based glare indices. Simulation-based studies employ geometric- and radiance-based methods to predict glare patterns; however, they frequently exclude human-centered metrics, lack established standards, and rarely validate perceptual data. Integrated approaches combine both, improving reliability; however, they are limited to consistently applying perception-based glare indices and conducting user-based validations. In conclusion, there is a critical need for developing standardized methodologies for glare assessment, including the consistent application of discomfort glare indices (e.g., daylight glare probability and unified glare rating), integration of user-centered validation, and development of standardized simulation protocols. Future research should prioritize comprehensive frameworks that combine physical and perceptual factors for accurate and reliable assessments to improve building design and urban planning.

1. Introduction

In recent years, the increasing population density in urban areas had led to a steady increase in the construction of high-rise buildings [1]. Architects frequently use materials such as glass facades or curtain walls to enhance the aesthetic appeal of such buildings [2]. However, these highly reflective surfaces reflect sunlight at various angles, potentially causing issues such as glare and thermal effects on the surrounding buildings and environment [3,4]. Representative examples include the Vdara Hotel in Las Vegas, where the reflective facade of the building concentrates sunlight and results in severe glare and burns [5]; the Walkie Talkie Building in London, which reflects sunlight to the streets below, causing discomfort to pedestrians and damage to vehicles,

including melted car parts [6]; and the curved metal facade of the Walt Disney Concert Hall in Los Angeles, which concentrates sunlight and causes significant visual discomfort because of the glare and even leads to the melting of the surrounding asphalt pavement [7,8]. In addition, other cases of damage caused by light reflected from building facades have been reported, including the Museum Tower in Dallas, the Shard in London, and the International Commerce Centre Tower in Hong Kong [2]. These cases demonstrate that sunlight reflected from building facades can cause severe glare, resulting in significant discomfort to nearby residents and pedestrians and posing risks to health and property. Therefore, solutions are required to address the challenges associated with reflected glare.

Glare is a critical element that significantly affects visual comfort

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experienced within a building [9]. It can impair vision and lead to either significant discomfort or mild irritation [10]. According to the *IESNA Lighting Handbook*, glare is defined as “the sensation produced by luminance within the visual field that is sufficiently greater than the luminance to which the eyes are adapted, causing annoyance, discomfort, or loss in visual performance and visibility” [11]. According to the *International Lighting Vocabulary*, discomfort glare is described as “glare that causes discomfort without necessarily impairing the vision of objects,” while disability glare is defined as “glare that impairs the vision of objects without necessarily causing discomfort” [12]. Such glare is a subjective phenomenon based on individual perceptions, making it challenging to achieve an accurate evaluation [13]. Furthermore, reflected glare complicates the problem because of the difficulty in predicting the direction and intensity of reflected sunlight on building facades.

Several countries have established regulations to address glare caused by reflective building materials and prioritize public safety and comfort in urban environments. In the United States, cities such as Long Beach, Salinas, and Dallas, as well as Los Angeles County, have implemented specific measures to limit reflected glare. For example, Long Beach prohibits reflective roofing and siding in residential zones and requires permits for exterior remodeling with glazing that exceeds 15 % reflectance, whereas commercial zones restrict ground-floor windows to a maximum reflectance of 8 % [14]. In Los Angeles County, reflective, glossy, or polished metal siding and roofing are prohibited, and all windows must use nonglare, nonreflective glass [15]. Similarly, Salinas restricted the use of mirrors or highly reflective glass and prohibited the use of highly reflective materials and metal or plastic siding in commercial districts [16]. Further, Dallas imposed reflectance limits on glass used for facades, classifying materials with a reflectance above 27 % as highly reflective and subject to restrictions [17]. Cities such as Sydney and Melbourne limit facade material reflectance to 20 % to reduce reflected glare and ensure safety for pedestrians, drivers, and nearby residents [18,19]. Sydney requires reflectance reports for high-rise buildings and those near major roads or Sydney Airport to demonstrate compliance [18]. In Singapore, building surfaces, including roofs, must be designed to prevent sunlight reflection from affecting the amenities of neighboring buildings [20]. Hong Kong prohibits the use of glass with an external reflectance exceeding 20 % on building exteriors to control visual glare [21]. These regulations highlight the increasing effort to mitigate the impacts of reflected sunlight from building facades on urban environments. However, limiting material reflectance alone may be insufficient, as even materials within the allowed reflectance thresholds can cause significant glare depending on factors such as facade geometry, building orientation, seasonal sun angles, and surrounding context [22].

Indoor glare assessment has been extensively studied for a long time in architectural environments [23]. To date, research has focused on glare assessments in artificial lighting and daylight environments, presenting various evaluation metrics and methodologies to address this issue [13,24]. However, glare from sunlight reflected by neighboring building facades can adversely affect indoor environments by causing visual discomfort and reducing occupant comfort and productivity. Despite the increasing attention paid to the glare caused by sunlight reflected from building facades, clear regulations and evaluation methodologies for this issue remain lacking [22]. In addition, specific discussions on assessing the indoor glare caused by sunlight reflected from building facades and a comprehensive literature review on this issue remain lacking. Therefore, this study aims to comprehensively analyze existing research on glare evaluation methods for sunlight reflected from building facades and identify trends and limitations in related studies. This analysis highlights the necessity of a glare evaluation methodology that considers the characteristics of sunlight reflected from building facades and discusses future research directions.

2. Review methodology

In this study, a comprehensive literature review was conducted to assess glare and studies related to reflected glare under indoor daylight conditions. The review focuses on the methods and procedures used to evaluate and predict the reflected glare. The objectives of this study are to (1) summarize the development and performance of existing glare indices, (2) review the methods and procedures used to measure reflected glare, (3) summarize the simulation techniques and processes used to predict and assess reflected glare, and (4) propose future research directions and the potential significance of further studies for developing methodologies to predict and assess reflected glare.

This review was conducted following established best-practice guidelines for systematic and narrative reviews proposed by Siddaway et al. [25], Dhillon [26], and Baker [27], emphasizing transparency, reproducibility, and critical synthesis. The procedure comprised four main stages: (1) identification of literature, (2) screening and eligibility assessment, (3) data extraction and categorization, and (4) critical synthesis and gap analysis.

A comprehensive search was conducted using Scopus, Web of Science, ScienceDirect, and Google Scholar, covering publications from 1980 to 2025. The following Boolean combinations of keywords were applied: (“reflected glare” OR “reflected sunlight”) AND (“building facade” OR “curtain wall”) AND (“glare” OR “visual comfort” OR “visual discomfort”). Reference lists of the selected papers were further examined through backward and forward snowballing to ensure comprehensive coverage.

Studies were included if they met all of the following criteria: (a) peer-reviewed journal or conference papers directly addressing glare caused by reflected sunlight from building facades; (b) use of measurement, simulation, or integrated approaches for glare evaluation; and (c) provision of quantitative or qualitative data on visual discomfort or luminance characteristics.

Studies were excluded if they were review articles without empirical content, non-scientific reports, patents, or architectural design guidelines lacking analytical data. Two reviewers independently screened the abstracts and full texts, and any discrepancies were resolved through discussion to enhance reliability. All 37 studies reviewed in this paper were published in peer-reviewed journals or international conference proceedings indexed in Scopus and Web of Science, with no non-refereed sources included.

The remainder of this paper is organized as follows: [Section 3](#) summarizes the development and performance of glare indices relevant to glare assessment in building and daylighting studies. [Section 4](#) reviews the measurement-based methods used to evaluate reflected glare. [Section 5](#) examines the simulation-based approaches for predicting and assessing reflected glare. [Section 6](#) integrates measurement and simulation studies, highlighting their combined applications and limitations. Finally, [Section 7](#) presents the discussion and conclusions of the study.

3. Discomfort glare indices

Several indicators have been developed to predict and evaluate the glare. Discomfort glare can be attributed to a high luminance contrast between the glare source and adaptation level, referred to as “contrast glare” or “relative glare,” and an excessive amount of light reaching the occupant’s eyes, which is referred to as “saturation glare” or “absolute glare” [24]. Discomfort glare indices are influenced by the following four variables: glare source luminance, solid angle, position index, and adaptation level [28]. However, identifying independent standardized indicators for glare evaluation remains challenging because of the lack of a sufficient understanding of uncomfortable glare [29].

This section summarizes the key aspects and functions of discomfort glare indices used in glare assessment and reviews how these indices are applied in studies related to reflected sunlight. This review is important because discomfort glare indices provide a foundation for understanding

and quantifying visual discomfort caused by reflected sunlight, which is essential for evaluating the effect of reflected glare from building facades.

Although these indices were originally developed for controlled indoor lighting conditions, they provide valuable conceptual insight into how luminance contrast and visual adaptation influence perceived discomfort. In the context of reflected solar glare from building facades, it is not appropriate to apply these indices directly, as the outdoor luminance distribution, solar geometry, and reflection dynamics differ significantly from indoor environments. Therefore, the following section does not aim to transfer indoor models to outdoor conditions, but rather to identify theoretical principles that can guide the development of new, reflection-specific evaluation methods.

Indoor glare indices were developed from photometric measurements correlated with human subjective responses in controlled laboratory conditions. The present study does not attempt to replicate or directly adapt these calibration procedures to outdoor contexts. Instead, it highlights the need for future outdoor-specific studies to establish new perceptual datasets that consider dynamic luminance distributions, solar position, and surface reflectance characteristics unique to outdoor environments.

3.1. British glare index (BGI)

$$BGI = 10 \log_{10} \left[0.478 \sum_{i=1}^n \left(\frac{L_{s,i}^{1.6} \cdot \omega_{s,i}^{0.8}}{L_b \cdot P_i^{1.6}} \right) \right] \quad (1)$$

The British Glare Index (BGI) is among the earliest quantitative metrics developed to assess glare discomfort in environments illuminated by small artificial light sources [30]. Introduced in the 1950s, BGI laid the conceptual foundation for many subsequent glare indices. It was designed for use in uniform indoor settings and is therefore not suitable for evaluating the glare produced by large, non-uniform natural light sources such as windows [31]. Despite this limitation, BGI played a pivotal role in shaping early lighting standards and informed the development of later indices, including the Illuminating Engineering Society (IES) glare index (GI), which extended the original BGI formulation to accommodate arrays of luminaires [32].

3.2. Visual comfort probability (VCP)

$$VCP = \frac{100}{\sqrt{2\pi}} \int_{-\infty}^{6.374 - 1.3227 \ln(DGR)} \exp(-t^2/2) dt \quad (2)$$

The Visual Comfort Probability (VCP) was originally developed by Guth to assess discomfort glare under controlled experimental conditions involving uniformly luminous light sources of standard size [33]. It was designed for use with ceiling-mounted luminaires that provide a uniform luminance distribution. According to previous studies, the VCP is not suitable for evaluating glare under daylight conditions and tends to report higher glare levels compared to other glare indices [23,29].

3.3. Discomfort glare index (DGI)

$$DGI = 10 \log_{10} \left[0.478 \sum_{i=1}^n \left(\frac{L_{s,i}^{1.6} \cdot \omega_{s,i}^{0.8}}{L_b + 0.07 \omega^{0.5} \cdot L_{win} \cdot P_i^{1.6}} \right) \right] \quad (3)$$

The Discomfort Glare Index (DGI) is a widely used metric developed to assess discomfort glare, particularly in spaces dominated by daylight or large-area light sources such as windows [10]. The DGI formula incorporates the luminance and solid angle of each glare source, the background luminance, and a position index, allowing it to account for both the intensity and size of glare sources relative to the observer's field

of view [34]. Therefore, DGI is well suited for evaluating glare in architectural environments where daylight plays a significant role. However, it is considered unreliable in situations where direct sunlight or specular reflections are present [35]. Previous studies have also indicated that in brightly lit environments, DGI may fail to detect glare even in the presence of direct sunlight, and no clear correlation has been found between DGI values and subjective glare perception [36].

3.4. CIE glare index (CGI)

$$CGI = 8 \log_{10} \left[2 \frac{1 + \left(\frac{E_d}{500} \right)}{E_d + E_i} \sum_{i=1}^n \left(\frac{L_{s,i}^2 \cdot \omega_{s,i}}{P_i^2} \right) \right] \quad (4)$$

The CIE Glare Index (CGI) is one of the earliest standardized metrics developed by the International Commission on Illumination (CIE) to evaluate discomfort glare in indoor environments [37]. The CGI was the first glare index to use vertical illuminance at eye level as the basis for visual adaptation, rather than relying on background luminance. The CGI is particularly appropriate for artificial lighting conditions involving multiple small to medium-sized luminaires, such as those commonly used in office settings. Therefore, CGI is not suitable for evaluating glare in daylight environments, and previous studies have shown that it tends to report significantly higher glare levels compared to other indices [23, 35].

3.5. Unified glare rating (UGR)

$$UGR = 8 \log_{10} \left[\frac{0.25}{L_b} \sum_{i=1}^n \left(\frac{L_{s,i}^2 \cdot \omega_{s,i}}{P_i^2} \right) \right] \quad (5)$$

The Unified Glare Rating (UGR) is a metric developed by the CIE to quantify discomfort glare in indoor lighting systems [38]. It was introduced to simplify the computational process associated with the CGI. UGR performs well when evaluating glare from small glare sources, making it more suitable for artificial lighting conditions than for large-area light sources such as windows or curtain walls [31]. According to previous studies, UGR provides reasonable accuracy for perceptible and disturbing levels of glare. However, its reliability decreases in environments with severe glare, direct sunlight, or high luminance contrast [39,40].

3.6. Daylight glare probability (DGP)

$$DGP = 5.87 \cdot 10^{-5} E_v + 0.0918 \cdot \log_{10} \left[1 + \sum_{i=1}^n \left(\frac{L_{s,i}^2 \cdot \omega_{s,i}}{E_v^{1.87} \cdot P_i^2} \right) \right] + 0.16 \quad (6)$$

The Daylight Glare Probability (DGP) is a widely adopted glare index specifically developed to assess discomfort glare under daylight conditions. Wienold and Christoffersen introduced a novel approach that measured glare based on the probability of disturbance rather than the absolute magnitude of the glare source, aiming to overcome the limitations of conventional indices [41]. A key feature of DGP is its consideration of vertical illuminance at the eye, which reflects the human visual adaptation to daylight. According to several cross-validation studies, DGP has been identified as the most robust and accurate glare index, particularly in environments dominated by daylight [42]. It shows strong agreement with subjective glare perception and has demonstrated superior performance compared to other existing glare indices in both laboratory and field studies [43,44].

3.7. Simplified daylight glare probability (DGPs)

$$\text{DGPs} = 6.22 \cdot 10^{-5} E_v + 0.184 \quad (7)$$

The Simplified Daylight Glare Probability (DGPs) is a reduced-complexity index designed to estimate discomfort glare in daylight environments, providing a practical alternative to the computationally intensive full DGP model [45]. Unlike the conventional DGP, which requires detailed luminance mapping and high dynamic range (HDR) imaging, DGPs relies solely on vertical eye illuminance (E_v), making it suitable for rapid annual and spatial glare assessments in architectural simulations. However, the authors emphasized that DGPs should only be applied in conditions where direct sunlight or reflected light does not fall within the observer's field of view, due to the omission of the contrast component [45].

3.8. Other glare metrics

In addition to the commonly used discomfort glare indices, several recent studies have proposed or reassessed alternative metrics aimed at improving robustness and applicability under complex daylight or outdoor conditions. Wienold et al. [46] conducted a cross-validation of 22 glare metrics using multiple experimental datasets and found that saturation-based and hybrid indices, Predicted Glare Sensation Vote (PGSV) and experimental Unified Glare Rating (UGR_{exp}), performed more consistently than contrast-only metric. The study also emphasized the need for robustness testing and dataset diversity, showing that DGP, PGSV, and UGR_{exp} provided the most stable correlations with subjective responses.

Moreover, several disability or physiological glare metrics are relevant for outdoor environments affected by strong facade reflections. These include the Veiling Luminance (L_v) approach and Threshold Increment (TI) used in road-lighting and automotive safety research, both of which quantify loss of visual performance rather than perceived discomfort. Other specialized measures such as the Equivalent Veiling Luminance (EVL) and CGI extend these principles by linking luminance contrast with retinal adaptation.

Although the discomfort glare indices reviewed in this section (e.g., BGI, DGI, CGI, UGR, and DGP) provide a foundation for quantifying visual discomfort under various indoor lighting conditions, most of them were not originally developed for evaluating glare from sunlight reflected on building facades. These indices were formulated under assumptions of uniform artificial light sources or typical diffuse daylight conditions, which differ substantially from the intense, localized, and dynamic nature of reflected sunlight glare. Consequently, their applicability in reflection-dominant environments remains uncertain.

To address these limitations, future research should aim to adapt or recalibrate existing glare indices and, where necessary, develop new metrics specifically designed for facade-reflected sunlight conditions. Integrating physiological-performance metrics with perceptual indices can provide a more comprehensive framework for evaluating reflected sunlight glare, capturing both visibility impairment and subjective discomfort. Future studies should therefore test these combined metrics in field validation studies involving HDR imaging, luminance mapping, and user perception data, to establish reliable and perception-validated glare assessment methods for reflected sunlight environments.

4. Measurement-based studies

The measurement of glare caused by sunlight reflected from building facades is essential for evaluating visual comfort and safety in architectural environments. Accurate measurement techniques enable the quantification of glare intensity and the assessment of its impact on the visual experiences of the occupants, encompassing both discomfort and disability glares. Measurement-based studies provide an empirical

foundation by capturing actual reflection conditions, user perceptions, and material properties that influence glare responses. These studies were applied to various building types such as schools and offices, and they considered diverse contextual factors including sky conditions, task characteristics, measurement positions, and observer viewpoints. These studies were typically conducted in real-world settings or controlled laboratory environments and employed a wide range of methodological approaches.

This section outlines the key approaches for evaluating reflected glare through direct measurements. The reviewed literature was categorized into three groups according to the primary methodological focus: (1) Physical measurements and observations, (2) HDR imaging-based evaluations, and (3) survey-based (perceptual) assessments. Table 1 summarizes empirical studies that assessed reflected glare from building envelopes through field measurements or laboratory observations. It highlights key variables such as reflection sources, measurement positions, evaluation methods, and physical parameters including luminance, irradiance, and surface properties.

4.1. Physical measurements and observations

This section introduces methods for evaluating reflected glare through on-site physical measurements and photographic analysis, including direct visual observations, field data collection using light measurement instruments, and photographic documentation under natural sky conditions. These approaches contributed to a clearer understanding of reflected sunlight behavior in built environments by analyzing the geometry, height, orientation, and surface materials of reflective facades and capturing glare events in real-world settings.

Shih and Huang [47] conducted a field survey in Taipei to examine the distribution of the reflection glare from glass curtain walls. A total of 30 buildings with notable glare issues were selected based on site observations, facade orientation, and adjacent street conditions. Using photographs and interviews with pedestrians and occupants, the study identified key risk factors, such as facades composed of over 50 % reflective materials (particularly glass), east- or west-facing orientations, and placement next to wide streets. They proposed a threshold-limit-value (TLV) framework linking building height and street width to the potential occurrence of glare. This study made a pioneering contribution by systematically identifying urban-scale parameters influencing reflection glare through on-site observation. However, its reliance on subjective visual judgment and limited interviews (16 respondents) restricted quantitative validation. No calibrated luminance or irradiance measurements were conducted, and the proposed TLV model was not empirically verified under diverse sky conditions.

Speroni et al. [7] conducted an experimental investigation to assess the effect of solar reflections from tall building facades on pedestrian-level environments. Three 1:100 models including planar, 10 percent tilted, and concave configurations were constructed and tested on a rooftop under clear summer-sky conditions in Milan (Fig. 1). Irradiance was measured using pyranometers and an albedometer on a grey-coated ground plane, while a thermal infrared camera captured localized heat concentration. The results showed that concave facades with specular finishes produced the strongest reflections, exceeding three times the ambient irradiance and indicating potential visual and thermal discomfort risks. This experiment made a valuable contribution by providing quantitative evidence of how facade curvature and reflectivity amplify both thermal and visual exposure at the pedestrian level. However, the study was limited by its focus on irradiance and temperature without incorporating standardized glare metrics or perception-based assessments. The simplified rooftop setting also does not fully capture the complex reflection behavior found in urban canyon geometries.

Moereke et al. [48] experimentally examined the reflective behavior of photovoltaic (PV) modules compared with conventional facade

Table 1
Summary of measurement-based studies on reflected glare assessment.

Year	Title	Method	Reflection source	Measurement position	Glare index	Measurement parameter	Location
2001	A study of reflection glare in Taipei	Observation	Glass curtain walls	Indoor, outdoor	–	Surface reflectance	Taipei, Taiwan
2022	Experimental assessment of the reflection of solar radiation from facades of tall buildings to the pedestrian level	Scale model, measurement	Tall building facades	Outdoor	–	Albedo, irradiance, surface temperature	Milan, Italy
2022	Light reflection analysis of PV modules: comparison to building facades and assessing the possibility of glare	Lab measurement	PV glass, facade materials	Outdoor	–	Luminance, gloss	Germany
2016	Is exterior glare problematic? Investigation on visual discomfort caused by reflected sunlight on specular building facades	HDR imaging, survey	Specular glass facades	Outdoor	–	HDR images, luminance	Los Angeles, USA
2017	Reflectivity and specularly of building envelopes: how materiality in architecture affects human visual comfort	HDR imaging, survey	Glass & metal facades	Outdoor	–	HDR images, luminance	Los Angeles, USA
2018	The effect of building facade reflectivity on urban dwellers in tropics	Survey, SEM	Glass & metal facades	Outdoor	–	Surface reflectance	Singapore
2019	Effect of reflective building facade on pedestrian visual comfort	Survey, SEM	Glass & metal facades	Outdoor	–	Surface reflectance	Kuala Lumpur, Malaysia
2021	The impact of building facade reflectivity on pedestrian visual comfort with the application of Bayesian structural equation modeling	Survey, Bayesian SEM	Glass & metal facades	Outdoor	–	Surface reflectance	Kuala Lumpur, Malaysia
2022	An examination of reflected glare prediction method based on luminance distribution	Survey, regression	Replica paintings	Indoor	–	Luminance ratio, gloss, surface reflectance	Chiba, Japan
2024	Reducing glare on building facade by implementing vertical greenery shading: user-sensation vs luminance-measurement	Measurement, survey	Glass office facade	Indoor	–	Luminance, illuminance	Surabaya, Indonesia

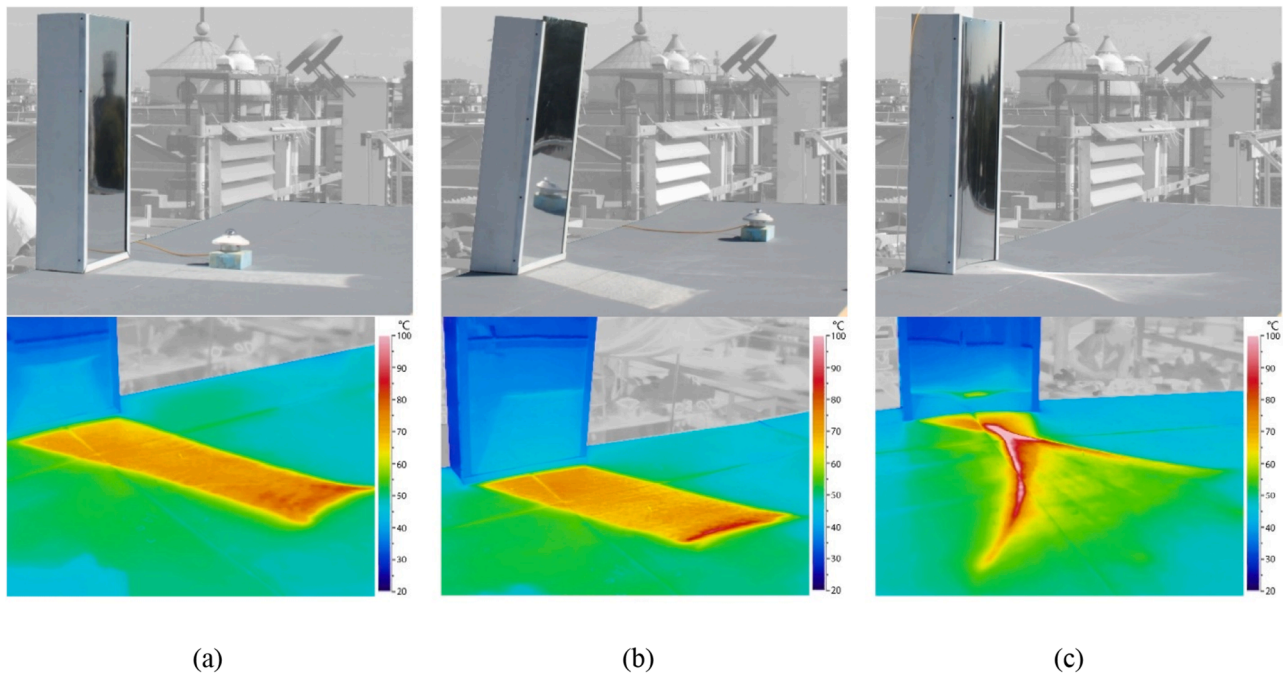


Fig. 1. Reflection shapes of the skyscraper scale models coated with reflective film: (a) flat vertical facade, (b) flat facade tilted at 10 %, and (c) curved vertical facade. Each set includes a photograph (top) and a thermographic image (bottom) [7].

materials to evaluate their potential for reflected glare. The study measured gloss values according to DIN EN ISO 2813 and conducted bidirectional reflectance distribution function (BRDF) analyses using gonireflectometers and spectroradiometers across two laboratories. The results showed that certain PV materials, although less glossy than specular building facades, could still produce high directional reflectance based on the surface coating and mounting angle. This study is valuable for reflected-glare research because it links surface optical characterization (gloss and BRDF) with luminance-based glare assessment. However, its evaluation was limited to physical reflection

parameters, without applying standardized glare indices or perceptual validation. Moreover, discrepancies between inter-laboratory BRDF results prevented quantitative comparison, restricting the analysis to qualitative interpretation.

The studies reviewed in this subsection relied on direct measurements or observational techniques to assess the impact of reflected glare. Shih and Huang [47] used photographic surveys and qualitative interviews to identify glare zones in Taipei, whereas Speroni et al. [7] and Moereke et al. [48] conducted controlled physical experiments to quantify the irradiance and luminance under various material and

geometric conditions. The primary advantage of these approaches is their ability to capture real-world phenomena that may be difficult to predict using only simulations. However, these studies share several limitations. Standardized glare indices or perceptual validation were not applied, making it difficult to quantify perceptual glare intensity or compare results across cases. Most investigations focused on radiometric or geometric aspects while overlooking how these physical reflections translate into perceived visual discomfort. Consequently, although field surveys, scale-model experiments, and optical measurements each address different aspects of reflected glare generation, their findings remain fragmented and difficult to compare.

4.2. HDR imaging-based evaluation

This section focuses on studies that employ HDR imaging to evaluate reflected glare under real-world lighting conditions. HDR imaging enables the detailed luminance mapping of glare sources using calibrated fisheye photography and image-based analysis. These methods are effective in capturing the spatial and intensity characteristics of reflected sunlight. All common glare indices, including DGP, DGI, CGI, and UGR, can be calculated from HDR images through validated tools such as Evalglare [49]. Several studies (e.g., Inanici [50], Pierson et al. [51]) have confirmed that HDR-based glare evaluation provides a reliable and standardized framework for quantifying visual discomfort, with detailed procedures established for image calibration, tone mapping, and bias correction to ensure robustness and reproducibility. This approach is effective for assessing glare phenomena by quantifying luminance distributions and analyzing their correlation with occupant perception.

Suk et al. [52] investigated visual discomfort caused by sunlight reflected from specular building facades through a controlled outdoor human-subject experiment using HDR imaging and MATLAB-based analysis. The study compared measured luminance distributions with subjective glare evaluations during reading tasks on digital and paper media. Although no intolerable glare was reported, about one-third of the tested scenes were perceived as perceptible or disturbing, confirming that reflected glare remains significant even under high outdoor luminance. The study proposed combining relative and absolute luminance thresholds to improve exterior glare prediction. This experiment made an important methodological contribution by isolating reflected sunlight as the only glare source in an outdoor setting, an approach that has been rarely achieved in prior studies. However, the study did not propose a specific luminance threshold, and its findings were constrained by the absence of standardized glare indices and a limited sample size.

Suk et al. [8] expanded upon their previous pilot study by conducting a more systematic investigation of reflected glare using HDR imaging and subjective evaluations. Using a controlled outdoor setting, the participants were exposed to reflected sunlight from specular facades under two lighting conditions (with and without reflection in the field of view) while performing various visual tasks (Fig. 2). HDR imaging and calibrated luminance measurements were used to detect glare sources and correlate them with subjective discomfort ratings. The results showed that 49 % of the scenes were perceived as having perceptible or disturbing glare, and a preliminary luminance threshold of 22,500 cd/m^2 was proposed to identify potential discomfort. However, the proposed threshold requires further validation due to the diversity of outdoor visual perception and environmental complexity. In addition, the absence of a standardized exterior glare index limits the generalization of the results and the comparability across studies.

Overall, HDR imaging-based studies have demonstrated strong potential for evaluating reflected glare by combining objective luminance measurements with subjective perception data. Compared to conventional field observations, these approaches enable precise spatial and photometric characterization of glare sources and provide a reproducible framework for assessing visual discomfort. The works by Suk et al. [8,52] significantly advanced the methodological foundation of exterior glare research by validating HDR imaging in real outdoor environments

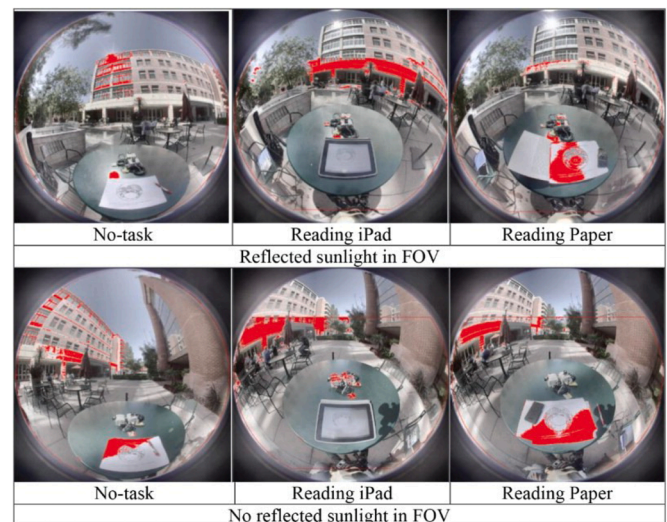


Fig. 2. Six different HDR images captured and processed in MATLAB [8].

and correlating measured luminance with perceptual responses. However, despite these advancements, current HDR-based studies remain limited by small datasets, context-specific conditions, and the lack of a universally accepted exterior glare index.

4.3. Survey-based (perceptual) assessment

This section reviews studies that assessed reflected glare using survey-based approaches, relying on subjective responses collected through structured questionnaires and controlled perception experiments. These methods aim to understand how individuals perceive visual discomfort caused by sunlight reflected from building facades in real or experimental settings. Commonly examined variables include age, glare duration, and exposure time, which are analyzed using regression analysis and structural equation modeling. In some cases, subjective evaluations are combined with physical measurements to support the glare assessment.

A series of studies conducted by Ishak et al. [53–55] explored the impact of reflected sunlight from building facades on pedestrian visual comfort in tropical urban environments, with empirical investigations conducted in Singapore and Kuala Lumpur. These studies employed conceptual modeling, field surveys, and advanced statistical techniques to progressively deepen the understanding of perceived glare in real-world outdoor settings.

The first study [53] introduced a conceptual framework for evaluating visual discomfort caused by reflected sunlight, identifying key influencing factors such as age, glare duration, glare timing, and avoidance behavior. The study applied Structural Equation Modeling (SEM) to analyze survey data collected from 240 respondents in Singapore, laying the foundation for subsequent investigations by structuring the components of perceived glare within tropical climates.

Building upon this framework, a second study [54] conducted a field survey with 500 respondents across four urban locations in Kuala Lumpur, Malaysia. The survey collected data on subjective glare perception, discomfort levels, and behavioral responses. The results highlighted that glare time and age were the most significant predictors of discomfort, while avoidance behaviors mitigated the perceived impact. This study emphasized the lack of standardized glare evaluation metrics in outdoor settings and suggested that facade reflectivity should be considered in urban design policies to enhance pedestrian comfort.

The third study [55] applied Bayesian SEM to the survey data to statistically test the relationships between influencing variables and perceived glare discomfort. The results confirmed that glare duration and age positively correlated with visual discomfort, whereas avoidance

behavior acted as a significant moderator. This modeling approach allowed for a more robust understanding of the causal mechanisms underlying glare perception in real-world environments.

Collectively, the studies by Ishak et al. [53–55] provide meaningful insights into pedestrian glare perception in tropical urban environments by emphasizing the role of subjective and behavioral factors such as age, glare duration, and avoidance behavior. These works advanced the conceptual understanding of reflected glare through the application of SEM and Bayesian modeling, offering a valuable human-centered perspective often missing in quantitative glare research. However, the exclusive reliance on perceptual survey data without objective luminance or irradiance measurements limits the ability to validate or compare their findings with physically measured glare metrics.

Sagawa et al. [56] examined a method for predicting reflected glare based on the luminance distribution in museum lighting environments. Using a full-scale experimental setup with mock paintings (Fig. 3), the study tested 108 lighting scenarios by varying the ambient-to-target light ratios, Munsell values, and presence of a varnish coating. Subjective glare evaluations were collected from 18 participants and luminance-based glare prediction models were developed using regression analysis. While single-variable luminance ratios showed a moderate correlation with perceived glare ($R^2 = 0.61$), a multiple regression model that included surface reflectance and specularity improved accuracy ($R^2 = 0.82$). Although the study did not address facade-induced sunlight reflections, it provided a valuable methodological foundation for quantifying reflected glare through combined photometric and perceptual analysis. However, the experimental setting was limited to controlled indoor conditions and a small sample size, which restricts the generalization of its findings to complex outdoor or architectural contexts.

Kristanto et al. [57] conducted an experimental study to examine reflected glare from glass building facades and to assess the potential of vertical greenery systems as a mitigation strategy. A mock office cubicle with a 50 % window-to-wall ratio was tested under three shading coverage scenarios using clear glazing. The study combined objective measurements, with luminance measured by a digital luminance meter and illuminance measured by a lux meter, and subjective evaluations from 32 participants using a glare sensation vote scale. Results showed that higher plant coverage reduced measured luminance and reported glare. However, the study did not employ standardized glare indices or HDR imaging, the sample size was small, and the single mock-up and controlled conditions limit external validity.

The studies reviewed in this section collectively highlight the

importance of human perception in understanding reflected glare phenomena, emphasizing that physical measurements alone cannot fully capture the subjective experience of visual discomfort. Research by Ishak et al. [53–55] advanced the conceptual understanding of pedestrian glare perception by integrating behavioral and demographic variables through structural and Bayesian modeling, while studies such as Sagawa et al. [56] and Kristanto et al. [57] linked subjective assessments with controlled photometric measurements to explore the correlation between luminance and perceived glare. Together, these works underscore the value of perception-based evaluation in identifying the human factors influencing glare discomfort. However, their methodological limitations are also evident. Most studies lacked standardized glare indices, objective luminance benchmarks, or HDR-based validation, making cross-comparison between studies difficult. Furthermore, the dominance of controlled or survey-based experiments restricts the applicability of their findings to dynamic outdoor environments where reflected sunlight varies significantly with context and time.

5. Simulation-based studies

This section reviews studies that evaluate reflected glare using simulation-based approaches. Unlike measurement-based methods, simulation techniques allow researchers to model various sunlight reflection conditions, material properties, and observer positions to assess and predict glare risk. These methods are particularly useful in the early stages of architectural design, where physical measurements are not feasible, and they enable the evaluation and prediction of annual glare patterns. Furthermore, simulation-based approaches support the development of glare mitigation strategies by allowing designers to test the impact of different materials, geometries, and orientations. Simulation studies range from geometric-based models that use simplified solar position and reflection calculations to physically-based simulations using ray-tracing engines such as Radiance, which simulate light behavior based on optical physics and material properties.

This section is divided into two categories based on the underlying modeling approach and computational method used: (1) Geometry-based simulations and (2) Radiance-based simulation. Table 2 summarizes simulation-based studies that assessed reflected glare through computational modeling techniques. Key variables include the type of simulation tool, reflection source, measurement position, and modeled location.

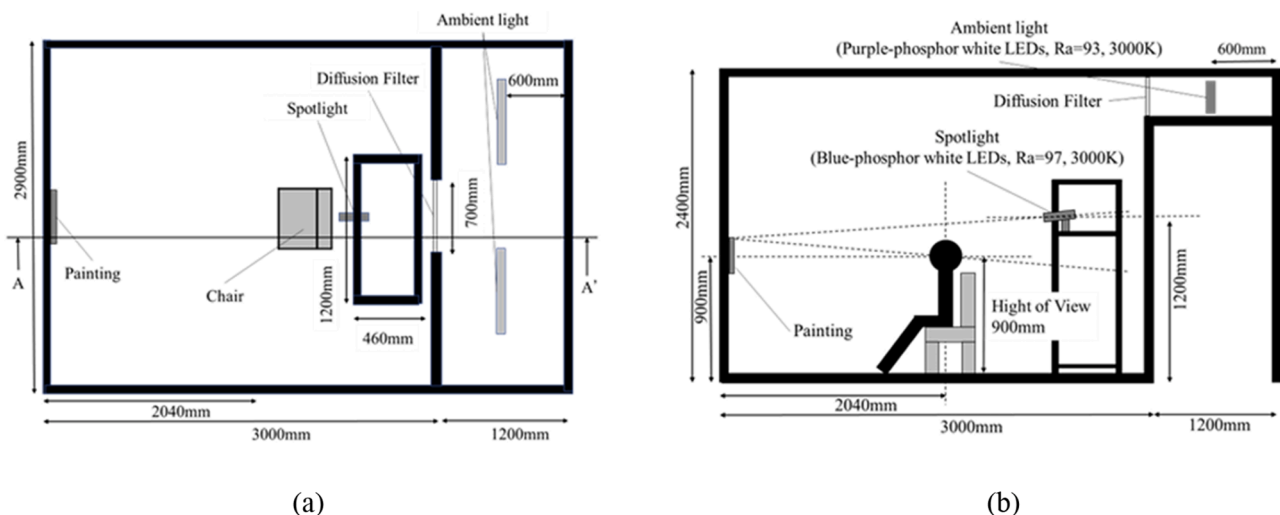


Fig. 3. Experimental room (a: Plane section b: A-A' Cross section) [56].

Table 2

Summary of simulation-based studies on reflected glare assessment. (Continued on next page).

Year	Title	Method	Simulation tool/ engine	Reflection source	Measurement position	Glare index	Location
1987	Prediction of reflected solar dazzle from sloping facades	Geometry modeling	–	Sloped glazed facade	Outdoor	–	UK
2001	An analysis and simulation of curtain wall reflection glare	Ray-tracing	–	Glass curtain wall	Outdoor	–	Taipei, Taiwan
2001	Volumetric study of reflected glare from glass curtain walls of buildings	3D volume simulation	–	Glass curtain wall	Outdoor	–	Taipei, Taiwan
2012	The influence of reflected solar glare caused by the glass cladding of a building: Application of caustic curve analysis	Ray-tracing, image analysis	3ds Max, ImageJ	Glossy glass facade	Outdoor	–	Warsaw, Poland
2016	A comprehensive ray tracing study on the impact of solar reflections from glass curtain walls	Ray-tracing	–	Glass curtain wall	Outdoor	–	Hong Kong
2022	A method of estimating the spatiotemporal distribution of reflected sunlight from glass curtain walls in high-rise business districts using street-view panoramas	Panorama analysis	–	High-rise glass wall	Outdoor	–	Dalian, China
2023	Environmental analysis reflected glare	Veiling luminance simulation	Rhino, Grasshopper, custom tool	Commercial glazed tower	Outdoor	–	Melbourne, Australia
2013	Simulation of reflected daylight from building envelopes	Forward/backward ray-tracing	Rhino, Grasshopper, Radiance	Composite facade	Outdoor	–	Zurich, Switzerland
2013	The assessment of daylight reflection from building envelopes	Forward/backward ray-tracing	Radiance, Rhino, Grasshopper	Office tower facade	Outdoor	–	Zurich, Switzerland
2016	Analysis and quantification of visual glare caused by photovoltaic panels installations in urban canyons	Annual glare simulation, HDR imaging	Radiance, DIVA, Grasshopper, Honeybee	PV on high-rise office	Indoor	DGP	Houston, USA
2016	Evaluation of solar glare from reflective facades: A general method	Ray-tracing	Radiance	Reflective glass facade	Outdoor	–	London, UK
2019	Computer simulation of sunlight concentration due to facade shape: Application to the 2013 Death Ray at Fenchurch St, London	Ray-tracing	Radiance, Rhino	Curved glass facade	Outdoor	–	London, UK
2019	The negative impact of solar reflections caused by reflective buildings' facades: Case study of the Nasher Museum in Texas	Glare simulation, HDR imaging	Radiance, DIVA, Grasshopper	High-rise glazed facade	Indoor, outdoor	DGP	Dallas, USA
2020	Automated computer vision recognition based method to determine glare causing patches on reflective building facades	Annual glare simulation	Radiance, OpenCV, Rhino	Glazed tower	Indoor, outdoor	DGP	Houston, USA
2021	Investigation on how daylight simulation should be used to characterize daylight-related issues for buildings in Hong Kong	Daylight simulation	Radiance, SketchUp	Glass curtain wall	Indoor, outdoor	–	Hong Kong
2022	A prediction model for fast evaluation of reflective glare from surrounding buildings	Parametric ray-tracing	Rhino, Radiance, DIVA	Residential high-rise	Indoor	DGP	Singapore
2024	Modelling solar disability glare reflected off modern building facades	HDR imaging	CPP tool(Radiance-based), ClimateStudio	Metal & glass facade	Outdoor	DGP	Sydney, Australia

5.1. Geometry-based simulations

This section reviews studies that use geometry-based simulation methods to evaluate the glare reflected from building facades. Geometry-based simulations assess the reflected glare by calculating the position and angle of sunlight relative to the facade geometry, without relying on complex optical properties or ray-tracing engines. These methods use simplified 3D models, sunpath diagrams, or vector-based tools to identify the spatial extent and timing of reflected sunlight.

Littlefair [58] proposed one of the earliest analytical methods for predicting solar glare from sloping reflective facades. This study introduced a geometric framework that calculates the azimuth and altitude of reflected sunlight based on facade orientation and solar position, thereby identifying glare periods using sun-path diagrams and a Building Research Establishment protractor. This method provided a foundational tool for early design-stage glare screening, particularly when simulation resources were limited. However, the approach was purely geometric and did not incorporate luminance calculations or material reflectance properties, limiting its applicability for evaluating visual discomfort or validating results under real conditions.

Shih and Huang [1] conducted a simulation-based study to evaluate the spatial extent of glare reflected from buildings with glass curtain walls in Taipei. In this study, a simplified cubic model with highly

reflective facades was used to simulate ground-level solar reflections at various solar positions. The authors proposed the boundary of the reflection area as a metric to represent the surface area affected by reflected glare. The simulation parameters included facade tilt and orientation angles, which were analyzed across different seasons. However, although the study presented a novel geometric approach to visualize reflection spread, it did not quantify glare luminance or evaluate perceptual discomfort, relying solely on simplified geometric and reflective assumptions.

Shih and Huang [59] developed a computer-aided method to simulate the volumetric distribution of glare reflected from glass curtain walls using a $1 \times 1 \times 1 \text{ m}^3$ test cube model. This study introduced the concept of reflection volume (RV) (Fig. 4), which is a three-dimensional polyhedron that captures the spatial extent of reflected sunbeams over time. Simulations were performed at hourly intervals between 8 a.m. and 4 p.m. across three regions in Taiwan to compare the RV behavior at solstices and equinoxes. The RV model enabled Boolean operations with the surrounding buildings to identify glare-affected and glare-free areas. However, while the RV method provided an innovative geometric framework for visualizing reflection behavior, it relied on idealized assumptions such as perfectly reflective surfaces (reflectivity = 1) and clear-sky conditions, which limit its applicability in real urban contexts.

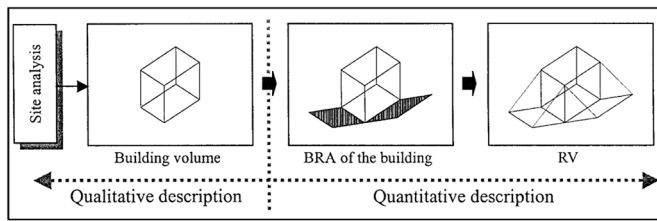


Fig. 4. Relation between BRA and RV in Quantitative Description [59].

Brzezicki [60] analyzed the effect of reflected solar glare from glass facades with varying geometries, focusing on concave surfaces and their potential to concentrate sunlight. They introduced the reflection glare area to quantify the spatial extent of reflected glare on the ground plane using ray-tracing simulations in 3D Studio Max and image processing via ImageJ. Among the flat, angled, convex, and concave facade types, the concave facade produced the most intense and localized glare, forming caustic curves where the reflected sunlight was concentrated. However, while the study provided a rigorous geometric and optical framework, it relied on simplified assumptions such as ideal surface smoothness and uniform reflectivity, and it was limited in addressing human visual discomfort and the variability of real materials.

Wong [2] conducted a comprehensive ray-tracing study to evaluate the annual effects of solar reflections from the International Commerce Centre (ICC) in Hong Kong, focusing on the influence of facade geometry and glass reflectivity. Using MATLAB and verified sun-path data (Fig. 5), the study simulated the direction, convergence, and intensity of reflected rays toward 73 nearby buildings. The results showed that the concave “Dragon Tail” facade and upward-tilted glass panels significantly amplified reflection intensity and spatial reach, with localized irradiance levels exceeding 1400 W/m^2 . This research made a significant methodological contribution by integrating large-scale urban geometry with temporal reflection modeling, providing valuable insight into the physical mechanisms of facade-induced solar reflections. However, the analysis relied exclusively on irradiance-based metrics without applying luminance or glare indices, limiting its relevance for evaluating perceptual glare and visual discomfort.

Zhu and Gu [61] introduced a panoramic image-based method to estimate the spatiotemporal distribution of reflected sunlight from glass curtain wall facades, aiming to address the computational and data limitations of conventional 3D simulation models. By applying panoramic projection transformation, the method calculated solar trajectories, reflection orientations, and annual reflection duration using street-view images instead of detailed geometric models. This study made a methodological contribution by introducing a scalable and data-efficient approach for analyzing large-scale urban reflection phenomena. However, the approach remains limited by its reliance on

two-dimensional panoramic imagery rather than physically based optical simulation or luminance measurements. As a result, it cannot quantify visual discomfort or glare intensity using standardized metrics.

Talarico and Engineer [62] conducted an environmental glare analysis for a commercial tower in Melbourne to assess the potential impact of reflected sunlight on nearby road users. Using a 3D model built in Rhinoceros 7 and an in-house Grasshopper simulation tool based on the Hassall method, the study modeled annual solar reflections under various sun positions, facade orientations, and reflectivity conditions. The assessment applied a veiling luminance limit of 500 cd/m^2 , derived from the Holladay formula, as the safety criterion for vehicular glare. This study represents a practical example of applying quantitative glare analysis to meet urban planning and safety regulations. Nevertheless, its exclusive focus on vehicular glare and the absence of perceptual or standardized glare evaluation methods limit its applicability to comprehensive visual comfort assessment.

The geometry-based simulation studies reviewed in this section collectively demonstrate how facade form, orientation, and material reflectivity determine the spatial and temporal behavior of reflected sunlight. Early analytical models, such as those by Littlefair [58] and Shih and Huang [1,59], provided valuable geometric frameworks for predicting the occurrence and extent of reflected glare, while more recent works, including Brzezicki [60], Wong [2], and Zhu and Gu [61], expanded these approaches through computational modeling and large-scale urban applications. These methods are particularly effective for identifying potential glare zones and reflection paths during early design or urban planning stages. However, their reliance on geometric or irradiance-based parameters, without incorporating luminance calculations or perceptual glare indices, limits their capacity to assess visual discomfort directly. Moreover, many models assume idealized material reflectivity, smooth surface conditions, and clear skies, which diverge from real-world complexities. Although studies such as Talarico and Engineer [62] have demonstrated practical applications of these simulations in urban safety analysis, geometry-based methods overall remain limited in their ability to integrate optical realism and human-centered perception, underscoring the need for more comprehensive and perception-validated modeling frameworks.

5.2. Radiance-based simulations

This section reviews studies that assessed glare reflected from building facades using Radiance-based simulation methods. Radiance is a physically based lighting simulation engine originally developed by Greg Ward at Lawrence Berkeley National Laboratory [63]. It computes luminance and illuminance values using backward ray tracing combined with the bidirectional scattering distribution function (BSDF) of materials. Radiance employs Monte Carlo sampling to account for diffuse interreflections and complex daylight interactions, allowing for highly accurate predictions of lighting distributions under real-sky conditions. Because of its ability to model spectral characteristics, material reflectance, and geometric complexity, Radiance has become one of the most reliable tools for daylighting and glare analysis. In reflected glare studies, Radiance is often integrated with parametric design platforms such as Rhinoceros, Grasshopper, DIVA, and Honeybee-Ladybug to perform point-in-time or annual simulations of glare indices, including DGP and other metrics.

Yang et al. [64,65] developed a Radiance-based simulation framework for assessing reflected daylight from building envelopes by combining forward and backward ray tracing (Fig. 6) within a parametric design environment. Implemented in Rhino and Grasshopper, the tool identified critical reflection zones in surrounding urban contexts and quantified annual irradiance through climate-based simulations using the daylight coefficient method. Case studies in Zürich demonstrated that southwest-facing curved glazing produced localized areas of high luminance exceeding $10,000 \text{ cd/m}^2$, with reflection duration varying seasonally and by facade geometry. The studies collectively

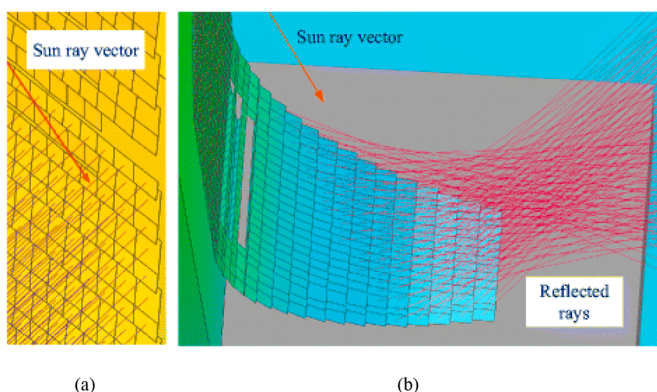


Fig. 5. Reflected ray vectors from (a) panels at 8° and (b) Dragon Tail [2].

advanced reflection assessment by integrating Radiance with parametric modeling for design-stage analysis and visual feedback on envelope performance. However, both studies relied on assumed reflectance properties and lacked experimental or perceptual validation, limiting their ability to verify visual glare risk under real conditions.

Gil [66] proposed a general method for evaluating veiling glare from reflective facades by integrating geometric reflection analysis with luminance estimation based on the Holladay formula. The approach automated glare-zone identification using Radiance ray tracing and produced false-color visualizations of areas where veiling luminance exceeded 500 cd/m^2 . This method effectively simplified the detection of potential glare hazards for vehicular scenarios and offered a reproducible workflow adaptable to different facade geometries. However, the evaluation focused primarily on veiling glare and did not include discomfort-based metrics that capture human perceptual responses. Furthermore, the assessment was conducted from a vehicular viewpoint, focusing on driver safety rather than pedestrian or occupant visual comfort, which limits the generalization of the findings to broader glare perception contexts.

Labib and Baltazar [67] simulated glare from PV panels installed on high-rise facades in an urban canyon using Radiance-based tools integrated with Rhinoceros, Grasshopper, DIVA, and Honeybee-Ladybug. Annual simulations for 400 viewpoints showed that PV facades generated higher DGP values than conventional glazing, particularly during morning and afternoon hours. The study presented a robust workflow for assessing annual glare risks in dense urban settings. While the use of DGP provided a quantitative means to compare glare intensity, the metric's applicability is limited for outdoor PV reflections since it was originally developed for indoor daylight conditions. In addition, the study focused on reflections from PV surfaces rather than building facades, which restricts its relevance to architectural facade glare evaluation.

Abdelwahab et al. [68] performed point-in-time Radiance-based simulations to assess visual discomfort caused by sunlight reflected from the Museum Tower's fully glazed facade onto the Nasher Sculpture Museum in Dallas, Texas. Using Rhinoceros, Grasshopper, and the DIVA plug-in, DGP values were computed for two occupant viewpoints under clear-sky conditions across four seasons and three times per day. The results revealed frequent intolerable glare ($\text{DGP} > 0.45$) from one viewing position, especially around noon and afternoon during the solstices and equinoxes. However, the analysis was limited by the use of clear-sky assumptions and the absence of perceptual validation through user studies.

Zhu et al. [69] conducted a Radiance-based backward ray-tracing simulation to investigate the extreme solar concentration effect observed at 20 Fenchurch Street in London, where the concave glazed facade caused significant thermal damage to surrounding objects. The simulation incorporated detailed building geometry, solar position, facade curvature, panel tilt, and atmospheric attenuation to generate hourly irradiance maps and identify spatial and seasonal hotspots, with

peak intensities exceeding 4000 W/m^2 . This methodology demonstrated an approach to reproducing actual reflection patterns through a Radiance-based simulation. However, the study focused solely on thermal effects and did not address visual glare perception, limiting its relevance for evaluating visual discomfort caused by reflected sunlight.

Labib and Clayton [70] developed an automated workflow that integrates Radiance-based daylight simulations with Python and OpenCV for detecting glare-causing facade panels. Using a dataset of more than 65,000 HDR images generated from 15 interior viewpoints (Fig. 7), the method spatially mapped glare pixels to specific facade panels through a grid-based masking system, creating a SQL database that records when and where glare occurs. This approach represented a significant methodological advancement in tracing glare sources and linking them to facade geometry. However, it did not provide a complete basis for evaluating the visual impact of reflected glare on occupants.

Wang [71] conducted a comparative study to evaluate different Radiance-based daylight simulation methods for characterizing reflected sunlight from a real curtain-walled building in Hong Kong. Four backward ray-tracing techniques (single point-in-time, two-phase, three-phase, and sun coefficient) were compared in predicting horizontal illuminance over a year, alongside a forward ray-tracing approach that identified the specific facade panels introducing reflections and the receiver locations. The study found that although all methods captured annual reflection trends, their intensity predictions varied significantly due to differences in sun modeling, BSDF resolution, and ambient parameters. The forward ray-tracing method effectively visualized spatial reflection distributions, while backward methods better quantified illuminance magnitudes. This research provided a rigorous methodological comparison of Radiance-based approaches for facade reflection analysis. However, it did not address perceptual glare indices or human comfort thresholds, limiting its applicability to visual glare risk evaluation.

Wen et al. [72] conducted a comprehensive parametric simulation to evaluate the indoor glare risk induced by reflections from surrounding building facades. Based on a typical high-rise residential unit in Singapore (Fig. 8), this study simulated 21,120 scenarios by varying five design parameters: facade reflectance, sun position, building orientation, height of the affected building, and inter-building distance. DGP was used as the primary glare metric, and simulations were conducted using Rhinoceros, Radiance, and DIVA under CIE clear-sky conditions. While the proposed model offers a useful framework for predicting glare in the early design stage, it has several limitations. It was applied to only one type of building, did not include validation through actual measurements or user perception studies, and assessed glare at just one location in the middle of the room.

Glanville et al. [73] developed a Radiance-based simulation framework to evaluate solar disability glare from modern building facades, with a focus on risks to drivers in urban environments. The method combined HDR imaging with the Evalglare tool to calculate veiling luminance and threshold increment, which quantify visibility reduction due to reflected sunlight. Simulation parameters included facade material reflectivity, sun position, and observer sightlines aligned with driver views. This research presented a validated and practical workflow for assessing facade-induced disability glare in transportation contexts. However, since it focused exclusively on driver visibility and not on perceptual discomfort or indoor glare, its applicability to broader architectural or occupant-centered glare evaluation remains limited.

The reviewed Radiance-based studies collectively demonstrate the growing sophistication and reliability of simulation methods for evaluating reflected glare from building facades. These studies highlight Radiance as a powerful and essential tool for accurately predicting luminance distributions and glare metrics, providing a solid foundation for both facade design and glare mitigation research. However, several consistent limitations remain. Many studies relied on assumed

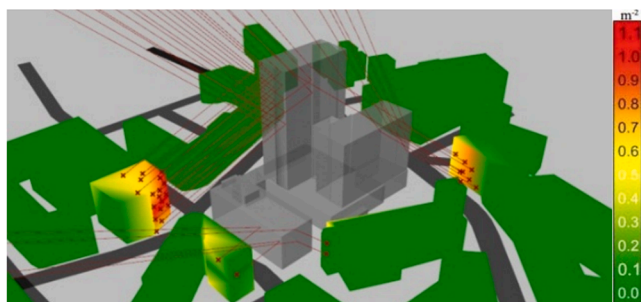


Fig. 6. Forward ray tracing to locate reflected daylight from assessed building envelop [64].

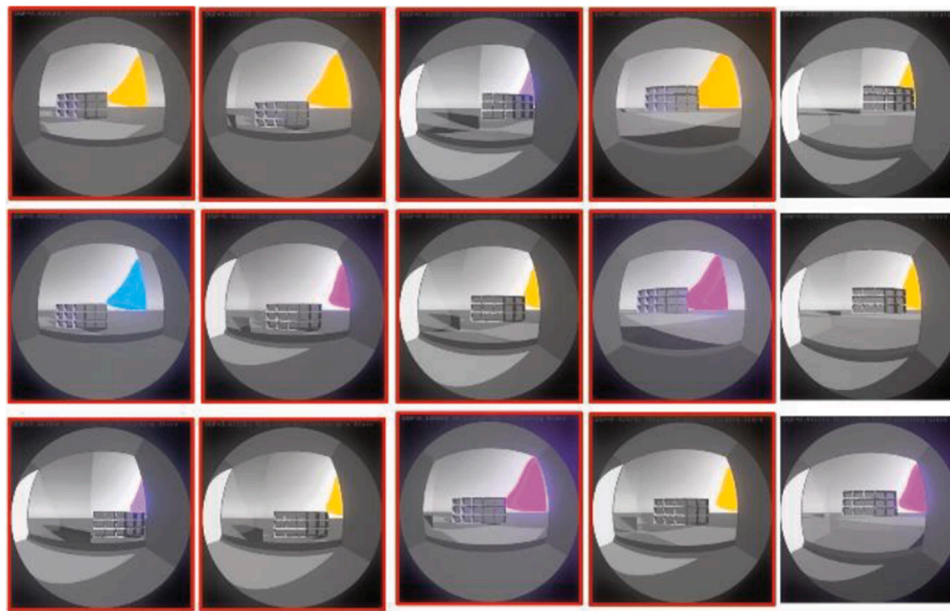


Fig. 7. HDR 180° fisheye renderings of 15 outward views from inside the three-story building, with glare sources automatically highlighted by Radiance for glare analysis [70].

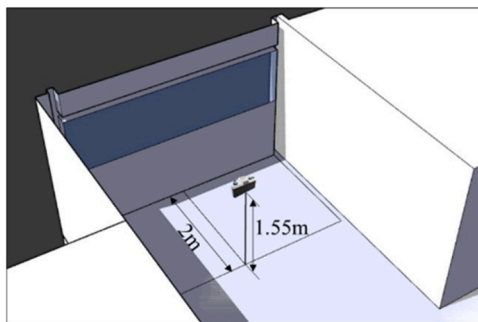


Fig. 8. Camera position for glare simulation [72].

reflectance properties and idealized clear-sky conditions, and few included field measurements or user-based perception data for validation. Moreover, inconsistencies in simulation setup, such as sky models, material definitions, and observer viewpoints, make it difficult to compare results across studies.

6. Integration of measurement and simulation approaches

This section reviews studies that integrate measurement and simulation methods to evaluate reflected glare from building facades. The combination of these two approaches bridges the gap between empirical observation and predictive modeling, allowing for more reliable and context-sensitive glare assessment. Measurement-based methods capture the actual luminance distributions and human visual responses under real environmental conditions, while simulation-based methods enable the systematic analysis of variables such as geometry, material reflectance, and solar position. When combined, these approaches enhance the accuracy of glare prediction and enable the calibration and validation of simulation tools using field data. Such integration represents a critical step toward establishing standardized and perception-validated workflows for assessing reflected sunlight glare in architectural and urban environments. Table 3 summarizes studies that integrated measurement and simulation to assess reflected glare from building surfaces. Key elements include the types of simulation and measurement methods used, reflection sources, and measurement

parameters such as surface temperature and spectral reflectance.

Schiller and Valmont [74,75] conducted a series of studies investigating the visual and thermal impacts of the reflective stainless-steel facade of the Walt Disney Concert Hall in Los Angeles. The analyses combined photographic observations with simulations using Radiance, Lightscape, and AGI32 to identify high-luminance reflection zones exceeding $12,000 \text{ cd/m}^2$. This work represented one of the earliest documented integrations of simulation and field validation for facade-induced glare assessment. Although luminance thresholds were applied, standardized glare indices were not used, so the analysis primarily focused on physical brightness rather than perceptual glare thresholds, which limits its applicability to human-centered visual comfort evaluation.

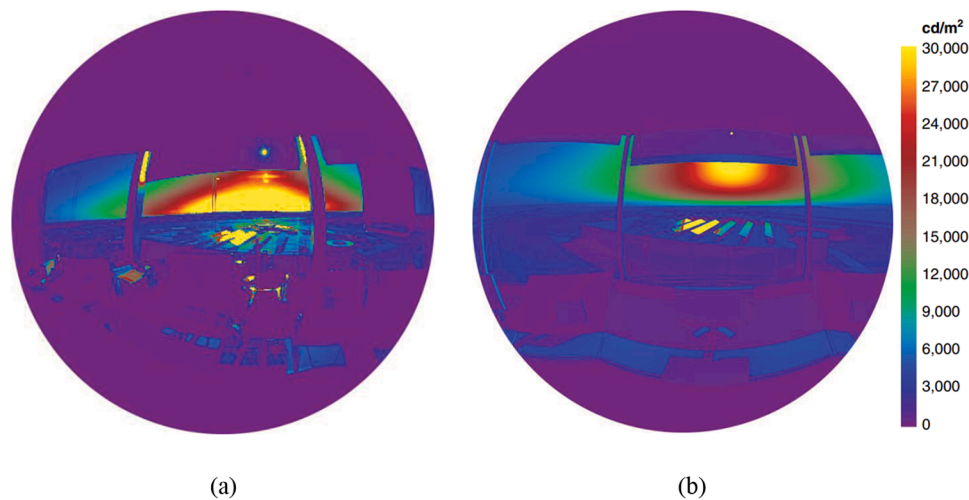
Jakubiec and Reinhart [3] proposed a Radiance-based simulation method to assess disability glare caused by specular reflections from PV arrays, using an airport case study where glare from PV panels impaired visibility from the air traffic control tower. The study modeled detailed 3D geometry and material reflectance of the PV system, validated through calibrated HDR photographs (Fig. 9). Annual simulations at 10-minute intervals identified spatial and temporal glare risks, and a luminance threshold of $30,000 \text{ cd/m}^2$ was proposed as a critical limit for disability glare. This study made a notable contribution by proposing a quantitative luminance threshold as a criterion for disability glare, providing one of the few empirical reference values available for evaluating high-intensity reflections. However, its relevance to architectural facade glare assessment remains limited.

Danks and Good [76,77] developed and validated a large-scale simulation framework, ECLIPSE, for predicting solar reflections within complex urban environments. The methodology integrates high-resolution geometric modeling, clear-sky irradiance data, and time-based reflection analysis to estimate both visual and thermal impacts of facade-induced reflections. Field measurements were conducted to validate simulation outputs, showing close agreement in reflection timing and peak irradiance levels. Subsequent case studies demonstrated the application of this tool in both predictive and forensic analyses, identifying glare hotspots and testing mitigation strategies such as shading structures and surface treatments. These studies represent one of the most comprehensive attempts to couple simulation and field validation for urban-scale reflected glare assessment, though the

Table 3

Summary of studies integrating measurement and simulation in reflected glare assessment. (Continued on next page).

Year	Title	Method	Simulation tool/engine	Reflection source	Measurement position	Glare index	Measurement parameter	Location
2005	Microclimatic impact: Glare around the Walt Disney Concert Hall	Field measurement, simulation, photo analysis	AGI32, Radiance, Lightscape	Curved steel facade	Indoor, outdoor	–	Luminance, surface temperature	Los Angeles, USA
2006	Urban environmental glare: The secondary consequence of highly reflective materials	Field measurement, photo analysis, simulation	- (not specified)	Reflective steel facade	Indoor, outdoor	–	Luminance, surface temperature	Los Angeles, USA
2014	Assessing disability glare potential of reflections from new construction	HDR imaging, field measurement, annual simulation	Radiance	PV panels	Indoor, outdoor	–	Luminance, spectral reflectance	USA (airport)
2016	Urban scale simulations of solar reflections in the built environment: methodology & validation	Urban-scale simulation, field validation	ECLIPSE, WINDOW	High-rise glazed/metal/concrete facade	Outdoor	–	Irradiance, solar radiation, material reflectance	North America (US city case studies)
2016	Urban solar reflection identification, simulation, analysis and mitigation: learning from case studies	Urban solar simulation, field measurement	ECLIPSE, WINDOW	Glass/metal facades, PV panels	Indoor, outdoor	–	Irradiance, surface temperature, reflectance	North America (USA)
2018	Simulation of urban solar reflections and their impact on building performance	Urban reflection simulation, case study	RWDL, WINDOW	High-rise glass facade (flat/curved)	Outdoor	–	Irradiance, surface temperature, reflectance	UK, USA (anonymized cases)
2020	Optic-energy and visual comfort analysis of retro-reflective building plasters	Experimental study, simulation	Custom tool	Retro-reflective plastered facade	Outdoor	DGP	Reflectance, thermal image	Italy
2020	Urban solar reflections identification, simulation and analysis	HDR imaging, field measurement, custom simulation method	Radiance (photon)	High-rise reflective facade	Outdoor	–	HDR images, luminance	Bratislava, Slovakia
2021	Comparison of daylight simulation methods for reflected sunlight from curtain walls	Forward/backward ray-tracing, matrix-based daylight simulation	Radiance, Rhino	Glass curtain wall	Outdoor	–	Illuminance, reflectance	Hong Kong
2023	Impacts of a highly reflective stainless-steel facade on a surrounding building: A case study in Singapore	Field measurement, regression analysis, ray-tracing simulation	Rhino, Ladybug	Reflective stainless steel facade	Indoor	–	Illuminance, temperature, surface reflectance	Singapore

**Fig. 9.** (a) HDR image and (b) simulation rendering of glare as seen from the air traffic control tower [3].

approach still focuses primarily on irradiance-based metrics rather than standardized perceptual glare indices.

Shilston and Danks [78] conducted case studies combining simulation and field measurements to assess solar reflections from concave glass facades in urban environments. Their custom-developed tool calculated reflection timing and irradiance intensity using clear-sky data and angle-dependent reflectance properties derived from the WINDOW database. Field validation confirmed focal reflections exceeding 4000 W/m², which were mitigated through shading and glazing redesign. This method effectively integrated simulation and measurement for detecting

critical reflection events, but it focused primarily on irradiance and thermal effects rather than perceptual glare indices, limiting its contribution to visual discomfort evaluation.

Castellani et al. [79] developed retro-reflective (RR) plasters for facade applications and evaluated their optical properties and influence on pedestrian visual comfort through a combination of laboratory testing, Radiance simulations, and on-site measurements. Two types of plasters were applied to south- and west-facing test walls, where luminance and illuminance were measured at eye level under real outdoor conditions, and DGP was calculated. This study effectively integrated

field measurements with Radiance-based simulations, providing methodological validation for assessing facade materials under realistic lighting conditions. However, the generalizability of this study is constrained when applied to varying facade environments and to the perspectives of indoor occupants.

Šujanová [80] developed an integrated methodology to identify and simulate solar reflections in urban environments by combining HDR imaging calibration with custom radiance-based tools. This study introduced a digital camera calibration workflow to capture outdoor luminance distributions and assess visual glare and proposed a simulation method adapted from Gil's solar glare model using bash scripting to generate the sun position and radiance data. Although the camera-based HDR system showed promise for field assessment, the adapted simulation approach was limited by geometric simplifications and failed to reliably predict glare conditions. This study did not incorporate standardized discomfort glare indices, and the proposed simulation method was not validated against measured perceptual responses.

Wang et al. [6] compared four Radiance-based daylight simulation methods, namely, single point-in-time backward ray tracing, two-phase, three-phase, and sun coefficient methods, to evaluate their effectiveness in quantifying sunlight reflected from curtain walls throughout the year. This study modeled the Jockey Club Innovation Tower in Hong Kong using highly specular curtain wall patches and examined the spatial and temporal distributions of reflected illuminance using each method. A simplified mirror-ground model was used to validate the consistency across methods. However, the simulations assumed 100 % specular reflection and omitted the surrounding buildings, limiting the generalizability of the results to real-world urban environments.

Wen et al. [4] investigated the thermal and visual impacts of a highly reflective stainless-steel facade on a neighboring school building in Singapore through field-based measurements. The indoor illuminance, air temperature, and surface temperature were continuously monitored at six classroom locations under both affected and unaffected reflection conditions. A regression-based model was proposed to estimate the intensity of reflection-induced effects using solar radiation and facade distance as predictors. This study offered valuable real-world evidence of reflection-related discomfort and proposed a practical prediction model; however, its applicability was limited by the exclusive focus on a single facade material and configuration and the absence of subjective discomfort assessments or standard glare indices.

A common feature among these studies is the use of ray-tracing tools such as Radiance or custom-built simulation engines, combined with empirical data including site photographs, HDR imaging, illuminance measurements, and surface temperature recordings to validate simulation results [3,4,74–78]. A key strength of this integrated approach is its ability to capture real-world reflection behavior and quantify its impact with a high degree of accuracy. However, these studies also exhibit several limitations. Most existing works emphasize technical validation or irradiance-based comparison rather than perception-driven evaluation, leaving the relationship between physical luminance metrics and subjective discomfort largely unexplored. The absence of standardized glare indices in field-validated simulations restricts comparability and reproducibility across studies. Moreover, most integrations remain case-specific, employing simplified geometry, uniform specular assumptions, or limited facade materials, which reduces their applicability to diverse architectural contexts. Finally, user-based perceptual validation has rarely been conducted, limiting the relevance of the findings to actual human visual experience.

7. Discussion and conclusions

This literature review examined studies assessing glare caused by sunlight reflected from building facades and categorized them into (1) measurement-based studies, (2) simulation-based studies, and (3) integrated studies combining both measurement and simulation approaches. The key findings of this review are as follows:

- (1) In measurement-based studies, the dominant trend was the use of field-based photographic surveys and HDR imaging to capture reflected glare phenomena in real environments. These methods enabled observing reflection behavior in actual settings; however, the absence of standardized measurement protocols limited the objective comparison of results and the evaluation of glare intensity. Survey-based assessments often focused on user visual discomfort; however, the lack of physical measurements and validation restricted their ability to quantify the intensity of the reflected glare.
- (2) Simulation-based studies were divided into geometry- and radiance-based simulations. Geometric approaches employed simplified models and sun path calculations to provide the spatial and temporal patterns of the reflected glare. Although useful in the early design phase, these methods cannot evaluate the glare intensity or incorporate human-centered glare metrics. Radiance-based simulations provided a detailed analysis of luminance distributions and glare indices; however, most studies did not employ standard glare metrics. In addition, there were no established standards regarding simulation tools or observer evaluation positions, and relatively few studies addressed the indoor glare caused by reflected sunlight.
- (3) Integrated studies combining measurements and simulations offered enhanced insights. These studies improved predictive reliability by validating the simulation results with physical measurements such as illuminance, luminance, and surface temperature. However, many of these studies did not apply human perception-based glare indices such as DGP, with only Castellani et al. [79] quantitatively validating simulation outputs using glare metrics. Furthermore, no studies employed HDR imaging for comparison with the simulation results, which limited the ability to verify the accuracy and reliability of the predictions.

While the reviewed literature establishes an important foundation for understanding reflected glare, several critical gaps remain. Future research should address the following priorities:

- (1) Developing and calibrating new glare indices for reflection-dominant environments: Existing indices such as DGP and DGI were originally designed for general indoor daylighting conditions and may not fully capture the localized, high-intensity characteristics of reflected sunlight glare. Future research should therefore focus on developing new or recalibrated glare indices specifically adapted to facade-reflected sunlight environments. These indices should incorporate both physical parameters (luminance, solar geometry, facade reflectance) and perceptual responses validated through field and simulation data to ensure robustness and applicability across diverse outdoor conditions.
- (2) Integrating user-centered validation methods such as structured surveys and HDR imaging: Human perception plays a critical role in glare experience; however, many studies rely only on physical measurements or simulated luminance data. Further research should incorporate subjective evaluation techniques with HDR image analysis.
- (3) Developing a consistent yet flexible framework of context-specific glare indices: Rather than defining a single “universal” discomfort glare indicator, future research should establish a structured family of indices validated for different outdoor conditions and user contexts—such as pedestrian comfort, vehicular glare, and facade reflections. Such an approach would enable comparability across studies while acknowledging the inherent variability of human perception and environmental dynamics.

To support the establishment of such a context-sensitive framework, Table 4 summarizes measurement- and experiment-based studies that have evaluated reflected glare under outdoor

Table 4

Summary of quantitative parameters used in outdoor reflected glare assessment.
(Continued on next page).

Author	Study type	Environment	Variable	Photometric measure	Reported value / threshold
Shih & Huang [47]	Measurement	Outdoor (urban facades in Taipei)	Solar altitude, azimuth, facade reflectance	Luminance (cd/m ²)	≈ 20,000 cd/m ² (glare noticeable above 10,000 cd/m ²)
Speroni et al. [7]	Measurement	Outdoor (urban scale, Milan)	Facade geometry, surface reflectance, irradiance ratio	Irradiance (W/m ²)	Up to 2500 W/m ² (pedestrian-level reflected radiation)
Moereke et al. [48]	Measurement	Outdoor (BIPV facades)	Gloss (DIN EN ISO 2813), BRDF angular reflection	Luminance (cd/m ²)	< 10 ⁴ cd/m ² (< 1.6 × 10 ⁵ cd/m ² safety limit)
Suk et al. [52]	Measurement	Outdoor (Los Angeles)	Solar reflection from specular facades, HDR imaging calibration, human subject study	Luminance (cd/m ²)	16,412–258,000 cd/m ² (HDR measured range); perceptible and disturbing glare observed, no intolerable glare reported
Suk et al. [8]	Measurement	Outdoor (controlled field test)	Specular facade reflection geometry, HDR imaging, visual comfort assessment	Luminance (cd/m ²)	≈ 22,500 cd/m ² threshold between perceptible and disturbing glare; field case up to 258,000 cd/m ²
Shih & Huang [1]	Simulation	Outdoor (urban facades in Taipei)	Solar altitude, azimuth, facade reflectance	Luminance (cd/m ²)	≈ 20,000 cd/m ² (glare noticeable > 10,000 cd/m ²)
Shih & Huang [59]	Simulation	Outdoor (Taiwan, three cities)	Latitude/longitude, facade orientation, reflection volume (RV)	Reflection Volume (unit ³)	3.9–13.2 unit ³ depending on season (largest at winter solstice)
Brzezicki [60]	Simulation	Outdoor (Warsaw, theoretical facades)	Facade curvature (concave, convex), solar position	Luminance (cd/m ²)	Up to 9 × 10 ⁵ cd/m ² for concave facades (focus zone); base-plane luminance ≈ 1.78 × 10 ⁴ cd/m ²
Zhu & Gu [61]	Simulation	Outdoor (high-rise business district, China)	Sun position, facade orientation, panorama reflection mapping	Irradiance (W/m ²), Duration (h)	Derived spatiotemporal maps showing reflection durations up to 3 h/day; method enables identification of reflection focus and shaded reflection scenarios
Talarico [62]	Simulation	Outdoor (urban roads, Melbourne CBD)	Facade reflectivity (20 %), observer view angle, solar position	Veiling luminance (cd/m ²)	Safety criterion 500 cd/m ² (Hassall 1991); observed exceedance mitigated by sun visor; reflectance ≤ 13 % keeps luminance ≤ 500 cd/m ²
Gil [66]	Simulation	Outdoor (urban canyon)	Glazing reflectance (0.2–0.7), orientation	Luminance (cd/m ²)	Peak facade luminance 1.2 × 10 ⁴ cd/m ² (clear sky)
Labib and Baltazar [67]	Simulation	Outdoor (urban canyon)	PV tilt, azimuth, surface reflectivity	DGP, Luminance (cd/m ²)	DGP = 0.45 (disturbing glare range), reflected luminance ≈ 10 ⁴ –10 ⁵ cd/m ²
Glanville et al. [73]	Simulation	Outdoor (road traffic)	Glare angle (°), direct normal illuminance, facade reflectance	Veiling luminance (cd/m ²)	500 cd/m ² threshold (Hassall, 1991) used as safety criterion
Abdelwahab, et al. [68]	Field observation	Outdoor (urban museum context, Texas)	Facade reflectivity, incident sunlight, visual impact	Luminance (cd/m ²)	Peak luminance on sculpture court estimated > 25,000 cd/m ² (visual discomfort, plant damage reported)
Wang [71]	Simulation	Outdoor (urban facades, Hong Kong)	Radiance simulations, facade reflectance, orientation	DGP	Recommended DGP < 0.35 for comfort; sensitivity tests confirm reliability
Wen, et al. [72]	Simulation	Outdoor (tropical urban high-rise, Singapore)	Reflectance (0–30 %), distance, height, orientation, sun position	DGP	21,120 cases; R ² adj > 0.9, reflectance < 20 % mitigates glare
Glanville, et al. [73]	Simulation	Outdoor (urban traffic and roadway context)	Specular/diffuse facade reflection, driver view angle	Veiling luminance (Lv, cd/m ²), Threshold Increment (TI)	Hazard threshold Lv = 500 cd/m ² (Hassall, 1991); population dosage risk > 10 ⁶ cd-s/m ² /day
Schiler and Valmont [74]	Field measurement + Simulation	Outdoor (Los Angeles, concave stainless-steel facades)	Facade curvature, solar position, surface temperature	Luminance (cd/m ²), Surface temperature (°C)	Peak luminance ≈ 12,000 cd/m ² , localized hot spots up to 70 °C
Littlefair [58]	Field observation	Outdoor (urban streets, UK)	Reflectance, viewing geometry, glare angle	Veiling luminance (Lv, cd/m ²)	Disability glare threshold ≈ 500 cd/m ² (adopted from road-lighting safety)
Jakubiec and Reinhart [3]	Field measurement + Simulation	Outdoor (control tower, US airport)	HDR imagery, reflective PV surfaces	Luminance (cd/m ²), DGP	Peak luminance ≈ 30,000 cd/m ² , DGP ≈ 0.40 – 0.45
Danks and Good [77]	Simulation + Field validation	Outdoor (urban facades)	3D geometry, reflectance (angle-dependent), solar position	Irradiance (W/m ²)	Validation error < 10 %; peak irradiance ≈ 3000–4000 W/m ²
Danks and Good [76]	Simulation + Field measurement	Outdoor (concave facade case study)	Irradiance mapping, reflectance (40 %), mitigation testing	Irradiance (W/m ²), Temperature gain (°C)	Peak irradiance > 6000 W/m ² , measured 1500–4000 W/m ² ; temp + 20 °C
Speroni, et al. [7]	Simulation	Outdoor (urban facades)	Solar reflectance (0.1–0.9), facade tilt, orientation	Irradiance (W/m ²)	Reflected irradiance up to 2800 W/m ² on adjacent facades
Castellani, et al. [79]	Simulation + Measurement	Outdoor test wall (Italy)	Surface type (retro-reflective vs diffuse), solar altitude	Luminance (cd/m ²), DGP	Retro-reflective facade reduced DGP ≈ 0.26–0.29 compared to conventional surface
Wang, et al. [6]	Simulation (Radiance-based)	Outdoor (Hong Kong high-rise facades)	Forward & backward ray tracing, BSDF, solar altitude	Illuminance (lux), Irradiance (W/m ²)	Peak ground illuminance > 50,000 lx; irradiance ≈ 2000–3000 W/m ²

and semi-outdoor conditions. The table lists key photometric parameters, including luminance, irradiance, and reflectance, together with their reported threshold or critical values. These empirical ranges provide a valuable reference for future efforts to calibrate and validate context-specific glare indices, enabling a

more consistent interpretation of reflection-induced glare phenomena across diverse environmental settings.

- (4) Establishing empirical datasets that couple physical measurements and perceptual responses: These datasets should include solar geometry, surface reflectance, luminance distributions, and

observer adaptation factors to facilitate the calibration of new outdoor glare indices.

- (5) Advancing integration of measurement and simulation platforms: The alignment of HDR imaging and Radiance-based simulations is essential for perception-validated glare assessment. Moreover, integrating reflective-glare sensing and facade control systems, as demonstrated by Kim et al. [81], represents a promising direction for adaptive glare mitigation in future building envelopes.

These advancements, supported by integrated datasets and simulation–measurement alignment, will enable more reliable assessment of reflected solar glare phenomena across diverse building and urban contexts.

Currently, no regulatory guidelines, standardized assessment protocols, or universally accepted methodologies exist for evaluating the glare caused by reflected sunlight. This lack of an established framework limits the consistency, comparability, and practical applicability of the current research findings. Further, most existing glare indices have been developed for general indoor daylight conditions and may not be directly transferable to reflected glare scenarios. Therefore, evaluations remain fragmented, and the findings are difficult to generalize across different studies and urban contexts. To address these limitations, future research should focus on developing standardized yet context-sensitive frameworks that integrate physical measurements, simulation methods, and perceptual evaluations. Such frameworks should include clear protocols for measurement and modeling, validation of context-specific glare indices under reflected light conditions, and incorporation of human-centered evaluation methods such as structured surveys and HDR imaging. Establishing these foundations will improve the reliability of reflected glare assessments and promote their practical use

in building design and urban planning.

In conclusion, there remains a critical need for standardized yet adaptive methodologies that combine physical, perceptual, and environmental parameters. Rather than seeking universality in a single metric, future research should aim for a harmonized framework that balances methodological rigor with flexibility across diverse outdoor conditions.

CRediT authorship contribution statement

Jisoo Lee: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis. **Hyungsun Kim:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Eunhyun Lim:** Writing – review & editing, Visualization, Validation. **Minjae Shin:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Jae Yong Suk:** Writing – review & editing, Validation, Resources, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table 1A

Table 1A
Overview of reviewed studies on reflected glare assessment. (Continued on next pages).

Year	Author	Title	Study type	What did the literature do?	Limitations
1987	Littlefair et al.	Prediction of reflected solar dazzle from sloping facades	Simulation	Presented a design-stage calculation method to predict times and locations of solar dazzle from sloping glazed facades.	Quantified geometric and temporal risk of dazzle only; did not assess visual glare with human subjects or standardized discomfort metrics.
2001	Shih & Huang	A study of reflection glare in Taipei	Measurement	Surveyed and observed reflection glare from curtain-walled buildings in Taipei to identify affected areas, times, and building factors.	Relied mainly on subjective, small-sample observations without standardized glare metrics or controlled environmental variables, limiting reproducibility and generalization.
2001	Shih et al.	An analysis and simulation of curtain wall reflection glare	Simulation	Developed computer-aided simulations (BRA) and surveyed buildings with glass curtain walls to analyze reflected glare patterns and influence on the urban environment.	Quantified reflection areas, but did not measure visual glare or discomfort via human subjects or standardized glare indices; relied on geometric simulation and qualitative interpretation.
2001	Shih et al.	Volumetric study of reflected glare from glass curtain walls of buildings	Simulation	Developed 3D simulation to predict volumes and boundaries of reflected glare for design and environmental evaluation of glass curtain wall buildings.	Focused on geometric simulation; did not quantify visual glare with human subjects or standardized discomfort metrics.
2005	Schiler & Valmont	Microclimatic impact: Glare around the Walt Disney Concert Hall	Measurement + Simulation	Measured and simulated glare and heat spots caused by reflective stainless steel surfaces; suggested surface treatment for mitigation.	Relied on simulation and photographic analysis without formal human glare testing or standard glare metrics.
2006	Schiler & Valmont	Urban environmental glare: the secondary consequence of highly reflective materials	Measurement + Simulation	Evaluated environmental glare and thermal impact of reflective materials in urban settings, focusing on material gloss and mitigation.	Mostly qualitative glare assessment without direct human discomfort testing or standardized metrics; results case-specific.
2012	Brzezicki	The influence of reflected solar glare caused by the glass cladding of a	Simulation	Used computer simulations and image analysis to examine how different facade	Quantified glare areas and luminance via simulation; did not directly assess visual

(continued on next page)

Table 1A (continued)

Year	Author	Title	Study type	What did the literature do?	Limitations
2013	Yang et al.	building: Application of caustic curve analysis Simulation of reflected daylight from building envelopes	Simulation	geometries affect glare formation and intensity. Developed a simulation tool using ray tracing to assess reflected daylight distribution and identify critical glare spots on building facades for design improvement.	discomfort or use standardized visual glare metrics. Assessment focused on simulated illuminance and radiance; did not include direct human subject evaluations or standardized visual glare discomfort metrics, limiting validation of perceived visual glare impact.
2013	Yang et al.	The assessment of daylight reflection from building envelopes	Simulation	Developed a ray tracing-based software tool to evaluate reflected daylight distribution and critical glare areas around building facades for design optimization.	Focused on simulated illuminance and radiance without direct human subject validation or standardized visual glare metrics, limiting perception-based evaluation.
2014	Jakubiec & Reinhart	Assessing disability glare potential of reflections from new construction: Case study analysis and recommendations for the future	Measurement + Simulation	Developed a simulation method combined with HDR imaging to analyze annual disability glare from a large PV array at an airport and tested remediation options.	Simulation focused on clear-sky conditions; lacked direct human glare discomfort tests; results based on a single case study limiting generalization.
2016	Suk et al.	Is exterior glare problematic? Investigation on visual discomfort caused by reflected sunlight on specular building facades	Measurement	Conducted on-site human subject tests with HDR imaging to investigate discomfort glare from specular facade reflections under outdoor conditions.	Field-based method sensitive to uncontrolled outdoor factors; did not establish exterior glare criteria; lacks generalized, standardized discomfort threshold.
2016	Wong et al.	A comprehensive ray tracing study on the impact of solar reflections from glass curtain walls	Simulation	Simulated solar reflections from the ICC building in Hong Kong to assess light intensity and hit times on surrounding buildings using a detailed ray tracing model.	Quantified solar reflection impact using geometric and intensity modeling; did not include human visual discomfort assessment or standardized visual glare metrics.
2016	Labib & Baltazar	Analysis and quantification of visual glare caused by photovoltaic panels installations in urban canyons	Simulation	Quantified potential glare from PV panels in an urban office canyon using annual simulations and HDR image analysis.	Relied on simulation and luminance indices; did not conduct direct human subject glare testing; limited by unavailable PV optical data and real-world condition variability.
2016	López-Rioboo Gil	Evaluation of solar glare from reflective facades: A general method	Simulation	Proposed a simplified ray-tracing method combining geometric reflection analysis and veiling glare intensity calculation to identify and quantify glare risks on building facades.	Relied on assumed formula parameters and fixed background luminance; no human subject tests or dynamic glare adaptation considered, limiting validation of visual discomfort.
2016	Danks & Good	Urban scale simulations of solar reflections in the built environment: methodology & validation	Measurement + Simulation	Developed and validated ECLIPSE, a simulation tool for predicting urban-scale solar reflections and irradiance levels, using detailed case studies with field measurements.	Focused mainly on solar irradiance and thermal impacts; did not assess human visual discomfort or apply standardized glare metrics.
2016	Danks & Good	Urban solar reflection identification, simulation, analysis and mitigation: learning from case studies	Measurement + Simulation	Developed and applied a simulation tool to model solar reflection impacts and mitigation in urban environments based on real cases; validated with field measurements.	Focused mainly on irradiance and heat; did not use standardized visual glare metrics or direct human discomfort assessment.
2017	Suk et al.	Reflectivity and specularity of building envelopes: how materiality in architecture affects human visual comfort	Measurement	Investigated visual discomfort from reflected sunlight using outdoor human subject study and HDR imaging, and proposed a luminance threshold for exterior glare.	Defined a preliminary exterior glare threshold, but results are limited by small sample and outdoor variability; no universally validated glare metric established.
2018	Ishak et al.	The effect of building facade reflectivity on urban dwellers in tropics	Measurement	Developed a framework for evaluating perceived outdoor glare among pedestrians near reflective facades in Singapore using questionnaire surveys and SEM.	Assessed perceived glare with self-reported survey data; did not include direct or standardized visual glare measurements.
2018	Shilston & Danks	Simulation of urban solar reflections and their impact on building performance	Measurement + Simulation	Developed and validated a simulation tool to analyze solar reflections in urban environments, assessed multiple facade case studies for visual and thermal impacts, and evaluated mitigation options.	Focused on heat and simulation glare; no direct human glare testing or standard metrics.
2019	Ishak et al.	Effect of reflective building facade on pedestrian visual comfort	Measurement	Surveyed 500 pedestrians in Kuala Lumpur to model the impact of reflective facade glare on visual comfort using Structural Equation Modeling (SEM).	Relied on subjective questionnaire data without direct or standardized visual glare measurements, limiting quantitative glare assessment.
2019	Zhu et al.	Computer simulation of sunlight concentration due to facade shape: application to the 2013 Death Ray at Fenchurch Street, London	Simulation	Simulated sunlight concentration hotspots caused by a concave glass facade to evaluate irradiance intensity, timing, and spatial distribution related to thermal effects and damage risk.	Focused on thermal irradiance; did not include direct or standardized visual glare measurements or perception studies, limiting evaluation of visual discomfort.
2019	Abdelwahab et al.	The negative impact of solar reflections caused by reflective buildings' facades: case study of the Nasher Museum in Texas	Simulation	Simulated point-in-time glare within a museum using DGP and HDR images to assess the impact of reflections from a	Limited by simplified ceiling/shading modeling; solution mainly focused on material reflectance; direct human

(continued on next page)

Table 1A (continued)

Year	Author	Title	Study type	What did the literature do?	Limitations
2020	Labib & Clayton	Automated computer vision recognition based method to determine glare causing patches on reflective building facades	Simulation	neighboring tower and test effects of less-reflective facade material. Proposed and demonstrated an automated computer vision method (OpenCV, Python) to accurately locate and analyze glare-causing facade patches from simulation-based HDR imagery across thousands of views.	perception testing and field validation of visual discomfort were not conducted. Method requires advanced programming; assesses glare via DGP in simulations only, with no physical measurements or human subject validation; usability limited for non-experts.
2020	Castellani et al.	Optic-energy and visual comfort analysis of retro-reflective building plasters	Measurement + Simulation	Developed and tested retro-reflective wall plasters; compared glare (DGP) and temperature between RR and diffusive facades in real outdoor settings.	DGP-based glare assessment limited to summer, short-term; no direct human discomfort testing or long-term validation.
2020	Šujanová	Urban solar reflections identification, simulation and analysis	Measurement + Simulation	Developed a new method and software for simulating and analyzing urban solar glare; performed HDR-based field calibration and tested existing theoretical models.	Combined simulation and HDR field data; lacked direct large-scale human glare discomfort evaluations; revealed critical flaws in the tested theoretical model.
2021	Ishak et al.	The impact of building facade reflectivity on pedestrian visual comfort with the application of Bayesian structural equation modeling	Measurement	Modeled the impact of building facade reflectivity on pedestrian visual comfort using questionnaire surveys and various statistical approaches (regression, SEM, Bayesian SEM).	Relied on self-reported survey data; lacked direct or standardized measurement of visual glare.
2021	Wang et al.	Investigation on how daylight simulation should be used to characterize daylight-related issues for buildings in Hong Kong	Simulation	Compared different daylight simulation methods and field data to assess daylighting and dimming system performance in Hong Kong buildings.	Focused on illuminance, daylight and energy savings; did not directly measure or model visual glare/discomfort perceptions.
2021	Wang et al.	Comparison of daylight simulation methods for reflected sunlight from curtain walls	Measurement + Simulation	Compared and validated four daylight simulation methods to assess reflected sunlight from real curtain walls; recommended efficient workflows.	Focused on illuminance from simulations; did not directly assess visual glare or discomfort perceptions, nor use standardized glare metrics.
2022	Speroni et al.	Experimental assessment of the reflection of solar radiation from facades of tall buildings to the pedestrian level	Measurement	Quantified pedestrian-level solar irradiance from different tall building facades using scale model experiments and simulations.	Focused on irradiance and thermal effects; lacked direct visual glare measurements or standardized glare indices.
2022	Moereke et al.	Light reflection analysis of PV modules: Comparison to building facades and assessing the possibility of glare	Measurement	Measured and compared reflection from PV modules and facade materials using gloss and BRDF methods to assess glare potential.	Relied on physical measurements and indirect luminance estimates without direct visual glare assessment or standardized glare indices, limiting glare quantification.
2022	Sagawa et al.	An examination of reflected glare prediction method based on luminance distribution	Measurement	Conducted experiments with subjects in a simulated exhibition room to predict reflected glare on paintings based on luminance, reflectance, and glossiness.	Focused on subjective ratings and regression modeling; controlled setting limits real-world generalizability, and did not establish standardized visual glare metrics.
2022	Zhu et al.	A method of estimating the spatiotemporal distribution of reflected sunlight from glass curtain walls in high-rise business districts using street-view panoramas	Simulation	Proposed a method using street-view panoramas to map and quantify spatiotemporal distribution of reflected sunlight from glass facades in urban streets.	Focused on distribution and thermal effects; visual glare assessed theoretically only, without direct measurement, subject tests, or standardized glare metrics.
2022	Wen et al.	A prediction model for fast evaluation of reflective glare from surrounding buildings	Simulation	Developed an empirical model using data from extensive parametric ray-tracing simulations to predict DGP and daylight metrics for urban facade glare evaluation.	Model focused on clear-sky, point-in-time scenarios; annual effects and occupant subjective responses not considered.
2023	Talarico	Environmental analysis of reflected glare	Simulation	Modeled glare from building facades using veiling luminance (500 Cd/m ²), 3D simulations, and assessed mitigation options for road safety in Melbourne.	Used veiling luminance simulation for safety but did not assess visual comfort or glare perception with human subjects or standardized discomfort indices.
2023	Wen et al.	Impacts of a highly reflective stainless-steel facade on a surrounding building: A case study in Singapore	Measurement + Simulation	Measured and modeled how a reflective stainless-steel facade affected daylight and temperature in classrooms of a neighboring school, quantifying changes by distance and proposing safe separation.	Focused on physical daylight and thermal impacts; did not directly assess visual glare discomfort, use standardized glare metrics, or evaluate subjective human responses.
2024	Kristanto et al.	Reducing glare on building facade by implementing vertical greenery shading: user-sensation vs luminance-measurement	Measurement	Tested vertical greenery as facade shading using user glare sensation votes and luminance measurements in a mock-up cubicle.	Glare sensation assessed by self-reported votes; lacked established standardized glare indices and long-term or broader contextual validation.
2024	Glanville et al.	Modelling solar disability glare reflected off modern building facades	Simulation	Modeled risk of solar disability glare for drivers caused by modern facade reflections using veiling luminance calculations and case studies.	Focused on traffic disability glare; did not address pedestrian or indoor discomfort glare, and human subject validation limited.

Data availability

No data was used for the research described in the article.

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