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EXPLORING THE LIGHTING ENVIRONMENT OF RESEARCH AND DEVELOPMENT LABORATORIES FOR DRIVING AND RIDING EXPERIENCE IN THE SMART TRANSPORTATION ERA

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EXPLORING THE LIGHTING ENVIRONMENT OF RESEARCH AND DEVELOPMENT LABORATORIES FOR DRIVING AND RIDING EXPERIENCE IN THE SMART TRANSPORTATION ERA

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Abstract

With the rapid development of smart transportation and autonomous driving technologies, creating realistic and immersive lighting conditions in vehicular research and development laboratories has become crucial for understanding the effects of in-vehicle lighting on visual and non-visual perceptions, comfort, health and overall experience. However, current experimental setups either lack immersion or fail to reproduce high-intensity dynamic light sources such as sunlight and headlights. To address this, field measurements of luminance distributions in urban driving scenarios were conducted, and key characteristics of in-vehicle lighting were identified, including variations influenced by natural and artificial light, vehicle directions, times of day, and obstructions such as buildings. Based on these findings, the paper proposes a novel laboratory design to better reproduce real-world lighting while ensuring essential immersion. The laboratory setup will support more precise investigations into in-vehicle lighting, providing technical support for optimising future smart transportation systems and improving driving and riding experience.

Keywords: In-vehicle lighting, Luminance distribution, Field measurements, Virtual driving and riding environment, Smart transportation.

1 Introduction

In the era of smart transportation and autonomous driving, the role of in-vehicle spaces is undergoing a profound transformation. Vehicles may no longer serve only as transportation tools but also as mobile multifunctional spaces that accommodate a variety of activities such as work and leisure (Pollmann et al., 2019). As a result, the demand for well-designed in-vehicle environments has drawn more and more scholarly attention. Among various environmental factors, in-vehicle lighting plays a crucial role in influencing both visual and non-visual perceptions, as well as comfort, health and overall experience. Accordingly, the design of experimental environments that can faithfully reproduce the in-vehicle lighting has become a critical research topic (Haycock et al., 2019).

Current driving and riding experimental setups often fail to fully reproduce the lighting environment of real-world scenarios. On one hand, traditional driving simulators prioritise the virtual environments, usually with screens, but struggle to reproduce the high-intensity, dynamic light sources such as sunlight, streetlights, and vehicle headlights with sufficient realism (Li et al., 2021). On the other hand, studies focusing on specific lighting effects, such as glare from sunlight or vehicle headlights, tend to use isolated light sources in simplified settings, which lack the immersive context of a driving and riding environment (Stanke et al., 2022). These limitations hinder the validity of the findings and their applicability to future autonomous and smart transportation systems.

To bridge these gaps, the study conducted field measurements of luminance distributions under urban driving scenarios to identify the key characteristics of in-vehicle lighting. Based on the findings, the paper proposes a novel research and development laboratory design that integrates both dynamic high-intensity light sources and an immersive environment, enabling a more accurate reproduction of real-world in-vehicle lighting conditions. The new laboratory

setup will support more precise investigations into in-vehicle lighting, contributing to the optimisation of smart transportation systems and the improvement of driving and riding experience.

2 Luminance distribution as a metric for in-vehicle lighting

In architectural lighting studies, illuminance is widely used as a primary metric, as it quantifies the amount of light falling on a given surface. Metrics such as Daylight Autonomy and Useful Daylight Illuminance further extend its applicability in evaluating long-term daylight performance. However, applying illuminance-based metrics to in-vehicle lighting presents significant challenges. Unlike architecture — where fixed, functionally consistent surfaces like desks or floors provide stable reference planes — vehicle interiors lack a single dominant visual reference. The drivers' primary attention is directed toward the road, while passengers may engage in diverse activities, making a universal reference surface impractical.

An alternative metric for in-vehicle lighting is eye illuminance, which accounts for the total luminous flux reaching the observer's eyes (Liu & Zhang, 2022). While this person-centred metric offers a generalised measure of perceived brightness, it reduces the entire visual field to a single numerical value. As such, it fails to capture the complex, dynamic, and non-uniform nature of in-vehicle lighting. For instance, during daytime driving, the sky may have a significantly higher luminance level compared with surrounding buildings or vehicle interiors. At night, small but intense light sources, such as streetlights or vehicle headlights, bring strong luminance contrasts within the visual field. These variations affect visual comfort, glare perception, and spatial awareness, none of which can be effectively evaluated using a single-point metric.

In contrast, luminance distribution — a spatial map of luminance values observed from the viewpoint — provides a more comprehensive description of the light perceived by drivers and passengers. By measuring the luminance values across the entire visual field, it preserves both intensity and spatial variation, allowing for a more detailed analysis of the impact of in-vehicle lighting. Moreover, luminance data contains the information to calculate eye illuminance, ensuring that no critical information is lost in the process.

In light of these considerations, the study adopts luminance distribution as the primary evaluation metric for in-vehicle lighting. This approach provides a more accurate basis for analysing lighting conditions, particularly in terms of spatial variation and luminance extremes.

3 Field measurements

To investigate the spatial and temporal characteristics of in-vehicle luminance distribution, field measurements were conducted in real-world urban driving environments. The objective was to collect panoramic luminance data at multiple locations and times of day, to help analyse the typical characteristics of in-vehicle lighting.

The field measurements were conducted in Beijing, China on March 8, 2025 — a clear day with minimal clouds. The local sunrise time was 06:37, and sunset time was 18:13. The measuring site was located in a few blocks near the East 5th Ring Road. A total of 12 measuring points were selected, with three oriented toward each of the four cardinal directions: north, south, east, and west. These measuring points were chosen to represent a variety of urban contexts, including wide roads, narrow streets, open spaces, and areas surrounded by tall buildings (Figure 1).

A luminance measuring device (LGM-200B lighting glare measurement system) was mounted at the front passenger's eye level within the vehicle to capture the luminance distribution from the occupant's viewpoint (Figure 2). Each panoramic luminance distribution image was generated by combining multiple exposures taken by the device, resulting in a capture time of over three minutes per image. Accordingly, all measurements were conducted with the vehicle parked at each measuring point, and the exact measuring times were recorded.

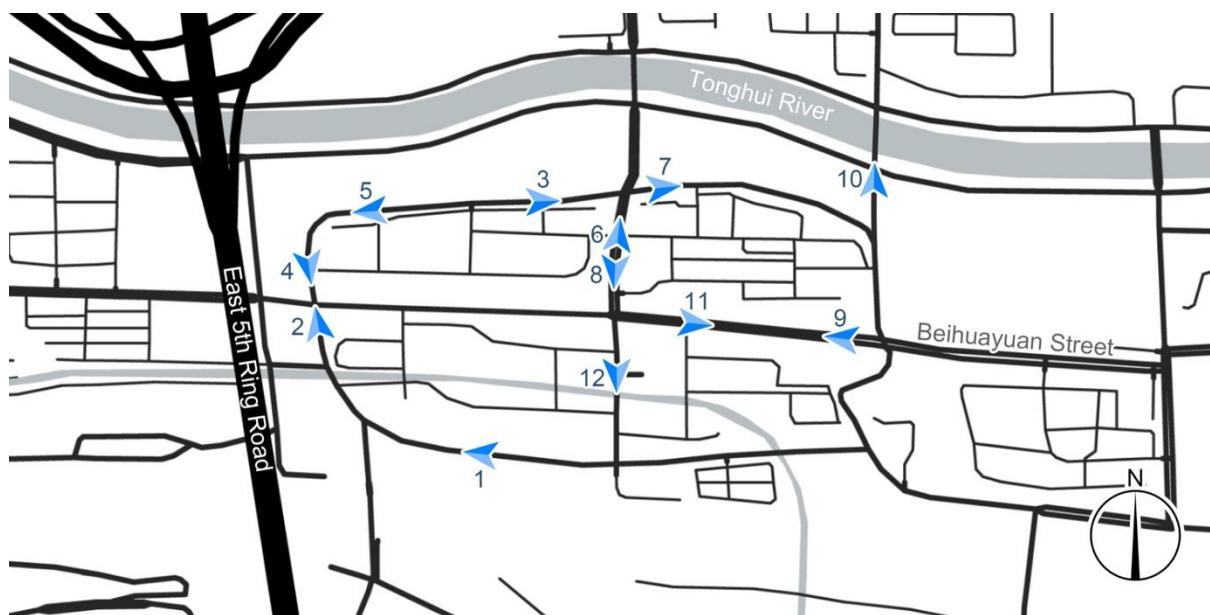


Figure 1 – 12 measuring points



Figure 2 – Field measurements setup

To evaluate the differences between times of day, each measuring point was revisited during four time periods: morning (08:00-11:00), afternoon (12:00-16:00), late afternoon (16:00-18:00), and night (19:00-21:00). In total, 48 luminance distribution datasets were collected, including 36 daytime measurements and 12 nighttime measurements.

These datasets, collected across different times and urban environments, provide valuable foundations for identifying the typical characteristics of in-vehicle lighting. Such findings can further support the design of an immersive research and development laboratory that can accurately reproduce the real-world lighting environments.

4 In-vehicle luminance distribution under real-world conditions

4.1 Typical in-vehicle luminance distribution during daytime

Figure 3 shows a typical daytime in-vehicle panoramic luminance distribution image captured at 15:38 on March 8, 2025, at measuring point 4, with the vehicle facing south. The results reveal a pronounced non-uniformity of luminance distribution across the in-vehicle visual field. To begin with, the exterior of the vehicle appears significantly brighter than the interior. Among the exterior elements, the sky is generally the brightest region in the visual field, with luminance often reaching several thousand to tens of thousands of cd/m^2 . Following the sky, the surrounding urban elements such as buildings, roads, and trees exhibit moderate luminance levels, generally falling within the range of $400\text{-}2000\text{ cd}/\text{m}^2$. Inside the vehicle, surfaces partially exposed to daylight, such as the upper part of the dashboard or the edges of the windshield, show lower luminance, mostly in the range of $100\text{-}400\text{ cd}/\text{m}^2$. Finally, areas that are not exposed directly to daylight, such as the interior ceiling or the lower part of the dashboard, are the darkest, with luminance values mostly below $100\text{ cd}/\text{m}^2$.

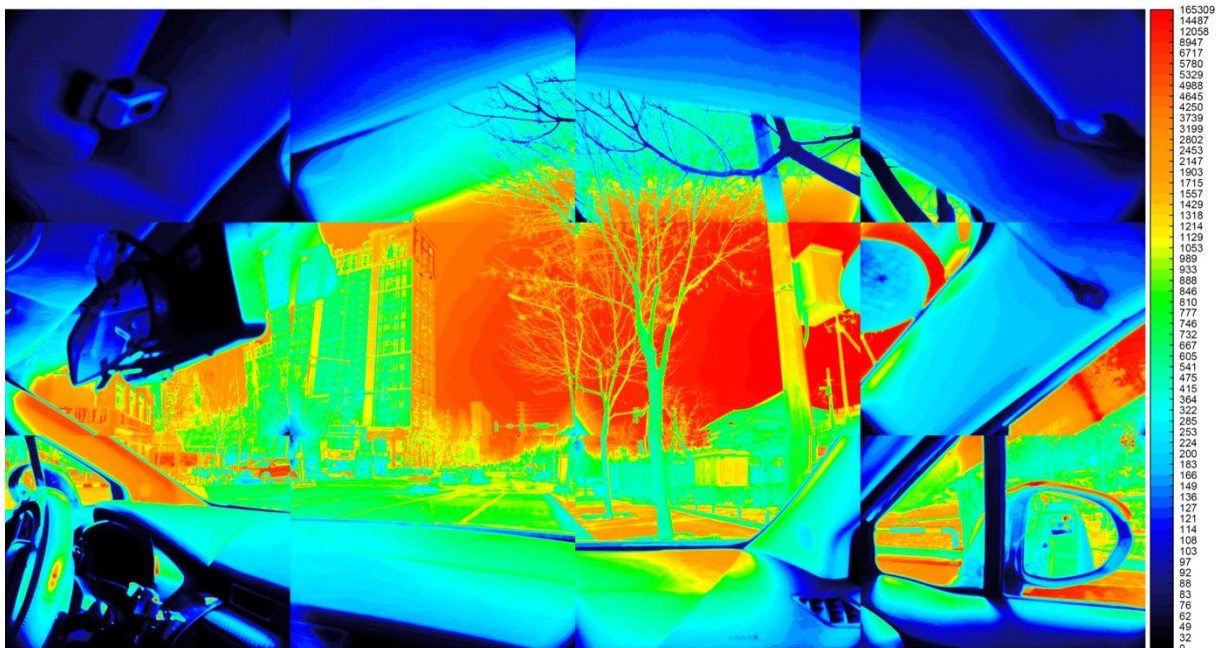


Figure 3 – A typical panoramic in-vehicle luminance distribution during daytime

To provide a quantitative understanding of this typical in-vehicle luminance distribution, a corresponding histogram of luminance values is shown in Figure 4. The horizontal axis is plotted on a logarithmic scale to better represent the wide luminance range. The histogram reveals a multimodal distribution pattern, with several distinct peaks corresponding to different elements in the typical daytime in-vehicle panoramic luminance distribution image.

The first and leftmost small peak, located below $40\text{ cd}/\text{m}^2$, represents the darkest areas within the vehicle, such as part of the ceiling and the lower dashboard. The dominant central peak spans from approximately $80\text{ to }200\text{ cd}/\text{m}^2$, and it shows the luminance of most of the vehicle interior. Another prominent peak emerges in the range of $500\text{ to }1000\text{ cd}/\text{m}^2$, which mostly represents some of the exterior elements, including the building facades and roads. A small portion of bright vehicle interior surfaces also falls in this range. Finally, the two rightmost peaks — extending beyond $4000\text{ cd}/\text{m}^2$ — represent the sky, which appears as the brightest region in the upper central field of the outside view. In some very small areas (less than 0.1%), especially near the sun or due to specular highlights, luminance exceeds $20000\text{ cd}/\text{m}^2$.

This typical luminance distribution demonstrates the non-uniform and high-contrast nature of in-vehicle lighting, suggesting that any laboratory-based simulation should be capable of reproducing both low-luminance and high-luminance areas at the same time to enhance realism.

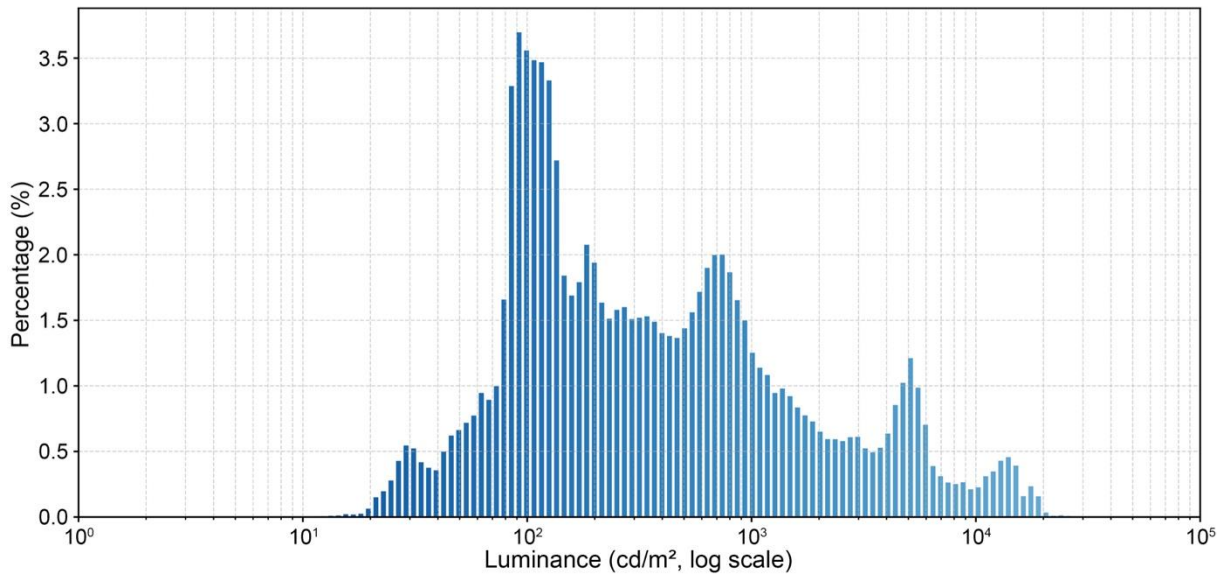


Figure 4 – Histogram of the typical daytime in-vehicle luminance distribution

4.2 Temporal and spatial variations in daytime luminance distributions

To examine how in-vehicle luminance distribution varies across times, locations, and directions, the luminance data distribution of all 36 daytime measurements were compared, as shown in Figure 5.

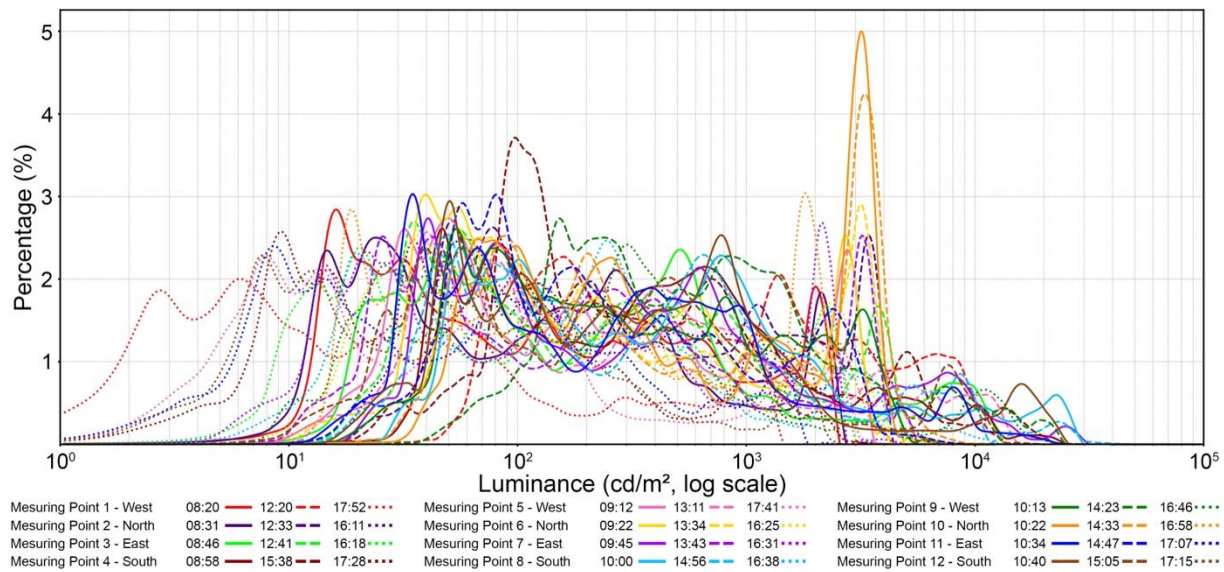


Figure 5 – 36 daytime in-vehicle luminance distributions

As for the temporal variations, the in-vehicle luminance distributions recorded during late morning, midday, and early afternoon generally show higher overall brightness, with larger proportions of high-luminance values above 1000 cd/m². This is primarily due to stronger skylight and higher solar altitude. On the contrary, in the earlier or later times of the day, the overall luminance shifts toward a lower range, with greater presence of darker regions within the visual field.

When it comes to directional differences, the in-vehicle luminance distributions recorded when facing south typically contain more intense daylight and brighter portions of the sky, resulting in more pronounced high-luminance peaks. When facing east and west, high luminance levels are also observed, particularly in the morning and afternoon respectively, due to the changing

solar angle. On the other hand, when facing north, the luminance distributions tend to be more stable throughout the day, with daylight-related peaks shifted toward lower values.

The spatial differences across measuring points are also significant. For those surrounded by tall buildings, the average luminance is lower, and most of them have a flatter distribution. In comparison, open spaces with less obstructions tend to show higher average luminance and most of them have a more pronounced and varied distribution.

These findings highlight the complexity and heterogeneity of in-vehicle lighting under real-world conditions. In order to faithfully reproduce such diverse and dynamic lighting distributions in laboratory setups, it is necessary to adopt lighting systems that can simulate both spatial variations in luminance and temporally dynamic lighting conditions.

4.3 Analysis of nighttime luminance distributions

After the complete disappearance of natural twilight, and artificial lighting became dominant, the in-vehicle luminance distributions were recorded again at the 12 measuring points. The overall data distributions under nighttime lighting conditions are shown in Figure 6.

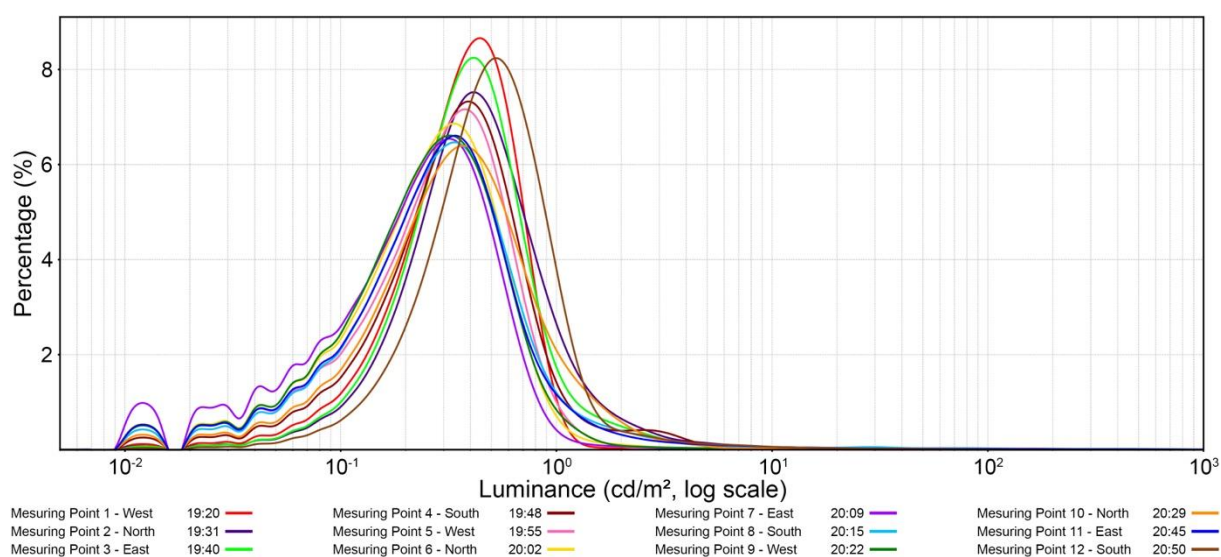


Figure 6 – 12 nighttime in-vehicle luminance distributions

Compared to daytime, the luminance values were significantly reduced, with most values concentrated in the very low luminance range below approximately 2 cd/m², and the distributions were highly skewed. It can be seen that the in-vehicle visual field at night is generally dim, with low luminance both inside and outside the vehicle.

Despite the overall darkness, some unusual luminance peaks were observed at several measuring points, suggesting the frequent presence of bright spots caused by headlights or streetlights. These bright spots are mostly small in size but extremely high in luminance. Although they account for only a very small portion of the overall luminance distribution and are barely visible in the data distribution curves due to their limited area, their perceptual impact is likely significant.

In general, the nighttime luminance distributions shifted from the daytime's complexity and variability to a condition dominated by low luminance with occasional high-luminance intrusions. For the laboratory setup, it should be taken into account on how to reproduce such "dark-dominated with scattered dynamic highlights" scenarios.

4.4 "Bright spots"

In the field measurements, it was observed that the in-vehicle visual field often contains areas with extremely high luminance concentrated in small regions. In the study, the term "bright spots" is introduced to describe this phenomenon — defined as high-intensity, small-in-size, and dynamic light sources commonly observed in the in-vehicle luminance distribution. Bright spots

are usually caused by direct or reflected sunlight during the daytime, and by headlights or street lights during the nighttime. They play an essential role in the in-vehicle lighting.

Due to technical limitations, direct measurement of sunlight was avoided during the study. Whenever the sun is within the visual field, the measuring device would fail to provide luminance data, for it would extremely exceed the available range. However, during the measurements, the sun frequently appeared in the visual field, and unfortunately, these circumstances were not measured. Literature suggests that the luminance of the sun can reach up to $1.93 \times 10^9 \text{ cd/m}^2$, which, even when accounting for atmospheric attenuation, windshield transmittance, and variations in solar angle, remains intensely bright, often dominating the visual field and reducing the perceived brightness of surrounding elements due to the high contrast (Karandikar, 1955).

As for the headlights and some street lights at night, they are, of course, much less in luminance compared with the sun. However, headlights and streetlights can have a significant impact on the visual field, creating notable bright spots.

The dynamic characteristic of the bright spots makes them even more complex to the in-vehicle lighting. Their position and intensity change constantly as the vehicle moves or the time changes. For instance, the sun shifts when the car turns, or it may be occasionally blocked by buildings, bridges, or clouds. Similarly, headlights from other vehicles appear, move, and disappear unpredictably.

Bright spots are unique for in-vehicle lighting compared with architectural lighting, where such high-intensity, small-in-size, and dynamic light sources are rarely encountered. Their ever-changing nature makes them difficult to study using conventional methods, yet, they play an important role in affecting visual comfort and glare perception. As such, accurately reproducing the bright spots in a controlled laboratory setting becomes essential for future research.

5 Designing a realistic and immersive laboratory for driving and riding research

The in-vehicle lighting is characterised by significant spatial non-uniformity, frequent dynamic changes, and the presence of bright spots such as sunlight or headlights. To reproduce such conditions in a laboratory setting, it is necessary to develop new solutions capable of creating wide and time-varying luminance ranges, spatial variability, and dynamic bright spots.

One promising approach is to install a spherical self-luminous high dynamic range (HDR) display. By placing the driving cockpit at the centre of the sphere and adjusting the luminance distribution and colour appearance on the screen to match the real-world scenarios, it seems feasible to reproduce the overall lighting environment and achieve a realistic visual experience (Figure 7a).

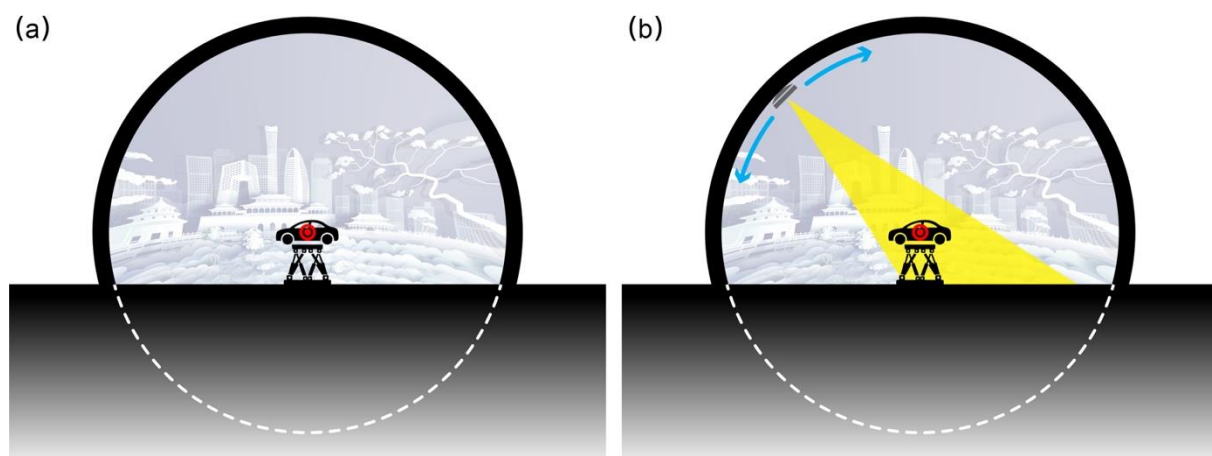


Figure 7 – (a) Spherical display is sufficient for most elements, but not for bright spots. (b) Movable light sources in front of the display compromise the immersive environment.

However, current self-luminous displays generally have a limited luminance range, usually with a peak luminance of approximately 20000 cd/m² (Lee et al., 2016). According to the field measurements, the range is sufficient for reproducing most real-world elements such as skylight, buildings, trees, roads, etc. However, when it comes to the bright spots frequently encountered in the in-vehicle lighting, such as sunlight and vehicle headlights, it could be insufficient in simulating these extremely high-intensity light sources.

To address such limitations, one straightforward solution is to install movable high-intensity light sources in front of the spherical display. However, this would introduce visible lighting fixtures, tracks, and structures that would probably compromise the immersive quality of the simulated driving and riding environment (Figure 7b).

A more creative idea is to use reflection. If these bright spots can be achieved in the visual field through reflections in the laboratory, they may appear naturally without exposing the physical lighting fixtures. Recent advances in mirror-type self-luminous displays provide a technical foundation for this idea, as they can simultaneously emit light and reflect external light through specular reflection.

An ellipse has two focal points and an important optical property: light emitted from one focal point can be reflected to the other. The same property applies to prolate spheroid, a type of ellipsoid of revolution, which inspires the idea of transforming the traditional spherical screen into a prolate spheroidal one (Figure 8a). If the screen is a high-reflectance mirror display, by positioning one focal point with high-intensity light sources and the other with the driving cockpit, it could be possible to reflect the light onto the cockpit (Figure 8b). Such a setup could help reproduce the bright spots on the surface of the screen, creating a realistic lighting environment for the driving and riding laboratory.

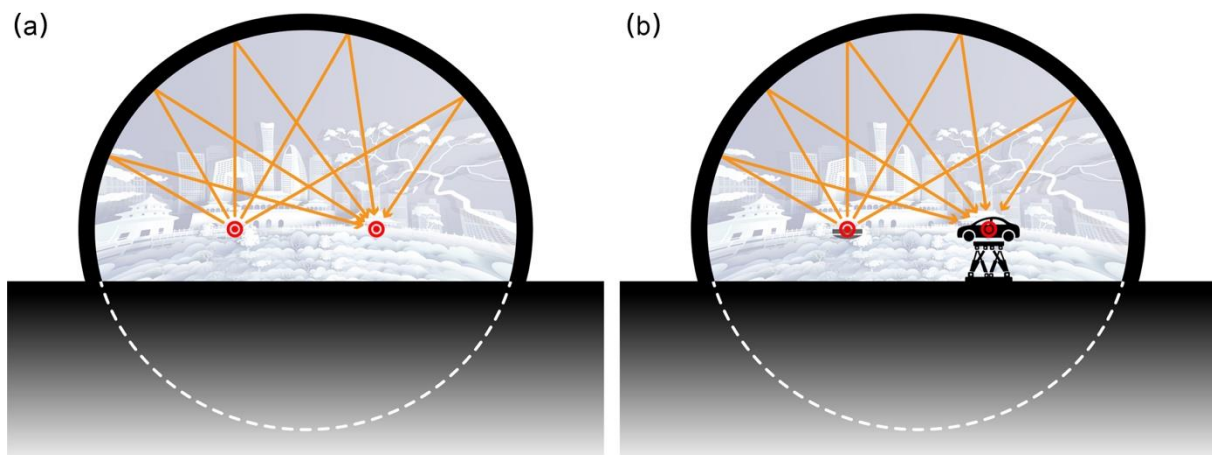


Figure 8 – (a) Light from one focal point of prolate spheroids can be reflected to the other. (b) Light sources at one focal point with a prolate spheroidal mirror display create bright spots.

To achieve an immersive lighting environment, the prolate spheroidal screen must support HDR rendering. This allows for regions of extreme brightness — such as the simulated sky — to coexist with much dimmer areas, such as buildings and roads, simultaneously. It reproduces the non-uniform luminance characteristics observed in real-world driving environments. However, unlike a spherical display, a prolate spheroidal one may lead to spatial distortions. Therefore, the panoramic environment should be geometrically transformed to align with the viewing perspective from the cockpit's focal point, ensuring that the displayed environment appears optically undistorted in the driver's and passengers' view.

Due to the optical property of prolate spheroids, all light rays emitted from one focal point — regardless of direction — are reflected toward the other focal point. As a result, if a small light source is used, it would create a highly focused light beam that converges to a single point at the cockpit (Figure 9a). This is not realistic for simulating the broad spatial distribution of natural or artificial light. Therefore, to create a wider beam of light that can evenly cover the entire cockpit, the light source should have a large emitting surface and be capable of projecting a

converging light cone (Figure 9b). The size of the light-emitting area and the beam divergence angle should both be adjustable to achieve the required lighting pattern around the cockpit.

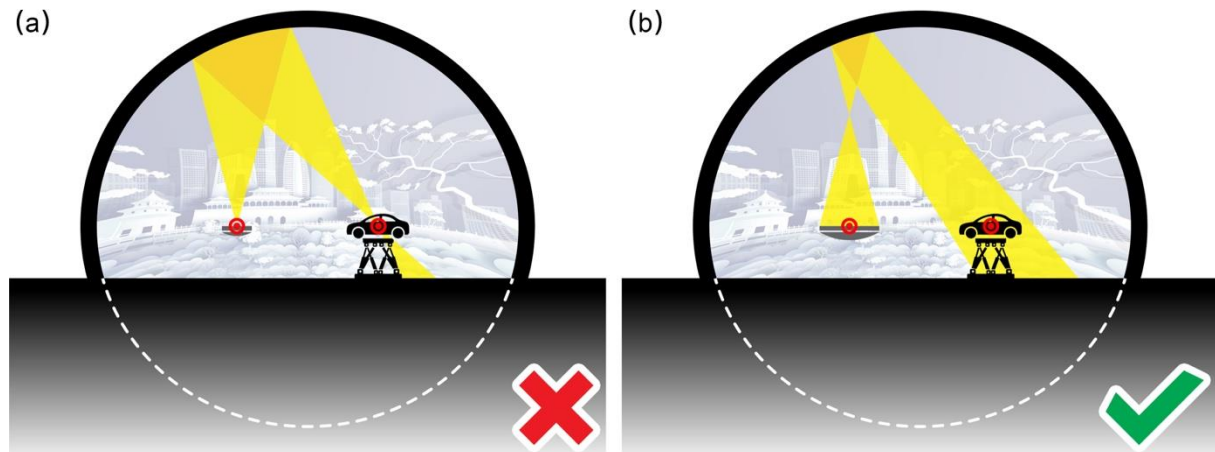


Figure 9 – (a) Light from one focal point converges to a single point. (b) A larger emitting surface with a converging light cone can create a wider beam after reflection.

To further conceal the artificial light sources, the first focal point, where the light sources are located, is placed lower than the second focal point, where the cockpit is installed, in vertical height, so that the lighting fixtures remain hidden from the drivers and passengers in the cockpit. Only the reflected light appears in the visual field as bright spots (Figure 10a).

The driving cockpit can be designed to rotate and tilt, allowing for simulation of vehicle movements such as turning, accelerating or braking. This enhances the immersive quality of the simulated driving and riding experience.

The high-intensity light sources are designed to be fully controllable in intensity, colour temperature, emission angle, emitting surface area, and the direction of the beam (Figure 10b). They can dynamically adjust to simulate sunlight, street lights, vehicle headlights, or other bright spots that may appear in the driving and riding context.

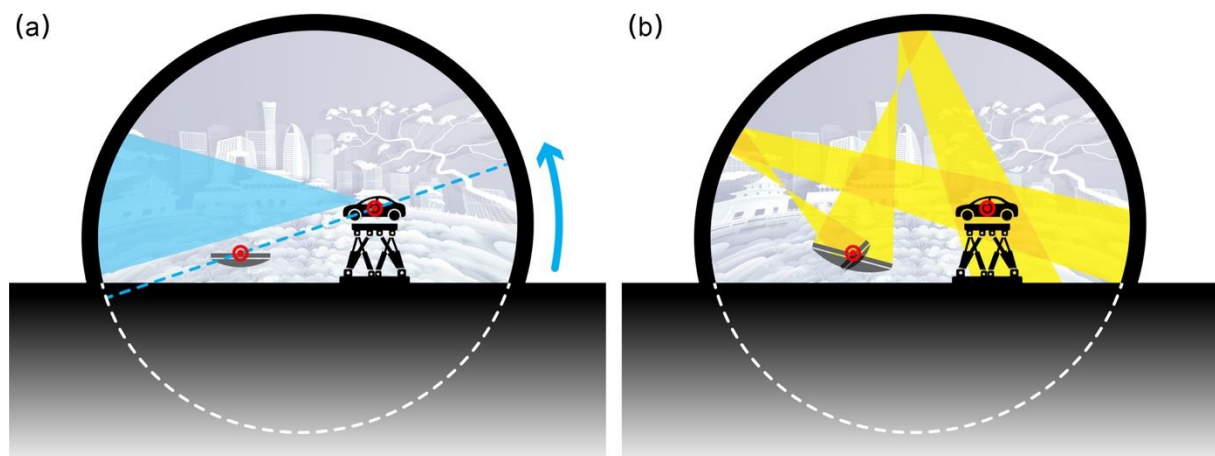


Figure 10 – (a) Rotate the prolate spheroidal display to conceal the light sources. (b) The light sources are controllable in intensity, colour temperature, angle, emitting surface, and direction.

Based on such principles, the proposed laboratory forms an integrated system that combines a high-reflectance prolate spheroidal mirror display, a dynamically adjustable driving cockpit, and a hidden high-intensity lighting module. The setup enables the reproduction of complex and dynamic luminance environments without sacrificing visual immersion. The concept establishes a new paradigm for in-vehicle lighting studies, and offers a technically feasible solution for future vehicular research focusing on visual perceptions and non-visual effects.

6 Conclusions

The study investigated the in-vehicle luminance distribution under real-world driving conditions, aiming to better understand the lighting characteristics that may affect visual and non-visual perceptions, comfort, and overall experience. Field measurements and data analysis revealed three fundamental characteristics of in-vehicle lighting: spatial non-uniformity, temporal variability, and the frequent presence of bright spots. These characteristics distinguish in-vehicle lighting from architectural lighting and present challenges for laboratory-based research.

To address these challenges, the study proposed a novel research and development laboratory design that integrates a high-reflectance prolate spheroidal mirror display, a rotatable and tiltable cockpit, and a dynamic lighting system capable of generating bright spots through controlled reflection. The design enables immersive and accurate reproduction of real-world luminance conditions within an experimental environment.

While the study offers a promising direction, several limitations should also be acknowledged. To begin with, the field measurements were conducted in a single urban area on a single day, which may not fully represent the diversity of in-vehicle lighting conditions. Furthermore, the proposed laboratory has not yet been prototyped or technically validated. These limitations present opportunities for future studies, including enhanced data collection, and step-by-step system development.

By designing a research and development laboratory that reproduces the complexity of in-vehicle lighting, the study aims to inspire future research to explore subjective driving and riding experience, human perception, and advanced cockpit design. As vehicles become more intelligent, connected, and human-centred, the ability to simulate, understand, and optimise the in-vehicle lighting will be essential in the smart transportation era.

References

- HAYCOCK, B.C., CAMPOS, J.L., KOENRAAD, N., POTTER, M. and ADVANI, S.K. 2019. Creating headlight glare in a driving simulator. *Transportation Research Part F: Traffic Psychology and Behaviour*, 61, 93–106.
- KARANDIKAR, R.V. 1955. Luminance of the Sun. *Journal of the Optical Society of America*, 45(6), 483–488.
- LEE, V.W., TWU, N. and KYMISSIS, I. 2016. Micro-LED technologies and applications. *Information Display*, 32(6), 16–23.
- LI, X., LING, J., SHEN, Y., LU, T., FENG, S. and ZHU, H. 2021. The impact of CCT on driving safety in the normal and accident situation: A VR-based experimental study. *Advanced Engineering Informatics*, 50, 101379.
- LIU, T. and ZHANG, X. 2022. Dynamic simulation on eye exposure of in-vehicle daylighting in urban environments of China. *Transportation Research Interdisciplinary Perspectives*, 16, 100727.
- POLLMANN, K., STEFANI, O., BENGSCHE, A., PEISSNER, M. and VUKELIĆ, M. 2019. How to work in the car of the future? A neuroergonomical study assessing concentration, performance and workload based on subjective, behavioral and neurophysiological insights. In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, 1–14.
- STANKE, L., VIKTOROVÁ, L. and DOMINIK, T. 2022. Discomfort glare perception by drivers—establishing a link between subjective and psychophysiological assessment. *Applied Sciences*, 12(8), 3847.