

Research Paper

The Effect of Perpendicular Lamp Position on Normal Plane Alignment for Light Distribution and Coverage in Adaptive Headlamps During Complex Driving Scenarios

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Abstract

Due to decreased visibility and an increased chance of accidents, driving at night requires increased vigilance. Drivers must be equipped to handle various road and terrain conditions, such as declines, inclines, turns, straight paths, and combinations. Following the law and ethical driving standards is crucial in these circumstances. Inadequate street illumination, poor lighting, and inexperienced drivers are all common causes of accidents. The risks increase at night when little ambient lighting reduces visibility. This study investigates the distribution of light intensity and illumination radius via a factorial design derived from headlamp activation configuration scenarios, simulated in MATLAB software, and validated using experimental test results. The results show that driver focus and vision range improve dramatically, particularly when the lights are triggered on flat roads, during turns, climbs, and combinations of these actions, by the New ADHL's headlamp activation configuration. Simulation-based activation of main and auxiliary light configurations shows that the New ADHL outperforms traditional headlamps, effectively addressing insufficient illumination to prevent nighttime accidents and providing a coverage radius of more than 3.5 m at the lowest intensity detectable by the driver.

Keywords: Accidents; Driving conditions; Safety; Visibility

1. Introduction

Car headlights are among the most essential styling and safety components of modern vehicles, and manufacturers continue to develop them to improve both visual appeal and driving performance [1]. The vehicle's front light is primarily intended to illuminate the road ahead so that drivers can see clearly while driving [2]. Mounted at the front of a vehicle, headlights also enable road users to recognize each other in dark conditions, supporting safer interaction in traffic environments [3]. The terms headlight and headlamp are often used interchangeably, and front lighting is widely regarded as a key safety feature not only in cars but also in motorbikes and trains [4]. In practice, front lighting systems

typically include high beams, low beams, and fog lights that can be used effectively at night depending on road and weather conditions [5]. Lighting has long been acknowledged as a major environmental factor affecting both the probability of accidents and the severity of injuries in accident-related research [6]. Because visibility determines how quickly drivers can detect surrounding vehicles and hazards, sight distance is a crucial parameter in highway design that influences operational and safety performance [7]. Limited visibility in darkness can delay driver reaction, so headlights should function reliably at night, in typical weather, and under unexpected driving conditions [8]. Clear visibility is therefore vital for night driving, and brighter lights generally increase the sense of security among



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road users [9]. Visible light wavelengths range from 401 to 701 nanometers [10]. Meanwhile, major-road street lighting commonly provides surface illuminance around 0.3 lux to 2.0 lux, and the human eye can detect variations in surrounding light conditions, tolerating up to about 3 lux in bright environments.

Adaptive Headlamp (ADHL) is an active safety system designed to improve visibility on curves and hills, enhancing safety when driving at night or in low-light conditions [11]. Increased visibility is linked to improved object recognition, including pedestrians and other road users, which provides drivers with more time to respond appropriately and helps avoid collisions [12]. In particular, lack of visibility during turning maneuvers on minor roads can result in fatal accidents and serious passenger injuries [13]. ADHL systems therefore focus on mechanisms that adjust or switch lighting when vehicles negotiate curves, including scenarios where vehicles travel uphill or downhill along curved roads at night, aiming to reduce accidents involving other road users. This challenge becomes more critical on mountainous routes, which are generally narrow, and where accidents may require several days to clear due to road constraints [14]. As urbanization continues and city populations grow, the number of automobiles increases and the frequency of traffic accidents tends to rise accordingly [15].

To ensure safer driving, road users must pay close attention to road conditions to avoid further accidents, especially at night or under adverse weather conditions [16]. Several factors, including alcohol consumption, exhaustion, driving while distracted by texting, speeding, distraction or falling asleep, and reduced ability to identify road hazards, significantly increase the risk of injury at night [17]. Traffic accident data indicate that many accidents occur at night, particularly on roads and traffic corners that still use traditional lighting systems [18]. These accidents are often associated with driver distraction during driving activities [19]. Research has reported that the risk of traffic accidents can be much higher at night, with more than 40% of fatal car accidents occurring after dark even though traffic volumes can be up to 80% lower than daytime conditions [20]. More than 50% of traffic fatalities also occur at night, and a significant portion of road injuries is related to

poor night vision [21]. At the same time, accidents can also happen frequently during daytime and peak hours, with higher vulnerability reported between 10 a.m. and 2 p.m. and between 6 p.m. and 10 p.m. [22]. These findings highlight that safe illumination must be maintained across different traffic conditions, including complex driving scenarios where visibility demand changes rapidly.

Beyond insufficient illumination, glare is another key concern during night driving; excessive light entering the driver's eyes may cause retinal adaptation, blurred vision, and temporary blindness. Therefore, a well-designed front-lighting system must support safe and comfortable driving in darkness and adverse weather by ensuring that obstacles can be detected at appropriate distances. This aligns with the broader goal of preventing accidents through adequate lighting, saving lives, and advancing affordable lighting technologies [23]. In recent years, many researchers have been attracted to computer vision studies focusing on detecting various light sources, estimating how light is distributed around an object, evaluating its impact, and determining how much area it can cover [24]. For adaptive headlamps, understanding light intensity distribution is essential because headlight patterns must illuminate crucial road sections while controlling how light is perceived by oncoming or passing drivers [25]. Modern front light modules are also expected to provide advanced features, such as projecting symbols and dynamically determining light distribution based on traffic and road conditions [26]. In this context, geometric alignment between lamp position and the illuminated region becomes important, as it directly influences the effective distribution and coverage on the target road plane.

To address diverse road conditions, many automakers incorporate multi-zone lighting into their designs to improve adaptability across weather and traffic environments [27]. Higher lighting resolution can be obtained by increasing the number of LEDs used within the headlamp system, enabling finer control over beam distribution, especially under challenging conditions [28]. However, the system must still provide sufficient illumination for drivers and pedestrians, particularly when street lighting is

inadequate or weather conditions are unusual. Although light intensity can be adjusted manually, this approach is often impractical in complex driving scenarios where conditions change rapidly. Conventionally, automobile front lights used halogen bulbs and high-intensity discharge lamps (HIDs) [29], yet these sources commonly suffer from lower efficiency, shorter lifetimes, and excessive heat generation. LEDs, in contrast, outperform halogen and xenon lights by offering adjustable brightness without sacrificing durability, and they are widely applied in daily life, healthcare, industry, smart farming, and both indoor and automotive lighting systems [30]. LEDs also offer advantages such as long lifespan, low energy consumption, compact size, mercury-free operation, improved durability, and fast switching [31]. LED lighting may consume up to 87% less energy than incandescent sources, and the automotive industry has rapidly adopted LED technology, including early LED headlamps introduced in premium vehicles with efficiencies below 100 lm/W, which marked a new era in automotive illumination. As conventional lighting remains inefficient, LED-based systems offer a practical solution for energy saving and reducing greenhouse gas emissions [32]. Within this technological shift, investigating how perpendicular lamp positioning affects normal plane alignment, and consequently light distribution and coverage in ADHL during complex driving scenarios, becomes an important step toward improving visibility and safety performance.

2. Methods

The research methodology for developing the ADHL system comprises several key stages. First, a research hypothesis is formulated to guide the discussion of design elements and to determine the switching mechanism capable of meeting the required illumination radius and light intensity within the recommended viewing range. Second, the study considers the selection of headlamp technology, emphasizing light sources with lower energy consumption, longer service life, and higher resolution compared to conventional alternatives.

Third, illumination performance is evaluated through numerical simulation using MATLAB R2022b. The simulation is designed to analyze the

spatial distribution of light intensity under various predefined scenarios. Key performance indicators include illumination coverage radius, projected illuminated area on a flat target surface at a specified wall distance (Z-distance), and the resulting illuminance levels for each scenario. Fourth, simulation outcomes are analyzed to quantify the influence of headlamp switching on illuminance distribution and to assess whether the generated visibility is sufficient for safe driving under different conditions.

Finally, an experimental validation is conducted using a lux meter to measure illuminance (in lux) at a fixed distance, typically 5 m, from the light source on a level and parallel target surface. The simulation model is considered valid when the measured illuminance values are consistent with the corresponding MATLAB results for the tested headlamp condition.

This study employs a simulation-based approach using a physics-based formulation with essential parameters to evaluate system performance. The target-plane illuminance E is calculated using the inverse-square law combined with cosine projection from each directional point light source, as expressed in Eq. (1).

$$E = \frac{I \cos \theta}{r^2} \quad (1)$$

where r is the distance (m) between the light source and the target point, I is the luminous intensity of the source in the direction of the target (cd), θ is the angle between the source-to-target direction and the lamp normal vector, and E is the illuminance at the target point (lux).

A critical factor in illuminance estimation is the geometric separation between the light source and the target. For a target point located at (x, y, z) and a light source located at (x_s, y_s, z_s) , the Euclidean distance r is computed by Eq. (2).

$$r = \sqrt{(x - x_s)^2 + (y - y_s)^2 + (z - z_s)^2} \quad (2)$$

This expression represents the straight-line distance in three-dimensional space and is used in the denominator of Eq. (1), reflecting the inverse-square dependence of illuminance on distance.

Furthermore, the cosine term $\cos \theta$ is obtained from the dot product between the normalized source-to-target direction vector and the normalized lamp orientation (normal) vector $\vec{n} = (n_x, n_y, n_z)$. This formulation accounts for the

angular projection effect of the emitted light on the target surface.

$$\cos \theta = \frac{(x - x_s)n_x + (y - y_s)n_y + (z - z_s)n_z}{r} \quad (3)$$

If $\cos \theta \leq 0$, the target point lies outside the effective illumination region of the light source. In this condition, the source-to-target direction forms an angle greater than 90° with the lamp normal vector, indicating that the target surface is oriented away from the incident light. Consequently, the contribution of the light source at that point is considered physically negligible. To ensure that only realistically illuminated regions are included in the analysis, the illuminance at that location is set to $E = 0$. When multiple light sources are present, the total illuminance at a given target point is obtained by summing the individual contributions from each source. This follows the principle of superposition, expressed as:

$$E_{total}(x, y) = \sum_{i=1}^n \frac{I_i \cos \theta_i}{r_i^2} \quad (4)$$

In this formulation, I_i denotes the luminous intensity of the i -th lamp in the direction of the target point, θ_i represents the angle between the lamp normal vector and the source-to-target direction, and r_i is the distance from the i -th lamp to the target point. The model assumes ideal point light sources with perfect alignment and does not account for optical obstructions, diffusion effects, or lens-related beam shaping.

To quantify the discrepancy between simulated and experimental illuminance values, this study employs the Mean Absolute Error (MAE), which measures the average magnitude of errors without considering their sign. Let $E_{sim,i}$ be the simulated illuminance at the i -th grid point and $E_{exp,i}$ the corresponding experimental measurement. The MAE is computed by averaging the absolute differences across all n grid points (e.g., $n = 121$ in an 11×11 grid). A smaller MAE indicates a stronger agreement between the simulation model and the experimental results.

$$MAE = \frac{1}{n} \sum_{i=1}^n |E_{exp,i} - E_{sim,i}| \quad (5)$$

The Root Mean Square Error (RMSE) is defined as the square root of the mean of the squared differences between simulated and experimental values. Unlike the MAE, the RMSE penalizes larger errors more strongly due to the squaring operation, making it particularly useful for identifying outliers or regions where substantial deviations occur between the simulation and the measurements. Therefore, a lower RMSE value indicates better predictive performance and a stronger agreement between the simulation model and the experimental data.

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (E_{exp,i} - E_{sim,i})^2} \quad (6)$$

2.1. Hypothesis Development

A key safety objective of the proposed ADHL system is to improve road illumination by reducing the duration and extent of insufficient visibility during nighttime driving. To ensure adequate lighting coverage, the system is designed to control the direction and distribution of illumination by selectively switching multiple headlamp sources on or off, thereby maintaining the required coverage radius and illuminance within the driver's viewing range.

In selecting the light source for this study, three commonly used technologies, laser, halogen, and LED, were considered prior to implementation in a multi-source headlamp assembly. As summarized in [Table 1](#), the lowest power consumption (57.15 W) is achieved using a multisource configuration composed of several low-wattage LED modules, while maintaining the targeted lighting performance and efficiency. Compared with halogen and xenon, LEDs offer superior performance in terms of energy consumption, cost-effectiveness, durability, brightness, and resolution, while meeting the Indonesian headlamp intensity requirement of 12,000 cd. Furthermore, [Table 2](#) presents a comparative analysis of primary and auxiliary lamp characteristics based on LED specifications collected from marketplace data.

This comparison highlights variations in luminous intensity, electrical power, and beam distribution patterns under high-beam and low-beam operating modes. These parameters provide practical insights into how each lamp contributes

to overall visibility and lighting effectiveness across different driving conditions.

To evaluate the ADHL performance under realistic vehicle operations, nine representative driving scenarios are investigated, including flat road, turning, uphill, downhill, and combined road conditions. This structured assessment enables the analysis of mechanical response and stability under varying elevation and road curvature, thereby supporting the optimization of both headlamp design and driving safety performance.

2.2. Configuration for the Proposed ADHL Support System

Headlamps play a critical role in ensuring driver safety and visibility under low-light conditions by enabling drivers to perceive the roadway, detect potential hazards, and remain visible to other road users, thereby reducing the risk of accidents. In most countries, headlamp usage is mandated by traffic regulations, and proper maintenance and alignment are required to achieve optimal performance, as illustrated in [Figure 1](#).

With the continuous growth of the automotive industry, enhanced lighting performance has become an essential safety requirement, particularly under diverse road geometries and weather conditions. In this study, the proposed ADHL system is designed to evaluate and optimize light intensity distribution and predicted visibility using a multi-level factorial design approach, as presented in [Figure 2](#), which also shows the experimental configuration developed for the ADHL system.

The prototype configuration incorporates adjustable mounting brackets to enable accurate headlamp positioning and to replicate pitch variations during uphill and downhill vehicle operation. In the proposed layout, L1 represents the primary headlamps. L2 and L4 correspond to the main turn-signal lamps, while L3 and L5 integrate small and large cornering lamps. L6 is assigned as the downhill-assist lamp, and L7 as the uphill-assist lamp. Key elements of the configuration include the angular adjustment mechanism, the multi-source lamp arrangement, and an intensity measurement grid used to map illuminance distribution.

This setup enables systematic evaluation of beam patterns across multiple headlamp orientations and driving scenarios, thereby supporting visibility improvement and ensuring compliance with applicable lighting performance requirements.

2.3. Factorial Design Scenarios

The proposed ADHL system represents an important safety feature intended to enhance road illumination under various operating conditions, including adverse weather, flat roads, uphill and downhill segments, as well as straight and curved road geometries. To evaluate system performance systematically, this study adopts a factorial design approach, in which predefined driving scenarios are represented as combinations of key operating factors.

The primary response variable in this analysis is the overall illuminance intensity distribution produced by the headlamp system during switching of the designated lamp modules. The modeling and scenario configurations used to obtain this response are summarized in [Table 3](#).

As shown in [Table 3](#), the experimental instrument design for the proposed ADHL configuration includes adjustable mounting brackets to precisely set the headlamp orientation and replicate vehicle pitch variations during uphill and downhill conditions. The configuration also integrates the light source modules, an angular adjustment mechanism, and a measurement grid to capture the spatial distribution of illuminance across the target surface. This setup enables consistent evaluation of beam patterns and illuminance performance across multiple scenario combinations, thereby supporting the assessment of visibility improvements under realistic driving conditions.



Figure 1. The Importance of headlamps in vehicle safety and visibility

Table 1. Select the appropriate lighting

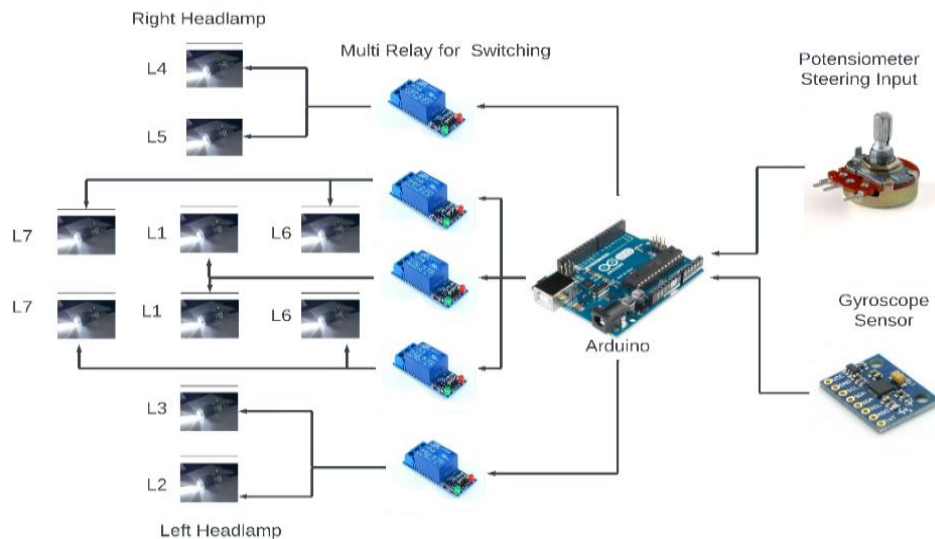
Type of Lamp	Light efficiency, (lm/watt)	Electrical Power for Lighting (watts)
Laser	10-20	571.48
Halogen	10-30	571.48
LED	100-200	57.15

Table 2. Technical details and headlamp configuration

Parameter	3-inch Main Headlamp	2.5-inch Supporting Headlamp
High beam/low beam	60 W/ 50 W	55 W/ 45 W
Lumen	8267 lm	6200 lm
Luminous intensity	14,038.03 Cd	12,865.88 Cd

Table 3. Framework of nine operational scenarios for nighttime ADHL analysis

Case	Road Condition	Turning Direction
1	Flat	Straight
2	Flat	Small turn
3	Flat	Large turn
4	Uphill	Straight
5	Uphill	Small turn
6	Uphill	Large turn
7	Downhill	Straight
8	Downhill	Small turn
9	Downhill	Large turn

**Figure 2.** Instrument design for new ADHL light configuration

2.4. Configuring Headlamp Activation Using Binary Logic

The lamp-array activation strategy in the proposed ADHL system is designed to enhance lighting performance across a range of driving conditions, as illustrated in Figure 3. By employing a structured activation sequence, the system enables adaptive illumination to improve driver visibility during nighttime operation and under adverse weather conditions. Figure 3 presents the

schematic of the sequential logic used to control lamp activation within the multi-source headlamp configuration. This logic defines the switching behavior of each lamp module based on the operating scenario, ensuring appropriate beam coverage and intensity distribution.

The activation rules are summarized in Table 4 using a binary logic representation, where a value of 1 indicates that a lamp is switched on and 0 indicates that it is switched off. This binary enco-

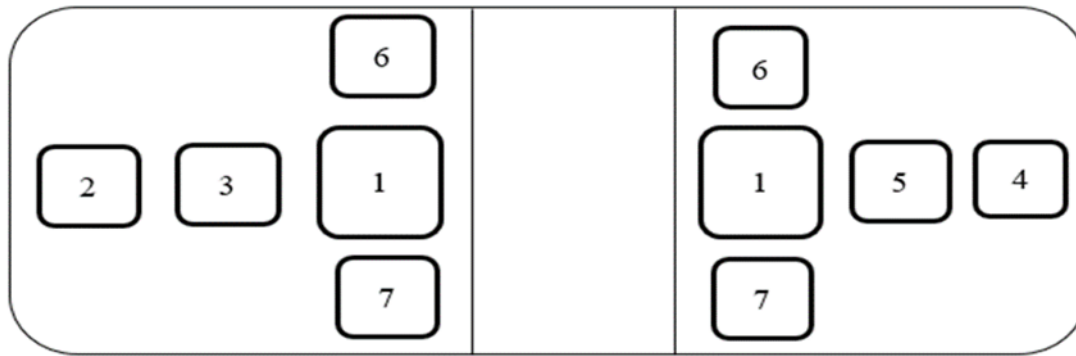


Figure 3. Development of a static ADHL mechanism with dynamic capabilities

Table 4. Logic for lamp array activation

Case	Left Side Lamp					Right Side Lamp				
	L2	L3	L1	L6	L7	L1	L5	L4	L6	L7
1	0	0	1	0	0	1	0	0	0	0
2	0	0	1	0	0	1	1	0	0	0
3	0	0	1	0	0	1	1	1	0	0
4	0	0	1	0	1	1	0	0	0	1
5	0	0	1	0	1	1	1	0	0	1
6	0	0	1	0	1	1	1	1	0	1
7	0	0	1	1	0	1	0	0	1	0
8	0	0	1	1	0	1	1	0	1	0
9	0	0	1	1	0	1	1	1	1	0

ding provides a clear and systematic way to represent lighting states under different scenario combinations. In addition, it facilitates case-by-case computation of the total illuminance distribution by enabling the superposition of contributions from the activated lamps. As a result, the model outputs can be presented consistently and interpreted more effectively, supporting the evaluation of lighting performance and the identification of configurations that improve driver visibility in low-light or inclement conditions.

3. Results and Discussion

3.1. Headlamp Illumination Scenario Analysis

The activation strategy of the proposed ADHL system was evaluated through a light distribution analysis based on nine representative nighttime operational scenarios, as illustrated in [Figure 4](#) to [Figure 12](#). This analysis was conducted to assess the adaptive lighting capability of the system under varying road conditions, including flat driving, uphill motion, downhill motion, and combinations of small- and large-radius turning maneuvers. These scenarios were selected to reflect changes in vehicle dynamics that influence headlamp orientation and beam projection during

nighttime operation, thereby enabling a comprehensive assessment of illumination performance.

A reference coordinate system was established to ensure consistent spatial representation across all simulations. The origin (0,0,0) along the X, Y, and Z axes was defined as the anchor point for the lamp position and served as the basis for orienting all other elements in the visualization. To maintain consistent visualization conditions, the analysis was performed at a fixed observation distance of 20 cm. This close-range configuration was selected to minimize blurring effects that may occur at larger distances, particularly near the left and right boundaries of the illuminated region. In addition, the target plane (Z-wall) used for mapping the illuminance distribution was also placed at a distance of 20 cm from the source. Collectively, these settings provide a clearer and more detailed representation of the beam pattern and intensity distribution, facilitating interpretation of variations in light spread and illuminance across the evaluated scenarios.

Case 1: Flat Road – Straight Driving

In this scenario, the vehicle travels on a level and straight roadway with only the left and right primary headlamps activated. This configuration

produces a symmetric forward illumination pattern that supports adequate visibility while minimizing excessive glare. In addition, operating only the main headlamps represents an energy-efficient mode that aligns with typical nighttime driving conditions. The resulting light intensity distribution is presented in Figure 4. As shown, the simulated illuminance exhibits two symmetric peaks located at $X = 0$ cm and $X = 80$ cm, reaching 3.5×10^5 lux. The distribution demonstrates a smooth radial decay with an overlapping central region, forming a focused and relatively uniform beam profile with improved width and intensity compared to conventional headlamp patterns.

Case 2: Flat Road – Slight Turning

This case represents a slight turning maneuver on a level road surface. In addition to the left and right primary headlamps, an auxiliary LED cornering lamp is activated, resulting in three active light sources during the maneuver. Figure 5 shows that activating the additional cornering lamp increases the total illumination distribution in the direction of the turn. This improves visibility and extends coverage toward the vehicle's turning path, thereby enhancing driving safety. The combined use of primary and auxiliary LED modules produces a wider and brighter beam pattern than conventional lighting systems during mild cornering conditions.

Case 3: Flat Road – Large Turning

In this scenario, the vehicle performs a large-radius turn on a level road. The system activates

four light sources, consisting of the two primary headlamps and additional cornering lamps to support enhanced illumination during sharper maneuvers. The simulated intensity distribution in Figure 6 that the four-lamp configuration significantly improves beam coverage across the turning direction. This wider distribution increases driver visibility along the curve and supports safer navigation under low-light conditions. Compared with conventional cornering lamps, the use of larger auxiliary lighting modules provides greater effective coverage during wide turns.

Case 4: Uphill Road – Straight Driving

Case 4 evaluates the vehicle operating on an uphill road segment while maintaining a straight trajectory. Under this condition, four lighting units are activated: the two primary headlamps on the left and right sides, along with two hill-assist lamps mounted laterally. Figure 7 illustrates a symmetric illuminance distribution generated by the four active lamps, with dominant intensity regions centered near $X = 0$ cm and $X = 80$ cm. The concentrated beam pattern supports improved visibility during uphill motion by enhancing forward illumination and maintaining balanced coverage on both sides. Compared with conventional headlamp operation, the inclusion of uphill-assist lamps provides a brighter and more stable illumination profile for ascending road conditions.

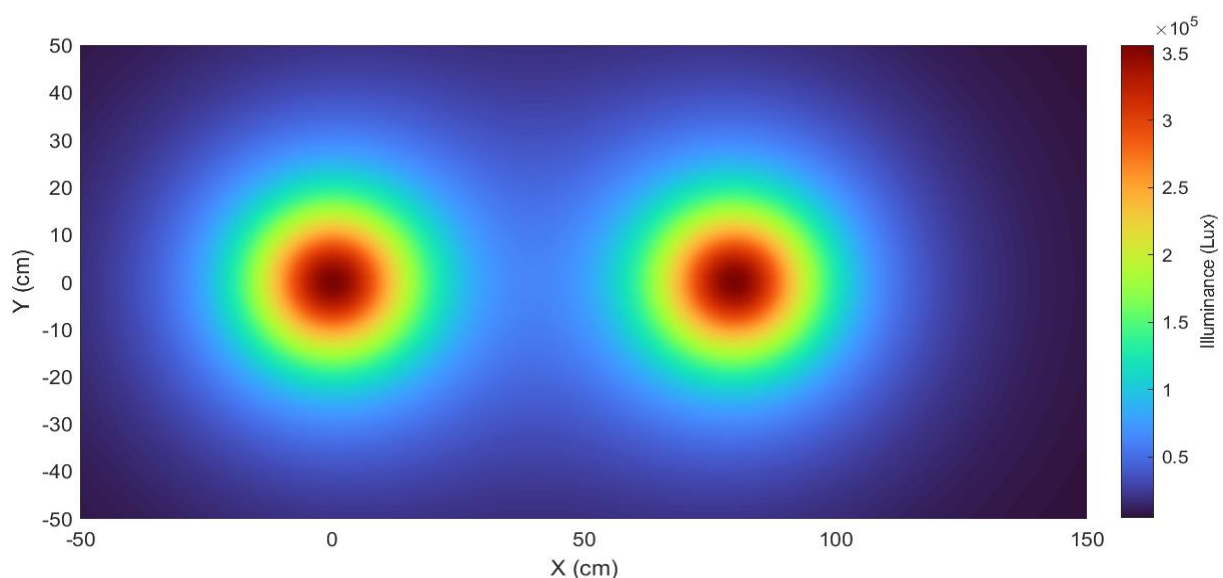


Figure 4. The car is traveling in a straight line on a flat road

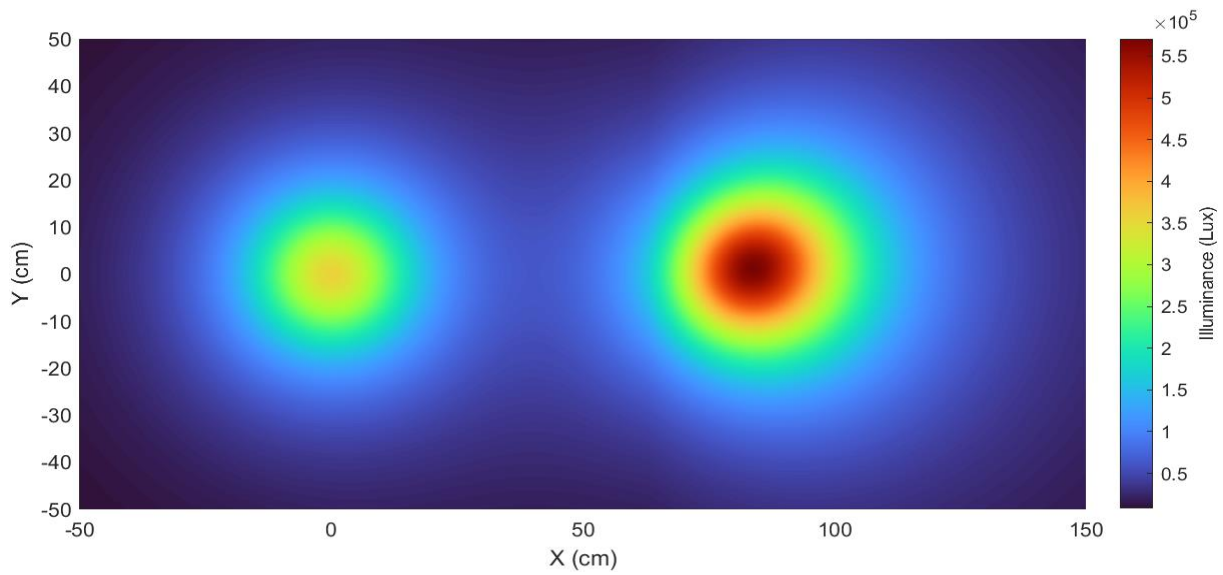


Figure 5. When the vehicle turns, the cornering lamp and main headlamps turn on

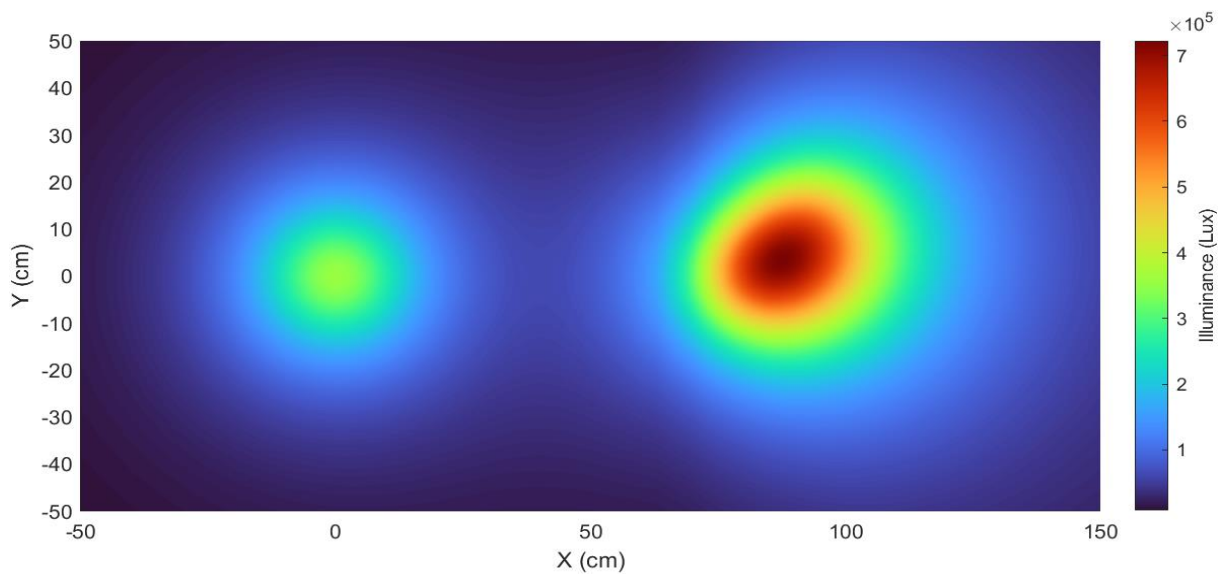


Figure 6. Both the main headlamps and the cornering lamp turn on during a turn

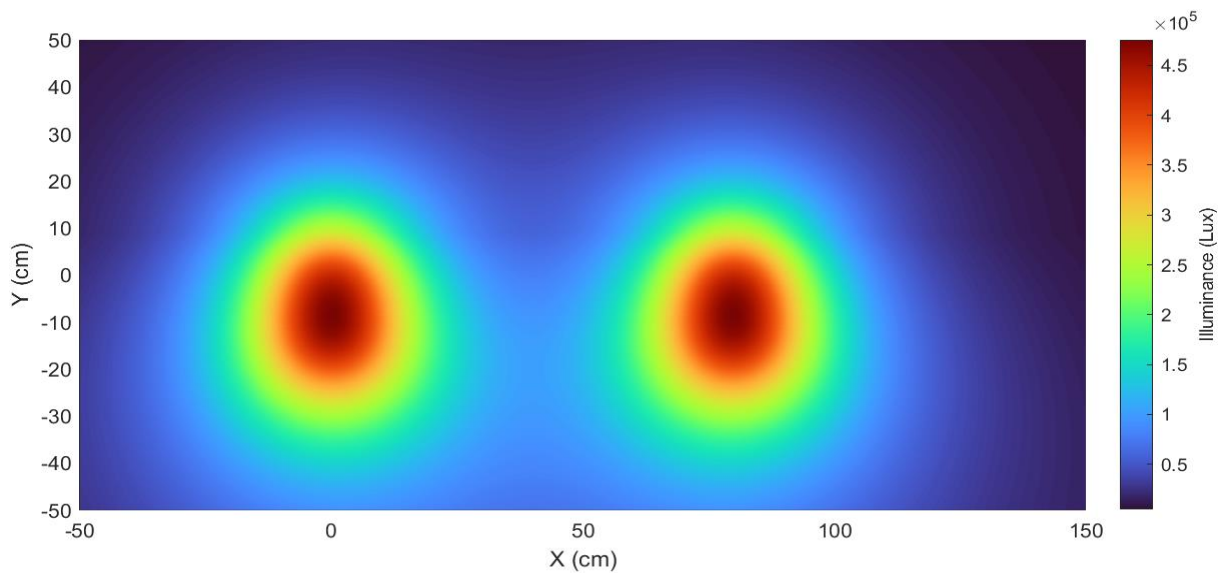


Figure 7. Condition of a straight, uphill road

Case 5: Uphill Road – Slight Turning

This case examines vehicle behavior during a slight turning maneuver on an uphill road segment. Under this condition, five lighting units are activated, consisting of the two primary headlamps (left and right), two laterally oriented hill-assist lamps, and one small cornering lamp. This selective activation strategy is intended to enhance visibility and provide focused illumination toward the turning direction while maintaining sufficient forward coverage for uphill driving.

As shown in [Figure 8](#), the combined lamp configuration produces a higher overall illuminance distribution during an uphill slight turn, thereby improving driver visibility under low-light conditions. The increased illumination toward the road surface enhances clarity of the driving path compared with conventional headlamp-only operation, which typically provides limited lateral coverage during turning. Overall, this configuration supports safer maneuvering during nighttime or low-ambient-light uphill turning conditions.

Case 6: Uphill Road – Large Turning

Case 6 represents a wide turning maneuver on an uphill road. In this scenario, six lighting units are activated: the two primary headlamps and two hill-assist lamps (left and right), combined with simultaneous activation of both the small cornering lamp and the larger turning lamp. This multi-lamp configuration is designed to provide

enhanced lateral illumination and improved beam coverage across the wider turning radius.

[Figure 9](#) indicates that the total illuminance distribution during a wide uphill turn is substantially higher than that observed in the slight turning condition. The additional wide-turn lighting module increases brightness and expands coverage toward the curve direction, enabling better perception of road curvature and obstacles. Compared with conventional lighting systems or the slight-turn configuration, this scenario demonstrates improved visibility support and safer navigation during sharp uphill turns under nighttime driving conditions.

Case 7: Downhill Road – Straight Driving

Case 7 evaluates the vehicle operating on a downhill road segment while maintaining a straight trajectory. Under this condition, four lighting units are activated, consisting of the two primary headlamps positioned symmetrically on the left and right sides, along with two downhill-assist lamps mounted laterally. This configuration is intended to maintain balanced forward illumination while compensating for changes in pitch that occur during downhill motion.

As illustrated in [Figure 10](#), the simulated illuminance distribution shows symmetric high-intensity regions centered at approximately $X = 0$ cm and 80 cm, corresponding to the left and right primary lighting units. The resulting beam pattern remains focused and balanced, providing stable forward lighting during downhill driving. Compared with conventional headlamp-only operation,

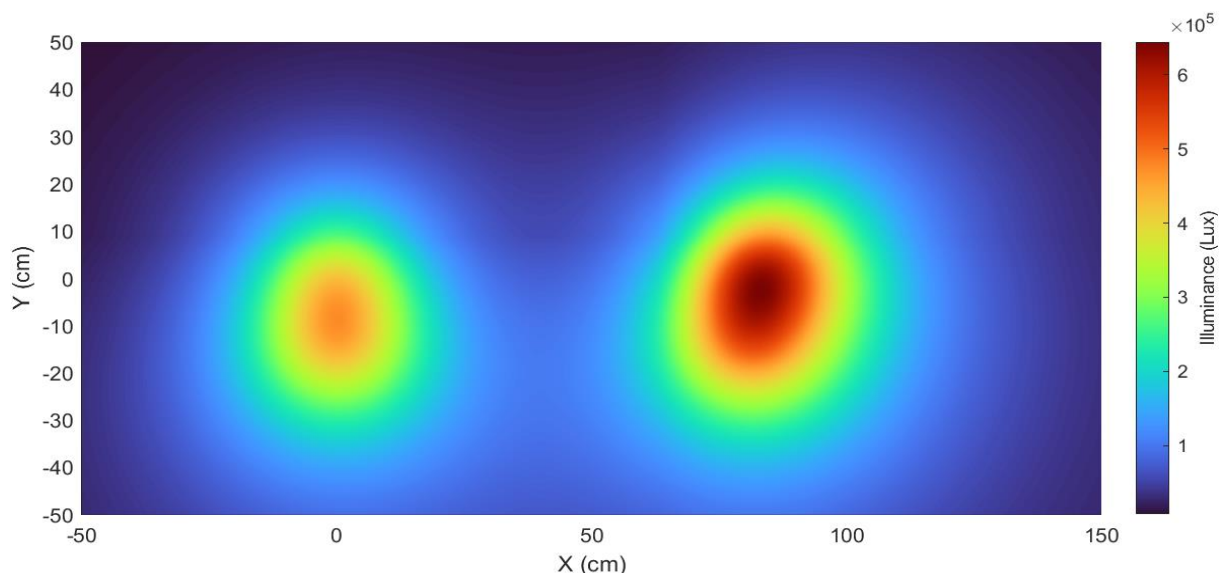


Figure 8. The condition of a slight uphill turn on the road

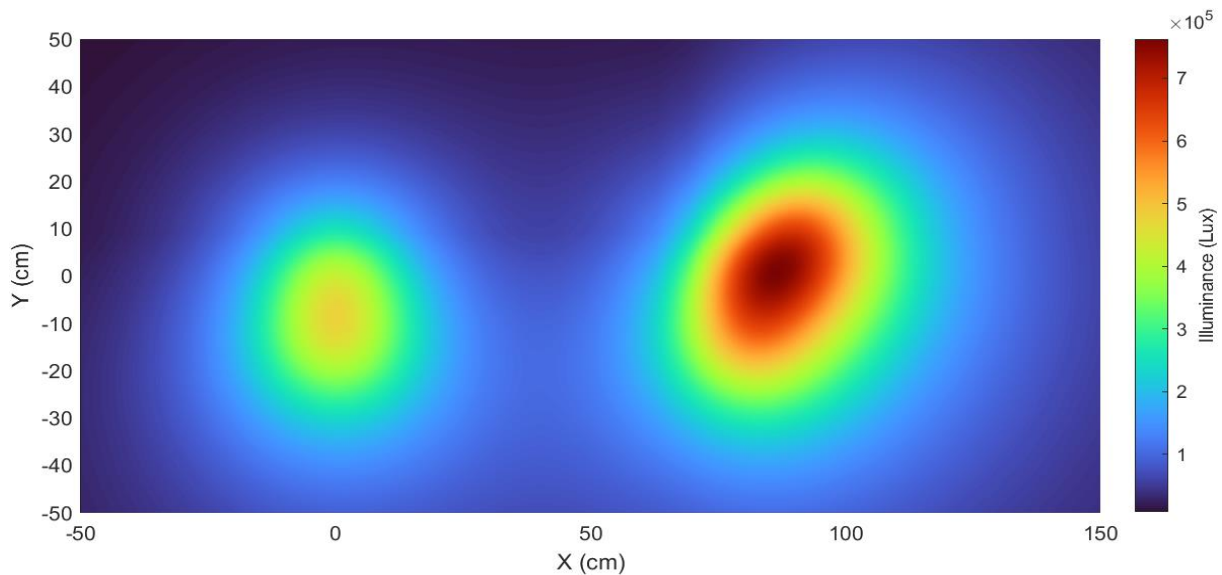


Figure 9. The condition of a significant uphill turn on the road

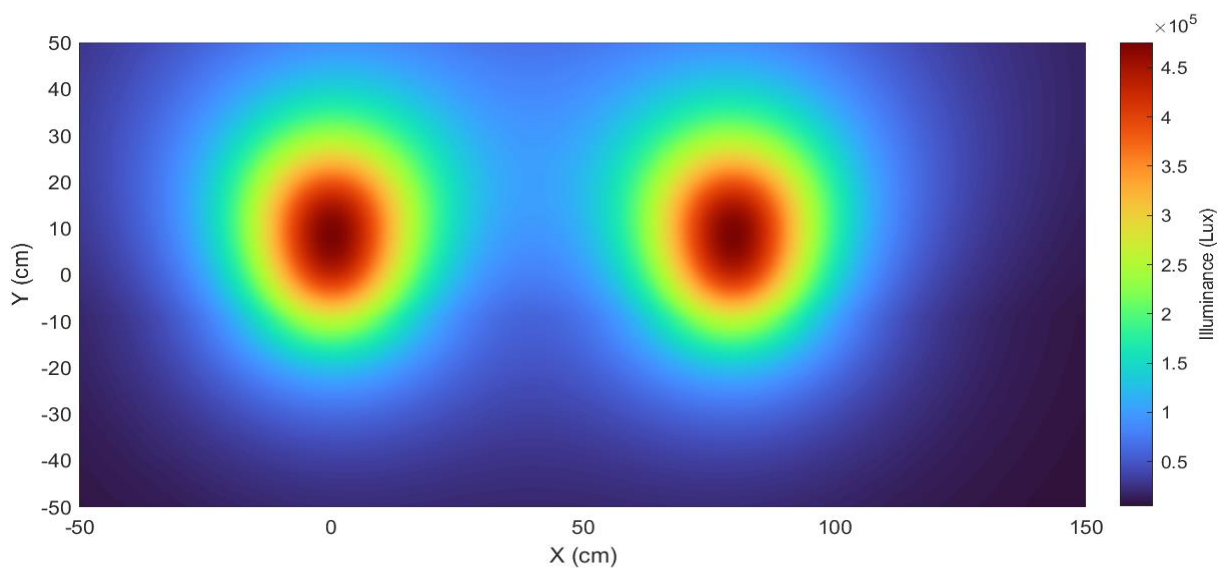


Figure 10. Condition of a straight, downhill road

ration, the ADHL configuration enhances both upward and downward visibility, extending illumination coverage and supporting safer navigation on descending road conditions.

Case 8: Downhill Road – Slight Turning

Case 8 represents a combined downhill and slight turning maneuver. Under this condition, five lighting units are activated, including the two primary headlamps (left and right), two downhill-assist lamps mounted laterally, and one small cornering lamp. This activation scheme is intended to improve beam coverage during turning while compensating for the vehicle pitch variation associated with downhill motion. As shown in Figure 11, the simulated distribution

indicates improved visibility of road curvature during downhill slight turns. The illuminance pattern appears to provide stronger coverage in the upward direction of the turn compared with the downward side. Nevertheless, both sides exhibit noticeably higher visibility than conventional headlamp-only systems, particularly due to the contribution of the additional downhill-assist lighting.

Case 9: Downhill Road – Large Turning

Case 9 evaluates the vehicle performing a wide turning maneuver while descending. In this scenario, a total of six lighting units are activated simultaneously: two primary headlamps, two downhill-assist lamps, and a combined cornering

configuration consisting of one small and one large cornering lamp. This multi-source activation is designed to maximize lateral illumination and provide enhanced beam distribution during sharp downhill turning conditions.

Figure 12 shows that the wide-turn downhill configuration produces a substantial increase in illuminance on the turning side compared with the slight-turn downhill case. Among all evaluated scenarios, this condition generates the highest intensity and the broadest effective coverage, resulting in the most favorable visibility performance. Consequently, the driver is better supported in detecting objects ahead under nighttime driving conditions with minimal ambient lighting.

3.2. Illuminance Threshold Impact on Light Coverage Radius

This study proposes a mathematical formulation to estimate the coverage radius of the simulated illumination distribution. The formulation enables analytical prediction of the effective illuminated area produced by a given light source based on its intensity and geometric characteristics. In addition, the approach facilitates the determination of an illuminance threshold, defined as the minimum illuminance level required to satisfy visibility or regulatory requirements. This threshold is essential for evaluating lighting effectiveness in applications that demand controlled illumination performance, such as automotive headlamps and

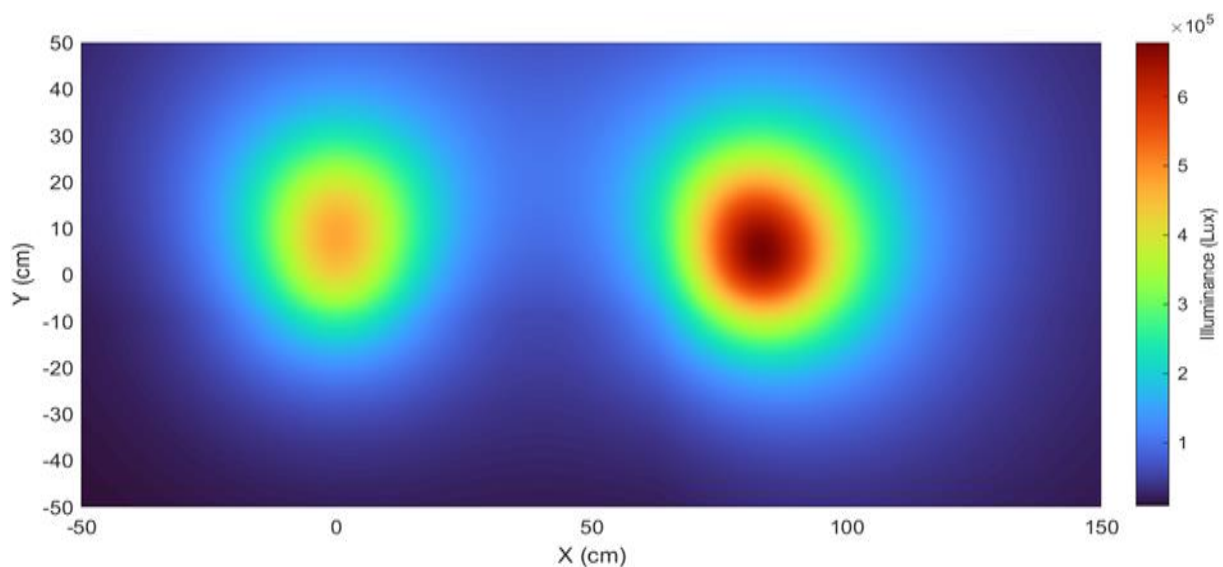


Figure 11. Condition of a minor, downhill road

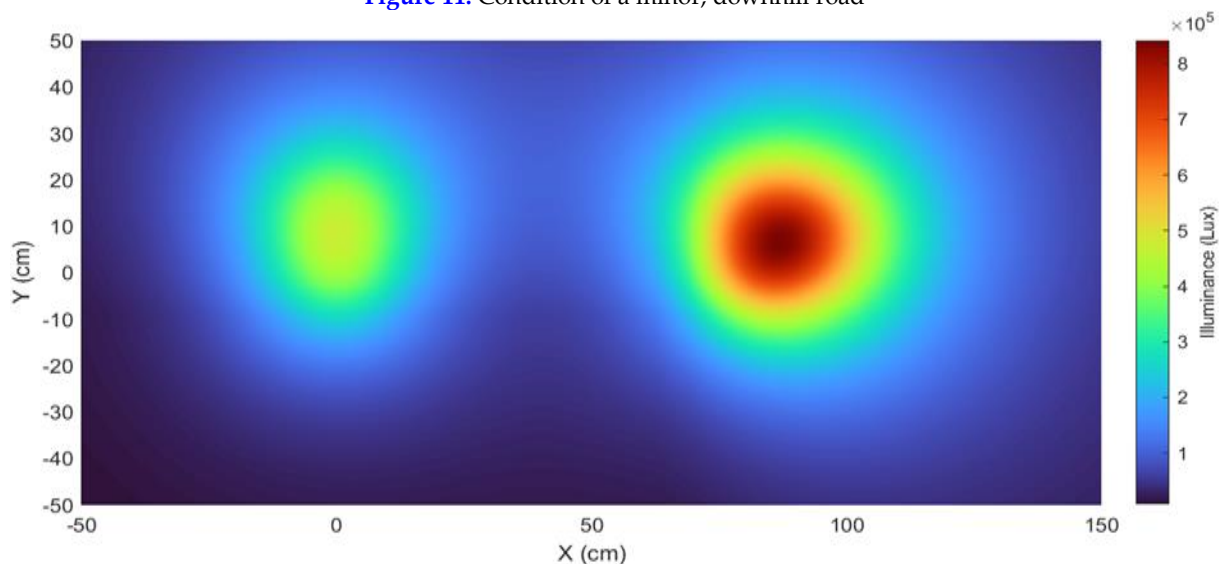


Figure 12. The condition of a significant turn is a downhill road

architectural lighting. The proposed method also supports design optimization by ensuring that the lighting configuration satisfies safety requirements while maintaining functional performance and energy efficiency, as illustrated in Figure 13.

According to the inverse-square law, an increase in the projected intensity term $I \cos \theta$ leads to a larger coverage radius for a given illuminance threshold. In practical terms, higher intensity allows light to reach a greater distance while still meeting the minimum required illuminance. For example, the coverage radius produced by two light sources rated at 12,865.88 cd and 14,038.03 cd differs by approximately 3–4%. Although this difference may appear small, it can influence illumination uniformity and layout decisions, particularly in systems requiring precise beam distribution, such as vehicle headlamps and controlled-area lighting installations.

3.3. Validity in Experimental Testing Results

To obtain reliable headlamp illuminance measurements, a dedicated measuring device such as a lux meter or a headlight tester is recommended, depending on the required accuracy level. A digital lux meter provides a practical and cost-effective option for personal or small-scale testing, whereas a headlight tester is more suitable for authorized workshops due to its more comprehensive assessment capabilities. In this study, the sensor was positioned perpendicular to the lamp centerline, and

measurements were conducted at a standard distance of 5 m on a level target surface with minimal reflected light. Prior to data acquisition, the lux meter was calibrated by covering the sensor and applying the zero-adjustment procedure. The measurement setup is illustrated in Figure 14.

Experimental validation was performed using a single headlamp unit as the test sample to evaluate the emitted illuminance distribution under controlled conditions. A lux meter was placed at multiple predefined points on the target plane to capture spatial variations of illuminance. The measured values were then organized into a matrix format to visualize the distribution pattern and facilitate comparison with simulation results. The measured illuminance map and corresponding lux values are presented in Figure 15, while the complete measurement dataset is summarized in Table 5.

The headlamp reference position was defined at (0,0,0) and centered within the experimental layout. An 11×11 measurement grid was used to ensure consistent coverage in both the X and Y directions. The grid spans an x -range from –50 cm to 150 cm and a y -range from –50 cm to 50 cm, enabling standardized data collection across all sampling points. The target (Z-wall) plane was placed at a distance of 5 m to measure illuminance using the calibrated lux meter. The primary objective of this validation was to assess the agreement between simulation outputs and experimental measurements.

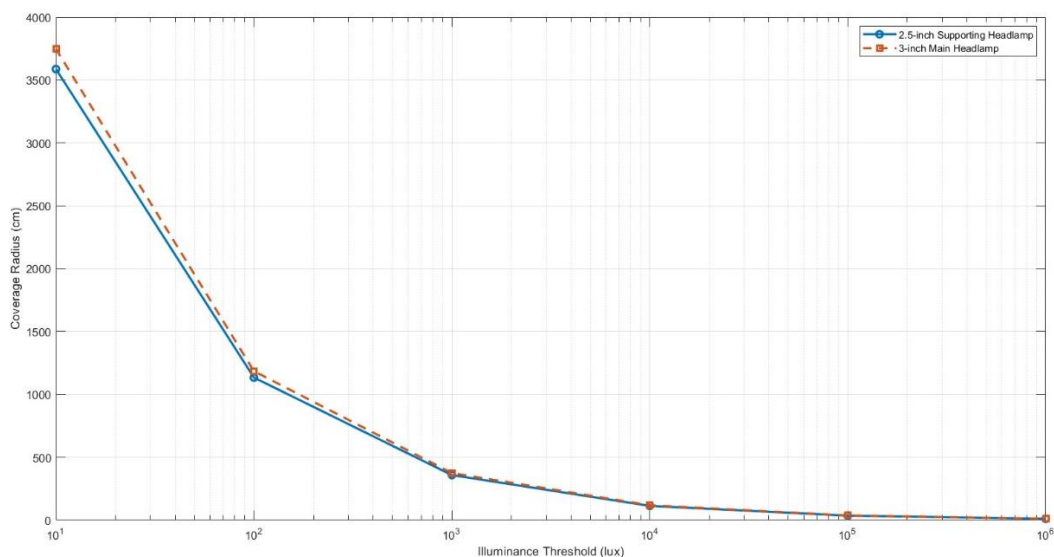


Figure 13. Reduced the lux threshold's impact on maximum illumination distance



Figure 14. Light intensity in lux is measured with a lux meter

Table 5. Configuration of the measurement grid and experimental setup

Y/X	-50	-30	-10	10	30	50	70	90	110	130	150
-50	540	545	560	538	563	533	538	517	497	498	498
-40	554	564	540	537	542	537	533	529	507	509	510
-30	548	529	559	547	575	555	518	541	530	522	493
-20	549	540	571	565	546	572	543	525	525	508	486
-10	553	557	662	571	539	566	527	539	520	516	491
0	550	564	571	555	529	553	549	532	517	509	504
10	546	575	576	558	558	554	540	524	525	519	509
20	556	548	556	567	543	544	540	534	520	506	509
30	554	526	540	540	540	538	543	517	520	500	498
40	537	554	544	553	558	547	545	524	516	506	496
50	541	550	545	556	556	543	531	518	517	497	492

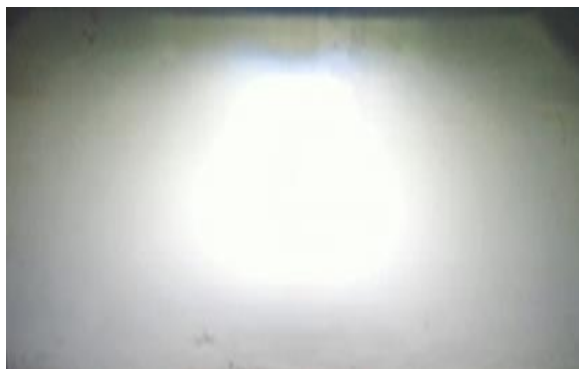


Figure 15. Experiments evaluated the intensity of the current light

Simulation accuracy was quantified using MAE and RMSE, and the comparison results are shown in [Figure 16](#). The simulated illuminance distribution (top-left) exhibits a smooth and symmetric pattern, while the experimental map (top-right) shows a similar overall trend with localized deviations attributable to practical measurement conditions. The error surface (bottom-left), computed as the pointwise difference between simulation and experiment, indicates strong agreement, with an RMSE of 6.08

lux and an MAE of 5.25 lux. The corresponding error contour (bottom-right) highlights areas of slight overestimation and underestimation, providing insight into the spatial distribution of deviations. Overall, the consistency between the simulation model and the experimental results is further confirmed in [Figure 17](#).

3.4. Comparative Study of the Proposed and Conventional ADHL Systems

Recent advancements in automotive lighting have led to the development of Adaptive Headlamp (ADHL) technologies, which aim to improve nighttime visibility, driving safety, and system responsiveness compared with conventional headlamp configurations. The proposed ADHL model presented in this study employs a multi-source configuration consisting of primary headlamps integrated with several auxiliary lamp modules. These auxiliary lamps are strategically positioned to support adaptive illumination under different vehicle maneuvers and road conditions. In contrast, conventional ADHL systems typically rely on a simpler configuration in which the primary headlamps

operate together with a limited auxiliary lamp function that activates during left or right turning events. As a result, conventional systems generally provide a narrower lateral illumination range, particularly under turning maneuvers where wider beam coverage is essential for detecting road curvature and obstacles.

A visual comparison between the conventional ADHL configuration and the proposed multi-lamp ADHL system is presented in Figure 18. The results indicate that the proposed ADHL provides a wider illumination coverage during turning

conditions due to the activation of additional auxiliary lamps. Specifically, while the conventional ADHL configuration typically involves two active lamps, the proposed ADHL employs three or more simultaneously activated lamp modules (one primary lamp supported by multiple auxiliary lamps) during turning events. This enhanced configuration increases lateral beam spread and improves visibility in the turning direction, demonstrating improved lighting performance compared with the conventional ADHL approach.

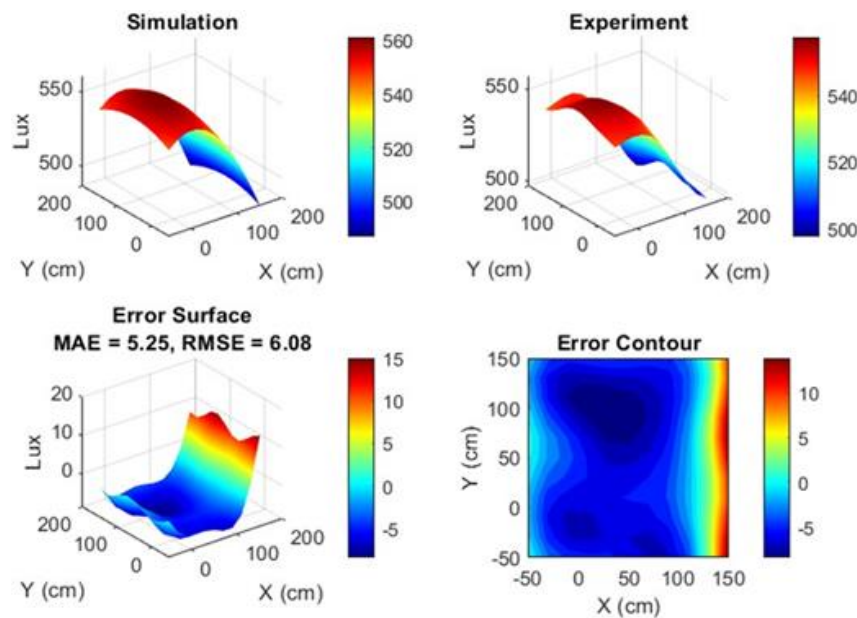


Figure 16. Comparison of simulation and experimental results

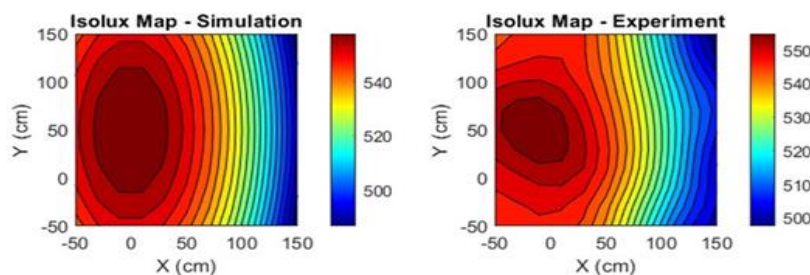


Figure 17. Distribution of simulated and experimental Isolux

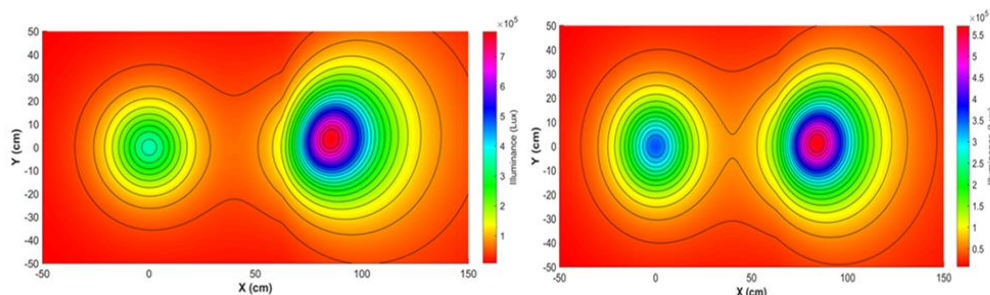


Figure 18. Light intensity and isolux contour new ADHL to conventional

4. Conclusion

The results indicate that implementing a multi-source, multi-lamp headlamp array improves driver visibility and illumination uniformity under complex driving conditions, including curves, slopes, and combined maneuvers. Both simulation and experimental measurements show a strong agreement in illuminance distribution across an 11×11 grid, supported by low error values (MAE = 5.25 lux and RMSE = 6.08 lux). The surface and isolux plots further confirm that the experimental patterns closely follow the predicted model, demonstrating adequate model accuracy and reliability. Compared with conventional headlamp systems, the proposed array configuration increases overall illuminance and provides a more evenly distributed beam profile, including under low-visibility conditions. Improved illumination coverage enhances driver perception and supports safer and more comfortable driving.

For further development, the new ADHL system is recommended to incorporate adaptive coordinate tilting, where lamp orientation is adjusted from the original horizontal alignment to multiple inclination angles based on driving conditions and design requirements. This approach is expected to expand illumination coverage in the turning direction and improve lateral visibility. In addition, future beam-pattern evaluation should consider different horizontal configuration strategies, with emphasis on beam overlap, peak (central) intensity, and lateral distribution, to achieve an optimized balance between coverage, uniformity, and visual comfort.

Author's Declaration

Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript.

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