INTERNATIONAL JOURNAL OF AUTOMOTIVE SCIENCE AND TECHNOLOGY

www.ijastech.org

2025, VOL. 9, NO:1, 106-113

e-ISSN: 2587-0963

Design of an LED and Laser Diode Based Optical Vehicle Alerting System

Selim Duru[1*], Buğra Er[1], Görkem Bavtar[1] and Ahmet Altuncu[2]

[1.]*Electronic Design Engineer, Sanel Auto Electronic, İstanbul, 34956, Turkiye*
[2.]*Electrical & Electronics Engineering, Faculty of Technology, Afyon Kocatepe University, 03200, Turkiye*

Abstract

The quiet operation of electric and hybrid vehicles at low speeds can pose a risk to pedestrians. To enhance pedestrian safety, Acoustic Vehicle Alerting Systems (AVAS) have been developed. The objective of this study is to develop an Optical Vehicle Alerting System (OVAS) that is integrated with vehicle speed data, with the aim of improving pedestrian awareness. By processing speed data transmitted via the Controller Area Network (CAN) bus, a variety of light patterns were projected on the road surface using optical sources in daylight conditions. In the pro-posed system, the efficacy of linear laser-based warning patterns generated by laser sources was compared with that of circular light patterns produced by arrays of light-emitting diodes (LEDs) com-bined with lens structures. A vehicle simulation was conducted to measure the light intensity and illumination profiles of laser and LED-based systems in a test environment. The findings revealed that an alerting pattern was generated with an illuminance of 90 lux at a distance of five metres when six LEDs with a wavelength of approximately 505 nm and an output power of 5 mW were employed. Similarly, a dynamic, speed-dependent linear alerting pattern was generated using three laser diodes operating at a wavelength of 532 nm and an output power of approximately 100 mW. The effectiveness of light intensity and illumination profiles was evaluated based on performance at different vehicle speeds. The OVAS system designed with LEDs was mounted at two different heights, 30 cm and 50 cm above the ground, and their performances were compared. It was observed that the OVAS positioned at 50 cm projected a light pattern covering 242% more area at a range of 1-3 metres compared to the system mounted at 30 cm. This emphasises the considerable impact of the installation height on the system's efficacy.

Keywords: Lighting Systems; Laser Diode; LED; Optical Vehicle Alerting System; Pedestrian Warning System

Research Article

History
Received 18.12.2024
Revised 23.02.2025
Accepted 07.03.2025

Contact
* Corresponding author
Selim DURU
selim.duru@sanel.com.tr
Address: Electronic Design Engineer, Sanel Auto Electronic, İstanbul, Turkey
Tel:+902164272650

To cite this paper: Duru, S., Er, B., Bavtar, G., Altuncu, A. Design of an LED and Laser Diode Based Optical Vehicle Alerting System. International Journal of Automotive Science and Technology. 2025; 9 (1): 106-113. http://dx.doi.org/10.30939/ijastech..1603306

1. Introduction

The interaction between vehicles and pedestrians in traffic has become increasingly complex with the development of electric and hybrid vehicles (EVs and HVs) [1]. Vehicle manufacturers design their vehicles and components in compliance with regulations to ensure the safety of drivers, passengers and pedestrians [2]. Regulations and national laws are key considerations in the design and production of vehicles and their components. The silent operation of EVs and HVs at low speeds has recently become a significant risk, particularly for visually disabled pedestrians. This highlights the importance of improving road safety measures for pedestrians [3]. Inadequate road lighting also negatively affects pedestrian and driver safety [4]. Therefore, estimating vehicle stopping points can be challenging and raise potential safety concerns [5]. Pedestrian accidents are among the most common and deadly road traffic accidents, and urban transport authorities need to take measures to improve pedestrian safety.

For this purpose, modeling vehicle-pedestrian interactions helps to predict collision risks and identify critical factors in preventing serious accidents [6]. Safety measures are particularly important for hearing-disabled pedestrians, who face difficulty detecting auditory warnings. For this reason, vehicle manufacturers need to take measures to increase pedestrian awareness of vehicle warnings.

Advancing LED technologies has significantly improved the efficiency of vehicle warning lights [7]. Technologies such as dynamic LED arrays and external vehicle projection lighting have been developed, with holographic projection technologies demonstrating their ability to project light patterns for pedestrians using powerful optical sources [8]. Electronic solutions for optical warning patterns have been tailored for the automotive industry, allowing the creation of different figures through micro-lens arrays [9]. Solutions combining reflectors, lenses and LEDs offer a variety of options. Linear light patterns can assist the driver in aligning with the road, thereby improving road safety. Lighting systems used in forklifts and similar vehicles are used as directional indicators to improve safety in industrial environments. These systems are being adapted for automotive use so that they can be mounted on vehicles. Optical projections have shown promise in marking safety zones, contributing to occupational safety by visually indicating hazardous areas. Such projections can be used to optically mark danger zones [10].

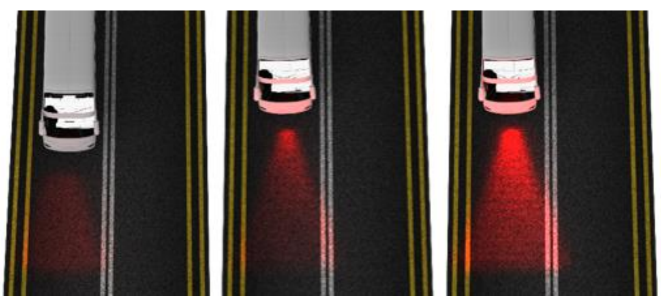

Figure 1. LED-based OVAS

One of the primary design principles aiming to ensure vehicle and pedestrian safety is to provide adequate lighting at the front and rear of the vehicle. In this context, compliance with the standards of the vehicle's headlight placement design is critical [11]. Simulation software developed for this purpose plays an important role in the development of automotive lighting products that comply with standards and regulations. For this purpose, software such as Zemax Optics Studio [12], LucidShape and CATIA V5 [13] have been used to optimize light distribution with advanced diffractive lens designs. On the other hand, predictive algorithm-based adaptive headlight systems increase night driving safety by illuminating the road according to the road illumination and slope level, as well as the load amount and speed of the vehicle [14]. Laser diode-based headlights offer significant advantages in adaptive lighting due to their high efficiency and compact size [15].

Figure 2. Laser-based OVAS

Today, since the silent operation of electric and hybrid vehicles poses a safety risk for pedestrians, the use of Acoustic Vehicle Alerting Systems (AVAS) has become mandatory in regions such as the European Union. UNECE Regulation R138, which came into force in 2021, requires all new electric and hybrid vehicles to use AVAS. The regulation requires vehicles to produce sounds within certain decibel ranges at low speeds and to provide frequency changes during acceleration and deceleration. These audible warnings are of great importance for silent vehicles to be noticed, especially by pedestrians. In addition to the AVAS system, the integration of the recently proposed Optical Vehicle Alerting System (OVAS) into automotive standards has been guided by the AVAS regulations.

Figures 1 and 2 illustrate the OVAS systems developed using LED and laser technologies respectively. With LED technology, the OVAS system can produce projection patterns and be integrated into vehicle components such as side mirrors, headlights or other suitable locations. In addition, LEDs can be added to signal lamps to project information such as the vehicle's charging status onto the ground. The integration of the OVAS system into the regulation can be achieved by complementing acoustic alerts with optical alerts. For example, as the vehicle's speed increases, optical alerts can be activated in addition to acoustic alerts, making both forms of alerts more noticeable to pedestrians. Similar to AVAS systems, the OVAS system should also provide dynamic alerts based on vehicle speed, which can be achieved by increasing the frequency or intensity of the optical alert with speed. In conclusion, the OVAS system should be developed in accordance with the sound and frequency variation rules outlined in UNECE R138. UNECE R138 is a regulation that mandates electric and hybrid vehicles to produce an audible warning sound for pedestrian safety. This regulation specifies key parameters, such as sound levels and frequency ranges, to standardize the audible alerts that should be emitted by vehicles. By aligning the technical testing and type approval processes with AVAS regulations, the OVAS system can gain wider acceptance in the automotive industry and make a significant contribution to pedestrian safety.

In this study, two different optical vehicle alerting systems (OVAS) based on LED and laser technologies were developed and their performances were compared. The systems were designed to operate using vehicle speed data and could also be manually controlled independently of speed. As there is no existing regulation in this area, the developed OVAS systems aim to contribute to the formulation of future regulations as innovative OVAS solutions. The systems developed use speed data from the vehicle's Controller Area Network (CAN) to project light patterns onto the ground to alert pedestrians. The first implementation used laser light sources and lenses to create linear patterns. The second implementation used LEDs with a dominant wavelength of 520nm and reflectors to create circular patterns. Both systems were designed to be suitable for mass production in electric and hybrid vehicles. To achieve this, a Hazard Analysis and Risk Assessment (HARA) was carried out in accordance with automotive standards to determine the Automotive Safety Integrity Level (ASIL) required for compliance. Multi-layer PCB designs were created using Altium Designer, and electrical surge tests were performed in accordance with ISO 7637-2 ve ISO 16750-2 standards. Mechanical designs for mounting the systems in vehicles were developed in Solid-Works and manufactured using 3D printing technology. For the LED-based systems, simulations were carried out using ANSYS Speos 2022 R2 to optimise the light patterns and optical measurements were carried out in a dark room. The vehicle CAN network was simulated using a DEW-43A DAQ instrument. Finally, the designs were validated through in-vehicle field tests to demonstrate effectiveness and reliability.

2. Simulation and Experimental Methods

The human eye's response to light energy is maximum around 550 nm (green light). For this reason, semiconductor-based compact LED and laser diodes used in OVAS design and operating around 550 nm can provide sufficient visual alerts at low power levels. Laser diodes produce narrow, linear patterns, while LEDs produce wide, circular patterns. LED and laser-based light sources eliminate the need for frequent replacement due to their long lives [11]. Specifically, LED-based light sources offer significant advantages in terms of long life, cost efficiency, and ease of use. Diffractive optical lenses can be used to precisely direct and focus light onto the illuminated surface [16].

In our simulations, ANSYS Speos 2025 R2 was used to model and characterize the optical performance of the proposed OVAS system. The Lambertian distribution used in Ansys Speos describes the illumination pattern of light on surfaces. This distribution is calculated from the cosine of the angle between the direction of incident light and the surface normal and is represented as a light intensity pattern [17]. In simulation studies, lenses with different reflector configurations were used for both light sources to obtain optimum light distribution.

In order to evaluate the contribution of the OVAS system to pedestrian detection at various speeds and environmental conditions, simulations were carried out and prototype designs were optimized using the simulation results. Experimental characterization of the optical pattern for the LED-based OVAS system was performed using the Everfine GO-HD5 automotive goniophotometer. The system's optical performance was analyzed within a ±180° horizontal and ±120° vertical rotation range, utilizing a pre-amplified, constant-temperature photometer head with CLASS L (f1'<1.5%) accuracy to ensure high-fidelity luminance measurements. Precise angular resolution of 0.01° enabled detailed gradient analysis, while the integrated laser alignment system optimized positioning accuracy during the test cycle. The photometric data, including illuminance curves and equal luminous intensity distributions, were processed in real-time through software-controlled automation, facilitating objective evaluation of the lighting performance. Measurements were taken at angles of 30° to the left, right, up and down from the centre of the source. During the measurements, the OVAS system was powered by the internal power supply of the Everfine GO-HD5 and aligned with an integrated laser system. The measurement point was positioned at a height of 50 cm to avoid interference with the connector panels on the unit. The simulation results carried out on ANSYS Speos during the design phase were compared with the measurement results. Six LEDs, each driven at approximately 700 mA, were used in the system during the measurements.

To simulate our OVAS system, a CAN simulation interface was designed using Dewesoft software and the DEWE-43A DAC device. This allows detailed testing and validation of the communication protocols and ensures reliable integration of the OVAS system into the overall vehicle architecture. The OVAS system allows ID information in data packets received over the CAN bus to be modified, ensuring seamless integration with vehicle software without ID conflicts. Vehicle speed data is monitored within predefined limits to control the light intensity. The direction of light is configured to project either towards the vehicle or forward, depending on the application. The functional block diagram of the system is shown in Figure 3, which effectively illustrates the integration and operation of the various system components. The controller processes the data from the CAN interface and adjusts the driver module to control the system's output based on the received commands. The power module varies depending on the use of LEDs or lasers.

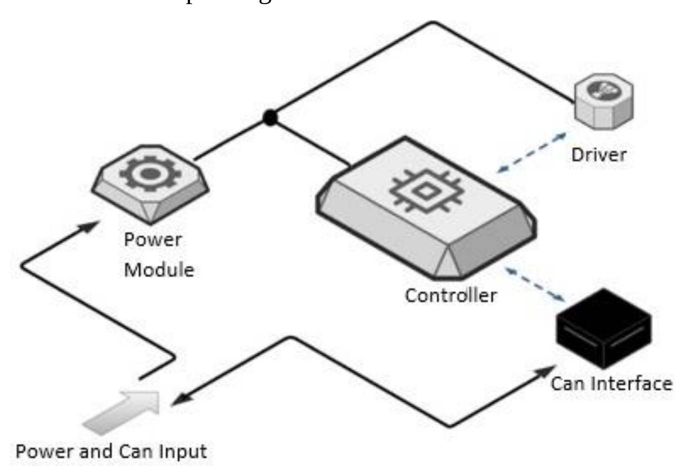

Figure 3. System functional block diagram

Figure 4 illustrates the design of the electronic control circuits, including the integration of the laser and LED. The laser driver circuit is integrated with the laser diode and uses a voltage stabilizer regulator. A modular electronic system design was implemented to test the OVAS system which consists of an electronic control module and a light source driver module. Light sources of different types and power levels can be connected and tested through the CAN communication-based control module. The OVAS system uses a TJA1042 transceiver IC to transmit and receive data using the CAN bus which is 4-wire controlled consisting of CAN H and CAN L communication and power supply cables. Filters and terminators are used to reduce noise on the CAN bus. The TJA1042 transceiver also includes an internal wake-up filter block and an additional software-based filtering feature. The power line passes through forward protection diodes and filters to form the power supply line. QM ASIL level components have been selected and the circuits are designed following automotive standards. The circuits operate independently and the general controller acts as a constant current and voltage source circuit. Transient Voltage Suppressor (TVS) diodes are used at the power input along with parallel resistors and capacitors to suppress voltage spikes and transient loads. Surge tests have shown successful results. The voltage from the input connector is converted to the required level using a DC-DC converter. A universal control board was designed to drive both laser and LED light sources. The LED driver circuit operates at constant current, while the integrated laser diode driver circuit operates at constant voltage. Both systems were designed to operate within a voltage range of 10-30 volts. The control board is used to switch between the laser and LED driver circuits. The constant current source circuit uses an AL8860 IC to switch and an Rset resistor to set the output current of the LED at 700 mA. The OVAS system using laser diodes has similar characteristics to LED diodes in terms of heat and efficiency. A LM317 IC is used in the laser driver board to provide voltage regulation. In addition to passive cooling, software-based temperature monitoring was implemented in the system for additional protection.

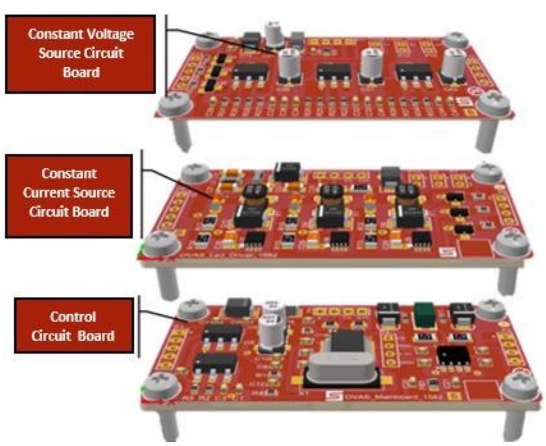

Figure 4. Electronic Circuit Designs

3. Simulation Results

LED and laser diode light sources used in ANSYS Speos simulations were selected based on their wavelengths, which are close to the peak sensitivity of the human eye: approximately 505 nm for LED and 532 nm faor laser diode. LED with a power of 5 mW and laser diode with a power of 100 mW were used in the simulations. The simulation results have shown that both the 505 nm LED and the 532 nm laser diode light sources produced distinct light patterns that improved pedestrian visibility. These results underscore the effectiveness of specificed wavelengths and power levels in producing high-visibility optical alerts, which are critical for pedestrian safety in low visibility or high-risk scenarios.

Figure 5 shows the lux value map of the light intensity produced by the LED source at heights of 30 cm and 50 cm above the ground obtained using ANSYS Speos. Figure 6 shows the visible colour and brightness of the light on a dark concrete surface at 30 cm (left) and 50 cm (right) obtained using ANSYS Speos. This visual comparison helps to evaluate the lighting quality of the LED-based OVAS system at different heights, focusing on the uniformity of light distribution and colour consistency. The data obtained using the Everfine GO-HD5 goniophotometer validates the design against the simulation results and demonstrates the expected performance of the system in use. In addition, immunity and emission tests were performed on the designed OVAS systems as parts of the electromagnetic compatibility (EMC) evaluation. The ISO 7637 standard is widely used in the automotive industry to test the electromagnetic compatibility of electronic systems and components. The same standard also evaluates the environmental factors (such as temperature, vibration, and humidity) that electronic components in vehicles may encounter and evaluates their resistance to these factors.

The functionality of the OVAS systems was simulated using Dewesoft software. Data acquisition was performed using DEWE-43A devices, leveraging their 24-bit sigma-delta ADCs with anti-aliasing filters to ensure high-precision signal processing. The synchronized sampling architecture enabled microsecond-level timing accuracy across analog, digital, and CAN input channels, ensuring reliable correlation of multi-domain data. Real-time analysis capabilities facilitated frequency-domain assessments and time-synchronized event detection, optimizing system validation under dynamic conditions. By changing the vehicle speed values in the simulation, the system's response to certain changes was observed. In dark room tests, the vehicle speed was simulated, and the warning lights were monitored accordingly. A unified simulation was performed for systems using both laser and LED sources, demonstrating compatibility in handling real-time changes. The systems designed are programmed to automatically deactivate when the vehicle speed exceeds 20 km/h. This threshold can be adjusted via software, providing flexibility to meet varying operational requirements. The simulation results have shown a strong correlation with real world conditions. Field tests to assess real-world performance confirmed that laser and LED light sources were particularly effective in alerting pedestrians at low speeds (below 20 km/h). These results confirm the reliability and practicality of OVAS in improving pedestrian safety in real-world conditions.

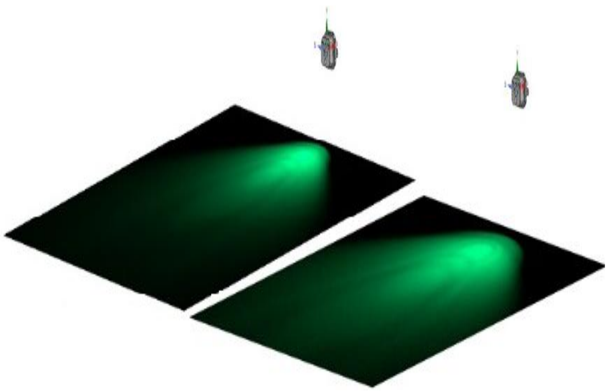

Figure 5. Lux value map of LED-based OVAS formed on the ground at 30 cm and 50 cm heights obtained in ANSYS Speos software.

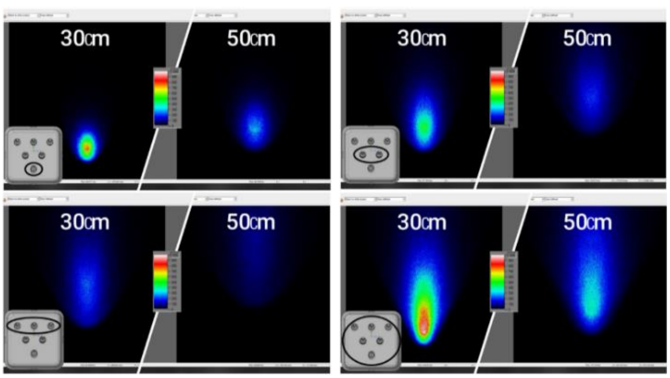

Figure 6. Visible color and light intensity on the dark concrete surface at heights of 30 cm (left) and 50 cm (right) obtained in ANSYS Speos software.

4. Experimental Results

For the experimental characterization of the system, electrical, mechanical, chemical and climatic tests in accordance with the ISO-16750 standard were realized. The electronic boards were tested over a temperature range of -40°C to +85°C, and no degradation in performance was observed. The electronics circuits' compliance with ISO 7637-2 standards was rigorously verified through tests conducted using the Teseq N5G instrument. Electrical pulses were applied to the circuits, and their responses were analyzed, offering critical insights into their classification according to ISO 7637-1:2015 standards [18].

Automotive electronic electromagnetic compatibility is not only one of the important performance indicators for evaluating automobiles and parts but also one of the necessary tests for the export of automobiles and parts to foreign markets [19]. CISPR-25 compliant measurements, as shown in Figure 7, indicated that the signal levels remained below the limit thresholds. The test detected dBμV levels up to 1 GHz. In the emission test, the entire frequency band was monitored, with white representing the average signal and orange representing the peak signal levels. The measurement results demonstrated that the signal levels stayed below the specified limits.

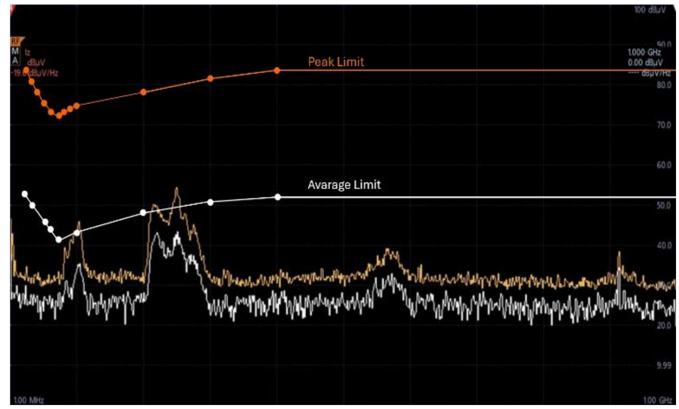

Figure 7. Emission Measurement with Near Field Probe.

The measurements were conducted using a near-field probe, providing an approximate idea of the results. For products intended for use in vehicles, accredited laboratories must perform tests under appropriate lab conditions, and certification should be obtained accordingly [20].

The OVAS system, designed with LED and laser light sources, demonstrated adaptability to various vehicle types. Simulation results obtained using LED sources were validated through vehicle-mounted OVAS system tests at heights of 30 cm and 50 cm. The light patterns and intensities were assessed to ensure the design's validation and effectiveness. Figure 8 shows the controlled dark room environment used for the light pattern measurements. The measurements were carried out in our goniophotometry laboratory using sensors that comply with automotive standards. In the photogoniometry laboratory, there are three sensors used for different classifications.The first sensor was selected, and the system was classified as a warning and signal lamp based on this classification.

Figure 8. Dark Room Measurements

Figure 9 provides a comparative analysis of isolux distributions obtained at 30 cm and 50 cm installation heights. The measurements indicated that the system installed at 50 cm affected 242% more area within the 1–3-meter range compared to the 30 cm setup. The measurement results indicated that the OVAS system met the CIE 1931 colour standard with a colour intensity of approximately 52.2%.

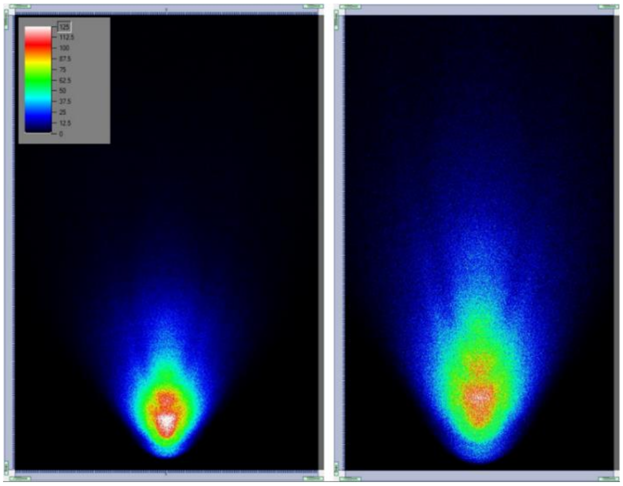

Figure 9. Diagram of Isolux Values from the Center Analyzed at 30 cm and 50 cm Heights.

The simulation studies were followed by tests on real applications. Photographs of the vehicle-mounted implementations are shown in Figure 10. Radiation characterisation results were consistent with the specifications defined in the simulation environment. The optical analysis and measurement results were supported by the overall design methodology and simulation details.

Figure 10. 50 cm Height - OVAS System with LED Light Source (17:00)

The image shows a green light pattern on asphalt, recorded on November 1, 2023, in Istanbul at 5:00 PM. The upper left corner features a vehicle with the OVAS system, which was activated and photographed on the same date. The light pattern on the ground closely resembles the OVAS system's illumination.

The OVAS system, which creates a linear light pattern using a laser diode, is shown on the right in Figure 11. On the left, the OVAS system utilizing LED technology is mounted on the vehicle. The developed laser and LED-based OVAS systems were controlled on the vehicle under different scenarios using CAN communication.

In the displayed image, the LED-based OVAS system creates a distinct light pattern on the asphalt surface, while the laser diode-based OVAS system on the right produces sharp and linear light patterns. Analyses of the LED sources were conducted using Ansys Speos software, and the results were compared with measurements obtained in the goniophotometry laboratory. The resulting graph, shown in Figure 11, demonstrates the correlation between simulation data and real measurements.

The experimental results indicate that when the system was installed at a height of 50 cm, it illuminated 242% more area in the 1-3 meter range compared to the 30 cm setup. This distribution is illustrated in Figure 12, highlighting the increased light coverage and effectiveness achieved with a higher mounting position.

Figure 11. 50 cm Height- OVAS System with LED and Lazer Light Source

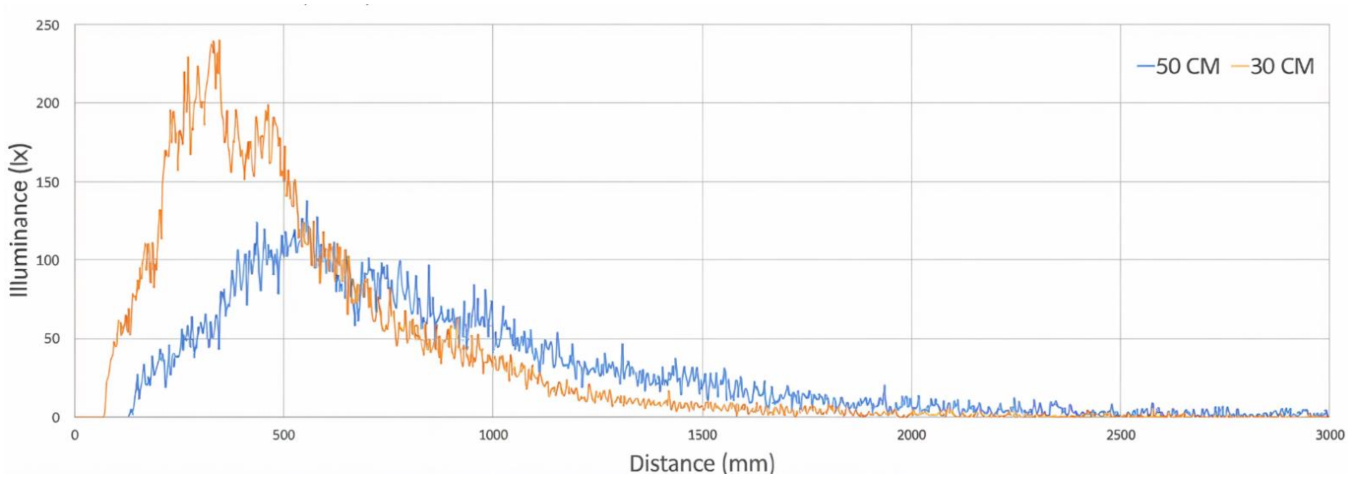

Figure 12. Illuminance (lx) variation as a function of distance (mm) for the OVAS system using LED light source at 30 cm and 50 cm heights on the vehicle front.

5. Conclusion

In this study, LED and laser diode light source based Optical Vehicle Alerting Systems (OVAS) designed to improve pedestrian awareness in electric and hybrid vehicles were successfully tested with the results agreeing well with both simulations and real-world performance. ANSYS Speos simulations were used to evaluate the performance of laser and LED light sources in conjunction with vehicle speed, producing different light patterns. The simulation results demonstrated the effectiveness of the LED and laser diode light sources under different lighting conditions (daylight and dark room environments). Specifically, LED light sources with a wavelength of 505 nm were observed to illuminate large areas, while laser diodes with a wavelength of 532 nm produced narrow, linear patterns.

Dark room tests showed that, in agreement with the simulations, both laser diode and LED light sources were effective in detecting pedestrians at low speeds. The dynamic light patterns produced by laser-based systems, which varied with vehicle speed, were shown to be effective in attracting pedestrian attention, demonstrating that the simulations accurately reflected real-world performance. Experimental tests also confirmed that the systems operated effectively in night-time or low-light conditions, confirming the suitability of the design for real-world applications. In conclusion, the proposed OVAS system provides a significant solution to the safety challenges posed by the silent operation of electric and hybrid vehicles and can be seamlessly integrated into automotive standards. The consistency between simulation and test results confirms the potential of the system for commercial applications. The simulations were performed under both day time and night time conditions. Further studies, particularly in low-light scenarios (e.g. rainy or foggy wheather), have shown that laser diode or LED based OVAS systems can be effectively used to alert pedestrians.

The OVAS system designed with LEDs was mounted at two different heights, 30 cm and 50 cm above the ground, and their performances were compared. It was observed that the OVAS positioned at 50 cm projected a light pattern covering 242% more area at a range of 1-3 metres compared to the system mounted at 30 cm. This emphasises the considerable impact of the installation height on the system's efficacy.

Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

CRediT Author Statement

Selim Duru: Conceptualization, Supervision, Software,
Buğra Er: Writing-original draft, Resources,
Görkem Bavtar: Methodology, Validation,
Ahmet Altuncu: Data curation, Supervision, Formal analysis,

References

[1] Abdel-Basset M, Gamal A, Moustafa N, Abdel-Monem A, El-Saber N. A security-by-design decision-making model for risk management in autonomous vehicles. IEEE Access. 2021; 9: 107657-107679. http://dx.doi.org/10.1109/access.2021.3098675

[2] Wu CF, Xu DD, Lu SH, Chen WC. Effect of signal design of autonomous vehicle ıntention presentation on pedestrians' cognition. Behavioral Sciences. 2022; 12(12): 502-522. https://doi.org/10.3390/bs12120502

[3] Tian K, Tzigieras A. Deceleration parameters as implicit communication signals for pedestrians' crossing decisions and estimations of automated vehicle behaviour. Accident Analysis & Prevention. 2023; 190: 17-37. https://doi.org/10.1016/j.aap.2023.107173

[4] Jägerbrand AK. LED (light-emitting diode) road lighting in practice: An evaluation of compliance with regulations and improvements for further energy savings. Energies. 2016; 9(5): 357-370 https://doi.org/10.3390/en9050357

[5] Neurauter ML, Roan M, Song M, Harwood L, Douglas M, Daniel G. Electric vehicle detectability by the vision impaired:

Quantifying impact of vehicle generated acoustic signatures on minimum detection distances. National Highway Traffic Safety Administration. 2017; 1(25): 17-0134.
[6] Alghodhaifi H, Lakshmanan S. Simulation-based model for surrogate safety measures analysis in automated vehicle-pedestrian conflict on an urban environment. Autonomous Systems: Sensors, Processing, and Security for Vehicles and Infrastructure. 2020; 1(11415): 8-21. https://doi.org/10.1117/12.2558830
[7] Kurtuluş OU. New trends and functionalities in automotive tail lighting. The Eurasia Proceedings of Science Technology Engineering and Mathematics. 2021; 14: 31-38. https://doi.org/10.55549/epstem.1050167
[8] Flachhuber M, Scheuchenpflug J, Hilbert T, Danz N, Schreiber P, Wilhelm LM, Metz M, Olaya JC, Reusch T. MaMeK: a wide-angle dynamic holographic projection system for human-vehicle communication. InDigital Optical Technologies 2023; 12624: 225-238). https://doi.org/10.3390/app9061182
[9] Tan CM, Singh P. Reliability and Failure Analysis of High-Power LED Packaging. Woodhead Publishing. 2022. http://dx.doi.org/10.1016/C2019-0-04104-0
[10] Wang L, Ma J, Su P, Huang, J. High-resolution pixel led headlamps: Functional requirement analysis and research progress. Applied Sciences. 2021; 11(8): 3368. https://doi.org/10.3390/app11083368
[11] Wördenweber B, Wallaschek J, Boyce P, Hoffman D. Automotive lighting and human vision (1st ed). New York: Springer Berlin Heidelberg. 2007. https://doi.org/10.1007/978-3-540-36697-3
[12] Khan MS, Saeed WM, Roth B, Lachmayer R. Diffractive optics based automotive lighting system: A rear end lamp design for communication between road users. Advanced Optical Technologies. 2020; 10(1): 49-57. https://doi.org/10.1515/aot-2020-0055
[13] Shatanawi M, Alatawneh A, Mészáros F. Implications of static and dynamic road pricing strategies in the era of autonomous and shared autonomous vehicles using simulation-based dynamic traffic assignment: The case of Budapest. Research in Transportation Economics. 2022; 95: 101231. https://doi.org/10.1016/j.retrec.2022.101231
[14] Santos-Berbel CD, Castro M. Effect of vehicle swiveling headlamps and highway geometric design on nighttime sight distance. Mathematics and Computers in Simulation. 2020; 170: 32-50. https://doi.org/10.1016/j.matcom.2019.08.012
[15] Choi H, Lee WS, Harisha BS, Kim WC, Lim J. Optical design for laser diode scanner headlamp with efficiently distributed optical power for adaptive driving beam system of automobiles. Applied Sciences. 2021: 11(2); 793-801. https://doi.org/10.3390/app11020793
[16] Waśniowska J, Sioma A. Modelling the Interaction of Illuminations with a Sensor Matrix Used in Vision Systems. Applied Sciences. 2023; 13(19): 10641. https://doi.org/10.3390/app131910641
[17] Amodeo D, Lucarelli V, De Palma I, Puccio A, Nante N, Cevenini G, Messina G. Efficacy of violet–blue light to inactive microbial growth. Scientific Reports. 2022; 12(1): 20179. https://doi.org/10.1038/s41598-022-24563-1
[18] Chen W, Mu X, Wang T, Zhang J, Liu Y. Analysis on the Change of the Electromagnetic Compatibility Test Method of Automobile and Parts based on the of the Changes in ECE R10. In 2022 International Conference on Wireless Communications, Electrical Engineering and Automation (WCEEA). 2022; (pp. 141-146). IEEE. https://doi.org/10.1109/wceea56458.2022.00037
[19] Duru S. Development of an Optical Vehicle Alert System for Hybrid and Electric Vehicles [Master Thesis]. Department of Electrical and Electronics Engineering, Kütahya Dumlupınar University, Graduate School of Education, Kütahya, 2024. https://doi.org/10.13140/RG.2.2.34364.45449