EVALUATING VISUAL COMMUNICATION INTERFACES BETWEEN PEDESTRIANS AND AUTONOMOUS VEHICLES USING VIRTUAL REALITY EXPERIMENTS

*P. Bouchner**, *S. Novotný**, *A. Orlický**, *L. Topol**

Abstract: This study explores the development and evaluation of external human-machine interfaces (eHMI) for communication between autonomous vehicles (AVs) and pedestrians. By employing advanced virtual reality (VR) simulations and leveraging behavioral data from 600 survey respondents, the research examines the intelligibility and effectiveness of seven eHMI prototypes. The experiments utilized eye-tracking and spatial analysis to measure pedestrian response to AV signals in realistic virtual environments. The findings emphasize the potential of LED strip-based communication interfaces, demonstrating their superiority in terms of visibility, clarity, and implementation cost. This research contributes to the broader field of artificial intelligence applications in transportation, with a focus on ensuring safety and trust in autonomous systems interacting with vulnerable road users.

Key words: *autonomous vehicles (AVs), pedestrian interaction, external human-machine interfaces (eHMI), virtual reality (VR), interactive simulation, visual communication*

Received: May 15, 2024
Revised and accepted: October 10, 2024

DOI: 10.14311/NNW.2024.34.015

1. Introduction

The advent of autonomous vehicles (AVs) represents a transformative era in urban mobility, where advanced artificial intelligence control systems replace human drivers. While current automated driving technologies excel on motorways, their adaptation to the complex urban environments introduces challenges, particularly in communication and interaction with vulnerable road users, such as pedestrians. Traditional driver-mediated cues, including gestures or headlight flashes, became obsolete in driverless systems. Thus, one of the key challenges in integrating AVs into urban environments is ensuring intuitive and comprehensible communication between AVs and pedestrians. This creates an urgent need for robust, intuitive,

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and universally comprehensible external human-machine interfaces (eHMI) to ensure safe and efficient road-sharing. These interfaces must not only be highly visible and easily understood but also overcome barriers caused by cultural differences, age, or varying levels of user experience. Moreover, such solutions can bring novel means of communication which could potentially reach higher levels of safety for human road users.

Developing and testing such systems requires a combination of human-centered design principles with advanced technologies, including virtual reality (VR), eye-tracking, and behavioral analysis. Virtual reality enables the simulation of functional virtual prototypes in combination with realistic traffic scenarios, allowing for efficient testing of various eHMI prototypes in controlled and 100% safe conditions. This approach ensures that the tested systems are optimized for real-world use cases while they are adaptable to diverse urban settings and user profiles.

Furthermore, the integration of VR with tools like eye-tracking provides detailed insights into pedestrian visual behavior and derived measures, such as reaction times, gaze patterns, and/or decision-making processes in response to AV signals. These data-driven methodologies not only validate the effectiveness of proposed eHMI concepts but also promote utilization of the artificial intelligence in transportation by supporting the development of safe and trustworthy interactions between AVs and vulnerable road users.

1.1 Pedestrians in Traffic

Pedestrians are among the most vulnerable road users, and any misjudgment in their interaction with vehicles can lead to severe or even fatal consequences. According to accident statistics from the Police of the Czech Republic in 2019, approximately 3,500 accidents involving vehicles and pedestrians occur annually in the Czech Republic, with 94% of these resulting in injury and 1 in 28 being fatal [1]. These alarming figures underscore the need for innovative and reliable communication systems between autonomous vehicles (AVs) and pedestrians to minimize risks in urban traffic environments.

A severity of pedestrian injuries is directly linked to a vehicle's impact speed [1, 2]. As shown in Fig. 1, a relationship between the driver's reaction time and the resulting impact speed illustrates a critical importance of timely and effective communication. For example, a one-second delay in braking can result in an impact speed of 46 km/h instead of a complete stop. The survival probability at different impact speeds is detailed in Tab. I, demonstrating that at 30 km/h, a pedestrian has a 90% survival chance, whereas at 50 km/h, this probability drops significantly to just 16%.

In conventional traffic, the drivers often communicate with the pedestrians with the use of specific gestures, such as hand waves, head shaking or headlight flashes, to indicate whether it is safe to cross or not. However, in the case of AVs, where drivers are absent, such communication must be replaced with external human-machine interfaces (eHMI). These systems must provide clear and universally understandable signals, regardless of the pedestrian's age, cultural background, and in its final stage also regardless of their visual or auditory capabilities. This requires designing eHMI solutions that are not only intuitive but also adapted to diverse real-world

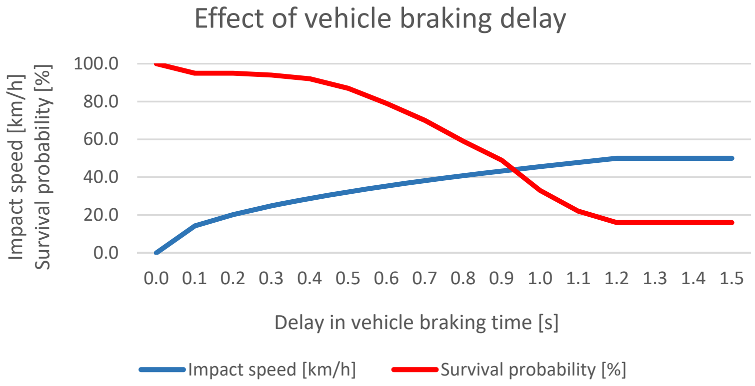

Fig. 1 *The effect of vehicle braking delay (authors' interpretation of data from [2, 3]).*

Delay in vehicle brake time [s]	Impact speed [km/h]	Survival probability [%]
0.0	0.0	100
0.1	14.2	95
0.2	20.2	95
0.3	24.9	94
0.4	28.8	92
0.5	32.2	87
0.6	35.3	79
0.7	38.1	70
0.8	40.8	59
0.9	43.3	49
1.0	45.6	33
1.1	47.8	22
1.2	50.0	16
1.3	50.0	16
1.4	50.0	16
1.5	50.0	16

Tab. I *Vehicle braking delay and its impact.*

scenarios. The development of such interfaces should benefit from interdisciplinary approaches that integrate engineering, artificial intelligence, and human-centered design.

This study highlights the role of data-driven methodologies, such as virtual reality simulations and behavioral analysis, in evaluating pedestrian responses to visual and auditory signals. By observing these interactions, researchers can ensure that proposed eHMI solutions are optimized for real-world traffic environments, thereby contributing to safer and more efficient urban mobility.

2. Experimental Evaluation of the Quality of External HMI

2.1 Visual Communication Between Pedestrians and AVs

Extensive survey research was conducted by the authors at the Faculty of Transportation Sciences, Czech Technical University in Prague (FTS CTU) to understand the pedestrian behavior and the driver contact in pedestrian crossing areas. The survey gathered and evaluated responses from almost 600 people acting as pedestrians while crossing a crosswalk. Based on the results, ten typical pedestrian crossing behaviors were categorized, based on what people usually do while crossing the road on the crosswalks.

The survey results, illustrated in Fig. 2, show that 81% of pedestrians utilize both visual and audible vehicle signals to notice vehicles when crossing, while only 7% of pedestrians rely solely on visual cues, and 10% depends exclusively on audible cues. Importantly, 2% of pedestrians do not rely on either visual or audible cues (probably relying on the law giving the pedestrian priority over cars at designated crossings), representing the most vulnerable group for future communication with AVs.

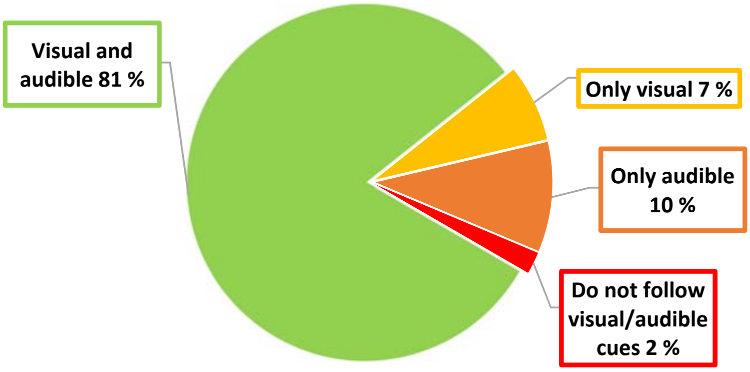

Fig. 2 *Pedestrian reliance on visual and auditory cues when crossing the road.*

Our findings align with other recent studies investigating communication interfaces between AVs and pedestrians [4, 5]. These studies confirmed that visual signals should be the primary element of AV-pedestrian communication, complemented by audible signals for situations involving pedestrian endangerment. Data in Fig. 2 approve such pedestrian behavior, testifying the need for well-designed eHMI systems.

The main advantage of visual communication lies in its clarity. It is immediately apparent which vehicle is sending the signal, and a well-designed visual system can ensure reliable operation over longer distances, regardless of environmental conditions. This makes visual communication the primary focus for current AV development efforts [4].

2.2 Visual AV-Pedestrian Communication Prototypes Considered

Currently, no standardized communication interface exists for AV-pedestrian interaction, leading to the development of various designs depending on each of car manufacturers. Upon our research of publicly available materials these prototypes can be grouped into seven categories based on their technical design and signal placement (a front grille area, signals placed on a front bumper, windshield projection, on-road projection, LED strip on windshield edge, bonnet projection, and a panel at the windshield base). Fig. 3 visualizes these different communication concepts using a Skoda Vision E vehicle prototype – see [17].

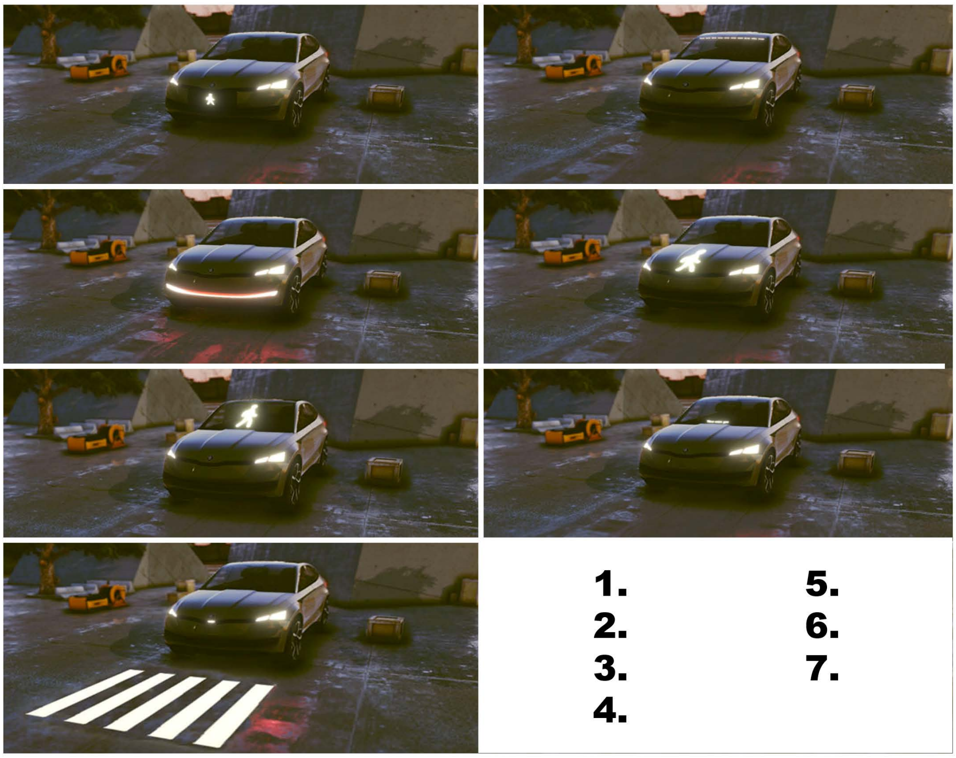

Fig. 3 *Visualized concepts of external communication interfaces on the Skoda Vision E prototype.*

1. Embedded panel in the front grille: Preferred by the Volkswagen group, this interface integrates visual signals directly into the vehicle's grille [6].

2. Modified front part with signals on the bumper: Proposed by Skoda Auto and featured on the Hyundai Staria, this design enhances visibility by placing signals on the bumper [6, 7].

3. Signals projected onto the windshield: A concept proposed by Lyft, where signals are displayed on the vehicle's windshield to communicate with pedestrians [8].
4. Road surface projection: Introduced by Mercedes-Benz, this technology projects images or symbols onto the road surface in front of the vehicle [9].
5. LED strip on the windshield's upper edge: The most used system, supported by Ford and 18 other automotive companies [10].
6. Bonnet projection: Proposed by Waymo, this concept involves projecting signals onto the vehicle's bonnet [11].
7. A panel at the bottom of the windshield: Demonstrated by Nissan, this concept places a communication panel near the base of the windshield [12].

Some designs also consider extending communication systems to the sides of the vehicle to improve visibility and safety (e.g., LED strips or side projectors), as shown in Fig. 4.

Fig. 4 *Additional designs considering side-mounted communication systems.*

Among these prototypes, the LED strip positioned on the top edge of the windshield demonstrates the greatest potential due to its simplicity, cost-effectiveness, and universal applicability across different vehicle designs. Other concepts, such as road projection and bonnet projection, face challenges related to visibility in varying lighting conditions or the vehicle's structural design.

2.3 The Experiment Using a VR Headset

The aim of the research conducted by the authors at the Faculty of Transportation Sciences, Czech Technical University in Prague was to propose objective methods for evaluating AV communication interfaces. The methodology of the experiment was designed to use both quantitative data and qualitative data, such as visibility, intelligibility, and pedestrian trust, to evaluate the essential characteristics of communication interfaces. Based on the research framework, two main methods were applied to assess these characteristics.

The first method is focused on a theoretical visibility of the communication interface. The principle of this method was to calculate the spatial angle (SA) defining how the object appears in the human eye's field of view, as illustrated in

Fig. 5 – a geometric diagram illustrating the spatial angle in the pedestrian's field of view, showing the relationship between object position and visibility.

This metric was used to determine whether the interface was suitably positioned and visible or whether additional side signaling systems might be necessary [13].

The second method evaluated pedestrian trust and the intelligibility of signals projected by the AV. These factors were assessed using participants' observations and ratings in a controlled virtual reality environment. Fig. 6 shows the laboratory setup, including the VR headset and simulated pedestrian crossing scenario.

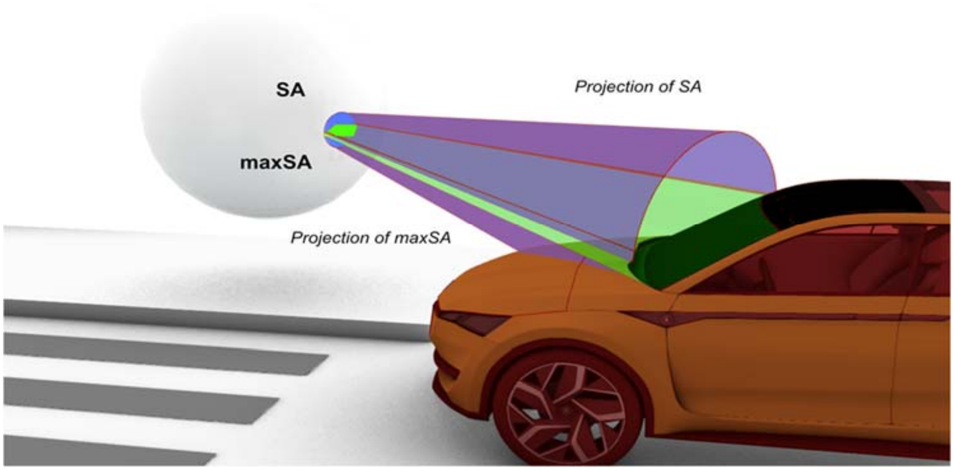

Fig. 5 *Measuring the spatial angle in the pedestrian's field of view.*

Fig. 6 *Laboratory setup for virtual reality experiments.*

This method was designed to analyze and assess pedestrians' behavior when faced with specific communication signals, measuring parameters such as reaction times and decision-making during crossing events.

2.3.1 Intelligibility

The method addressing intelligibility was designed to monitor pedestrian behavior before entering a road when a vehicle with a communication interface approached. The vehicle communicated its status and intent with the use of visual signals. The pedestrians' reactions were observed and recorded in each test scenario. Key measures, such as the distance at which the pedestrian first noticed the AV or the timing of their decision to cross, were analyzed.

To capture these parameters, eye-tracking technology was used to record gaze direction and attention. The delay between the AV's signal and the pedestrian's reaction served as the primary measure for evaluating intelligibility. This delay is influenced by factors such as signal visibility, clarity, and environmental conditions, and is critical for understanding the effectiveness of different eHMI prototypes.

2.3.2 Experiment Scenario and Hardware Setup

The experiment, which evaluated seven proposed visual eHMI concepts, was conducted by authors in a laboratory at Faculty of Transportation Sciences, Czech Technical University in Prague using a complete virtual reality setup. A realistic virtual environment simulating an urban pedestrian crossing was created using Unity software [14]. The scenario was designed so that participants stood on the sidewalk near a crosswalk, as illustrated in Fig. 7.

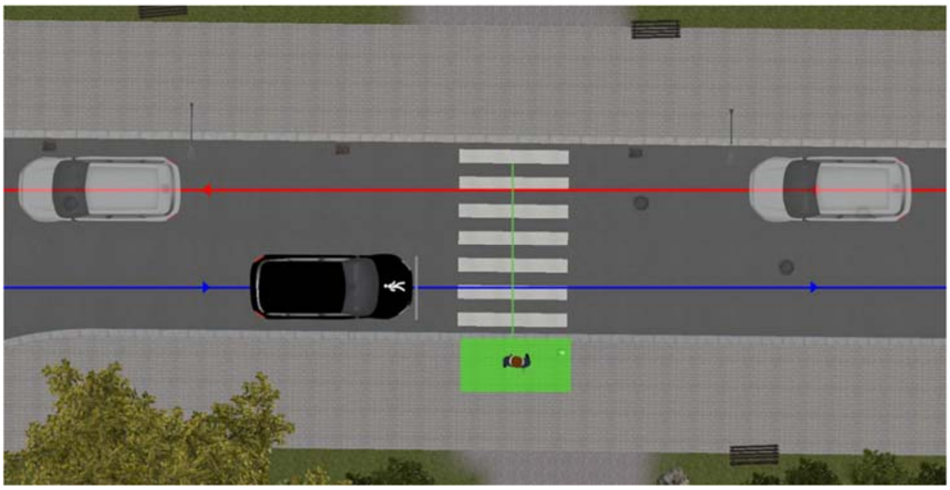

Fig. 7 *Top view of the simulated pedestrian crossing scenario.*

The vehicles approached the crosswalk from both directions, with AVs signaling their intent to yield. The AVs in the simulation traveled at a consistent speed of 45 km/h, corresponding to real-world conditions, and displayed various visual signals as they approached the crosswalk. Vehicles without communication systems were used as a control group. Participant behavior was analyzed for each of the seven eHMI concepts, focusing on reaction times and crossing decisions.

A head-mounted HTC Vive Pro Eye display, shown in Fig. 8, was used to immerse participants in the virtual environment and to record eye-tracking data.

Fig. 8 *HTC Vive Pro Eye headset used for the experiments.*

This headset features OLED displays with a resolution of 1440×1600 pixels per eye, a 110° field of view, and an integrated eye-tracking system with 120 Hz refresh rate [15]. Positional tracking was conducted using external base stations, with the experiment area set to approximately $100\,\mathrm{m}^2$ for accurate movement detection.

2.3.3 Experiment Results

The results of the experiment demonstrated significant differences in the intelligibility and acceptance of the seven tested prototypes. As shown in Fig. 9, the LED strip on the upper edge of the windshield provided the best results in terms of visibility and clarity. Participants were able to understand signals from this interface at distances of 25–30 m, with highly consistent responses across all test scenarios. Other prototypes, such as the bonnet projection, achieved moderate results but faced limitations due to vehicle design constraints. Similarly, road surface projections struggled with visibility over longer distances, particularly under varied lighting conditions. Prototypes with embedded panels in the grille or lower windshield positions were less effective due to poor visibility and limited recognition from participants.

2.4 Discussion

The experimental results of testing the AV-pedestrian communication interfaces indicated clear differences in the performance and acceptability of the seven tested

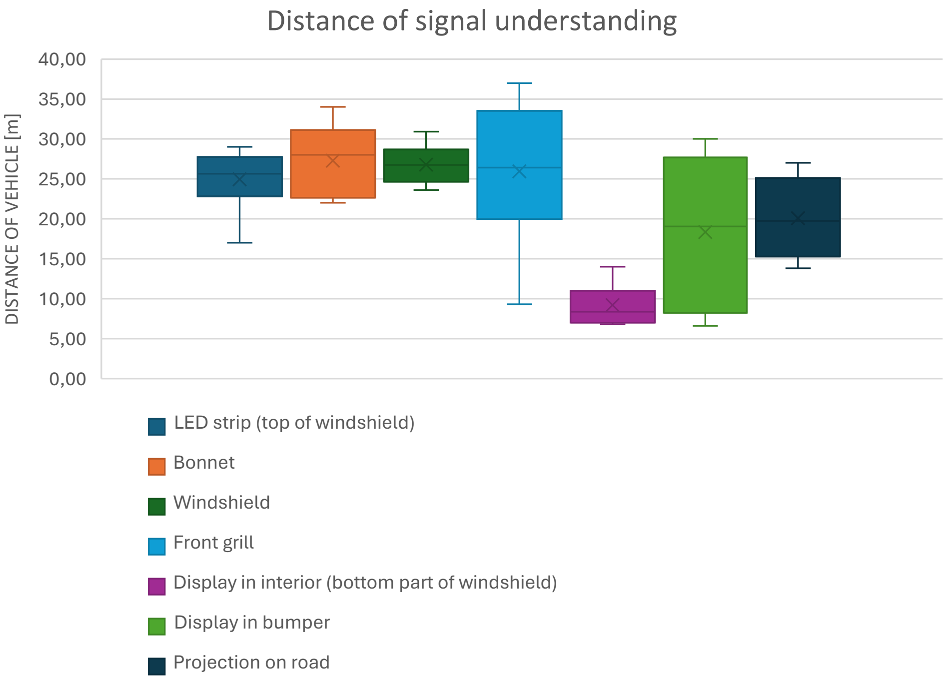

Fig. 9 *Average distance of signal recognition for each eHMI prototype.*

prototypes. The LED strip positioned on the upper edge of the windshield consistently demonstrated superior performance, achieving the highest levels of intelligibility and visibility in various scenarios. As shown in Fig. 9 – average distance of signal recognition for each eHMI prototype, participants were able to recognize and interpret signals from this interface at distances of 25–30 m, significantly outperforming other designs.

While the LED strip proved to be the most effective, other concepts revealed limitations that highlight challenges in designing universally applicable external human-machine interfaces. For instance, the bonnet projection offered promising results in terms of clarity but faced significant constraints related to vehicle design, as the projection surface depends heavily on the vehicle's body shape. Without standardizing vehicle designs, such an interface may not be viable across the automotive industry [12].

Similarly, road surface projection technologies showed potential in controlled environments but struggled in scenarios with variable lighting conditions. This issue, combined with the risk of obstructed visibility due to uneven road surfaces or weather conditions, limits the practical application of these systems. Further development would be required to address these challenges and enhance their robustness.

Prototypes incorporating embedded panels in the front grille or lower windshield positions showed limited effectiveness due to their poor visibility at typical pedestrian viewing angles. These systems often required closer proximity for recognition, as evidenced by the shorter distances recorded during the experiment (see Fig. 9). This highlights the importance of positioning eHMI systems at heights and angles that align with the pedestrian's natural field of view, as discussed earlier with reference to Fig. 5.

The experiment also underlined the importance of considering pedestrian trust and behavior in the design of eHMI systems. While the LED strip design was highly effective, some participants expressed skepticism about whether the signals accurately interpreted the vehicle's intent. This emphasizes the need for further studies focusing on long-term user acceptance and trust in autonomous systems.

Additionally, the use of virtual reality (VR) in this research demonstrated its value as a modern and advanced tool for testing and evaluating AV communication interfaces. VR simulations provided a controlled yet realistic environment, enabling detailed behavioral analysis without exposing participants to real-world risks. However, certain limitations of VR must be acknowledged. For example, the resolution of current VR headsets remains lower than the human eye's capacity, which may affect the perceived clarity of small visual signals, such as LEDs [16]. Improvements in VR technology, including higher resolutions and refresh rates, could further enhance the validity of future experiments.

3. Conclusion

This research presents a comprehensive evaluation of external human-machine interfaces (eHMI) designed to facilitate communication between autonomous vehicles (AVs) and pedestrians. Addressing one of the most critical challenges in urban integration of Avs – ensuring intuitive and effective communication with vulnerable road users – this study tested seven eHMI prototypes using the advanced virtual reality (VR) interactive simulation tools and behavioral analysis.

The results underscore the significance of well-positioned and easily interpretable visual signals. Among the tested designs, the LED strip positioned on the upper edge of the windshield emerged as the most promising solution. It demonstrated high visibility and intelligibility, allowing pedestrians to recognize and respond to signals at distances of 25–30 m consistently. This solution also stood out for its technological simplicity, cost-effectiveness, and potential for standardization across different vehicle types. These findings align with broader trends in the automotive industry, where intuitive and universally accessible eHMI designs are prioritized to foster trust and safety in autonomous systems.

While the LED strip proved to be highly effective, other prototypes revealed specific limitations. The bonnet projection and road surface projection, for example, showed potential but faced practical challenges related to vehicle design constraints and environmental variability. Such findings emphasize the need for further refinement of these concepts, especially to enhance their robustness under real-world conditions.

In addition to evaluating eHMI prototypes, this study highlighted the critical role of pedestrian behavior and trust in the design process. Trust in autonomous systems remains a key barrier to widespread adoption, as some participants expressed skepticism about whether AV signals accurately reflected vehicle intentions. This finding suggests that future research should explore the long-term acceptance of eHMI systems, considering factors such as cultural differences, demographic variations, and the impact of repeated exposure on user trust.

Moreover, this research showcased the utility of virtual reality as a tool for testing and validating eHMI designs. VR technology allowed for the safe and controlled simulation of complex traffic scenarios, providing valuable insights into pedestrian-vehicle interactions. However, the study also identified limitations in current VR hardware, such as resolution constraints and refresh rates, which could impact the perceived clarity of visual signals. As VR technology continues to evolve, future experiments could leverage these advancements to achieve even more realistic simulations and improve the reliability of experimental results.

Future work in this domain should aim to address three critical aspects. The first is the standardization of eHMI systems, which is essential to ensure consistency across different manufacturers and vehicle types, enabling widespread deployment and user familiarity. Second, there is a need for enhanced user studies that evaluate the long-term impact of eHMI systems on diverse demographic groups, providing insights into societal and psychological factors influencing their acceptance. Third, further exploration into multimodal communication systems, which integrate visual, auditory, and haptic signals, could create more comprehensive and inclusive solutions tailored to the needs of various pedestrian groups and environmental conditions.

By addressing these challenges, the field can move closer to achieving fully autonomous transportation systems that are not only technologically advanced but also socially integrated, safe, and trusted by road users.

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