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Evaluating the External Human-Machine Interface of Autonomous Vehicles on Pedestrian Safety at Mid-Block Crossings: A Virtual Reality-Enabled Simulation Study

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ABSTRACT
With the emergence of autonomous vehicles (AVs), urban traffic conditions are becoming increasingly complex. The presence of AVs may pose a danger to pedestrians making mid-block crossings. As a countermeasure, the external Human-Machine Interface (eHMI) is a promising solution to enhance communication between AVs and pedestrians. This study employs virtual reality technology with built-in eye tracking to support the analysis of pedestrians' eye gaze behavior during mid-block crossings while interacting with AVs with different eHMIs. Preliminary results show that color and the types of the messages (i.e., texts vs. symbols) are critical factors to draw pedestrian attention. To gather more statistically meaningful results, tests on a larger sample of participants are planned for further study.
Keywords: External Human-Machine Interface; Mid-Block Crossings; Autonomous Vehicles; Pedestrian Safety; Virtual Reality; Eye Tracking

INTRODUCTION
Autonomous driving technology has increased the complexity of urban traffic, especially with pedestrians making unpredictable mid-block crossings, posing significant safety challenges as autonomous vehicles (AVs) may fail to detect and respond appropriately. This study investigates the use of external Human-Machine Interfaces (eHMIs) on AVs to improve safety by enhancing communication between AVs and pedestrians in a virtual reality (VR) setting. VR simulation provides a lifelike and controlled environment to study pedestrian reactions. Additionally, the integrated eye-tracking technology in the VR headset can capture detailed data on pedestrian gaze movements and offers insights into how different eHMI designs influence attention. By leveraging VR and eye tracking, this research aims to assess the effectiveness of eHMIs in enhancing pedestrian safety and decision-making at mid-block crossings. The findings are expected to improve AV-pedestrian interactions and contribute to safer and more efficient urban transportation systems.

Methodology
The Meta Quest Pro VR headset is chosen due to its built-in eye-tracking capabilities, which facilitate the analysis of pedestrian attention and responses to various eHMI cues. A two-lane roadway simulation scenario is created as the base map for the VR environment, illustrating typical urban mid-block crossing conditions. The simulation includes an AV equipped with various eHMIs designed to communicate the AV's intent to pedestrians. As a conceptual exploration, one participant was involved and large-scale study will be done in next phase. The eHMI signals, as shown in Figure 1, vary between textual and symbolic messages to assess their relative effectiveness. Pedestrians' gaze data was recorded, and the frequency of eye gaze intersections with the vehicle and eHMI will be analyzed.

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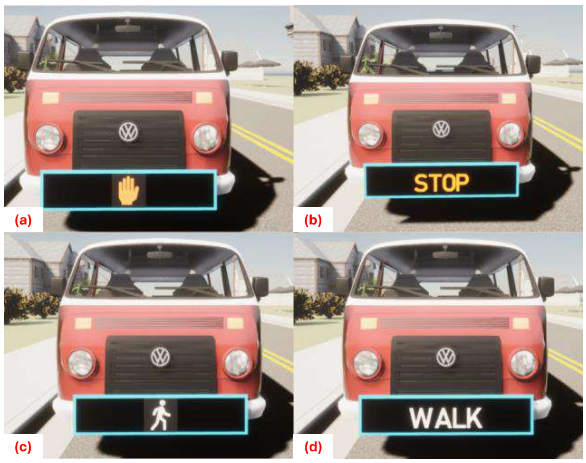

Figure 1. Various eHMI designs: (a) an AV displays an orange “STOP” symbol; (b) an AV displays an orange “STOP” text; (c) an AV displays a white “WALK” symbol; and (d) an AV displays a white “WALK” text.

Results and Analysis

In VR settings, the eye-tracking system captures 3D information with XYZ coordinates. The intersections of eye gaze with the AV's bounding box and eHMI are recorded (i.e., Figure 2). The heatmap displays the gaze intersection density on the AV, generated by a two-dimensional Kernel Density Estimation:

$$\hat{f}(y,z) = \frac{1}{nh_y h_z}\sum_{i=1}^{n} K\left(\frac{y-y_i}{h_y}, \frac{z-z_i}{h_z}\right) \quad (1)$$

where K is kernel function and $h_y, h_z = 1$ are selected as the bandwidth. It is worth mentioning that each scenario has a different number of data points because the total time varies. A longer total time results in more data points, which affects the heatmap density scale across the four scenarios. The results indicate that while crossing, pedestrians pay more attention to the eHMI if the AV is equipped with it. Comparing different eHMI designs, the orange color captured more attention, while the white "WALK" text did not attract much notice. This may be because pedestrians are more familiar with orange, as it is commonly used in warning signs and safety equipment, conveying a higher sense of urgency. In contrast, the white "WALK" text may not carry the same level of attraction. However, the white "WALK" symbol does attract attention, suggesting that larger samples should be included for further analysis.

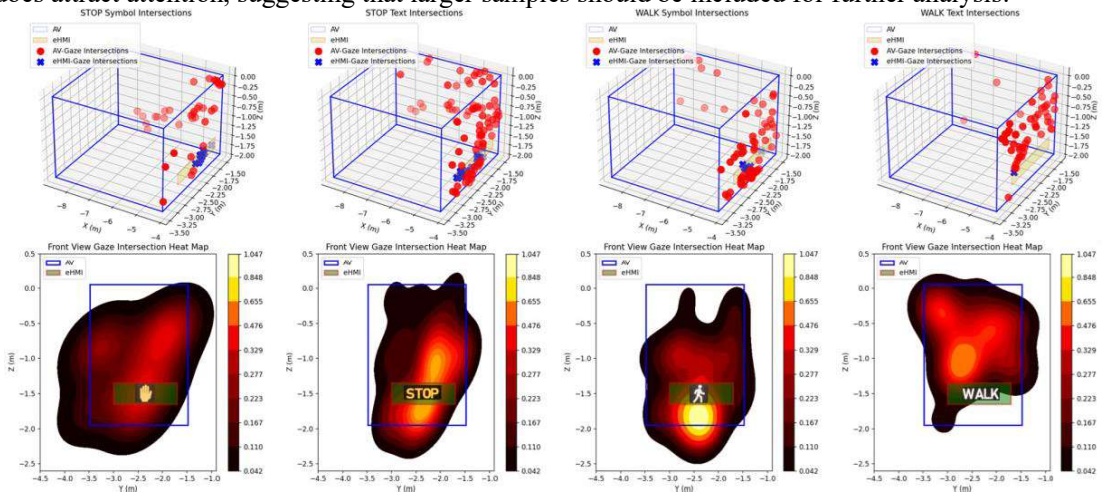

Figure 2. Top: Eye Gaze Intersection with the AV and eHMIs of Different Designs; Bottom: Heatmap of Gaze Focus Area.

Conclusion

This study's initial findings highlight the potential of eHMIs in enhancing pedestrian attention during mid-block crossings involving AVs. Preliminary results indicate that the color and type of eHMI messages influence pedestrian awareness. To validate these findings and increase the statistical significance, future research should involve more participants. Also, comparative studies with AVs not equipped with eHMIs will provide a comprehensive understanding of the effectiveness of eHMIs.