Allusion 2: External Communication for SAE L4 Vehicles

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Abstract

With SAE Level 4 and above (L4+) Automated Driving Systems (ADSs) being integrated on roadways, stakeholders worldwide are developing external communication systems for other road users to communicate effectively. Most research on SAE L4+ ADS external communication has used simulators or virtual reality platforms to assess driver/road user knowledge, opinions, and attitudes via survey metrics evaluating a single L4 vehicle. However, it is vital to understand perception of external communication in real-world conditions and with multiple SAE L4+ ADSs present. This research explored how the presence of multiple SAE L4+ ADSs with external communication displays affected participants' crossing decisions. A within-subject design assessed participants' understanding of SAE L4+ ADS intentions. Results indicated that the presence and condition of external human-machine interfaces (eHMIs) did not influence willingness to cross. It was difficult for participants to focus on the eHMI when multiple vehicles competed for their attention. Participants typically focused on the vehicle that was nearest and most detrimental to their crossing path. Scenario type caused participants to make more cautious crossing decisions but did not influence willingness to cross. This study implies that eHMI with two patterns may still require simplification for pedestrians to interpret in a complicated traffic environment.

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Introduction

Various stakeholders have discussed integrating Automated Driving Systems (ADSs) into common roadway use for decades. Automated vehicles (AVs) promise to improve road safety by enhancing traffic efficiency, reducing traffic crashes associated with human errors, and improving the safety of vulnerable road users (VRUs) (Fagnant & Kockelman, 2015; F. Guo et al., 2022; J. Guo et al., 2022; Kaye et al., 2022; Tabone et al., 2021). Many challenges still need to be addressed before AVs can meet the expectation that they will improve road safety, especially regarding how AVs and non-automated road users interact in complex traffic environments, where transparency and predictability are required for safe encounters.

Pedestrians have higher perceived safety and willingness to cross when nonverbal cues are present to keep the AVs transparent and predictable (Habibovic et al., 2018; Lundgren et al., 2017). However, this direct line of communication will be eliminated as AVs with SAE International Levels 4 and above (SAE L4+) automation are integrated, as drivers will no longer be in control of dynamic driving tasks, and those responsibilities will be transferred to AVs. Researchers have argued that the communication of intentions must be substituted technically to bridge this resulting gap given the lack of nonverbal communication to pedestrians (i.e., eye contact, gestures) from AVs (J. Guo et al., 2022; Haimerl, Colley, & Riener, 2022; Lundgren et al., 2017; Merat et al., 2018; Schieben et al., 2019). Replacing the mechanism for conveying such information is of key importance during the initial introduction of mixed traffic environments, where pedestrians' sense of comfort may be compromised due to apprehensions about technical safety with AVs (J. Guo et al., 2022).

Countless researchers across academia and industry have proposed the use of external human-machine interfaces (eHMIs) to convey information unidirectionally from vehicles to their environment (Clamann et al., 2016; de Clercq et al., 2019; Dey et al., 2021; Sahaï et al., 2022). These eHMIs have been recommended to compensate for the lack of nonverbal communication between the driver and VRU (J. Guo et al., 2022; Habibovic et al., 2018, 2019; Schieben et al., 2019). Researchers have found that pedestrians primarily rely on vehicle kinematics to understand and interpret vehicle intent (Dey et al., 2021; Dey & Terken, 2017; Lee, Madigan, Giles, et al., 2021; Madigan et al., 2022; Moore et al., 2019; Rasouli et al., 2017). However, when the intent of an AV is not clear from kinematics alone, eHMIs have been found to be beneficial (Ackermans et al., 2020; de Clercq et al., 2019; Dey et al., 2021; Faas et al., 2020; Faas & Kraus, 2021; Holländer, 2019; Holländer et al., 2019; Shuchisnigdha et al., 2018).

The eHMI designs that have been tested include light bars, pictorial, text-based messages, and auditory cues. Researchers have placed these designs in different locations outside the vehicle or projected them on the roadway (Chu et al., 2022; Colley et al., 2022; Dey et al., 2022; Haimerl, Colley, Löcken, et al., 2022; Kaleefathullah et al., 2020; Lee, Madigan, Uzondu, et al., 2021; Rothenbucher et al., 2016; Shuchisnigdha et al., 2018). The light bar eHMI design is a frequent choice in research due to its relative simplicity, ease of implementation, and abstract execution

(Böckle et al., 2017; de Clercq et al., 2019; Dey et al., 2018; Faas & Baumann, 2020; Habibovic et al., 2018; Hensch et al., 2020; Lee, Madigan, Giles, et al., 2021; Petzoldt et al., 2018; Wilbrink et al., 2021; Zhang et al., 2017). Training and education about eHMIs are necessary to optimize understandability, and eHMI learnability will improve over time (Faas et al., 2021; Kalda et al., 2022). Because the general public has no previous mental model currently established for these displays, education will be required to help VRUs make an immediate association analogous to nonverbal communication with human drivers (Rothenbucher et al., 2016). Throughout the research evaluating eHMIs, it is vital to understand how eHMIs will affect pedestrian behavior and influence their decision-making abilities.

eHMI Communication Patterns

There has yet to be a consensus on the optimal physical and functional eHMI characteristics. However, some researchers found that communication should be relevant to the current situation without being distracting and should be allocentric (informing on the vehicle's current circumstances) rather than instructing or advising pedestrians how or when to act (Dey, Habibovic, Löcken, et al., 2020; Mahadevan et al., 2018; Rasouli & Tsotsos, 2020; Tabone et al., 2021; Yang, 2017). Yang (2017) found that when pedestrians made crossing decisions, they did not rely on the eHMI that conveyed advisory information.Click or tap here to enter text. Other studies found that eHMIs comprising complex text and pictorial messages did not play a significant role in pedestrian crossing decisions. However, LED-sequence eHMI signals were preferred (Chu et al., 2022; Mahadevan et al., 2018; Rasouli & Tsotsos, 2020). Lastly, some research found that a consistent pattern, such as a slow-pulsing animation in cyan color, is acceptable for exhibiting yielding intention (Dey, Habibovic, Pfleging, et al., 2020; Faas & Baumann, 2020; Hensch et al., 2020).

A few studies have examined two patterns via the eHMI (Barendse, 2019; Dey et al., 2021; Holländer et al., 2019). Dey et al. (2022) conducted a video-based study with eHMI concepts that offered pedestrians information via two vehicle states (yielding or non-yielding). Click or tap here to enter text.This was compared with a baseline of an AV without an eHMI present. Both explicit and implicit eHMI conditions were adequate and performed better than the baseline. However, there was no significant difference in crossing decision performance across the two evaluated eHMI conditions. Across the subjective findings, participants preferred eHMIs that explicitly communicated an AV's intent at all times (Dey et al., 2022). In addition, the yielding and non-yielding states need to be distinguishable.

Research Questions

This study was designed to understand how pedestrian crossing behavior is affected when multiple vehicles with eHMIs are present across various vehicle maneuvers in live situations. The following research questions were addressed:

eHMI Evaluation

- Research Question 1: Does the presence of multiple AVs with and without eHMI affect participants' crossing decisions?

- Research Question 2: How do colors (i.e., white and amber) of eHMI impact the decision-making of pedestrians?
- Research Question 3: Is an eHMI that provides two levels of information (i.e., yielding and driving) more understandable/interpretable than an eHMI with three levels (i.e., driving, yielding, and ready)?

Testing Scenarios

- Research Question 4: Did the complexity and type of scenarios impact participants' crossing decisions?

Law Enforcement Officer Cohort Preferences

- Research Question 5: What are law enforcement officers' preferences across light bar color conditions (i.e., white, amber, teal)?

Method

Study Design

Participants

Forty participants (20 male, 20 female) took part in this study, and participant ages were distributed across ranges falling between 18 to 65 years old (18-29 years: 9 participants; 30-39 years: 12 participants; 40-49 years: 8 participants; 50-65 years: 11 participants). All participants were recruited using the Virginia Tech Transportation Institute (VTTI) participant database. All 40 participants reviewed and signed an informed consent form approved by the Virginia Tech Institutional Review Board (IRB # 21-926). Every participant had normal or corrected-to-normal vision (20/40 or above). These participants were compensated $60 for a 2-hour test session.

Law Enforcement Cohort

The evaluation of varying eHMI colors has been repeated throughout the literature. However, through conversations with industry partners, the team also wanted to gain insight into the perspective of law enforcement officers (LEO) on the light bar colors. Specifically, the goal was to understand the impact of light bars on LEO everyday tasks and to help guide design principles of future eHMI concepts. Of the 40 participants, 10 LEOs were recruited, and nine participated. To meet study criteria for an LEO, participants had to be an active LEO with current or previous years of experience driving a patrol vehicle. In addition, they must have been on active patrol duty within the past 6 months.

This separate cohort completed all the same tasks and procedures as all other participants. After they completed all other study activities, LEOs were pulled aside to answer specific questions about the light bar, and one of the vehicles was pulled to the side of the road, where it switched its displays between white, amber, and teal. These questions were targeted to elicit the law enforcement cohort's thoughts on the colors used from their perspective and experience on patrol.

VTTI Smart Roads and Experimental Apparatus

The study was conducted on the Virginia Smart Roads Surface Street (Figure 1), a closed test-bed research facility managed by VTTI.

Figure 1. Aerial photo of section of VTTI Smart Road.

Driver Logistics

The operators each wore a seat-suit (Figure 2), which allows a human driver to be disguised as an empty driver's seat, creating the illusion of a fully automated vehicle. This deception was deemed necessary to test and evaluate participants' responses to encounters with what they believed were fully automated vehicles.

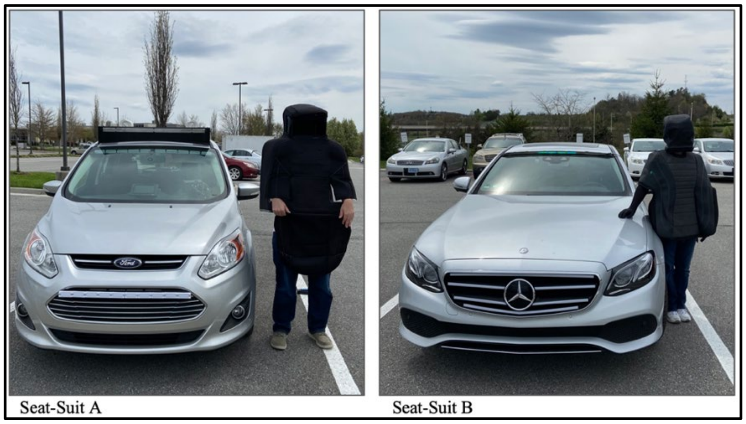


Figure 2. Photos. Seat-suit used for each SAE L4+ ADS.

Decision-making Box – To Cross the Street

To comply with safety protocols, participants were not allowed to physically cross the street in front of the testing vehicle; a decision-making box was utilized instead (Figure 3). A box outlined with four traffic cones was set up on the sidewalk facing the intersection.

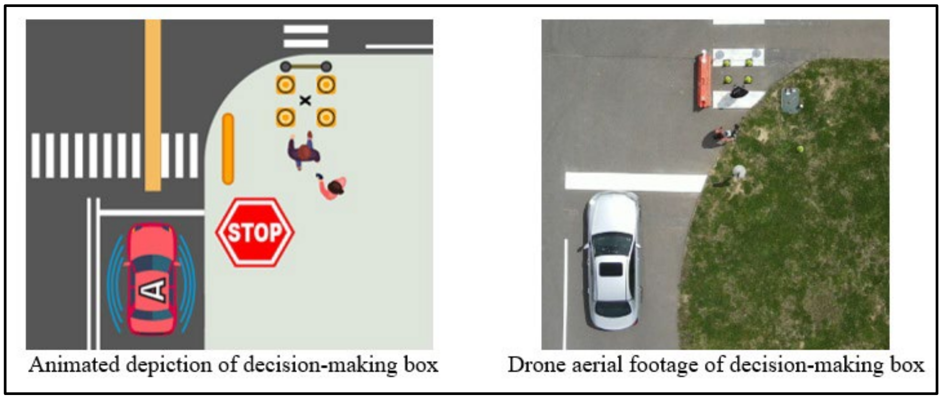


Figure 3. Illustration and photo. Depiction of the decision-making box.

The box made from four cones had rope safety barriers in front to deter participants from walking into the intersection. Participants stood outside the box as the experimenter provided instructions. Participants were asked to decide when they deemed it safe to cross the street without physically crossing the street. They stepped inside the box when they felt they would cross the street. When they felt they would not cross the street, they stepped outside the box. They were allowed to step back and forth inside or outside the box as often as they wanted per trial.

SAE L4+ ADSs External Interface Design

There were two vehicles emulating SAE L4+ ADSs in this study: SAE L4+ ADS-A, with LED light bars that changed between white and amber, and SAE L4+ ADS-B, which only displayed white LED light bars (Figure 4). This study was conducted in conjunction with several partners. The design of the external interfaces (including color and pattern selection) was provided by the research sponsors, who leased all testing vehicles to VTTI. SAE L4+ ADS-A's light bar was slightly thicker than the light bar installed in SAE L4+ ADS-B. However, luminance testing was conducted, and the luminance levels of both vehicles were adjusted to match before testing began with participants. The light bar color was changed between scenarios, so all participants experienced all color combinations. The color was counterbalanced across all scenarios and trials and between the two vehicles to minimize any order effects.

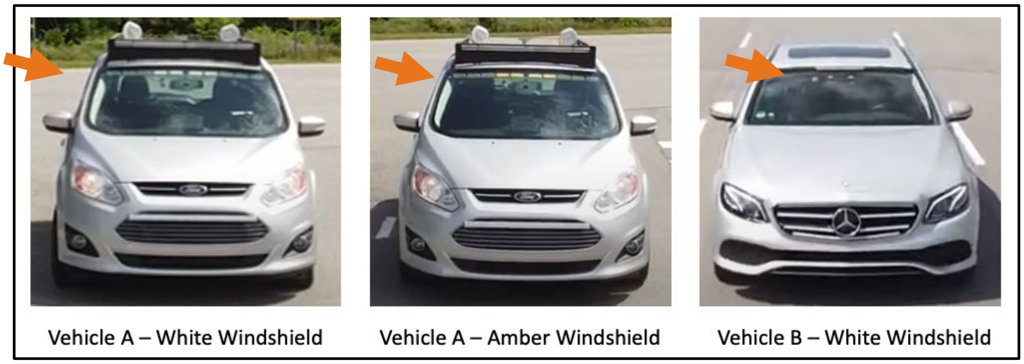


Figure 4. Photos. Overview of external communication location and color for SAE L4+ ADS-A and SAE L4+ ADS-B.

Both SAE L4+ ADSs communicated vehicle intent using (1) drive state and (2) yield state. The drive state was communicated by the light bar being uniformly lit (i.e., no motion or blinking) and indicated that the vehicle was in motion and would remain in motion. The yield state was communicated by the light bar flashing outwards to inwards, indicating that the vehicle was preparing to stop.

The light bar patterns were the same across the entire study. The order of the patterns was directly correlated to the action of the vehicle. Due to safety constraints, all vehicles began braking at exactly 100 yards away from the participant (marked with cones around the test track) at a consistent and replicable deceleration rate (excluding the high-speed Scenario 4, in which drivers decelerated at .7 g). The yield pattern was triggered as soon as the vehicle operator initiated the braking. The vehicles were stopped for 3 seconds before the drive pattern was triggered. After the yield state, the vehicle triggered the drive pattern and accelerated slowly after stopping at the intersection (< .05 g). All vehicles went through both states (drive and yield) during every exposure to the system.

Two SAE L4+ ADSs

Two pseudo-SAE L4+ ADSs were used in this study. Both LED bars were controlled by a switch mounted inside the vehicle. Both vehicles were equipped with a data acquisition system (DAS), which included cameras recording the forward view to capture participant behavior as pedestrians. All vehicles followed standard traffic laws and utilized their turn signals when necessary.

Procedure

Once a participant arrived at VTTI, an experimenter escorted them to a conference room. The experimenter reviewed the information sheet, consent form, and pre-session questionnaire. After completing the paperwork, the experimenter and participant walked outside to the Smart Roads Surface Street.

The experimenter and participant walked out to the Smart Roads Surface Street intersection. The experimenter provided instructions on the decision-making box and a high-level overview of the vehicle safety protocols. To reinforce the illusion that the test vehicles were driverless SAE L4+ ADSs, the experimenter communicated with the control tower via a short-wave radio communication device to program the vehicles for a specific scenario and trial. After each trial, the experimenter administered a questionnaire via a tablet. The researcher also used verbal probes to obtain participants' subjective feedback on the eHMI. This process was repeated until the participant was exposed to all the pedestrian trials. At no time was the participant given any instruction or training on the meaning of the eHMI displays.

Following the on-road experiment, the experimenter debriefed participants regarding the need for deceit about the "fully automated vehicle." Moderators also explained that it was important for participants to believe that the vehicles were highly automated to ensure that their perceptions and responses regarding their decisions to cross the streets would generalize to traffic scenarios where an ADS may control vehicles. Afterward, the participant was re-consented, indicating their preference that their study data be removed or retained by the research team.

Experimental Design

There were several conditions included in the study. The independent variables are depicted in Table 1.

Table 1. Independent Variables

Variable	Levels	Description
Light Bar Color	2	1) White 2) Amber
Exposures	12	1) Scenario 1, Trial 1 2) Scenario 1, Trial 2 3) Scenario 1, Trial 3 4) Scenario 2, Trial 1 5) Scenario 2, Trial 2 6) Scenario 2, Trial 3 7) Scenario 3, Trial 1 8) Scenario 3, Trial 2 9) Scenario 3, Trial 3 10) Scenario 4, Trial 1 11) Scenario 4, Trial 2 12) Scenario 4, Trial 3

Dependent Variables

Dependent variables included several forms of measurement. Qualitative feedback, as well as surveys, were also collected after each exposure.

Crossing Decision

Data reductionists recorded participants' willingness or unwillingness to cross the street for each scenario type, vehicle condition, and over time. This variable was individually coded to calculate pedestrians' movement and the number of steps inside and outside the decision-making box. This was calculated across each pedestrian scenario that utilized the decision-making box.

Crossing Decision and Vehicle Motion

Data reductionists calculated participants' willingness or unwillingness to cross when the vehicle stopped or actively approached the intersection. Specifically, reductionists noted the vehicle's movement (whether approaching or braking) each time a participant stepped in or out of the box.

Glances to Vehicles

The number of glances the participants made to the AVs was coded across each scenario to understand to which vehicle participants were attending. Due to limitations with the camera clarity, movements of the head, as opposed to the eyes, were used to define glance direction for coding.

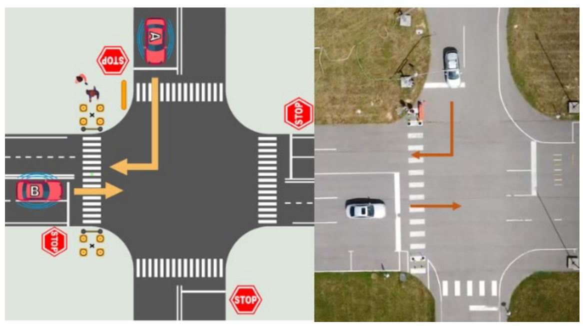
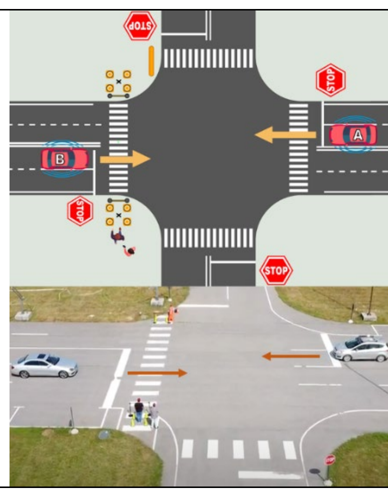
Learning Over Exposure

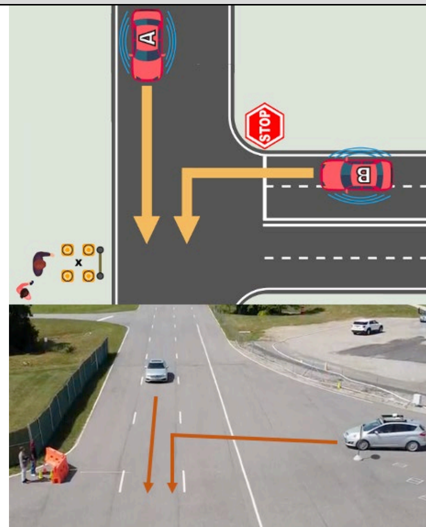
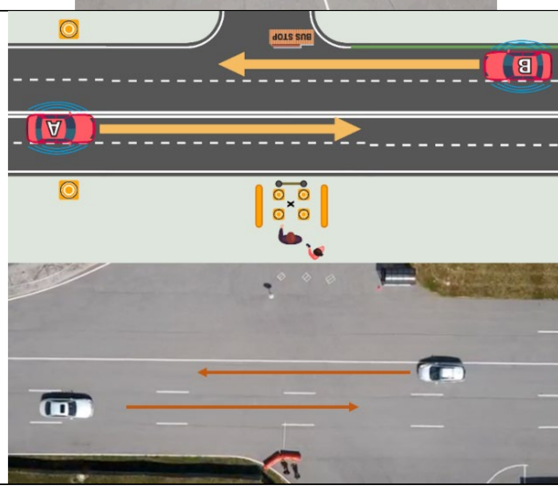
The number of times participants verbally confirmed they noticed the light bars and correctly interpreted the pattern meanings was recorded as well. This variable was calculated by the researcher who moderated the sessions. The researcher indicated if the participant noticed and correctly interpreted the meaning of the eHMI for all scenarios and trials.

Testing Scenarios

All participants experienced four different scenarios (depicted in Table 2 and detailed in Appendix A) that were repeated for three exposures (i.e., trials). One trial included both vehicles' eHMI being white. Another trial had a white eHMI and an amber eHMI. In another trial, both eHMIs were off, and this was treated as the baseline condition. Participants were exposed to the eHMI 12 times (four scenarios X three trials each). All scenarios selected were complex traffic scenarios that may confuse humans interacting with SAE L4 + ADSs.

Table 2. Testing Scenario Matrix

Scenario Overview	Illustration	Location	Maximum Speed
Scenario 1: Right Turn (RT) at a Four-way Stop		Intersection	10 mph
Scenario 2: Straight Four-way Stop		Intersection	10 mph

Scenario Overview	Illustration	Location	Maximum Speed
Scenario 3: Mid-Block Left Turn		Mid-block	35 mph
Scenario 4: Mid-Block Straight Crossing Path		Mid-block	35 mph

Results

Analysis Overview

Participant video data was collected from each DAS installed in the SAE L4+ ADSs. The DAS captured all kinematic and driver performance data and video of the participants' decision-making. The video and kinematic data were **combined** to understand vehicle distance and speed compared to a participant's decision to cross or not cross the street.

Willingness and Unwillingness to Cross

Crossing decisions were measured by the number of times a participant decided to cross the street throughout the scenario (i.e., the number of times they fully stepped inside the decision-making box). This data was analyzed across the four scenario trials, the three light bar conditions tested, and vehicle movement for the four pedestrian scenarios. Willingness to cross was defined when the participant stepped into the box at least once during an active trial. The number of times they stepped inside the box was also collected. Unwillingness to cross was defined as when a participant did not step into the box during the active trial. Indecision to cross was defined as when the participant demonstrated a physical inability to decide.

A primary coder reviewed the video and recorded participants' decision to cross, and a second coder analyzed a subset of data from each vehicle. Cohen's κ was run to determine if there was an agreement between the two coders on each participant's willingness or unwillingness to cross. There was moderate agreement between the two coders' judgments, $\kappa = .569$, $p < .001$. Willingness and unwillingness to cross were analyzed across 12 trials that utilized the decision-making box.

Crossing Decisions by Age and Gender

Participants' willingness or unwillingness to cross the street by age and by gender were analyzed. The number of participants who were willing to cross the street was not statistically significantly different across age. The number of participants who were willing to cross the street was also not statistically significantly different across gender.

Crossing Decisions by Gender

Cochran's Q test was used to assess the difference between gender and participants' decision to cross (Figure 5). Cochran's Q was used to assess the change in categorical results across time or within subjects in a dichotomous data set. The sample size met assumptions, so the χ^2-distribution approximation was used. The number of participants who were willing to cross the street was not statistically significantly different according to gender, $\chi^2(3) = 3.001$, $p = .392$.

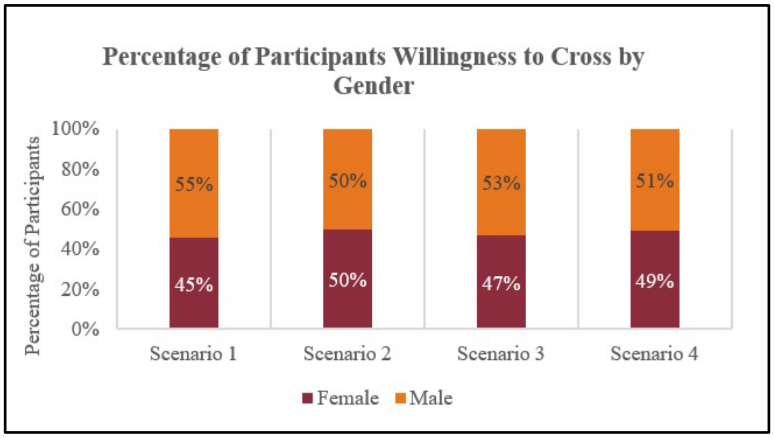


Figure 5. Chart. Willingness and unwillingness to cross by gender.

Crossing Decisions by Scenario

Participants' willingness or unwillingness to cross the street by scenario is outlined in Figure 6. Cochran's Q test was used to assess the difference between the testing scenarios and participants' decision to cross. The number of participants who were willing to cross the street was not statistically significantly different among the different scenarios, $\chi^2(3) = 5.155$, $p = .161$.

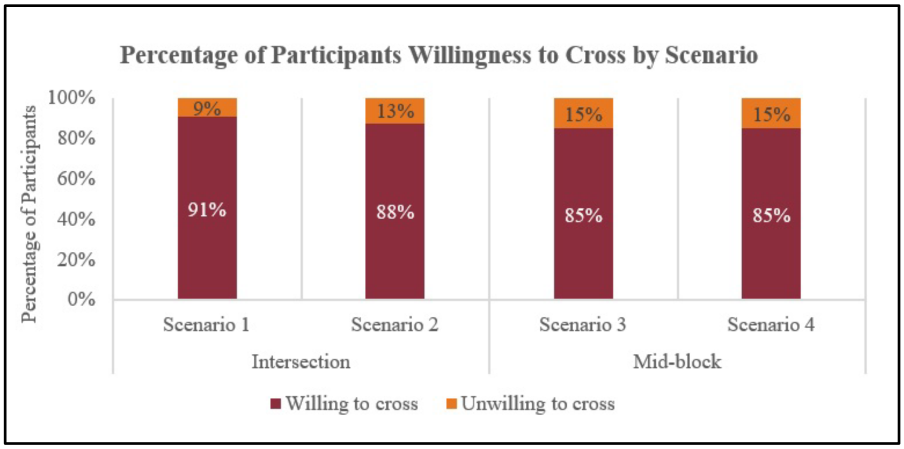


Figure 6. Chart. Willingness and unwillingness to cross by scenario.

Crossing Decisions by Trial

Participants' willingness or unwillingness to cross the street for each trial is outlined in Figure 7. Cochran's Q test was used to assess the difference between the testing trials and participants' decision to cross. The sample size met assumptions, so the χ^2-distribution approximation was used. The number of participants who were willing to cross the street was not statistically significantly different for the different trials, $\chi^2(11) = 12.392$, $p = .335$.

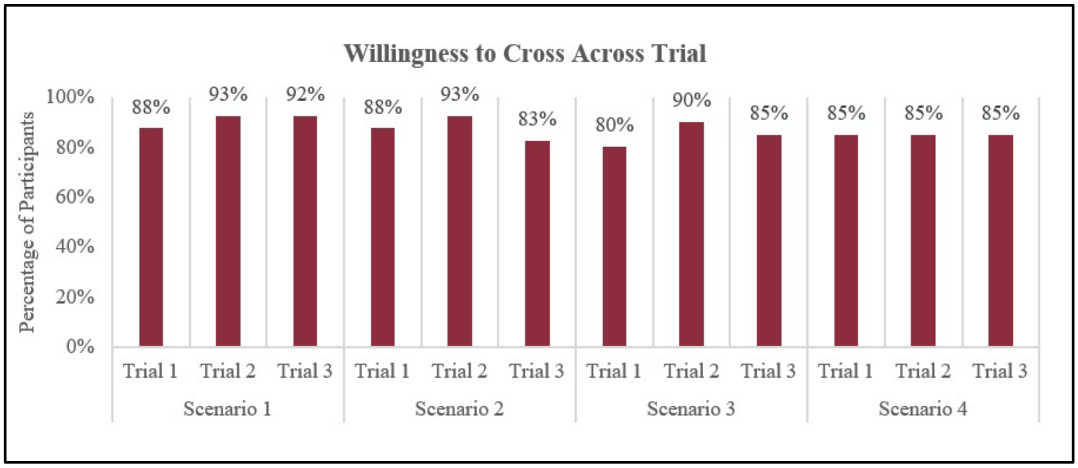


Figure 7. Chart. Willingness and unwillingness to cross across trial.

Number of Crossings by Trial

The number of times a participant decided to cross was coded. A one-way repeated measures ANOVA was conducted to determine whether there were statistically significant differences in the number of crossings pedestrians made across 12 trials. There was varied willingness to cross across trials, but the differences were not statistically significant, $F(11) = 2.648$, $p = .111$.

Crossing Decision by Condition

To assess the difference between the light bar conditions and participants' decision to cross, a Cochran's Q test was run (Figure 8). The percentage of participants who were willing to cross the street was not statistically significantly different across different light bar conditions and scenarios, $\chi^2(2) = .176$, $p = .916$.

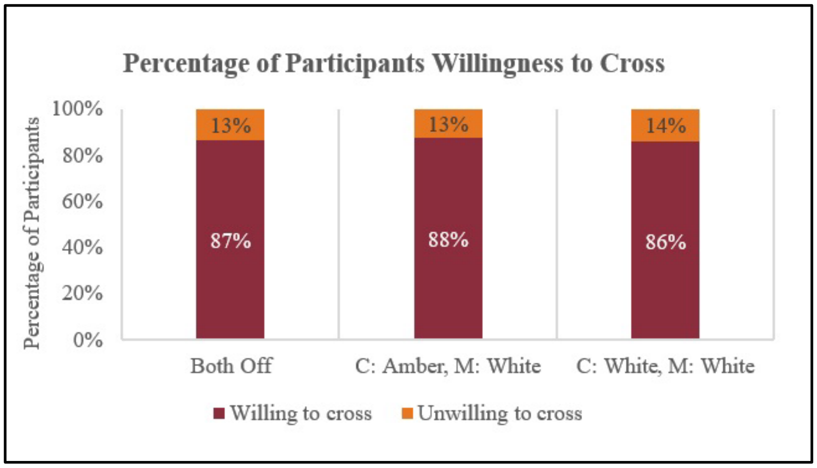


Figure 8. Chart. Crossing decision by light bar condition (C indicates CMAX, M indicates Mercedes).

Crossing Decision by Condition and Scenario

To assess the difference between the light bar conditions, scenarios, and participants' decision to cross, a Cochran's Q test was run (Figure 9). The percentage of participants who were willing to cross the street was not statistically significantly different across different light bar conditions and scenarios, $\chi^2(11) = 6.211$, $p = .859$.

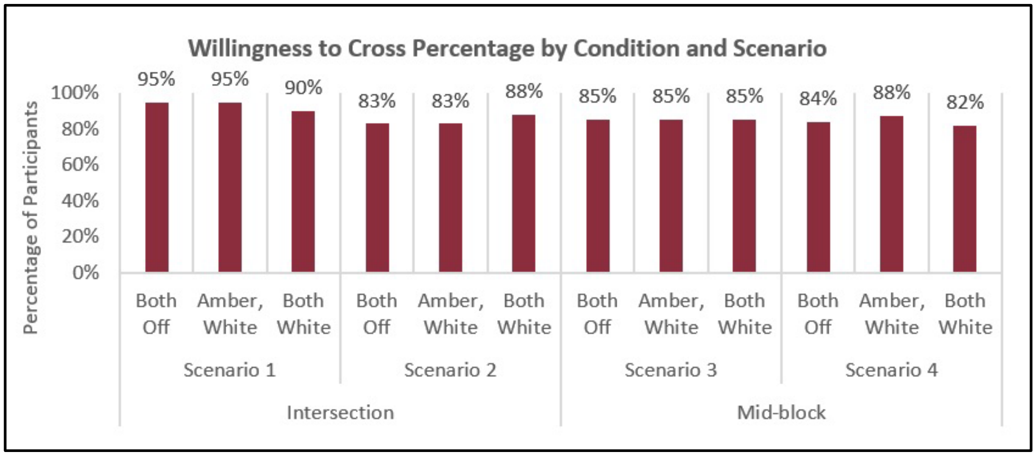


Figure 9. Chart. Crossing decision by light bar condition and scenario.

Crossing Decision by Experience Order

Figure 10 depicts the average number of participants' crossing decisions, grouped by either never crossing the street (left), did not cross the street while the vehicle was actively approaching them (middle), or crossed the street while the vehicle was actively approaching them (right).

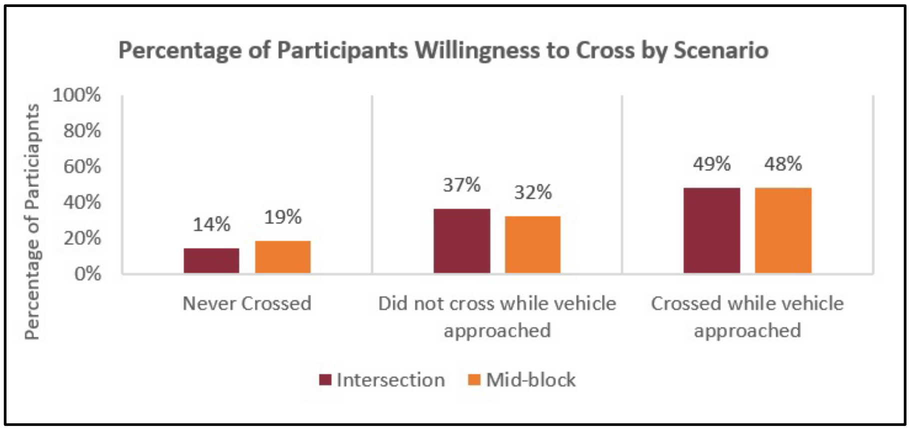


Figure 10. Chart. Average crossing behavior by participants' first experience of eHMI.

Learning Over Exposure Analysis

After each exposure to the light bars, participants' knowledge of the light bar patterns and correct interpretation of the patterns were recorded. The following sections analyze how long it took participants to notice the light bar pattern and correctly articulate the pattern meaning.

Analysis of Noticing the Patterns

Forty participants were exposed to the light bar patterns over 12 trials. The experimenter denoted when the participant noticed and successfully understood the light bars during the semi-structured interviews after each exposure (Figure 11).

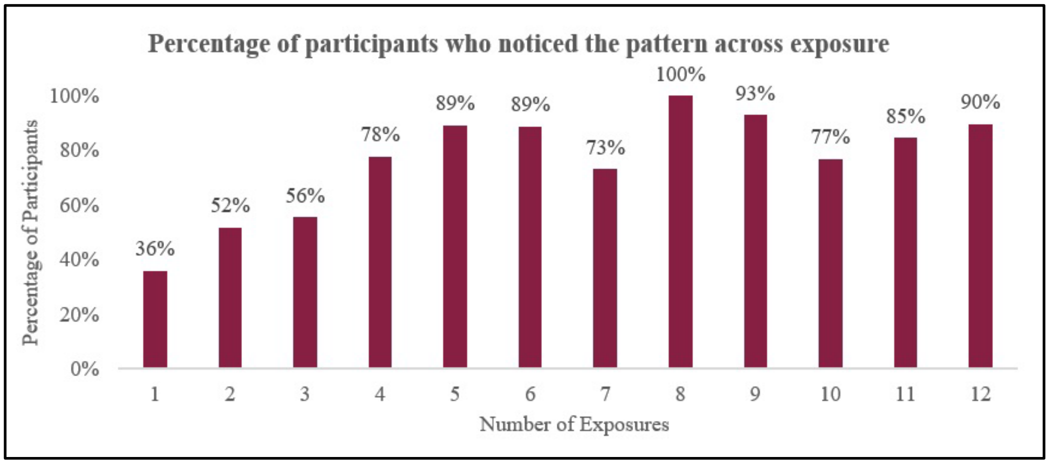


Figure 11. Chart. Participants who noticed the light bars over exposure.

Cochran's Q test was run to determine if the percentage of participants noticing the light bars was different at the different time points. Sample size was satisfactory to use the χ^2-distribution approximation. The percentage of participants noticing the light bars was statistically significantly different at the different time points, $\chi^2(39) = 93.44$, $p < .001$. Pairwise comparisons were completed using Dunn's procedure with a Bonferroni correction for multiple comparisons (Appendix B).

Analysis of Correctly Interpreting Patterns

The number of trials participants took to identify the meaning of all patterns completely and correctly was documented (Figure 12). A participant correctly interpreted the patterns when they could denote the two displayed patterns and accurately state the information being portrayed. Cochran's Q test was run to determine if the percentage of participants understanding the patterns differed across the number of exposures. The sample size was satisfactory to use the χ^2-distribution approximation. The percentage of learning was statistically significantly different over several exposures, $\chi^2(39) = 79.93$, $p < .001$. Pairwise comparisons were completed using Dunn's procedure with a Bonferroni correction for multiple comparisons (Appendix C).

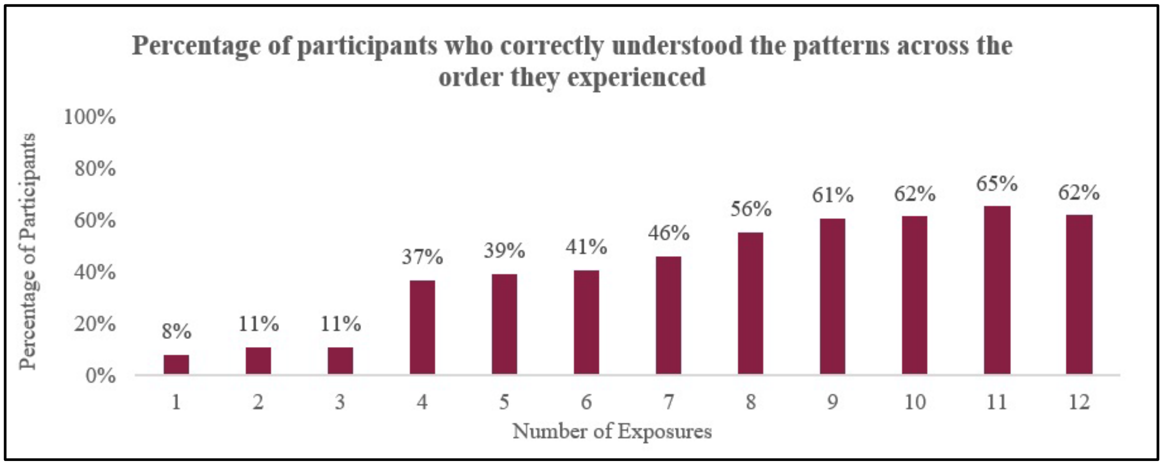


Figure 12. Chart. The number of exposures until the correct interpretation of patterns.

Qualitative Analysis Results

Qualitative feedback was collected through semi-structured interviews at the end of each exposure and after the entire session to gain insight into the subjective reasoning of the participants. This data was bucketed and clustered through an inductive coding process. The general findings are divided by the three main areas the research questions aimed to address: the presence of eHMI on multiple vehicles, type of eHMI, and interpretation of eHMI.

Presence of eHMI

The presence of multiple vehicles increased task complexity and created a hierarchy of attention. It was difficult for participants to split their attention between two vehicles operating within their vicinity. Specifically, when participants made crossing decisions, paying attention to two vehicles simultaneously was challenging. As a result, the vehicles received unequal amounts of attention. Participants often had to prioritize the vehicle they deemed more hazardous to their crossing path.

Perception of distance is crucial in determining personal safety. Participants would cross before the vehicles got close to them. Participants preferred to err on the side of caution and cross when the vehicle was far away. Participants justified this as they needed to secure their safety and would not rely on the vehicle to guarantee their well-being.

Participants stated they relied more on explicit cues, vehicle kinematics, and implicit cues for crossing decisions over the display. Participants' crossing decisions relied more on implicit cues (speed, distance, stopping the behavior, vehicle sounds) over the eHMI display. Speed and distance were the most repeated measures across all participants. Participants stated that in everyday crossing decisions, this is the typical information they rely on to make their decisions. They did not feel confident placing their safety in the hands of unfamiliar technology (i.e., not worth risking their lives, they would rather wait for the vehicle to pass by).

Type of eHMI

Participants wanted the vehicle to provide some physical cue or change in vehicle behavior. Therefore, they looked for something other than a light pattern change. Specifically, participants were **looking for a change in the vehicle's behavior** to indicate when the vehicle would start driving again. For example, a few participants mentioned that before the vehicle switches back to the drive mode, it should inch forward slightly, to emulate a real driver, to indicate it is about to start moving.

The relative size of the eHMI, the vehicle's distance, and the external environment impacted the visibility of the eHMI. Participants found it challenging to see the eHMI when the vehicle was far away because of the eHMI's relative size. As a result, they could only view the eHMI and assess what it displayed when it was in their immediate vicinity. Additionally, sunlight also affected visibility. If it was too sunny, the eHMI was washed out, and participants had to wait until the vehicle was almost in front of them to see the display.

Participants expect eHMI to be standardized across vehicles if they are deployed. Participants needed clarification when they saw two vehicles displaying different colored displays. Some thought that the different colors signalized different actions. When participants viewed two vehicles with the same color (e.g., white), many commented that they wanted consistency across the design and implementation of the display.

Aspects of the eHMI were distracting. Some participants thought the eHMI would detract their attention from their environment, causing them to miss other important information. Specifically, participants were concerned that if they were distracted by the flashing lights, they might miss other vehicles at higher risk of impeding their safety.

Interpretation of eHMI

Training and time with the eHMI are desired for easier predictability and transparency of AVs' behavior. Light bars are not immediately understandable; it took time for participants to begin to piece together the information the light bars were trying to convey. Often participants noted their learning speed and stated that the more exposure they had to the system, the easier it would be to apply that information to their crossing behavior. In this conversation, participants stated they wanted training or awareness of the eHMI systems integrated with the vehicle before deployment.

Light bar patterns contradict other real-world applications. For example, a small population thought the pattern of the lights was inversed. Two participants used the example of a railroad crossing, where the blinking light illuminated means “do not cross; the train is coming,” verses, in this instance, indicating the vehicle is stopping and it is safe to cross.

Specific to the mid-block scenarios, participants understood they did not have the right of way. They did not expect the vehicles to stop for them because that is different from what would happen in real-life scenarios. Participants commented that the eHMI suggested that the vehicle would stay in driving mode.

If eHMI behaved like a brake light, participants would want this technology on manually driven vehicles. A few participants stated that since the eHMI informs them of when the vehicle is braking, it acts like a front brake. Other participants stated they would want the eHMI to turn off when the vehicle was accelerating and only illuminate when braking. From a pedestrian perspective, participants thought this feature would have a benefit for manually driven vehicles by showing more clearly whether the vehicle was stopping or going. This information would allow them to make better, more informed crossing decisions.

Over time, participants stated that they felt more comfortable relying on the eHMI to make crossing decisions. Once participants noticed the eHMI was present and, over time, learned what the eHMI meant through exposures, they stated they began to rely more on that information. Participants said they felt more comfortable and gained experience to cross earlier once they understood the eHMI.

LEO Perspective

LEOs' perspectives were split on the advantages and disadvantages of eHMI. Half the LEO participants stated that the eHMI has many potential benefits as long as people know of its presence and functionality. Additionally, a few officers stated they hoped the information stored from the vehicle’s current state being displayed could be helpful in accident reconstruction.

The other half of LEOs expressed concerns about the lack of awareness of the presence of eHMIs. This unawareness may lead an officer to initiate a traffic stop if they are unaware of the system's existence. The displays can also be confusing or distracting, especially in scenarios with multiple AVs and emergency vehicles with active lights. Additionally, a few participants in this cohort stated they were concerned that the light bar may cause people to confuse the SAE L4+ ADS vehicle with an undercover officer vehicle. There is a learning curve for new features; if there is training, this confusion can be mitigated.

Most LEOs discussed standardization at some point. They stated that standardization across the dimensions, color, and functions that would trigger the light must be the same across vehicle manufacturers. Standardization would aid system-wide learning and make it easier for LEOs when patrolling.

Teal Light Bar

When the teal light bar was triggered, almost all LEO participants stated the light bar was green. Most participants stated they liked that the green was different from blue, white, amber, and red, which are currently displayed by emergency vehicles on the roadway. However, a few were concerned that the associated meaning with green (i.e., green means go) might affect other road users' behaviors (e.g., they see a "green" solid light, which means the vehicle is driving, but they think it means they can cross).

Amber and White Light Bar

Light bars with colors have various meanings across counties, stated some LEOs. For example, many Virginia Department of Transportation (VDOT) vehicles include amber or sometimes white light, which may confuse officers on patrol. However, of the white and amber light bar condition displays, more participants in this cohort preferred the amber because it was more visible than the white light. A few mentioned that some Uber and Lyft vehicles contain white (or purple/magenta) lights, and they have become accustomed to them.

Discussion

This research aimed to understand how multiple AVs equipped with eHMI impact pedestrian crossing behavior.

eHMI Evaluation

Research Question 1: Does the presence of multiple AVs with and without eHMI affect participants' crossing decisions?

A baseline measurement was integrated with this study to understand if there was a change in behavior across each scenario when an eHMI was present versus absent. The presence or absence of the eHMI on the AVs did not impact pedestrian crossing behavior. Participants primarily relied on vehicle distance and speed (and a few stated they relied on the vehicle sound) when making their crossing decisions. Additionally, some participants were looking for a change in vehicle behavior (e.g., vehicle inching forward) to indicate that the vehicle would resume driving.

Participants expressed concern when interpreting eHMIs on multiple vehicles in their environment. Multiple AVs complicated the environment, and participants had to continually assess the vehicle's behavior to adjust their crossing decision.

Research Question 2: How do colors (i.e., white and amber) of eHMI impact the decision-making of pedestrians?

Across the color conditions presented, there was no significant difference in participants' willingness or unwillingness to cross. However, even though the color condition did not impact crossing behavior, the amber light bar was preferred over white light bars.

Amber was preferred because the color was more visible, as there was a contrast between the eHMI, vehicle, and environment. Participants have pre-established mental models associated with the color amber. Some misinterpreted the eHMI color and became confused if the vehicle was indicating an alert to them not to cross or if it indicated it was safe to cross. The white eHMI color was not preferred due to low visibility. Often the white eHMI blended in with the vehicle or was washed out from the sunlight.

Research Question 3: Is an eHMI that provides two levels of information (i.e., yielding and driving) more understandable/interpretable than an eHMI with three levels (i.e., driving, yielding, and ready)?

There was a shorter learning curve for interpreting eHMI with two patterns than with three (Rossi-Alvarez et al., 2022). After the first three exposures, participants' understanding of the eHMI increased, with the most participants (65%) understanding the eHMI after 11 exposures. This was shorter than in the previous study (Rossi-Alvarez et al., 2022), where it took 12 exposures to the eHMI to understand, and only a little over half of the participants could correctly interpret the meanings throughout the session. The simpler eHMI pattern design took fewer exposures for participants to understand its meaning.

Testing Scenarios

Research Question 4: Did the complexity and type of scenarios impact participants' crossing decisions?

Participants found it challenging to focus on a vehicle's light bars when multiple vehicles were competing for their attention in the same crossing vicinity. They had to prioritize their focus on the vehicle they felt had the most risk to their crossing decision. As a result, participants gave up looking at the vehicle that was not directly impacting their intended crossing path and prioritized their attention on the most relevant vehicle. Participants were more cautious about their crossing behavior for mid-block versus intersection scenarios. However, their overall willingness to cross was not impacted.

LEO Cohort Preferences

Research Question 5: What are law enforcement officers' preferences across light bar color conditions (i.e., white, amber, teal)?

LEO participants thought the eHMI could benefit VRUs if people were educated on its purpose and function. There was no clear preference for color when exposed to white, amber, and teal eHMIs. However, LEOs had caveats for each color condition. All participants in this cohort perceived the teal light bar as green and interpreted the eHMI to indicate “green means go.” They preferred this to “blue” or “red” because those colors were associated with emergency vehicles, as LEO participants mentioned. The amber and white eHMIs have some associations with emergency vehicles, such as road assistance and undercover officer vehicles.

Conclusion

This study examined how eHMIs on multiple AVs would impact pedestrians' decision-making across various complex traffic scenarios in a live environment. Pseudo-AVs (i.e., vehicles with hidden human drivers to give the impression of greater automation) operated around participants in the intersection and mid-block scenarios equipped with different conditions of eHMI. Results from the study found that the presence and condition of eHMI did not influence participants' willingness to cross. Participants primarily relied on the speed and distance of the vehicle to make their crossing decision. It was difficult for participants to focus on the eHMI when multiple vehicles competed for their attention. Participants typically prioritized their focus on the vehicle that was nearest and most detrimental to their crossing path. The type of scenario (i.e., intersection or mid-block) caused participants to make more cautious crossing decisions. However, scenario type did not influence their willingness to cross. This study implies that eHMIs with two patterns may still need to be simplified for pedestrians to interpret in a complicated traffic environment.

Future Work

To further evaluate the eHMI patterns, a design with one indication of intent should be tested. Specifically, the eHMI would be illuminated only when the vehicle is actively braking, and the eHMI would be absent when the vehicle is actively driving.

Study Limitations

The triggering of the light patterns was manually configured by the human drivers concealed in the seat-suit costume. Since the lights were manually triggered, consistency across trials may have varied. For future studies, the patterns should be wired to trigger when the human operator places their foot on the brake, and these patterns should be programmed to the speedometer. When the vehicle reaches 0 mph, the corresponding pattern would be triggered.

Additional Products

The Education and Workforce Development (EWD) and Technology Transfer (T2) products created as part of this project can be downloaded from the project page on the Safe-D website. The final project data set is located on the Safe-D Collection of the VTTI Dataverse.

Safe-D Project Website: https://safed.vtti.vt.edu/projects/allusion-2-external-communication-for-sae-l4-vehicles-2/

VTTI Dataverse:
https://dataverse.vtti.vt.edu/dataset.xhtml?persistentId=doi:10.15787/VTT1/8MPNZK

Education and Workforce Development Products

This project provided students with the opportunities to take part in high-fidelity vehicle research throughout all phases of the experiment. Both undergraduate and graduate students were heavily involved in performing the literature review, developing the research plan, conducting research, analyzing the data, and final report delivery. Throughout the process, students took on primary responsibility of the project and ensured it adhered to VTTI safety policies.

Students also gained vital public speaking skills through presenting the research plan, analysis updates, and final deliverable presentation to all key stakeholders, and even an international organization. Additionally, students expanded their technical writing experience through a paper submission to an academic journal.

Visual external communication signals are being heavily investigated in the U.S. as well as abroad. The research team is involved in domestic and international committees exploring the potential for standardization in the design and deployment of L4+ AV external communication.

Technology Transfer Products

This project produced an abstract that was submitted and accepted for presentation at the Transportation Research Board (TRB) Annual Meeting in 2023. Additionally, an academic journal article will be submitted.

Data Products

A subset of data collected as part of the study is available via the Safe-D collection on the VTTI Dataverse (https://dataverse.vtti.vt.edu/dataset.xhtml?persistentId=doi:10.15787/VTT1/8MPNZK).This data includes crossing decision, glance data for both L4+ AVs, distance of crossing decision, vehicle condition (i.e., light bar color, light bar thickness), number of decisions, and number of vehicles in participants' intended crossing path.

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Appendix A. Study 2 Testing Scenario Details

Scenario 1: Right Turn (RT)

Participants act as pedestrians. A participant will never enter the roadway while vehicles are navigating an intersection. Instead, the participant will stand on the side of the road utilizing the decision-making box. Vehicles will start at 25 mph, and at the markings 100 feet from the intersection, the human driver will release the gas pedal and the AV will decelerate to 10 mph. The SAE L4+ ADS-B arrives first, followed by the SAE L4+ ADS-A. Vehicles stop at the stop sign for 5 seconds. The SAE L4+ ADS-B proceeds straight first, followed by the SAE L4+ ADS-A.

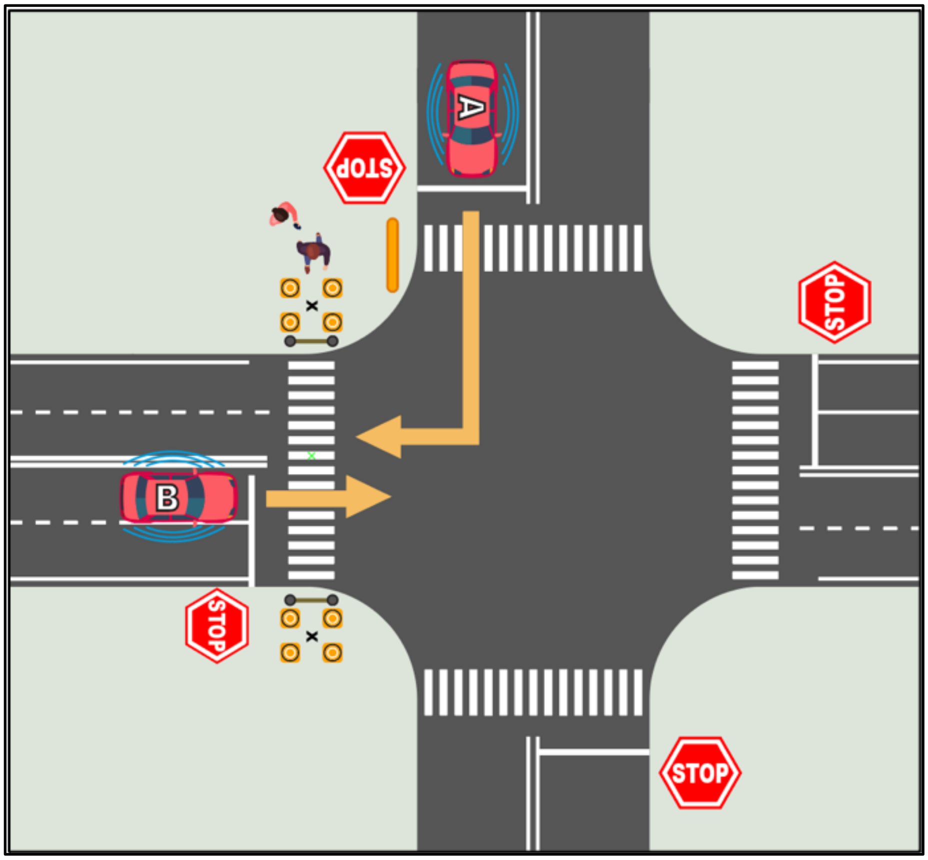

Figure 13. Illustration. Scenario 1 aerial depiction.

Scenario 2: Two-vehicle Straight Crossing Path (2 Veh SCP)

Participants act as pedestrians. A participant will never enter the roadway while vehicles are navigating an intersection. Instead, the participant will stand on the side of the road utilizing the decision-making box. Vehicles will start at 25 mph, and at the markings 100 feet from the intersection, the human driver will release the gas pedal and the AV will decelerate to 10 mph. The SAE L4+ ADS-B arrives first, followed by the SAE L4+ ADS-A, with the vehicles facing each other in the intersection. Vehicles stop at the stop sign for 5 seconds. The SAE L4+ ADS-B proceeds straight first, followed by the SAE L4+ ADS-A.

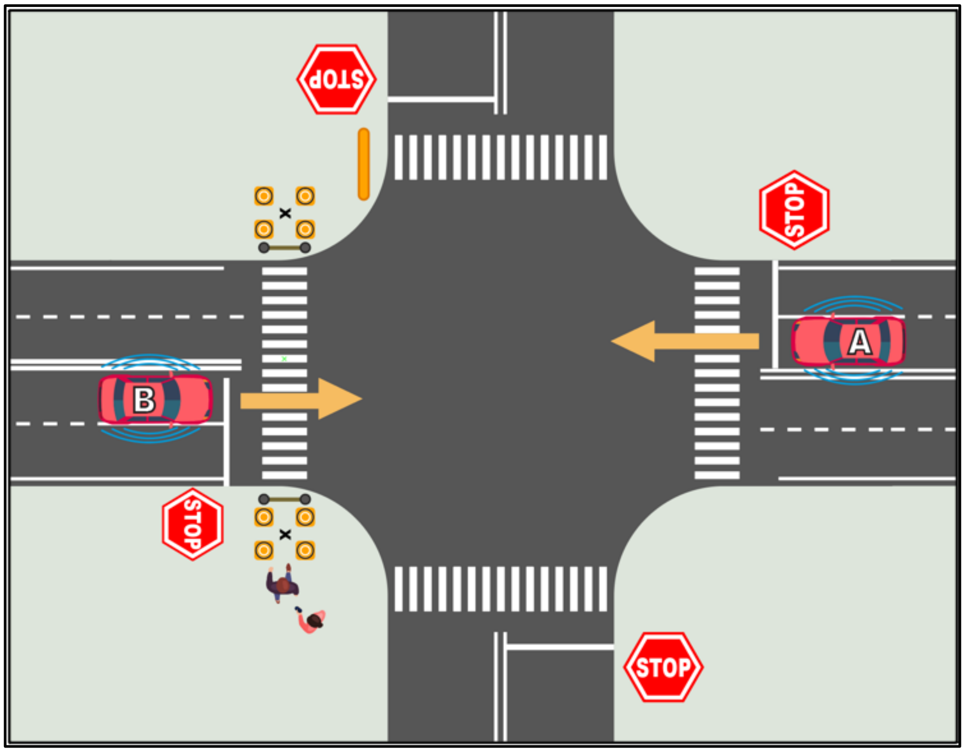

Figure 14. Illustration. Scenario 2 aerial depiction.

Scenario 3: Two-vehicle Straight Crossing Path at One-way Stop

Participants act as pedestrians. A participant will never enter the roadway while vehicles are navigating an intersection. Instead, the participant will stand on the side of the road utilizing the decision-making box. Vehicles will start at 25 mph, and at the markings 100 feet from the intersection, the human driver will release the gas pedal and the AV will decelerate to 10 mph. SAE L4+ ADS-B will approach the intersection first and come to a complete stop. Then, SAE L4+ ADS-A will proceed down the roadway and drive straight through while SAE L4+ ADS-B remains stopped at the stop sign. After SAE L4+ ADS-A is clear from the roadway and has passed, then SAE L4+ ADS-B will make a left turn and proceed down the roadway.

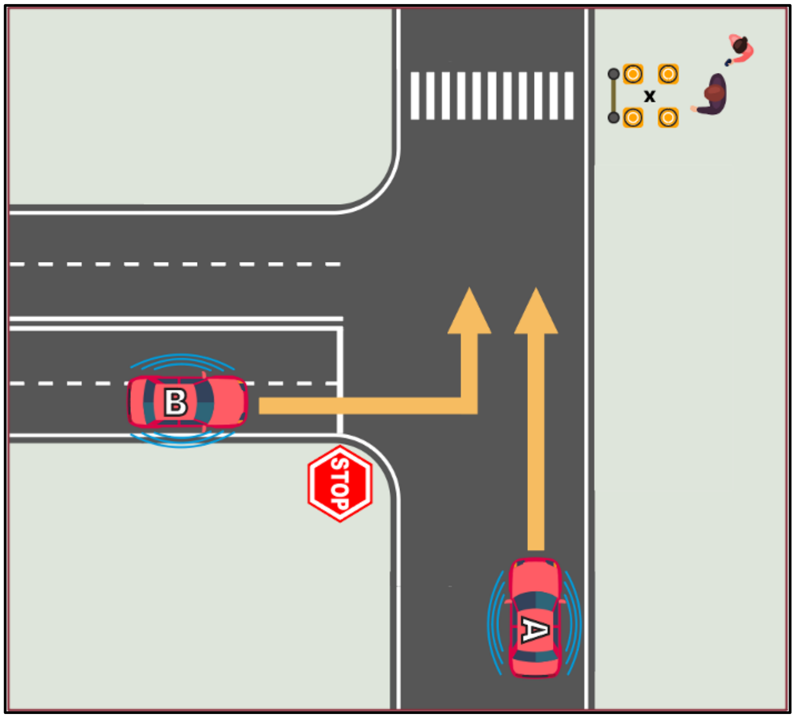

Figure 15. Illustration. Scenario 3 aerial depiction.

Scenario 4: 2 Vehicle Straight Crossing Path at Mid-block

Participants act as pedestrians. The participant will never enter the roadway while vehicles are navigating an intersection. The participant will not be informed of the meaning of the light bar and will not cross in this scenario. Vehicles will start at 30 mph and remain at that constant speed. SAE L4+ ADS-A and SAE L4+ ADS-B will arrive at the cross point at the same time. They will both proceed straight without stopping for this mid-block scenario.

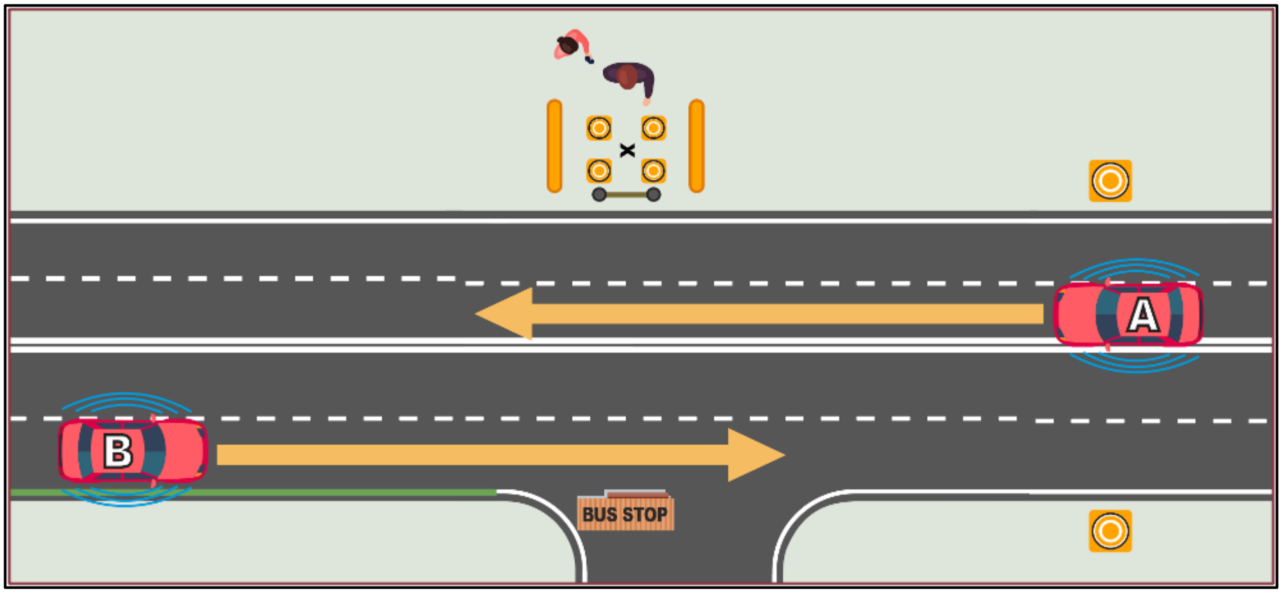

Figure 16. Illustration. Scenario 4 aerial depiction.

Appendix B. Analysis of Noticing the Patterns

Table 3. Pairwise Comparisons, Noticing the Patterns

	1	2	3	4	5	6	7	8	9	10	11	12
1	-	0.201	**0.003**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**
2	0.201	-	0.089	**0.003**	**0.000**	**0.000**	**0.011**	**0.000**	**0.000**	**0.003**	**0.000**	**0.000**
3	**0.003**	0.089	-	0.201	**0.011**	**0.011**	0.394	**0.000**	**0.003**	0.201	**0.033**	**0.001**
4	**0.000**	**0.003**	0.201	-	0.201	0.201	0.670	**0.011**	0.089	1.000	0.394	**0.033**
5	**0.000**	**0.000**	**0.011**	0.201	-	1.000	0.089	0.201	0.670	0.201	0.670	0.394
6	**0.000**	**0.000**	**0.011**	0.201	1.000	-	0.089	0.201	0.670	0.201	0.670	0.394
7	**0.000**	**0.011**	0.394	0.670	0.089	0.089	-	**0.003**	**0.033**	0.670	0.201	0.011
8	**0.000**	**0.000**	**0.000**	**0.011**	0.201	0.201	**0.003**	-	0.394	0.011	0.089	0.670
9	**0.000**	**0.000**	**0.003**	0.089	0.670	0.670	**0.033**	0.394	-	0.089	0.394	0.670
10	**0.000**	**0.003**	0.201	1.000	0.201	0.201	0.670	**0.011**	0.089	-		**0.033**
11	**0.000**	**0.000**	**0.033**	0.394	0.670	0.670	0.201	0.089	0.394	0.394	-	0.201
12	**0.000**	**0.000**	**0.001**	**0.033**	0.394	0.394	**0.011**	0.670	0.670	**0.033**	0.201	-

Appendix C. Analysis of Correctly Interpreting the Patterns

Table 4. Pairwise Comparisons, Correctly Interpreting the Patterns

	1	2	3	4	5	6	7	8	9	10	11	12
1	-	0.201	**0.003**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**
2	0.201	-	0.089	**0.003**	**<.001**	**<.001**	**0.011**	**<.001**	**<.001**	**0.003**	**<.001**	**<.001**
3	**0.003**	0.089	-	0.201	**0.011**	**0.011**	0.394	**<.001**	0.003	0.201	**0.033**	**0.001**
4	**<.001**	**0.003**	0.201	-	0.201	0.201	0.670	**0.011**	0.089	1.000	0.394	**0.033**
5	**<.001**	**<.001**	**0.011**	0.201	-	1.000	0.089	0.201	0.670	0.201	0.670	0.394
6	**<.001**	**<.001**	**0.011**	0.201	1.000	-	0.089	0.201	0.670	0.201	0.670	0.394
7	**<.001**	**0.011**	0.394	0.670	0.089	0.089	-	**0.003**	**0.033**	0.670	0.201	**0.011**
8	**<.001**	**<.001**	**<.001**	**0.011**	0.201	0.201	**0.003**	-	0.394	0.011	0.089	0.670
9	**<.001**	**<.001**	0.003	0.089	0.670	0.670	**0.033**	0.394	-	0.089	0.394	0.670
10	**<.001**	**0.003**	0.201	1.000	0.201	0.201	0.670	0.011	0.089	-	0.394	**0.033**
11	**<.001**	**<.001**	**0.033**	0.394	0.670	0.670	0.201	0.089	0.394	0.394	-	0.201
12	**<.001**	**<.001**	**0.001**	**0.033**	0.394	0.394	**0.011**	0.670	0.670	**0.033**	0.201	-