Designing Communication for Automated Vehicles in Urban Traffic

Zur Erlangung des akademischen Grades einer
DOKTORIN DER PHILOSOPHIE (Dr. phil.)

von der KIT-Fakultät für Geistes- und Sozialwissenschaften
des
Karlsruher Instituts für Technologie (KIT)
angenommene

DISSERTATION

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Tag der mündlichen Prüfung: 28 Nov 2025

Intellectual Property and Publications

The candidate confirms that the work submitted is her own, except where contributions from jointly authored publications have been included.

As part of this dissertation, four publications have been produced. Each publication is listed below in detail, along with its corresponding location within the dissertation. References for the published papers are provided collectively at the end of the dissertation. The specific contributions of the candidate and co-authors to each work have been explicitly stated below. The candidate affirms that appropriate credit has been given within the dissertation whenever reference has been made to the work of others.

1. The work in Chapter 2 has been published.

Li, Y., Cheng, H., Zeng, Z., Liu, H., & Sester, M. (2021, September). Autonomous vehicles drive into shared spaces: eHMI design concept focusing on vulnerable road users. In *2021 IEEE International Intelligent Transportation Systems Conference (ITSC)* (pp. 1729-1736). IEEE. https://doi.org/10.1109/ITSC48978.2021.9564515

These four co-first authors contribute equally to the work.

Li, Y.: Conceptualisation, Investigation, Methodology, Software, Validation, Formal analysis, Visualisation, Writing - Original Draft. Cheng, H.: Conceptualisation, Methodology, Formal analysis, Writing - review & editing. Zeng, Z.: Conceptualisation, Methodology, Formal analysis, Writing - review & editing. Liu, H.: Conceptualisation, Methodology, Software, Formal analysis, Writing - review & editing. Sester, M.: Writing - review & editing, Project administration, Funding acquisition, Supervision.

2. The work in Chapter 3 has been published.

Li, Y., Lee, Y. M., Yang, Y., Tian, K., Daly, M., Horrobin, A., Solernou, A., Merat, N. (2023, September). Do Drivers Have Preconceived Ideas about an Automated Vehicle's Driving Behaviour? In Proceedings of the 15th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (pp. 291-299). https://doi.org/10.1145/3580585.3607155

Li, Y.: Conceptualisation, Investigation, Methodology, Software, Validation, Formal analysis, Visualisation, Data Curation, Writing - Original Draft. Lee, Y. M.: Conceptualisation, Investigation, Methodology, Validation, Writing - review &

editing. Yang, Y.: Data Curation, Formal analysis. Tian, K.: Data Curation, Formal analysis. Daly, M.: Resources. Horrobin, A.: Resources. Solernou, A.: Resources. Natasha Merat: Conceptualisation, Investigation, Writing - review & editing, Project administration, Funding acquisition, Supervision.

3. The work in Chapter 4 has been published.

Li, Y., Lee, Y. M., Madigan, R., Grünwald, A., Deml, B., Merat, N. (2025, June), Investigating Driver Responses to Automated Vehicles in a Bottleneck Scenario: The Impact of Lateral Offset and eHMI. Transportation Research Part F: Traffic Psychology and Behaviour. Volume 114, 2025, Pages 621-632, ISSN 1369-8478, DOI:1016/j.trf.2025.06.016

Li, Y.: Conceptualisation, Investigation, Methodology, Software, Validation, Formal analysis, Visualisation, Writing - Original Draft. Lee, Y. M.: Conceptualisation, Investigation, Methodology, Validation, Writing - review & editing. Madigan, R.: Validation, Writing - review & editing. Grunwald A.: Writing – review, Supervision. Deml B.: Writing – review, Supervision. Merat, N.: Conceptualisation, Investigation, Writing - review & editing, Project administration, Funding acquisition, Supervision.

4. The work in Chapter 5 has been published.

Li, Y., Cheng, H., Zeng, Z., Deml, B., & Liu, H. (2023). An AV-MV negotiation method based on synchronous prompt information on a multi-vehicle bottleneck road. Transportation Research Interdisciplinary Perspectives (TRIP), 20, 100845. https://doi.org/10.1016/j.trip.2023.100845

Li, Y.: Conceptualisation, Investigation, Methodology, Conducting the experiment, Formal analysis, Writing – original draft. Cheng H.: Conceptualisation, Methodology, Writing – review & editing. Zeng Z.: Formal analysis, Writing – review & editing. Deml B.: Conceptualisation, Writing – review & editing. Liu H.: Conceptualisation, Methodology, Formal analysis, Writing – review & editing, Funding acquisition.

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Acknowledgement

I would like to express my deep gratitude to my supervisors at KIT, Prof. Armin Grunwald, Prof. Barbara Deml, for their invaluable patient guidance, enthusiastic encouragement, and useful critiques of this research work. I am particularly grateful to my supervisor Prof. Natasha Merat at the University of Leeds, for her mentorship, patience and support during my one-year PhD visiting study there.

I would also like to thank Dr. Hailong Liu, Dr. Yee Mun Lee, Dr. Ruth Madigan for their guidance, expert advice, and assistance in keeping my progress on research work. I am particularly grateful for the support from Dr Hailong Liu in funding me the visiting to NARA Institute of Science and Technology (NAIST). My thanks are extended to my colleagues and friends who provided me with every form of support I needed during my research from both the KIT group and the Leeds group. Special thanks go to Yue Yang, Chen Peng, Rafael Goncalves, Athanasios Tzigieras, Ibrahim Ozturk, Kai Tian, Sofie Ehrhardt, and many others. My sincere thanks also go to friends from my co-authors, Zhe Zeng, Hao Cheng for guiding me and supporting me.

I am particularly grateful for the assistance given by the technical staff Anthony Horrobin, Michael Daly, Jorge Garcia de Pedro and Albert Solernou Crusat in the Virtuocity at the University of Leeds, with their great help, the simulator study ran successfully and the great data has been collected.

I would like to acknowledge the financial support granted by the China Scholarship Council (CSC) (No. 201906260302), Karlsruhe House of Young Scientists (KHYS), KIT strategic partnership fund (DV.MATH.333666) and The Hi-Drive project (Grant agreement 101006664) funded by the European Union's Horizon 2020 research and innovation program, which was invaluable to the completion of this dissertation.

I am writing this thesis while embracing a new chapter in life: as a mother. I am deeply grateful for the priceless experience of being both a PhD candidate and a mum. Though the journey has been challenging, it has brought immense personal growth. I am profoundly indebted to my family for their understanding, support, and love, my grandmother JING Li, my husband PENG Cong and our daughter PENG Lexi, my parents WANG Haiyan and LI Weihong, my younger brother LI Xiang, and my parents-in-law ZHENG Xiuzhen and PENG Guoxing through the duration of my studies.

Abstract

Human drivers rely on a combination of explicit and implicit cues, such as hand gestures, head nods, eye contact, headlight flashing, deceleration, and lateral positioning, to communicate with other road users. These behaviours are particularly important in ambiguous right-of-way scenarios, such as shared spaces and bottleneck roads, where formal traffic rules may not be sufficient to resolve interactions. However, as vehicles become increasingly automated, the human driver is removed from the control loop, engaging instead in non-driving-related activities. This shift necessitates the development of alternative communication strategies to facilitate effective and unambiguous interaction between automated vehicles (AVs) and other road users in mixed traffic environments.

This thesis investigates communication strategies between AVs and manually driven vehicles (MVs), using bottleneck encounters as a representative case. It examines the types of communication and information human drivers expect from AVs, and whether they behave differently from interactions with conventional vehicles. Furthermore, the research explores how AV kinematic behaviours and the design of external human-machine interfaces (eHMIs) affect drivers' subjective responses, such as perceived safety, comprehension, and trust, as well as their actual driving performance. Additionally, this work provides a novel HMI for visibility-limited scenarios with more traffic agents in the bottleneck roads, providing a potential solution for AV-MV communication.

This thesis adopted a mixed-method approach, combining driving simulator studies with online/post-trial questionnaires and interviews. This allowed for the controlled investigation of AV behaviour and HMI design under varying traffic conditions. Novel evaluation metrics, such as passing initiation time (PIT) and yielding initiation time (YIT), were developed to more accurately capture decision-making processes. The results show that AV kinematics, especially lateral movements plays a key role in how AV-MV communication. eHMIs can improve perceived safety and trust, but are most helpful when the vehicle's kinematics patterns are unclear. The proposed novel HMI was preferred by drivers and improved communication outcomes. These findings contribute to evaluations and recommendations for properties of the design of communication strategies including kinematics patterns and HMIs for an AV.

Zusammenfassung

Menschliche Fahrer verlassen sich auf eine Kombination expliziter und impliziter Signale – wie Handgesten, Kopfnicken, Blickkontakt, Blinken mit den Scheinwerfern, Verzögern und laterale Positionierung –, um mit anderen Verkehrsteilnehmern zu kommunizieren. Diese Verhaltensweisen sind besonders in Situationen mit unklarer Vorfahrtsregelung wichtig, etwa in Shared Spaces oder an Engstellen, wo formale Verkehrsregeln oft nicht ausreichen, um Interaktionen eindeutig zu regeln. Mit dem zunehmenden Automatisierungsgrad von Fahrzeugen wird der menschliche Fahrer jedoch aus der Steuerung herausgenommen und widmet sich stattdessen fahrfremden Aktivitäten. Dieser Wandel erfordert die Entwicklung alternativer Kommunikationsstrategien, um eine effektive und eindeutige Interaktion zwischen automatisierten Fahrzeugen (AVs) und anderen Verkehrsteilnehmern im Mischverkehr zu gewährleisten.

Diese Dissertation untersucht Kommunikationsstrategien zwischen AVs und manuell gesteuerten Fahrzeugen (MVs) anhand von Engstellensituationen als repräsentativem Anwendungsfall. Sie analysiert, welche Arten von Kommunikation und Informationen menschliche Fahrer von AVs erwarten und ob sich ihr Verhalten gegenüber konventionellen Fahrzeugen unterscheidet. Darüber hinaus wird erforscht, wie das kinematische Verhalten von AVs sowie das Design externer Mensch-Maschine-Schnittstellen (eHMIs) die subjektiven Reaktionen der Fahrer – etwa das Sicherheitsempfinden, das Verständnis und das Vertrauen – sowie deren tatsächliches Fahrverhalten beeinflussen. Zusätzlich wird ein neuartiges HMI für Szenarien mit eingeschränkter Sicht und einer höheren Anzahl an Verkehrsteilnehmern in Engstellen vorgestellt, das eine potenzielle Lösung für die AV-MV-Kommunikation bietet.

Die Arbeit verfolgt einen Mixed-Methods-Ansatz, der Fahrsimulationsstudien mit Online- und Nachbefragungen sowie Interviews kombiniert. Dadurch konnten das Verhalten von AVs und die Gestaltung von HMIs unter kontrollierten Verkehrsbedingungen systematisch untersucht werden. Neue Evaluationsmetriken wie die Initiierungszeit des Überholens (Passing Initiation Time, PIT) und die Initiierungszeit des Wartens (Yielding Initiation Time, YIT) wurden entwickelt, um Entscheidungsprozesse präziser erfassen zu können. Die Ergebnisse zeigen, dass die Fahrzeugkinematik, insbesondere laterale Bewegungen, eine zentrale Rolle in der AV-MV-Kommunikation spielt. eHMIs können das Sicherheitsempfinden und das Vertrauen verbessern, sind jedoch vor allem dann hilfreich, wenn die Kinematik des Fahrzeugs nicht eindeutig ist. Das vorgeschlagene neuartige HMI wurde von den Fahrern bevorzugt und führte zu besseren Kommunikationsergebnissen. Diese Erkenntnisse tragen zur Bewertung

und Empfehlung von Gestaltungseigenschaften für Kommunikationsstrategien, einschließlich Kinematikmustern und HMIs, für automatisierte Fahrzeuge bei.

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List of abbreviations

A number of abbreviations and acronyms are used throughout this thesis. They are listed here for reference in alphabetical order.

AVs	Automated Vehicles
DDT	Dynamic Driving Task
DDT	Dynamic Driving Tasks
eHMIs	external Human-Machine-Interfaces
HRUs	Human Road Users
iHMIs	internal Human-Machine-Interfaces
LOA	Levels of Automation
MVs	Manually Vehicles
ODD	Operational Design Domain
OEDR	Object Event Detection and Response
SAE	Society of Automotive Engineers
VRUs	Vulnerable Road Users

CHAPTER 1. Introduction

1.1 Background

In the foreseeable future, automated vehicles (AVs) will be integrated into our urban environments, interacting with other road users such as manually driven vehicles (MVs), pedestrians, cyclists, and powered two-wheelers. AVs are classified from Level 0 (no driving automation) to Level 5 (full driving automation) according to the SAE standard (SAE International, 2021). At Level 4, the human operator no longer has to be ready to intervene under certain conditions. At Level 5, the vehicle can handle all driving tasks under all conditions without human input (SAE International, 2021).

Even though AVs are expected to revolutionise urban transportation by enhancing safety, reducing traffic congestion, and providing new mobility solutions for individuals, they face significant technical, regulatory, and social challenges that must be overcome to realise their full potential. For instance, bad weather conditions may limit AV's ability by affecting the sensor perception, preventing road users from seeing the designed external human-machine interface (eHMI) on vehicles. AVs might drive in an over-cautious way that does not fit human expectations, such as more yielding decisions when encountering vehicles at bottleneck scenarios, following the front vehicle with a big gap, unnecessarily slowing down, or braking for nearby traffic agents, thus, other road users could take advantage of this cautious behaviour and "bully" AVs. Furthermore, there is still scepticism among the public regarding the safety and reliability of L4 and L5 vehicles. Building trust in these systems through extensive testing, transparency, and user education is necessary before they can be fully integrated into society. Although real-world trials of Level 4 AVs are already underway in regions such as North America and China (Hawkins, 2023; McKinsey, 2023), widespread adoption still depends on whether these issues can be solved.

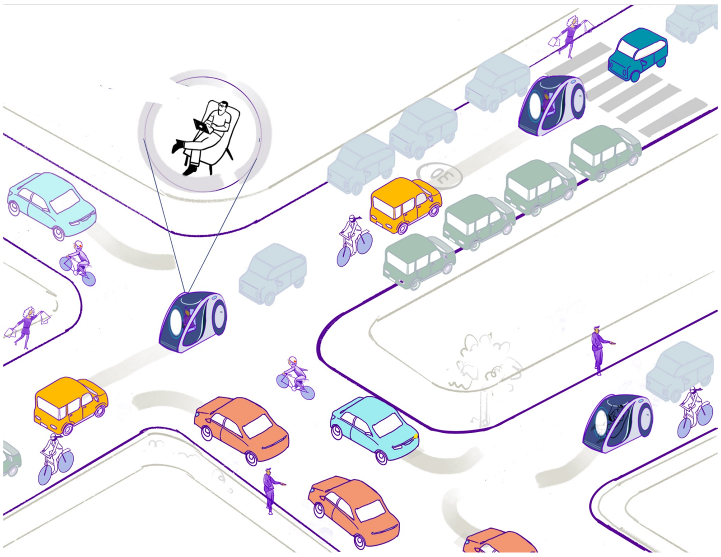


Figure 1.1 A mixed traffic setting, including AVs in urban roads.

Adapted from Li et al. (2023), "Do Drivers have Preconceived Ideas about an Automated Vehicle's Driving Behaviour," in *Proceedings of AutomotiveUI 2023*, ACM, pp. 291–299. © 2023 ACM. Used by permission.

Besides, the interaction between AVs and human road users (HRUs) presents significant challenges, particularly in ambiguous right-of-way scenarios, such as bottleneck roads, unmarked intersections, or residential junctions without traffic lights (Imbsweiler et al., 2019). Road users communicate their intentions to each other, especially when both actors intend to occupy the same road space as a result of their movement in a shared space (Markkula et al., 2020). In such scenarios, human road users often communicate their intentions explicitly through hand gestures, head movements, or flashing headlights (Imbsweiler, Wolf, et al., 2018; Rasouli et al., 2017). However, this can be a problem for SAE 3-5 AVs which do not currently have any means of communicating intent, making it difficult for HRUs to anticipate their behaviour (Fuest et al., 2018; Nuñez Velasco et al., 2021). Hawkins (2023) highlights the necessity of effective communication of a vehicle's status and intentions to prevent such misunderstandings. This is particularly important for higher-level automated vehicles (AVs), such as those at SAE Level 4/5, which are not controlled by a human driver. For interactions among AVs and human road users (HRUs) to occur safely and smoothly, it is imperative to understand how HRUs would behave when encountering AVs, what information is used for communication, and how they communicate with each other, etc.

This thesis aims to explore effective communication methods in ambiguous right-of-way situations to enhance traffic safety, improve traffic efficiency and reduce traffic jams, thus, facilitate harmonious traffic sociability and increase AV acceptance. Based on the current research gaps, it is hoped that the present thesis will enhance the design and development of safer, more comprehensive, and acceptable future AVs. For a better understanding of this research topic, the next section of this chapter provides and overview of automated driving and human-factor challenges. Then, an examination of AV integration in urban traffic and ambiguous driving scenarios. This is followed by a review of existing AV communication strategies and their limitations and a summary of the key research questions addressed in this thesis.

1.2 Automated driving and its potential challenges

1.2.1 Levels of automated driving

Automation refers to the execution of tasks or functions by a machine agent that was previously performed by humans, with actions predefined by the programmer and no ability to adapt or deviate based on the situation (Parasuraman, 1987, 2000; Parasuraman & Riley, 1997). In the 1940s, an automation program of the Ford Motor Company was organised (Hounshell, 1995). Later on, Diebold (1955) created the term "automation" by stating "Automation is a new word means both automatic operation and the process of making things automatic" (Vagia et al., 2016). Since then, automation systems have been designed to replace the massive manual labour, increasing productivity in terms of energy and materials saving, and improvement of quality, accuracy and precision. Sheridan & Verplank (1978) stated that the human will shift the role from the operator to the supervisor. Automation systems can be designed and implemented to optimise the strengths and address the limitations of both humans and machines, ensuring a balanced integration of their capabilities. For human-machine interaction, Levels of Automation (LOA) are used to indicate the degree of task automation, varying from fully manual to fully automated (Vagia et al., 2016).

There has been an evolution of the LOA during the years from the end of the 1950s to 2015 (Vagia et al., 2016). Various taxonomies have been developed for applications such as avionics, teleoperation systems, remote control operations, advanced manufacturing, and space lift teleoperation. Notably, even within the same domain, such as avionics, differing LOA taxonomies exist (e.g., Parasuraman, 2000; Sheridan & Verplank, 1978). The definitions of automated driving levels have been established by three major authorities. The German Federal Highway Research Institute (Gasser & Westhoff, 2012), which defines five levels from Level 0 (driver only) to Level 4 (full automation); the United States National Highway Traffic Safety Administration (NHTSA, 2023), which defines six levels from Level 0 (momentary driver assistance) to Level 5 (full automation); and the Society of Automotive Engineers (SAE International, 2021), which also defines six levels, from Level 0 (no driving automation) to Level 5 (full driving automation).

Among these taxonomies, the SAE J3016 standard (SAE International, 2021) is perhaps the most widely recognised and adopted by academics and industry. This thesis also follows the definitions of SAE LOA. The SAE Levels of driving automation categorise vehicles based on their degree of automation, ranging from Level 0 to Level 5, shown in Table 1.1. At Level 0, there is no automation, and the driver is responsible for all driving tasks. Levels 1 and 2 provide driver assistance, where the system can control either steering or speed, but the driver must remain alert. Level 3 offers conditional automation, enabling the vehicle to handle all driving tasks in certain situations, although the driver must be prepared to take over. Level 4 vehicles can operate autonomously within defined areas or conditions without human intervention, while Level 5 represents full automation, where the vehicle can drive itself in all environments without any human involvement (SAE International, 2021). The SAE levels are based on three key dimensions: the Dynamic Driving Task (DDT), Object Event Detection and Response (OEDR), and Operational Design Domain (ODD). DDT refers to the operational (e.g., steering, acceleration) and tactical (e.g., honking, manoeuvring, signalling) functions necessary for vehicle operation. OEDR refers to the vehicle's ability to detect and react to the environment, including planning manoeuvres. ODD specifies the conditions and environments in which automation is intended to operate, such as road types, speed limits, and time of day.

Table 1.1 Levels of automation according to SAE J3016 (SAE International, 2021). Dynamic Driving Task (DDT), Object Event Detection and Response (OEDR), and Operational Design Domain (ODD).

Level of automation	Description	Dynamic Driving Task (DDT)	Object Event Detection and Response (OEDR)	Operational Design Domain (ODD)
0 **Driver only**	The human driver performs all aspects of the DDT	Driver	Driver	n/a
1 **Assisted automation**	A driver assistance system performs either steering or acceleration/deceleration, while the human driver is expected to carry out the remaining aspects of the dynamic driving task	Driver and System	Driver	Limited
2 **Partial automation**	One or more driver assistance systems perform both steering and acceleration/deceleration, while the human driver is expected to carry out all remaining aspects of the dynamic driving task	System	Driver	Limited

3 Conditional automation	An automated driving system performs all aspects of the dynamic driving task (in conditions for which it was designed), but the human driver is expected to respond appropriately to a request to intervene	System	System (switch to the driver during fallback)	Limited
4 High automation	An automated driving system performs all aspects of the dynamic driving task (in conditions for which it was designed), even if the human driver does not respond appropriately to a request to intervene	System	System	Limited
5 Full automation	An automated driving system performs all aspects of the dynamic driving task under all roadway and environmental conditions	System	System	Unlimited

The development of AVs is advancing rapidly in Europe, China, and the USA, supported by technological progress and evolving regulations. In Germany, initially, only Level 2 systems were permitted, in 2017, the Road Traffic Act (StVG) allowed the approval of vehicles with Level 3 driving functions under specific conditions, such as operation during daylight on highways. In 2022, the first Level 4 vehicles from a German manufacturer were approved in specific conditions, such as shuttle services on defined routes (Fraunhofer IKS, 2025). In China, major companies like Baidu and WeRide are conducting extensive road tests, and the government has created favourable conditions for the commercial deployment of AVs. Currently, at least 19 cities, such as Wuhan, Beijing, Guangzhou and Shanghai are conducting tests on robotaxis and robo-buses, and in June 2024, nine automakers received approval to trial advanced automated driving technologies on public roads (Rajpal, 2024). The USA has widely adopted Level 2 technologies, with Tesla's Autopilot and Level 4 deployments, such as Waymo's and Cruise's autonomous taxi services, operational in select cities (Brinley, 2024).

This thesis discusses communication between AVs and manually driven vehicles (MVs) in ambiguous right-of-way scenarios. MVs, operated by human drivers at SAE Level 0, perform the entire DDT. In contrast, AVs at Levels 4 and 5, where drivers or passengers are not involved in driving, rely on automated systems to perceive situations, communicate with road users, predict intentions, make decisions, and execute actions. This research focuses on AVs with advanced automation capable of handling vehicle control and interacting with other road users.

1.2.2 Potential human factors challenges in automated driving

Highly automated mobility is claimed to have the potential to support human drivers and reduce injuries, crashes, and economic tolls caused by human errors (NHTSA, 2023). The advent and popularity of AVs will let them directly interact with human road users, such as MVs, pedestrians, and cyclists. However, this direct interaction inevitably causes many concerns, Human Factors (HFs) researchers have claimed the critical role of humans in automated systems. Bainbridge (1983) reported that automation reduces routine tasks but creates new challenges by requiring humans to intervene during unforeseen situations, often under demanding conditions. Parasuraman & Riley (1997) also highlighted the need for humans to use automation correctly, avoid over-reliance, and maintain trust in these systems. They warned that poor use or design of automation can reduce its effectiveness, showing that human involvement is crucial for smooth use.

Automated driving technology, though promising, faces several significant human factors challenges before it can be widely adopted. At Levels 1 and 2, where drivers must remain engaged and monitor their surroundings, even as the vehicle assists with certain functions. A significant concern is the drivers may over-reliance and misunderstandings about system capabilities, which often lead to complacency and slower reaction times during control takeovers (Rasouli & Tsotsos, 2020). As automation advances to Level 3, a key challenge is in ensuring drivers are prepared to take over control in emergencies, with challenges including reduced situational awareness, mental workload and delayed responses, leading to potential safety risks. At Levels 4 and 5, where systems operate autonomously in some or all conditions, human factors challenges shift towards public trust and acceptance of fully autonomous systems. NHTSA (2023) concerns about the reliability and safety of these vehicles can hinder widespread adoption. Additionally, ethical considerations arise regarding decision-making in complex traffic scenarios, such as unavoidable accidents, where the vehicle must make decisions. Across all levels, safety, user acceptance, and behaviour design remain key challenges to AV adoption, as distrust and negative perceptions strongly impact people's willingness to embrace this technology (Färber, 2016).

Research challenges include the interaction and communication between AVs and other road users as well. Particularly in mixed traffic scenarios where negotiations are required, such as bottleneck roads (Miller, Koniakowsky, et al., 2022; Rettenmaier, Requena Witzig, et al., 2020), intersections (Papakostopoulos et al., 2021), or during lane changing and merging (Kauffmann et al., 2017). AVs face challenges because they lack explicit input from drivers disengaged from driving tasks (Fuest et al., 2018), and inattentive passengers may unintentionally use gestures or make eye contact that cause confusion (Färber, 2016). Additionally, the differing kinematics of AVs and manual vehicles (MVs) can lead to misunderstandings among human road users (Fuest et al., 2020). These insufficient or erroneous AV-MV communications can increase hesitation in yielding or taking right-of-way (Liu et al., 2021) and reduce traffic efficiency (Rettenmaier & Bengler, 2020). In severe cases, they may even result in MV-drivers' uncertain feelings about AV movements (Färber, 2016), decreased sense of safety (Kaparias et al., 2015; Liu et al., 2021), and lowered trust in AVs (Hoff & Bashir, 2015; Liu et al., 2021). To improve the sense of relief and trust in AVs, they should be able to interact and communicate their driving intentions unambiguously and comprehensibly with other human road users (Fuest et al., 2018; Liu et al., 2021; Schieben et al., 2019).

1.3 AV drives into the urban traffic

1.3.1 Urban traffic

The term "Urban Traffic" refers to the flow of vehicles, cyclists, pedestrians and other traffic modes within urban areas, which often leads to congestion due to the dense concentration of human activities in limited spaces. This situation contributes to significant challenges, including severe traffic jams, air quality issues, parking shortages, and reduced efficiency and safety on the roads (Loo, 2009). As defined by the Swedish Institute for Transport and Communications Analysis (SIKA) (Archer & Vogel, 2000), urban traffic occurs in areas with dense populations and infrastructure, featuring frequent junctions, roundabouts, and pedestrian crossings, and usually have a maximum speed limit of no more than 50 km/h or less.

As of 2023, around the world, the population of urban areas is 4.4 billion -- about 56% of the total global population. Projections show that by 2050, this figure is expected to rise to 68%, adding 2.5 billion more people to cities worldwide (United Nations Department of Economic and Social Affairs, 2018; World Bank Group, 2023). In Germany, the urban population increased from 51.9 million (71.38%) in 1960 to 65.6 million in 2023, with around 77.77% of the total population now living in urban areas (Macrotrends, 2024).

Urban traffic is time-consuming, which significantly affects productivity and quality of life. Despite efforts to promote alternative transportation modes such as cycling and public transit, vehicles remain the dominant mode of urban transport, in Europe, 68% of urban trips are car-based. According to the INRIX Global Traffic Scorecard (INRIX, 2022), commuters in urban areas spend an average of 30-60 minutes daily in traffic, leading to 50-100 hours annually lost to congestion in the world. In cities like Munich, peak-hour traffic can increase travel times by up to 60% compared to off-peak periods (TomTom Traffic Index, 2023).

Urban congestion is not only a time drain but also a financial and environmental problem. In Germany, congestion costs amount to approximately €1,100 per driver each year due to wasted time and fuel (INRIX, 2022). Beyond the damage to the economy, wasted fuel adds to increased emissions, pollution, and a decline in health and the quality of life in urban areas (Willingham, 2019).

What is bigger than the financial loss is traffic safety. The complicated and high-density nature of urban traffic increases the risk of accidents and fatalities. Urban roads accounted for 30% of traffic fatalities in Germany in 2020, with vulnerable road users, including cyclists and pedestrians, representing 16% and 14% of fatalities, respectively (*National Road Safety Profile - Germany*, 2023). Across Europe, pedestrian fatalities in urban areas constituted 19% of total road deaths, underscoring the heightened risks within cities. For vehicle drivers as road users, urban areas pose unique challenges, with a great number of rear-end and turning collisions, and a greater proportion of accidents occurring at junctions. The urban environment's complexity, with its diverse mix of road users and their varying needs, places significant physical and mental demands on all participants. This is evident in the comparatively higher number of injury-related accidents in urban settings (Archer & Vogel, 2000).

1.3.2 Ambiguous driving scenarios in urban areas

Urban traffic environments are often characterised by high densities of diverse road users, including vehicles, pedestrians, and cyclists, as well as complex road layouts and unpredictable human behaviour. These factors frequently lead to ambiguous situations, such as unclear right-of-way at unregulated intersections, shared spaces without formal traffic rules and bottleneck roads, etc. Although most driving situations are regulated by traffic laws, there are some exceptional cases that remain unregulated. In such cases, the German traffic regulations (StVO) contain a special paragraph concerning communication in road traffic: paragraph 11 section 3 (Bundesministerium für Justiz und Verbraucherschutz, 2013) states that, when right-of-way is unclear, drivers must communicate and negotiate to resolve the situation collaboratively (Imbsweiler, Ruesch, et al., 2018).

Ambiguous driving scenarios in urban areas present a significant challenge for both human drivers and AVs, due to the complex interaction of dynamic road users, unpredictable behaviours, and varied infrastructure designs. Such scenarios commonly occur at unregulated intersections, shared pedestrian-vehicle spaces, and areas with inadequate or inconsistent signals, where the intentions of other road users are difficult to predict. Studies show that ambiguity in these settings increases drivers' cognitive load and raises the likelihood of collisions (Rasouli & Tsotsos, 2020). For autonomous systems, the challenge is heightened by the need to perceive and respond to subtle social cues and implicit rules that are often absent from formal traffic regulations. For example, flashing headlights can signal a willingness to yield in one context, while in another, they may serve as a warning. Similarly, non-verbal cues such as head nods, eye contact and hand gestures are commonly used forms of communication among road users (Liu et al., 2021; Merat et al., 2018; Pool et al., 2019; Vissers, van der Kint, et al., 2016). Effectively understanding and managing these ambiguous situations is essential for enhancing safety in urban traffic and for the successful deployment of intelligent transportation systems.

1.3.3 The bottleneck scenario

A traffic bottleneck refers to a localised disruption where the flow of vehicles is restricted, causing reduced speeds, delays, and congestion (Wikipedia, 2023). This typically happens when the capacity of a particular segment of the road is lower than the volume of traffic, leading to slowdowns and congestion. Common causes include lane reductions, poorly synchronised traffic signals, merging lanes, construction zones, and even temporary incidents like accidents or congested vehicles (The Geography of Transport Systems, 2006). Bottlenecks always occur in narrow passages, T-junctions, X-junctions, roundabouts, entry and exit ramps, etc. (Imbsweiler, Wolf, et al., 2018; Strelau et al., 2024).

In this thesis, the term bottleneck scenario specifically refers to the scene caused by double-parking vehicles in the resident areas with a speed limit of 30km/h (Imbsweiler, Ruesch, et al., 2018; Rettenmaier et al., 2019). This scenario represents a typical ambiguous driving scenario, where two approaching drivers must negotiate the right-of-way in the absence of clear traffic rules. This often requires interpreting informal social cues, such as vehicle positioning, speed adjustment, or body language, including hand gestures, head nods and eye contact, to determine whether to yield or proceed. The bottleneck caused by double parking provides an effective and realistic experimental setup for examining human behaviour in traffic. With only two agents interacting, it offers a simple, intuitive, and easily replicable environment for studying driver decision-making and communication under ambiguity. In some studies, this kind of bottleneck road was also named as narrow-passage or equal narrow-passage (Imbsweiler, Ruesch, et al., 2018; Imbsweiler, Wolf, et al., 2018; Miller et al., 2021).

Double-parking roads are very common in Europe, however, the specific data on how many vehicles park on double-parking roads is rarely available, to my knowledge, observational evidence suggests that this practice is widespread in European urban neighbourhoods, where residential street width is narrow and parking spaces are scarce. As a result, bottleneck scenarios are a common feature of everyday driving, especially in older city districts with dense infrastructure. Figure 1.2 illustrates examples of such bottleneck roads in Germany.

Figure 1.2 A typical bottleneck scenario with parking cars on both sides of the road in residential areas (the photo was taken by Yang Li in Karlsruhe, Germany)

1.3.4 Mixed traffic in bottleneck scenario and the challenges

Mixed traffic, typically refers to a transportation system or network where different modes of transport, such as cars, buses, bicycles, pedestrians, and sometimes even trains or trams, share the same road space or infrastructure, as depicted in Figure 1.1. In mixed traffic, various types of vehicles and modes of transportation coexist and operate together, often requiring careful management and coordination to ensure safety and efficiency. The advent of AVs will make the interactions among types of traffic modes even more complicated when an unmanned AV, i.e., SAE level 3–5 AV, and other road users encounter ambiguous right-of-way driving scenarios, such as shared space, bottleneck scenarios, T-junction, and intersections where driving situations are regulated by traffic laws.

Even though AVs offer a significant potential to improve safety and efficiency in urban transport, thus, reducing time consumption and good for the environment. AVs can reduce human errors, optimise traffic flow, and enhance accessibility for underserved populations (NHTSA, 2023), integrating AVs into our current traffic environment and introducing them to other road users presents a series great challenges, particularly in ambiguous situations with uncertain right-of-way scenarios, such as shared space, bottleneck scenarios, unmarked intersections, or residential junctions without traffic lights (Imbsweiler et al., 2019). In slow-moving traffic or ambiguous right-of-way scenarios, human road users sometimes make use of explicit signals from drivers, such as hand gestures, head motions, or flashing lights of the vehicle (Imbsweiler, Wolf, et al., 2018; Rasouli et al., 2017). But this can be a problem for SAE 3-5 AVs which do not currently have any efficient and adequate means of communicating intent since the drivers are absent and the speed limits in such scenarios (Fuest et al., 2018; Nuñez Velasco et al., 2021). To ensure safety, the behaviour strategies of current AVs are conservative in such unregulated situations, the AVs would stop and wait until the situation is resolved (Färber, 2016; Rahmani et al., 2025). However, this passive behaviour is often uncomfortable for passengers and uncooperative for other road users. In cases where another road user adopts a defensive behaviour, such as deceleration or pullover, and signals their willingness to yield, the AVs may fail to recognise or interpret the gesture correctly. As a result, road users and AVs can not even achieve a mutual understanding, let alone cooperation. This again would lead to longer and unnecessary waiting times and finally, it might cause a traffic situation of breakdown. As a consequence, the use, socialisation and acceptance of AVs could decrease (Imbsweiler, Ruesch, et al., 2018).

1.4 Improving communication between AV-MV

1.4.1 Interaction and communication

Markkula et al. (Markkula et al., 2020) define interaction as “a situation where the behaviour of at least two road users can be interpreted as being influenced by the possibility that they are both intending to occupy the same region of space at the same time in the near future”. Conflicts between two or more road users could happen due to misinterpretation of others’ driving intentions, behaviour, and communication (Ameen et al., 2021), which could lead to traffic congestion or even accidents, impacting transportation efficiency and safety, particularly in driving scenarios with an unclear right-of-way (Gutiérrez-Moreno et al., 2022). To prevent conflicts in ambiguous road settings that have no formal traffic rules, vehicles must communicate their intentions and negotiate the right of way (Imbsweiler et al., 2018).

1.4.2 Learning from human communication

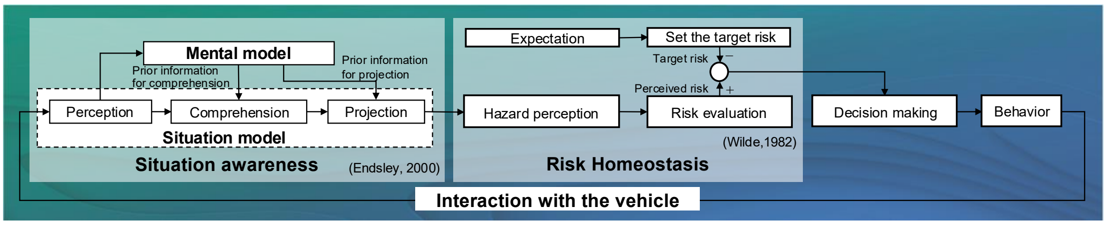


Figure 1.3 Human road users' cognition-decision-behaviour process in human-vehicle interactions (Liu et al., 2021).

Reproduced from Liu H., Hirayama T., & Watanabe M. (2021), "Importance of Instruction for Pedestrian–Automated Driving Vehicle Interaction with an External Human-Machine Interface: Effects on Pedestrians' Situation Awareness, Trust, Perceived Risks and Decision Making," *Proceedings of IEEE Intelligent Vehicles Symposium (IV 2021)*, © 2021 IEEE. Reprinted with permission.

Figure 1.3 shows the cognitive–decision–behaviour process of a human road user during human-vehicle interaction and communication (Liu et al., 2021). The model comprises four key components: situation awareness (Endsley, 1995), risk homeostasis (Wilde, 1982a), decision-making, and behaviour generation. In the situation awareness stage, HRUs undergo a cognitive process involving perception, comprehension, and projection, building their overall awareness of the surrounding environment. Subsequently, within the risk homeostasis framework, HRUs perceive hazards based on predicted outcomes and evaluate the subjective risk of the current situation relative to their personal risk acceptance level (i.e., target risk). Additionally, the expectation is an important factor in risk evaluation. Liu et al. (2021) further argue that trust in the approaching manually driven vehicle interacts with risk evaluation, influencing the perceived danger. Based on this comparison between subjective and target risk, HRUs then make behavioural decisions, such as whether to pass or yield, which are executed through specific driving actions. These behaviours in turn affect interactions with the environment, feeding back into the cycle continuously. Additionally, human drivers communicate through explicit signals (e.g., turn indicators, gestures) and implicit cues (e.g., vehicle movements, eye contact) to negotiate and cooperate with other road users, ensuring smooth interactions in dynamic traffic environments.

Implicit communication

Implicit communication refers to motion patterns and behaviours of vehicles, such as speed adjustments (deceleration, acceleration and maintaining speed), lane positioning, and or distance adjustment to show vehicles' intention to surrounding road users (Imbsweiler, Stoll, et al., 2018; Rasouli & Tsotsos, 2020). These cues play significant roles for road users in efficient traffic negotiations, especially in ambiguous or unregulated situations.

For example, a natural driving video analysis (Risto et al., 2017) identified three distinct yielding patterns in traffic encounters: advancing, early slowing, and short stopping, each signalling a driver's intention to yield. However, participants also stated in the interview that unexpected motion behaviour in manual or partially automated driving can lead to discomfort and misunderstandings among road users. Similarly, a driving simulator study (Kauffmann et al., 2018) illustrated that deceleration, the amount of velocity reduction, and reaction time influence how willing a driver appears to cooperate during lane changes. In T-intersections during deadlock scenarios, offensive cues such as acceleration and lane holding were associated with non-yielding intentions, while defensive actions like slowing down or stopping indicated willingness to yield (Imbsweiler, Ruesch, et al., 2018). Imbsweiler, Ruesch et al. (2018) further reported from an online questionnaire study that behaviours such as stopping increased the perceived likelihood of yielding, whereas acceleration and speed maintenance were interpreted as non-yielding. A traffic observation study on a double-parking bottleneck scenario (Rettenmaier et al., 2020) found that driver negotiation relies almost entirely on implicit communication, particularly through speed adjustments. Notably, vehicles showing non-yielding intentions maintained a constant speed, likely due to urban speed constraints, whereas vehicles intending to yield decelerated. An eye-tracking study by (Imbsweiler, Wolf, et al., 2018) analysed where drivers focus when assessing oncoming traffic. They found that drivers primarily look for vehicle kinematics, such as braking patterns or speed changes. Clear deceleration and stopping were interpreted as yielding (defensive) behaviours, while speed maintenance or acceleration were viewed as offensive, signalling a non-yielding intent. However, it is important to note that mere deceleration alone in vehicle interactions has not been uniformly classified as insisting or yielding (Imbsweiler et al., 2019; Weinreuter et al., 2019).

Explicit communication

Besides the implicit communication methods, to help the traffic move smoothly, drivers explicitly communicate by using hand gestures, body postures, head nods, head position, and eye contact, besides, car signals, for instance, headlights, turn indicators, horn and engine sounds are also used to convey drivers' intentions (Bazilinskyy et al., 2021; Dey & Terken, 2017; Imbsweiler, Ruesch, et al., 2018; Li et al., 2021; Rasouli et al., 2017; Vinkhuyzen & Cefkin, 2016; Yang et al., 2024).

Regarding the communication between vehicles and vulnerable road users, pedestrians seek eye contact at approaching cars at non-signalized crossings to judge a vehicle's intent to yield (Dey, 2020), and hand gestures can positively influence drivers' yielding decisions and confidence in intersections (Kitazaki & Myhre, 2015). However, there are research focusing on AV-pedestrian communication, reporting that eye contact is not a significant factor (Dey & Terken, 2017), and in some cases, drivers in vehicles may not even be noticed, therefore, their body gestures are not important as well (Straub & Schaefer, 2019; Sucha et al., 2017). Additionally, explicit communication is described as “rare to non-existent” (Dey & Terken, 2017; Y. M. Lee et al., 2021; Rasouli & Tsotsos, 2020), such signals are not universal, they are culturally dependent and may be misinterpreted by users (Färber, 2016). Regarding communication between vehicles, Imbsweiler, Stoll et al. (2018) illustrated that explicit cues such as hand gestures and flashing headlights can function as defensive signals, indicating a willingness to yield. Cooperation is often initiated and triggered when one party sends a clear explicit signal (Imbsweiler, Ruesch, et al., 2018).

Notably, in SAE Level 4 and 5 AVs, drivers are out of the loop and no longer responsible for monitoring the driving environment. Consequently, traditional explicit human signals like eye contact or gestures disappear, bringing challenges for communication and coordination with other road users. Currently, it is not clear if the explicit communication methods and information contribute to AV communication, with the results showing mixed results. AVs will need to communicate with conventional vehicles on the road during the transition period to full automation. To replace human driving behaviour in automated driving, a considerate behaviour has to be designed that covers the communicational aspect of vehicle movement and is meaningful to passengers and surrounding road users by matching their prior experiences and expectations.

Färber (2016) reports that the current AV response to unregulated situations is typically to stop and wait until the situation is resolved, which could lead to inefficient traffic and discomfort and confusion to users. Risto et al. (2017) illustrates that AVs should mimic or emphasise human drivers’ driving behaviours to enhance predictability. Ideally, as participants in the social dynamics of traffic, AVs must communicate their intentions clearly and effectively to integrate seamlessly into human-centred road environments. However, there is still limited research on how AVs should behave to convey their intention and negotiate with human road users while also maintaining passenger comfort. Whether this is best achieved through exaggerated motion, supplementary communication methods like eHMIs, or a combination of both, remains an open question requiring further investigation.

1.4.3 Communication issues between AV and human road users

The integration of AVs into urban roads introduces a series of challenges. As highlighted by (Färber, 2016), AVs may cause confusion and hesitancy among road users in urban traffic, who struggle to predict AV behaviour, particularly in ambiguous or unregulated situations.

To address these concerns, various studies have designed AVs' behaviours considered human-like driving styles, social expectations, road rules, policy and lawfulness, etc. (Bin-Nun et al., 2022; Koopman et al., 2019; The Mercedes-Benz Group, 2019). AVs could be programmed to behave according to certain specific environments and optimize their operational characteristics accordingly (Bin-Nun & Binamira, 2020). However, the programmed AV behaviour may not always match the human road users' predictions and expectations (Bin-Nun et al., 2022). Compounding this issue, speed limits in urban areas restrict AV movement, making it difficult for road users to interpret their intentions through movement dynamics, particularly longitudinal jerk - such as acceleration and deceleration (Matsunaga et al., 2019). The low-speed operation of AVs further reduces the clarity of their intended actions, increasing uncertainty among other road users.

In addition, road users may have difficulties in perceiving or understanding the intentions of the AV because some of the conventionally used communication methods from the driver, e.g., eye contact, head nod, and hand gesture, will be altered or vanish (Liu et al., 2021; Merat et al., 2018; Vissers, van der Kint, et al., 2016). Furthermore, inattentive drivers or passengers inside AVs may unconsciously make hand gestures or eye contact, leading to misinterpretation by other road users (Färber, 2016; Lundgren et al., 2017). The absence of these familiar human interactions can further reduce traffic efficiency, and complicate AV integration into mixed-traffic environments.

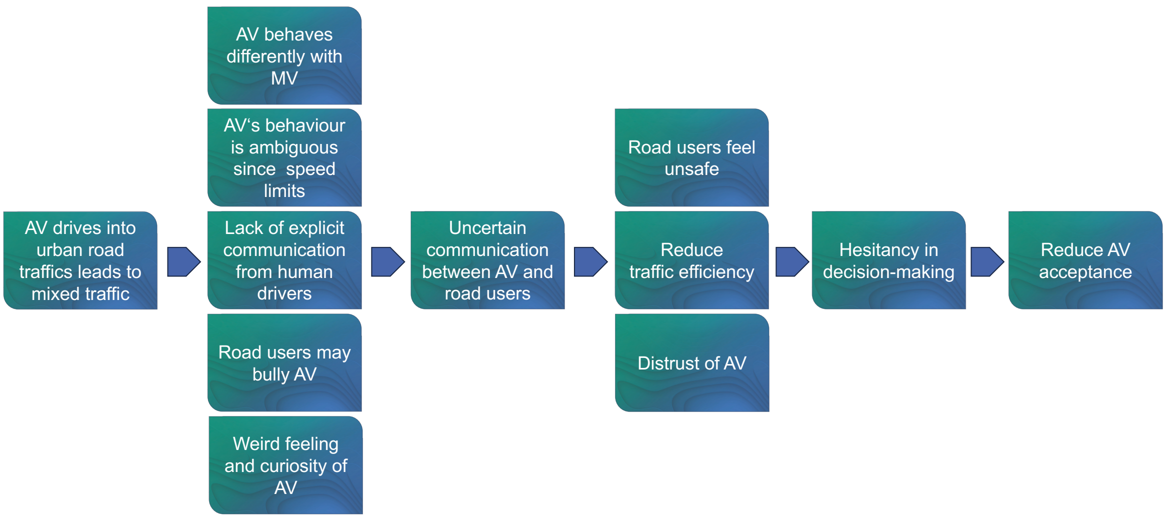


Figure 1.4 Communication issues when AV drives into urban roads

Färber (2016) concluded that identifying a vehicle as an AV may lead to confusion and hesitancy among other road users, as AVs may not yet fully follow the established local and social driving norms. Some road users may even exploit AV behaviour, knowing that AVs prioritize safety and adhere strictly to programmed rules. A questionnaire study by (P. Liu et al., 2020) found that participants exhibited more aggressive behaviour toward AVs compared to human drivers. Similarly, a Wizard of Oz study by (Şahin İppoliti et al., 2023) revealed that participants perceived AVs as untrustworthy, confusing, and unpredictable, with concerns that AVs might fail to detect pedestrians, potentially increasing accident risks. However, a Wizard of Oz study (Moore et al., 2019) found minimal variance in pedestrian decision-making when interacting with AVs versus conventional vehicles at crosswalks. Specifically, pedestrians showed no increased hesitation before crossing in front of the Ghostdriver, where a human driver was hidden to simulate an AV vehicle, suggesting they rely primarily on vehicle motion rather than its autonomous status. Despite these findings, it remains unclear whether drivers perceive and respond differently to AVs compared to manually driven vehicles and, if so, how their behaviour is affected.

The lack of clear communication and distinct intent from AVs makes it difficult for other road users to predict their reactions in ambiguous traffic scenarios, leading to uncertainty and reduced perceived safety, and also likely to increase conflicts between them (Liu et al., 2023; Schönauer, 2017a). The current behaviour design of AV is more defensive to guarantee safety, but excessive caution can result in frequent braking, slow responses, and unnecessary yielding, causing a reduction in traffic efficiency. This inefficiency, combined with a lack of knowledge about AVs' inner workings, their inability to adapt to human-like driving behaviours, and uncertain about AV reliability and decision-making processes, contributes to distrust among road users (Hoff & Bashir, 2015; Liu et al., 2021). As a result, road users feel more hesitant in decision-making. Ultimately, these factors lead to a decline in AV acceptance, making people less likely to support widespread AV adoption. In summary, clear and predictable communication between AVs and other road users is critical. To build trust and promote acceptance, AVs must effectively convey their intentions in ways that are intuitive, clear, familiar, and contextually appropriate within ambiguous and mixed-traffic environments.

1.4.4 Current implicit and explicit communication design for AVs

Implicit communication design

Naturalistic observation studies suggest that in urban deadlock situations, vehicle movement remains the most common form and the best way of communication for cooperation among drivers (Imbsweiler, Stoll, et al., 2018; Rasouli & Tsotsos, 2020). To date, few experimental studies have investigated the potential of the design for implicit communication during AV and MV encounters. Recent studies have highlighted that human road users' ability to interpret vehicle intentions is significantly influenced by two types of cues: longitudinal and lateral cues. Longitudinal cues encompass changes in speed, deceleration rate and stopping distance (Imbsweiler, Stoll, et al., 2018; Y. M. Lee et al., 2021; Miller, Koniakowsky, et al., 2022; Rettenmaier et al., 2021; Rettenmaier & Bengler, 2021; Weinreuter et al., 2019). Lateral cues refer to the direction of lateral movements, towards or away from the road centre, or remaining in position (Miller, Leitner, et al., 2022; Rettenmaier et al., 2021).

In a driving simulator study, Rettenmaier et al. (2021) explored longitudinal kinematic patterns showing AVs' yielding and non-yielding intentions. For indicating yielding, there are two types of deceleration: one-step deceleration from 30 km/h to a complete stop, as well as a two-step deceleration pattern where the AV slowed from 30 km/h to 15 km/h, maintained this speed for a moment, and then decelerated to a stop. In both cases, the vehicle came to a halt 10 meters before the bottleneck centre. For showing non-yielding intentions, the AV maintains its speed when approaching the oncoming MV, signalling its intent to proceed first. In addition to the longitudinal driving behaviour, the lateral deviation is designed for AV movements. To show yielding intention, the AV steered toward the edge of the road at distances of 30 or 50 meters before the bottleneck. To indicate non-yielding, the AV steers to the centre of the road also at distances of 30 or 50 meters before the bottleneck. In a video-based experiment, Miller, Leitner, et al. (2022) investigated similar longitudinal and lateral behaviours. To present yielding, the AV either decelerated from 25 km/h to 15 km/h or stopped completely. To communicate non-yielding intentions, the study examined maintaining speed, as well as accelerating from 25 km/h to 35 km/h, though the latter was not recommended due to urban speed limit regulations. The study also tested lateral movements by comparing AVs that maintained a straight path with those that deviated 1.0 meter either toward the road centre or edge, at distances of 32 and 20 meters before the bottleneck.

Yet, only a few studies addressed lateral movements and their impact on human drivers' subjective feelings and driving behaviour. Existing findings suggest that while longitudinal cues can communicate vehicle intent, they are often difficult to detect in bottleneck scenarios, particularly when the vehicle approaches from the oncoming direction. In contrast, lateral deviations have been shown to reduce both passing time and decision-making time compared to longitudinal offsets (Rettenmaier & Bengler, 2021). Nonetheless, these results are based on a narrow set of experimental conditions and analytical methods. Therefore, studies can systematically validate the effectiveness of lateral cues across diverse traffic scenarios and experimental settings are needed.

Explicit communication design

As AVs increasingly operate in shared traffic environments, the lack of traditional driver-based communication, such as eye contact or hand gestures, which poses challenges for interaction with other road users. To address this, researchers and developers have proposed various explicit communication strategies, particularly through external human-machine interfaces (eHMIs). These interfaces employ visual, auditory, or haptic signals to communicate an AV's current status, awareness, intentions, or next actions to surrounding traffic participants, including pedestrians, cyclists, and manually driven vehicles (Bengler et al., 2020; Dey et al., 2020).

Most research to date has focused on visual eHMIs, especially for interactions with vulnerable road users (VRUs). Examples include different types of lighting (S. Faas et al., 2020; Y. M. Lee et al., 2020), light stripes (Kaup et al., 2019; Markowski, 2020; Schieben et al., 2019) , text (Liu et al., 2021; Nissan, 2015), symbols (Rettenmaier, Schulze, et al., 2020), or anthropomorphic signals (JLR Corporate Website, 2018). These can be presented on the vehicle, or projected on the road (Dey, van Vastenhoven, et al., 2021; Rettenmaier et al., 2019). For instance, externally presented lights can provide information about an AV's yielding intentions, enhancing drivers' confidence in making crossing decisions (Papakostopoulos et al., 2021), and increasing their subjective perceived safety and acceptance of AVs (Avsar et al., 2021). Auditory eHMIs, although less commonly studied, include verbal message announcements like "stopping", "driving", or "please cross" (Dey et al., 2020), as well as sound effects, horn cues and engine sound (Vinkhuyzen & Cefkin, 2016). Current research on using eHMIs to convey AVs' intentions primarily focuses on visual cues.

Studies have demonstrated a wide range of content types that eHMIs can communicate in interactions between AVs and other road users. These include messages about the AV's current driving state (e.g., "cruising", "at rest"), its intentions regarding right-of-way negotiation (e.g., "yielding", "not yielding"), and kinematics state (e.g., "slowing down", "accelerating", "stop. Beyond kinematic information, eHMIs have also been used to offer advisory or instructive cues to surrounding users, for example: "please cross", "safe to cross", "do not cross", "unsafe to cross", or "waiting for you"(Dey, 2020; Li, Cheng, et al., 2023). (Loew et al., 2022) provides some other eHMI designs including intention-based messages, such as a light-band signal that conveys "I'm letting you go ahead", and perception-based messages, like "I saw you", indicating that the AV has detected the nearby road user. A combined approach has also been explored, such as using a light band and signal lamp to simultaneously convey "I saw you" and "I'm letting you go ahead". Additional message types include situation awareness cues (S. Faas et al., 2020); warnings (Li et al., 2021), and expressions of gratitude, showing “thanks” after other road users yield (Li et al., 2021). Overall, communicating the vehicle's intentions seems to be the prevailing trend (Dey, 2020).

It is important to note that, providing advice particularly in the form of action-based commands (e.g., “please cross”), could raise legal and safety issues, as it may imply responsibility or mislead users in uncertain situations. The (ISO/TR 23049, 2018) explicitly advises against using directive messaging in eHMIs and instead recommends focusing on conveying vehicle state and intent. Similarly, (ISO/PAS 23735 TC 22/SC 39) suggests that eHMIs should primarily be used when the AV intends to stop and yield, rather than for conveying complex or multilayered intentions.

In terms of eHMI positioning, studies reported that eHMIs have been mounted across various parts of the AV body, such as the windshield, hood, roof, bumper (including grills and headlights), sides, and rear (Dey et al., 2020; Rettenmaier, Schulze, et al., 2020). Communication is also achieved by projecting messages like symbols to show trajectories, stopping points, and intentions on the road (front, side, rear, all around) (HiPfi X, 2025). Few studies also reported that the HMI could be located on the traffic infrastructure (e.g., traffic lights or intersections), and road users (e.g., wearable, phone, or tablet). Despite this variety, most designs are still in the conceptual or prototype stages (Dey et al., 2020; Rettenmaier, Schulze, et al., 2020).

Empirical research has begun to validate the benefits of eHMI for AV-MV communication, and they are found to be particularly valuable for scenarios which need road users to cooperate to negotiate the right-of-way. For example, Rettenmaier & Bengler (2021) reported in a driving simulator that a symbol & bumper eHMI improved traffic efficiency by reducing passing time, ahead of an AV in a bottleneck scenario. Likewise, other driving simulator studies focusing on T-junctions reported that a novel light-band eHMI improved MV drivers’ perceived safety and acceptance of AVs (Avsar et al., 2021); Şahin İppoliti et al. (2023) noted that HMI signals indicating an AV's deceleration enhanced its prosocial perception. Other studies reinforce these findings, a video-based online study (Li, Cheng, et al., 2023) found that the additional information provided by HMIs on AVs enhances the subjective experience of MV drivers, fostering trust and acceptance of AVs in bottleneck scenarios. Similarly, a field study by Papakostopoulos et al. (2021) demonstrated that eHMIs, such as externally displayed lights, effectively communicate an AV’s yielding intentions, boosting drivers' confidence in crossing decisions at junctions. Regarding the showing time of eHMIs, Rettenmaier, Albers et al. (2020) noted that early eHMI activation helped manual drivers anticipate AV behaviour more effectively in bottlenecks compared to delayed displays. More importantly, eHMI can be effective in situations where a vehicle cannot move laterally towards the road's centre and can be used to provide a salient message (Rettenmaier et al., 2021). Besides, drivers may decide to pass more confidently with eHMI on bottleneck roads.

Figure 1.5 showcases several examples of eHMI design concepts, illustrating a wide range of visual strategies used by both researchers and industry. These include light bands, animated icons, and messages integrated into the AV's physical design or projected onto the environment.

Figure 1.5 Examples of various eHMI concepts demonstrating different approaches to achieving effective communication. Arranged clockwise from the top left: Toyota Concept i (Toyota Concept-i, 2017), HiPfi X (HiPfi X, 2025), Mercedes Benz Concept Car F015 (Best, 2016), Smart vision EQ for two (Kuther, 2017), Volvo Concept 360 (Volvo Concept 360c, 2018), Continental (*Continental*, 2019), Zhiji L7 (*Zhiji L7*, 2021), eHMI concept for AV-pedestrian communication (Kaleefathullah et al., 2020), eHMI concept for AV-MV communication (Rettenmaier, Albers, et al., 2020)

Despite these advancements, to date, compared to the extensive focus on eHMIs for AV-VRU interactions, little is known about the use of such interfaces for drivers of MVs, especially in ambiguous right-of-way scenarios which require communication and cooperation between the AV and MV, such as bottlenecks, shared space, and unregulated intersections. Li, et al. (2023) pointed out that additional messages from eHMIs may cause confusion if the information is excessive or ambiguous. Besides, Dey, van Vastenhoven, et al. (2021) reported that eHMIs are less effective in resolving ambiguities for vehicles travelling at higher speeds. Thus, whether the value seen for eHMIs in AV-VRU communication is the same as that required for AV-MV communication is currently unknown. Additionally, few studies have systematically investigated how combinations of eHMI and AV kinematic design influence human drivers' decision-making time or subjective feelings in traffic interactions. Although drivers are more familiar with implicit cues, such as vehicle movement, AVs do not always behave like human drivers, and their intentions may be less predictable. Therefore, a well-designed combination of implicit cues and explicit signals may be necessary to ensure clarity and improve cooperation.

There are emerging standards and guidelines for the design and deployment of eHMIs. For instance, the recent ISO Publicly Available Specification (ISO/PAS 23735 TC 22/SC 39) recommends that eHMIs should be used specifically to indicate an AV's intent to stop and yield, rather than as a method of communication for all potential vehicle intentions. The more potential eHMI meanings that are included, the greater the potential for misunderstanding. In line with this, ISO/TR 23049 (2018) emphasized that the number of signals should be limited. Although eHMIs offer a promising solution to the communication gap created by the absence of human drivers in AVs, their design and application must be carefully tested, particularly in AV-MV interactions under complex traffic scenarios.

1.4.5 Drivers' evaluation of AV-MV communication

To understand how drivers evaluate communication, recent studies have investigated the effect of implicit and explicit communication design on drivers' experiences. These investigations have focused on objective driving performance, in terms of decision-making time, passing time, average speed, average lateral deviation, and passing frequency, and subjective evaluations, in terms of feeling of safety, comprehensibility, trust, cooperativeness and comfort from human drivers (Miller et al., 2021; Miller, Leitner, et al., 2022; Rettenmaier et al., 2021; Rettenmaier & Bengler, 2021).

Despite increasing interest, only a few studies have addressed interactions between AVs and oncoming human-driven vehicles (MVs) in bottleneck scenarios, such as those caused by double-parked cars. To assess the impact of communication strategies on drivers' performance, Miller, Leitner, et al. (2022) examined how drivers interpret oncoming vehicle trajectory to predict its intentions (yielding or insisting on priority) and measured intention recognition time using video-based studies. Participants watched simulated driving videos created with SILAB 6.5 (WIVW GmbH) on their personal computer or laptop. After each trial, they indicated their presumed intention of the oncoming vehicle by answering the question: "How do you think will the oncoming driver behave?" (1 = wants to go first, 2 = wants to go second) using designated keyboard keys. To measure the intention recognition time, participants were instructed to press the key as soon as they recognised the vehicle's intent ("F" if the oncoming vehicle wanted to go first, and "J" if it wanted to yield). Results showed that decelerating and stopping were more likely to be presumed as the intention to yield, with lateral movements interpreted fastest and more decisively compared to longitudinal movements. This finding led the authors to suggest that AV should communicate via lateral kinematics. However, the response times have a big likelihood of differing from reactions while driving, keyboard-based settings may not accurately reflect real-world reaction times while driving, as motor responses differ when engaging in active driving tasks. Additionally, differences in participants' computer hardware and display settings could introduce variability in response times, potentially affecting the accuracy of the findings.

Miller, Koniakowsky, et al. (2022) investigated if drivers have different reactions to AVs and MVs in a bottleneck scenario through a driving simulator study, the results showed that participants expected AVs to drive yield more and the yielding AV matched more expectations compared to MV, with an improved behaviour such as faster passing time, higher average speed, and higher lateral position. However, the same experimenter was responsible for driving both the AV and MV. This introduces variability in driving behaviour across trials, as it is nearly impossible for the experimenter to replicate driving patterns with absolute consistency. Small variations in speed, acceleration, lane positioning, or reaction timing could unintentionally influence participant responses, potentially confounding the results. Additionally, since human drivers naturally exhibit slight behavioural differences even when attempting to follow a strict protocol, this inconsistency may reduce the reliability of comparisons between automated and manual vehicle conditions. The lack of a standardized, algorithm-driven approach for AV behaviour further limits the experiment's ability to accurately simulate real-world automated driving, making it difficult to generalize findings to real-world mixed-traffic scenarios.

Beyond video-based studies, driving simulator studies have been conducted to assess human drivers' behaviour and eHMI when encountering oncoming vehicles in bottleneck scenarios. These studies measured participants' passing time, averaged lateral position, average speed and minimal speed when passing through the bottleneck (Miller, Koniakowsky, et al., 2022; Rettenmaier, Albers, et al., 2020; Rettenmaier et al., 2021). Passing time was defined as the duration required for participants to drive through the bottleneck when the AV yielded the right of way. The results showed that, compared to only longitudinal movements, longitudinal movements with a lateral offset of the oncoming AV significantly shortened passing time, helped participants maintain a more stable lateral position, and allowed for higher and more consistent speeds, thereby reducing delays and minimizing the need for complete stops, therefore, improving traffic efficiency (Rettenmaier et al., 2021). Rettenmaier, Albers, et al. (2020) reported that eHMI can reduce the passing time and have a higher average speed. However, during AV-

MV interaction, drivers undergo a sequence of cognitive processes, including perception, decision-making, and action execution (Liu et al., 2021; Rettenmaier & Bengler, 2020). A critical gap in existing research is understanding the exact moment drivers make a yielding or passing decision before reaching the bottleneck. Passing time does not accurately reflect the time point of decision-making, making it unclear which factor, lateral or longitudinal movement of the AV, or the employment of eHMI, has a stronger influence on drivers' decision-making. Currently, no studies have examined precisely when drivers commit to a passing or yielding decision in bottleneck scenarios. A more detailed investigation into the impact of lateral offset, longitudinal offset, as well as eHMI integration, on AV-MV communication is essential to refine AV behaviour in mixed traffic environments.

Regarding subjective feelings, studies have evaluated drivers' emotional and cognitive responses. For example, Rettenmaier et al. (2021) assessed the impact of communication strategies on drivers' trust, perceived safety, efficiency and comfort while Miller, Leitner, et al. (2022) examining distinctiveness and perceived cooperativeness. Trust and perceived safety are critical in the context of AVs, as perceived safety was a steady and direct predictor of both the acceptance measures and trust also indirectly affects AV acceptance (Z. Xu et al., 2018). Some studies have used custom questionnaires to evaluate drivers' subjective feelings, for example, (Rettenmaier et al., 2021) did a self-designed questionnaire to evaluate the comprehension of oncoming vehicles' behaviours and eHMI messages. To date, a comprehensive psychological evaluation using validated multi-item scales including trust, perceived safety, efficiency, and acceptance is still lacking.

To explore eHMI preferences, (Rettenmaier, Albers, et al., 2020) provided and evaluated a novel eHMI design for AV-MV communication on the bottleneck road in a driving simulator study. They did brainstorming and promoted 14 self-designed eHMI concepts for both AVs yielding and insisting intentions. The participants ranked the concepts according to their preference. The results showed that eHMI can shorten passing times compared to the baseline without eHMI. Several studies provided a series of eHMI for AV-MV communication on bottleneck scenarios, T-junctions and intersections (Avsar et al., 2021; Li, Cheng, et al., 2023; Papakostopoulos et al., 2021; Şahin İppoliti et al., 2023), using arrows, light bands, and pulsing bars showing AV's intention and kinematics. However, the eHMIs are hard to replicate, and it is not good for holistic eHMI design. Currently, the light band is the most common and verified eHMI design for communication between AVs and vulnerable road users (VRUs). Using the same eHMI helps build holistic eHMI and is good for eHMI standardisation.

Additionally, Miller, Koniakowsky et al. (2022) evaluated drivers' reactions to AVs and MVs in a multi-agent driving simulator. The results showed that driving behaviour improved, i.e., faster passing time, higher average speed, and higher lateral position, when AVs yielded and matched drivers' expectations, compared to MVs that behaved the same way. This experiment was done on two linked stationary driving simulators, and the two simulators were spatially separated in different rooms. One simulator was driven by the participant and the other by a well-trained experimenter, the experimenter drove manually in all conditions, acted as MVs or with AVs. However, as the experimenter's actions could not fully replicate the precise compared to pre-programmed behaviours, which could have a big impact on participants' performance.

1.5 Research questions

This thesis aims to find and design appropriate communication methods between AVs and human road users, especially for human drivers, to enhance driving safety, improve the comprehension between AVs and road users, increase traffic efficiency, and AV acceptance. The investigations include subjective evaluations and objective vehicle metrics. We take a step-by-step approach of first exploring whether communication is lacking when human drivers are not involved in driving tasks in the interaction among human road users, providing a potential eHMI concept to enhance communication between AV and other road users. Subsequently, investigate the impact of kinds of AV kinematics design and eHMI on MV drivers' behaviours and subjective feelings, and find out how MV's performance and subjective feelings change for an AV as compared to a MV. Finally, explore other interface design possibilities except for eHMI for the communication between AV and MV drivers. The research questions are summarized in Table 1.2.

Table 1.2 Summary of research questions and corresponding chapters

No	Research Questions (RQs)	Chapter
RQ1	What communication methods and information do road users expect when communicate with automated vehicles (AVs)?	2
RQ2	How do human drivers communicate with AVs differ from communication with manually driven vehicles?	3, 4
RQ3	How do designs of behaviour and eHMI influence human drivers' subjective responses?	3
RQ4	How do designs of behaviour and eHMI influence human drivers' driving performance?	4
RQ5	What are the human drivers' preferences for internal and external HMIs when communicating with AVs in a more complicated scenario?	5

We begin by exploring road users' general expectations regarding information exchange and the communication strategies they use when interacting with conventional vehicles in ambiguous right-of-way scenarios. This investigation provides valuable insights into whether communication becomes insufficient when human drivers are no longer involved, as in interactions between Level 3–5 AVs (SAE International, 2021) and human road users. These findings inform the potential need for supplementary communication solutions, such as the development of external Human-Machine Interfaces (eHMIs) and the design of AV kinematic behaviours (RQ1, CHAPTER 2).

Subsequently, the focus shifts to a specific road user and traffic context: manually driven vehicles (MVs) driving in bottleneck scenarios. In this setting, we investigate the influence of the labelled AV or MV (RQ2), along with their behavioural designs and the presence of eHMI cues (RQ3 & RQ4) on drivers' subjective experiences and driving performance. Specifically, we explore whether simply knowing that an approaching vehicle is autonomous, as opposed to manually driven, affects driver behaviour and feelings, and how these responses vary based on different combinations of labelling, vehicle behaviour design, and eHMIs. While extensive research has explored eHMI and AV kinematic design in the context of interactions with vulnerable road users (VRUs), much less is known about their effectiveness in communication with human drivers of MVs, particularly in ambiguous scenarios that require cooperation, such as bottlenecks. As noted by Dey et al. (2021), eHMIs tend to be less effective at higher speeds, raising questions about whether findings from AV-VRU interactions can be translated and applied to AV-MV contexts, where vehicles move significantly faster than pedestrians. Furthermore, it remains unclear whether a combined approach, integrating behavioural design with eHMI cues, can form an effective communication strategy. These research questions are addressed in CHAPTER 3 and CHAPTER 4.

Finally, we address the practical limitations of eHMI usage in real-world conditions. When considering the development of effective interactions with AVs using eHMIs, a question arises, in the realistic driving scenario, MV drivers can fail to perceive the eHMI information deployed on the AV due to the bad weather conditions, and the obscuration from other traffic agents, etc. Instead, an internal human-machine interface (iHMI) deployed in MV is direct to MV drivers and visible in visibility-blocked situations. To address this, we explore the use of internal HMIs (iHMIs) displayed within the MV as an alternative communication method. Since iHMIs provide direct and reliable communication even in visibility-limited scenarios, we compare their impact against eHMIs in influencing MV drivers' subjective experiences (RQ5). The specific research can be found inCHAPTER 5.

1.6 Methodology

This thesis applies a mixed-methods research design to examine how road users, especially human drivers perceive, evaluate, and respond to AVs in ambiguous right-of-way scenarios, with a particular focus on bottleneck roads in urban traffic.. The methodology combined quantitative and qualitative approaches, using controlled laboratory experiments, online questionnaires, driving simulator studies, post-trial questionnaires and interviews to address the research questions systematically. The empirical research was structured around four interrelated studies, beginning with an exploration of road users' expectations regarding communication information and methods, followed by three studies focusing on specific aspects of AV-human driver communication. The first study (CHAPTER 2) used an online questionnaire to investigate communication preferences between conventional vehicles and VRUs in shared spaces. The next two studies (CHAPTER 3 and **Error! Reference source not found.**) employ driving simulators to examine the impact of AV labelling, kinematic behaviours, and external HMIs on human drivers' decision-making in bottleneck scenarios, supported by post-trial questionnaires and interviews. The final study (CHAPTER 5) uses a video-based online questionnaire to evaluate drivers' subjective perceptions of a combined internal HMI and external HMI communication strategy in multi-vehicle bottleneck situations.

1.6.1 Approaches to studies

Driving simulator study

The driving simulator studies employed a pseudo-coupled setup that replicated urban bottleneck scenarios, where participants encountered either AVs or MVs, investigating drivers' preconceived notions about manoeuvres of AVs compared to MVs. Participants are informed that the MV is controlled by an experimenter using another simulator despite all trials having the same preprogrammed behaviours. This approach is highly controlled in the laboratory, to limit confounding factors. The experimental conditions systematically varied three key factors: the type of the approaching vehicle (AV or MV), its kinematic behaviour (yielding or non-yielding, with or without lateral offset), and the communication strategy used (presence or absence of an eHMI). Throughout the experiments, objective driving performance metrics, including Passing Initiation Time (PIT) and Yielding Initiation Time (YIT), were recorded to capture precise measurements of participants' decision-making processes during the AV-human driver interactions.

Questionnaires and interview

Multiple questionnaires and interviews are used in this research to collect both quantitative and qualitative data. An online questionnaire is designed to explore road users' communication expectations and information needs when interacting with others in shared spaces. Participants are asked to evaluate the importance of different communication cues, such as gestures, vehicle movements, and signals. In the driving simulator studies, participants complete a short post-trial questionnaire after each scenario (see Figure 3.7), rating their trust, comprehension, and perceived safety of the approaching vehicle or eHMI on a 5-point Likert scale (1 = strongly disagree, 5 = strongly agree). Participants are also asked to provide brief verbal explanations for their ratings, which were recorded by the experimenter. After completing all trials, participants take part in a structured interview (see Table 4.2) to further elaborate on their experiences and perspectives. To complement the lab-based studies, a video-based online questionnaire was developed, simulating multi-vehicle interactions on a bottleneck road. This study examined how different HMI strategies (no HMI, eHMI only, iHMI only, or combined iHMI + eHMI) influenced drivers' subjective evaluations. After each video, participants rated their experience using a 5-point Likert Scale on communication clarity, efficiency, perceived safety, trust in the AV, and overall acceptance.

In this thesis, objective driving performance measures and subjective responses including post-trial questionnaires, and structured interviews are collected. The objective data allowed for the precise analysis of drivers' behavioural responses, while the subjective data provided insights into their perceived safety, comprehensibility, trust, and acceptance of AV communication strategies. The interviews further enriched the findings by capturing participants' personal reflections and rationales behind their decisions.

1.6.2 Data analysis

Different analytical approaches were applied to handle the various types of data collected across the experiments. To compare participants' preferences for communication methods, such as eye contact, hand gestures, and head nods, Fisher's exact test with Benjamini-Hochberg (BH) correction was used to control for multiple comparisons (in CHAPTER 2**Error! Reference source not found.**). Repeated measures ANOVA was conducted to examine the effects of vehicle types and behaviours on participants' subjective ratings collected from post-trial questionnaires (in CHAPTER 3). Generalised Linear Mixed Models (GLMM) were applied to analyse performance metrics, effectively handling the repeated-measures structure of the data and addressing the non-normal distribution commonly found in behavioural studies. In addition, participants' verbal responses from interviews were categorised and analysed thematically to extract key insights (in CHAPTER 4). For non-parametric data from the online questionnaire study (in CHAPTER 5) related-samples Friedman's ANOVA by Ranks (two-sided) for each evaluation item is applied, followed by Wilcoxon signed-rank tests for post-hoc pairwise comparisons. This approach allows for robust statistical comparisons across experimental conditions and ensures the reliability of the results.

The key evaluation metrics used throughout the research included drivers' passing and yielding initiation times, the correctness of their decisions in the bottleneck encounters, and subjective ratings of communication clarity, perceived safety, trust, and overall acceptance of the AVs' behaviour and HMI design. These measures ensured a comprehensive assessment of both objective performance and subjective user experience, contributing to a clear understanding of AV-MV communication in complex urban traffic scenarios.

1.7 Thesis structure

The thesis follows a systematic research strategy and is structured around four empirical studies, each presented as a chapter based on a peer-reviewed publication. CHAPTER 1 outlines the overall structure of the thesis, as shown in Figure 1.6. The research starts in the shared space environment (CHAPTER 2), where various communication issues were identified between AVs and different human road users (HRUs). These complex and dynamic interactions highlighted the need for clearer communication strategies, especially in ambiguous situations. A review of the literature further revealed that the research focus on the communication between AV and MV is much more limited compared to AV and pedestrians. Based on these findings, the focus then narrowed to a simpler and more controlled driving scenario, bottleneck situations, where right-of-way is unclear and requires negotiation between AVs and MVs (CHAPTER 3 and CHAPTER 4). These chapters systematically examined human drivers' perceptions of AV behaviours, including whether they held preconceived ideas about AV driving style, and how different AV kinematic patterns and eHMIs affected their decision-making, trust, and perceived safety. Building on these insights, CHAPTER 5 proposed a new communication approach, combining internal and external HMI designs to improve AV-MV negotiation in multi-vehicle bottleneck scenarios. The integrated HMI design achieved higher subjective ratings in comprehension, trust, and acceptance. Overall, the arrangement of these studies reflects a progressive research trajectory: identifying real-world communication problems, focusing on a specific negotiation context for in-depth analysis, and eventually developing and testing a practical HMI solution to enhance AV-human communication.

CHAPTER 2 lays the foundation by exploring communication methods and the types of information exchanged between conventional vehicle drivers and VRUs in shared spaces. This investigation, conducted via an online questionnaire, provides insights into the need for clearer communication strategies.

CHAPTER 3 and CHAPTER 4 explore how drivers respond when encountering an oncoming vehicle in a bottleneck scenario. These two chapters examine whether drivers' subjective experiences and performance are influenced by the vehicle's labeling (AV vs. MV), its kinematic behaviour, the presence of an eHMI, or the combination of these factors. Chapter 3 focuses on drivers' subjective responses, while Chapter 4 emphasises objective driving performance.

CHAPTER 5 extends the investigation into AV–MV communication by examining the impact of visual interface design in a more realistic bottleneck scenario involving multiple vehicles and increased complexity. The study provides a novel HMI for AV-MV communication and compares the impact of internal (iHMI), external (eHMI), and combined (iHMI + eHMI) interface designs on drivers' subjective feelings.

CHAPTER 6 highlights the principal findings of this thesis, summarises theoretical, methodological, and practical contributions, reflects on the research limitations, and provides suggestions for future studies.

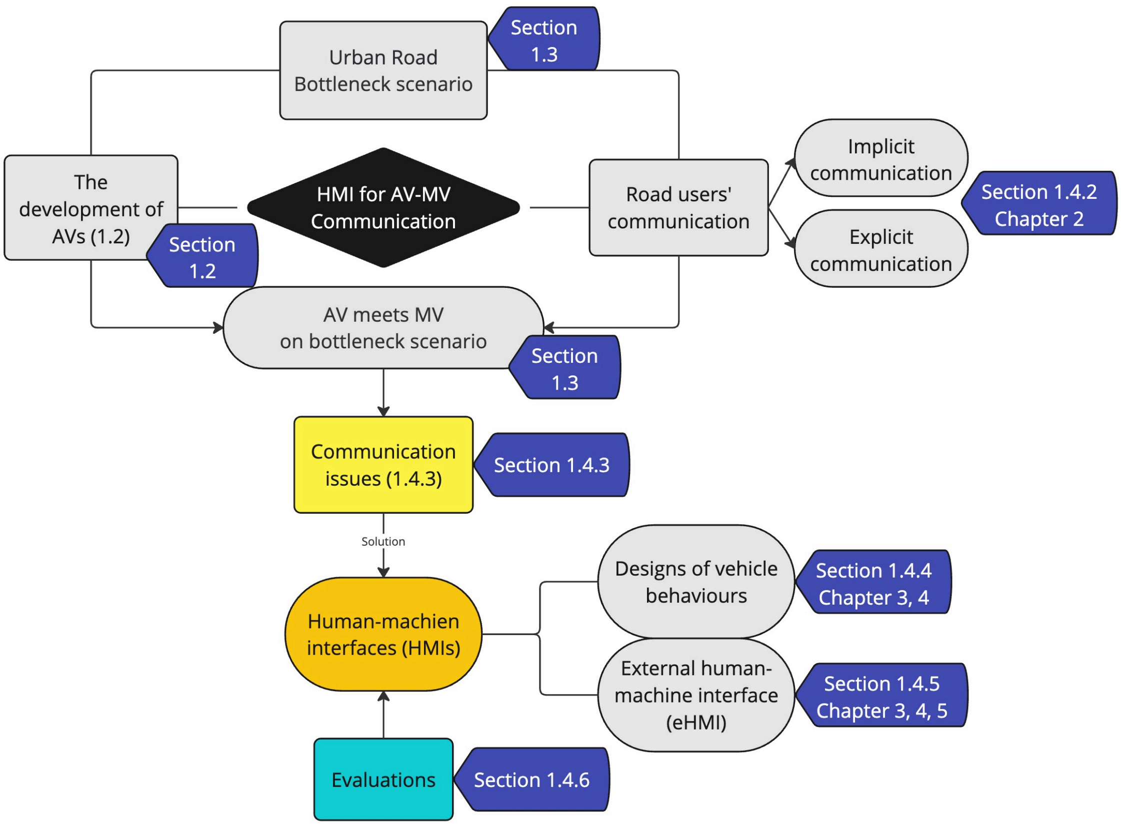


Figure 1.6 The structure of the thesis

CHAPTER 2. Investigating Communication Challenges of Automated Vehicles in Shared Spaces

Abstract

In comparison to conventional traffic designs, *shared spaces* promote a more pleasant urban environment with slower motorized movement, smoother traffic, and less congestion. In the foreseeable future, shared spaces will be populated with a mixture of autonomous vehicles (AVs) and vulnerable road users (VRUs) like pedestrians and cyclists. However, a driver-less AV lacks a way to communicate with the VRUs when they have to reach an agreement of a negotiation, which brings new challenges to the safety and smoothness of the traffic. To find a feasible solution to integrating AVs seamlessly into shared-space traffic, we first identified the possible issues that the shared-space designs have not considered for the role of AVs. Then an online questionnaire was used to ask participants about how they would like a driver of the manually driving vehicle to communicate with VRUs in a shared space. We found that when the driver wanted to give some suggestions to the VRUs in a negotiation, participants thought that the communications via the driver's body behaviours were necessary. Besides, when the driver conveyed information about her/his intentions and cautions to the VRUs, participants selected different communication methods with respect to their transport modes (as a driver, pedestrian, or cyclist). These results suggest that novel eHMIs might be useful for AV-VRU communication when the original drivers are not present. Hence, a potential eHMI design concept was proposed for different VRUs to meet their various expectations. In the end, we further discussed the effects of the eHMIs on improving the sociality in shared spaces and the autonomous driving systems.

Keywords: AV-VRU communication; Explicit communication; eHMI; Shared space.

2.1 Introduction

In the 1970s, the concept of shared spaces as a traffic design was introduced by the Dutch traffic engineer Hans Monderman (Clarke, 2006). It was later formally defined by Reid (Reid et al., 2009) as “a street or place designed to improve pedestrian movement and comfort by reducing the dominance of motor vehicles and enabling all users to share the space rather than follow the clearly defined rules implied by more conventional designs”. Shared-space designs largely remove road signs, markings, and traffic lights with no or minimum traffic regulations to allow vehicles with a limited speed to directly interact with pedestrians and cyclists. In other words, road users are not separated by time or space segregation according to their transport modes, e.g., as a driver, a pedestrian, or a cyclist. They negotiate to take or give their right of way based on social and physical context, e.g., courteous behaviour and low vehicular travel speed (Hamilton-Baillie & Jones, 2005). Compared to conventional traffic designs, shared spaces promote a more pleasant urban environment with slower motorised movement and safer and smoother traffic and less congestion (Clarke, 2006). These designs nowadays can be found in urban areas of many European cities, like the Laweiplein intersection in the Dutch town Drachten, Skvallertorget in Norrkoping, Kensington High¨ Street in London (Hamilton-Baillie, 2008), and the shared space in the German town Bohmte (Weßling et al., 2009), as well as in many other countries [1].

Figure 2.1. AV-VRU communication in a shared space.

[1] https://en.wikipedia.org/wiki/Shared_space

However, with the advent of autonomous vehicles (AVs), the established shared spaces may face new challenges with respect to traffic safety and smoothness, and frequent communication between AVs and vulnerable road users (VRUs) is needed (see Figure 2.1). In this paper, we first review the challenges of the current shared-space designs and seek the potential solutions by leveraging eHMI to build the communication between AVs and VRUs, in order to seamlessly integrate AVs into shared-space traffic.

2.1.1 Shared space as a traffic design

In the past decades, various aspects have been considered in shared-space designs. (Schönauer, 2017) reviewed the most¨ important aspects, which are traffic flows, safety and accident aspects, driving speeds, parking demand, change in traffic behaviour, and impact on urban development and land use. In urban areas, shared spaces have been shown to improve both vehicle and pedestrian travel times and maintain safe and mixed use of road surface (Wargo & Garrick, 2016). Clarke et al. (Clarke, 2006) found that the removal of traffic rules increases the perceived risk by vehicle drivers and therefore leads to a more cautious driving behaviour, e.g., driving at decreased speeds and more frequently giving way to VRUs; The shared-space designs have changed road users’ behaviours, e.g., cyclists start to use hand signals and road users seek eye contact with each other for communication. In addition, shared spaces have been found to increase the functionality of public places, e.g., the decrease of vehicle dominance increases pedestrian activities and dwelling time (Karndacharuk et al., 2013).

Besides the positive aspects, shared spaces still remain controversial. On the one hand, in comparison to conventional traffic roads, they are designed to improve the activities of pedestrians and to achieve better traveller comfort and safety, where a slower vehicle speed is required and both drivers and pedestrians remain vigilant. On the other hand, people who oppose this concept argue that shared spaces may also lead to more pedestrian-vehicle conflicts (Kaparias et al., 2013). One of the biggest concerns is about the safety of the elderly, children and other disabled road users, who have a limited capacity to perceive the surrounding environment (Kaparias et al., 2013). As a driver, the presence of the elderly and children is a very important factor regarding the driving behaviour and the driver is supposed to pay more attention to them (Kaparias et al., 2012). Another key issue is how to deal with high-volume road space. At low vehicular traffic conditions pedestrians feel more comfortable (Kaparias et al., 2012), whereas high volume road space increases the number of collisions between pedestrians and bicycles in non-motorized shared spaces (Gkekas et al., 2020). In addition, intention misunderstanding between drivers and pedestrians is the frequently stated problem in shared spaces (Hamilton-Baillie & Jones, 2005). Pedestrians hope to get relevant information clearly by setting safe zones, where rich physical and multi-sensory cues in terms of surface tactility, colour contrast and the enhancement of sound are provided (Vissers, Kint, et al., 2016).

2.1.2 Issues of AV-VRU interacting in shared spaces

In the foreseeable future, shared spaces will be populated with an unprecedented mixture of AVs and VRUs. Figure 2.1 depicts the mixed traffic in a shared space. The advent of AVs will make the interactions even more complicated, where the shared-space designs purposely introduce ambiguities to hope for more cautious behaviour (Clarke, 2006). When an unmanned AV, i.e., SAE level 3–5 AV (SAE International, 2021), and VRUs encounter in a shared space, the following issues with respect to their interactions should be considered:

- The VRUs may have difficulties in perceiving or understanding the intentions of the AV because some of the conventionally used communication methods from the driver, e.g., eye contact, head nod and hand gesture, will be altered or vanish (Liu et al., 2021; Merat et al., 2018; Vissers, van der Kint, et al., 2016).
- The low-speed driving makes it difficult for VRUs to obtain the intention and predict the behaviour of the AV from its movement dynamics, especially acceleration and deceleration (Matsunaga et al., 2019).
- The VRUs may feel not safe if they cannot easily understand the intentions of the AV (Hamilton-Baillie & Jones, 2005; Kaparias et al., 2012; Liu et al., 2023). It is also likely to increase conflicts between them (Merat et al., 2018).
- The VRUs may become hesitant and nervous because of the distrust of the AV due to, e.g., the lack of knowledge of the AV's inner workings or logic (Hoff & Bashir, 2015; Liu et al., 2021).

The above issues challenge the justifications of the shared space designs. The potential conflicts between AVs and VRUs could reduce the safety and efficiency of the traffic flow (Merat et al., 2018), and the lack of commonly used explicit communication could reduce the traffic climate, leading to the so-called bad pro-sociality and hindering the public acceptance and broad deployment of AVs in shared spaces (S. Sadeghian et al., 2020). Hence, in this paper we explore plausible solutions to these new challenges the shared-space traffic confronts with no or minimum alterations of the already established shared spaces in many places.

2.1.3 eHMI design as a solution to AV in shared spaces

As mentioned above, AV-VRU interacting in shared spaces has several integrated and typical issues due to, e.g., disappeared explicit communication from the driver, low-speed driving, misunderstanding AV's intention, mixed driving environment and ambiguous agreement, which needs frequent communication between AV and VRUs. A novel explicit communication such as external human-machine interface (eHMI) could be one solution to these issues (Busch et al., 2018; Liu et al., 2021; Schieben et al., 2018; Uttley et al., 2020). eHMI is an interface located on or projecting from the external surface of a vehicle that can convey information about its driving intention to the surrounding VRUs substituting the driver (Bengler et al., 2020; Tabone et al., 2021). eHMIs are especially helpful in low-speed scenario (Matsunaga et al., 2019), e.g., in a shared space, because they not only can be designed to express the current and future driving intentions to the VRUs and help them make quick decisions in ambiguous driving scenarios (Dietrich et al., 2018; Liu et al., 2021), but also can improve the perceived safety of VRUs (de Clercq et al., 2019; Liu et al., 2023). Moreover, the communication cues of the eHMIs are beneficial for prosocial aspects (S. Sadeghian et al., 2020) because they are useful in improving trust among VRUs, meanwhile, giving them a feeling that the AV is polite, building a good traffic climate (Tabone et al., 2021).

Some traditional eHMI signaling methods, such as blinkers, brake lights and headlights, are legally required and highly standardized (Bengler et al., 2020). These traditional methods may not be suitable for shared spaces and they should be tailored according to the AV-VRU interactions with the consideration of the uniqueness of shared space traffic (see Sec. I-B). A typical example is that, it can be difficult for an AV to use the traditional signaling methods to make VRUs understand its driving intentions and suggestions when VRUs and the AV have to negotiate the right of way.

Currently, some novel eHMI designs have been proposed (Deb et al., 2020), such as display on vehicle, projection on road, light strip or light spot, as well as anthropomorphic eHMIs, amongst others (Fridman et al., 2017). In addition, other information can be communicated, e.g., by projecting virtual paths. This can be the path that the AV is following and thus showing its intention explicitly, whereas an AV can also project paths relating to the VRUs: this can be the projected path which the AV assumes that an VRU is going to take. It can, however, also be a "safe path" to allow both road users to safely interact. Such a projection modality has been realized from a technical point of view in (Busch et al., 2018) by projecting road markings and signals to visually indicate an AV's intended behaviour.

However, how to design effective eHMIs for share spaces is still not fully explored. First and foremost, we need to understand what are the most important factors that guide the shared-space traffic and how can we adopt these factors for the eHMI designs? To be more specific, the research questions of eHMI designs in shared spaces are as follows:

1. What information and the communication methods are expected by VRUs when the AV needs to communicate to them in shared spaces?
2. Do VRUs expect that the AV communicates to them by only using traditional signaling methods such as turn signal, headlight, break light and horn?
3. Do VRUs need different eHMI communication methods with respect to their transport modes?

2.2 Experiments by an online survey

To answer what information an AV needs to convey to VRUs, i.e., pedestrians and cyclists, the communications between VRUs and the driver in a manually driving vehicle when they interact in shared spaces were surveyed via an online questionnaire. We use this surveyed data to analyse their communications, and then to guide the eHMIs designs for AV-VRU communication. The questionnaire includes the following questions corresponding to three transport modes:

Q1: As a driver driving a car in a shared space, how do you intend to convey information to pedestrians and cyclists in real life?

Q2: As a pedestrian walking in a shared space, how do you expect the driver to convey information to you?

Q3: As a cyclist cycling in a shared space, how do you expect the driver to convey information to you?

For each question, nine items can be multiple selected that are 1) headlight flashing, 2) turn signal, 3) brake light, 4) horn, 5) car movement, 6) hand gesture, 7) eye contact, 8) head nod, and 9) no communication. The items 1) to 8) are all explicit communication methods except for 5) car movement. The 9) no communication represents their willingness to communicate. Meanwhile, headlight flashing, turn signal, brake light and horn are explicit communications via the vehicle's traditional signalling methods; hand gesture, eye contact and head nod are explicit communication methods via the driver's body behaviours. After that, participants were asked to explain what specific information they wanted to convey regarding each selected communication method.

2.2.1 Participants

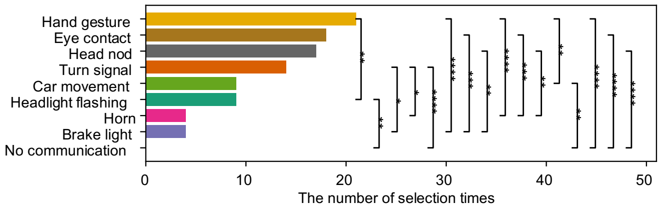
Thirty-one participants (20 males and 11 females) within the age range of 24–59 (mean: 32.2, standard deviation: 5.0) were invited to the questionnaire. All participants are from Europe, especially Germany and most of the them are familiar with the concept of shared space. We used the publicly available video recorded in the shared space Sonnenfelsplatz Graz (Schönauer, 2017b) as an example to demonstrate the shared-space traffic and help them recall their experience in shared space. Note that we discarded the data from the four participants without driving license for Q1 and the data from the two non-cycling participants for Q3.

2.3 Results

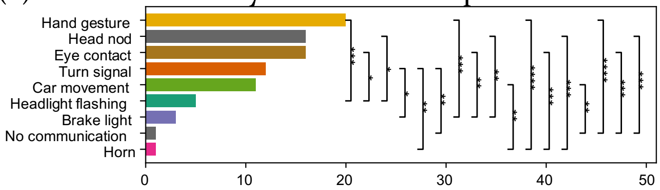
2.3.1 Communication methods w.r.t. transport modes

Here, we analyse the communication methods in a shared space intended by drivers and expected by pedestrians and cyclists from the drivers. The differences among multiple methods are compared by the Fisher exact test with the Benjamini-Hochberg (BH) correction. The corresponding results are presented in Fig. 2 for each transport mode. The horizontal axis is the selection count and the vertical axis is the communication methods ranked by the counts.

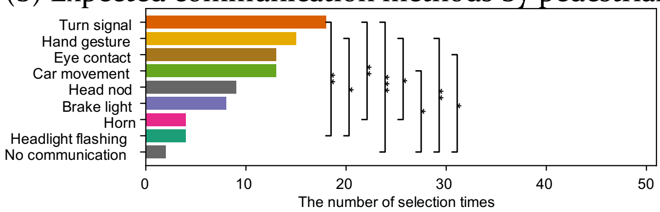
Figure 2.2 (a) and (b) illustrate that in a shared space, the communication methods intended by drivers and expected by pedestrians are highly aligned with each other. The top three intended/expected communication methods were hand gesture, head nod and eye contact, which were significantly more frequently selected than implicit communication by car movement and explicit communication on vehicle by horn and brake light. However, in Figure 2.2 (c), the expected communication methods from cyclists to receive information was not aligned with what drivers intended to convey (see Figure 2.2 (a)). Turn signals and car movemenst were expected by cyclists, which were not highly intended by drivers and pedestrians. Compared to pedestrians walking at low speed, the higher speed and less flexibility (e.g., stabilising the bicycle) of cyclists may impact their choice of methods to receive information from vehicles. The direct communication cue of turn signal is more straightforward to be understood by cyclists. Hand gestures and eye contact are still in the top three communication methods selected, which are significantly more frequent than horn and headlight flashing.



(a) Drivers to convey information to pedestrians and cyclists



(b) Expected communication methods by pedestrians from drivers



(c) Expected communication methods by cyclists from drivers

Figure 2.2 Communication methods w.r.t transport modes, multiple comparisons by Fisher exact test with BH correction method p<0.5:* p<0.01:** p<0.001:*** p<0.0001:****

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2.3.2 Communication methods to different information

The communication method is a carrier of the information to be disseminated. For information that expresses the same intent, road users may intend to use different methods associated with their transport modes, i.e., the methods drivers intend to use and the ones VRUs expect the drivers to use could be different. To investigate this difference, we further categorized the information sent by the drivers to the VRU receivers (pedestrians and cyclists) into situation awareness, risk evaluation and decision making, based on the criteria reported by (Liu et al., 2021). In this way, we can analyse the effectiveness of an eHMI in terms of each category for the AV in shared spaces.

Category A: information to help VRUs to be aware of situations. A driver conveys information about her/his intentions and the states of the car e.g., "I'm stopping", "I want to turn left/right" and "I will go".

Category B: information to help VRUs perceive risks. A driver conveys information about caution, such as "danger", "warning" and "emergency situation".

Category C: information to help VRUs make decisions. This information includes suggestions and gratitude from drivers, such as “you go first”, “go ahead” and “thanks”.

Note that the information about gratitude from a driver, e.g., “thanks”, could be considered as positive feedback for the decision made by the VRUs. It could encourage the VRUs to quickly make a decision that satisfies both parties in the next interaction with the driver.

For each category, the communication methods intended by drivers and expected by VRUs, denoted as driver-vs pedestrian, driver-vs-cyclist and pedestrian-vs-cyclist in Table I, were ranked by the number of selections. The corresponding ranks in each category are visualized in Fig. 3, where the value in each circle denotes the selection number and different communication methods are colour coded, and a large slope of the connected edges denotes a bigger rank difference among different transport modes.

The Spearman’s correlation coefficient (r_s) was used to compare the ranks and the t-test to estimate the corresponding statistical significance. The null hypothesis Ho is that there is no correlation between the methods intended and expected in each category, i.e., r_s is 0; Only if r_s close to 1 and $p < 0.05$, then there is a significantly strong correlation between them. Otherwise, the categorized Table 2.1. Spearman’s correlation among the communication method ranks for each information category tendency and expectation are different (i.e., not correlated) with respect to their transport modes.

Table 2.1 Autonomous Vehicles Drive into Shared Spaces: eHMI Design Concept Focusing on Vulnerable Road Users.

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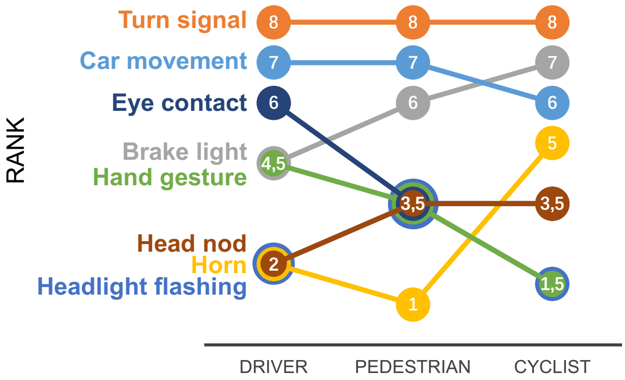
	Category A		Category B		Category C	
	r_s	*p*-value	r_s	*p*-value	*p*-value	*p*-value
driver-vs-pedestrian	0.804	**0.016**	-0.312	0.452	0.994	**<0.0001**
driver-vs-cyclist	0.578	0.134	-0.308	0.458	0.897	**0.003**
pedestrian-vs-cyclist	0.668	0.070	0.875	**0.004**	0.892	**0.003**

In the category A, with respect to intention information, there was a significantly strong correlation (r_s = 0.804, 0.016) for driver-vs-pedestrian. However, the correlation coefficients reduced to r_s = 0.578 and r_s = 0.668 for driver-vs-cyclist and pedestrian-vs-cyclist, and no significance was found. Moreover, Fig. 3(a) shows the following patterns: 1) As a driver, turn signal and car movement were intended to convey her/his intentions, e.g., “I am turning to a certain direction”, “I will drive now” and “I will stop now”. Eye contact, hand gesture and brake light were also used to convey information in a smaller amount. But head nod, horn and headlight flashing were not often used to convey the intention of the driver to help the VRUs to be aware of situations. 2) As a pedestrian, turn signal and car movement were expected to convey the information from the driver, which are aligned with what the driver was intended. Interestingly, pedestrians preferred the driver to use brake light over eye contact to convey her/his intentions. 3) As a cyclist, the ranks of turn signal, car movement and eye contact were in the upper position. Meanwhile, horn was also required to convey information from the driver. This indicates that compared to pedestrians, cyclists may expect information via clearer and more striking communication methods from the driver to help them obtain situation awareness.

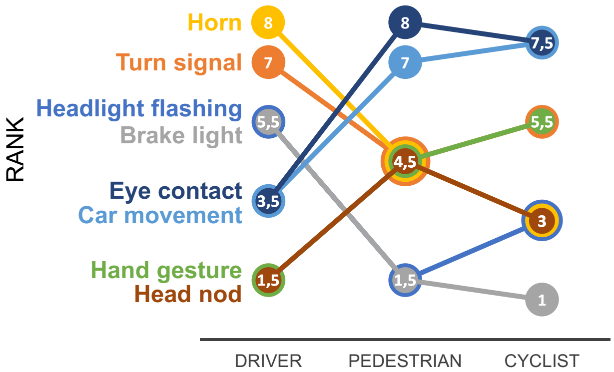
In the category B, pedestrians and cyclists expected communication methods regarding caution information from drivers are different from the ones the drivers intended to use. There were non-significant correlations for driver-vspedestrian ($r_s = -0.312$, 0.452) and driver-vs-cyclist ($r_s = -0.308$, 0.458). In addition, the results also show that pedestrians and cyclists had a similar expectation for the communication methods from drivers, indicated by a strong pedestrian-vs-cyclist correlation ($r_s = 0.875$, 0.004). Multiple intuitive examples can be seen in Fig 3(b). Drivers intended to use horn, turn signal, headlight flashing and brake light to raise the caution of pedestrians and cyclists, whereas pedestrians and cyclists expected drivers to warn them through eye contact and car movement. Besides, cyclists also expected that drivers could use obvious communication methods, e.g., turn signal and hand gestures, to help them perceive risks correctly. These results are in line with the on-site study in a shared space setting and the questionnaires carried out by (Merat et al., 2018), which show that the information about an AV’s actions, such as turning, stopping and acknowledgment of the detection of other road users was highly expected by the VRUs it encountered.

In the category C, significant positive correlations ($r_s > 0.890$, $p < 0.01$) for driver-vs-pedestrian, driver-vs-cyclist and pedestrian-vs-cyclist were found for making decisions. Figure 2.3 (c) also shows that the communication method ranks intended/expected by them were almost the same. The top three of intended/expected communication methods were all conveyed through the driver’s body behaviours, i.e., hand gesture, head nod and eye contact. These results are consistent with the study reporting that active communications through the body were often used in shared spaces, especially for cyclist (Clarke, 2006).

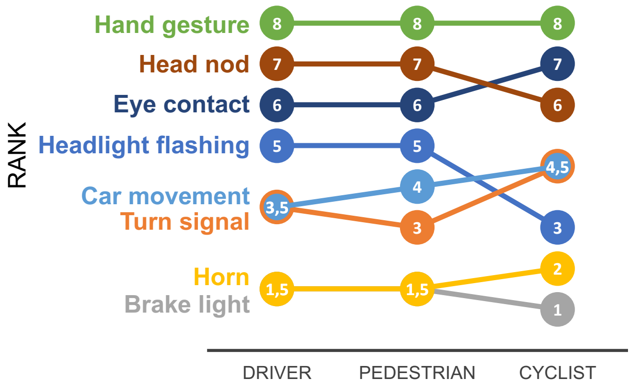
In summary, participants thought that the communication via the driver's body behaviours was necessary when the driver wanted to give some suggestions or indicate intentions to the VRUs in a negotiation. Besides, when the driver conveyed information about her/his intentions and cautions to the VRUs, participants selected different communication methods with respect to their transport modes. These results suggested that novel eHMIs might be useful for AV-VRU communication when the original drivers are not present, and the eHMIs need to be dedicated to VRUs' transport modes to meet their distinctive expectations.



a. Category A



b. Category B



c. Category C

Figure 2.3 The intended/expected communication method ranks for conveying information in the categories A, B and C.

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2.3.3 Potential eHMI design concept

Although, the questionnaire mainly looked at mimicking (human) communication, the availability of eHMIs will also allow for new methods, such as windshield display, light bar around the AV and the brake light projects on the ground. Furthermore, the eHMI design concept could be used for improving VRUs' feeling of safety, reducing distrust and hesitancy (Liu et al., 2021). Most importantly, the explicit information shown on eHMIs should match the implicit information (Dey, Matviienko, et al., 2021), e.g., AV movement, otherwise, it may result in distrust between VRUs and AV.

We propose a framework with a potential eHMI design concept to address the aforementioned issues of AVs driving in shared spaces. In the design component for AV-VRU communication, the eHMI designs respond to, i.e., situation awareness, risk perception, decision making, and gratitude based on the analysis of the replies of the questionnaire. As a prototype, some scenarios are used to demonstrate the functionalities of the eHMIs, more specifications of design will be explored in our future work.

First, Figure 2.4 (a) and (f) are used as baselines with no eHMI displayed, if there is no VRU in the AV's neighbourhood.

In response to intention misunderstanding, the eHMI lightning on windshield and the brake light projecting on the ground are used to reduce the ambiguity of implicit communication due to speed limit. It aims to raise the VRUs' awareness of the situation, e.g., informing the VRUs that the AV has recognized them and currently is decelerating.

We located the eHMI on windshield at driver's place to meet the expected communication methods by VRUs from the driver's body, such as hand gesture. In this case, a brake light pulsing can even present a strong sense that the AV is still moving with deceleration but has not yet fully stopped (Figure 2.4 (b) and (g)). Note that this eHMI design is not targeted on any particular VRU, but only explicitly showing the AV's intention to the VRUs in the vicinity.

In a potential danger, apart from horn signal, an extra visualisation warning signal will be displayed on the windshield to warn the running pedestrian (Figure 2.4 (c)) and the offensive cyclist (Figure 2.4 (h)) of the risk of collision, so that the VRUs can notice the AV promptly.

Hand gestures are used to reduce the ambiguity and give positive feedback in communications. For example, waving gesture can be used by the AV to give the right way to the VRUs (Figure 2.4 (d) and (i)) after confirming that they can interact safely by in-vehicle cameras and sensors, and a thumb-up to express gratitude to the VRUs' courteous behaviour (Figure 2.4 (e) and (j)).

Moreover, side bar lighting of the AV, as a more direct and obvious turn signal, can be used to emphasize the car movement with the aim to help cyclist understand the AV's intention and make a quick decision (Figure 2.4 (g) and (i)).

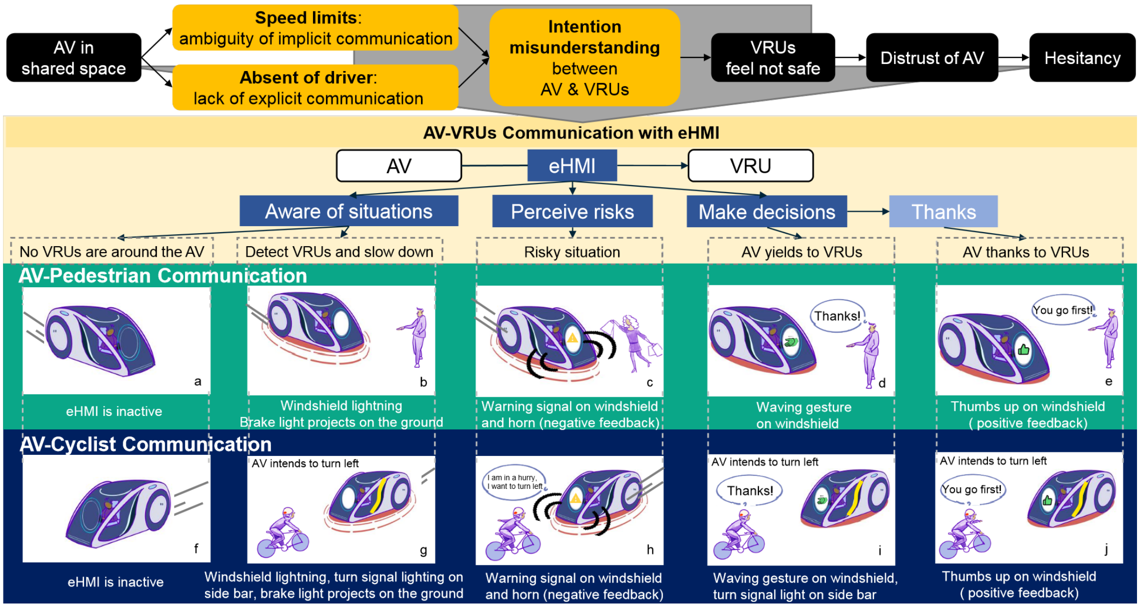

Figure 2.4 The addressed issues and potential eHMI design concept.

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2.4 Discussions

In this section, we further discuss the benefits of the eHMIs on not only the sociality in shared spaces but also the autonomous driving systems.

2.4.1 Effect of eHMI on the sociality in shared spaces

From the results of the questionnaire, we found that there is positive feedback between the drivers and the VRUs, such as saying "thank you" after the negotiation. This positive feedback makes them understand that their previous decisions are received with praise and gratitude from each other. Including gratitude design element (e.g., Figure 2.4 (e) and (j)) may strengthen mutual trust between them and improve sociality in shared spaces. For the AV, if it can give this positive feedback via the eHMI when interacting with VRUs in shared spaces, then the sociality of the AV and the VRUs' trust in the AVs could be promoted (Liu et al., 2021).

On the other hand, we also consider that the negative feedback is important as well for AV-VRU interactions, such as warnings. According to the risk homeostasis theory (Wilde, 1982), if the allowable level of risk for the VRUs is high, then they may tolerate the actual receipted risks and take some risky behaviours, especially when they over-trust themselves (Liu & Hiraoka, 2019). In this situation, if the AV conveys a warning message through eHMI, it may promote pedestrians to calibrate the endurable level of risk and their over-trust in themselves.

In summary, along with the driving intention information disseminated by eHMIs, appropriate positive and negative feedback from the AV is beneficial for calibrating the trust of VRUs in the AVs and themselves. A harmonious and mutually trustworthy traffic society could be possibly formed through an appropriate communication and feedback loop between AVs and VRUs in shared spaces.

2.4.2 Effect of eHMI on the autonomous driving systems

In recent years there has been a large body of research on interaction modelling among road users for autonomous driving in urban areas of mixed traffic, as well as in shared spaces (Chandra et al., 2019; Cheng, Liao, Tang, et al., 2021; Helbing & Molnár, 1995; N. Lee et al., 2017; Nagel & Schreckenberg, 1992; Park et al., 2020; A. Sadeghian et al., 2019). The most well-known conventional approaches are, e.g., rule-based approaches such as social force model (Helbing & Molnár, 1995) and cellular automate (Nagel & Schreckenberg, 1992). Game theory (Myerson, 1991) is also applied to mimic the negotiation among road agents in shared spaces to achieve the equilibrium for each single agent (Cheng, Johora, et al., 2021). Early machine learning approaches rely on manual extracted features to stimulate complex decision-making process in interactions, such as Gaussian processes (Wang et al., 2008) and Markov decision processing (Kitani et al., 2012). In recent years, deep learning (LeCun et al., 2015) approaches are trained to automatically learn interactions from large amount of real-world data. The most widely used approaches are recurrent neural networks with long short-term memories (Alahi et al., 2016; Chandra et al., 2019) and deep convolutional neural networks (Cui et al., 2019). In addition, deep generative models are employed to learn the multi-modalities of interactive behaviours, such as generative adversarial nets and variational auto-encoder (Kingma & Welling, 2013; N. Lee et al., 2017). Furthermore, attention mechanisms (Vaswani et al., 2017; K. Xu et al., 2015) are incorporated into these models for modelling complex sequential patterns (Cheng, Liao, Yang, et al., 2021; Park et al., 2020; A. Sadeghian et al., 2018) and reinforcement learning are applied to teach agents to behave like human road users (Co-Reyes et al., 2018; N. Lee et al., 2017). However, most of the works simplify the interaction process of road users as road agents considering only their motion behaviour, and the possibilities of communications and feedback among them are over simplified or neglected.

On the other hand, some of the machine learning methods, especially deep learning models, have tried to extract explicit information from the training data to improve the accuracy of prediction, such as body pose (Ghori et al., 2018; Quintero et al., 2014; Shinmura et al., 2018), head direction (Hasan et al., 2018), gesture (raising arms) (Pool et al., 2019), eye contact (Onkhar et al., 2021), environmental scene context (Cheng et al., 2020; S. Sadeghian et al., 2020). The major drawback of the approaches above is that even though some of the explicit information is encoded, there is no way for the agents to communicate with and provide feedback to each other. There is still a gap in realistic interaction modelling. One reason is that at the current research phase these explicit communications are difficult to be encoded into these models given the high complexity of individual behaviours. To this end, as suggested by many other works and the findings in this paper, eHMIs are a supplementary way to mimic the communications between the automation systems and human road users, in order to establish effective and unambiguous understanding. Hence, it is meaningful to take eHMIs into consideration when designing the automation systems for interaction modelling.

2.5 Conclusion

This paper discussed the issues of interaction between AV and VRUs in shared spaces, i.e., an AV lacks a way to communicate the VRUs when they want to reach an agreement. To find a solution to these issues, we focused on the communication methods between manual driving vehicles and VRUs that have been popularized in shared spaces. A questionnaire was used to ask drivers, pedestrians and cyclists about how they would like a driver of a manually driving vehicle to communicate with VRUs in a shared space. From the results, we found that the communication via the body behaviours of the driver, e.g., hand gesture, head nod and eye contact, were expected by the pedestrians and cyclists, and even intended by the driver. These communication methods were especially important when the driver wanted to suggest VRUs to reach an agreement. In other words, some traditional eHMIs, e.g., headlight, horn and brake light, were not often used for communication in this situation. Besides, when the driver wanted to convey some information to help the VRUs obtain situation awareness and perceive risk, the intended/expected communication methods of drivers, pedestrians and cyclists were different. Therefore, we considered that the novel eHMIs are useful to communicate with the VRUs replacing the original drivers in shared spaces, and a low-fidelity eHMI prototype was proposed to meet their various expectations.

In the discussion, we looked forward to the potential effects of eHMIs on the intelligent transportation. We expect that the AVs can promote the formation of a harmonious and mutual trust transportation society through communication with VRUs via the eHMIs. Besides, we expect that the AVs can induce/suggest VRUs to quickly make a unified decision by using the eHMIs. This may indirectly improve the accuracy of AV prediction of VRUs behaviour and reduce the error range of the prediction.

Nevertheless, our current study is limited to only a relatively small number of participants and no on-site experiments with AVs were carried out. However, the results are highly in lines with other recent studies that also seek eHMIs to improve the traffic safety and smoothness in a shared-space setting (Merat et al., 2018) for a trustworthy (Liu et al., 2021) and socially acceptable traffic climate (S. Sadeghian et al., 2020; Tabone et al., 2021). In addition, our study is dedicated to shared spaces in general, and we hope that this preliminary study can pave the road to more in-depth research on analyzing autonomous driving in shared spaces.

In future, we would like to further propose design guidelines for designing eHMIs from the perspective of VRUs, and establish an evaluation metric for AV-VRU interaction in shared spaces. To achieve this goal, the AV-VRU interaction model and the trust process of VRUs in AV will be discussed based on a cognitive-decision-behaviour model of VRUs proposed in (Liu et al., 2020, 2021). Furthermore, we would like to realize the AV-VRU communication and the high-precision prediction of VRUs' behaviours based on the interaction model. Also, the communication methods for interactions between the AVs and the drivers in the manually driving vehicles also should be designed. Moreover, in the future work, communications between multiple AVs and multiple VRUs should be considered as well, not only the interaction between single AV and VRU. The visualisation of virtual information can also be realized via augmented reality, which also allows VRUs to communicate their virtual paths (Kamalasanan & Sester, 2020). In this way, a virtual infrastructure can be created, which potentially allows users to fall back to established rules. As a matter of fact, such (potentially highly dynamic) virtual infrastructures have to be investigated further in real world scenarios.

CHAPTER 3. Drivers' Preconceptions of Automated Vehicles in a Bottleneck Scenario

Abstract

This study investigated drivers' preconceived notions about manoeuvres of Automated Vehicles (AVs) compared to manually driven vehicles (MVs) using a pseudo-coupled driving simulator. The simulator displayed a message indicating the state of approaching vehicles (AV/MV) in a bottleneck scenario, while participants were informed that the MV was controlled by an experimenter using another simulator, despite all trials having the same preprogrammed behaviours. Results showed that the types of AV/MV did not impact participants' subjective responses. Communication through kinematic cues of the AV/MV was effective, with higher perceived safety, comprehension, and trust reported for approaching vehicles that yielded with an offset away from participants. Perceived safety and trust of the AV were also higher for trials with a light-band external Human Machine Interface (eHMI). This study highlights the value of both explicit and implicit cues for the communication of AVs with other drivers.

Keywords: AV-MV communication; AV behaviour; Implicit communication; eHMI; Bottleneck Road.

3.1 Introduction

In the foreseeable future, it is anticipated that SAE Level 4/5 Automated Vehicles (AVs) (SAE International, 2021) will be integrated within our urban areas, interacting with other manually driven vehicles (MVs). As a result, we will encounter mixed traffic scenarios where AVs and human road users (i.e., MVs, pedestrians, and cyclists) will have to interact with each other on the road (see Figure 3.1). For these interactions to be safe and seamless, it is crucial to understand how drivers of MVs would behave when encountering AVs versus MVs. Since AVs will not be controlled by humans, they may also need to communicate their intention to other road users, when interacting in shared space, especially if both actors are intending to occupy the same road space as a result of their movement (Markkula et al., 2020).

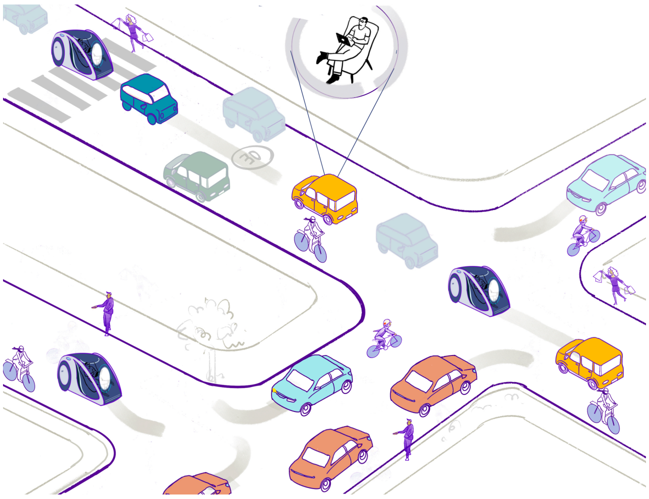

Figure 3.1. A mixed traffic setting, including AVs in urban roads.

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Recent studies have demonstrated that the ability of human road users to interpret the intentions of vehicles is heavily influenced by implicit longitudinal and lateral cues. Specifically, longitudinal cues include changes in speed, deceleration rate, and stopping distance (Imbsweiler, Stoll, et al., 2018; Y. M. Lee et al., 2021; Miller, Koniakowsky, et al., 2022; Rettenmaier et al., 2021; Rettenmaier & Bengler, 2021; Weinreuter et al., 2019), while lateral cues include time and direction of lateral movements (Miller, Leitner, et al., 2022; Rettenmaier et al., 2021). Recent studies have also shown that communication via external human-machine interfaces (eHMIs) can provide information about an AV's yielding intentions, improving drivers' confidence to make faster crossing decisions (Papakostopoulos et al., 2021), and increasing their subjective perceived safety and acceptance of AVs (Avsar et al., 2021). This is particularly true for scenarios which need road users to cooperate with each other to negotiate the right-of-way. Examples of externally presented visual messages, mostly used to study AV interaction with Vulnerable Road Users (VRUs) such as pedestrians, include different types of lighting (Rettenmaier et al., 2019; Schmider et al., 2010), text (Liu et al., 2021; Nissan, 2015), symbols (Rettenmaier, Schulze, et al., 2020), or anthropomorphic signals (Dey, van Vastenhoven, et al., 2021) on the vehicle, or projections on the road (Dey, van Vastenhoven, et al., 2021; Rettenmaier et al., 2019). Auditory signals such as voice, horn, engine sound (Vinkhuyzen & Cefkin, 2016) and verbal messages (Dey et al., 2020) have also been used to communicate the AV's intention. Rettenmaier et. al., (2020) (Rettenmaier, Albers, et al., 2020) reported that an eHMI deployed on the AV's bumper increased traffic efficiency on bottleneck roads. However, to date, compared to the extensive focus on eHMIs for AV-VRU interactions, little is known about the use of such interfaces for drivers of MVs, especially for more ambiguous scenarios which require communication and cooperation between the AV and MV.

(Dey, van Vastenhoven, et al., 2021)reported that eHMIs are less effective in resolving ambiguities for vehicles travelling at higher speeds. Thus, whether the value seen for eHMIs in AV-VRU communication is the same as that required for AV-MV communication is currently unknown.

Automated vehicles have the potential to significantly enhance driver and road safety, and reduce crashes and injuries (NHTSA, 2023). However, integrating these vehicles into our current traffic environment, and introducing them to other road users presents a challenge, particularly in ambiguous situations with uncertain right-of-way scenarios, such as bottleneck roads, unmarked intersections, or residential junctions without traffic lights (Imbsweiler et al., 2019). For scenarios where traffic is moving at a slow pace, or where the right-of-way is ambiguous, human road users sometimes make use of explicit signals from drivers, such as hand gestures, head motions, or flashing lights of the vehicle (Rasouli et al., 2017).But this can be a problem for higher level AVs which do not currently have any means of communicating intent (Nuñez Velasco et al., 2021; Rasouli et al., 2017) Recent studies have also shown that more implicit forms of communication by the AV, such as a slight lateral deviation or pitching of the vehicle are useful for illustrating yielding intention (Miller, Leitner, et al., 2022; Quante, 2023; Rettenmaier et al., 2021).

It has been argued that once a vehicle is identified as being automated, other road users may experience some confusion, demonstrate hesitancy, or even take advantage of the AV, which does not yet behave according to local and social norms of the road (Färber, 2016; Moore et al., 2019). Studies have reported that participants had a greater intention to bully AVs than to bully other human drivers if driverless vehicles are programmed to follow the law (Best, 2016; P. Liu et al., 2020). However, a Wizard of Oz study found that there was little difference in pedestrians' decision-making time, when comparing their interactions between automated and conventional vehicles (Moore et al., 2019).

To date, a few studies have been conducted to investigate driver behaviour and communication strategies between AVs and MVs at bottleneck roads. These include driving simulator studies (Avsar et al., 2021; Rettenmaier, Albers, et al., 2020), video-based online surveys (Li, et al., 2023) and field tests (Papakostopoulos et al., 2021). Regarding vehicle kinematics, one-step and two-step deceleration, and driving to the edge of the road have been used to demonstrate a vehicle's yielding behaviour, while maintaining speed and acceleration, and driving to the centre of the road tend to indicate a vehicle's non-yielding behaviour efficiency (Miller, Leitner, et al., 2022; Rettenmaier et al., 2021). Studies have also reported that earlier braking by an approaching vehicle can reduce efficiency losses caused by unnecessary braking manoeuvres (Rettenmaier & Bengler, 2021), while lateral offset (driving to the edge of the road) increases traffic safety and efficiency (Miller, Leitner, et al., 2022; Rettenmaier et al., 2021).

Based on these studies, the aim of the current experiment was to address some of the research gaps which remain in this context. In particular, we wanted to investigate if drivers' subjective feelings about an approaching vehicle are based on its kinematic behaviour, or whether its identity (i.e., whether it is labelled as an AV or MV) influences this subjective response. To understand how yielding and lateral deviation affect subjective feelings, the approaching vehicles displayed two yielding behaviours and two non-yielding behaviours combined with different types of lateral deviation. The following research questions were addressed:

1. Do drivers have preconceived ideas about an AV's driving behaviour when interacting with an AV at a bottleneck road?

2. How does the AV's behaviour influence human drivers' subjective feelings?

3. How does an eHMI on AVs influence human drivers' subjective feelings?

3.2 Methods

3.2.1 Participants

Following approval from the University of Leeds Ethics board (Ref: LTTRAN-151), a total of 40 participants (12 female, 28 male) with a mean age of 34.65 years (SD = 14.81; range = 21-79) were recruited to take part in this experiment. The requirement for participation was the possession of a UK driver's license for at least one year. The average driving experience of participants was 12 years (SD = 12.61) and 8506.25 miles per year (SD = 7473.01). The study invitation was distributed via mailing lists at university sampling pools. Participants were compensated £15 for their time.

3.2.2 Apparatus

This experiment was conducted using a fixed-based coupled simulator at University of Leeds (see Figure 3.2), which provided a controlled and safe environment for investigating driving behaviours. Each simulator had a 49-inch 32:9 (3840 x 1080 pixels) monitor, a sliding seat, and a steering wheel with buttons, used to start the trials. The accelerator and brake pedals were placed on a stable Next Level Racing® Wheel Stand DD. The scenario and the vehicle behaviours, including engine sound were programmed on Simulator3, an in-house developed software. A black opaque curtain was used to separate the participant and the experimenter, and they were asked not to talk with each other during the study.

The participants were informed that their driving simulator was connected to the experimenter's driving simulator (coupled), so they would drive in the same virtual environment. The experimenter used a webcam to monitor the participant. For the MV trials, the experimenter pretended to drive by pressing the gas/brake pedals, creating the right sounds to trick participants into believing that the experimenter was controlling the approaching vehicles (see below for further details).

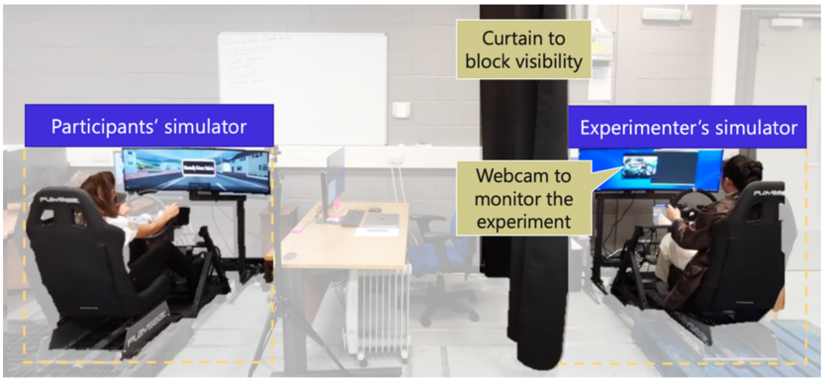

Figure 3.2. Coupled (pseudo-linked) driving simulators, showing the participant and experimenter, blocked by a curtain.

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3.2.3 Experimental design and scenarios

For this study, we focused on a bottleneck road, an ambiguous driving scenario which needs human drivers to negotiate with each other as they try to pass through a single lane, created by parked cars in a two-lane urban road. Drivers are therefore required to negotiate the right-of-way through the bottleneck.

A within-subjects design was used, where all participants experienced 32 trials (presented randomly) involving three independent variables as follows (Table 3.1).

i. Type of approaching vehicle (AV/MV).
ii. Approaching vehicle's kinematic behaviour (Yielding without offset, Yielding with "away offset" / Non-yielding without offset, Non-yielding with "towards offset").
iii. eHMI status (present/absent).

Table 3.1. Experimental Design - Number of trials in each condition.

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Approaching vehicle's type	Approaching vehicle's kinematics	eHMI status	No. of trials

Automated Vehicle (AV)	Yielding without offset	present	2
	Yielding with "away offset"	present	2
	Yielding without offset	absent	2
	Yielding with "away offset"	absent	2
	Non-yielding without offset	N/A	4
	Non-yielding with "towards offset"	N/A	4
Manually Driven Vehicle (MV)	Yielding without offset	absent	4
	Yielding with "away offset"	absent	4
	Non-yielding without offset	N/A	4
	Non-yielding with "towards offset"	N/A	4

3.2.4 Type of approaching vehicle

A message was presented on the driving scene at the start of each trial to inform drivers whether they would encounter an Automated or Manually Driven vehicle (see Figure 3.3), although as outlined, the behaviour of the vehicle was controlled by the software, for all trials.

Figure 3.3. The tag shown on the participant's monitor at the start of each trial, which stated whether the approaching vehicle was an AV or MV.

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3.2.5 Vehicle kinematics

As shown in and Figure 3.4 and Figure 3.5, at the start of the trial, the ego and approaching vehicle were positioned 50m away from the bottleneck. The ego vehicle was placed at the centre of the lane at the start of the trial, while the approaching vehicle was 1.25m from the edge of the road, to allow its easy detection by the participants. Both vehicles' initial speed was 15 mph (ca. 6.71m/s). The participant pressed a button on the steering wheel to begin a trial. The approaching vehicle then began travelling when the ego vehicle was 5m away. For the yielding without offset conditions, the approaching vehicle decelerated at a constant rate, when it was 30m from the bottleneck, stopping when it was 10m away from the bottleneck. In the yielding with 'away offset' conditions, the approaching vehicle deviated away from its initial lateral position and towards the ego vehicle, by 1m, during this linear deceleration (see Figure 3.4). However, if the participant decided not to pass the bottleneck, the approaching vehicle drove through the bottleneck after 5 s.

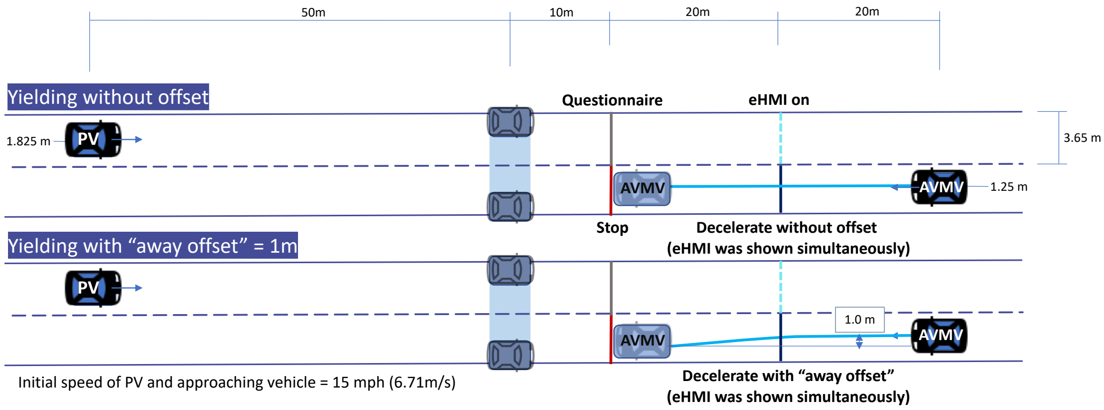

Figure 3.4. Approaching vehicle's yielding behaviours.

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In the non-yielding without offset trials, the approaching vehicle maintained its speed and started to steer to the middle of the bottleneck, when it was 30m from the bottleneck. In the non-yielding with "towards offset" conditions, the approaching vehicle maintained its speed and deviated an additional of 0.6m to the right (see Figure 3.5).

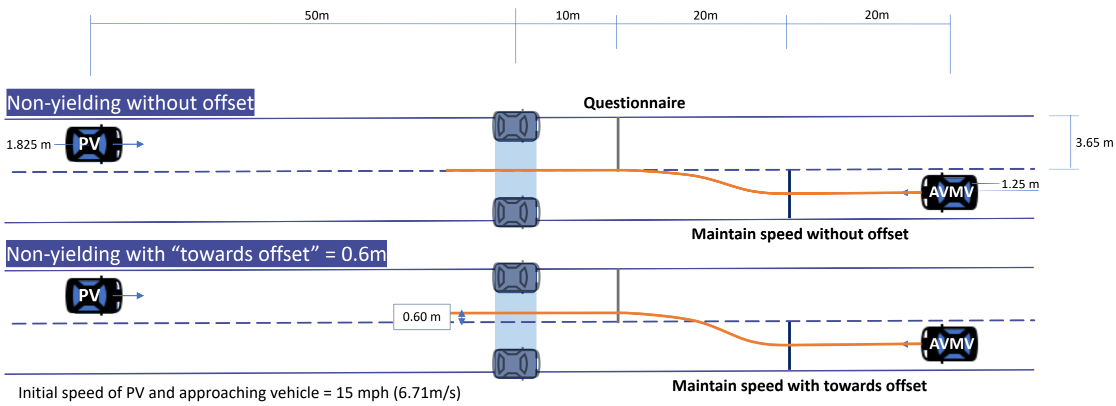

Figure 3.5 Approaching vehicle's non-yielding behaviours.

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3.2.6 External Human-Machine Interface (eHMI)

In this study, a cyan light-band, located at the bottom of the approaching vehicle's windshield, was used to indicate the AV's intention to yield, which could improve the MV driver's comprehension of the AV's behaviour [12], [32], as depicted in Figure 3.6. Participants were told the meaning of the eHMI before the experiment.

The eHMI was presented in conjunction with the AV's deceleration, which was 30m before the bottleneck for both types of yielding trials.

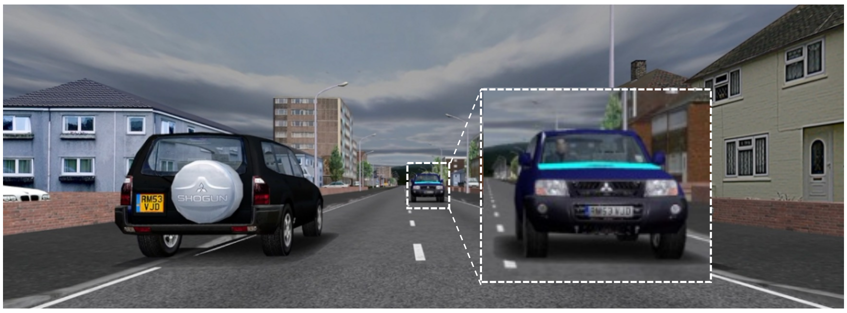

Figure 3.6. The eHMI presented for some of the yielding trials.

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3.2.7 Post-trial ratings

After each trial, participants saw a short set of questions on the driving scene (see Figure 3.7), and were asked to use a 5-point Likert scale: 1 "strongly disagree"- 5 "strongly agree", to rate their trust, comprehension and feelings of safety about the approaching vehicle/eHMI. Participants provided a verbal response for each question, which was manually recorded by the experimenter. After answering the questionnaire, participants pressed the button on the steering wheel to start the next trial.

3.2.8 Procedure

Participants received a participation information sheet by email around 48 hours prior to the experiment. Upon arrival at the lab, they completed a demographic survey and a practice session to familiarise themselves with the simulator and the experimental setup. Participants then began the experiment when they were ready, interacting with the approaching vehicle. For each trial, they were asked to decide whether they could pass through the bottleneck or yield for the approaching vehicle. If participants did not pass the bottleneck for over 5 seconds after the approaching vehicle had yielded, the approaching vehicle would start to drive and pass through the bottleneck. Each trial ended automatically, 10 m after drivers passed the bottleneck. A 5-point Likert Scale questionnaire measuring feelings of safety, comprehensibility, and trust towards the approaching vehicle was completed after each trial (Figure 3.7). Participants took part in a short interview after the last trial and were then paid and thanked for their participation. The entire study took approximately 60 minutes to complete.

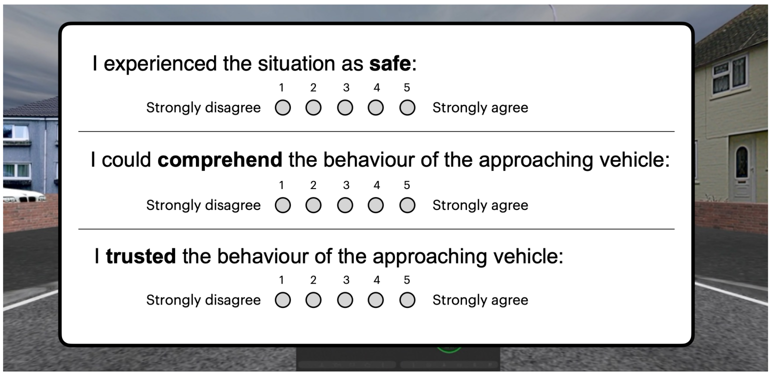

Figure 3.7. The post-trial questionnaire used after each trial.

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3.3 Results

The data was prepared using MATLAB R2022a and MS Excel 16.72, and SPSS 25 was used for the statistical analysis. Given the differences in kinematic patterns of the yielding and non-yielding trials, two separate analyses of variance were conducted to investigate the impact of the independent variables, on participants' subjective responses. For yielding trials, a 3 x 2 repeated measures ANOVA was conducted to examine the impact of the types of approaching vehicle (AV with eHMI, AV without eHMI, MV), and behaviours (yielding without offset, yielding with "away offset") on subjective responses. For non-yielding trials, a 2 x 2 repeated measures ANOVA was conducted to evaluate the effect of the types of approaching vehicle (AV without eHMI, MV), and behaviours (non-yielding without offset, non-yielding with "towards offset") on subjective ratings, see Table 3.2. The repeated measures ANOVA was used to do the analysis considering its robustness against a violation of the normal distribution (Cohen, 2013). If sphericity was violated (Mauchly's test: $p < .001$), Greenhouse Geisser corrections were used for degrees of freedom. The alpha level was .05. Cohen's d was calculated as a measure of the effect size (Kaleefathullah et al., 2020). Partial eta squared (ηp^2) are reported, where .01 is considered to be a small effect, .06 is a medium effect, and .14 indicates a large effect (Kaleefathullah et al., 2020). Only the results from the post-trial questionnaire are included in this paper.

Table 3.2. Repeated measures ANOVA of participants' subjective feelings across vehicle types, behaviours and eHMI presence (N=40), * $p < .05$, ** $p < .01$, *** $p < .001$.

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	F	df	p	ηp^2	F	df	p	ηp^2
	Yield				Non-yield			

"I experienced the situation as safe"								
Vehicle types	15.054	2 (78)	**< .001*** **	.279.	.526	1 (39)	.957	.000
Behaviours	45.169	1 (39)	**< .001*** **	.537	.003	1 (39)	.473	.013
Vehicle types * behaviours	2.318	2 (78)	.105	.056	1.760	1 (39)	.192	.043
"I could comprehend the behaviour of the approaching vehicle"								
Vehicle types	32.989	2 (78)	**< .001*** **	.458	.002	1 (39)	.963	.000
Behaviours	70.778	1 (39)	**< .001*** **	.645	6.706	1 (39)	**.013** **	.147
Vehicle types * behaviours	13.816	2 (78)	**< .001*** **	.262	.393	1 (39)	.534	.010
"I trusted the behaviour of the approaching vehicle"								
Vehicle types	22.905	2 (78)	**< .001*** **	.370	1.183	1 (39)	.283	.029
Behaviours	69.454	1 (39)	**< .001*** **	.623	.228	1 (39)	.636	.006
Vehicle types * behaviours	8.028	2 (78)	**< .001*** **	.171	.072	1 (39)	.789	.002

3.3.1 Perceived safety of the situation

For the yielding trials, there was a significant main effect of vehicle type, whereby the AVs with eHMI were rated safer than AVs without eHMI ($p < .001$). No significant difference was found between AV without eHMI and MV. There was also a significant main effect of approaching vehicle's yielding behaviour on responses, whereby approaching vehicles with 'away offset' were rated safer than those without an offset ($p < .001$). There was no significant interaction. The analysis showed no significant main effects or interactions for the non-yielding trials (see Figure 3.8 and Table 3.2).

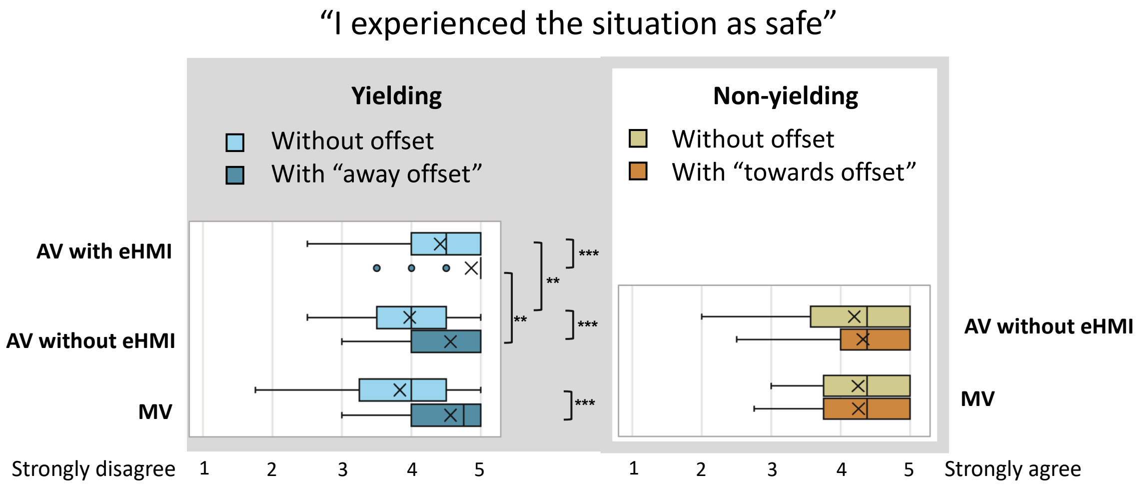

Figure 3.8. Participants' perceived safety of the approaching vehicle (N=40).

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3.3.2 Comprehension of approaching vehicle's behaviour

For yielding trials, results showed a significant main effect of vehicle type, whereby the AVs with eHMI were rated more comprehensible, than AVs without eHMI ($p < .001$). No significant difference was found between the AV without eHMI and MV trials. There was a significant main effect of approaching vehicle's yielding behaviours, whereby the behaviour of the approaching vehicles yielding with 'away offset' were rated as more comprehensible than those without offset (p < .001). There was also a significant interaction effect, with the AVs with eHMI being rated as more comprehensible when they yielded without an "away offset" (p < .001).

For non-yielding trials, results showed there was no significant main effect of vehicle type, but there was a significant main effect for non-yielding behaviours. Here, approaching vehicles with 'towards offset' were rated more comprehensible than without offset (.013). There was no significant interaction effect, shown in Figure 3.9 and Table 3.2.

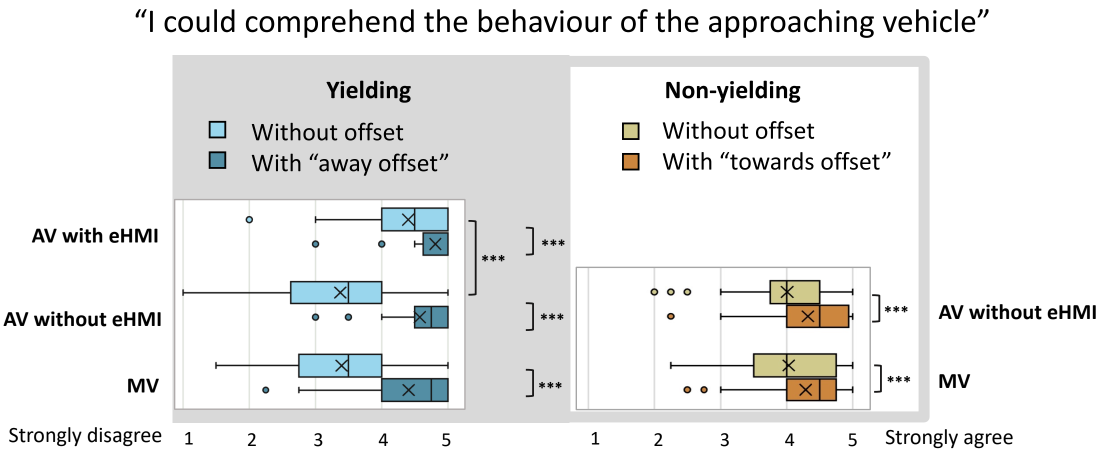

Figure 3.9. Participants' comprehension of the approaching vehicle's behaviours (N=40). Reproduced from Li et al. (2023), "Do Drivers have Preconceived Ideas about an Automated Vehicle's Driving Behaviour," in *Proceedings of AutomotiveUI 2023*, ACM, pp. 291–299. © 2023 ACM. Used by permission.

3.3.3 Trust in approaching vehicle's behaviour

For yielding trials, there was a significant main effect of vehicle type, with higher trust ratings given for AVs with eHMIs, than those without an eHMI (p < .001). No significant difference was found between the AV without an eHMI and the MV. There was also a significant main effect of approaching vehicle's yielding behaviours, with the approaching vehicles that displayed an 'away offset' being rated as higher for trust, compared to those without an offset (p < .001). There was a significant interaction between vehicle type and kinematic behaviour. Even though yielding AVs with eHMI had higher trust ratings than AVs without eHMI (Applicable to two yielding behaviours, i.e., yielded without offset and with "away offset"), the presence of the eHMI improved drivers' trust more when the AV yielded without the "away offset". For non-yielding trials, there was no significant main effect or interactions, regarding trust ratings (see Figure 3.10and Table 3.2).

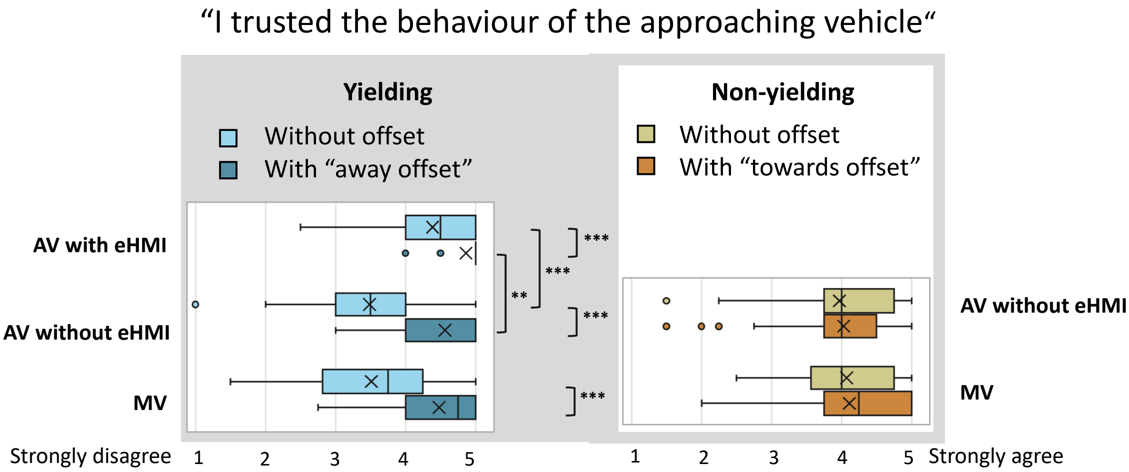

Figure 3.10. Participants' trust in the approaching vehicle's behaviours (N=40).

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3.4 Discussion

This distributed driving simulator study was designed to investigate the effect of the type of approaching vehicle (AV vs MV), its kinematic features (i.e., its longitudinal and lateral behaviours), and the presence of an eHMI, on drivers' subjective feelings during a bottleneck scenario. After each encounter with the approaching vehicle, drivers used a 5-point Likert scale to report on their trust, perceived safety, and comprehension of the approaching vehicle's behaviour. Although the behaviour of the AV and MV was exactly the same, and always controlled by the simulator software, a simple message at the start of each drive was used to lead drivers into believing that the vehicles were controlled by the computer or another driver, respectively.

We found that knowing if a vehicle was automated or manually driven did not affect drives' perceived safety, comprehension and trust. This suggests that drivers' subjective feelings about an approaching vehicle in a bottleneck road are based on its kinematic behaviour, rather than whether it is labelled as a computer- or human-driven vehicle, especially if the two vehicles look exactly the same. This finding is in line with the results of (Miller, Koniakowsky, et al., 2022).

Our participants felt significantly safer and reported a significantly higher comprehension and trust when the approaching vehicles yielded with an "away offset", compared to the yielding without offset trials. This finding supports results from previous studies which report that the addition of lateral movements for a yielding vehicle provides a clear additional cue to other road users, when compared to longitudinal cues alone. This is especially for ambiguous scenarios, such as bottleneck roads (Miller, Leitner, et al., 2022; Rettenmaier & Bengler, 2021). Our study also showed that the presence of a "towards offset" improved drivers' comprehension of the vehicles' behaviour in non-yielding conditions. Future studies should explore the further use of such lateral deviations for communication of AV intention, in a wider range of scenarios.

In terms of the value of eHMIs, the presence of an eHMI improved drivers' perceived safety and trust of a yielding AV, regardless of whether this was accompanied by an "away offset". However, subjective response for comprehension of the AV with an eHMI was only high during the "no offset" conditions, eHMI did not impact drivers' comprehension of the approaching AV's behaviour when the AV yielded with the "away offset". These results are not line with the results of Rettenmaier & Bengler (2021) (Rettenmaier et al., 2021), who found that participants' comprehension of approaching AVs with an eHMI improved with and without an away offset. Our results suggest that the lateral deviation of the yielding vehicle in isolation was quite powerful in itself, with additional messages from an eHMI possibly causing some confusion about the vehicle's intentions. This result stresses the importance of using intuitive kinematic behaviour for AVs to communicate intention (Y. M. Lee et al., 2021), and confirms these can be a better solution than potentially misleading externally presented messages (Kaleefathullah et al., 2020).

In terms of limitations, this study only focused on evaluating drivers' subjective feelings about the approaching vehicles. Future studies would benefit from investigating how drivers behave in these scenarios, using vehicle metrics, also assessing if objective and subjective responses correlate. Finally, understanding if drivers' perceived safety, comprehension and trust for approaching vehicles is determined by a vehicle's shape or other external features is important, to establish if vehicles that look more like an AV are treated differently to those that look more like conventional vehicles.

CHAPTER 4. Driver Responses to Automated Vehicles in Bottlenecks: Effects of Lateral Offset and eHMI

Abstract

This driving simulator study investigated drivers' responses to an approaching automated or manual vehicle in a bottleneck scenario. Participants were asked to decide whether to pass through the bottleneck, or yield for the approaching vehicle, across numerous trials. Prior to each trial, they were informed whether the approaching vehicle was an automated vehicle (AV) or a manually driven vehicle (MV). Although participants were told that the MV was controlled by the experimenter using a distributed simulator, both vehicles were actually controlled by the system, and behaved in the same way. The kinematics of the approaching vehicle, such as its yielding behaviour (with or without lateral offset), and the presence of external Human Machine Interfaces (eHMIs, AV only) were manipulated. 40 participants took part in this study. Results indicated that participants' subjective responses and behaviours did not differ between the AVs and MVs. The approaching vehicle's lateral offset was seen to be the most influential source of information for participants, followed by information from the eHMI. Participants were more likely to pass through the bottleneck first, and had a shorter decision time, when encountering yielding vehicles with "away offsets", which involved the vehicle moving away from the road centre line. This condition also led to higher perceived safety, comprehension, and trust ratings. Conversely, drivers were more likely to yield and had a shorter decision time when encountering non-yielding vehicles without any lateral offset. The lateral offset of non-yielding vehicles did not have an impact on drivers' perceived safety and trust. However, non-yielding with "towards offsets" (towards the centre line) led to a higher comprehension score. Participants also passed through the bottleneck significantly more often and provided higher ratings for perceived safety and trust when the yielding vehicles presented an eHMI. This was regardless of lateral deviation. However, the eHMI only led to a higher rating of comprehension when the AV yielded without an offset. This study shows the value of using lateral offsets to communicate vehicles' intentions in bottleneck scenarios. While the eHMI could enhance the driver's understanding of the yielding AV, some participants also noted that it introduced uncertainty. Therefore, the need for eHMI should be further discussed.

Keywords: AV-MV communication; AV behaviour; Implicit communication; eHMI; Bottleneck Scenario.

4.1 Introduction

Interaction occurs when at least two road users intend to occupy the same road space at the same time (Markkula et al., 2020). Conflicts between two or more road users often happen due to misinterpretation of others' driving intentions, behaviour, and communication (Ameen et al., 2021), which can be precursors to accidents. Conflicts could also lead to traffic congestion, impacting transportation efficiency and safety, particularly in driving scenarios with an unclear right-of-way (Gutiérrez-Moreno et al., 2022). To prevent conflicts in ambiguous road settings that have no formal traffic rules, vehicles must communicate their intentions and negotiate the right of way (Imbsweiler et al., 2018). One example is the bottleneck scenario, which requires human drivers to negotiate with each other as they attempt to pass through a single lane caused by cars parked on both sides of a two-lane urban road (Miller, Leitner, et al., 2022; Rettenmaier et al., 2019; Weinreuter et al., 2019).

In the foreseeable future, automated vehicles (AVs) will be integrated within our urban areas, interacting with other road users, such as manually driven vehicles (MVs), pedestrians, cyclists, and powered two-wheelers. Indeed, trials of these vehicles are currently taking place in North America and China (Hawkins, 2023; McKinsey, 2023). Hawkins (2023) underlined the necessity of effectively communicating an AV's status and intentions to prevent misunderstandings between road users. This is particularly vital for higher-level AVs such as those at SAE Level 4/5 , which are not controlled by a human driver. Based on the communication between traditional vehicles and current AV technologies, Färber (2016) concluded that identifying a vehicle as an AV may lead to confusion and hesitancy among other road users, some may even exploit the AV's behaviour, given that AVs may not yet adhere to the established local and social driving customs. Studies found that human drivers drive more aggressively and are less willing to yield before AVs compared to manually driven vehicles, which could result in a more unsafe driving environment (Jiang et al., 2025; Y.-C. Lee et al., 2021; P. Liu, 2024; P. Liu et al., 2020; Youssef et al., 2024). Further research by (P. Liu, 2024) highlights related phenomena, including increased road rage and aggression from human drivers toward AVs, the exploitation of AVs' cautious behaviour, and negative peer influences of AVs on human driver behaviour. A questionnaire study by P. Liu et al. (2020) found that participants tend to display more aggressive behaviour towards AVs, compared to human drivers. However, a Wizard of Oz study showed minimal variance in the time pedestrians took to make decisions when interacting with AVs compared to conventional vehicles at a crosswalk. Specifically, pedestrians were no more likely to hesitate before crossing in front of the Ghostdriver car than conventional cars, suggesting that they rely primarily on vehicle motion as a crossing cue (Moore et al., 2019). However, it is not yet known whether drivers have a different perception and behave differently when encountering AVs compared to MVs, and how they do so.

To date, a few studies have been conducted to investigate driver behaviours and communication strategies between AVs and MVs. Vehicle kinematic patterns including one-step and two-step deceleration behaviour, as well as driving to the edge of the road, have been used to demonstrate a vehicle's yielding behaviour during interactions at bottleneck scenarios. Conversely, maintaining speed and acceleration, and driving to the centre of the road tends to indicate a vehicle's non-yielding behaviour. Driving simulator studies have reported that lateral offset could increase traffic efficiency by reducing an MV's passing time through a bottleneck, as these were interpreted as more distinct compared to longitudinal movements. In addition, providing a lateral offset has the potential to increase traffic safety, and decrease the crash rate when the approaching vehicle insists on the right-of-way (Miller, Leitner, et al., 2022; Rettenmaier et al., 2021). However, the passing time through the bottleneck used in previous studies does not accurately measure drivers' decision-making times before reaching the bottleneck. No studies have explored the exact time point at which drivers make a yielding or passing decision before the bottleneck. In this study, a more precise metric will be used to determine when participants decide to pass or yield in bottleneck scenarios. This will allow for a more detailed exploration of the effects of longitudinal and lateral offsets on AV-MV communication in bottleneck scenarios.

External human-machine interfaces (eHMIs) can provide explicit information about an AV's intentions in ambiguous right-of-way scenarios. For example, Rettenmaier et al., 2019 reported that an eHMI deployed on an AV's bumper increased traffic efficiency in bottleneck scenarios. A video-based online study also reported that the extra information offered by HMIs on AVs improves MV drivers' subjective feelings and builds trust and acceptance of AVs in bottleneck scenarios (Li et al., 2023). Additionally, a field study by Papakostopoulos et al. (2021) demonstrated that eHMIs, such as externally presented lights, can provide information about an AV's yielding intentions. They found that the eHMI enhanced drivers' confidence in making crossing decisions at junction roads. Similarly, a driving simulator study (Avsar et al., 2021) reported that a novel light-band eHMI (Schieben et al., 2019) increased MV drivers' subjective perceived safety and acceptance of AVs in a T-junction. HMI signalling the AV's deceleration was reported to increase the prosocial perception of the AV (Şahin İppoliti et al., 2023), while research has also found that displaying eHMI to human drivers earlier was rated as better for improving traffic efficiency compared to showing it later (Rettenmaier, Albers, et al., 2020). These eHMIs were found to be particularly valuable for scenarios requiring road users to cooperate to negotiate the right-of-way. Rettenmaier & Bengler (2021) reported that combining eHMI and lateral offset was the most effective in reducing human drivers' passing times ahead of an AV in a bottleneck scenario. Furthermore, eHMI can be effective and safer in situations where a vehicle cannot move laterally towards the road's centre, and can be used to provide a salient message (Rettenmaier, Albers, et al., 2020; Rettenmaier et al., 2021). However, to date, there has been little investigation of the impact of lateral offset and eHMIs on drivers' exact decision time before the bottleneck.

Drawing from these studies, this research aims to determine whether drivers' performance in response to an approaching vehicle in a bottleneck scenario is dictated by its movement patterns, or whether its identity (i.e., whether it is labelled as an AV or MV) influences driver behaviour. To examine the impact of different vehicular behaviours on drivers' performance, the approaching vehicles displayed two yielding behaviours and two non-yielding behaviours, combined with different types of lateral deviation, and the presence / absence of an eHMI. We posed the following research inquiries:

1. Does labelling the approaching vehicle as an AV or MV affect driver behaviour?

2. How does the AV's lateral offset influence human drivers' decision-making and driving performance?

3. How does the inclusion of an eHMI on the AV influence human drivers' decision-making and driving performance?

4.2 Methods

4.2.1 Participants

After obtaining approval from the University of Leeds Ethics Board (Ref: LTTRAN-151), this experiment recruited a total of 40 participants (12 female, 28 male) with a mean age of 34.65 years (SD = 14.81; range = 21-79). Participants were required to hold a valid UK driver's license for at least one year. On average, participants had 12 years of driving experience (SD = 12.61; range = 21-79) and drove approximately 8506.25 miles per year (SD = 7473.01). The study recruitment was conducted through university mailing lists of participants who had signed up to take part in simulator studies. Participants received £15 compensation for their participation in this experiment.

4.2.2 Apparatus

This study utilized a fixed-based driving simulator located at the University of Leeds, as illustrated in Figure 4.1. The setup displayed offered a controlled and secure setting for examining driving behaviours. Each simulator featured a 49-inch 32:9 monitor with a resolution of 3840 x 1080 pixels, a movable seat, and a steering wheel equipped with buttons for initiating trials. The accelerator and brake pedals were positioned on a stable Next Level Racing® Wheel Stand DD. The Simulator3 proprietary software, developed in-house, was used to program the scenario and vehicle behaviours, including engine sounds. A black opaque curtain separated the participant from the experimenter, who refrained from communicating during the study. Participants were informed that their simulator was synchronized with the experimenter's, allowing them to drive within the same virtual environment. The experimenter monitored participants via a webcam. During the MV trials, the experimenter simulated driving by operating the gas and brake pedals, creating authentic sounds to deceive participants into believing they were controlling the approaching vehicles. Further details are provided below.

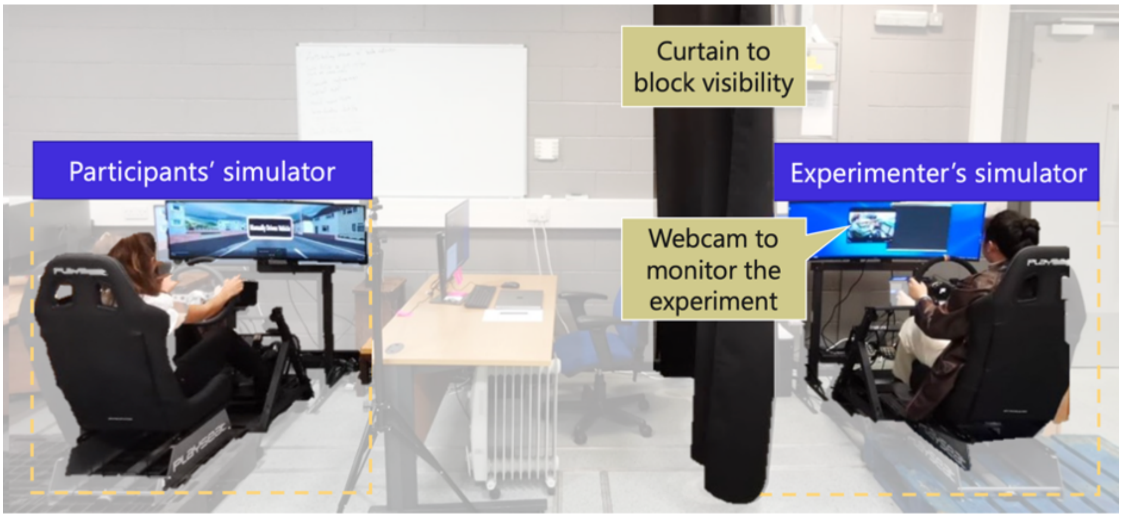

Figure 4.1 Coupled driving simulators, showing the participant and experimenter, blocked by a curtain.

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4.2.3 Experimental design and scenarios

For this study, a bottleneck scenario was chosen as the interaction scenario. A within-subjects design was employed, whereby all participants underwent 32 trials (randomly presented by using the "RAND" function in Microsoft Excel). These trials involved three independent variables: the type of approaching vehicle, which included automated vehicles (AV) and manually driven vehicles (MV); the approaching vehicle's kinematic behaviour, which encompassed yielding without offset, yielding with an "away offset" (vehicle moves away from the road centre line), non-yielding without offset, and non-yielding with a "towards offset" (vehicle moves towards the road centre line); and, for AVs only, the eHMI status, which was either present or absent. Each trial incorporated different combinations of these variables to assess their impact on the participants' responses in the bottleneck scenario. Detailed information on these variables can be found in Table 4.1.

Table 4.1 Experimental Design - Number of trials in each condition.

Approaching vehicle's type	Approaching vehicle's kinematics	Presence of eHMI	No. of trials
Automated Vehicle (AV)	Yielding without offset	eHMI	2
	Yielding with "away offset"	eHMI	2
	Yielding without offset	No eHMI	2
	Yielding with "away offset"	No eHMI	2
	Non-yielding without offset	n/a	4
	Non-yielding with "towards offset"	n/a	4
Manually Driven Vehicle (MV)	Yielding without offset	No eHMI	4
	Yielding with "away offset"	No eHMI	4
	Non-yielding without offset	n/a	4
	Non-yielding with "towards offset"	n/a	4

4.2.4 Type of approaching vehicle

At the beginning of each trial, a message appeared in the driving scene to notify participants whether they would encounter an automated or manually driven vehicle (see Figure 4.2). However, as previously mentioned, the vehicle's behaviour was controlled by the software for all trials.

Figure 4.2 The tags shown on the participant's monitor at the start of each trial, which stated whether the approaching vehicle was (a) an AV or (b) an MV.

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4.2.5 Vehicle kinematics

As shown in Figure 4.3 and Figure 4.4, the participant's vehicle (PV) was positioned in the centre of the lane at the beginning of the trial, while the approaching vehicle was situated 1.25 meters from the edge of the road to ensure easy detection by the participants. At the start of the trial, both the PV and the approaching vehicles (AV/MV) were at an equal initial distance to the bottleneck, which was 50 meters away, and were traveling at the same speed of approximately 15 miles per hour (6.71m/s). To initiate a trial, the participant pressed a button on the steering wheel and started to drive. Once the participant had moved 5 metres (i.e. was located 45 metres from the bottleneck), the approach vehicle's movement was initiated, with the timings designed to ensure an interaction occurred.

The approaching vehicle then displayed one of four kinematic behaviours, as outlined below:

i. Yielding without offset: The approaching vehicle maintained a constant rate of deceleration, which started when it was 30 meters from the middle of the bottleneck, coming to a stop when it reached a distance of 10 meters from the bottleneck, see Figure 4.3.

ii. Yielding with "away offset": The approaching vehicle deviated away from its initial lateral position and towards the PV by 1 meter, during its' linear deceleration (see Figure 4.3). However, if the participant decided not to pass the bottleneck, the approaching vehicle drove through the bottleneck after 5 seconds.

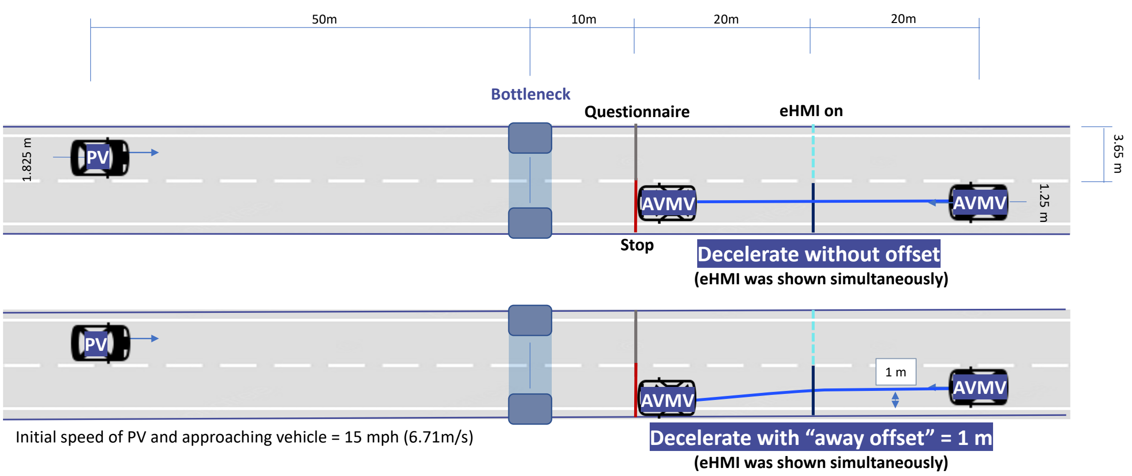


Figure 4.3 Approaching vehicle's yielding behaviours.

iii. Non-yielding without offset: The approaching vehicle maintained its' speed and started to steer to the middle of the bottleneck when it was 30 meters from the bottleneck, see Figure 4.4.

iv. Non-yielding with "towards offset": The approaching vehicle maintained its' speed and started to deviate an additional 0.6 meters to the right when it was 30 meters from the bottleneck (see Figure 4.4).

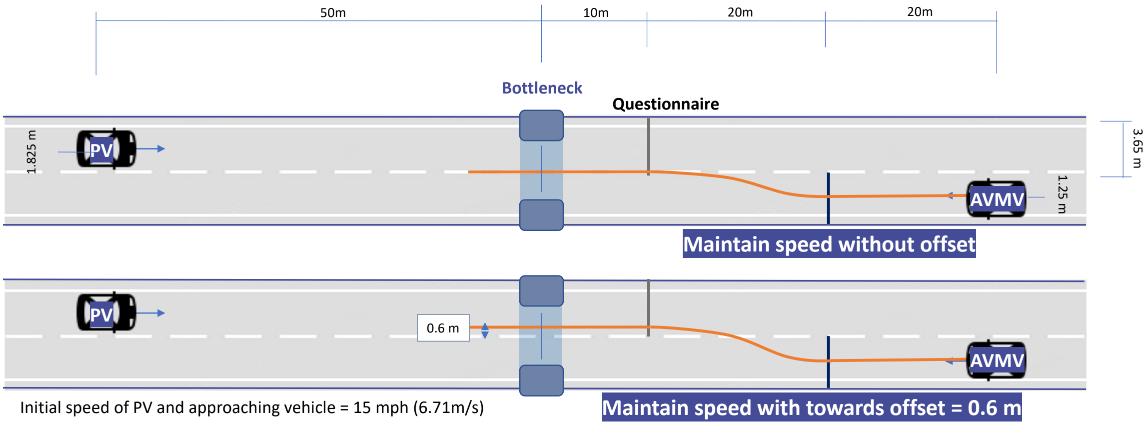
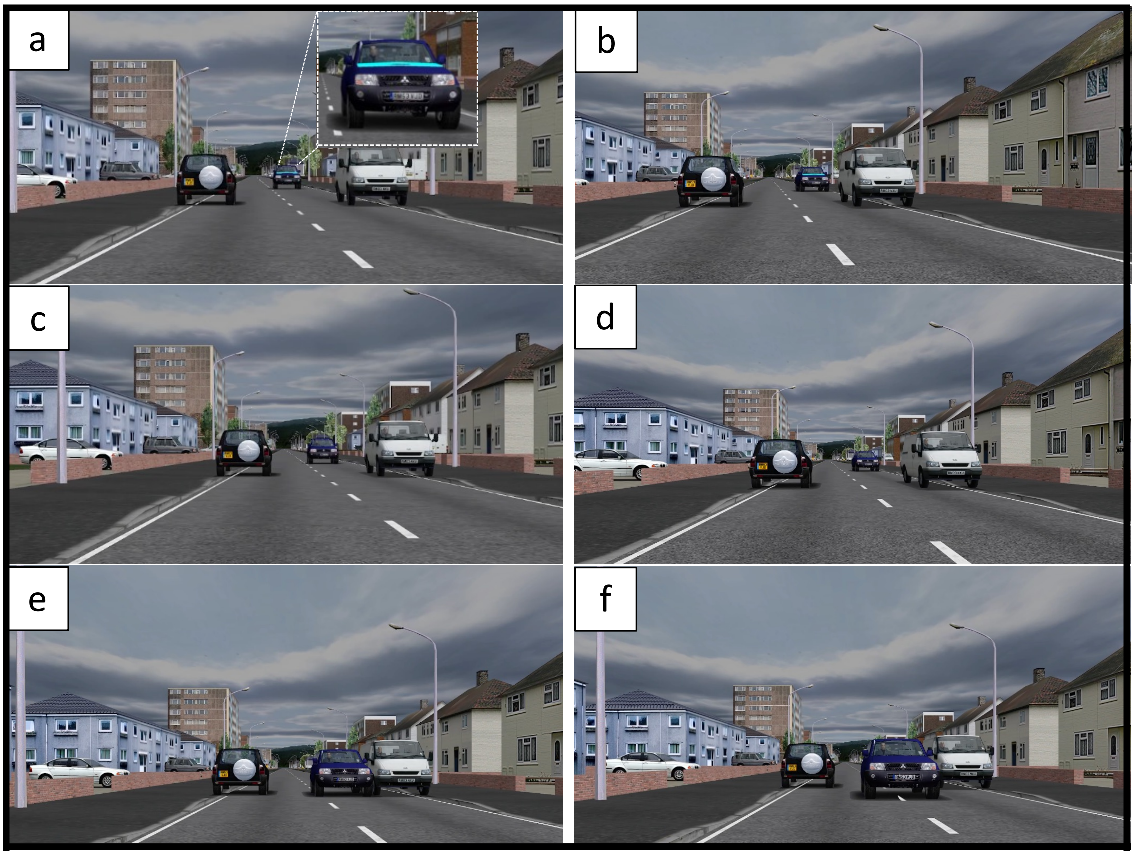


Figure 4.4 Approaching vehicle's non-yielding behaviours.

4.2.6 External Human-Machine Interface (eHMI)

In this study, participants were provided with information about the meaning of the eHMI in the Participant Information sheet. They were told that "*an external human-machine interface (eHMI) - a 360-degree cyan band is deployed on some of the automated vehicles, indicating the yielding intention of the approaching AV*". This 360° cyan lightband has been successfully used to convey yielding intentions across a number of previous studies in the Horizon 2020 EU-Project 'interACT' (Kaup et al., 2019; Markowski, 2020; Schieben et al., 2019). The eHMI was presented in conjunction with the AV's deceleration onset, at 30 meters before the middle of the bottleneck for both yielding conditions (see Figure 4.5).



	Experimental condition		Experimental condition
a	Yield without offset, AV, eHMI	b	Yield with away offset, AV, eHMI
c	Yield without offset, AV/MV	d	Yield with away offset, AV/MV
e	Non-yield without offset, AV/MV	f	Non-yield with towards offset, AV/MV

Figure 4.5 Examples of the experiment condition.

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4.3 Procedure

Participants were provided with a participation information sheet via email approximately 48 hours prior to the experiment. Upon arrival at the laboratory, the experimenter introduced the experiment to participants in detail again, "*You are required to drive through an urban city road which includes a section with parked cars on both sides, allowing only one car to pass at any one time (we call this driving scenario as bottleneck roads). The speed limit on this road is 20mph. On approaching the parked vehicles section with an initial speed of 15mph, you will encounter a vehicle from the opposite side. This vehicle may be controlled by the simulator software (automated vehicle, no human driver in charge with the driving tasks) or manually driven by the experimenter (manually-driven vehicle), At the beginning of each trial, a tag appears on the screen to indicate whether the approaching vehicle* *runs in autonomous mode or is controlled by the experimenter on the distributed simulator*". The participants then completed a demographic survey and engaged in a practice session to acquaint themselves with the simulator and experimental setup. For each experimental trial, participants were told that "*you are required to drive through the bottleneck road with parked cars on both sides, allowing only one car to pass at one time. You can decide whether to yield to the approaching vehicle - brake to allow the approaching vehicle to pass - or yield for the approaching vehicle*". If participants did not pass the bottleneck within 5 seconds after the approaching vehicle had yielded, the approaching vehicle would start to drive and pass through the bottleneck first. Each trial concluded automatically 10 meters after drivers successfully passed through the middle of the bottleneck. Following each trial, participants completed a 5-point Likert scale in relation to the approaching vehicle (see Li et al. (2023)). After completing the final trial, participants took part in a brief interview (see Table 4.2), then, they were compensated and thanked for their participation. The entire study lasted approximately 60 minutes.

Table 4.2 Questions asked in the interview.

ID	Question	Question type
1	What information from the vehicle was important to help with your decision to pass/not pass? The given factors were "speed", "distance", "braking pattern", "offset (vehicle drives to edge or centre)", "knowing the approaching car is an AV or MV".	5-point Likert scale 1 "unimportant" 2 "slightly unimportant" 3 "neutral" 4 "slightly important" 5 "important"
2	Did knowing the approaching car is AV or MV affect your expectation and passing decisions? In what way? /Why not?	Open question
3	Did the eHMI (light-band) have an impact? In what way?/Why not?	Open question
4	During the experiment, was there any other information you would like to have had to decide it was safe to pass?	Open question

4.4 Results

A Generalized Linear Mixed Model (GLMM) was employed to analysethe data, taking into account the repeated measures experiment design, and the non-normally distributed data. GLMM is recommended for analysing both binary responses and longitudinal data and is suitable for dealing with missing data (Rabe-Hesketh & Skrondal, 2010). The effect of lateral offsets, type of approaching vehicles, and the presence of eHMI on participants' decision-making and their decision-making initiation time was investigated. Given the differences in kinematic patterns of the yielding and non-yielding approaching vehicles, separate analyses were conducted to examine the effects of yielding and non-yielding trials on participants' driving performance.

For yielding trials, lateral offsets (without offset / with away offset) and vehicle types (AV with eHMI, AV without eHMI, and MV) were assessed using the percentage of passing decisions and the passing initiation time (PIT). PIT refers to the moment when participants decide to pass through the bottleneck first, specifically indicating the point in time when the participants initiated the last acceleration before reaching the bottleneck.

For non-yielding trials, the effect of lateral offsets (without offset / with towards offset) and vehicle types (AV / MV) on the percentage of yielding decisions and yielding initiation time (YIT) was evaluated. YIT refers to the moment when participants decide to come to a stop before the bottleneck. This metric was used to indicate the point in time when the participants initiated their final deceleration before reaching the bottleneck.

Following the data collection, the experimenter reviewed the recorded videos of each trial to identify any "incorrect decisions". For yielding trials, four specific situations were classified as "incorrect decisions". These were:

i. Did not pass: Participants stopped before the bottleneck, opting to wait for the yielding vehicle to pass first.
ii. Passed too late, resulting in collisions before the bottleneck: Participants had a delayed response, starting their movement when the approaching vehicle had already moved, leading to collisions.
iii. Did not pass and stopped too close to the bottleneck, resulting in a collision.
iv. Collisions after the bottleneck: Participants initially waited for the yielding approaching vehicle and stopped near the bottleneck. However, they subsequently decided to pass the bottleneck, resulting in collisions after passing through the bottleneck.

For non-yielding trials, two specific situations were classified as "incorrect decisions":

i. Stopped too close to the road centre and crashed.
ii. Passed through first and crashed.

The number of trials with "correct" decisions in each condition is shown in Table 4.3. When encountering yielding vehicles, there were 572 trials with passing decisions, 47 trials with non-passing decisions, and 21 trials with collisions. When encountering non-yielding approaching vehicles, there were 556 trials with yielding decisions and 84 trials with non-yielding decisions resulting in collisions.

Table 4.3 The number of trials with correct decisions across approaching vehicle types, behaviours and eHMI.

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	Yield without offset	Yield with away offset	Non-yield without offset	Non-yield with towards offset
	Number of passing		Number of yielding	
AV with eHMI	78 (97.5%)	80 (100%)	/	/
AV without eHMI	64 (80%)	77 (96.3%)	149 (93.1%)	130 (81.3%)
MV	123 (76.9%)	150 (94.4%)	147 (91.9%)	130 (81.3%)
Total	572 (89.3%)		556 (86.9%)	

The next section provides the results of the GLMM analysis.

4.4.1 Percentage of passing decisions when the approaching vehicle yielded

For the yielding trials, 619 trials in total were included in the analysis. 572 trials with passing decisions and 47 trials with non-passing decisions were compared, across vehicle type and lateral offset, using GLMM.

There was a significant main effect of lateral offset (F (1, 61) = 23.44 $p < .001$). Post hoc Bonferroni tests showed that yielding with an "away offset" led participants to pass significantly more often than trials without an offset. There was also a significant main effect of vehicle type (F (2, 613) = 34.05, $p < .001$), whereby the AVs with eHMI led participants to pass significantly more often than AVs without eHMI and MVs. There was no interaction effect (F (2, 613) = .29, .79), (see Figure 4.6).

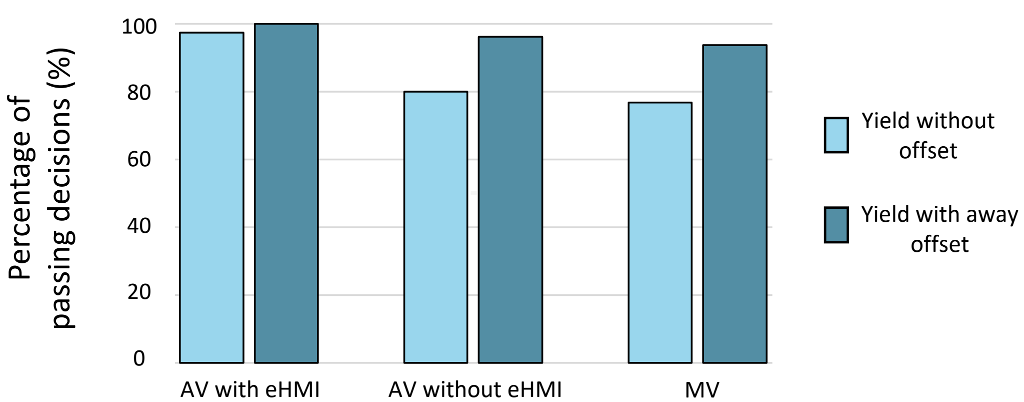

Figure 4.6 Percentage of passing decisions when participants encountered yielding vehicles.

4.4.2 Percentage of yielding decisions when the approaching vehicles did not yield

For non-yielding trials, 640 trials were included in the analysis, which included 556 trials where the participant made a yielding decision and 84 trials with non-yielding decisions.

There was a significant main effect of the approaching vehicle's non-yielding lateral offset (F (1, 636) = 17.74, p < .001) on behaviour. Post hoc Bonferroni results showed that non-yielding without offset resulted in a significantly higher passing percentage than trials with a "towards offset". There was no significant main effect of vehicle type (F (1, 636) = 6.47, .42), and no interaction effect (F (1, 636) = .23, .63), see Figure 4.7.

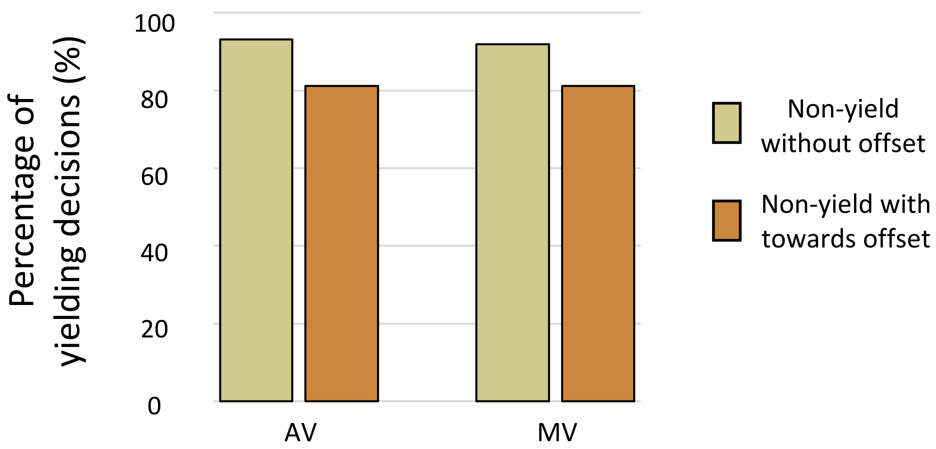

Figure 4.7 Percentage of yielding decisions when the approaching vehicle did not yield.

4.4.3 Passing Initiation Time (PIT)

572 trials were included in the pasting initiation time (PIT) analysis, the trials that "did not pass" and "with collisions" were excluded. There was a significant main effect of approaching vehicle's lateral offset (F (1, 566) = 29.48, p < .001), whereby yielding with an "away offset" (M = 5.15 s, SE = .19) led to significantly shorter PITs than without offset (M = 6.72 s, SE = .23). There was also a significant main effect of vehicle type (F (2, 566) = 6.11, .002), whereby encountering AVs with eHMI (M = 5.27 s, SE = .23) led to significantly shorter PITs than MVs (M = 6.33 s, SE = .21),

but not compared to AVs without eHMI (M = 6.19 s, SE = .30). There was no interaction effect (*F* (2, 566) = .92, .40), see Figure 4.9.

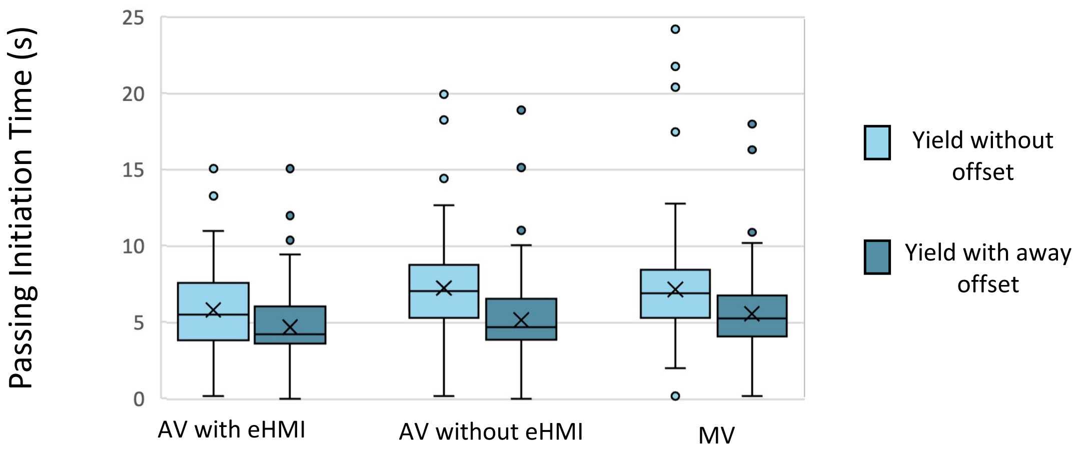

Figure 4.8 Participants' passing initiation time (PIT) when encountering yielding vehicles. Reproduced from Li et al. (2025), *Transportation Research Part F: Traffic Psychology and Behaviour*, 114, 621–632. licensed under CC BY 4.0.

4.4.4 Yielding Initiation Time (YIT)

556 trials were included in the yielding initiation time (YIT) analysis. There was a significant main effect of the non-yielding vehicle's lateral offset on YIT (F (1, 552) = 133.91, $p < .001$), whereby encountering a non-yielding vehicle with towards offset (M = 10.75, SE = .19) led to a significantly longer YIT than those without offset (M = 13.91, SE = .20, 95). There was no significant main effect of vehicle type (F (1, 552) = .41, .52), and no interaction effect (F (1, 552) = .04, .85), see Figure 4.9.

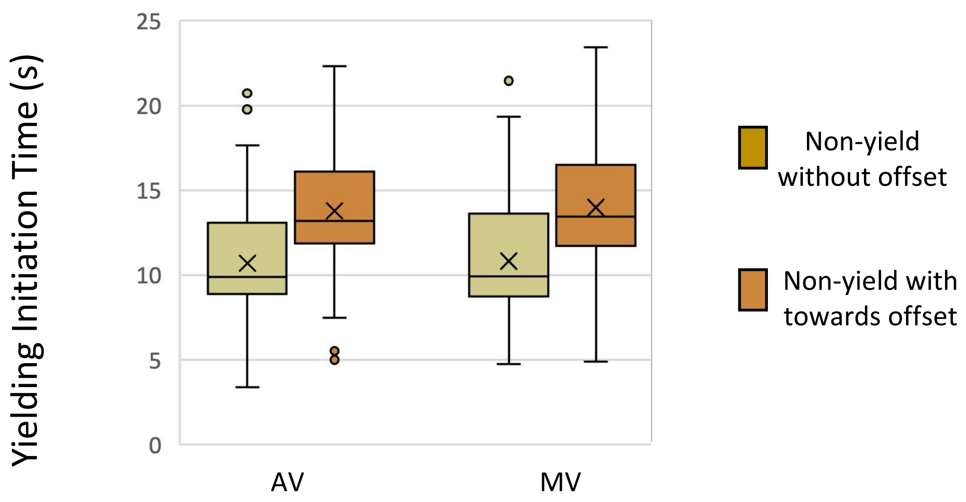

Figure 4.9 Participants' yielding initiation time (YIT) when encountering non-yielding vehicles.

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4.4.5 Interview Analysis

Interviews were automatically transcribed using the transcription function on Microsoft Teams, and these transcripts were then manually checked and revised by the authors.

4.4.6 Factors affecting drivers' decision making

The first question we asked participants was to rate the importance of the factors influencing their passing or yielding decisions using a 5-point Likert scale. Of the 40 participants, 35 considered "offset" to be an important factor affecting decision-making, followed by "braking pattern" (28 participants), "speed" (26 participants), "distance" (22 participants), and "AV or MV" (4 participants). None of the participants rated "offset" as unimportant, while 9 participants considered "AV or MV" to be an unimportant factor in their decision-making, see Figure 4.10. Specifically, all 35 participants emphasised that the "away offset" was helpful in the decision-making of passing through the bottleneck, as indicated in interview comments such as "driving to the edge is definitely important", "the easiest form was to see if the vehicle drove over to the edge", "I trusted more if they pulled up, and I can brake quickly and earlier.", and "moving to the edge of the road is important when I decided to pass". Speed and distance also played a crucial role, with participants noting, "of course I'm judging the speed as well", "how fast oncoming vehicles were approaching the two parking cars helps". For the non-yielding approaching vehicles, the answers regarding offset are inconsistent, for instance, 1 participant indicated "towards offset" is ambiguous, stating *"if the approaching vehicle goes to the centre, I know I need to slow down. But when the vehicle drives towards to the centre, I do not know when to brake"*. Similarly, "without offset" was also considered ambiguous, for example, 1 participant stated that "*coming through but staying slightly to the left* (non-yield without offset) *is ambiguous*". Brake pattern and speed also influenced the decision-making, with participants noting, "*I know I should yield when the oncoming vehicle maintains speed without slowing down" and "not showing any obvious deceleration"*. It is important to note that participants relied on multiple cues rather than a single factor when determining whether an oncoming vehicle was non-yielding or not.

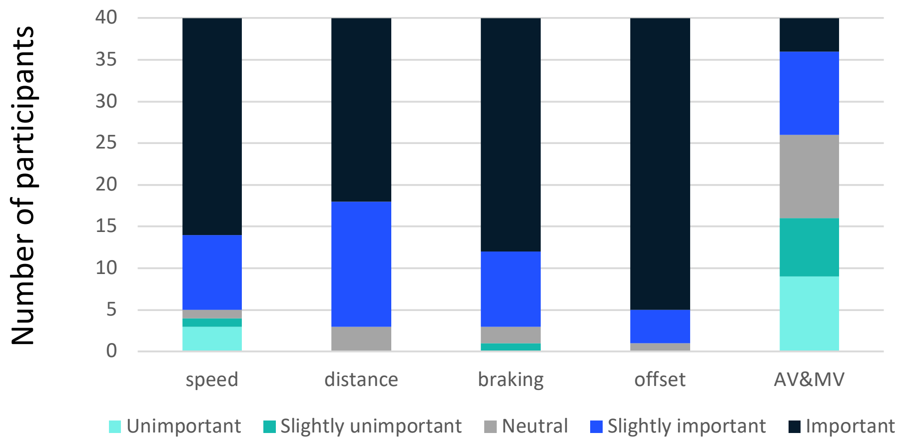


Figure 4.10 Factors affecting participants' decision-making.

4.4.7 Drivers' attitude towards AVs, MVs, and eHMI

We then asked participants about their attitudes toward the types of vehicles encountered. Out of the 40 participants, 31 stated that the type of vehicle did not seem to be a major factor influencing their decisions of passing or yielding, 8 stated that it did, and 1 was unsure. Specifically, 31 stated, "I just check the approaching vehicle's behaviour", "not really, I would imagine that they follow a similar pattern as the human driver", and "not initially, the behaviour seemed pretty similar from both, so it didn't really play much of a factor at all". They emphasised that key factors influencing their decisions were more related to speed, distance, braking patterns, and the distribution of vehicles. Only a small number of participants (N=8) expressed differing expectations regarding the type of approaching vehicle. Specifically, 3 participants indicated a higher expectation for AVs compared to MVs, stating, "*I expected AVs to yield more than human drivers*", and "*I feel an automated car would drive better than a manual person*". However, they also noted, "*It did not significantly impact my own decisions*". On the other hand, 5 participants expressed a higher expectation for MVs over AVs, citing reasons such as, "*I do not trust and am unsure about computers and automated driving systems*", "*I feel safe with the manual vehicle*", "*I trust manual vehicles more because human drivers have experience*", "*My initial thought would be that if it's automatic, I should wait*", "*MV can react to me more*". One participant mentioned having no clear stance on their attitude towards AVs or MVs.

Finally, we asked participants about their attitudes toward the eHMI. Two participants indicated that the eHMI did not solely dictate their decision to pass through the bottleneck, as they still relied on judgment based on other factors.

One participant remarked, "*The blue light provided extra information, but the decision is still up to the driver*", while another mentioned, "*The blue light-band helped me with decision-making but I still rely on other cues like car positions and speed*". Two participants mentioned that the eHMI light band created some uncertainty. One participant mentioned frustration with AVs equipped with eHMI stopping and proceeding very slowly through the bottleneck, leading to uncertainty about their intentions. While another participant stated, "*Unless the AV indicated its intention clearly, I might consider messing with it to confuse its systems*", a statement that suggests some uncertainty about how to interact with AVs equipped with eHMI. The remaining participants (N = 34) stated that the eHMI helped them understand the intentions of the AV, helped improve their trust in the AV, and allowed them to proceed with more confidence when they saw the light indicating the AV would yield. Specifically, six participants mentioned that the eHMI aided their better understanding of the AV's intention to yield the right-of-way, thus improving their confidence in making passing decisions. One participant remarked, "*The blue light was very obvious, it's almost like knowing someone is waving at you*", while another likened it to "*similar to how human drivers use signals*". Seven participants stated that the eHMI helped provide information and increased their trust and feelings of safety. One participant mentioned, "*I would say I would feel equally as safe around an automated car as a manual car when there was a blue light on the AV*", while another expressed the feeling that "I *feel safer, more comfortable and confident when I decided to pass the bottleneck first*", and another stated "*when I saw the light, I knew that I should just go so I didn't slow down*".

4.5 Discussions

This study aimed to provide insights into the impact of various factors on drivers' decision-making and yielding behaviour during bottleneck scenarios. It investigated the effect of type of approaching vehicle (AV vs MV), its' kinematic features (i.e., its longitudinal and lateral offsets), and the presence or absence of an eHMI on drivers' subjective experiences and their driving behaviours (i.e., drivers' decision and initiation time).

Results showed that knowledge of whether a vehicle was automated or manually driven did not affect drives' subjective feelings (Li, et al., 2023) or behaviours. Human drivers may have different expectations about automated and manual vehicles (Miller, Koniakowsky, et al., 2022). However, the results showed that drivers' decision-making about whether to pass or yield to an approaching vehicle in a bottleneck road is based on the vehicle's kinematic behaviour, rather than whether it is labelled as a computer- or human-driven vehicle, especially if the two vehicles look exactly the same.

Our participants passed significantly more often, and with a shorter passing initiation time (PIT) when the approaching vehicles yielded with an "away offset", compared to the trials where yielding occurred without an offset. This observation is in line with previous research suggesting that integrating lateral movement cues radically improves the clarity of signals for yielding vehicles, particularly in ambiguous situations such as bottleneck scenarios (Miller, Leitner, et al., 2022; Rettenmaier & Bengler, 2021). When approaching vehicles did not yield, participants had a longer yielding initiation time (YIT) and passed less often when "towards offsets" were presented than when they were not. The "towards offset" also led to a higher number of collisions since it occupied the participants' lane excessively. Thus, we do not recommend this approach for the AV behaviour design, as it increases the risk of a collision.

Previous studies used passing / yielding duration to compare the impact of different conditions on drivers' decision-making times (Miller, Leitner, et al., 2022; Rettenmaier et al., 2021). Our methodology stands out in this approach by utilizing specific time points (PIT and YIT) to pinpoint the exact decision times. Compared to the duration, the time point is a more precise metric for knowing when the participants decide to pass and yield.

In terms of the value of eHMIs, the presence of an eHMI improved drivers' perceived safety and trust in a yielding AV (Li, et al., 2023). Participants passed through the bottleneck first significantly more often when encountering a yielding AV with eHMI compared to the trials without eHMI, regardless of whether this was accompanied by an "away offset". eHMI only led to a higher level of comprehension of AV behaviours under the "no offset" conditions, with no additional benefit when the approaching AV yielded with an "away offset" (Li, Lee, et al., 2023). This illustrates that the participants prioritise interpreting vehicle kinematics over relying on eHMI. When drivers were able to accurately discern the intention of approaching vehicles through their movement characteristics, the influence of eHMI became negligible. These findings diverge from those of Rettenmaier & Bengler (2021), who observed an improvement in participants' comprehension of approaching AVs with an eHMI, both with and without an away offset. In addition, while the eHMI influenced participants' passing decisions, it did not significantly affect the passing initiation times (PITs), suggesting that its impact may be more pronounced at the decision-making stage rather than during the execution of manoeuvres. This means that while drivers may decide to pass more confidently with eHMI, they still rely heavily on kinematic cues to verify their decisions. This emphasises the need for kinematic communication even when eHMI is present. Drivers still feel compelled to verify the behaviours of approaching vehicles independently, thereby limiting the significant improvement of PITs by eHMI. Although some participants reported that the eHMI may have created more uncertainty, most participants stated that eHMI helped them understand the intentions of the AV, and proceed with more confidence in passing decision-making. These results indicate that the vehicle's lateral movement was a strong indicator of its intent, with the added messages from an eHMI possibly causing some confusion if this accompanied the lateral movement, but being useful in the absence of this kinematic cue. These results confirm the importance of using intuitive kinematic behaviour for AVs to communicate intention (Y. M. Lee et al., 2021), also supporting the suggestion that these can be a better solution than potentially misleading externally presented messages (Kaleefathullah et al., 2020). eHMI should be further evaluated in more complex and uncertain scenarios, including those involving multiple vehicles behind the approaching vehicle, and adverse weather conditions with poor visibility, where the potential benefits of eHMIs may be particularly pronounced.

In terms of limitations, our study focused on a simplistic and ideal driving scenario, a bottleneck scenario with only two moving agents, to analysethe impact of the approaching vehicles' kinematics without any external influences. However, real road traffic scenarios are often more complex, influenced by diverse road layouts and the presence of other road users. Youssef et al., 2024 showed that environmental factors, such as the presence of other road users influence human drivers' likelihood of yielding. Indeed, during the interviews, participants in our study suggested that their decisions and subjective feelings would be influenced by the presence and types of other vehicles behind them, and also those following the approaching vehicles, as well as the broader traffic context, including the presence of pedestrians or cyclists. Weather conditions and whether it was day or night were also mentioned as factors that might have influenced the passing behaviour of our participants. In addition, it is important to take the more complex traffic scenarios with ambiguous right-of-way, such as junction roads without traffic lights (Imbsweiler, Ruesch, et al., 2018; Imbsweiler, Stoll, et al., 2018) and shared spaces (Li et al., 2021) into account, to understand if lateral deviation and eHMI still have the same impacts on drivers' decision-making. Moreover, some other eHMIs have been reported (Dey et al., 2020), such as anthropomorphic cues, traffic symbols or even auditory eHMI, and more research is needed to understand if the use of different eHMIs may also lead to different driving decisions. Finally, it should be noted that this experiment was conducted on a static driving simulator, therefore, more research is needed to understand whether similar results would emerge in a real-world scenario, where the participants feel greater risk, and may drive more cautiously.

CHAPTER 4. Investagating driver's responses to AVs: the impact of lateral offset and eHMI

This study highlights the critical role of kinematic cues, particularly lateral offsets, in enhancing drivers' understanding of an approaching vehicle's yielding and non-yielding intentions. The potential benefits of an eHMI are linked to the clarity of the kinematics. If kinematic cues are unambiguous, for example, approaching AV yields with an away offset, the benefits of eHMIs are limited. Thus, designers should consider how eHMIs can provide additional information where kinematic cues are not possible. These insights can guide the future design of AVs and contribute to safer and more reliable interactions between AVs and MV drivers in bottleneck scenarios. Furthermore, our driving simulator study shows that knowing whether the approaching vehicle is an AV or MV does not impact driver performance; instead, the kinematics of the vehicle are the key factors influencing drivers' decision-making.

CHAPTER 5. Developing a novel HMI Strategy for AV–MV Interaction in Multi-Vehicle Bottlenecks

Abstract

Bottleneck roads with narrowed width often only allow one vehicle to pass at once. In this situation, human drivers need to negotiate their right-of-way via, e.g., hand gestures and eye contact. However, when a human-driven vehicle (MV) confronts a driver-less automated vehicle (AV), explicit communication between drivers is no longer possible. External human–machine interfaces (eHMIs) on AVs may facilitate communication in unobscured situations, but MV-drivers can fail to perceive the eHMI information on the AV with other vehicles in front of the AV, blocking the MV's view. Even if the visibility is not impaired, AV broadcast communications do not target on specific receivers, it is not unlikely that other vehicles may wrongly perceive this information. Instead, an internal human–machine interface (iHMI) can uni-cast the AV intention to MVs since the information on iHMIs is direct to MV-drivers and visible in visibility-blocked situations. However, iHMIs require vehicle-to-vehicle communication technology, and the conveyed information might not be highly trusted as the information is transmitted to MVs rather than being seen directly from AVs. Therefore, this paper proposes a synchronous iHMI+eHMI method for a more unambiguous communication in this multi-vehicle bottleneck road situation. The designed *iHMI+eHMI* is compared with the baseline i. e., *without HMI*, *iHMI*, and *eHMI* in a video-based driving simulation by subjective evaluations from structured questionnaires. The results (N=24) indicate that HMIs (*iHMI*, *eHMI*, and *iHMI+eHMI*) are more helpful than vehicles without any HMI for the AV-MV communication, and *iHMI+eHMI* achieves the best performance when the views of MV-drivers are obscured.

Keywords: Automated vehicle; Human-AV communication; External human–machine interface (eHMI); Internal human–machine interface (iHMI); Bottleneck road; Traffic psychology.

5.1 Introduction

In the foreseeable future, we will be witnessing a revolution in mobility, e.g., level 4 and 5 automated vehicles (AVs) (SAE International, 2021) integrating into urban areas rapidly (Heineke et al., 2021). Highly automated mobility is claimed to have the potential to support human drivers and reduce injuries, crashes, and economic tolls caused by human errors (NHTSA, 2023). The advent and popularity of AVs will let them directly interact with human road users, such as manually driven vehicles (MVs), pedestrians, and cyclists. This direct interaction inevitably causes many concerns about traffic safety as AVs behave differently to MVs (Färber, 2016). To improve the sense of relief and trust in AVs, they should be able to interact and communicate their driving intentions unambiguously and comprehensibly with other human road users (Fuest et al., 2018; Liu et al., 2021; Schieben et al., 2019). However, establishing good communication between AVs and other human road users is very challenging in mixed traffic, especially in ambiguous right-of-way use cases when negotiations are needed, such as on bottleneck roads (Miller, Leitner, et al., 2022), at intersections (Papakostopoulos et al., 2021), or for lane changing and merging (Kauffmann et al., 2017). This is because (1) AVs lack explicit information from drivers when they are not involved in driving tasks (Fuest et al., 2018), (2) inattentive drivers and passengers in the AVs may lead to unconscious hand gestures and eye contact that could imply misdirection (Färber, 2016), and (3) the AVs' kinematics may differ from MVs' (Fuest et al., 2020) and consequently cause misunderstanding for the other human road users. These insufficient or erroneous AV-MV communications can increase hesitation in yielding or taking right-of-way (Liu et al., 2021) and reduce traffic efficiency (Rettenmaier & Bengler, 2020). In worse cases, it may even result in MV-drivers' uncertain feelings about AV movements (Färber, 2016), a decreased sense of safety (Kaparias et al., 2015; Liu et al., 2021), and lowered trust (Hoff & Bashir, 2015; Liu et al., 2021) in AVs.

This paper focuses on a bottleneck road, especially with a narrow passing gap and obstacles on both sides (Imbsweiler, Stoll, et al., 2018; Rettenmaier et al., 2019). This type of bottleneck road is one of the ambiguous driving situations where a driver needs to communicate the right-of-way with an oncoming vehicle and decides whether to yield or proceed (Bundesministerium für Justiz und Verbraucherschutz, 2013). As shown in Figure 5.1, an MV encounters a leading vehicle (LV) in front of the AV. In this case, the visibility of the MV-driver towards the AV is partially blocked by the LV. The passage is narrowed by two parked vehicles (in grey) on both sides, and only one vehicle can pass at once. We aim to explore an effective communication method in this situation in order to facilitate harmonious traffic sociability and reduce traffic jams and conflicts. To achieve this goal, we explore several different communication strategies to identify an optimal way for AV-MV communication on the bottleneck road.

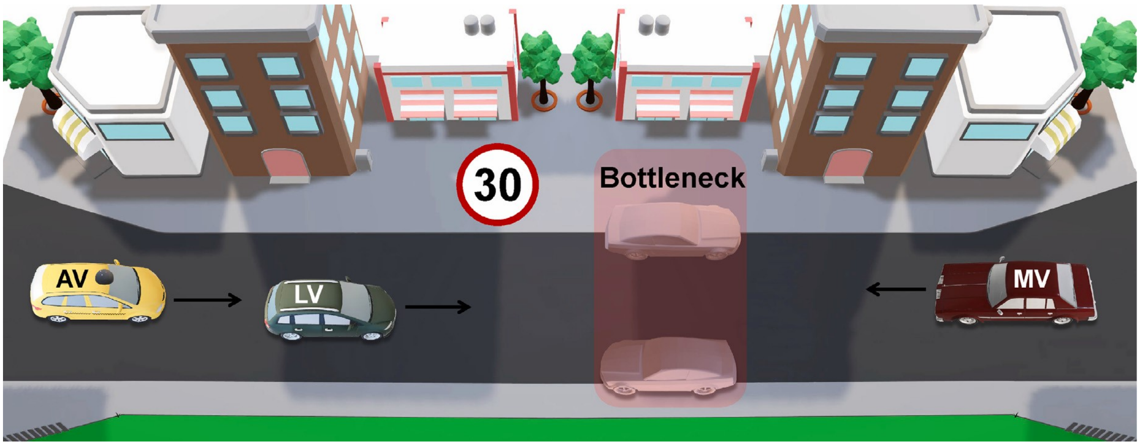


Figure 5.1 An example of multi-vehicles on a bottleneck road. The LV blocks the visibility of the MV-driver to the AV. (Speed limit: 30 km/h; AV: automated vehicle; LV: leading vehicle; MV: manually-driving vehicle).

5.1.1 Related works

Generally, two methods are utilised for communication between AVs and other human road users: vehicle kinematics, i. e., implicit communication (Colley et al., 2017; Habibovic et al., 2018) and human–machine interface (HMI), i. e., explicit communication (Avsar et al., 2021; Papakostopoulos et al., 2021; Rettenmaier et al., 2019). On bottleneck roads, in terms of vehicle kinematics, AVs are expected to perform both lateral offset and longitudinal speed adjustment to communicate their right-of-way (Miller, Leitner, et al., 2022; Rettenmaier & Bengler, 2021). For example, Rettenmaier & Bengler, 2021, and (Miller, Leitner, et al., 2022) report that one-step and two-step deceleration are likely to indicate a vehicle's yielding behaviour, while maintaining speed and acceleration tend to show a vehicle's non-yielding behaviour. In addition, HMIs are further specified as external HMIs (eHMIs) (Dey, 2020; S. M. Faas & Baumann, 2020) and internal HMIs (iHMIs) (Li et al., 2022) to facilitate AV-MV communication. eHMIs are deployed outside of an AV to show its messages, and iHMIs are deployed inside an MV to show the messages transferred from the AV.

For eHMIs, many early works mainly focus on the communication between AVs and vulnerable road users (Merat et al., 2018) other than MV-drivers. Specifically, different kinds of eHMIs, such as light patterns (S. M. Faas & Baumann, 2020; Y. M. Lee et al., 2022), and textual (Liu et al., 2021; Nissan, 2015), symbolic (Rettenmaier & Bengler, 2020) and anthropomorphic (Rover, 2018) signals, were proposed to show an AV's intention and status in order to strengthen the communication between the AV and vulnerable road users, like pedestrians and cyclists, in crossing scenarios. An another type of eHMI is projecting information about right-of-way on the road based on the principle of knowledge-in-the-world, in a way that vulnerable road users are already familiar with (Dey, van Vastenhoven, et al., 2021). Moreover, (Li et al., 2021) designs an eHMI to project colours on the road under and in front of the AV, allowing other vulnerable road users in all directions to easily understand the status of the AV from a distance.

For AV and MV-driver communication, eHMIs are explored to increase traffic efficiency and a feeling of safety. (Rettenmaier & Bengler, 2021) provided an eHMI with orange and green arrows deployed on an AV's bumper that can show its intention to an MV on bottleneck roads. Their method shows an increase in traffic efficiency. Similarly, light-bands on an AV are reported to improve safety feelings and acceptability of AVs at T-junctions (Avsar et al., 2021), strengthen human drivers' confidence, and reduce overall crossing time at intersections (Papakostopoulos et al., 2021). Nonetheless, realistic traffic scenarios are more complicated as the presence of other road users (see Figure 5.1), and weather conditions such as foggy, snowy, and rainy days, may heavily impair the visibility of the MV-driver. In this case, the human driver can fail to detect the message on the eHMI when the AV is blocked. Moreover, it was reported that eHMIs only have the potential to optimise AV-MV interaction in bottleneck situations when the AV is visible (Rettenmaier et al., 2019). (Liu et al., 2023) also points out that when participants do not easily understand the implicit communication of AVs, their sense of danger will increase, and trust in the AVs will decrease.

To overcome the shortcomings of impaired visibility and ambiguity, the communication between AVs and MVs could be established alternatively by iHMIs with the development of the so-called vehicle-to-vehicle communication system (V2V) (Liu et al., 2023). It has been predicted that 40% of the vehicles will be equipped with V2V systems by 2030 (Barua et al., 2014). Given that MV-drivers are used to receiving information from iHMIs presented on, e.g., dashboards, head-up displays (HUDs), and central panels, iHMIs can be easily deployed via V2V using those interfaces for conveying AVs' intentions directly to MVs, to mitigate the ambiguous communication between AVs and MVs. For example, (Li et al., 2022) propose an iHMI-based communication strategy for AV-MV communication. In their study, AVs' communication information is transferred to MVs based on V2V and displayed on iHMIs using HUDs. The simulation result shows that subjective evaluations of the iHMI have a more favourable score than the eHMI in a scenario where one AV encounters one MV at a bottleneck road. However, it is still not clear whether the benefits of the information on iHMIs or eHMIs outweigh the drawbacks of the added complexity, or whether this balance is maintained across different use cases, especially in more complex scenarios with multiple vehicles (Rettenmaier & Bengler, 2021).

1.1.1 Advantages and disadvantages of iHMIs and eHMIs

From an MV-driver's viewpoint, as shown in Figure 5.2, we further summarise the advantages and disadvantages of iHMI and eHMI. First, the information is directional from V2V-based iHMIs, i. e., the information sent by the AV can be transmitted to a specified MV-driver. In contrast, eHMI information is broadcast to all the other road users in the vicinity (Merat et al., 2018). Hence, in multi-object scenarios, with an iHMI rather than eHMI, an MV-driver can clearly understand whether the communicating object is him/her or not.

Second, the information of iHMIs in the vehicle is not impaired by the occlusion of other vehicles, even in traffic congestion and low visibility weather conditions such as foggy, snowy, and rainy days. On the other hand, the eHMI deployed on an AV body or projected on the road is invisible or partly invisible in situations when an MV-driver's vision is obstructed. For example, (Rettenmaier et al., 2019)09/12/2025 11:39:00 report that eHMIs can only optimise the AV-MV interaction during a bottleneck situation when the AV is visible to the MV-driver.

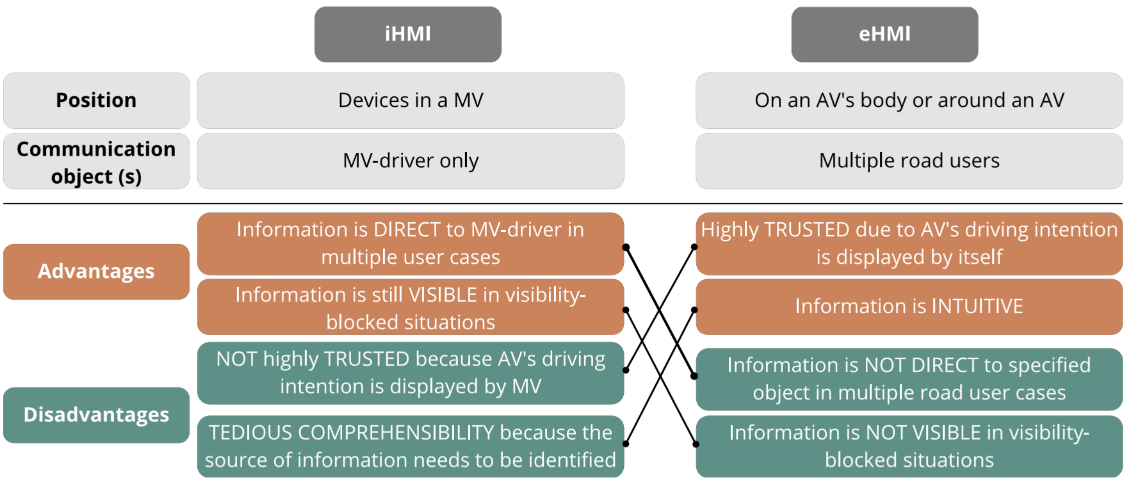


Figure 5.2 Advantages and disadvantages of an iHMI and an eHMI as well as their complementary from the MV-driver's viewpoint.

A typical disadvantage of V2V-based iHMI is that the information from an AV is relayed by the MV's iHMI, which the AV does not directly show. In comparison, an AV can display its intention directly with its eHMI. Hence, compared to the relayed information displayed on the MV's iHMI, the MV-driver may have higher trust when the information is directly represented on the AV's eHMI.

Another disadvantage of iHMI is that an MV-driver may not immediately recognise who is sending the information. In other words, after receiving the information through iHMIs, the MV-driver must find the information sender in various environments and match the sender's intention. In contrast, the information on eHMI deployed on an AV's body or projected on the road accurately indicates where the information comes from. Thus, eHMIs can be more intuitive and precise than iHMIs in multiple road user situations.

5.2 Proposition and Hypotheses

5.2.1 Proposition

This paper proposes a synchronous HMI for AV and MV-driver communication based on the analysis of the advantages and disadvantages of iHMIs and eHMIs. It allows an iHMI in an MV and an eHMI on an AV to display the same information about the AV's intention simultaneously. The synchronous HMI proposes a novel way to make up for single displayed HMIs — it aggregates the directability and visibility of iHMI and a higher sense of relief and intuition of eHMIs. We call this synchronous HMI *iHMI+eHMI* in this paper.

5.2.2 Hypotheses

In order to find potential and proper communication strategies in real traffic scenarios with multiple road users, the following four hypotheses are explored. The effectiveness of the proposed *iHMI+eHMI* is compared with three variant settings, *iHMI* only, *eHMI* only, and implicit communication by an AV's kinematics only, i. e., no HMI on the AV (*w/o HMI*) as a baseline design in this study.

H1. Compared with the explicit communication methods (*eHMI*, *iHMI* and *iHMI+eHMI*), the implicit communication method (i. e., *w/o HMI*) is insufficient for comprehensibility, feeling of safety, efficiency of AV-MV communication, and building trust and acceptance of AVs.

H2. Compared with single-display *iHMI* or *eHMI*, *iHMI+eHMI* can improve drivers' comprehensibility, feeling of safety, and efficiency of AV-MV communication. Furthermore, it can build trust and acceptance of AVs.

5.3 Methods

In this paper, to fix the driving behaviours of the MV, LV, and AV in different trials using multiple HMIs, a video-based experiment was administered. In this experiment, an online study including videos and post-trial questionnaires was used to analyse participants' subjective feelings about the four types of HMIs focused on a bottleneck road with multiple vehicles. This work differs from our previous study (Li et al., 2022) that also focuses on AV-MV communication with *iHMI*, *eHMI*, and *iHMI+eHMI* in bottleneck roads in the following ways: (1) We consider a more complex traffic environment with not only the interaction between two vehicles but with interactions among multiple vehicles; (2) The MV-driver's view is partially obscured by another vehicle in front of the AV, which is practically common in a realistic traffic environment, such as traffic jams.

This research was carried out in accordance with the Declaration of Helsinki ethical principles. All the participants provided their informed consent before participating in the studies.

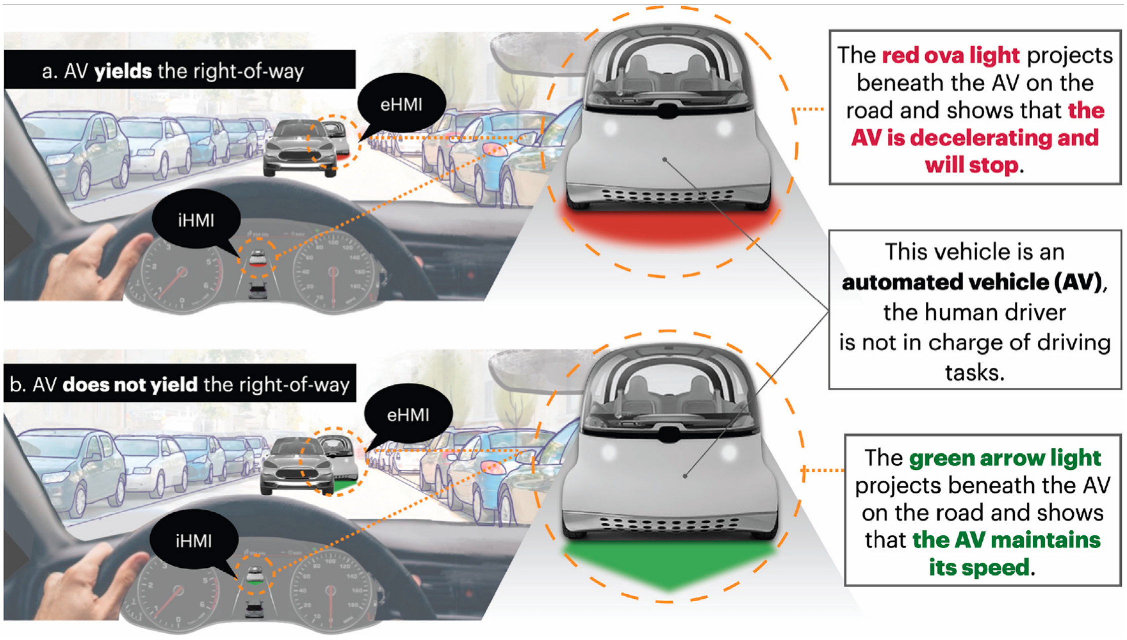


Figure 5.3 The demonstration of the proposed iHMI and eHMI. The iHMI displays its information on the MV's dashboard. In contrast, the eHMI is located beneath and in front of the AV and projects its intention on the road using different colours. iHMI+eHMI enables iHMI and eHMI to display the same information synchronously. a. shows that the AV yields its right-of-way to the MV, while b. shows that the AV does not yield (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Reproduced from Li et al. (2023), *Transportation Research Interdisciplinary Perspectives*, 20, 100845.

5.3.1 The HMI designs for AV-MV communication

Figure 5.3 demonstrates the *iHMI* and *eHMI* designs for AV-MV communication on a bottleneck road. We adopt a popular eHMI design proposed by a previous study (Li et al., 2021) – the communication is achieved by projecting the AV's intention onto the road (in front of and beneath the AV). In this study, a red ova light (R=184, G=29, B=19) indicates that the AV is decelerating and will stop, showing its intention to yield to the MV, and a green arrow light (R=76, G=187, B=23) indicates that the AV maintains its speed, showing its intention to insist on its right-of-way. The *iHMI* is designed identically to the *eHMI* but it is located on the MV's dashboard. In total, three types of HMI designs are leveraged in this study: *eHMI*, *iHMI*, and *iHMI+eHMI*. We treat the case of no HMI on the AV (*w/o HMI*) as the baseline design. For the sake of simplicity, if not otherwise stated, our four types of communication strategies are written in italics in this paper.

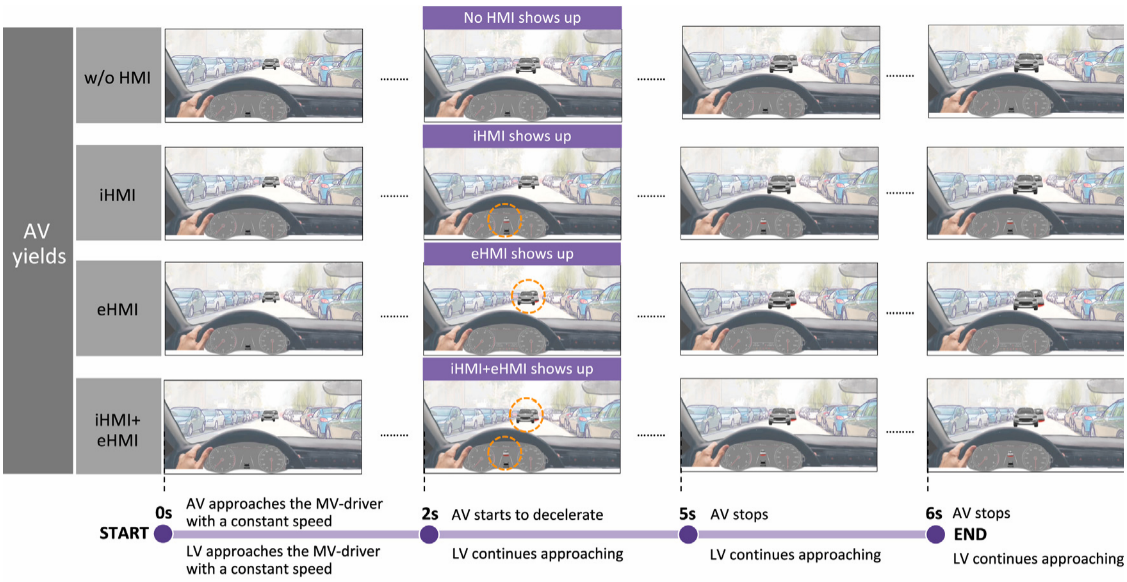
It should be noted that, in this paper, we do not focus on the detailed HMI designs, but rather on the performance of the combined *iHMI+eHMI*, i. e., whether it provides adequate information or is considered redundant in the bottleneck road situation. We leave the high-fidelity design to future work.

5.3.2 Online simulator study

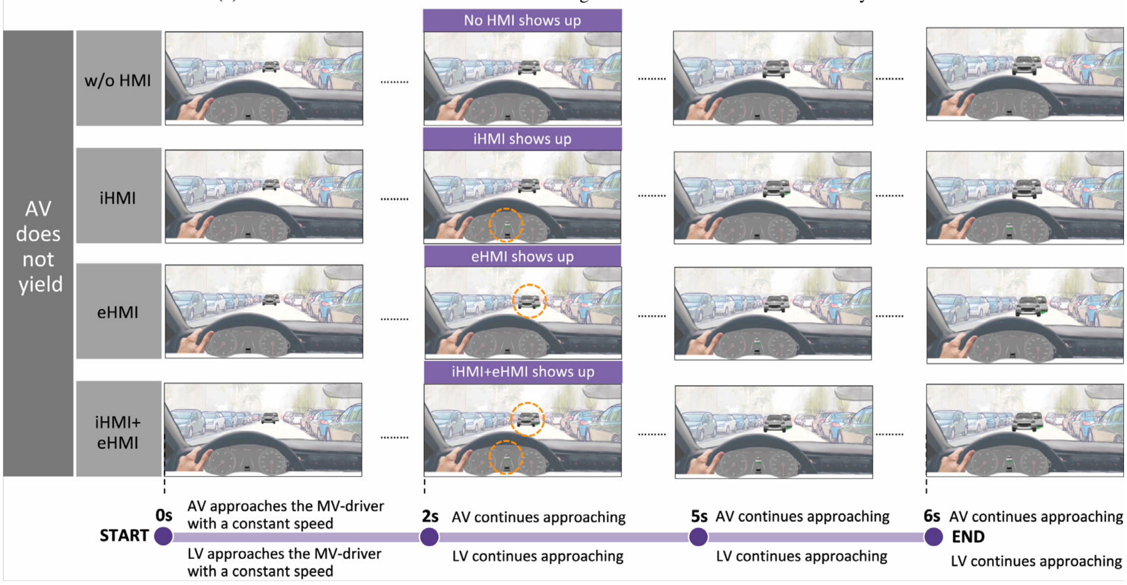
We prepared a video-based online simulator study with structured questionnaires to analyse: (1) compared to the baseline design, if HMIs are needed on a bottleneck road with multiple road users; (2) compared to the single *iHMI* or *eHMI*, if the *iHMI+eHMI* has a more positive subjective evaluation.

As shown in Figure 5.4, the videos simulate multiple vehicle interaction scenarios on a bottleneck road. Two types of behaviour displayed by the AV (yields and does not yield the right-of-way) with four interfaces (*w/o HMI*, *iHMI*, *eHMI*, and *iHMI+eHMI*) are demonstrated. Specifically, an LV in front of the AV always drives with non-yielding behaviour, i. e., passing through the bottleneck road at a constant speed (20 km/h). Following the LV, if the AV yields the right-of-way, it decelerates from 20 km/h to 0 km/h (stopping) to indicate its yielding behaviour, as shown in Figure 5.4(a). Concurrently with deceleration, the HMIs are turned on to show the yielding information (see Section 5.3.1). If the AV insists on its right-of-way, the AV follows the LV and approaches at a steady speed of about 20 km/h (maintaining) to indicate the non-yielding behaviour, as shown in Figure 5.4(b). At the same time as determining non-yielding intention, the HMIs are turned on to show the corresponding information (see Section 5.3.1). In the baseline (*w/o HMI*) setting, only AV movements are available, and there is no HMI shown.

The online simulator study took approximately 20 min after the personal data policy statement. It was structured in four sections as follows:



(a) Video with timeline of AV-MV encountering on a bottleneck road when the AV yields.



(b) Video with timeline of AV-MV encountering on a bottleneck road when the AV does not yield.

Figure 5.4 Videos of AV-MV encountering on a bottleneck road (This video recording is from the MV-driver (participant)'s view). (a) The approaching AV yields to the MV. At the start of the video, both the AV and the LV approach the MV with a constant speed. After two seconds, the AV starts to decelerate and the HMIs show up (except for w/o HMI) while the LV continues approaching. At the fifth second, the AV stops but the LV continues approaching until the end of the video. (b) The approaching AV does not yield to the MV. Both the AV and the LV approaches the MV at a constant speed continuously until the end of the video. At the second, the HMIs show up (except for w/o HMI). Note that the duration of all the videos is the same, which is six seconds. The orange circles are used to highlight the HMIs in this figure, but they were not shown to participants in the online simulator study.

5.3.3 Online Simulator study

We prepared a video-based online simulator study with structured questionnaires to analyse: (1) compared to the baseline design, if HMIs are needed on a bottleneck road with multiple road users; (2) compared to the single iHMI or eHMI, if the iHMI+eHMI has a more positive subjective evaluation. As shown in Figure 5.4, the videos simulate multiple vehicle interaction scenarios on a bottleneck road. Two types of behaviour displayed by the AV (yields and does not yield the right-of-way) with four interfaces (w/o HMI, iHMI, eHMI, and iHMI+eHMI) are demonstrated. Specifically, an LV in front of the AV always drives with non-yielding behaviour, i. e., passing through the bottleneck road at a constant speed (20 km/h). Following the LV, if the AV yields the right-of-way, it decelerates from 20 km/h to 0 km/h (stopping) to indicate its yielding behaviour, as shown in Figure 5.4(a). Concurrently with deceleration, the HMIs are turned on to show the yielding information (see Section 5.1). If the AV insists on its right-of-way, the AV follows the LV and approaches at a steady speed of about 20 km/h (maintaining) to indicate the non-yielding behaviour, as shown in Figure 5.4(b). At the same time as determining non-yielding intention, the HMIs are turned on to show the corresponding information (see Section 5.1). In the baseline (w/o HMI) setting, only AV movements are available, and there is no HMI shown.

The online simulator study took approximately 20 min after the personal data policy statement. It was structured in four sections as follows:

- Demographic Survey: We asked the attendees to fill in a demographic questionnaire, including questions about their age, gender, and prior driving experience on bottleneck roads.
- Bottleneck road introductory video: A three-minute realistic driving video was shown to the participants. The videos were recorded on bottleneck roads in the urban area of the city of Karlsruhe, Germany. This video assists them in recalling and immersing themselves in the situations based on their driving experience. After that, we asked how often the participants drove on bottleneck roads.
- HMI instruction: We described designs of these three HMIs specifically in order to make sure that the participants understood the information conveyed to them, as shown in Figure 5.3.
- Eight experimental videos with post-trial questionnaires: The participants were asked to watch eight videos including two types of driving behaviour of the AV (i. e., yielding and non-yielding) with the four types of HMIs, as shown in Figure 5.4. In order to control carry-over effects, the order of the videos followed by the post-trial questionnaires handed out to the participants was randomised.

After each video, the participants needed to evaluate the HMIs in terms of comprehensibility, feeling of safety, trust, efficiency, and acceptance with using different communication strategies. At the end of the study, the participants were asked to give an overall assessment of the iHMI, eHMI and iHMI+eHMI, as well as the baseline design.

5.3.4 Participants

A total of N = 24 participants (8 females and 16 males) between the age of 28 and 40 years (M = 31.25, SD = 7.54) took part in this study. All of them had a German driver's license. Most participants had good experiences driving on bottleneck roads, i.e., 4 participants drove almost every day, 11 participants drove at least once a week, and 5 participants drove at least once a month. The participants were compensated with a €5 of Amazon voucher for their participation if they had finished all the required questions.

5.3.5 Measurements

After each video of the different HMIs and the baseline group w/o HMI, the participants were asked to evaluate the communication between the AV and MV according to the following perspectives:

- Comprehensibility: We concluded two sub-items, i.e., item 1 "the communication is clear" and item 2 "the communication is adequate" (Matthews et al., 2017);
- Feeling of safety: item 3 "I feel safe when I communicate with AV in this situation" (Liu et al., 2021);
- Trust in AV: item 4: We concluded two sub-items, i.e., "I trust the AV will take appropriate actions" and item 5 "I trust the AV more than the leading vehicle when it communicates with me in this way in this (Liu et al., 2021; Matthews et al., 2017);
- Efficiency: item 6 "This communication strategy of the AV is efficient for me to decide to go or wait" (Mandrick et al., 2016);
- Acceptance: We adopted the following bipolar items from the acceptance questionnaire by (Van Der Laan et al., 1997). The sub-scale of satisfaction was used to reflect participants' attitudes towards the AV in this study, i. e., item 7 "unpleasant or pleasant", item 8 "annoying or nice", item 9 "irritating or likeable", and item 10 "undesirable or desirable".

Table 5.1 Cronbach's Alpha of the sub-items of comprehensibility, trust, and acceptance.

Subjective feeling items	Number of items	Cronbach's Alpha
Comprehensibility	2	.804
Trust	2	.846
Acceptance	4	.933

The items 1–6 were rated on a 5-point Likert scale, namely, −2 "strongly disagree", −1 "disagree", 0 "neutral", 1 "agree", and 2 "strongly agree". Items 7 to 10 were evaluated in a 5-point bipolar scale from −2 to + 2, corresponding to bilateral attitudes. In these cases, zero reference point means that participants have a neural attitude on both sides. At the end of the study, we did an overall assessment with the following question: "which communication strategy do you like most to communicate with the AV when it yields/does not yield the right-of-way in this situation? (choose only one option)". The selection rate of each HMI was later analysed.

5.4 Results

We evaluate the effect of communication strategies on subjective feelings about comprehensibility, feeling of safety, trust, efficiency, and acceptance. Since the 5-point Likert scale was used to measure subjective feelings for each evaluation item, non-parametric related samples's ANOVA (two-sided) followed by Wilcoxon signed ranks test for the post-hoc pairwise comparisons were applied. The corresponding results of "AV yields the right-of-way to MV" and "AV does not yield the right-of-way to MV" are presented in Figure 5.5. The vertical axis shows the scores of the 5-point Likert scale, and the horizontal axis indicates items of subjective feelings. The horizontal line in each bar represents the median of the rating. The results of all the evaluation items, regardless whether the AV behaves yielding or not yielding the right-of-way, w/o HMI scores the lowest median, while iHMI+eHMI scores the highest median. Cronbach's alpha was used to measure the internal reliability of the questions that have sub-items. As shown in Table 5.1 Cronbach's Alpha of Comprehensibility, trust and acceptance overcome the threshold of 0.7, which proves the internal consistency reliability across the sub-items (Gerbing & Anderson, 1988).

5.4.1 When approaching AV yields the right-of-way

From the results of Friedman's ANOVA, when the AV yields (see Table 2), statistically significant differences are found regarding item 1: communication is clear ($p < .05$), item 2: communication is adequate ($p < .01$), item 3: feeling of safety

($p < .01$), item 5: trust AV more than LV ($p < .05$). There is no significant difference regarding item 4: trust AV will take appreciate actions, item 6: the communication strategy is efficient, and items 7–10: acceptance of AV. When the AV does not yield (see Table 5.4), no significance is found in item 1, but statistically significant differences are found in items 2, 5, 6, 7, 8, 10 ($p < .01$), and items 3, 4, 9 ($p < .05$). From the results of the post-hoc pairwise comparisons by the Wilcoxon signed ranks test, when AV yields the right-of-way (see Table 3), the communication via iHMI+eHMI and eHMI regarding comprehensibility scores the same highest median (1.0), while the median of iHMI is 0.0. The communication with eHMI is significantly clearer and more adequate than w/o HMI and iHMI ($p < .05$). Moreover, the communication with iHMI+eHMI is also significantly clearer and more adequate thanw/o HMI and iHMI ($p < .01$). Compared to communication by w/o HMI, MV-driver's "feeling of safety" is significantly higher via iHMI, eHMI and iHMI+eHMI ($p < .05$, $p < .01$, $p < .01$, respectively). However, there is no significant difference across the types of HMI regarding the feeling of safety. Regarding trust-related evaluation items, when the participants communicate via iHMI+eHMI, they significantly "trusted AV will take appropriate actions" compared to communicating via w/o HMI ($p < .05$). Both iHMI+eHMI and eHMI led to a significantly higher score for "trusted AV more than LV" compared to w/o HMI ($p < .01$, $p < .05$, respectively). Moreover, the communication with iHMI+eHMI leads to a significantly higher score for "trusted AV more than LV" compared to iHMI ($p < .05$). There are no significant differences across the four types of HMI in the rest of the evaluation items i. e., efficiency and acceptance. Except for item 10, the evaluation of the communication with iHMI+eHMI is significantly higher compared to w/o HMI ($p < .05$).

5.4.2 When approaching AV does not yield the right-of-way

When AV does not yield the right-of-way (see Table 5.4), the communication with eHMI significantly improves the clearness of the communication compared to w/o HMI ($p < .05$). But no significant differences are found among the types of HMI regarding item 1 "the communication is clear".

Communication with both iHMI+eHMI and eHMI are significantly more adequate than w/o HMI ($p < .05$), and communication with iHMI+eHMI is significantly more adequate than iHMI ($p < .05$). eHMI significantly improve participants' "feeling of safety" when communicating with AV compared to w/o HMI ($p < .05$), while iHMI+eHMI shows significantly higher score than iHMI ($p < .05$). Regarding the evaluation items of trust, the participants have a significantly higher trust in that the "AV will take appropriate actions" by the communication via iHMI, eHMI and iHMI+eHMI compared to the communication via w/o HMI ($p < .05$). Both iHMI+eHMI and iHMI lead to participants "trust the AV more than LV" compared to w/o HMI respectively ($p < .01$), among the types of HMIs, iHMI+eHMI shows significantly higher score than eHMI ($p < .05$). Compared to w/o HMI, the communication with iHMI, eHMI, and iHMI+eHMI significantly improves participants' perceived efficiency when they communicated with the AV ($p < .01$, $p < .05$, $p < .01$, respectively). The communication with iHMI, eHMI and iHMI+eHMI significantly improves participants' acceptance of AV. No significant differences across iHMI, eHMI, and iHMI+eHMI are found in other acceptance evaluation items. Except for item 9, the evaluation of the communication with iHMI+eHMI is significantly higher than w/o HMI ($p < .01$), iHMI ($p < .05$) and eHMI ($p < .05$).

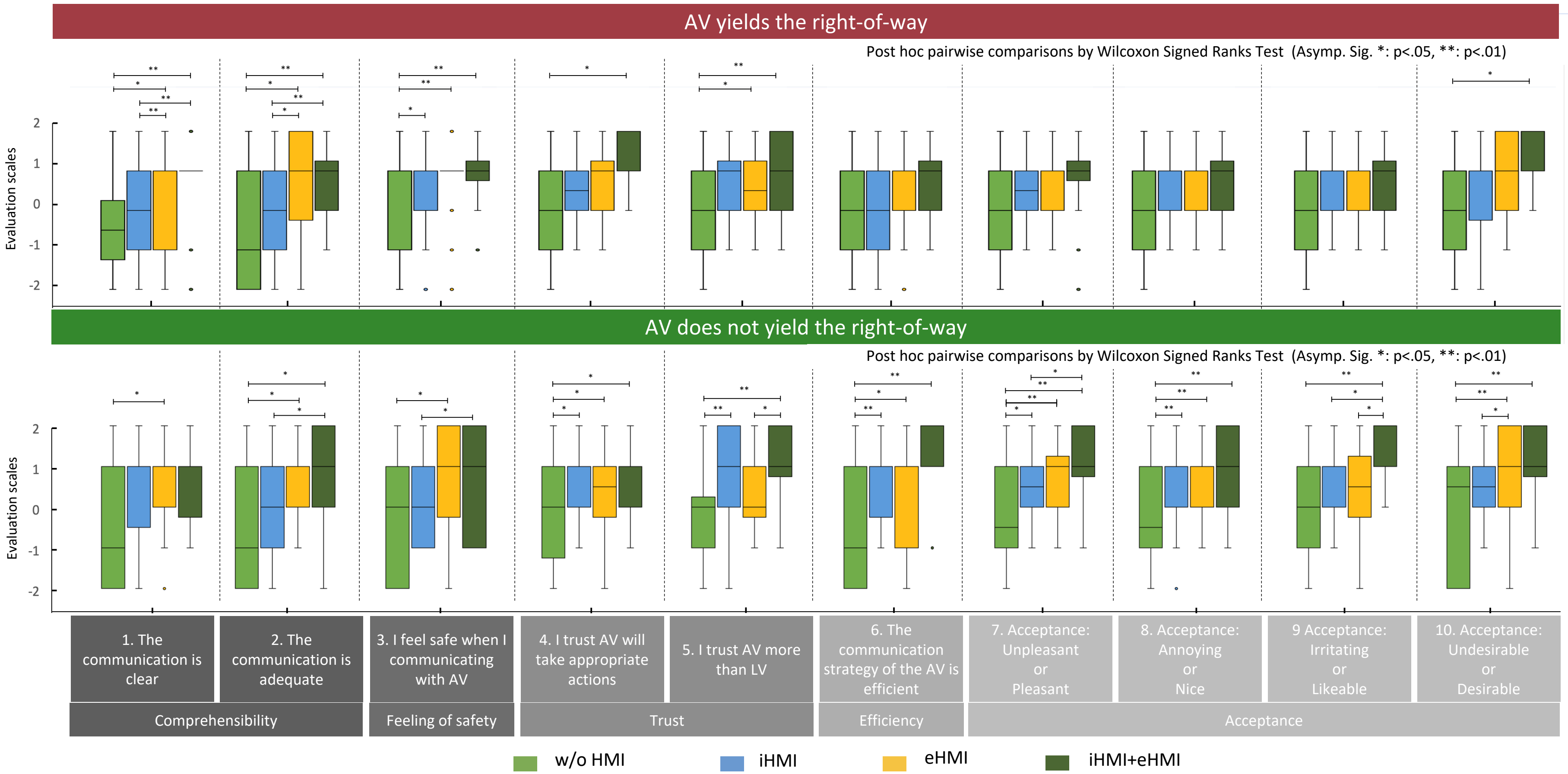


Figure 5.5 Subjective evaluation results of the AV-MV's communication from participants (MV-drivers), horizontal lines in the boxes represent the median of the ratings.

Reproduced from Li et al. (2023), *Transportation Research Interdisciplinary Perspectives*, 20, 100845.

Table 5.2 Related-Samples Friedman's ANOVA by Ranks (two-sided) for each evaluation item (n=24).

		Comprehensibility		Feeling of safety	Trust		Efficiency	Acceptance			
		tem 1 The communication is clear	Item 2 The communication is adequate	Item 3 I feel safe when I communicate with AV	Item 4 I trust AV will take appropriate actions	Item 5 I trust AV more than LV	Item 6 The AV communication strategy is efficient	Item 7 Unpleasant or Pleasant	Item 8 Annoying or Nice	Item 9 Irritating or Likeable	Item 10 Undesirable or Desirable
AV yields	F	9.441	13.047	12.865	3.479	10.665	5.946	4.741	3.249	2.328	5.579
	p	**.024**	**.005**	**.005**	.323	**.014**	.114	.192	.355	.507	.134
AV does not yield	F	4.624	11.592	9.179	10.288	15.685	16.365	16.516	12.087	11.022	11.983
	p	.201	**.008**	**.027**	**.016**	**.001**	**.001**	**.001**	.007	**.012**	**.007**

Table 5.3 Post hoc pairwise comparisons by Wilcoxon signed ranks test for each evaluation item when AV yields the right-of-way (n = 24).

		Item 1 The communication is clear	Item 2 The communication is adequate	Item 3 I feel safe when I communicate with AV	Item 4 I trust AV will take appropriate actions	Item 5 I trust AV more than LV	Item 6 The AV communication strategy is efficient	Item 7 Unpleasant or Pleasant	Item 8 Annoying or Nice	Item 9 Irritating or Likeable	Item 10 Undesirable or Desirable
w/o HMI vs. iHMI	Z	−1.022	−.915	−2.246	−.680	−1.776	−.736	−1.114	−1.054	−.618	−.691
	p	.307	.360	**.025**	.496	.077	.462	.265	.292	.537	.490
w/o HMI vs. eHMI	Z	−2.137	−2.372	−3.189	−1.298	−.2346	−1.528	−1.291	−.947	−.821	−1.425
	p	**.033**	**.018**	**.001**	.194	**.019**	.126	.197	.344	.412	.154
w/o HMI vs. iHMI+eHMI	Z	**−2.832**	−2.811	−3.229	−2.335	−2.914	−1.938	−1.802	−1.842	−1.822	−2.538
	p	**.005**	**.005**	**.001**	**.020**	**.004**	.053	.071	.065	.068	**.011**

iHMI vs. eHMI	Z	−2.099	−2.087	−1.434	−.806	−.522	−1.224	−.611	−.227	−.382	−.877
	p	.036	.037	.151	.420	.602	.221	.541	.821	.702	.381
iHMI vs. iHMI+eHMI	Z	−2.876	−3.161	−1.745	−1.842	−1.227	−1.742	−1.163	−.966	−1.119	−1.930
	p	**.004**	**.002**	.081	.065	**.021**	.082	.245	.334	.263	.054
eHMI vs. iHMI+eHMI	Z	−1.252	−4.454	−.405	−1.035	−.924	−.613	−.644	−1.032	−1.164	−1.417
	p	.210	.650	.685	.301	.356	.540	.519	.302	.244	.156

Table 5.4 Post hoc pairwise comparisons by Wilcoxon signed ranks test for each evaluation item when AV does not yield the right-of-way (n = 24).
Reproduced from Li et al. (2023), *Transportation Research Interdisciplinary Perspectives*, 20, 100845.

			Comprehensibility		Feeling of safety	Trust		Efficiency	Acceptance			
			Item 1 The communication is clear	Item 2 The communication is adequate	Item 3 I feel safe when I communicate with AV	Item 4 I trust AV will take appropriate actions	Item 5 I trust AV more than LV	Item 6 The AV communication strategy is efficient	Item 7 Unpleasant or Pleasant	Item 8 Annoying or Nice	Item 9 Irritating or Likeable	Item 10 Undesirable or Desirable
w/o HMI	vs. iHMI	Z	−1.807	−1.220	−.446	−2.022	−2.645	−2.668	−2.430	−2.600	−1.786	−1.715
		p	.071	.223	.655	.043	**.008**	**.008**	.015	**.009**	.074	.086
w/o HMI	vs. eHMI	Z	−2.494	−2.410	−2.464	−1.992	−1.826	−2.219	−2.697	−2.648	−1.646	−2.608
		p	.013	**.016**	**.014**	.046	.068	.026	**.007**	**.008**	.100	**.009**
w/o HMI	vs. iHMI+eHMI	Z	−1.958	−2.234	−1.579	−2.583	−3.416	−3.205	−3.174	−3.194	−2.782	−2.661
		p	.050	.026	.114	.010	**.001**	**.001**	**.002**	**.001**	**.005**	**.008**
iHMI vs.	eHMI	Z	−1.101	−1.412	−1.848	−.353	−1.211	−.032	−.843	−.370	−.122	−.699
		p	.271	.158	.065	.724	.226	.974	.399	.711	.903	.485
iHMI vs.	iHMI+eHMI	Z	−.919	−2.360	−2.150	−.426	−1.463	−1.458	−2.553	−1.035	−2.351	−2.164
		p	.358	.018	.032	.670	.143	.145	**.011**	.301	.019	.030
eHMI vs.	iHMI+eHMI	Z	−.640	−9.79	−2.84	−1.303	−2.438	−1.605	−1.590	−1.368	−1.989	−1.144
		p	.522	.328	.777	.193	**.015**	.108	.112	.171	.047	.252

5.4.3 Overall assessment

Figure 5.6 shows the results of the overall assessment across the three communication strategies. When the AV yields the right-of-way, 8.3%, 33.4% and 58.3% of the participants prefer to communicate with iHMI, eHMI and iHMI+eHMI, respectively. Also, when the AV insists on its right-of-way, 8.3%, 16.7% and 75.0% of the participants prefer to communicate with iHMI, eHMI and iHMI+eHMI, respectively. In summary, according to reports from the participants, iHMI+eHMI has the highest assessment amongst the other types of HMIs when AV behaves yielding and not yielding the right-of-way.

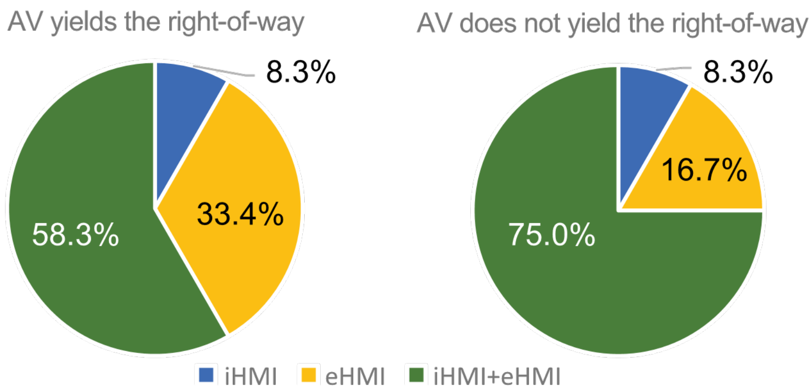


Figure 5.6 The overall assessment of iHMI, eHMI and iHMI+eHMI (N =24).

5.5 Discussions

In this study, we measured how the participants' subjective feelings in terms of comprehensibility, feeling of safety, efficiency, trust, and acceptance of AV were influenced by the types of communication strategies on bottleneck roads with blocked visibility. Through a video-based online simulator study, we explored whether the benefits of the extra communication information on HMI could compensate for the lack of communication between AV and MV or if it adds more complexity. Moreover, we further validate our hypotheses based on the experimental results in the following sections.

5.5.1 Hypotheses

Hypothesis 1. Compared with the explicit communication methods (eHMI, iHMI and iHMI+eHMI), the implicit communication method (i. e., w/o HMI) is insufficient for comprehensibility, feeling of safety, efficiency of AVMV communication, and building trust and acceptance of AVs. H1 can be accepted as the results illustrated that in the visibility-blocked traffic scenarios, the explicit communication information, whether iHMI, eHMI or iHMI+eHMI, can help the MV-driver understand the intention of the AV. Thus, the MV-driver feels safer, and the communication is more efficient, which in turn helps the MV-driver improve their trust in and acceptance of the AV regardless whether the AV yields or insists on its right-of-way. These results are in line with the studies of Imbsweiler et al. (2018), Rettenmaier and Bengler (2021), and Liu et al. (2021) on the evaluation of eHMIs for communications between AVs.

Hypothesis 2. Compared with single-display iHMI or eHMI, iHMI+eHMI can improve drivers' comprehensibility, feeling of safety, and efficiency of AV-MV communication. Furthermore, it can build trust and acceptance of AVs. H2 is partly accepted according to the experimental results. When the AV yields right-of-way, subjective evaluation results show that iHMI+eHMI has significantly higher comprehensibility scores than iHMI and eHMI. Although there are no significant differences in the remaining ten evaluation items, we can still see that iHMI+eHMI has a higher median than that of iHMI and eHMI, respectively. When AV does not yield the right-of-way, participants' comprehensibility and the feeling of safety are significantly higher using iHMI+eHMI than using iHMI or eHMI. In addition, participants trust the AV more than the LV when they communicate using iHMI+eHMI compared to eHMI and iHMI.

5.5.2 Further discussion

Interestingly, when AV yields, although the median of iHMI, eHMI and iHMI+eHMI are higher than w/o HMI, no significant differences were found between the communication strategies. However, when AV does not yield, participants report a significantly higher AV acceptance communicating with iHMI, eHMI and iHMI+eHMI compared to w/o HMI. This finding suggests that when AV does not yield, the extra communication information on HMI could improve MV-driver's acceptance of AV. In terms of iHMI, the MV-driver first needs to match the information shown on iHMI into the traffic situations. It is more difficult in the multiple-vehicle scenario. Subsequently, the MV-driver needs to interpret the AV's intention based on the traffic context, This process increases the difficulty of comprehending the communication between AV and MV-driver. Thus, this result suggests that eHMI or iHMI+eHMI are more comprehensive compared to iHMI. In addition, participants report a significantly more adequate communication using iHMI+eHMI compared to w/o HMI and iHMI, respectively. However, no significant differences were found in the evaluation of the item "communication is clear" between w/o HMI and iHMI+eHMI, iHMI and iHMI+eHMI when AV does not yield. This result suggests that even the implicit information from the AV or the single displayed iHMI could provide sufficient clarity of the communication, participants may still expect more intuitive information from AVs. Interestingly, there are no significant differences regarding trust between iHMI and eHMI when the AV is conducting yielding or non-yielding behaviour. However, the median of iHMI is higher than that of eHMI, indicating that the participants trust more in the AV when communicating via iHMI. The reason could be that although we explained the meaning of the types of HMIs to the participants at the beginning of the experiment, this eHMI is still a new design for the participants as a novel communication message in a traffic environment. As discussed by (Rettenmaier et al., 2019), eHMIs are only optimal when the users are familiar with them. The participants may need more time to become familiar with the eHMIs and build trust.

To summarise, the combination of iHMI and eHMI, i. e., iHMI+eHMI helps the MV-driver feels safer, and the communication is more efficient, which in turn helps the MV-driver improve their trust and acceptance of the AV regardless of whether the AV yields or insists on its right-of-way using for communication of AVs and MV-drivers. Furthermore, the overall assessment shown in Figure 5.6. indicates that most participants have chosen the synchronous HMI for AV-MV communication. Hence, the synchronous HMI provides a double-check option to the participants. In this way, the redundant information displayed on both iHMI and eHMI can significantly improve the MV-driver's comprehensibility of the AV's intention. In other words, eHMI helps the participants understand from whom the information is sent intuitively, and iHMI helps them easily identify to whom the information is sent. Therefore, the source and target of the information displayed on the iHMI+eHMI is clearer, which helps participants trust the information sent from the AV and in turn, improves their acceptance of the AV. This result is consistent with (Liu et al., 2021) for trust between an AV and pedestrians - a clear understanding of the information transmitted from the AV can improve pedestrians' trust in it.

5.6 Contributions

Previous studies have focused on how eHMI affects AV-MV communication on bottleneck roads with one target, i. e., there are only one AV and one MV in the test scenarios. Our work focused on a scenario with the MV-driver being visually blocked, which is very common in traffic jam situations. A new HMI-based communication strategy: a synchronous HMI (iHMI+eHMI), was proposed to aggregate the advantages of iHMI and eHMI. The results showed that whether AV yields or takes the right-of-way, the synchronous HMI gains the highest score in comprehensibility, feeling of safety, efficiency, and trust in and acceptance of AV, compared to w/o HMI, iHMI and eHMI, respectively.

5.6.1 Limitations and future works

In order to fix the kinematics of the MV and its distances to the LV and AV during the trials, the participants were not allowed to drive the MV based on their own intention. In realistic scenarios, driving intentions from individual drivers of the MV may affect the understanding of the information transferred from the AV. Another limitation is that most of the participants are young males. They cannot fully represent the subjective feelings of AV-MV communication across all user groups. To reduce the potential effects of age and even gender, a balanced sample should be considered in the next-step experiment. Even though the G-power (Faul et al., 2009) showed that the results from 24 participants have a medium effect size (0.25) (Funder and Ozer, 2019) in this study, a driving simulator experiment with a larger sample size is under our plan to further verify the results of this study. In addition, the videos used in this study are based on videos recorded in Germany. The results of this experiment may only apply to situations in Germany.

5.6.2 Conclusion

AV's ambiguous and invisible intention poses communication issues between AV and MV in unclear right-of-way scenarios. In this paper, we focused on bottleneck roads with blocked visibility as a more complex scenario—more than one target compared to previous studies, and MV drivers who cannot easily receive communication information from the oncoming AVs due to the blocked visibility. This scenario is very common in various realistic traffic situations, especially traffic jam situations. To find a potential solution to this issue, we aggregated the advantages of an AV-based eHMI and a V2V-based iHMI, and proposed a synchronised iHMI+eHMI to better support AV-MV communication. An online simulator study was used to evaluate whether iHMI+eHMI has better subjective evaluation in terms of comprehensibility, feeling of safety, trust, efficiency, and acceptance of AV-MV communication on a bottleneck road scenario with multiple vehicles. From the results, first of all, we confirmed that HMI is needed in AV-MV communication on the bottleneck road regardless whether the AV yields or does not yield the right-of-way. Secondly, when the AV yields, we also found that iHMI+eHMI has higher ratings in all the subjective evaluations compared with the single displayed iHMI or eHMI, except for the ratings for acceptance of the AV. When AV does not yield, communicating with iHMI+eHMI makes the MV-driver gain clearer comprehensibility, feel safer and more efficient in AV-MV communication, and have higher trust in and acceptance of the AV compared to the communication with the single displayed HMIs. This new communication strategy iHMI+eHMI could be expanded and measured in multiple road-users' ambiguous scenarios, such as T-junctions and intersections. Our next step works will further cross-validate driving simulator, naturalistic, and traffic observation studies in a realistic traffic environment. These experiment methodologies will explored to determine how the communication strategy should be applied to various complex and ambiguous AV-MV communication scenarios.

CHAPTER 6. Overall Discussions

6.1 Summary

This thesis offers a comprehensive investigation into communication strategies between automated vehicles (AVs) and manually driven vehicles (MVs), addressing a critical but underexplored area of human-machine interface in the context of mixed traffic environments. As AVs transition into real-world deployment, ensuring safe, efficient, and understandable communication with other road users including human drivers is essential.

While much existing literature focuses on AV-pedestrian interaction, this work systematically expands the scope to AV-MV communication. Through four peer-reviewed studies employing both qualitative and quantitative methods, the thesis explores road users' expectations, behavioural responses, and preferences regarding AV signalling, kinematics, and interface design.

Based on the findings, several implications could be made for system designers and future research. These implications aim to assist the development of more understandable and acceptable AVs. Insights of AV behaviour design and Implications of eHMI design on AV. Help standardized the eHMI, and design the holistic eHMI.

To answer the research questions, this thesis contributes in several key ways:

- It proposes a novel simulator setup to isolate and test perceptions of AVs versus MVs.
- It introduces precise decision-making metrics such as Passing Initiation Time (PIT) and Yielding Initiation Time (YIT), improving behavioural assessment over traditional timing measures.
- It verifies how kinematic cues, especially lateral deviation, strongly shape human driver responses.
- It evaluates external (eHMI) and internal (iHMI) communication strategies, offering empirical insights for future design and standardisation.
- It addresses a research gap by extending AV communication research beyond pedestrian scenarios to include AV–MV interactions in ambiguous traffic environments.

This chapter discusses how the main research questions have been addressed, outlines contributions in terms of the experiment setup, designs and measurements, and discusses research limitations and recommendations for future research.

6.2 Answers to the research questions

In this section, the research questions introduced in CHAPTER 1 are gathered, providing an overview of key findings.

RQ1: What communication methods and information do road users expect when communicating with automated vehicles (AVs)?

RQ1 was addressed in CHAPTER 2 with an focus on vulnerable road users in shared spaces. By surveying participants on how they expect a driver to communicate in such vulnerable road users rich traffic environments, we identified the gap that arises when the "driver" is removed. Road users expect a rich combination of cues, for instance, eye contact, hand gestures, vehicle movement, turn signals, and brake lights to convey intentions and facilitate interaction. The study revealed that road users anticipate AVs to mimic human-like communication. For example, many participants suggested that vehicles should communicate key information, such as motion status ("I'm stopping", "I will go"), risks ("emergency situation"), suggestions ("you go first", "go ahead"), and even gratitude ("thanks") through both vehicle movements (kinematics) and human-like signals. Preferred methods included body language cues, such as head direction, gestures and eye contact. However, in the current research phase, these explicit communications are difficult to encode into automated system models given the high complexity of individual behaviours. To this end, as suggested by many other works and the findings in this paper, eHMIs are a supplementary way to compensate for the communication between the automation systems and human road users, to establish effective and unambiguous understanding in mixed traffic. eHMIs are expected to help AVs and road users build the formation of a harmonious and mutual trust transportation society through communication. Besides, AVs are expected to suggest road users to quickly make a unified decision by using the eHMIs. This may indirectly improve the accuracy of AV prediction of road users' behaviour and reduce the error range of the prediction.

RQ2: ***How do human drivers communicate with AVs differ from communication with manually driven vehicles?***

This question was explored through CHAPTER 3 and CHAPTER 4. We found that knowing if a vehicle was automated or manually driven did not affect drives' performance and subjective feelings. While human drivers may have different expectations about automated and manual vehicles (Miller, Koniakowsky, et al., 2022), our studies revealed that their driving performance, subjective feelings (including perceived safety, comprehension, and trust), and decision-making (e.g., whether to pass or yield at bottlenecks) were determined primarily by the vehicle's kinematic behaviour rather than whether it is labelled as a computer or human-driven vehicle, especially if the two vehicles look exactly the same. This result contributes a critical piece of evidence to the literature. While some have speculated that drivers might either be overly timid or overly aggressive when facing AVs (uncertain whether the AV will follow human norms or always play "nice"), our studies in a controlled bottleneck found no strong inherent bias in driver response to AVs. Communication dynamics between cars were dictated by implicit right-of-way negotiation cues rather than the novelty of the AV. Of course, this is within a setting where the AV behaved in a human-like manner. The implication is that if an AV drives conservatively and respects the informal rules of negotiation, human drivers will treat it similarly to any other vehicle. While existing studies have hypothesised that human drivers might behave either more cautiously or more assertively in the presence of AVs, due to uncertainty about their adherence to social rules. In the controlled studies illustrated in CHAPTER 3 and CHAPTER 4, no evidence of such bias was found. Instead, communication between vehicles were significantly impacted by implicit right-of-way negotiation cues, not the novelty of automation. It is important to note that this finding holds in contexts where AVs exhibit well-designed kinematic behaviour. The implication is that if AVs drive in a socially appropriate manner, adhering to informal driving norms and conveying their intentions clearly, human drivers are likely to interact with them as they would with any conventional vehicle.

RQ3: How do designs of behaviour and eHMI influence human drivers' subjective responses?

RQ3 was addressed by the driving simulator study in CHAPTER 3. The subjective responses in the post-questionnaire include drivers' perceived safety, comprehension and trust of the AV's behaviour. Our findings show that both the AV's kinematics and its use of eHMI cues can significantly shape these subjective feelings. The participants felt significantly safer and reported a significantly higher comprehension and trust when the approaching vehicles yielded with an "away offset", compared to the yielding without offset trials. This finding supports results from previous studies which report that the addition of lateral movements for a yielding vehicle provides a clear additional cue to other road users, when compared to kinematics cues alone. This is especially for ambiguous scenarios, such as bottleneck roads (Miller, Leitner, et al., 2022; Rettenmaier & Bengler, 2021). Our study also showed that the presence of a "towards offset" improved drivers' comprehension of the vehicles' behaviour in non-yielding conditions.

In terms of the value of eHMIs, the presence of an eHMI improved drivers' perceived safety and trust of a yielding AV, regardless of whether this was accompanied by an "away offset". However, subjective response for comprehension of the AV with an eHMI was only high during the "no offset" conditions, eHMI did not impact drivers' comprehension of the approaching AV's behaviour when the AV yielded with the "away offset". This reveals an important point: the benefit of the eHMI depended on the clarity of the AV's behaviour. If the AV's yielding intention is already obvious from its movements (slowing down at a certain distance with an "away offset"), adding an eHMI made no difference to drivers' comprehension since drivers already understood the AV's intention through its behaviour pattern. The participants stated in the interview in CHAPTER 4, that they were confused by the additional message, perhaps finding the eHMI is redundant or unclear in meaning. Our results suggest that the lateral deviation of the yielding vehicle was quite powerful in itself, with additional messages from an eHMI possibly causing some confusion about the vehicle's intentions. This result stresses the importance of using intuitive kinematic behaviour for AVs to communicate intention, and confirms these can be a better solution than potentially misleading externally presented messages.

R*Q4*: How do designs of behaviour and eHMI influence human drivers' driving performance?

CHAPTER 4 directly addressed RQ4, by analysing drivers' decisions (to go or yield) and their decision timing in the bottleneck encounter under various conditions. The results show that AV's behaviour can significantly impact human drivers' decisions and performance on bottleneck scenarios. Specifically, participants passed the bottleneck significantly more often with a quicker decision (shorter passing initiation time (PIT)) when the approaching vehicles yielded with an "away offset", compared to the trials where yielding occurred without an offset. This observation aligns with prior research suggesting that lateral movement cues provide a salient and intuitive signal of yielding intention, particularly in ambiguous situations such as bottleneck scenarios (Miller, Leitner, et al., 2022; Rettenmaier & Bengler, 2021). When approaching vehicles did not yield, "towards offset" behaviours, where the AV moved toward the centreline without yielding, resulted in longer decision time (yielding initiation time (YIT)), fewer passing decisions, and a higher incidence of collisions since it occupied the participants' lane excessively. These results suggest that such designs may introduce unnecessary risk and are therefore not recommended for AV behaviour modelling in constrained scenarios.

In terms of the value of eHMIs, the presence of an eHMI had a positive effect on participants' perceived safety and trust in a yielding AV. Participants passed through the bottleneck first significantly more often when encountering a yielding AV with eHMI compared to the trials without eHMI, regardless of whether this was accompanied by an "away offset". However， eHMI only enhanced behavioural comprehension under conditions where no lateral offset was present, when away-offset kinematics were available, the eHMI offered no additional interpretative value. This implies that human drivers continue to prioritise kinematic cues over supplementary displays, using visual signals from the AV's motion as the primary source of intent interpretation. Interestingly, while eHMI influenced drivers' decisions to proceed, it did not significantly affect the timing of these decisions (PIT), suggesting that its impact may be more pronounced at the decision-making stage rather than during the execution of maneuvers. This means that while drivers may decide to pass more confidently with eHMI, they still rely heavily on kinematic cues to validate their decisions. This observation highlights a broader trend: eHMI is most beneficial when kinematic intent is ambiguous, but potentially redundant or even confusing when clear behavioural cues are present. Drivers still have to verify the behaviours of approaching vehicles independently, thereby limiting the significant improvement of PITs by eHMI.

Participant feedback in the interview supported this interpretation. While some participants reported that the eHMI may be redundant and have created more uncertainty, most participants stated that eHMI helped them understand the intentions of the AV, and proceed with more confidence in passing decision-making. These findings indicate that the vehicle's lateral movement that intuitive and clear remains the most effective channel for AV communication, with the added messages from an eHMI possibly causing some confusion if this accompanied the lateral movement, but being useful in the absence of this kinematic cue. These results confirm the importance of using intuitive kinematic behaviour for AVs to communicate intention (Y. M. Lee et al., 2021), also supporting the suggestion that these can be a better solution compared to potentially misleading externally presented messages (Kaleefathullah et al., 2020).

***RQ5**: What are the human drivers' preferences for internal and external visual HMIs when communicating with AVs in a more complicated scenario??*

RQ5 was investigated in CHAPTER 5Error! Reference source not found., proving a novel HMI, internal HMI deployed on in-vehicle displays alongside eHMI on AV. MV, compared to other road users such as pedestrians, has the possibility to display the information from AVs. we exposed participants to scenarios with three communication strategies: an external HMI (eHMI) on the AV only, an internal HMI in the participant's vehicle only, and a combination of iHMI + eHMI, as well as a baseline of no explicit communication. Participants then rated these and indicated their preferred mode of communication. The results clearly indicate that drivers appreciate having explicit communications through both channels, with a strong preference for combined signals. In situations where the AV yielded the right-of-way, a majority of drivers (over half) said they would prefer the AV to use both an external display and an in-car message to communicate its intention. No one likes having no message at all, confirming that drivers do see value in additional communication from the AV. These preferences align with the performance and subjective data which showed that any form of HMI (internal or external) improved outcomes over having none, and the combination was most effective on all counts. Drivers likely view the external eHMI as something similar to seeing the other driver's turn signal or hand gesture, a direct visual cue from the other vehicle, while the internal message provides personal, tailored confirmation that "yes, the AV is talking to you and yielding." The combination maximises the chance the message is received and understood, which drivers seem to intuitively favour. This answers RQ5 by highlighting that human drivers are open to new forms of communication like iHMIs, but do not necessarily want to replace external signals with them, instead, they prefer a complementary approach. The study's contribution is one of the first to empirically evaluate driver preferences for iHMI vs eHMI in an interaction scenario, extending the literature on AV communication beyond just external displays. It suggests that a design which links an AV's external signal with a synchronised in-car alert could be well-received and effective, especially in complicated environments (e.g., when the signals on AVs might be missed by the driver).

6.3 Contributions

This thesis provides a comprehensive investigation into effective communication strategies between automated vehicles (AVs) and manually driven vehicles (MVs), offering several key contributions across methodology, behavioural insights, and interface design. Specifically, it (1) verifies the design of AV kinematics patterns, (2) offers implications for future HMI development and standardisation in automated driving, (3) proposes a novel simulation setup for controlled AV-MV interaction studies, (4) introduces refined evaluation metrics to measure driver decision-making time, and (5) addresses a research gap by extending AV communication studies beyond pedestrian interaction to include other road users, such as human drivers.

6.3.1 Insights of AV behaviour design

This thesis verified the important role of AV kinematics, particularly the lateral yielding behaviour, significantly shape driver performance and subjective perceptions. Drivers are more likely to proceed and made quicker decisions when the AV used an “away offset” strategy, while “towards offset” designs led to hesitation and increased collision risk. Furthermore, a combined approach, integrating behavioural design with eHMI cues, can form an effective communication strategy. These findings underline the importance of designing AV motion to convey clear intention and align with social driving norms.

6.3.2 Implications of HMI design on AV

This thesis extends the scope of prior eHMI research, primally focused on AV–pedestrian interaction in the AV–MV domain. The studies tested the validated lightband-based eHMI for pedestrian communication into AV–MV communication. The results show that the lightband eHMI can be translated and applied to AV-MV contexts, despite the increased speeds and complexity associated with vehicular traffic. Specifically, eHMIs can improve trust and perceived safety in ambiguous right-of-way situations, particularly when AV behaviour is not sufficiently informative on its own. However, when AV behaviour is clear, such as through distinct lateral offset, eHMIs offer limited additional value, and may even bring confusion. This highlights the lightband-based eHMI has the potential to be generalised to different road users. The implications of testing the eHMI are discussed. The implications of these findings contribute to future efforts in eHMI design and standardisation.

In addition to eHMIs, the thesis introduces an internal HMI (iHMI) to convey AV’s intention to human drivers within their own vehicles, the iHMI deployed on existing in-vehicle displays, such as dashboards, head-up displays, and central consoles to present synchronised information alongside external eHMIs. The integrated iHMI+eHMI approach provided participants with a secondary confirmation channel, resulting in improved outcomes in terms of perceived safety, comprehensibility, and trust, particularly under complex traffic environments involving multiple vehicles and limited visibility. Compared to most prior work focusing solely on eHMI employed on AVs, iHMI is a novel contribution.

Moreover, the results also point to the importance of informing road users about the meaning of HMI signals. Without a shared understanding of these cues, even well-designed interfaces could produce unintended or unsafe outcomes. Therefore, the successful implementation of eHMI systems depends not only on effective design but also on widespread user education and the development of international standards for signal consistency and interpretation.

6.3.3 Novel simulator setup

We developed a pseudo-coupled driving simulator setup to investigate whether participants (acting as human drivers) have different reactions when encountering AVs or MVs, with a controlled, realistic, and believable method. Participants were led to believe they were interacting in real-time with a human driver in another simulator (for the manual vehicle condition), though in reality the behaviour was scripted the same for AV and MV conditions. Unlike previous studies that relied on an experimenter to manually operate the simulator for both vehicle types, our approach eliminates potential confounding variables related to the experimenter's driving skills. This setup also provides a novel application of the Wizard-of-Oz technique in a driving simulator context.

Moreover, the multi-vehicle scenario in **Error! Reference source not found.** employed video simulations to efficiently pilot-test new interface concepts (iHMI) before moving to more complex driving experiments, a methodological approach that balances experimental control with realism.

6.3.4 Comprehensive measurement approach

Across these studies, more precise metrics: passing initiation time (PIT) and yielding initiation time (YIT), are used to capture the exact moments that participants decide to pass or yield in bottleneck scenarios. These measures offer a more precise understanding of the decision-making process compared to traditional passing duration metrics. By measuring PIT and YIT, this thesis enables a more exact analysis of how longitudinal and lateral offsets influence AV-MV communication.

Furthermore, subjective questionnaires (perceived safety, trust, and comprehension, etc.) are also combined with objective performance metrics (the decision to go/yield, decision time, and braking behaviour), offering a holistic and comprehensive way of measuring the communication strategies.

6.3.5 Broader contributions to AV–road user communication research

While there were loads of studies focused on the communication strategies between AVs and vulnerable road users, relatively little attention has been given to AV communications with MVs. This thesis addresses that gap by systematically investigating AV–MV communication strategies on bottleneck scenarios. With the rapid deployment of AVs, road users including pedestrians, cyclists and also human drivers, must drive together with AVs, resulting in mixed traffic for the foreseeable future. Therefore, advancing research on AV–MV communication is essential to support road safety, traffic efficiency, and public trust in shared spaces.

6.4 Limitations and future research

This thesis provides valuable insights into AV-MV communication by proposing and evaluating communication strategies; however, several limitations must be acknowledged.

First, the experimental design focused on a simplified and controlled traffic scenario: a bottleneck encounter involving only two vehicles and no realistic risk of collision. This was intentional to isolate the effects of AV kinematics and external communication (e.g., eHMI, iHMI) without the interference of external traffic dynamics. However, real-world environments are significantly more complex. Participants in our studies themselves reported that their behaviour and subjective responses might have been different with additional contextual elements being present. These include the presence of other road users such as pedestrians, cyclists, or following vehicles; variations in road user type (e.g., vehicle size, appearance, or category); and the overall traffic context, such as intersections or shared spaces. Factors such as lighting conditions (day vs. night) and adverse weather, which directly affect visibility and perceived risk, were also noted as potentially influential. As such, it remains unclear whether the behavioural patterns observed in our study would generalise to more valid driving contexts. Future research should move beyond simplified driving scenarios to investigate how AV communication strategies perform in more complex, realistic traffic environments. It will help assess the robustness and adaptability of communication designs in real-world applications.

Our scenarios were limited to a single ambiguous traffic setting: a bottleneck without formal right-of-way rules. Future work should investigate other common unregulated or semi-regulated scenarios, such as T-junctions, unmarked intersections, or shared pedestrian-vehicle spaces. These environments may introduce different decision-making dynamics and could help test the robustness of the proposed communication strategies.

This thesis evaluates both longitudinal and lateral kinematic patterns for AV behaviour. However, driving styles vary significantly across individuals, regions and countries, some environments are characterised by more assertive driving behaviours, while others are more cautious. To ensure broader applicability, future research should investigate a wider range of implicit cues and consider how AVs can adapt their behaviour to align with local driving cultures. In addition, the design of AV kinematic patterns should take into account the experience of passengers within the vehicle. It is essential to assess whether passengers feel comfortable with the vehicle's motions and whether they accept the AV's decisions, such as yielding or insisting the right-of-way. Addressing these factors contributes to a more holistic user experience.

Moreover, despite a broader range of communication modalities being proposed in the literature (Dey et al., 2020), such as anthropomorphic signals, symbolic traffic cues, or even auditory eHMI, only visual-based eHMIs were examined in this thesis. Future studies should compare the effectiveness of different eHMI types, including particularly in scenarios where visual signals may be compromised (e.g., due to fog or occlusion). Furthermore, understanding the combinatory effects of kinematics and multi-modal eHMI systems could lead to different driving decisions and provide more comprehensive design insights.

While the participant samples in our studies were adequate for experimental purposes, they may not fully represent the broader population. The participants in the online questionnaire studies are mostly young to middle-aged licensed drivers, which may limit the generalizability of the findings. Older drivers, for instance, might respond differently, perhaps more cautious or, conversely, relying more on explicit signals due to slower reactions to implicit ones. Moreover, the participants are based in Europe, given that driving cultures and communication norms can vary significantly across regions, the results may carry a cultural bias. Thus, future research should include a broader range of ages and cultural backgrounds, exploring whether the observed effects of AV kinematics and eHMI generalise across broader demographic and cultural contexts.

It should be noted that our studies were conducted on a static driving simulator, meaning participants did not experience motion or real physical feedback. This could limit how realistically they judged speed or distance, potentially making them rely more on visuals than they would in a real car. Similarly, many of the insights regarding drivers' subjective feelings, perceived safety, comprehensibility, trust, stress etc. are collected from self-report measures, which can differ from what they feel when actually encountering a moving vehicle. Participants might be more aggressive or more hesitant in the real world than they say on paper. Therefore, future studies should aim to increase realism by using motion-based driving simulators or conducting field experiments. This would allow researchers to better understand how physical sensations, environmental conditions, and perceived risk influence driver behaviour, factors that are difficult to fully replicate in controlled or static settings.

Finally, long-term exposure to AV interactions may influence human drivers' perceptions and performance over time. Future research should explore how repeated experience with AVs affects their subjective feelings, including perceived safety, trust, comprehension etc., and driving performance. By addressing this and other outlined areas, future studies can contribute to the development of more adaptive, effective, inclusive, and context-aware communication strategies that support the safe and seamless integration of AVs into everyday urban traffic environments.

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