You, Me, and the AV: Designing Interactions between Remote Operators of Autonomous Vehicles and Road Users

Felix Tener[1,*], Joel Lanir[1], and Avishag Boker[1]

[1] *University of Haifa, Ha-Namal 67, Haifa, 3303221, Israel*

Abstract

The advent of autonomous vehicles (AVs) presents both opportunities and challenges. While AVs promise enhanced traffic safety and efficiency by mitigating human errors, they also encounter complex, unpredictable scenarios - such as unusual road conditions, unexpected obstacles, or sensor failures - that challenge their autonomous decision-making. In addition, regulatory frameworks further necessitate human oversight in specific situations. Teleoperation, which allows remote human operators to assist or intervene when needed, has emerged as a critical safety and regulatory mechanism. While having various advantages, AVs introduce a critical communication gap with pedestrians and other road users (RUs). Without clear signaling, pedestrians may struggle to interpret an AV's intent, raising concerns about safety and trust. Research on external Human-Machine Interfaces (eHMIs) tackles this issue by enabling AVs to convey their status and intentions through various modalities such as lights, displays, or projections, facilitating safer interactions with their surroundings. The current research aims to investigate how eHMI solutions can be adapted for and integrated with teleoperation, enabling remote operators (ROs) to communicate with pedestrians and other RUs effectively. By bridging this gap, our work aims to enhance trust, safety, and the overall efficacy of AV interactions in real-world environments.

Keywords

Human-centered computing, Human-computer interaction, Interaction design, Automobile, Tele-operation, External human-machine Interfaces(eHMIs), Research through design, User-centered design, Human-AI collaboration.

1. Introduction

Recent strides in technological progress within domains such as computer vision, sensor fusion, and artificial intelligence have facilitated the rapid advancement of AVs as an innovative and transformative mode of transportation. Prominent automotive manufacturers, alongside emerging startups, are actively developing diverse cutting-edge technologies to realize AV's capability of independent operation. Nevertheless, the current state of AV development reveals their inability to handle every conceivable road scenario autonomously. Instances such as road construction, malfunctioning traffic lights, or a busy intersection might prevent an AV from moving autonomously [5–7,19,21,27].

Consequently, a consensus prevails across both academic and industrial circles that, in the foreseeable future, AVs will encounter traffic situations with inherent ambiguity that they cannot handle on their own, thus underscoring the need for remote human intervention [22,26]. An encouraging strategy for effectively addressing these scenarios and presenting a feasible solution for AVs in levels of automation 4 and 5 (i.e., no human driver in the vehicle) is Teleoperation.

AutomatinXP'25: Hybrid Automation Experiences, April 27, 2025, Yokohama, Japan. In conjunction with ACM CHI'25.
felix.tener@gmail.com (F. Tener); ylanir@is.haifa.ac.il (Y. Lanir); avishbo.uoh@gmail.com (A.Boker)
0000-0001-6376-3978 (F.Tener); 0000-0002-9838-5142 (Y.Lanir); 0009-0005-7689-8907 (A.Boker)

Teleoperation involves a remote human operator who can oversee and govern the vehicle's actions from a distance. When a car encounters challenges within specific contexts, the RO can be summoned to evaluate the circumstances and guide the car until the issue is resolved. Teleoperation can be done by monitoring one (or more) remote vehicles, taking over and driving the remote vehicle (tele-driving) when needed, or issuing high-level guidance to the remote vehicle (tele-assistance).

Several teleoperation systems for AVs are presently operational and are undergoing further research and refinement by diverse automotive enterprises (e.g., DriveU[1]).

For autonomous vehicles to be accepted by the public and integrated into urban traffic, it is critical that AVs can communicate and show their status and intent to pedestrians and other RUs. Surveys of the public's perception of AVs revealed concerns about safety, liability, and interaction with pedestrians and other RUs [12]. Besides controlling the vehicle's movements, driving is a social act that requires communication and understanding between all RUs to ensure traffic flow and guarantee safety [23]. Social interaction plays a vital role in resolving traffic ambiguities. For example, if a driver needs to enter a busy junction, she might wait for another driver's signal before entering. A small gesture or eye gaze often communicates this signal. Another example is a pedestrian crossing the street first making eye contact with the driver before crossing the road to ensure safe passage [11].

The current paper introduces and outlines the scope for a novel field of research: ways in which an AV controlled by a remote operator can communicate and interact with other RUs, such as pedestrians, cyclists, compound guards, law enforcement representatives, and drivers of manually operated vehicles (see Figure 1). Both communication of awareness of an AV (i.e., what it detects and identifies) and the communication of its intent (i.e., what actions the AV is about to take) are known to be critical for AVs to convey to other RUs [20]. Existing works have explored various mechanisms for AVs to communicate awareness and intent. These eHMIs include displaying text messages on external displays, using LED lights to convey messages, using laser projections on the street, using personalized messages for smart and wearable devices, and more [4]. We propose extending these works and exploring how a teleoperator, monitoring or controlling a remote vehicle, can use different eHMI interfaces to communicate with other RUs.

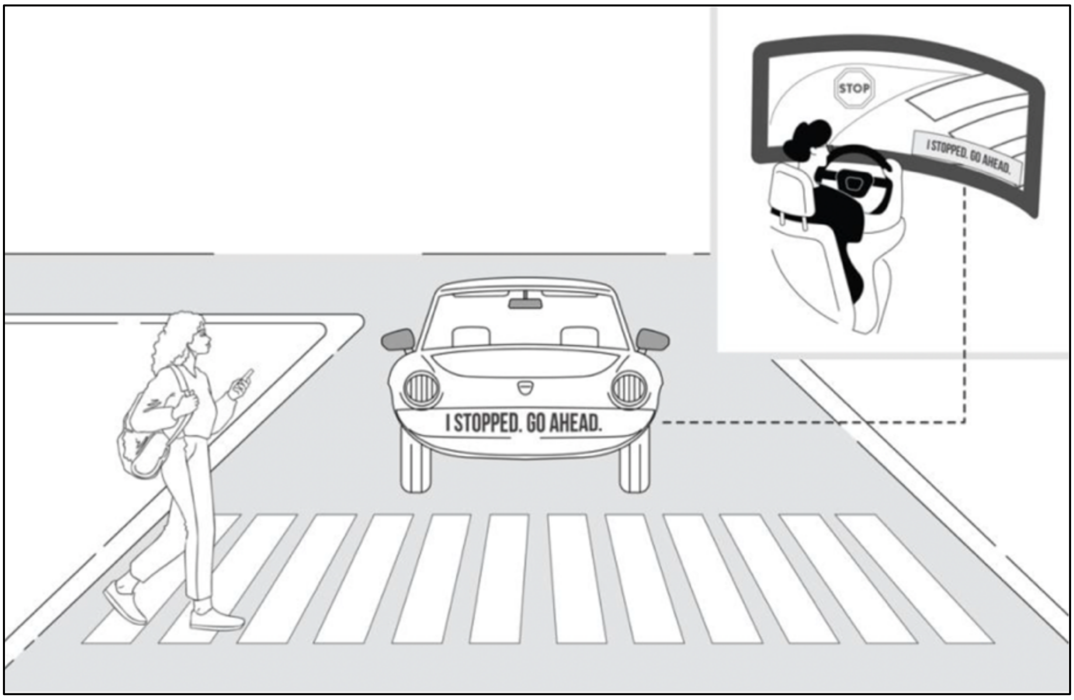

Figure 1. A teleoperator communicates AVs' intent to the pedestrian via an eHMI[2].

[1] https://driveu.auto/

[2] Designed using Freepik and Vectorjuice.

2. Theoretical Background and Previous Research

2.1. Teleoperation of autonomous vehicles

Autonomous vehicle teleoperation is a relatively new field of research. Although there might be long periods of self-driving in highly automated vehicles, it is widely acknowledged today that AVs cannot handle all road situations [22,27]. The underlying assumption is that there are many exceptional situations that a vehicle might encounter when driving. These situations may occur, for example, due to perception problems (i.e., bad weather), because the car encounters an unknown situation (i.e., an animal blocks the road), rules or regulations (need to cross a continuous separation line), or because the AV cannot unambiguously determine the situation. Furthermore, in automation level 4, the vehicle is still limited to some aspects, and regulations might require humans to perform certain actions. Despite the advancements in AV sensors and AI algorithms, humans still have higher-level interpretation skills for complex or novel situations. Thus, for a vehicle to operate in automation level 4 or 5, where no human is behind the steering wheel, an RO must be available to interpret edge case scenarios and remotely intervene when a problem occurs.

Teleoperation of AVs involves an RO who can oversee and govern the vehicle's actions from a distance. The RO can be located in a remote operation center and may assist many AVs during a single teleoperation shift. Various companies develop teleoperation systems for AVs today [10,31]. Companies such as Ottopia[3], Phantom.auto[4], and DriveU[5] are all developing teleoperation solutions that AV manufacturers can use to help get AVs on the road. Most of these stations focus on supporting remote driving using a teleoperation station that includes a steering wheel, pedals, and screens to show real-time video from several cameras, having the teleoperator remotely drive the vehicle. However, studies have shown that it is very challenging to drive vehicles remotely [26]. Issues such as latency, lack of physical sensing, impaired situational awareness, and cognitive load make remote driving challenging. Tele-assistance, or remote assistance as it is sometimes called, may alleviate some of these problems. In tele-assistance, the remote operator provides high-level guidance, entrusting the execution of low-level maneuvers to the AV. The operator still receives the video feed and information from the AV. However, remote vehicle control is done through interface commands rather than direct driving [2,8].

Several works investigated the requirements for AV teleoperation [9]. The following works have started looking at the design of such interfaces, designing prototypes and specific techniques for tele-assistance [13,28,29]. Among the issues raised, communication with pedestrians, drivers, and other RUs was highlighted as a major challenge for teleoperation [27,29].

2.2. External Human-Machine Interfaces

Much effort has been devoted to having AVs identify other Rus, such as pedestrians and cyclists, so vehicles can be aware of their presence, make decisions, and act accordingly [3]. However, it is also critical for pedestrians and other RUs to understand and anticipate the AV's behavior. Communication between drivers and pedestrians can help prevent accidents, reduce ambiguities, and increase trust [17]. Today, human drivers use various communication mechanisms such as hand gestures, eye contact, or vehicle aids such as honking or high beam lighting to convey their awareness and intent. However, as the role of the driver changes in an AV and does not necessarily require constant attention to the road and the surroundings, the driver may be engaged in non-driving tasks or might not be there at all, and therefore, a human might not be available to interact with other RUs [30].

To enhance communication between AVs and pedestrians or other RUs, various external human-machine interfaces have been proposed for highly autonomous vehicles [24,25]. These devices are

[3] https://ottopia.tech/
[4] https://phantom.auto/
[5] https://driveu.auto/product/driveu-300/

designed in multiple forms (displays on the vehicle showing texts or icons, LEDs, light bands, speakers, etc.). They can display various types of information, such as the vehicle's driving mode, the vehicle's intent, awareness of the pedestrians, and more [1,11]. Roughly speaking, there are four categories for eHMI devices: (1) Interfaces that reside on the vehicle; (2) Interfaces that reside on the vehicle and road infrastructure; (3) Interfaces that reside on the vehicle and the pedestrian (e.g., by using the mobile phone of the pedestrian to convey messages), and (4) Interfaces that reside in conjunction with the vehicle, street infrastructure, and the pedestrian. eHMIs were shown to positively affect perceived safety and trust and positively impact indicators such as pedestrian decision-making, gap acceptance, and crossing timing [14,15]. However, these effects were usually examined in simple scenarios, for example, with a typical scenario of a pedestrian trying to cross the road with an AV slowly approaching, signaling whether it is about to stop.

Given the variety of eHMIs, it remains unclear how a remote teleoperator can use them to communicate with pedestrians. A remote operator may have a broader view of the situation and may be able to convey more information to various RUs. For example, a remote operator who takes over an AV because of road construction may want to communicate to the road workers that he noticed the road markings and the workers. Another example is an RO who might want to communicate with a police officer who controls the traffic at an intersection with a malfunctioning traffic light, acknowledging that a human controls the AV. The fact that a remote human controls the AV changes the Human-Machine Interaction in an eHMI to a *Human-to-Human Interaction mediated through a machine*, as two humans communicate on both ends. This can allow a richer communication space than the simple and specific messages usually conveyed in eHMIs. We aim to explore this space, investigating the best ways technology supports this type of interaction.

3. Research Space Definition

The fact that a human-to-human interaction is mediated through a machine (AV) raises a multitude of research questions. However, most of these questions can be divided into three primary interconnected realms.

3.1. Defining the role of the machine in the interaction

We believe the AV can act as an enabler, an augmenter, or a mediator. When acting as an enabler, the AV enables the interaction between the RO and the RUs, similar to a telephone, which provides the necessary infrastructure to help two distant humans talk with one another. One example of such interaction can be video-based communication between an RO and a pedestrian, which is enabled through a video feed of the RO that may be displayed on top of the AV's windshield. Such an interaction resembles a video call via Skype or Zoom video conferencing tools, with the main difference being that the screen is placed on an AV.

When acting as an augmenter, the machine adds to the RO's capabilities without necessarily detaching between the RO and the RU. For instance, if the AV's road is blocked and the RO wants to bypass the obstacle, she might communicate her intention via an audio channel (e.g., say, "Bypassing from Left") and then plot an alternative route to bypass an obstacle. This route may be projected on the roadway to communicate the AV's intentions to pedestrians and other human drivers. In this example, the AV uses a computation and projection system that can translate a two-dimensional route, plotted using the RO's graphic user interface, into a light-based trajectory in the physical proximity of the AV. By doing so, the machine augments the human's communication capabilities but doesn't necessarily detach between the two humans.

On the contrary, when acting as a mediator, the machine mediates all communication, and there is no *direct* video or audio communication between the ROs and the RUs. For instance, the RO might type a message she wants to deliver to the pedestrians who are located around the vehicle, and the AV can display the message on the AV's body or designated screens. Another example is an RO's voice message that can be translated into a different dialect or language compatible with pedestrian needs.

The roles mentioned above may be predefined but can also be adaptive to the use case and the actors involved. For instance, the RO might start by typing a message visible on the car's body, making the AV a mediator. Nevertheless, if pedestrians do not correctly understand the message, the RO can choose to activate a direct communication channel, making the AV an enabler for more effective communication.

3.2. Designing the interaction method and user interface

The intervention scenario and the involved actors will dictate the interaction method and require specific affordances and communication channels from the system. For example, suppose the AV blocks someone's vehicle, and the blocked vehicle owner wants to talk with the RO to resolve the issue. In this case, there should be a way for the vehicle owner to initiate a conversation with an RO and a means for the latter to respond. This can be implemented, for example, with a button on the AV's body. Following the button press, an audio-based channel with an RO in the teleoperation station should be supported.

Another example is an AV's malfunction. Let's assume that the RO wants to notify all the surrounding road users about the problem and its estimated resolution time. One possible way is for the RO to type an appropriate message, which the AV can then project on a designated screen. Finally, if the RO wants to plot a route and project it on the road ahead of the AV, it should have a specialized projection system to support this.

While there are many possible intervention use cases [27] and a variety of creative ways to resolve them, it is evident that when designing teleoperation-eHMI solutions, one will have to consider (1) The Machine's role, (2) Interaction modalities (e.g., video channel), (3) The teleoperation station affordances, (4) The AVs interface with the surrounding world (e.g., projection lights), and possibly (5) The limitations (age, disabilities, etc.) and capabilities of the various road users that might be in contact with the AV.

3.3. Evaluating the influence of the interaction on the RO and the RUs

The interaction and interface design of the communication methods between the RO and the RUs can potentially affect RU's road behavior and ROs performance. Thus, it would be necessary to evaluate any designed solution thoroughly. First, exploring how design decisions influence trust, safety, and social dynamics is essential. For instance, do RUs trust AV technology more if direct video communication between the RO and RUs is enabled compared to if it is presented textually? What is the safest way to transmit a message from the RO to the RUs in an urgent situation? Will the RU's ability to talk with an RO through the machine change behavioral norms and social interactions? In other words, will it be normal for people to speak with AVs on the street?

Another interesting research angle is exploring the effect of the interactions mentioned above on the RO. How do design decisions influence RO's cognitive load, situational awareness, and efficiency? Is it more efficient to talk with a guard who should open a compound gate than type a message that will be projected on the AV-mounted screen? How do these types of interactions affect the RO's required skill set?

Finally, the interaction might influence and be influenced by ethical and regulatory considerations. It might not be clear who is legally and ethically responsible for misinterpretations or accidents arising from machine-mediated human interactions. Should there be global standards for AV-mediated communication, or should it be adaptable to different cultural and urban environments? How do privacy concerns impact live teleoperator communication (e.g., voice, video, personalized messages) in AVs? These and many other aspects of the interaction, along with the machine's role in it, may be explored in future research.

4. Conclusions

AVs are poised to revolutionize urban mobility by enhancing safety, reducing traffic congestion, and promoting sustainable transportation. However, to gain public trust and achieve seamless integration into urban environments, AVs must communicate effectively what they perceive and their intentions to RUs. eHMI is crucial for bridging this communication gap, ensuring AVs can seamlessly interact with pedestrians, cyclists, and drivers. While much AV research has focused on technical challenges such as perception, localization, and control, less emphasis has been placed on AV-human interaction, particularly in teleoperation. By integrating eHMIs into teleoperation systems, ROs can convey information and intent to pedestrians, cyclists, law enforcement, and other RUs. This approach transforms AV communication from a *machine-to-human* paradigm into *human-to-human interaction mediated through a machine*, fostering greater transparency, trust, and social acceptance of AV technology.

By bridging the gap between teleoperation, eHMI, and AV-RU interactions, we aspire to progress advancements in intelligent transportation systems. As AVs transition from experimental technology to widespread adoption, ensuring seamless human oversight and effective communication will be crucial in fostering public confidence and achieving safer, more efficient autonomous mobility.

Acknowledgments

This research was funded by the Israeli Ministry of Innovation, Science, and Technology through project number 0008064.

Declaration on Generative AI

During the preparation of this work, the author(s) used ChatGPT-4-turbo and Grammarly in order to: Grammar and spelling check. After using these tool(s)/service(s), the author(s) reviewed and edited the content as needed and take full responsibility for the publication's content.

References

[1] Claudia Ackermann, Matthias Beggiato, Sarah Schubert, and Josef F. Krems. 2019. An experimental study to investigate design and assessment criteria: What is important for communication between pedestrians and automated vehicles? *Applied Ergonomics* 75: 272–282. https://doi.org/10.1016/j.apergo.2018.11.002

[2] Daniel Bogdoll, Stefan Orf, Lars Töttel, and J. Marius Zöllner. 2021. Taxonomy and Survey on Remote Human Input Systems for Driving Automation Systems. Retrieved from http://arxiv.org/abs/2109.08599

[3] Long Chen, Shaobo Lin, Xiankai Lu, Dongpu Cao, Hangbin Wu, Chi Guo, Chun Liu, and Fei Yue Wang. 2021. Deep Neural Network Based Vehicle and Pedestrian Detection for Autonomous Driving: A Survey. *IEEE Transactions on Intelligent Transportation Systems* 22, 6: 3234–3246. https://doi.org/10.1109/TITS.2020.2993926

[4] Debargha Dey, Azra Habibovic, Andreas Löcken, Philipp Wintersberger, Bastian Pfleging, Andreas Riener, Marieke Martens, and Jacques Terken. 2020. Taming the eHMI jungle: A classification taxonomy to guide, compare, and assess the design principles of automated vehicles' external human-machine interfaces. *Transportation Research Interdisciplinary Perspectives* 7. https://doi.org/10.1016/j.trip.2020.100174

[5] Vinayak V. Dixit, Sai Chand, and Divya J. Nair. 2016. Autonomous vehicles: Disengagements, accidents and reaction times. *PLoS ONE* 11, 12. https://doi.org/10.1371/journal.pone.0168054

[6] Francesca Favarò, Sky Eurich, and Nazanin Nader. 2018. Autonomous vehicles' disengagements: Trends, triggers, and regulatory limitations. *Accident Analysis and Prevention* 110: 136–148. https://doi.org/10.1016/j.aap.2017.11.001

[7] Jiacheng Feng, Shengbo Yu, Guihua Chen, Weijie Gong, Qiao Li, Juejian Wang, and Haiting Zhan. 2020. Disengagement causes analysis of automated driving system. *Proceedings - 2020 3rd World Conference on Mechanical Engineering and Intelligent Manufacturing, WCMEIM 2020*: 36–39. https://doi.org/10.1109/WCMEIM52463.2020.00014

[8] Frank Ole Flemisch, Klaus Bengler, Heiner Bubb, Hermann Winner, and Ralph Bruder. 2014. Towards cooperative guidance and control of highly automated vehicles: H-Mode and Conduct-by-Wire. *Ergonomics 57*, 343–360. https://doi.org/10.1080/00140139.2013.869355

[9] Gaetano Graf, Henri Palleis, and Heinrich Hussmann. 2020. A Design Space for Advanced Visual Interfaces for Teleoperated Autonomous Vehicles. *ACM International Conference Proceeding Series*. https://doi.org/10.1145/3399715.3399942

[10] GreyB. 2021. Top 30 Self Driving Technology and Car Companies. Retrieved from https://www.greyb.com/autonomous-vehicle-companies/#

[11] Michal Hochman, Yisrael Parmet, and Tal Oron-Gilad. 2020. Pedestrians' Understanding of a Fully Autonomous Vehicle's Intent to Stop: A Learning Effect Over Time. *Frontiers in Psychology* 11. https://doi.org/10.3389/fpsyg.2020.585280

[12] Howard Daniel and Dai Danielle. 2014. *Public Perceptions of Self-driving Cars*. Washington DC. Retrieved February 3, 2025 from https://www.ocf.berkeley.edu/~djhoward/reports/Report%20-%20Public%20Perceptions%20of%20Self%20Driving%20Cars.pdf

[13] Carmen Kettwich, Andreas Schrank, and Michael Oehl. 2021. Teleoperation of highly automated vehicles in public transport: User-centered design of a human-machine interface for remote-operation and its expert usability evaluation. *Multimodal Technologies and Interaction* 5, 5. https://doi.org/10.3390/MTI5050026

[14] Lars Kooijman, Riender Happee, and Joost C.F. de Winter. 2019. How do eHMIs affect pedestrians' crossing behavior? A study using a head-mounted display combined with a motion suit. *Information (Switzerland)* 10, 12. https://doi.org/10.3390/info10120386

[15] Yee Mun Lee, Ruth Madigan, Chinebuli Uzondu, Jorge Garcia, Richard Romano, Gustav Markkula, and Natasha Merat. 2022. Learning to interpret novel eHMI: The effect of vehicle kinematics and eHMI familiarity on pedestrian' crossing behavior. *Journal of Safety Research* 80: 270–280. https://doi.org/10.1016/j.jsr.2021.12.010

[16] Yang Li, Hailong Liu, and Barbara Deml. 2022. HMI-based Communication Methods for Negotiation between a Manually Driven Vehicle Driver and an Autonomous Vehicle in an Ambiguous Traffic Scenario. In *2022 IEEE/SICE International Symposium on System Integration, SII 2022*, 244–249. https://doi.org/10.1109/SII52469.2022.9708797

[17] Dokshin Lim and Byungwoo Kim. 2022. UI Design of eHMI of Autonomous Vehicles. *International Journal of Human-Computer Interaction* 38, 18–20: 1944–1961. https://doi.org/10.1080/10447318.2022.2061123

[18] Dokshin Lim and Yongwhee Kwon. 2023. How to Design the eHMI of AVs for Urgent Warning to Other Drivers with Limited Visibility? *Sensors* 23, 7. https://doi.org/10.3390/s23073721

[19] Chen Lv, Dongpu Cao, Yifan Zhao, Daniel J. Auger, Mark Sullman, Huaji Wang, Laura Millen Dutka, Lee Skrypchuk, and Alexandros Mouzakitis. 2018. Analysis of autopilot disengagements occurring during autonomous vehicle testing. *IEEE/CAA Journal of Automatica Sinica* 5, 1: 58–68. https://doi.org/10.1109/JAS.2017.7510745

[20] Karthik Mahadevan, Sowmya Somanath, and Ehud Sharlin. 2018. Communicating awareness and intent in autonomous vehicle-pedestrian interaction. *Conference on Human Factors in Computing Systems - Proceedings* 2018-April: 1–12. https://doi.org/10.1145/3173574.3174003

[21] Mario Herger. 2024. 2023 Disengagement Reports from California. *https://thelastdriverlicenseholder.com/2024/02/03/2023-disengagement-reports-from-california/*. Retrieved August 26, 2024 from https://thelastdriverlicenseholder.com/2024/02/03/2023-disengagement-reports-from-california/

[22] Clare Mutzenich, Szonya Durant, Shaun Helman, and Polly Dalton. 2021. Updating our understanding of situation awareness in relation to remote operators of autonomous vehicles. *Cognitive research: principles and implications* 6, 1: 1–17.

[23] Amir Rasouli and John K. Tsotsos. 2020. Autonomous vehicles that interact with pedestrians: A survey of theory and practice. *IEEE Transactions on Intelligent Transportation Systems 21*, 900–918. https://doi.org/10.1109/TITS.2019.2901817

[24] Alexandros Rouchitsas and Håkan Alm. 2019. External Human–Machine Interfaces for Autonomous Vehicle-to-Pedestrian Communication: A Review of Empirical Work. *Frontiers in Psychology 10*. https://doi.org/10.3389/fpsyg.2019.02757

[25] Anna Schieben, Marc Wilbrink, Carmen Kettwich, Ruth Madigan, Tyron Louw, and Natasha Merat. 2019. Designing the interaction of automated vehicles with other traffic participants: design considerations based on human needs and expectations. *Cognition, Technology and Work* 21, 1: 69–85. https://doi.org/10.1007/s10111-018-0521-z

[26] Felix Tener and Joel Lanir. 2022. Driving from a Distance: Challenges and Guidelines for Autonomous Vehicle Teleoperation Interfaces. 1–13. https://doi.org/10.1145/3491102.3501827

[27] Felix Tener and Joel Lanir. 2023. Investigating intervention road scenarios for teleoperation of autonomous vehicles. *Multimedia Tools and Applications*. https://doi.org/10.1007/s11042-023-17851-z

[28] Felix Tener and Joel Lanir. *Toward the Design of a Tele-assistance User Interface for Autonomous Vehicles*. Retrieved from https://www.dmv.ca.gov/portal/

[29] Felix Tener and Joel Lanir. *Guiding, not Driving: Design and Evaluation of a Command-Based User Interface for Teleoperation of Autonomous Vehicles*. Retrieved from https://www.sae.org/

[30] Victor Malmsten Lundgren, Azra Habibovic, Jonas Andersson, Tobias Lagström, Maria Nilsson, Anna Sirkka, Johan Fagerlönn, Rikard Fredriksson, Claes Edgren, Stas Krupenia, and Dennis Saluäär. 2016. Will There Be New Communication Needs When Introducing Automated Vehicles to the Urban Context? 485–497.

[31] Tao Zhang. 2020. Toward Automated Vehicle Teleoperation: Vision, Opportunities, and Challenges. *IEEE Internet of Things Journal* 7, 12: 11347–11354. https://doi.org/10.1109/JIOT.2020.3028766