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Designing cooperative interaction of automated vehicles in mixed traffic environments: Insights from the interACT project

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Abstract As Automated Vehicles (AVs) will be deployed in mixed traffic, they need to interact safely and efficiently with other traffic participants. The EU H2020 project interACT works towards the safe integration of AVs into mixed traffic environments. In this paper, we summarize the main objectives of the project and the results achieved to date. Starting from the observation and modelling of human-human interactions in urban environments, we improved the intention and behaviour recognition algorithms for the AV, worked on the core intelligence of the vehicle – the Communication and Cooperation Planning Unit – and designed new external and internal HMI concepts to communicate with surrounding traffic participants and promote safe interaction. The results of the project are evaluated by using new evaluation methodologies to assess the cooperation quality of the AV.

Keywords: Automated vehicles, human behaviour models, external HMI, vehicle intelligence, intention recognition algorithms

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1. Designing cooperative interaction of Automated Vehicles: Introduction

There is currently a strong desire by manufacturers to introduce Automated Vehicles (AVs) to the market. As AVs are likely to be deployed in mixed traffic, they need to interact safely and efficiently with other road users, including other vehicles, cyclists, and pedestrians. Although obstacle detection by AVs is almost flawless, currently AVs cannot communicate their intentions to other road users. This limitation reduces their appeal and value to the user. To ensure intuitive and cooperative interaction between AVs and others, and a smooth flow of traffic, it is essential that there is good means of communication between all actors – the AV, the on-board user, and the other road users (Fig. 1).

Fig. 1 Future interaction needs of the on-board user and other traffic participants when interacting with an AV in mixed traffic environments

This is exactly the focus of the EU H2020 project interACT (https://www.interact-roadautomation.eu/). In the following sections, the main objectives and results of the project to date are summarized.

2. Safe integration of AVs in mixed traffic

The project interACT enables the safe integration of AVs (SAE level 3 and higher) into mixed traffic environments by designing, implementing, and evaluating solutions for safe, cooperative, and expectation-conforming interactions between AVs and both its on-board driver and other traffic participants. Five main objectives were outlined to achieve the main goals of interACT as follows (Fig. 2):

1. **Observation of human interactions, and development of psychological models** covers the modeling of interaction between different road users that helps designing and selecting appropriate and safe interaction strategies for AVs;
2. **Assessment of intentions, and predicting the behaviour of other traffic participants** in order to achieve efficient cooperation between road users;
3. **Development of the Cooperation and Communication Planning Unit (CCP Unit)** to enable the integrated planning and control of AV’s behaviour, and the provision of time-synchronized Human Machine Interfaces (HMI) for both the user on-board and surrounding road users;
4. **Design of human-vehicle interaction** to assist the interaction of the on-board user, the AV, and other road users, by implicit and explicit HMI;

5. **Definition of new evaluation methodologies** to assess the interactions of road users with AVs, and investigate user acceptance, and safety, while studying the impact of these interactions on traffic flow for those vehicles.

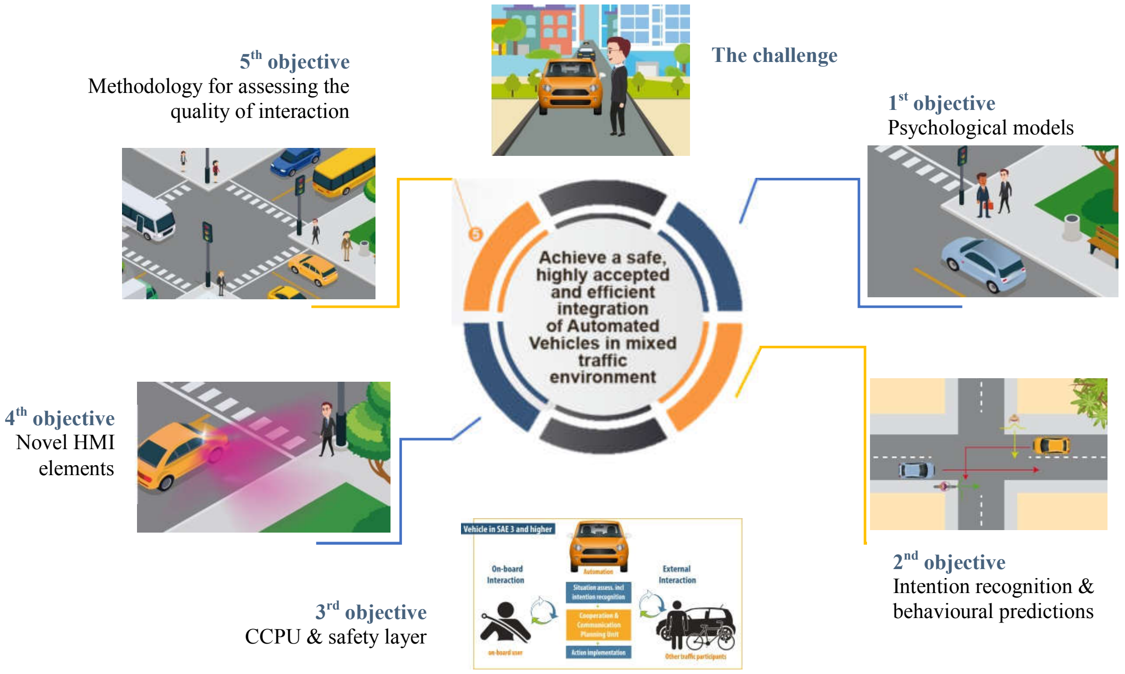

Fig. 2 The five main objectives of the interACT project

3. Results achieved in the interACT project

3.1. Definition of use cases and scenarios

As the natural traffic environment creates a variety of traffic scenes, we began the project by considering a manageable number of, less complex, relevant use cases and scenarios that an would involve interactions between AVs and other road users. The interACT project decided to focus on urban environments as we can observe and research the most interaction-demanding situations for AVs and other traffic participants in such settings. The use cases and scenarios were selected based on their relevance for safety, frequency of occurrence, influence on traffic flow and the need for interaction with other human road users. The final main use cases for the project are those that involved the interaction of AVs with other manually driven vehicles, pedestrians or cyclists a) at non-signalized intersections and b) in parking spaces (Wilbrink et al., 2017). Fig. 3 shows two typical scenarios: An interaction of the AV with a relevant traffic participant (TP 1) at an intersection (while TP 2 is not classified as relevant) and an interaction with multiple pedestrians in a parking space. These scenarios were also modelled and provided in *CommonRoad* (Althoff et al., 2017).

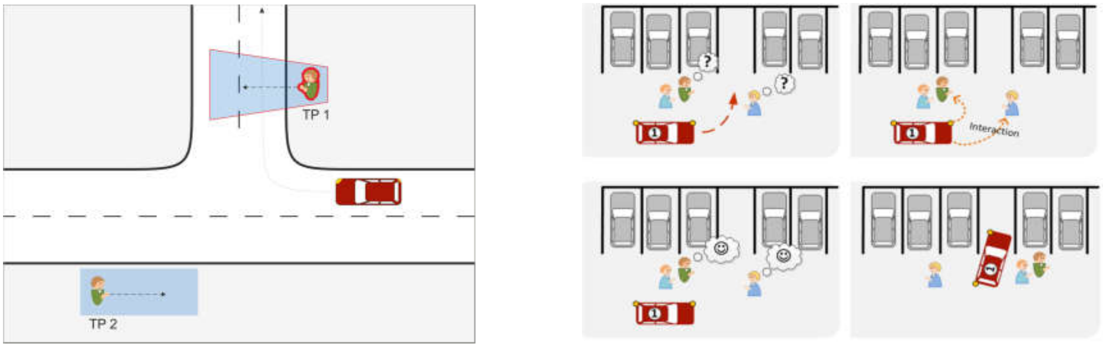

Fig. 3 Example of selected scenarios at a non-signalized intersection with one relevant traffic participant (TP1, left) and parking scenario with multiple relevant interaction partners (right)

3.2. Psychological models on human-human interaction

Across three European countries (Germany, Greece, and the UK), data were collected on how human participants interact in real traffic conditions. The observation sites were chosen in a way that they covered the project use cases. Data from video cameras, light detection and ranging (Lidar), questionnaires, observation protocols, and from a field driving study with an eyeglass mounted gaze sensor, and retrospective commentary, were recorded. In total, over 100 observation protocols per use case and country as well as a combined 100 hours of video and LiDAR data were collected. Over 150 pedestrians were interviewed to give insights into how they perceive interactions in traffic.The main outcome of the observational studies can be summarized as follows (see Dietrich and Ruenz, 2018, Dietrich et al., 2018, Dietrich et al., 2019, Markkula et al., 2018, Portouli et al., 2019):

- As depicted in Fig. 4 we classified human interaction behaviour in traffic into four main types of behaviour: *movement-achieving, movement-signaling, perception-achieving,* and *perception-signaling* behaviour. These helped us to describe the observed interaction behaviour of humans in traffic.

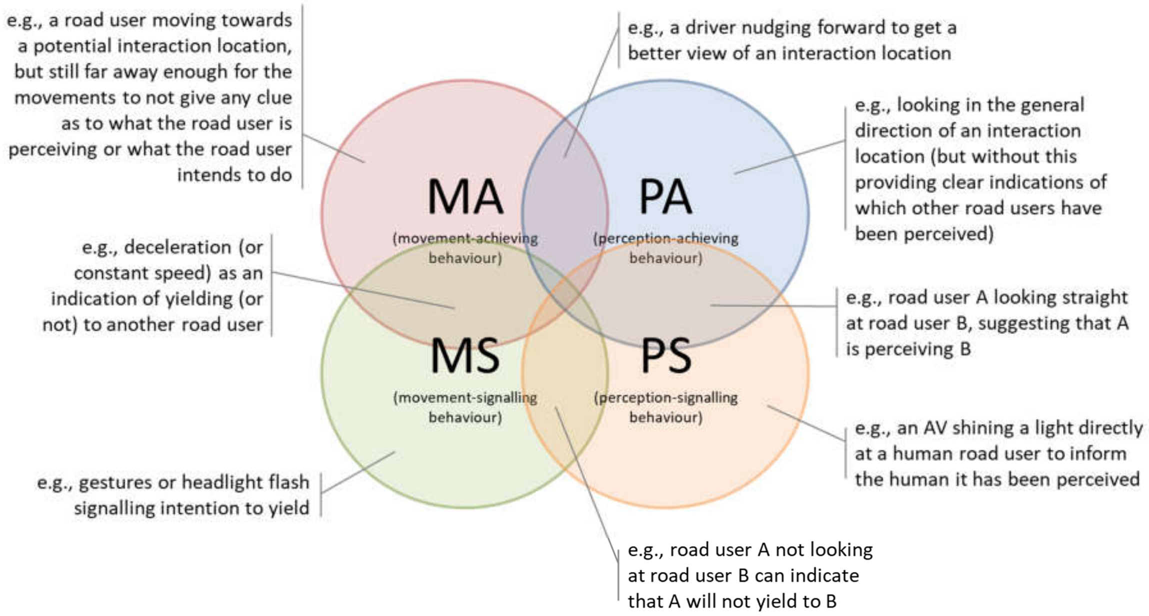

Fig. 4 Classification of human interaction behaviour in mixed traffic

- Further, we built psychological models on human-human interaction, showing that pedestrians had a tendency to base their decisions mainly on the vehicle behaviour, using explicit communication methods, such as gestures, mainly in ambiguous, slow-speed traffic situations. In general, the specific traffic situation and situational factors play an additional role in such communication, such that drivers showed more cooperative behaviour when they had to stop or slow down due to a red traffic light or traffic congestions. As an example, Fig. 5 shows a view generated by the Lidar, with velocities in km/h written above the trajectory. The top left image shows that the initial velocities of the two highlighted vehicles on the main road are comparable. However, the driver in the second vehicle sees the waiting traffic on the side road, and decides to increase his headway by not accelerating (top right). The headway increases to approximately 25m (bottom left) and the gap is accepted by the waiting driver on the side road (bottom right). Sometimes, the driver of the yielding vehicle supported this interaction by using an explicit signal, such as a headlight flash. This observation revealed that communication and interaction only seems to occur during congestions, where the velocity is greatly reduced due to high traffic density. A velocity threshold for such interactions is considered to be between 25 and 35 km/h. Below this threshold, road users were likely to let others merge in congested situations, whereas, above the threshold, drivers on the main road rarely decelerated to create sufficient gaps for pedestrians and other vehicles.

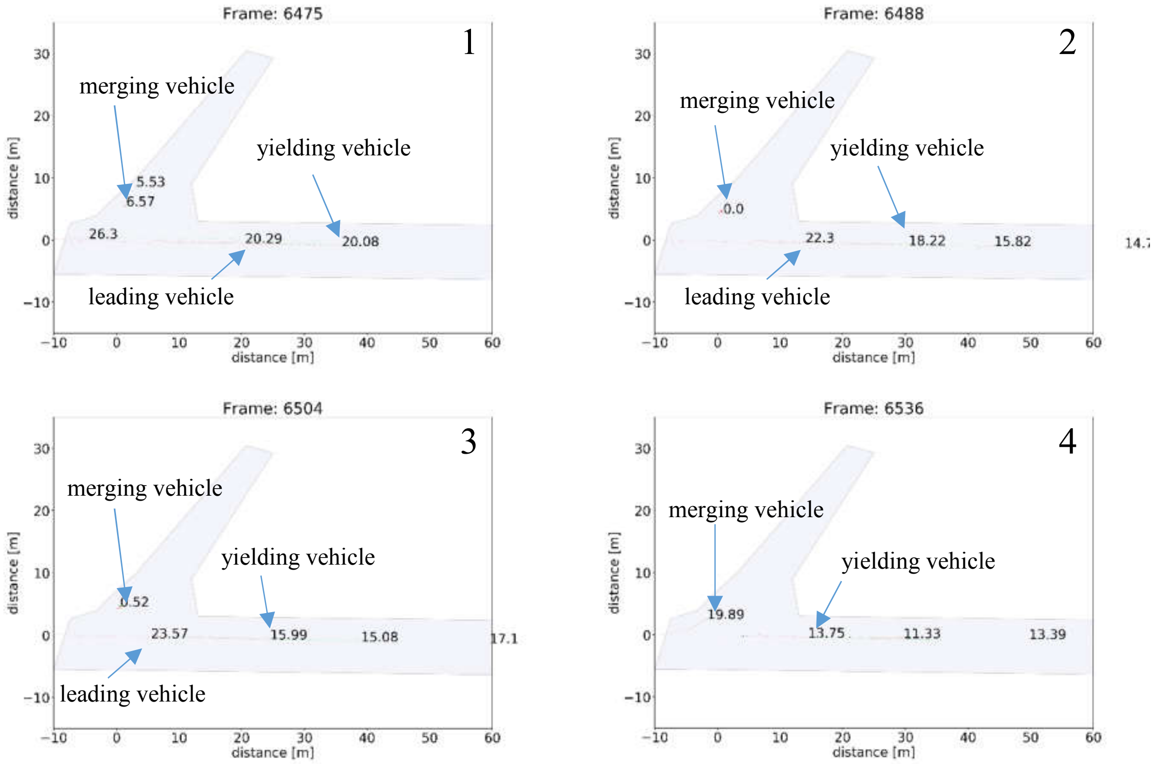

Fig. 5 Typical behaviour sequence of a driver on the main road increasing the headway to let another vehicle from the side road merge (numbers represent velocity in km/h) (Dietrich et al., 2019)

- Finally, we developed quantitative models of human road user behaviour that predict the timing of pedestrian crossing and vehicle turning decisions, as a function of the behaviour of an approaching (automated) vehicle. These models are provided as software models and can be used in virtual development and testing of AVs.

The psychological models on human-human interaction guided the development of the intention recognition algorithms for the AV, the AV’s behaviour, as well as the design of new internal and external HMI (iHMI and eHMI) (see sections 3.3, 3.4 and 3.5).

3.3. Intention recognition and behavioural predictions

For the correct interpretation of the traffic scenario, and the adjustment of the AV behaviour, the AV needs to assess intentions of other traffic participants. Therefore, a new method was introduced, which is suitable for both long-term and short-term prediction of pedestrian behaviours, based on Markov chains (Fig. 6). With an intrinsic pedestrian model, interaction models with other traffic participants, automatic goal estimation, and a semantic map, a spatiotemporal position prediction is provided (Wu et al., 2018). Furthermore, a method to determine optimized model parameters for both, position prediction accuracy, as well as classification accuracy for pedestrian crossing, was developed (Wu et al., 2019).

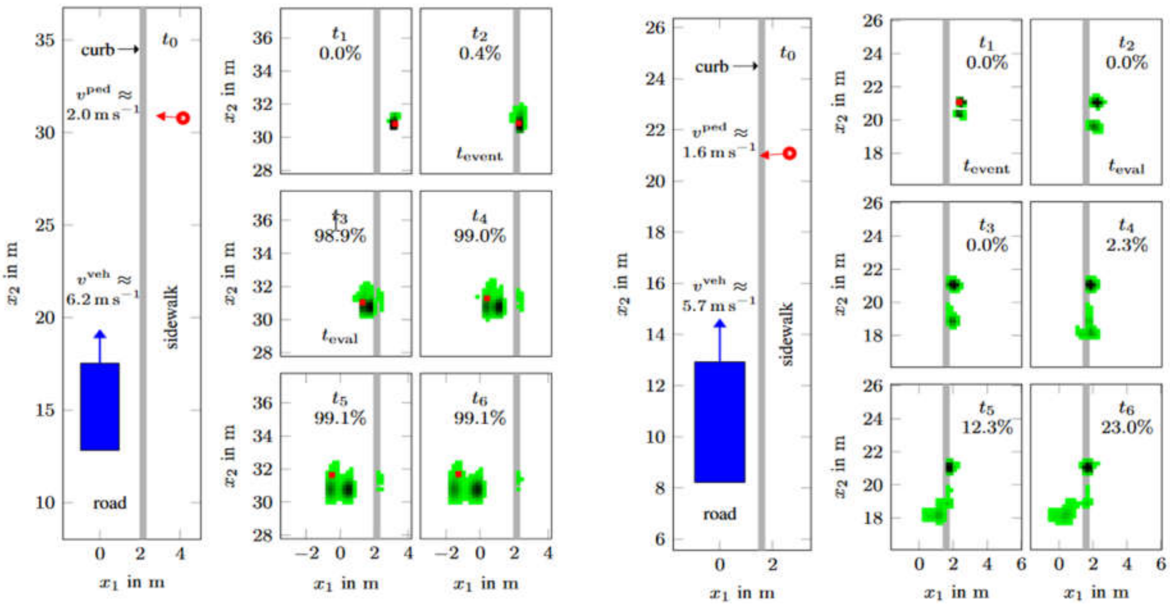

Fig. 6 Example of the pedestrian intention recognition: Pedestrian crossing scenario (left); pedestrian stopping scenario (right) (Wu et al., 2019)

To further analyze pedestrian intention features, such as head orientation, and hand waving gestures of pedestrians, AI-based algorithms and datasets were developed to detect these features automatically, from video and radar measurements. Further, the head orientation and hand waving gestures of the pedestrians were detected and analyzed.

The project also worked on intention recognition for motorized traffic participants. Motion model-based trajectories are reliable only for prediction horizons of, at most, 2 seconds, while by introducing the vehicle intention in the prediction, this horizon is extended. Two components have been developed for this intention recognition:

1. The *motorised traffic participants' (TP) intention feature recognition* recognises the intentions of the motorised TPs that are perceived by the AV. The term *intention* of a motorised TP is referring to the next *manoeuvre* that is expected to be performed by its driver. This is determined considering mainly its kinematic state (e.g. velocity, heading), its signals (e.g. turn indicator is flashing), the road topology (e.g. traffic signs, existence of adjacent lanes), possible interactions with other TPs (e.g. vehicle in front is slowing down), and the behaviour of its driver (e.g. head movement, driving style). Each possible intention was interpreted as a (hidden) vehicle state, the transition probabilities between all states have been defined, and the whole system was modelled as a Bayesian network that calculates the possible intentions of each motorised TP.
2. The second component, named *TPs' behaviour prediction*, predicts the motorised TPs' trajectories, based on their recognised intentions. The intention-based trajectory is created by considering the vehicle's intention, and the road topology, and the final predicted category is calculated as a combination of the motion-based and intention-based trajectories.

3.4. Cooperation and Communication Planning Unit

For the core intelligence of the AV, the Cooperation and Communication Planning Unit (CCPU) was developed, to enable the AV to behave and interact with its on-board user, and the surrounding traffic participants, according to their expectations. Taking into account gestures, anticipated intentions, and the predicted behaviour of surrounding traffic participants, the CCPU provides an expectation-conforming, safe, plan for the future motion of the AV, optimizing its interactions with other TPs and its on-board user. To achieve this goal, the CCPU has been split into four software components (Fig. 7), namely the *Situation Matching*, the *Interaction Planning*, the *Trajectory planning*, and the *Safety Layer* (Drakouli et al., 2018).

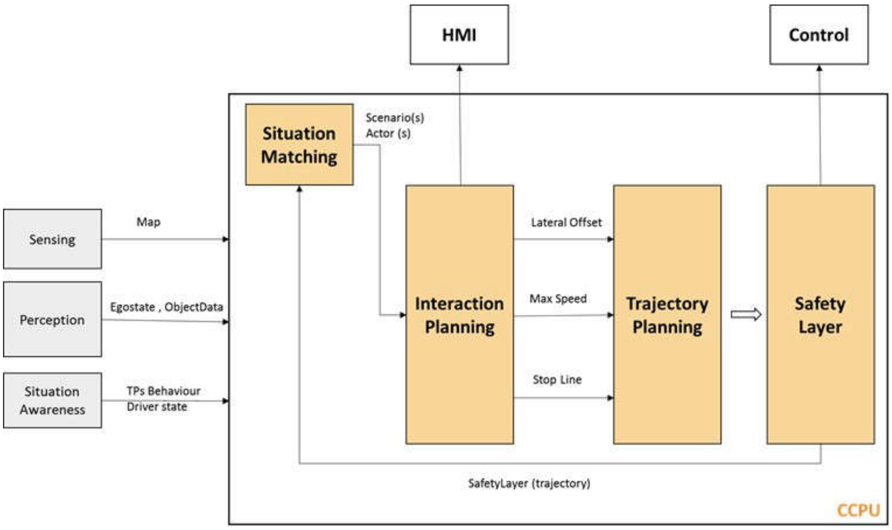

Fig. 7 Architecture of the CCPU

The functionality of the software components has been supported by two data enablers: the digital *Scenario Catalogue* and the *Interaction Strategies Catalogue*. The *Situation Matching* is responsible for recognizing a potential conflict situation between the AV and surrounding TPs. It processes the following information: Other traffic participants' intention-related data, which is provided by the *Situation Awareness* module, AV kinematics data, provided also by the *Perception* module, and the map information, which is provided indirectly via the motion state and the predicted trajectories of all actors. The *Situation Matching* output is transmitted to the *Interaction Planner*, which can deduce the exact occurring sub-scenario from the *Scenarios Catalogue*.

The *Interaction Planner* loads the map file, the route file and calculates the route on the given map. Furthermore, it checks whether the current plan is still applicable in the current situation, or if a complete re-planning is necessary. The plan generation submodule takes over the actual planning process by implementing the behaviour patterns that represent the interaction strategies enablers. It takes the abstract inputs, runs them through fuzzy controllers for each other traffic participant, and combines the different plans into one plan. This abstract data is then returned to the environment submodule to convert it back into environment values.

After that, a constraint and HMI management submodule organizes both the constraints for the *Trajectory Planning* module and the instructions for the *HMI controllers*. It sends regular updates about relative positions of other TPs to the *HMI controllers* and deletes constraints of the *Trajectory Planning* module if necessary. Additionally, it takes into account explicit HMI instructions that are only dependent on the current state of the AV, and do not take into account other traffic participants.

Receiving inputs for the aforementioned modules and information on the environment from the map and from the sensors, the *Trajectory Planning* module computes both the long-term and the short-term trajectory of the AV.

Finally, the *Safety Layer* receives the long-term trajectory planned by the *Trajectory Planner* along with the future path, the measured states and shapes of all static and dynamic obstacles from the *Perception* module, and the current state of the ego vehicle. In the first step, the set-based predictions for all dynamic obstacles are computed. Subsequently, the fail-safe planner computes the fail-safe trajectory which branches off from the long-term trajectory, and avoids all set-based predictions of other traffic participants (Althoff and Lutz, 2018; Koschi et al., 2018). In case the long-term trajectory is found to be safe, it is forwarded as the output of the *Safety Layer*; otherwise, the fail-safe trajectory is engaged.

3.5. Novel HMI elements

The project team also developed the overall interaction strategies and HMI solutions to govern the interaction and communication between the AV and the on-board user, as well as that between the AV and surrounding human road user, including pedestrians and drivers of other vehicles (Wilbrink et al., 2018 and Weber et al., 2019). Based on general design considerations by Schieben et al. (2018) two interaction strategies – the perception-based and the intention-based communication strategy – were developed. While the perception-based design provides information on the detected interaction partners in the environment to the on-board user and surrounding traffic participants, the intention-based design informs about the current and next manoeuvres of the

AV. For the eHMI solutions, the technical development in the project focused on a 360° light band, installed on the vehicle body and a directed signal lamp, to indicate that a specific traffic participant is detected (Fig. 8).

Fig. 8 eHMI variants – 360° light band (left) and directed signal lamp (right) for the interACT demonstrators

The results of several user studies with more than 100 participants in pedestrian (Fig. 9) and driving simulators helped the project partners to establish which interaction strategies are most promising with regard to the traffic participant's behaviour, and their subjective acceptance of these interfaces (Lee et al., 2019; Kettwich et al., 2019, Schieben et al., 2019, Weber et al., 2019). Results showed that there was no clear preference in the interaction strategies (intention-based vs perception-based) and both designs were well accepted by the participants of the studies. All eHMI designs provided useful information to pedestrians, and drivers of manually driven vehicles, for all the interACT urban scenarios tested, whereby the presence of the eHMI was more informative than a "no eHMI" conditions, in terms of assisting with crossing decisions. The subjective ratings showed that participants experienced a safer, and more comprehensible, interaction with the AV, when eHMI was used for the AV, compared to a baseline condition with no eHMI.

Fig. 9 Testing different eHMI variants in a VR pedestrian simulator, using a Head Mounted Display

3.6. Integration into demonstrator vehicles

As we approach the end of the interACT project, the project partners are integrating the developed software and hardware modules (see section 3.2, 3.3, 3.4) into two interACT demonstrator vehicles, a BMW i3s and a Fiat JEEP Renegade (developed by CRF). The main focus of the BMW demonstrator is the integration of different eHMI hardware components for evaluation studies. The CRF demonstrator will focus on the integration of the fully functional perception platform and the CCPU (Fig. 10).

Fig. 10 BMW prototype vehicle (left) and CRF prototype vehicle (right)

3.7. Methodology for assessing the quality of communication and interaction

To test the effects of our new interaction strategies, on human behaviour, and the on-board user, interACT partners worked on a series of evaluation methodologies. These use multi-actor experiments in simulated environments, such as pedestrian simulators, studies with head mounted displays, and driving simulators. Crossing decisions and behaviours of pedestrians are evaluated by using objective measures (e.g. Lee et al., 2019b). Other methods such as real-world scenarios are also be used, to evaluate the behaviour of the other traffic participants, and the on-board user, when interacting with AVs equipped with the interACT modules and components. Evaluation of the vehicles (see Fig. 10) are being achieved in Munich and Turino, in real-world and test track settings. Further, the impact of the interACT prototypes on road safety, traffic flow, cooperation, road design, traffic signal, and infrastructure needs are evaluated to determine how the addition of newly designed interaction elements and the adjusted trajectory planning may help with the better integration and acceptance of AVs in future traffic.

4. Summary and Outlook

The results of the interACT project significantly support the short-term introduction of AVs in mixed traffic environments on several levels. User needs have been considered right from the beginning of the project, starting with the real-life observation of humans in current urban scenarios, followed by several user-focused tests to increase user acceptance and trust. The project solutions are designed to improve the awareness of on-board users and surrounding traffic participants about the AV's intentions and maneuvers as well as to technically ensure fail-safe maneuvers of the AV and by this, to promote safe interaction of AVs in urban settings. Intention recognition algorithms were further developed to understand the intention of surrounding traffic participants and to allow the AV to enhance its situation awareness, while the software unit of the CCPU calculates the control of vehicle movements, which is, for the first time, integrated with the vehicle's eHMI and iHMI elements. The interACT project results are evaluated and demonstrated by two demonstrator vehicles, and several research simulators. Due to the significant involvement of industrial partners, it is ensured that the project findings are fully exploited, to help increase the potential safety benefits, sales, and adoption of AVs.

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