









## A Virtual Reality-based Platform to Validate HMI Design for Increasing User's Trust in Autonomous Vehicle

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**Abstract.** This research aims at providing an example of how Virtual Reality technology can support the design and development process of the Human Machine Interaction system in the field of Autonomous vehicles. The autonomous vehicles will be an important role in the future's daily life, as widely concerned. However, the relationship between the human user and the vehicle changes in the autonomous driving scenario, therefore a new interactive modality should be established to guarantee the operational precision and the comfort of the user. But as an underdevelopment sector, there are no mature guidelines for the interaction design in autonomous vehicles. In the early phase of the autonomous vehicle popularization, the first challenge is to build the trust of the user towards the autonomous vehicle. Keeping high transparency of the autonomous vehicle's behavior to the user will be very helpful, however, it is not possible to communicate the information that the sensors of the autonomous vehicle are collecting because it can create safety risks. In this research, two hierarchical Human Machine Interaction information systems have been introduced and a virtual reality scenario has been developed, based on the most popular applying scenario: the autonomous taxi. Possible verification methods are also discussed to apply the tool, considering the current design and development procedure in industry, in order to give constructive help to the researchers and practitioners in the field.

**Keywords:** Virtual Reality, VR, Autonomous Vehicle, Fully autonomous vehicle, Human Machine Interaction, HMI design.

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## 1 INTRODUCTION

Automation of the vehicles has been changing human driving habits. In the high-level automated driving, due to the fact of driving task falling onto the technical agent other than the human driver, the Human Machine Interaction (HMI) varies from the driving experience in conventional vehicles, which might create gaps between the autonomous control and the human's control when necessary, such as under emergency[12]. In a 2018 fatal car crash, Tesla's semi-autonomous driving feature, 'Autopilot' had been activated by the rider while he was engaged in a smartphone video game. In the recently published investigation result by the US National Transportation Safety Board (NTSB)[41], Tesla was partially blamed by overstating its vehicle's autonomous capabilities, and the victim had been over-reliant on the software of Autopilot[40]. There were also other accidents of Tesla caused by the same reason: the users did not act as instructed to keep their hands on the steering wheel during the autonomous driving mode was activated. Failure in the HMI design leads to misuse[39]. On the other hand, in several studies, it has been revealed that people are negatively predisposed toward utilizing an autonomous vehicle [25][48][31][1]. It implies that an appropriate way of communicating between the user and autonomous driving vehicle is necessary for on-road safety and comfort.

Fully autonomous vehicles free users from the driving task so that they can engage in non-driving-related-tasks (NDRTs) during their journeys. More possibilities are given to the automobile designer to create car interior infrastructure and interactions less connected to the car movement control[50]. General Motor and Honda, have unveiled their conceptual autonomous car 'Cruise Origin' at the beginning of the year[15]. It is a six-seated electric vehicle that has no steering wheel, brake or accelerator pedals, and the layout of the seats is re-designed in the way that there is no obvious front or back. The prototype car of Mercedes-Benz 'F 015 Luxury in Motion' presents a rotating seat solution, giving the possibility of transforming among working space, lounge, and living space. With six displays mounted in the instrument panel and the rear and sidewalls, a continuous exchange of information between vehicle, users and the outside world can be realized[28]. Most of the leading OEMs of the automobile have launched their autonomous car concepts, but till now, there are no HMI design details on the exchanging of the information in such a scenario. Researches have been done focusing on the single elements of constructing a trustful driving experience: A survey study by demonstrating simulated videos with different types of communicating features in an autonomous car, suggests that colored lights are not suitable for explaining the state of the autonomous vehicle, while the features in pictures are explicit[11]. The authors also suggested introducing the audio features in HMI design. A framework for HMI design is proposed aiming at creating appropriate trust in semi-autonomous vehicle systems (Level 3) [13], in a more comprehensive way, incorporating usage phases, autonomous driving events, trust affecting factors, and levels explaining each event from a trust perspective. In this paper, with a similar approach, two potential frameworks of HMI design in fully autonomous vehicles will be introduced, following two different logics, and finally implemented into virtual reality scenarios for preliminary configuration, visual realization, and preparation for the user evaluation.

Virtual Reality technology has been used in the preliminary configuration for design method development for an assembly line[33]. It is also introduced as a user test tool in a study focus on increasing trust in fully automated driving, which evaluated 5 scenarios with different Augmented Reality User Interfaces, and the authors found that feedback about the system state, particularly in the form of route information increased trust significantly in Autonomous Vehicles[43]. This study demonstrated the applicability of virtual reality technology in the fully automated vehicle HMI design scope, while the types of UI should be extended, especially multi-modality interactions. To address the issue of incidental-failure caused lack-of-trust, [36] utilized virtual reality autonomous driving simulator to investigate how the driving scenarios change users' trust level and the time needed to rebuild the trust. This research proposes a method to consider all the elements in a structural way, so that designers and practitioners in the industry can easily locate their needs in the framework, therefore easily find their technical solutions correspondingly.

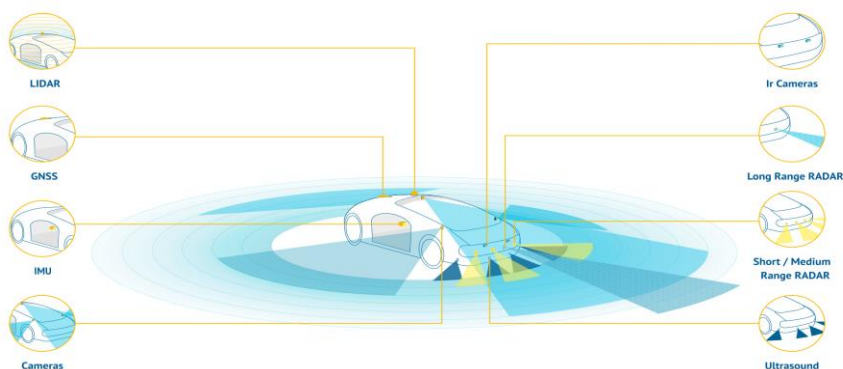
## 2 AUTONOMOUS DRIVING

According to the taxonomy of automation level of SAE International[10], the vehicles are defined in six levels: from Level 0 to Level 5, from no automation to full automation. The dynamic driving tasks fall mostly onto human drivers in low automation levels, while which fall mainly on the autonomous driving system in high automation levels. In Level 5, the driver is required to back in charge of the driving task only in case the autonomous driving system is not activated, which means that the user can get both their eyes and hands off when the system is engaged. However, having no need to care about the driving task does not mean that there is nothing to worry about for the user. People's attitude is complex in the utilization of autonomous vehicles. The technology has not conquered its potential consumers. In an investigation in public opinions on autonomous vehicles, 22% of the over 5000 respondents from 109 countries did not want to pay more than \$0 for a fully automated driving system, and on average, they found manual driving was the most enjoyable mode of driving[24]. In another investigation in the US, the UK, and Australia, 75% of the 1533 respondents were concerned about system/equipment failure and vehicle performance in unexpected situations[1]. The possibility for users to check the state of the autonomous vehicle's movement and situational awareness is needed.

The capabilities of an autonomous vehicle determine its Operational Design Domain (ODD). The ODD includes but is not limited to the restrictions from the environment, geography, and time-of-day. For the fully autonomous vehicle, the ODD is unlimited, which means a huge number of data should be collected by its cameras and sensors and high computing power should be engaged in order to fuse these data to make decisions[46]. The process of continuously exploring the surroundings to build a map and localize the car itself into it, by using the data comes from sensors and pre-existing maps created by artificial intelligence and human is called Simultaneous Localization and Mapping (SLAM). SLAM process relies on a series of sensors (not limited to)[32]:

- Ultrasonic sensors
- RADAR
- LIDAR
- Mechanical scanning
- Microelectromechanical mirrors (MEMS)
- Flash LIDARS
- Phased-Array LIDARS
- Metamaterials

The common solutions of various vehicle manufactures are always a combination of different types of sensors, in order to get a mixture of optical and Time-of-Flight (ToF) sensors which can cover various sensing demands. Figure 1 demonstrates a typical solution of sensor combination, and from which we can understand intuitively how the autonomous vehicle perceives the objects and situation in around in the SLAM process.

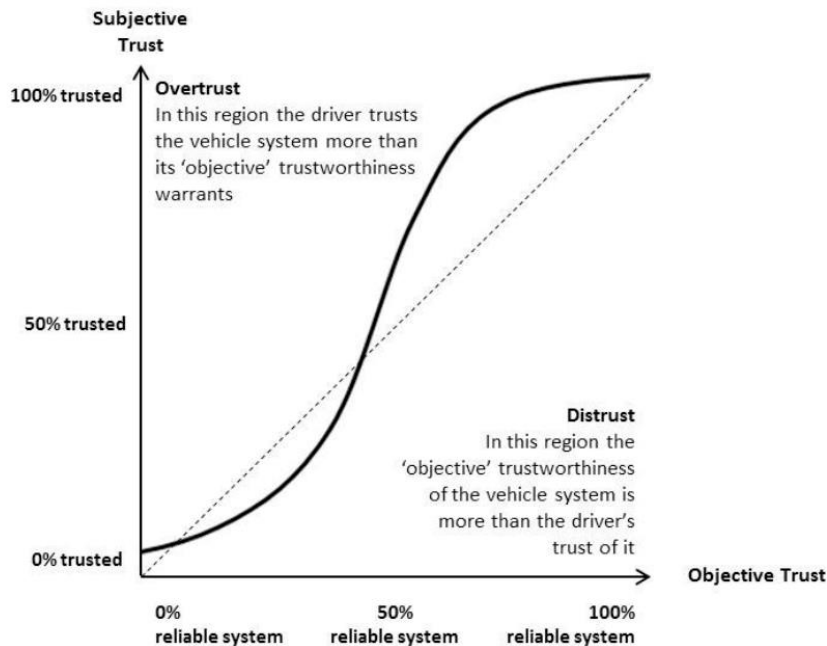


**Figure 1:** Typical sensors incorporated on an autonomous car[46].

The economic aspects of the autonomous driving technique are not ignorable for the manufacturers and designer in the industry, because it decides the form of the service (as individual property or sharing) and thereby affects the final needs of the design and development. As widely known, the manufacturing cost of full automation vehicles is high, therefore the self-driving taxi will be the principal mode of use[5, 48]. In a comparison of the costs per passenger-kilometer between autonomous vehicles and conventional vehicles, the results showed that this cost in an autonomous taxi was only 80% of that in a private autonomous cars, considering both the variable cost and the variable cost, while was merely 15% of that in a conventional taxi[5]. The autonomous vehicle manufacturers and designers have to consider the fact that autonomous taxi is the potential development direction.

### 3 BUILD THE TRUST

Trust is a key factor in many aspects of the autonomous vehicle HMI design, which determines the acceptance of the technology, and it is important for safe, efficient, comfortable and enjoyable driving in general. But it does not mean that more trust the better, there is a trust-curve showing the relationship between objective system reliability and driver trust (subjective trust) in Figure 2. When the driver trust is higher than the system reliability, 'overtrust' occurs with misuse and might lead to danger even accidents, for example the Tesla incidents mentioned in the introduction part. While when the driver's trust is under the system reliability, a situation of distrust and disuse arises. The ideal trust level is to keep the driver trust and the trustworthiness of the autonomous system balanced.



**Figure 2:** Trust curves and the relationship between objective system reliability and subjective trust[44]. (Dotted line represents a theoretical trust continuum; Solid line is an approximate curve based on empirical studies[22, 23])

An investigation in Hungarian in 2017 of 200 people on their trust towards the autonomous cars showed that only 15% of the respondents' trust or would trust in autonomous car [25]. Regarding

the reason why they would not use the new technology, 41% of the respondents selected 'I do not trust it' and 37% chose 'I want to be in charge'. In the condition of the autonomous taxi, how to build the trust of the user towards the car in a relatively short time is crucial. In general, for all levels of automation in vehicles, to keep a certain 'transparency' of the autonomous system so that the users can keep the sense of 'in charge'[12][13][44]. Some preliminary works have been done in exploring the communication features in HMI design in the autonomous vehicle. A framework has been established in [13] regarding particularly to HMI design in the control-transition feature in semi-autonomous vehicles. In a virtual-reality based user study on User Interface (UI) design showed that in the fully autonomous vehicle, users in general preferred route information over either no information at all or the real-time information, because real-time information led to great confusion as information about maneuvers is obtained at the same time the maneuvers are happening[43]. But this investigation was conducted in only one of the typical scenarios in autonomous driving: driving through a crossroads. Other critical scenarios need to be verified, for instance, passing by a construction site, in order to give a relatively comprehensive and instructive suggestion to the designers.

#### 4 ORGANISE INTERACTION MODALITIES

Engendering correct calibration of trust is crucial for the HMI design in autonomous vehicles, but there are also other important elements need to be considered in the design procedure: for instance providing required understanding of the vehicle's capabilities and status, stimulating appropriate level of attention and intervention (in case of emergency in automated driving scenarios), and providing comfort to the human user and reduce the uncertainty and stress level cognitively[6]. In the previous studies, different interaction modalities or interaction modalities have been demonstrated to generate the diversity of cognitive workload and stress level[3, 4, 16, 27].

The intent here is to organize the interaction modalities in the HMI design of the fully autonomous vehicle in a systematic manner, in order to create a general method for the future works in the industry field. Two approaches have been considered in the development of this method. The first one is based on the functions of the communication content in the driving task and the second one is based on the importance level of the communication content for the user. The word 'communication content' refers to the information that should be transferred between the autonomous vehicle and the user.

##### 4.1 By Function

Although in fully autonomous vehicles, the driving tasks are demanded to be done by the driving automation systems, delivering the communication contents organized by their functions in the driving task would be in line with user habits, especially in the starting stage of the universalization of the technology. A complete driving task cycle consists of three levels of functions[34]:

- Strategic functions: Route and destination timing and selection;
- Tactical functions: Planning and execution for event or object avoidance and expedited route following;
- Operational functions: Basic vehicle motion control, including lateral vehicle motion control and longitudinal vehicle control.

Tacking reference to which, the possible communication contents are categorized into four types: longitudinal movement information, external events, system events, and the emergency conditions, as shown below in Table 1.

<i>Functions</i>	<i>Longitudinal movement</i>	<i>External events</i>	<i>System events</i>	<i>Emergency</i>

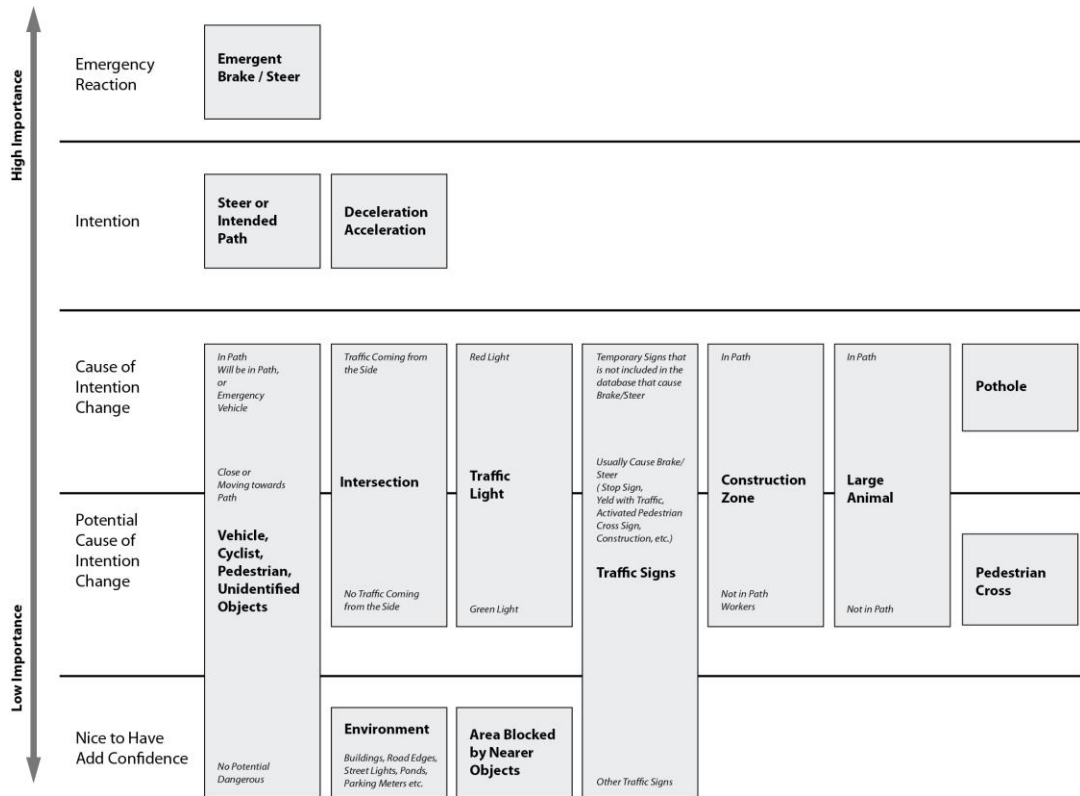
<i>Communication contents</i>	Car starting the ride	Car Approaching road works	Sensors in bad conditions	Car emergency braking
	Car stopping the ride	Car switching to the other line (for surpassing road works)	Sensors in good conditions	Car emergency braking event (after)
	Car accelerating	Car Overtaking another car	Uncertainty Level of detected objects	Car emergency lane switching (with enough time for communicating it to the user)
	Car decelerating	Car Approaching a pedestrian cross (without pedestrian)	Bad sensor ranges due to weather conditions	
	Car preparing to accelerate	Car Approaching a pedestrian cross (with pedestrian)	Change of itinerary for traffic or road conditions	
	Car preparing to decelerate	Car Approaching a pedestrian cross with undecided pedestrian		
	Car stops at traffic light (traffic light red)	Car switching lane		
	Car starts at traffic light (traffic light green)	Road/Terrain conditions change		
	Car Approaching a crossroad with traffic lights green (do not slow down)	Animal or object detected on the road		
	Car exiting/entering the city (or other area)	Road condition changing ahead		
	Change of speed limit (range)			
	Car entering the highway Car exiting the highway			

**Table 1:** Communication contents in HMI of fully autonomous driving organized by driving task functions.

Each type of communication content could be connected to one or more technologies and locations of the display, in order to align the reaction from the user side to the same general of information from the car. For instance, all the communication content belongs to the 'longitudinal movement' in the context of autonomous vehicle could be delivered by visual modality as a textual signal shown on the windshield display, while the ones belonging to external events should be addressed in a Graphical User Interface (GUI) to make it more intuitive for understanding. Because in the classification by function, the longitudinal movements are under Operational functions and are operated automatically by the intelligent system, while the external events are under the tactile functions, demanding more intention from the human user.

### 4.2 By Importance Level

Another reasonable logic to organize the communication contents is by their importance level to the human user from the aspect of intention change. Figure 3 is a schematic diagram of the possible elements in an autonomous driving journey categorized into five levels, from high importance to low importance: Emergency reaction, Intention, Cause of intention change, Potential cause of intention change, and Nice to have add confidence.



**Figure 3:** Diagram of elements in importance levels in vehicle HMI design [8].

Similar to the previous classification by function, the classification by importance level could also be displayed in different technologies and locations accordingly. To demonstrate the communication contents belonging to the same importance level in the same modality will help the user to perceive the behavior of the autonomous vehicle and understand the situation.

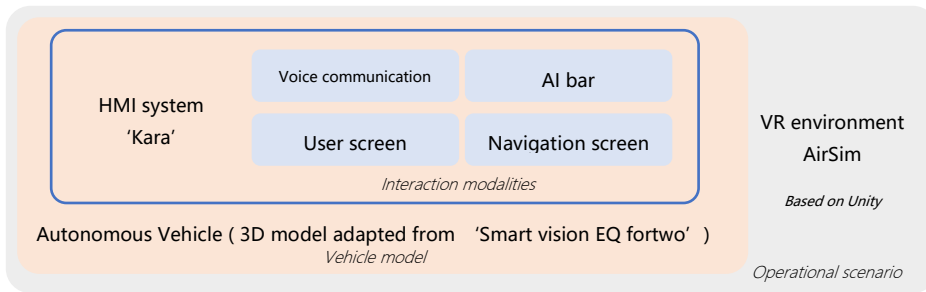
### 5 CASE STUDY

A concrete prototype and scenario need to be specified before applying the two methods of organization of the interactive modality. The development of the virtual reality scenario for HMI design in autonomous vehicles consists of three parts (Figure 4):

- Vehicle model: development of the autonomous vehicle model with interactive functions;
- Operational scenario: the virtual reality environment in which the autonomous vehicle model runs, with necessary events in order to trigger relevant features in the HMI design;



- Interaction modalities: establishing the correspondence between the communicating contents and interaction modalities according to the two methods mentioned in the previous part.



**Figure 4:** Components of the prototype proposed in the study.

The core of this prototype is the innovative approach to design the interaction modalities in the HMI of the autonomous vehicle, which is shown in the blue wireframe in Figure 4. Other components are redesigned and utilized under the domination of this part.

### 5.1 Vehicle model

The current under testing autonomous vehicles are generally considered for multi-passenger use, especially under the scenario of the self-driving taxis[28, 46]. While the user behavior study is still at the stage of the single user, that is focusing on the interaction between single-user and the car, regardless of the interaction between users inside the car[12, 49, 50]. Therefore, the choice was single-user scenario into a vehicle model taking the form of a concept electric autonomous vehicle 'Smart vision EQ fortwo'[38].



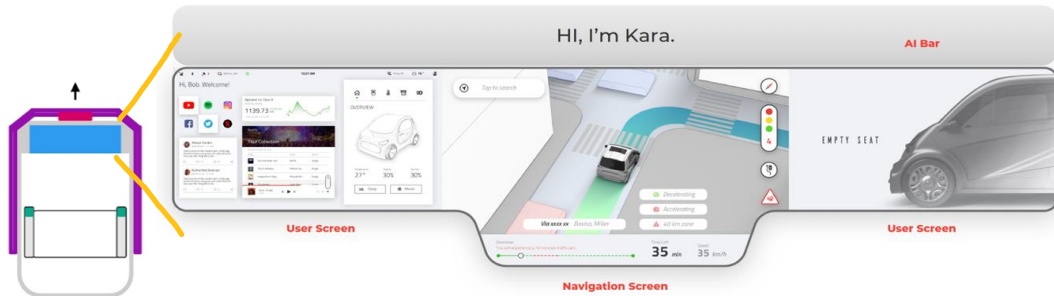
**Figure 5:** Model of the autonomous vehicle based on 'Smart vision EQ fortwo'. (a) the concept car 'Smart vision EQ fortwo'[38], (b) the image of the model developed.

#### 5.1.1 User Interface

The layout of the HMI display on board is shown in Figure 6. The main communication area is in the front of the car, in the forwarding direction. Regarding the visual interaction modality, there are two displays. The upper one named 'AI Bar' delivers information in text form, describing the states and actions of the car, and the one below is a touch screen which consists of three function areas: Two User screens have repeated functions just in case of two-user mode, where users can log in their personal profile in order to get all their preferences set, to increase immediately the familiarity of the user and therefore increase their trust. The Navigation screen in the middle visualizes the



surroundings of the car and highlights the important elements on the right with GUI icons, for example, the traffic lights. As suggested in [17], 3D visualization of the environment helps to increase the trust of the user, also it is more intuitive for the user to sense the process of SLAM, giving a similar point of view of the sensors, in the same way as in Figure 1.

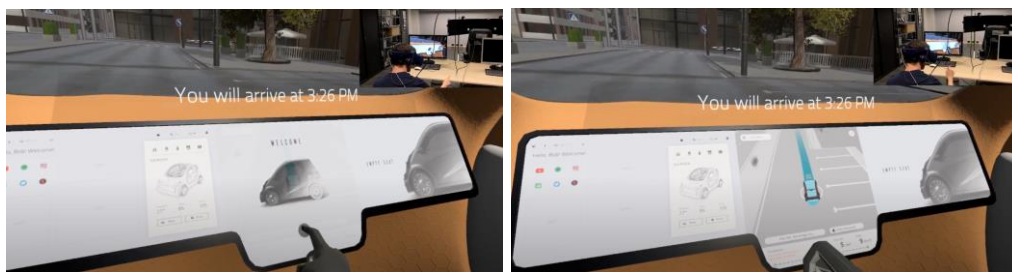


**Figure 6:** Layout of the developed model, touch screen and the AI bar.

Besides the visual modality of interaction, an auditory interaction is included: An AI character called 'Kara' is build-in and is able to give a simple conversation with users[9], by pre-establishing a series of keywords recognition inside the dictation. Auditory signals have some unique advantages, such as it is omnidirectional, which means that auditory cues can be received from any direction[2]. The female-voiced AI provides a human-like character to the car and is preferred and trusted in the previous HMI studies [29][45]. On the other hand, Kara should hear what the users say. The voice recognition features inside unity are based on the already existing libraries of speech recognition which use specific "keywords" recognition to enable Kara to quickly respond to the user.

### 5.1.2 Interaction with the HMI

By using the combination of the HTC vive pro[20] head-mounted display, a visor with 6DOF (Degrees of Freedom) and full-scale room tracking capability, and the Leap Motion sensor[26] for hands and fingers tracking, the user can be immersed into the simulation scenario and interact with the car through hand movement and voice, as shown in Figure 7. When the user is prepared with personal account logged in, and preferences set, pressing the start button in the center of navigation screen will start the car.



**Figure 7:** Interacting with the autonomous vehicle in tactile modality: (a) press the button on the navigation screen to start the car, (b) car started and the navigation screen shows 3D map and the circumstances in the surrounding.

## 5.2 Operational Scenario

The operational scenario has been developed with Unity 3D, which is a game engine widely used in virtual reality driving simulation because of its flexibility and compatibility [37, 43, 47]. The scenario

is based on a ready-to-use simulator AirSim by MIT [35]. AirSim (Figure 8) is released under MIT license, allowing modifications and adaptations to the simulation environment without infringing copyrights. It is a solid foundation for the creation of the autonomous vehicle scenario, it provides a good level of immersion for the user, and the availability of several environments in one map enabled the simulation to encompass a broader range of events and situations to test with the user[32]. The development effort focused on the areas surrounding the user and its field of vision by integrating additional assets like parked cars and road works. Traffic and pedestrians were added using the asset "UTS Pro." [42]



**Figure 8:** Street view in AirSim scenario.

As introduced in the previous sections, a 3D visualization of the surrounding environment, as perceived by the autonomous vehicle, gives an intuitive representation of the sensors' status, which support the autonomous driving task and it is helpful for the construction of trust. In Figure 9 (a), it can be observed that the pedestrians crossing the road in front of the car are projected on the navigation screen with their precise positions, not only showing the user onboard what the sensors captured, but also showing the convincing self-driving capacity, therefore leading to the reliability of the user. In Figure 9 (b), an event of switching lane when approaching the construction site in the road, both text description in the AI bar and the 3D visualization of the cause of the event are shown in the navigation screen.



**Figure 9:** 3D visualization of the events in the scenario: (a) pedestrians crossing the road, (b) switching lane when approaching the construction site.

### 5.3 Interaction modalities

In section 5.1.2 it has been introduced that the user can interact with the autonomous driving system by textual information on the AI bar, GUI in the navigation screen, 'touch' gesture and conversation with Kara, hence via visual, tactile and auditory modality. The HMI of a single type of information or modality has been discussed in [43][49][17], but a systematic organization of the interaction modalities and different types of information being conveyed is still missing. In section 4, two ways to assign the communication contents to interaction modalities in a systematical manner have been

proposed, in order to minimize the possible confusion and to build the trust of users: by function and by importance level. In the testing scenario, a series of events have been planned along the journey, leading to a series of communication contents. The same scenario can be applied in both methods of interaction classification, in order to demonstrate the usability of Virtual Reality technology in the fully autonomous vehicle HMI design. In Table 2, 29 events and their corresponding interaction solutions at both methods of organization are listed, with the detail of information type, technology or location used, and the interaction modality type.

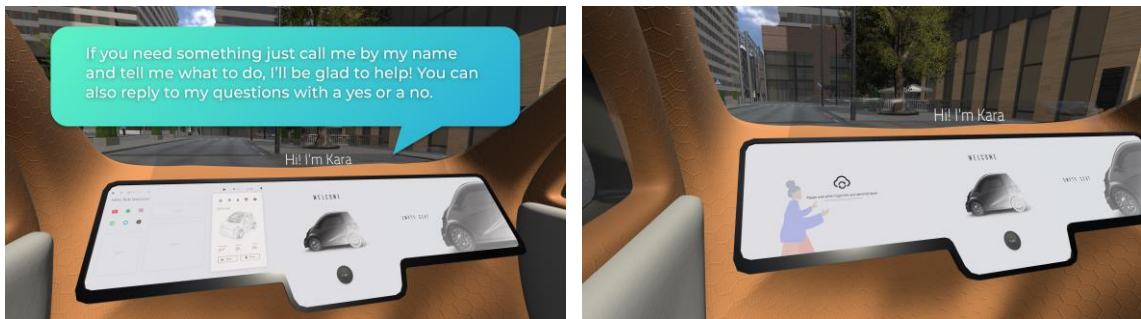
Content	Organized by Function			Organized by Importance		
	Information Type	Technology/Location	Modality	Information Type	Technology/Location	Modality
01. Kara welcome procedure	System events	Navigation screen + AI Voice + AI Bar	Visual, Auditory	Cause of intention change	Navigation screen + AI Bar	Visual
02. Message "You will arrive at ..."	System events	Navigation screen + AI Voice + AI Bar	Visual, Auditory	Cause of intention change	Navigation screen + AI Bar	Visual
03. Car starts with the button on the screen	In road movement	Navigation screen + AI Bar	Visual	Intention	Navigation screen + AI Voice + AI Bar	Visual, Auditory
04. Car turns right	In road movement	Navigation screen + AI Bar	Visual	Intention	Navigation screen + AI Voice + AI Bar	Visual, Auditory
05. Car slowing down and stopping for traffic light + pedestrian crossing	External events	Navigation screen	Visual	Cause of intention change	Navigation screen + AI Bar	Visual
06. Car emergency line switching + emergency break	Emergency	Navigation screen + AI Voice + AI Bar	Visual, Auditory	Emergency Reaction	Navigation screen + AI Voice + AI Bar	Visual, Auditory
07. Car turning Left	In road movement	Navigation screen + AI Bar	Visual	Intention	Navigation screen + AI Voice + AI Bar	Visual, Auditory
08. Pedestrian Crossing without Pedestrian	External events	Navigation screen	Visual	Potential Cause of Intention change	Navigation screen	Visual
09. Car accelerating	In road movement	Navigation screen + AI Bar	Visual	Intention	Navigation screen + AI Voice + AI Bar	Visual, Auditory
10. Car decelerating	In road movement	Navigation screen + AI Bar	Visual	Intention	Navigation screen + AI Voice + AI Bar	Visual, Auditory
11. Pedestrian crossing with undecided pedestrian	External events	Navigation screen	Visual	Potential Cause of Intention change	Navigation screen	Visual

12. Car turning Right	In road movement	Navigation screen + AI Bar	Visual	Intention	Navigation screen + AI Voice + AI Bar	Visual, Auditory
13. Car approaching the road works	External events	Navigation screen	Visual	Potential Cause of Intention change	Navigation screen	Visual
14. Car switching left lane	External events	Navigation screen	Visual	Intention	Navigation screen + AI Voice + AI Bar	Visual, Auditory
15. Car passing the road construction site	External events	Navigation screen	Visual	Potential Cause of Intention change	Navigation screen	Visual
16. Car return to the right lane	In road movement	Navigation screen + AI Bar	Visual	Intention	Navigation screen + AI Voice + AI Bar	Visual, Auditory
17. Car enter and exit the roundabout	In road movement	Navigation screen + AI Bar	Visual	Potential Cause of Intention change	Navigation screen	Visual
18. Car exiting the city	In road movement	Navigation screen + AI Bar	Visual	Cause of intention change	Navigation screen + AI Bar	Visual
19. Car approaching hairpin turn	External events	Navigation screen	Visual	/	/	
20. Car enter and exit the roundabout	In road movement	Navigation screen + AI Bar	Visual	Potential Cause of Intention change	Navigation screen	Visual
21. Car entering the highway	In road movement	Navigation screen + AI Bar	Visual	Cause of intention change	Navigation screen + AI Bar	Visual
22. Car turn Left	In road movement	Navigation screen + AI Bar	Visual	Intention	Navigation screen + AI Voice + AI Bar	Visual, Auditory
23. Car speedup on the highway	In road movement	Navigation screen + AI Bar	Visual	/	/	
24. Car overtake another car	External events	Navigation screen	Visual	Cause of intention change	Navigation screen + AI Bar	Visual
25. Remaining time notification	System events	Navigation screen + AI Voice + AI Bar	Visual, Auditory	/	/	
26. Car decelerating	In road movement	Navigation screen + AI Bar	Visual	Intention	Navigation screen + AI Voice + AI Bar	Visual, Auditory
27. Car turn Right	In road movement	Navigation screen + AI Bar	Visual	Intention	Navigation screen + AI Voice + AI Bar	Visual, Auditory
28. Car enter a dirt road	External events	Navigation screen	Visual	Cause of intention change	Navigation screen + AI Bar	Visual

29. Car approaching the destination	System events	Navigation screen + AI Voice + AI Bar	Visual, Auditory	Intention	Navigation screen + AI Voice + AI Bar	Visual, Auditory
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**Table 2:** Events in the virtual reality driving scenario and their corresponding interaction modality information, organized by function and by importance.

According to Table 2, some of the contents have the same interaction modality in both classifications, while others have different modalities due to the different information types belonging to. For example, the welcome procedure in Organization by function belongs to the 'system events', so accordingly it will be communicated in a combination of the AI bar, Kara's voice, and the navigation screen, as shown in Figure 10 (a). The same event in Organization by importance belongs to the information type of 'Cause of intention change', therefore the interaction modality is only visual, and the form of the information is by the navigation screen and a textual message on AI bar (see Figure 10, (b)).



**Figure 10:** Welcome procedure in the scenario: (a) HMI modality organized by function, phrases in the bubble are the voice message, (b) HMI modality organized by importance, with the textual message shown in the AI bar and GUI message in the navigation screen.

#### 5.4 Evaluation tools

As discussed in the introduction, Virtual Reality technology has been demonstrated to be efficient for HMI design in the autonomous vehicle, with high flexibility and availability for multi-modality interaction simulation. It is also convenient for validations with the user test. Questionnaires could be employed in order to get a quantitative measurement of the usability and trust at the subjective level, for example:

- Technology Acceptance Model [14] measures four aspects, namely Perceived ease of use, Attractiveness, Trust, and Intent of the HMI design,
- Trust in automation questionnaire [21] is a scale with five items measuring mistrust and seven items measuring trust between users and automation and it is one of the most commonly used scales for assessing trust in automation[19], in [43] it is employed together with the TAM scale for a comprehensive insight into the user's trust in fully automated driving,
- Trust scale [47] developed for user tests in the virtual reality environment, combining and optimizing the other trust-relevant scales.

For the HMI design, it is also important to evaluate user comfort, especially in the context of the fully autonomous vehicle, in which comfort is one of the motivations and development focus. User comfort is a concept on both sides of physical and psychological. Fundamentally, the fatigue and stress level of user when they are interacting with the HMI should be recorded and analyzed in order to improve the design and reach a balanced state for the user[6], which can be done by monitoring

the physiological data of the user, for instance Heart Rate Variability and Electrodermal activity[18][7]. Then, since users are supposed to conduct a non-driving-related task inside a fully autonomous vehicle, an HMI that requires less attentional resources and lower mental cognitive workload will be preferred, which can be conducted by monitoring and analyzing the cognitive and emotional data in the interaction process[51], also can be measured in a subjective way by adapting the Driving Activity Load Index(DALI) [30].

## 6 CONCLUSION

In this paper, a general technical and functional overview of the HMI design for fully autonomous vehicles has been provided. The main focus of the new establishment is the systematical organization of the communication contents and the interaction modalities in the HMI design, which related directly to the events during a ride of automated driving, and the development of simulation in the Virtual Reality scenario. The requirements of HMI design in the specific fully autonomous vehicle context is very different from the conventional driving scenario, especially for the early period of the application of autonomous vehicle technology, building the trust is an essential task. Also, because the most promising application scenario is self-driving taxi, every ride the user will experience a different car, offering a personalizable user interface will be helpful to get the user's trust and increase the comfort level. Keeping a reasonable level of transparency of the decision and movements of the autonomous system to users is helpful to increase their trust, which has been comprehensively discussed and applied in the current model. Introducing the 3D visualization of the SLAM process is a promising and applicable solution in the user interface design of fully autonomous vehicles. Need to be noticed that the current method treats only the single-user mode, in the future, multi-user mode needs more elements to be considered, for instance, the interaction between users. Finally, the possible verifying tools have been introduced for the researchers and practitioners in the research area and industry to take a reference.

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