Department of Creative Informatics
Graduate School of Information Science and Technology
THE UNIVERSITY OF TOKYO

Master's Thesis

# Pedestrian-centric Augmented Reality Visualization of Real-time Autonomous Vehicle Intentions

歩行者中心の拡張現実による自動運転車の意図のリアルタイム可視化

**Yiwei Cheng**
程 屹偉

Supervisor: Manabu Tsukada, Associate Professor

January 2024

# Abstract

Connected Autonomous Vehicles (CAVs) produce a variety of information within their systems. With the advancement of communication and V2X (Vehicle-to-Everything) communication technology, there is a growing challenge to effectively convey this information to pedestrians and enhance their sense of safety when encountering such vehicles. Efforts to communicate this information to pedestrians have been made through various means, with Augmented Reality (AR) emerging as a notable approach. We found that previous studies have yet to integrate a functional AR application with a real-world autonomous driving system. In response to this gap, we proposed an AR application that visualizes real-time data from an active CAV and subsequently developed the system. Furthermore, we conducted field experiments using this developed system and conducted user studies to gather insights into the public's perception of the system. Our results showed that the system can effectively transmit information from the CAV, and when provided with additional information, people tend to feel safer and confident regarding understanding the vehicle's intentions.

# 概要

接続型自動運転車（CAV）は、そのシステム内でさまざまな情報を生成します。通信および V2X（Vehicle-to-Everything）通信技術の進歩に伴い、歩行者にこの情報を効果的に伝え、そのような車両と遭遇した際の安全感を高めるための新たな課題が生じています。この情報を歩行者に伝えるためのさまざまな手段が試みられており、拡張現実（AR）が注目すべきアプローチとして浮上しています。これまでの研究では、機能的な AR アプリケーションを実際の自動運転システムに統合することはまだありませんでした。このギャップに対応して、私たちは活動中の CAV からのリアルタイムデータを視覚化する AR アプリケーションを提案し、そのシステムを開発しました。さらに、この開発されたシステムを使用して現場実験を行い、システムに対する一般の認識を収集するためのユーザー研究を実施しました。私たちの結果は、このシステムが CAV からの情報を効果的に伝達できることを示し、追加情報が提供されると、人々は安全感を持ち、車両の意図を理解する自信が増すことがわかりました。

# Contents

Contents v

List of Figures vii

List of Tables ix

Chapter 1 Background 1
1.1 Introduction on Autonomous Vehicles and Intelligent Transport System 1
1.2 Introduction on Vehicle-Pedestrian Communication to Enhancing Pedestrian Safety . . . 4
1.3 Proposal and Contribution . . . 6
1.4 Organization . . . 7

Chapter 2 Related Work 8
2.1 eHMI-based Pedestrian Support . . . 8
2.2 AR-based Pedestrian Support . . . 9

Chapter 3 Approach 12
3.1 Overview . . . 12
3.2 Design . . . 12
3.3 Implementation . . . 15

Chapter 4 Experiments 21
4.1 Overview . . . 21
4.2 Latency Test . . . 21
4.3 Questionnaire Survey . . . 22
4.4 User Study . . . 27

Chapter 5 Discussion 32
5.1 Latency Test . . . 32
5.2 Questionnaire . . . 32
5.3 User Study . . . 33
5.4 Summary . . . 34
5.5 Future Directions . . . 34

Chapter 6 Conclusion 35

Publications 36

References 37

# List of Figures


1.1 An illustration of ITS, where a single AV not only do decisions by itself, but also utilize information from outside. . . . 2
1.2 A general scenario of cooperative perception where the RSU helps the AV to “see” the objects behind obstacles . . . 3
1.3 A general architecture of a smartphone-based V2P collision avoidance system, from [20]. . . . 5
1.4 Possible scenario of pedestrians equipped with AR devices that shows the intention of a CAV . . . 7

2.1 Figures of eHMI concepts on vehicles, including light bands, projection, ”smile”, and ”eyes” on a vehicle, from [33]. . . . 9
2.2 AR interface to warn the pedestrian, by [37]. . . . 10
2.3 Examples of AR interface on the road. . . . 10
2.4 AR interface on a vehicle designed by Tabone *et al.* . . . 11

3.1 Architecture of the proposed system . . . 12
3.2 An AR HUD design [23]. . . . 15
3.3 General workflow of putting an AR object to the scene of the application. 19
3.4 A screenshot during experiment with the system. . . . 20

4.1 Record of the AR Application . . . 23
4.2 Record of the Experiment. . . . 24
4.3 Map of the experiment field. . . . 24
4.4 Live demo demonstrated on the exhibition. . . . 25
4.5 Pie charts for results of demographic questions. . . . 26
4.6 Questionnaire results for the rest of questions. . . . 27
4.7 The experiment field and scenario. . . . 28
4.8 Record of the user study. . . . 29

# List of Tables

4.1 Specifications for general hardware and software used in implementation and experiments. . . . . 21
4.2 Latency test results. . . . . 22
4.3 User study results. . . . . 29

# Chapter 1

# Background

## 1.1 Introduction on Autonomous Vehicles and Intelligent Transport System

### 1.1.1 Autonomous Vehicle

The concept of autonomous driving can be traced back to the early 20th century when science fiction imaged vehicles that could navigate without operation from humans. In the late 20th century, the Defense Advanced Research Projects Agency (DARPA) in the United States supported a series of early development of autonomous vehicles (AVs), which catalyzed the research in this field.

After entering the 21st century, with the development of computer science and communication technology, the development made large breakthroughs. In 2005, Stanford University equipped a vehicle with a camera, a LiDAR, radar, and a Global Positioning System (GPS) to make the vehicle capable of running in harsh and complex environments. In the 2010s, as the development of neural networks and supercomputing, AVs can be tested or even made for public use on some urban roads. [1]

Generally, an autonomous vehicle depends on the integration of advanced sensors, and machine learning algorithms. Sensors such as LiDAR (Light Detection and Ranging) provide 360-degree, 3D information about the vehicle's surroundings by emitting light pulses and measuring their reflections [2], and cameras capture visual information which is essential for tasks like object recognition. Well-designed algorithms then process such real-time data about the vehicle's surroundings to achieve all kinds of tasks that can help the vehicle run on the road. This includes localization, object detection and classification [3], which helps the vehicle to understand the current state of driving and what is happening around the vehicle. After that, the vehicle can make instantaneous decisions based on such information and control the car appropriately.

The industry of automotive usually applies a six-degree (Level 0 to Level 5) of classification standard to measure the level of autonomous vehicles, as defined by the Society of Automotive Engineers (SAE International) [4]. Level 0 means there is no automation and the driver is in full control of the vehicle. Level 1 is known as driver assistance which includes basic automation features such as cruise control or lane-keeping assistance. Level 2, partial automation requires the vehicle to control steering and acceleration/deceleration under certain conditions, the human driver is still at their position and ready for manual control at any time. When it comes to level 3, the vehicle can handle all driving tasks in specific scenarios, such as a test field or highway with the human driver ready to take over. Level 4 allows the vehicle to perform all tasks in specific scenarios without human intervention. Finally, level 5, full automation imagines a vehicle that is capable of running under all conditions without any human intervention. [5] As for now, the devel-

opment of autonomous driving is dynamic. There are numerous companies and research institutions actively developing and testing AV technologies. As stated in the previous section, innovations in artificial intelligence is dramatically improving the capabilities of autonomous driving systems. For practical deployment, in China, there are experimental operations of autonomous taxis on public roads [6]. Although recently there still have been accidents of intelligent vehicles [7], the researchers are still moving forward. And the U.S. Department of Transportation (U.S. DOT) is also promoting the deployment of intelligent transportation and connected autonomous vehicles (CAVs). [8].

### 1.1.2 Cooperative Intelligent Transport System

Besides all kinds of sensors, other devices and algorithms on board, autonomous vehicles can also utilize external resources and join a traffic network. This shift in focus enables the evolution of modern transport systems. Vehicle-to-everything (V2X) communication is at the front line of this trend, serving as an important link between individual autonomous vehicles and the huge domain of intelligent transport systems (ITS). V2X includes a vehicle's communication with other vehicles (V2V), road infrastructure like traffic lights, road signs and embedded sensors (V2I) and pedestrians (V2P). By enabling such instantaneous communication between vehicles and the surrounding environment, V2X is expected to reduce the risk of traffic accidents, increase traffic efficiency and form a cooperative intelligent transport system (C-ITS). The following figure depicts primary components in such a C-ITS, where an autonomous vehicle is not only able to perform driving tasks by itself, but also communicates with other vehicles and infrastructure like road side units (RSU) on the road to contribute or receive useful information for driving.

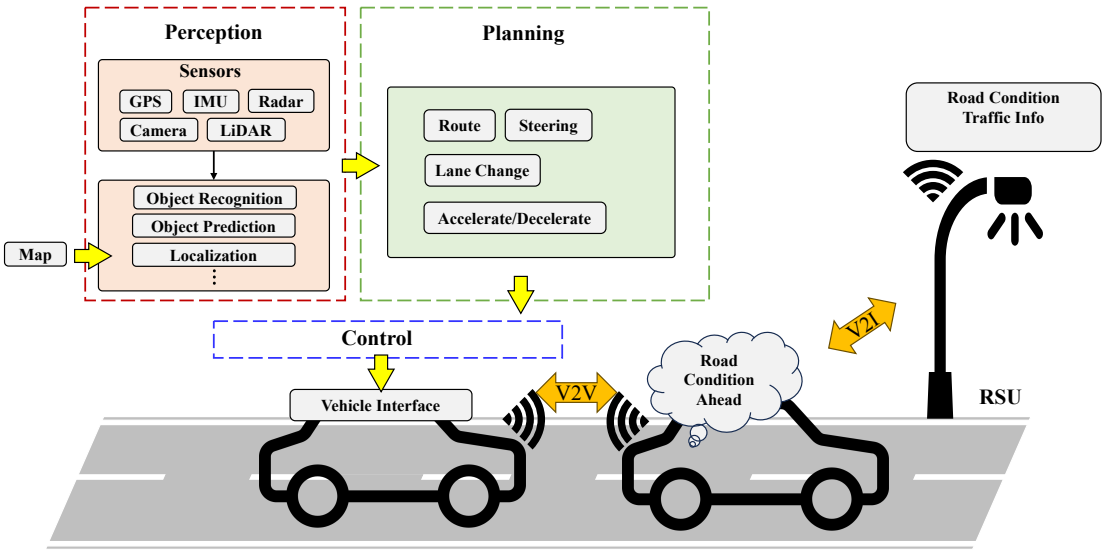



Fig. 1.1: An illustration of ITS, where a single AV not only do decisions by itself, but also utilize information from outside.

The application of V2X usually includes cooperative perception and localization, vehicle platooning, and emergency notification. Asabe *et al.* implemented an open-source implementation of a V2X router that can work with an autonomous driving system [9]. In their experiment, a pedestrian appeared behind a tall wall and walked toward the center of an

intersection, the AV could not detect the pedestrian with its own equipment. To prevent potential accidents, the authors set an RSU around the intersection that has a LiDAR to detect surroundings. The approaching pedestrian was detected by the RSU and the data was sent to the AV with a cooperative perception message (CPM). CPM is a standard message format defined for such cooperative, or collective perception scenarios. In the end, the AV receives the message and made an emergency stop although it didn't "see" the pedestrian. Jiang *et al.* also uses a similar RSU, but their work focuses on localization, the RSU will tell the vehicle additional information to help them know where they are [10]. Bergenhem *et al.* worked on a platooning model based on V2V communication, they tested that their communication module can have superior results for a communication range larger than 70 meters [11].

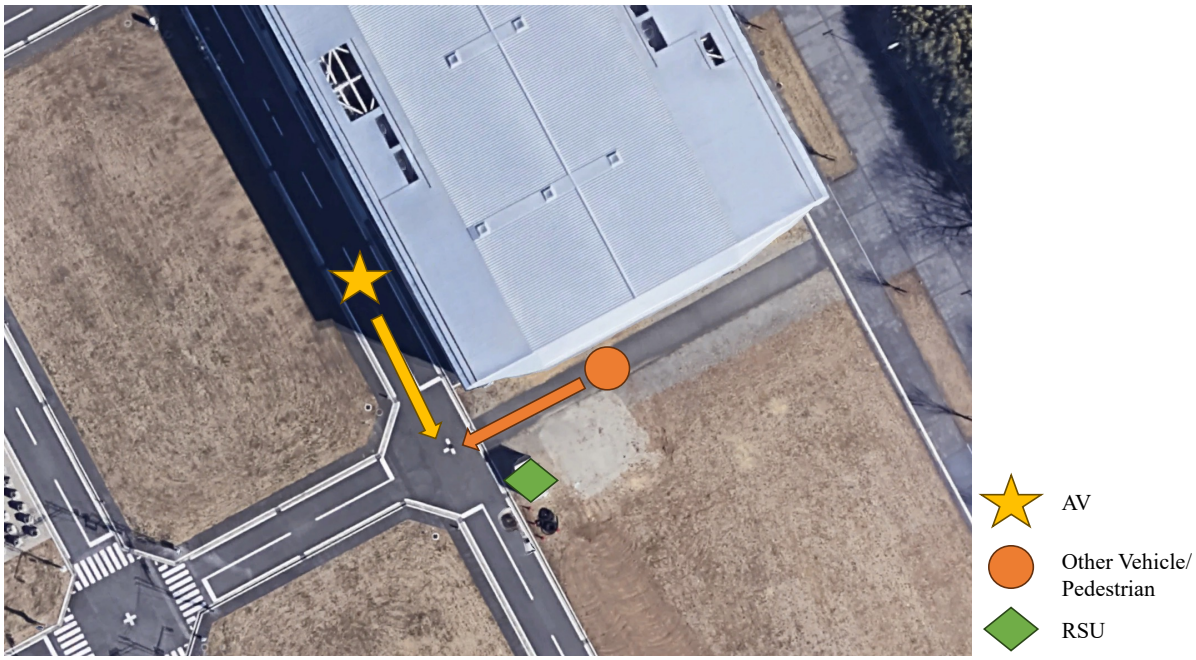



Fig. 1.2: A general scenario of cooperative perception where the RSU helps the AV to "see" the objects behind obstacles

As for emergency notification, people are focusing on the aspects of V2V and V2P communication. In the domain of emergency notification, a critical area of research is the optimization of routing strategies for non-emergency vehicles to facilitate the rapid and unimpeded passage of emergency response vehicles, such as ambulances. Osman *et al.* proposed such a management strategy where the vehicle that is closest to the emergency vehicle will communicate with other vehicles to clear a lane in the road for the emergency vehicle [12]. In addition to assisting emergency vehicles, this domain also includes V2V communication to reduce the risk of collision between vehicles. Focusing on a single vehicle, the Advanced Driver Assistance System (ADAS) has emerged as a crucial module. It plays a vital role in bolstering the safety of passengers and pedestrians alike and is swiftly becoming a staple in modern vehicles [13]. Besides such ultimate measures, spotting the emergency in advance is also concerned. Sidorenko *et al.* have tested that with communication via DENM, a V2V message broadcast among vehicles due to hazardous road conditions, the braking time for a vehicle that brakes due to a sudden stop of another vehicle ahead can be shortened [14].

Emergency notification for pedestrians is another center of research. This area of study concentrates on the design and implementation of advanced warning mechanisms to alert pedestrians of imminent emergencies, thereby enhancing pedestrian safety and situational awareness in urban environments. This is also the focus of this thesis, in the following, there will be a new section introducing this field of study.

## 1.2 Introduction on Vehicle-Pedestrian Communication to Enhancing Pedestrian Safety

### 1.2.1 V2X Communication-based Pedestrian Safety Enhancement

Before any communication or detection techniques were applied, people were already trying to reduce the damage to pedestrians when there's an accident between a vehicle and pedestrians. They take measures such as designing light vehicles and adding airbags and bumpers to components of a vehicle that usually hit pedestrians in accidents [15]. Such methods are called passive solutions for pedestrian protection.

When it involves V2X communication, besides RSU-based cooperative perception, which has been introduced, that can help vehicles detect pedestrians in non-line-of-sight(NLOS), there are more vehicle and pedestrian-based techniques that actively detect and predict the movement of pedestrians to prevent accidents. For instance, García *et al.* tried to fuse sensor data from multiple vehicles via V2V to achieve pedestrian tracking, they designed a procedure to detect pedestrians that are possible to collide with a vehicle [16].

Till now, the pedestrian hasn't been counted as an active member of the ITS. With the advancement of mobile personal devices like smartphones, people are also making pedestrians an active member who can communicate with infrastructure and vehicles. The general approach is installing an application on the pedestrian's smartphone. To prevent accidents, some research directly lets the application monitor the smartphone's motion state and warn the pedestrian not to watch the smartphone while walking outside to prevent accidents due to distraction, for example, Zhou *et al.* simply let the application lock the screen of the smartphone as a warning message [17]. In other studies, people tried to let the smartphone report more information to vehicles or the transport system. The system proposed by Bagheri *et al.* is representative: in their application, they transmit the position data of the smartphone constantly to a cloud server via the cellular network. The cloud server also receives contextual information from vehicles so that it can predict whether there's a risk of collision between the vehicle and the smartphone user or the pedestrian [18] and then the smartphone will vibrate or have some display on its screen to tell the user that there's a vehicle approaching and there's possiblity of collision. Similarly, Hwang *et al.* also proposed a cloud-based system [19], they further proposed a traffic control center in the ITS to form a more intelligent transport system. Edge computing was also integrated into this field. Nguyen *et al.* proposed a similar system where the smartphone also report its location, the server aggregates the data from vehicles and the smartphone then calculates the risks of collision. The point is that they tried to use multi-access edge computing (MEC) in the system to replace the cloud server and help calculate the risk [20].

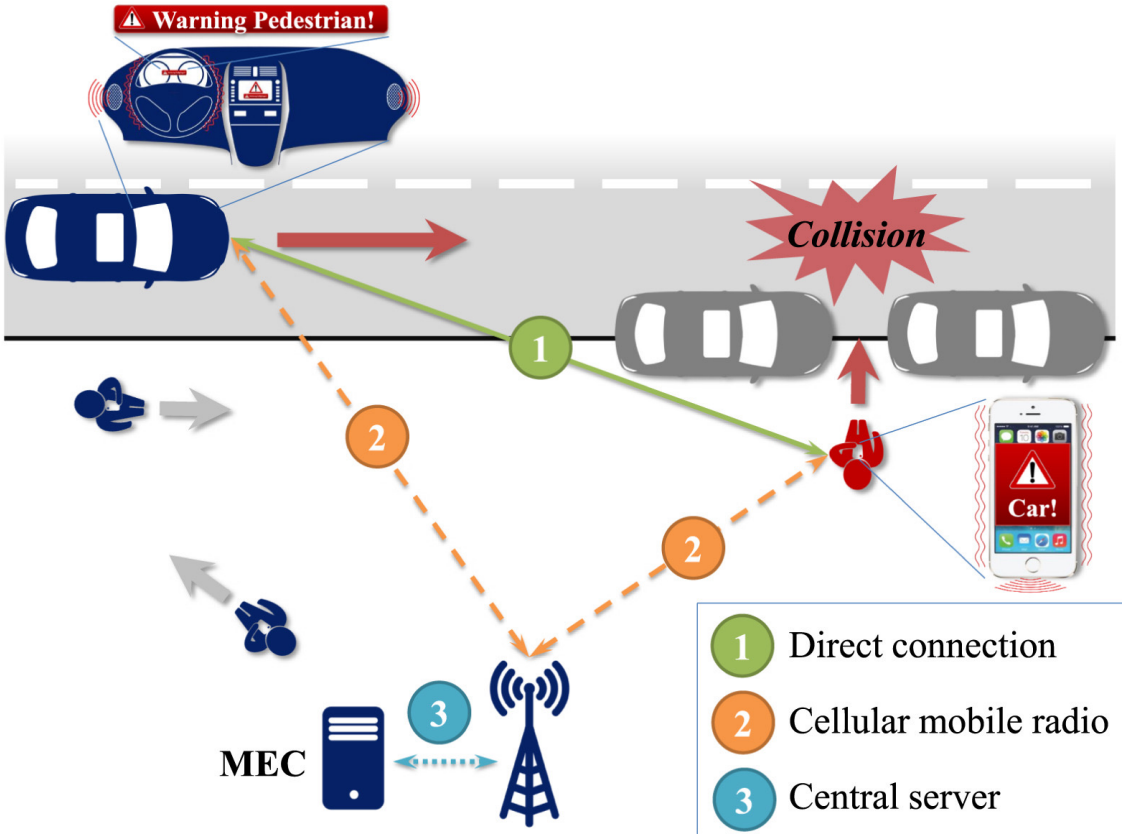



Fig. 1.3: A general architecture of a smartphone-based V2P collision avoidance system, from [20].

### 1.2.2 Pedestrian Safety Enhancement By Interaction and intention Communication

To achieve an efficient and safe ITS, it is not enough to only focus on reducing damage or preventing the happening of accidents. Research is also being conducted to increase pedestrians' sense of safety regarding AVs. Some people may be concerned that drivers on conventional vehicles can use cues such as eye gaze and hand gestures to convey that they are aware of the pedestrians. On the other hand, when it comes to autonomous vehicles, drivers can be distracted or absent, which leads pedestrians to infer intention from the AV by themselves [21].

#### External Human-machine Interface

It is believed that the external human-machine interface (eHMI) is potentially effective in serving as the bridge of communication between AVs and pedestrians. EHMIs are designed to facilitate clear and intuitive interactions between autonomous vehicles and external road users, including pedestrians, cyclists, and drivers of non-autonomous vehicles. These interfaces play a crucial role in conveying an AV's intentionions, status, and awareness, which can hopefully enhance the safety and trust in automated systems. Generally, people mainly set eHMIs on the vehicle or roadside where pedestrian-vehicle interactions are likely to happen. For eHMI on the vehicle, people usually use LED light bands or displays to

express the status of the vehicle.

### Augmented Reality

As autonomous systems evolve, another technological paradigm is emerging alongside the metaverse. The metaverse, a collective virtual shared space created by the convergence of physical, virtual reality, and the internet, is poised to reshape various industries and societal norms in the coming era [22]. Within this trend, augmented reality (AR) and virtual reality (VR) has become a public focus. Through an AR device, in addition to what is present in the real world, the user can experience digital content that is projected onto real-world objects by the AR device and software.

Applications of AR and VR extend beyond mere entertainment [23], evident in innovations like in-car AR, which offers drivers a head-up display detailing navigation and vehicle status. As personal portable smart devices get more and more powerful, the prospect of universal access to AR experiences via smartphones or smart eyewear becomes increasingly feasible. Furthermore, given that user interface (UI) components in AR devices are typically rendered on the fly through software, there is notable flexibility in modifying attributes such as shape, color, and other visual properties. This adaptability makes it possible to present more diverse and inclusive content. Therefore, using AR on the pedestrian's side in an ITS may be flexible and effective to convey the intention of CAVs.

Researchers have proposed several AR design concepts, particularly for interactions during road crossings [24]. However, the existing research focuses on the design of AR objects, and to the best of our knowledge, no previous study has examined an autonomous driving system and conducted experiments using a CAV in operation with such an AR application.

## 1.3 Proposal and Contribution

Safety has always been a concern topic in the field of ITS. In addition to accident prevention, constructing a system that makes road users other than AVs, such as pedestrians and cyclists feel safe is also crucial in the future. As an emerging technique, AR has the potential to set up a bridge between the ITS network and pedestrians. Tech companies such as Apple is also putting concentration on AR that it will release its first AR device in 2024.

In this thesis, a system that directly conveys information from an autonomous driving system to pedestrians via an AR application is proposed. One open-source autonomous driving software, Autoware [25] is the main system that supports the operation of CAV in the research, it integrated a new module to transmit data about the autonomous vehicle, including its kinematic status, planning, and perception results. These data is then visualized using AR while running the CAV in real-time. The information is relayed from the vehicle via a cloud server to a handheld device capable of AR, primarily smartphones and tablets. This system was showcased at the exhibition of Interop 2023 Tokyo[*1] and a workshop paper was published in November 2023 [26].

In this research, we aim to illuminate the perspective of autonomous vehicles in designing and implementing a realistic AR-based V2P communication system, making research in this field closer to practice. By presenting such a system that demonstrates AVs' intention, our ultimate goal is to augment pedestrians' sense of safety when interacting with autonomous vehicles, as illustrated in Figure 1.4.

[*1] https://www.interop.jp/2023/en/

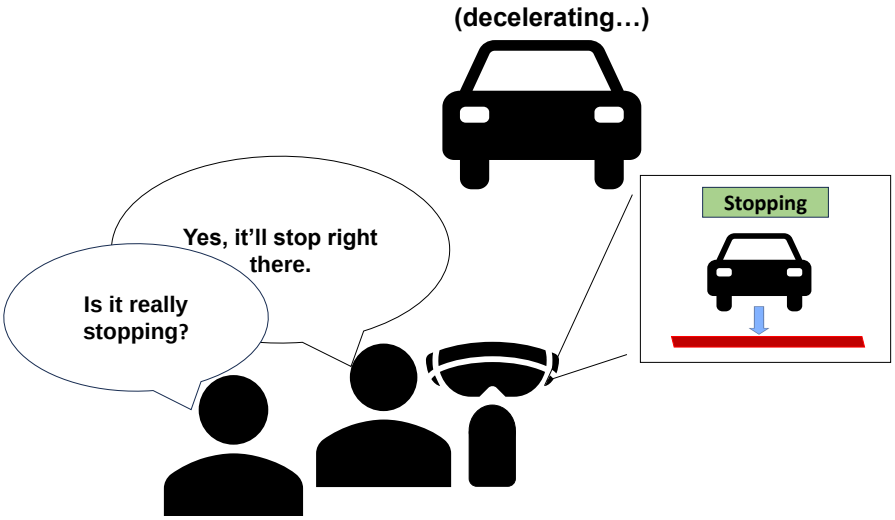



Fig. 1.4: Possible scenario of pedestrians equipped with AR devices that shows the intention of a CAV

## 1.4 Organization

Chapter 2 introduces related work in eHMI hardware and AR-based pedestrian support in ITS. Then chapter 3 will describe details of the system we proposed and implemented. Chapter 4 will depict the experiments we have done to evaluate people's feelings and comments on the system. Finally after discussion on the results in chapter 5, the conclusion will be given in chapter 6.

# Chapter 2

# Related Work

As stated in the previous chapter, efforts have been made to enhance pedestrian safety in intelligent transportation systems. Based on vehicles and road infrastructure, people had a lot of designs of eHMIs. When making pedestrians an active role in the ITS, smartphones are central to the research because they are ubiquitous and possess various types of sensors, such as GPS and inertial measurement unit IMU. Conventional research harnesses these sensors to obtain pedestrians' location and movement information as well as dispatch necessary warnings using the smartphone's vibration or audio functions. Recently, improvements in smartphone performance have created additional possibilities in this field. This chapter will introduce related work in the field of pedestrian support, based on eHMI and AR.

## 2.1 eHMI-based Pedestrian Support

In the work presented by Wilbrink *et al.* , they equipped a vehicle with an LED light band around the top of the vehicle. Dey *et al.* studied pedestrians' reactions and preferences on the color of such light band [27], while Bazilinskyy *et al.* did a comprehensive study on the effect of activation distance and install location of such eHMI concepts [28]. There's also a growing interest in using light projection, in addition to the more common LED panels and bands on vehicles. Bazilinskyy *et al.* have looked into several innovative ideas for light-projection eHMIs. For example, a vehicle could project a zebra crossing on the road to let pedestrians know it's safe to cross. It could also use light arrows projected in front or behind to show if it's moving forward or backward [29]. Furthermore, people also introduced some creative and user-friendly bionic eHMI concepts. One such idea is the use of LED displays to create a "smile" on the vehicle [30]. This kind of display can be used to communicate a friendly and non-threatening intentionion to pedestrians and other road users, enhancing trust and interaction. Another intriguing concept involves integrating "eyes" into the vehicle design. These eyes can move and blink, mimicking human eye gestures to convey messages or intentionions, such as looking at the pedestrian to convey that "I'm aware of your presence" to make the pedestrian feel safe [31], or tell the pedestrian about the vehicle's driving direction [32]. This approach not only adds a human-like element to the interaction but also leverages pedestrians' innate ability to read and respond to eye movements, making communication more intuitive and effective.

Besides hardware on the vehicles, there are also eHMI concepts that add equipment on the roadside. The smart pole is another promising concept for enhancing vehicle-pedestrian communication in ITS. A smart pole can be equipped with many devices such as a 5G communication module, solar panel, road condition sensor, charging socket for



Fig. 2.1: Figures of eHMI concepts on vehicles, including light bands, projection, ”smile”, and ”eyes” on a vehicle, from [33].

electric vehicles, and a smart display for instant road conditions [34]. Specifically, Chauhan *et al.* have explored the usage of a smart pole to help convey a vehicle's intention to the pedestrian. The pole will display different colors according to the vehicle's intention to help pedestrians understand whether the vehicle is going to yield or not when they want to cross the road [35].

## 2.2 AR-based Pedestrian Support

Regarding AR-driven support for pedestrians using smartphones, independent of autonomous driving, multiple applications have emerged offering AR navigation features, with Google Maps on smartphones being a notable example. An advantage of AR is that pedestrians can stay aware of the surrounding environment while receiving extra information. Azuma *et al.* [36] showed that displaying information on AR is natural, and users' situational awareness was improved. Dey *et al.* [33] also addresses that with smartphones, AR allows multiple users to receive information from connected eHMI concepts simultaneously.

In the advantages of AR, research has been conducted to design possible AR concepts to protect pedestrians or enhance the communication between them and the transport system. Several existing types of AR concept design proposed for pedestrian support exist.

### 2.2.1 Head-up Display

Tong *et al.* [37] designed an AR application that warns the user about a possible conflict with a vehicle when he approaches the crossing (in figure 2.2). The user interface is designed in a 2D convention where all elements appear to stick on the display screen and the authors made efforts to project the AR interfaces such that they seemed to be at the right place. Although this work does not work with autonomous vehicles, it claims that the design can be extended into an autonomous driving environment where it can give warnings to pedestrians about the malfunction of the vehicle.

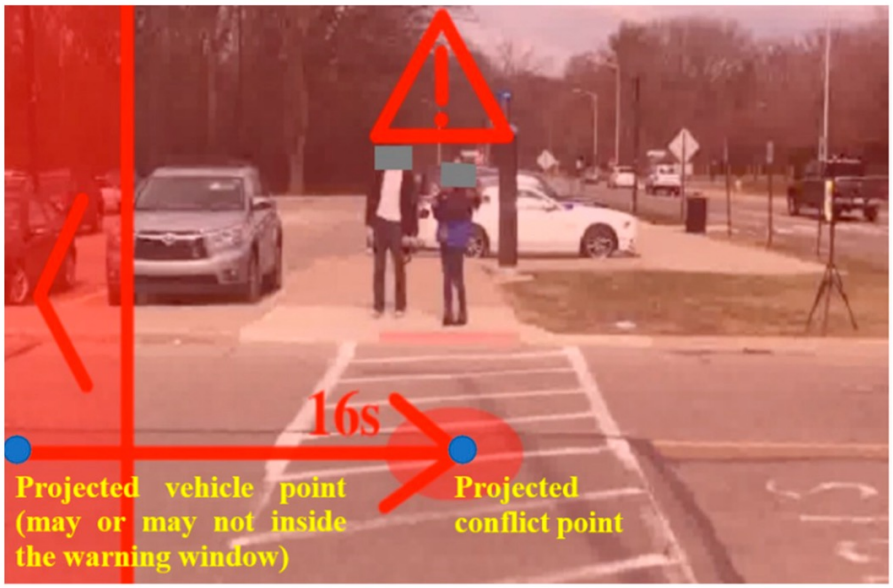
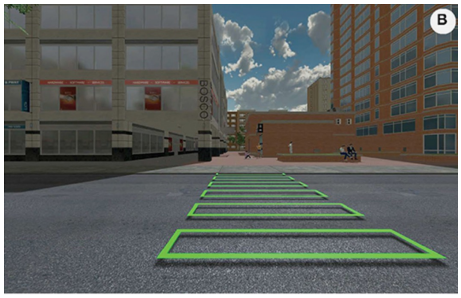



Fig. 2.2: AR interface to warn the pedestrian, by [37].



(a) AR navigation path with vehicle intentions.



(b) AR zebra crossing by [24]

Fig. 2.3: Examples of AR interface on the road.

### 2.2.2 AR Interface on the road and Other Infrastructure

It is normal for pedestrians to encounter multiple vehicles when they are about to cross a street. To aggregate the information from AVs and meanwhile provide a clear interface for pedestrians, Tran *et al.* proposed to show an AR zebra to demonstrate that the vehicles are coordinated to stop and yield for the pedestrian [24].

Hesenius *et al.* integrated three different AR interfaces into their work: AR safe zone, navigation path, and vehicle intention. Their proposed use case is also crossing the street.

Figure 2.3a showed their design of AR navigation with vehicle intentions. Their ad-hoc user study shows that people rate the design of vehicle intentions with navigation path most trustworthy[38]. This work has inspired us to consider that displaying the intentions and status of autonomous vehicles (AVs) may be crucial in making pedestrians feel safer around them.

### 2.2.3 AR Interface on the Vehicle

In Tabone *et al.* 's work, they proposed several AR interface prototypes, in their second proposed concept, they placed AR objects on a vehicle's surface to display information about whether the vehicle was yielding the pedestrian at a crossing [23]. This is more similar to the conventional eHMI concept that is installed on the vehicle but is more flexible due to its digital nature.



Fig. 2.4: AR interface on a vehicle designed by Tabone *et al.* .

Existing research has proposed and investigated thoroughly with multiple design concepts for AR-assisted V2P based on user studies. Some of these studies performed simulations to implement their designs using VR and evaluated the concepts with user studies. However, they seldom concentrate on the AVs' side to verify a complete system with autonomous driving software in real-time. To address this gap, we attempted to extract information from an autonomous driving system, presented it in an AR application, and conducted field experiments with a physical AV.

# Chapter 3

# Approach

## 3.1 Overview

As figure 3.1 demonstrates, the system primarily comprises three parts: a program integrated with Autoware, a server, and an AR application on a mobile device. This chapter describes the details of each part, including how we obtained information from Autoware and technical details such as how we utilized the AR framework to demonstrate the information.

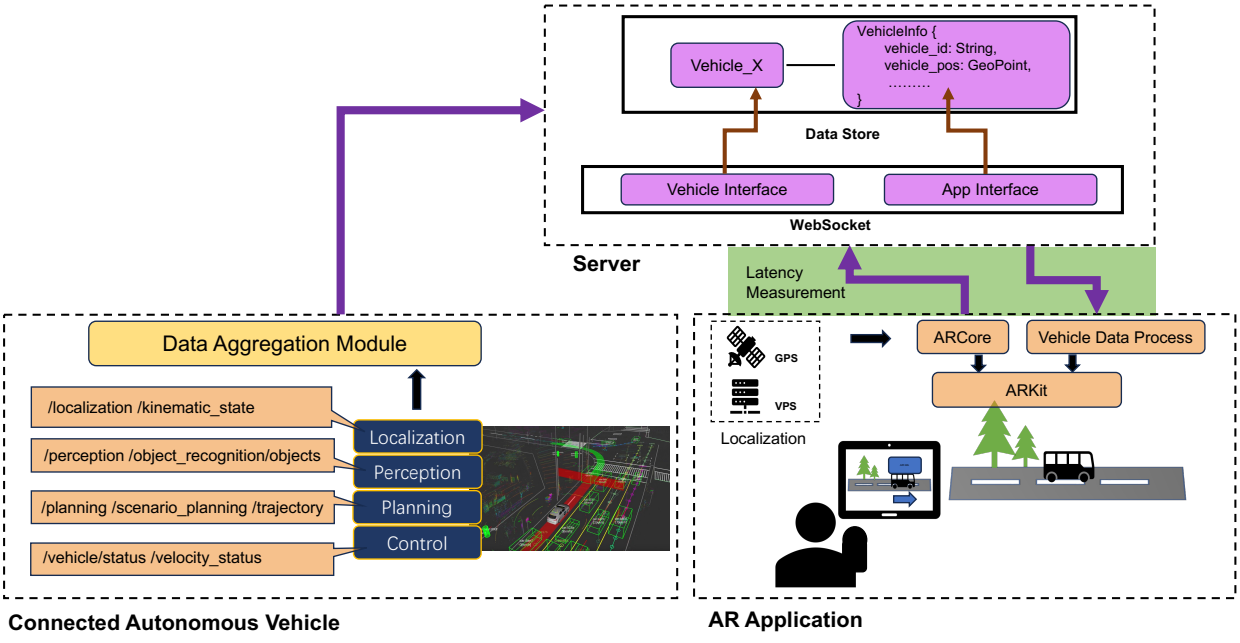



Fig. 3.1: Architecture of the proposed system

## 3.2 Design

### 3.2.1 Integration with Autonomous Driving Software

As stated earlier, the main target is to convey information from the AV (or CAV)'s side to pedestrians. Therefore it is better to work with open-source software where we can have

access to all functions of the software. As an autonomous driving system, the architecture of Autoware is similar to the general autonomous driving system introduced in figure 1.1. It can be roughly divided into four modules:

- A perception module to observe the surroundings of the vehicle, classify the objects, and recognize the driving lane.
- A planning module. Generally, it can make a route for the vehicle from the current place to the destination. More specifically, this module also tells the vehicle how to move step by step, such as the time to brake when there's a red signal ahead. When there's a stop line or zebra crossing ahead, the planning module will also command the vehicle to reduce speed or stop.
- A localization module, this module tells the vehicle's actual place on the map. This is often done by analyzing the data from Global Navigation Satellite System (GNSS) combined with local LiDAR information.
- A control module that communicates with the vehicle hardware to move the physical vehicle.

In the context of V2P, in addition to filtering out raw data generated by low-level sensors within the system, selecting suitable upper-level information to convey to pedestrians to demonstrate the vehicle's intention is also essential. Existing research has shown a lot of interest in scenarios where an AV will or will not yield when it encounters a pedestrian near a crossing where there are no signals or traffic signs. This is directly connected to the planning module as introduced above. In Lu *et al.* 's research, they also suggests that the NLOS scenario should be considered for the pedestrians [39]. As a result, considering the actual implementation of Autoware, the following several types of information are concentrated.

- Kinematic information. In conventional vehicles, such information can be easily read by the human driver. It describes the vehicle's location, velocity, and acceleration status. When provided for pedestrians, it can show a trend that the vehicle will stop if the value velocity decreases continuously and can also warn that the vehicle will not stop if the velocity value keeps or even increase. The location information, can be used to set an annotation or mark on the interface of the AR application to remind the user of AVs nearby. Location information will also help pedestrians' device to display AR objects, which will be introduced later.
- Perception information. Specifically, perception of surrounding objects such as vehicles and other pedestrians. This information seems far from telling the intention of the AV, however, we think it can help visualize objects obstructed by the vehicle to avoid the non-line-of-sight situation, or those observed by the vehicle but can not be seen by the pedestrian, like V2X cooperative perception introduced in the first chapter.
- Trajectory information. This information can be found in both planning and perception module. For trajectory in the perception module, the Autoware calculates a short predicted route for movable objects around the vehicle. Like the perception information, such trajectory may be helpful in the "cooperative perception"" mentioned above. As for trajectory information in the planning module, it demonstrates a segment of the vehicle's route and is perfect for showing the intention of the vehicle, such as its direction at an intersection.
- Stop planning information. This information is more concrete that it commands the vehicle to stop at a specified location calculated by the Autoware which includes the location and orientation of the vehicle and it should be the most convincing information we can show to pedestrians in the scenario of "yield or not yield"".

· In addition to perception and planning information mentioned above, some control-related upper level information is also found, such as blinker and emergency light control information. Although vehicles are generally equipped with such lights themselves, adding additional related information on the interface may help.

### 3.2.2 Server

There have to be measures for the CAV to send the information to pedestrians' AR devices. Existing V2P research has investigated the way of communication. The dedicated short-range communications (DSRC) is an existing technology applied in modern ETC devices. It has been proposed to apply in V2P collision avoidance scenarios in early years, where the vehicles sent emergency messages directly to the pedestrians' devices [40] [15]. However, till now, there is no trend for mainstream smartphone manufacturers to install a DSRC module on new products. To make our application more flexible, the cellular network was finally chosen as the AR application's main method of communication. The cellular network is widely covered and generally, there is not a concern of communication distance problems. Corresponding to the cellular network, a server located on the cloud should be deployed to relay the data from the CAV to the pedestrian. Locating on the cloud also ensures that the data can be accessed by vehicles and pedestrians anywhere.

In our design, the server retrieves and retains all essential information from the autonomous vehicle, attributing a unique ID for distinct vehicle identification. Because the data is all real-time, there is no database for data persistence currently. So the data is stored in a map data structure in the memory, which will also be mentioned later. The pedestrian's AR device similarly communicates its location to the server. However, to optimize data transfer, the server selectively transmits only the information about vehicles within a proximate range of the pedestrian, thereby avoiding the transmission of excessive and useless data. The example below shows the data structure used in transmitting the information from the CAV's side to the AR application.

```
struct ARVehicle {
    id: String,
    loc: GeoPoint,
    orient: Quad,
    speed: f64,
    turn_status: TurnStatus, // Blinker
    stop_info: StopInfo,
    predicted_objects: PredictedObjects,
    trajectory: Trajectory,
    route: Trajectory, // Overall route
}
```

### 3.2.3 AR Application

To verify our whole system, the AR application needs to visualize all messages that have been selected before we can come up with a scenario and evaluate it. To begin with, the design of the AR interface needs to be considered, different messages should fit in different AR shapes or text. According to the information we obtained from Autoware, the gist for designing AR interface can be summarized to the following:

· The displayed objects should have a conspicuous display with clear contours, as




Fig. 3.2: An AR HUD design [23].

Hancock *et al.* suggest in their research. In our case, the displayed AR objects should not have any transparency if they want to pass important messages to pedestrians. In addition, some physical characteristics, such as the reflection of light, should be turned off to make sure that the object can be seen from all angles.

- Capability to work with multiple CAVs and display vehicle-specific information should be considered. We think Tabone *et al.* 's design concepts include most of the popular and intuitive designs in this field. For vehicle-specific information, intuitively we think panels on the vehicle will be a good design, as it works like an eHMI, but it's in software. Therefore, this design will be familiar but more flexible.
- If there's any text on the AR objects, then the text should always "look at"" the pedestrian's device. In their following work, Tabone *et al.* did an online study with over one thousand participants, asking for the intuitiveness and convincingness of their designs. They found that among their designs, the two HUD designs (Nudge HUD, as shown in figure 3.3 and Pedestrian Lights HUD) are voted as the most intuitive and convincing [41]. However, we think that if we are working with multiple vehicles, content on such HUDs can be crowded, leading to distraction of pedestrians. By putting the information further onto the vehicles, this problem may be solved, which leads us to the concept of panels on the vehicle. However, the panels ranked low in their result of the questionnaire so modification is needed. Considering the characteristics of HUDs, we think making the displayed content face the pedestrian may be the key to making it clearer and easier to recognize.

In conclusion, in our design, we decided to attach the AR objects to the vehicle in the application, with a face-to-face information panel over the vehicle as the main body of the display. To achieve this, the location of the vehicle is needed for the display of AR objects, this will be introduced in the implementation section. The information panel displays the status of the vehicle, such as current speed and text demonstrating whether it is going to stop. Furthermore, we designed AR arrows to visualize the vehicle's trajectory and AR boxes to indicate objects observed by the vehicle, hoping to evaluate the pedestrian's cognitive load when presented with multiple types of information. Providing more information may also help in increasing the pedestrians' sense of safety.

## 3.3 Implementation

### 3.3.1 Integration with Autonomous Driving Software

As stated above, the Autoware is based on ROS. Like other ROS programs, Autoware is build upon nodes. A **node** is a process that performs computation. They are combined together and meant to operate at a fine-grained scale, a robot control system will usually

comprise many nodes [42]. For example, one perception node on Autoware noticed that the vehicle is approaching an obstacle, it will need to send information to a node that is in charge of planning or emergency. Such information is called **messages**. A message is a simple data structure, like *struct* in C or C++. It can encapsulate primitive data types like integer and boolean values and also supports nested data structures [43]. And the mechanism to send messages is through **topics**. The node that generates and wants to give out information will need to publish the data to a topic. On the other hand, the node that is interested in a certain type of message will have to subscribe to a topic to obtain the data[44]. As the publisher-subscriber mechanism suggests, once a topic is subscribed, the data will be transmitted to the subscriber continuously, and there can be multiple subscribers listening to one topic.

As the basic principle of ROS, we have the access to the messages that all important nodes publishes to perform autonomous driving tasks within Autoware. Therefore, we can obtain the information we want by creating subscribers to certain topics that are publishing messages. As shown in the left part of Figure 3.1, there are four topics we decided to concentrate on the following topics. Note that Autoware applies the Military Grid Reference System (MGRS) as the default coordinate system for the vehicle to localize.

- */localization/kinematic_state*. This topic publishes kinematic information about the vehicle, including the vehicle's location (x, y coordinate, and altitude) and orientation (in quarternion).
- */perception/object_recognition/objects*. This topic sends information about the objects detected by the perception modules. For each object, there is data about its classification, location, orientation and size, as recognized by Autoware. As introuduced earlier, this topic also includes the predicted path of the objects, they are stored in an array of location points.
- */planning/scenario_planning/trajectory*. This topic contains the planned trajectory of the vehicle itself, which is also stored in the form of an array of location coordinates.
- */planning/scenario_planning/status/stop_reasons*. This topic is more complicated than the former three. A single message contains multiple data structures, each structure contains reason for the stop command, such as obstacle ahead, around, stopline or red signal. There are also expected stop location and orientation in the rest of the data structure, with a *dist_to_stop_pose* represents the distance from the vehicle's current location to the planned point of stop.
- */vehicle/status/velocity_status*. This topic reports velocity of the vehicle.

As a demonstration, an example code of subscribing to one of the topics in Autoware and deal with the data that the topic distributes will be presented below. The implementation is done using C++, which is also the language used by ROS.

```
class VehicleStatusSubscriber : public rclcpp::Node {
    private:
    double velocity;
    rclcpp::Subscription<autoware_auto_vehicle_msgs::msg::VelocityReport
        ↪ >::SharedPtr vehicle_velocity_subscription;
    void vehicle_velocity_callback(const autoware_auto_vehicle_msgs::msg::
        ↪ VelocityReport::SharedPtr msg);
}

VehicleStatusSubscriber::VehicleStatusSubscriber(): Node("
    ↪ vehicle_status_subscriber") {
```

```
    vehicle_velocity_subscription = this->create_subscription<
        ↪ autoware_auto_vehicle_msgs::msg::VelocityReport>(
    "/vehicle/status/velocity_status", 10, std::bind(&
        ↪ VehicleStatusSubscriber::vehicle_velocity_callback, this,std::
        ↪ placeholders::_1)
  );
}
void VehicleStatusSubscriber::vehicle_velocity_callback(const
    ↪ autoware_auto_vehicle_msgs::msg::VelocityReport::SharedPtr msg){
  this->velocity = msg->longitudinal_velocity;
}
```

As stated earlier, a node is needed to join the communication with Autoware, which is dependent on ROS. After registering the subscription, a callback function is needed to receive the published data. Within the callback function, data from each topic is assembled to a large custom data structure, which will be sent out to the server as JSON.

### 3.3.2 Server

As a bridge between the CAV and the pedestrian, the server will receive data from the vehicles and store their information. It will then wait for the AR application (the pedestrian's side) to register the device and establish a communication channel. After receiving the AR device's location, the server will calculate the distance between the pedestrian and registered CAVs, and then send back information about the CAVs that are close to the pedestrians.

As both the server and AR device will be sending information, WebSocket was chosen as the communication protocol. Websocket is similar and compatible with the hypertext transfer protocol (HTTP) that people are familiar with. The different point is that Websocket is a full duplex protocol, which means both ends of the communication can actively send data packets to each other. In HTTP however, only the client can actively send requests to the server, and the server then sends back the responses. In conclusion, WebSocket is a more suitable and meanwhile generally-used communication protocol in such a scenario of real-time data communication, compared to HTTP. As for the serialization of data, JSON was applied.

The rate of transmitting data should also be controlled to save data and battery usage of the pedestrian's device. For example, Autoware generates the *stop_reason* message at a rate of 40 HZ and a general data update rate is 10 HZ in an AV. To throttle the data from different topics, the server will not simply forward what it received from the CAVs directly to the pedestrians. Instead, the server will store the information about each CAV (currently, data persistence is not implemented, the data is stored in the memory while the program is executing) and update its local value each time.

```
Ok(msg) => {
            let user_loc = Location::new(msg.lat, msg.lon);
            let mut rsp_vehicles = Vec::<ARVehicle>::default();
            vid_vehicles.read().await.iter().for_each(|(_, v)| {
                let v_loc = v.loc.clone().into();
                let dis = user_loc.haversine_distance_to(&v_loc).meters();
                if dis <= 50.0 {
                    rsp_vehicles.push(v.clone());
                }
                eprint!("{}", dis);
```

```
        });
        let rsp = ARResponse {
            vehicles: rsp_vehicles,
        };
        tx.send(Message::binary(json!(rsp).to_string().as_bytes()))
            .map(|res| {
                //handle results...
            })
            .await;
        }
```

As an example, the example code above shows the process of receiving location data from a pedestrian's AR device and then sending back information about vehicles that are within 50 meters away from the pedestrian.

### 3.3.3 AR Application

#### AR Framework

Considering the availability of the hardware, smartphones and tablets were set as the target devices. And ARKit was chosen as the base AR framework. The AR framework takes visual input from the camera of the device, additionally, it can also obtain depth information and detect surface from current images from LiDAR that is integrated with the camera. Some cameras can also obtain depth information, depth means the distance inferred from the camera to points in the scene. Combining those visual data with other sensors on the smartphone, the framework can build a map of the surrounding environment. With techniques such as surface detection and ray tracing, the location can be specified by the AR application user and the AR object can be put onto the expected point.

The workflow of putting an AR object (entity) into the current scene can be represented by the following figure:

In the conventional way of creating an AR experience, as stated above, creating a local map based on visual data is necessary to put AR objects onto the scene. However, vehicle-pedestrian communication is expected to mostly happen outdoors, and doing such a job on an outdoor scale can be so heavy for current mobile devices that the framework may lose track of the objects. There are two ways to solve this problem, one is to build a map of the outdoor scene for the application, which can be costly and is far from the target of this project. The other way is to apply a new API provided by the AR framework: geographic AR. This technique combines GPS, the device's compass, and the world-tracking feature in AR to track specific geographic locations. Given a latitude and longitude, the AR framework can put a virtual anchor onto the specified location to keep track and continually modify the display in the camera feed as the device moves [45]. This technique is critical for stably displaying AR objects at a moderate distance, typically a few tens of meters away. Besides GPS and compass data, street view images are also crucial for this technique to obtain an accurate localization within one meter. With street view images being uploaded to the dedicated server that works with the framework, it can obtain accurate localization information after the server compares the street view with that in its database. The two IT giants, Apple and Google both have provided this capability to their AR framework. Initially, the implementation was based on ARKit and Apple's framework, but later it was found that Apple's framework couldn't work if its database did not have the street view information for the current location. That is not convenient for carrying out experiments on the university campus as both of the

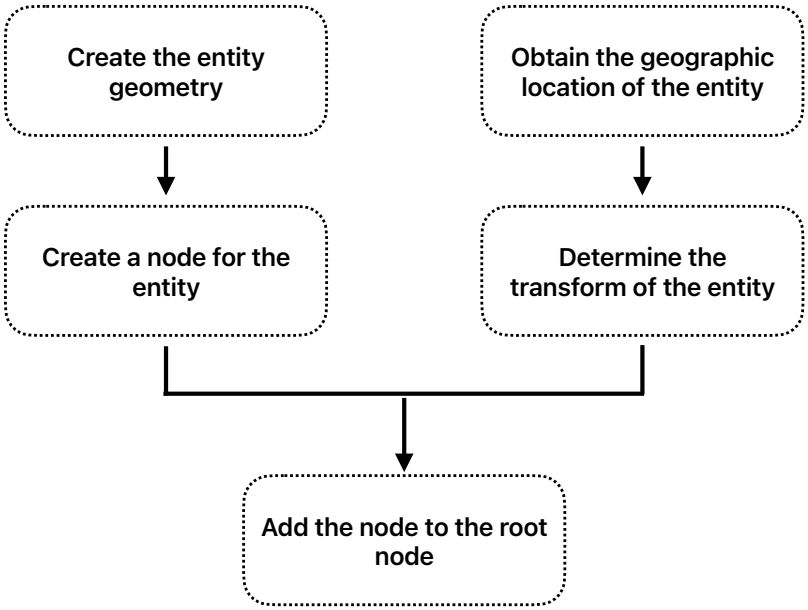



Fig. 3.3: General workflow of putting an AR object to the scene of the application.

companies doesn't have street view data of the UTokyo campuses. In the end, ARCore, the framework provided by Google was applied because it could work independently without street view-assisted localization, which they called the visual positioning system (VPS).

As figure 3.3 shows, before it is possible to visualize an AR object, the framework needs to be provided with the geographic location of the entity. As the CAV will continuously report its location, it is straightforward to utilize this information to display the AR content. This is also a reason for choosing the design of "a panel on the vehicle".

### Data Handling

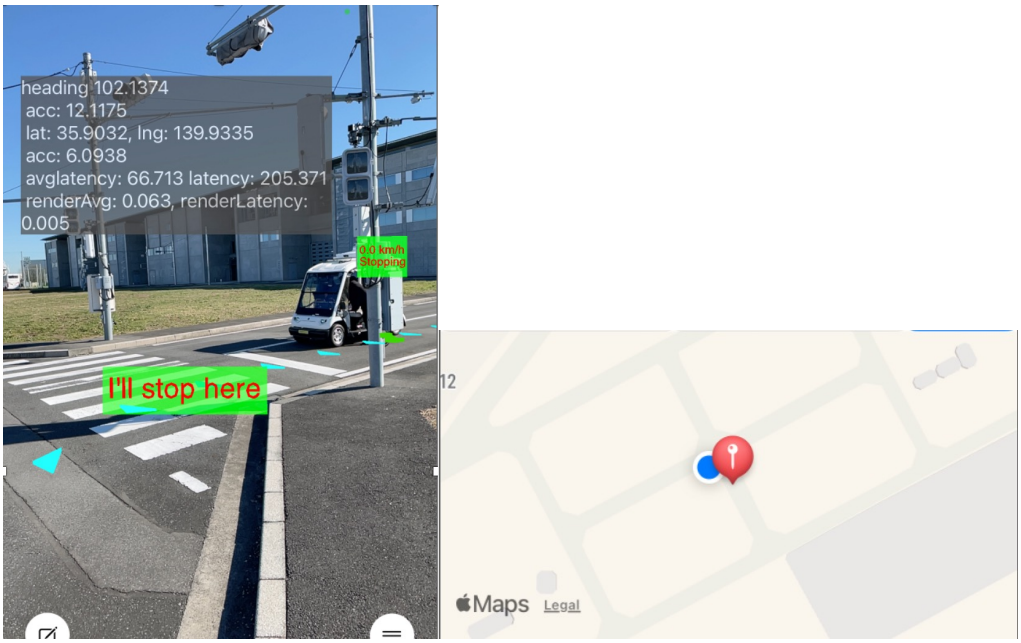
Like the server, the application also keeps temporal storage for current nearby vehicles. But besides textual information, it will also store references to the AR objects (entities), which helps the program manage the entities and control their visibility. Every piece of information from the server contains the current location of the reported vehicle, once it is received, the AR application will create a *GARAnchor* based on the latitude and longitude value.

```
self.garSession.createAnchorOnTerrain(coordinate: coordinate,
    ↪ altitudeAboveTerrain: 0, eastUpSouthQAnchor: simd_quaternion(0.0,
    ↪ 0.0, 0.0, 1.0))
```

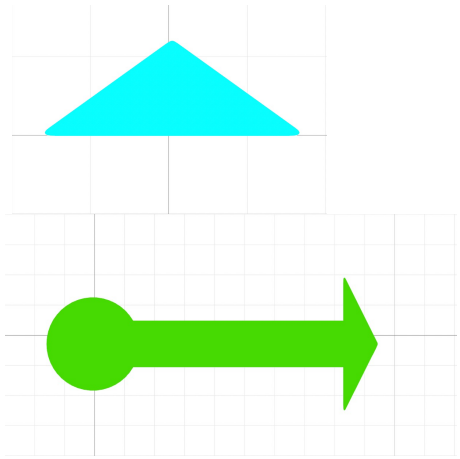
Then the rest of the information will be stored into a map to update the application's local information about the vehicle. Then several tasks will be created and put into different task queues. These different task queues are used to distinguish different types of AR entities and make it possible for the application to retry creating them in the AR scene if there's any error.

### Visualization

The final designs are shown in figure 3.4. As it can be seen from figure 3.4a, the green




(a) An overview of all AR objects, from a screenshot of the application on iPhone 12.



(b) Arrow designs.

Fig. 3.4: A screenshot during experiment with the system.

panel on the CAV displays the real-time speed and explanation of the current status of the vehicle ("stopping" e.g.). And another green panel was put in a further point from the vehicle. As the text on the panel suggests, this information comes from the *stop_reason* message and reflects the exact point that the CAV's planning module expects the vehicle to stop at. For arrows in figure 3.4b, the green arrow is set to be at the same place with the vehicle, indicating the direction that the vehicle is heading. The blue triangles are used to indicate the trajectory of the vehicle, as in this ROS message gives only points to describe the vehicle's route. In addition, to give more information to the user, a small map is added at the bottom of the application, there the user can see red indicators which represent surrounding CAVs.

# Chapter 4

# Experiments

## 4.1 Overview

Three different experiments were carried out to verify the functions of this system and collect ideas from experiment participants. The experiments include a test on the latency of the system, a questionnaire to the participants of a technology exhibition about the visual effect of the AR interface, and another small-scale user study.

Before introducing the experiments in detail, specifications for general devices and software used will be listed in table 4.1.

## 4.2 Latency Test

The latency test aims to have an idea of how long it takes for a message to be generated from Autoware until this message is transmitted to the AR device. A long latency may lead to misunderstanding of the vehicle's intention and cost the pedestrian more time in interacting with the vehicle, which may cause a decrease in efficiency or even accidents. From the previous chapter, it is clear that the transmission of the data through the cellular network will take up the most time. Therefore network latency test is necessary for both CAV-server and server-AR application links. The tested part is shown in figure 3.1.

### 4.2.1 Scenario Design

For the latency test, we did not run the CAV in the field. Instead, the test data was crafted and put into the server and tested like an API test. This is because we want to test the latency when there are multiple vehicles nearby, which means there will be an array of vehicle information that can make the data size big. In the test, the AR device will be put in the same place. For every test, the application will be launched and kept running for 30 seconds after all functions are initialized. During this period,

| Item | Version |
|---|---|
| AR Application | Swift 5.8 with ARCore 1.35.0 |
| Autoware | awsim-stable branch |
| Autoware Device | Ubuntu 22.04 on an Intel Core i9-10980HK CPU with 64G RAM |
| Server | Ubuntu 20.04 on AMD EPYC-Rome @ 2x 2.495GHz with 4G RAM |
| Server program | Rust v1.65.0 with warp v0.3 |

Table 4.1: Specifications for general hardware and software used in implementation and experiments.

| Data Size | Network Latency(ms) |
|---|---|
| 1 | 30.468 |
| 3 | 37.635 |
| 10 | 40.801 |
| 50 | 39.797 |
| 100 | 41.887 |

Table 4.2: Latency test results.

the application would continuously request the server for vehicle data and calculate the average value of latency. To highlight, the timing period is after sending the request and until receiving the response, calculating only the transmission of vehicle data.

### 4.2.2 Test Setup

The test was carried out in the test field of Kashiwa Campus, The University of Tokyo, the cellular network provider was KDDI (povo), and the AR device was an iPhone 12. The PC running Autoware and AR device was connected to the same cellular hotspot to ensure they had the same network environment.

### 4.2.3 Test Results

The test results are listed in table 4.2, the dimension of network latency is milliseconds and data size means the number of different vehicles. As the same data would be transmitted from the Autoware side to the server side at first, we can expect a similar latency value as the CAV also applies the same cellular network in our experiments.

It should be noted that this measurement did not count in the time that ARCore cost to initiate because we assumed that the AR application was running continuously.

## 4.3 Questionnaire Survey

After verifying the functionalities of the system, a field experiment was conducted to solicit subjective feedback from a broader audience. We captured the display of the AR application for illustrative purposes, as depicted in Figure 4.1. During the 2023 Interop technology exhibition, the screen record of the application, with the clips that explain the use case was played to the audience. This figure further showcases the design elements, including the AR bounding boxes, the status panel, and the route indicators. It should be noted that the design of the bottom figure differs from the previous ones because it's a design from our collaborator, Antyba Inc. who was assigned to provide a better visual effect for this application.

### 4.3.1 Scenario Design

The experiment was conducted in the Hongo Campus, The University of Tokyo, as illustrated in Figure 4.3. The vehicle traverses a brief distance on a one-way road, with our primary emphasis being on the journey from the starting green point to the red line. The red line was designated as the location where the pedestrian will intersect with the vehicle. Point A was also marked as a stop line in the vehicle's map data, ensuring that the vehicle is programmed to halt at that point from the outset.

Similar to the experiment in the previous section. The pedestrian, or the user of the

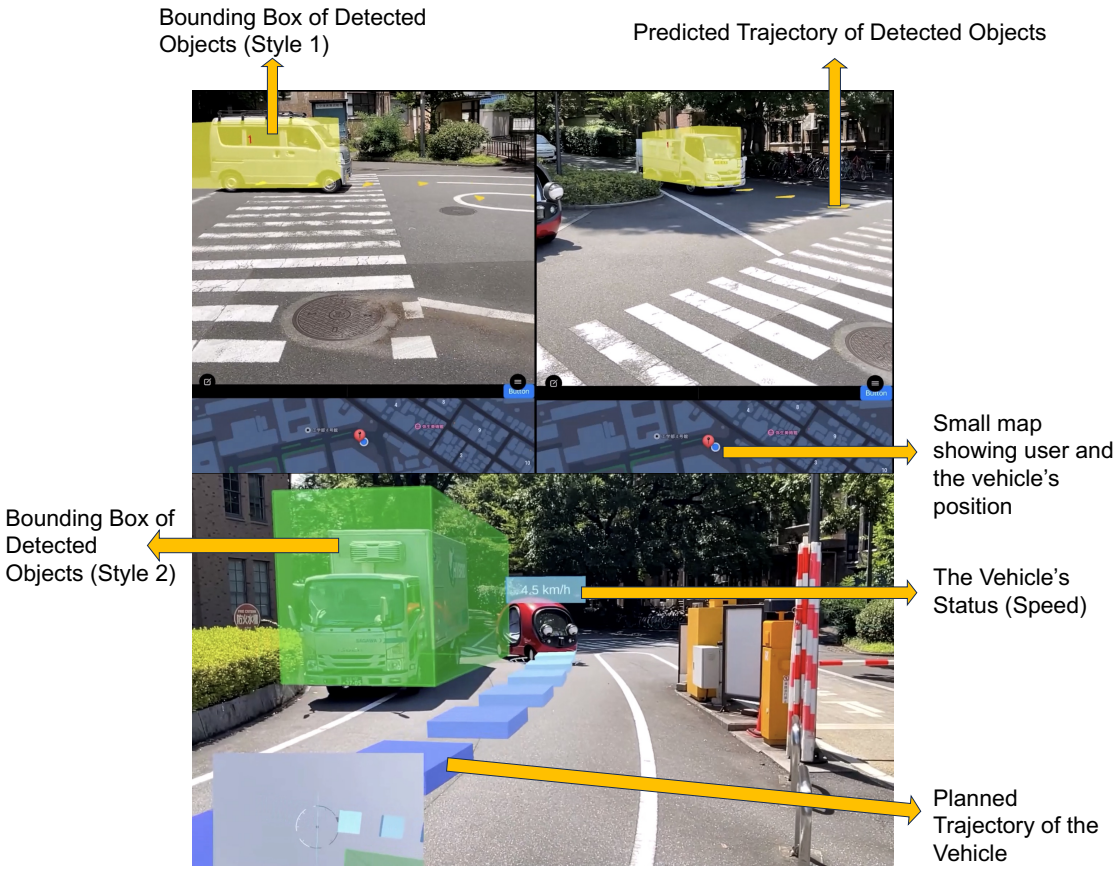



Fig. 4.1: Record of the AR Application

AR application, will begin their walk towards the red line from the side of the road as the vehicle autonomously approaches the same point. Upon reaching point A, the pedestrian assesses the vehicle's status before crossing to the other side of the road. For comparative purposes, we also documented scenarios where the pedestrian, without the aid of the AR application, approached the vehicle. This served as a control group for our subjective evaluation. During this process, we didn't have objective metrics, instead, the scene of the experiment and the application screen were recorded and later edited to demonstrate on the Interop.

### 4.3.2 Experiment Setup

The CAV in this experiment is a Postee [31] vehicle equipped with a VLP-16 LiDAR to localize itself and recognize its surrounding environment. Pedestrians use an iPad (3rd Generation) with iPad OS 16.6 as the AR device.

### 4.3.3 Questionnaire Procedure

To collect people's ideas, a questionnaire was designed and distributed to the audience who visited our exhibition space.

At first, the audience was explained about the project. The introduction included basic knowledge about autonomous driving, augmented reality, the motivation of this project,

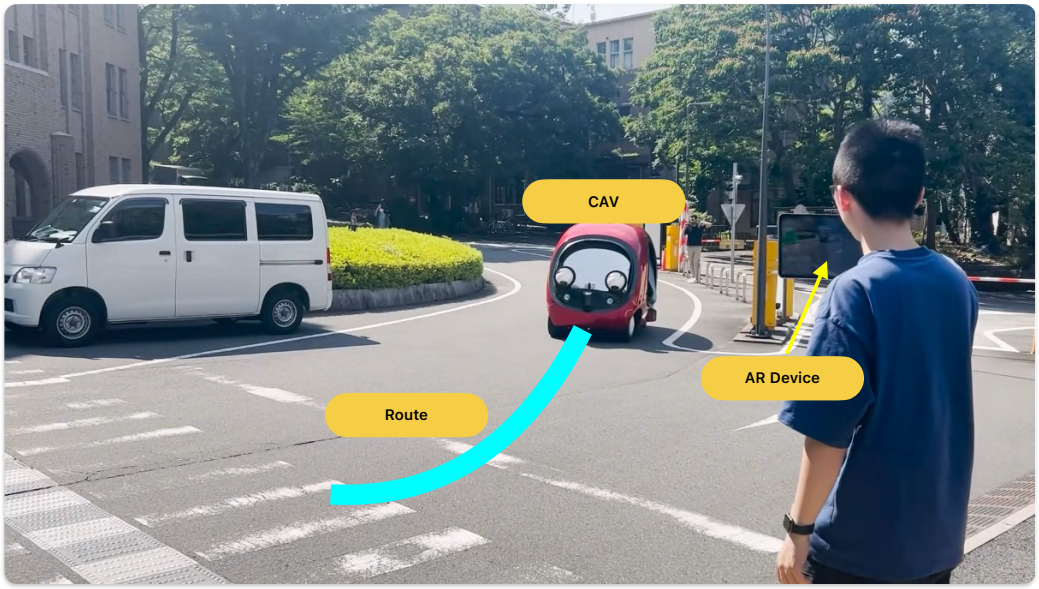



Fig. 4.2: Record of the Experiment.

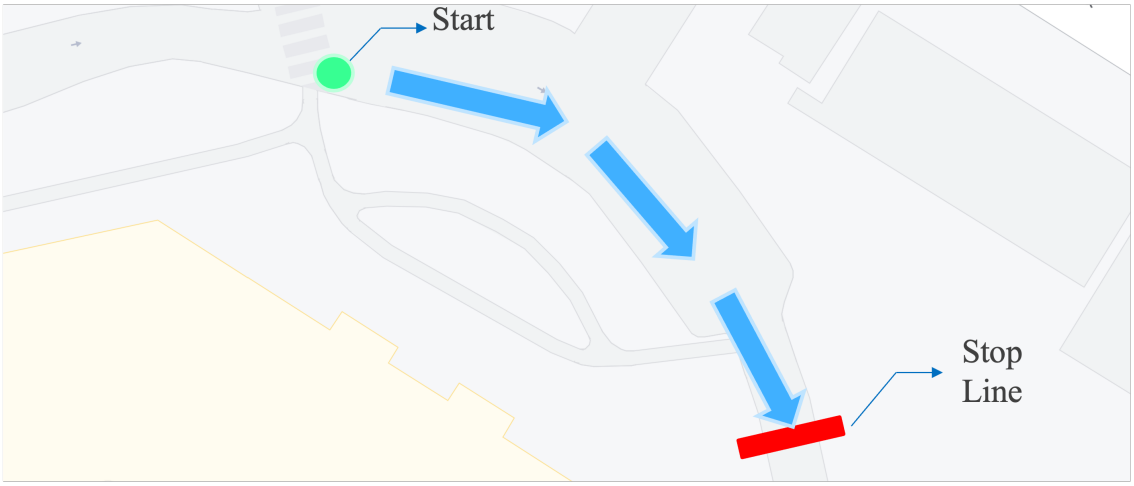



Fig. 4.3: Map of the experiment field.

and a description of the scenario for demonstration. Then, they watched the two-minute demonstration video. The video first described a dilemma where a pedestrian encounters an AV at a crossing and hesitates to cross because he knows nothing about the vehicle and is afraid that the vehicle will not stop, which was recorded during the experiment. The rest of the video demonstrated the screen recording of the application under the scenario described previously in the Scenario Design part. Before the pedestrian encounters the vehicle, the video is shot in a third-person view to give the participants a clear image of the experiment field. When the pedestrian encounters the vehicle and starts to use the AR application, the video switches to a first-person view of the AR application to provide the participants with a more immersive experience.

After watching the video, to leave more impression on the participants, they were provided with tablets we used in the experiment to experience the indoor version of the AR application. This indoor version of the application was developed by Antyba Inc. to help debug and demonstrate the system at the exhibition. In this version, a randomly generated QR code was used as the reference point for placing AR objects, just like typical AR applications do. As the application and the autonomous driving system work independently, we recorded the data sent from the AV's side, replayed it to create a dummy autonomous vehicle, and made the entire system work. Corresponding to the AR application shown in Figure 4.4, the video played on the laptop's screen is from the AV simulator, AWSIM. In the video, the simulated vehicle drove along a planned route, and necessary data for the AR application were played synchronously with the simulator's screen. The participants could continue experiencing the demo until they wanted to quit. Finally, the participants were provided with the questionnaire and were asked to answer




Fig. 4.4: Live demo demonstrated on the exhibition.

the questions on the spot.

### 4.3.4 Questionnaire Desgin

#### Demographics

The participants were first asked about their age (*Q1*), familiarity with autonomous driving (*Q2*), familiarity with AR applications (*Q3*), and frequency of walking on a public street (*Q4*). Q4 was set according to [46].

#### Investigation of Viewpoints

Next, the questionnaire investigated participants' perception about safety when encountering AVs. They were asked whether the lack of a human driver made it challenging for them to trust autonomous vehicles (*Q5*).

#### Rating of the AR Interface

After experiencing the demonstration, the participants were asked the following questions:

*Q6. Do you agree that, upon receiving additional information about the vehicle, you perceive it as more manageable and consequently feel an increased sense of safety?*

*Q7. Do you think you can maintain situational awareness of your surroundings while processing information from the AV?*

*Q8. Do you believe this system offers the flexibility to be utilized in any road setting to address various requirements, such as in a residential area's narrow street lacking zebra crossings or other markings?*

*Q9. How would you evaluate the visual quality of the AR interface, considering both the clarity of the presented information and the responsiveness of its updates?*

*Q10. Do you feel the AR interface displays excessive information, potentially diverting your attention from the road, or do you believe it would be feasible to present more details?*

Questions 5 to 10 were rated on a 5-point Likert scale. For Q10, we asked participants what information they wanted to add to or remove from the AR interface as an open question.

### 4.3.5 Results

In total, 58 valid answers to our questionnaire were collected. Here, $n$ indicates the number of answers. For general characteristics (Q1), most of the participants are at the age of 20 to 39 (58.6 %, $n = 34$), 15.5 % (n = 9) of them are over 50, and 6.9 % ($n = 4$) of them were under 20. Most (81 %, $n = 47$) participants walk almost every day on a public road (Q4), therefore, their responses based on their experience of walking were reliable. Regarding knowledge about autonomous driving and augmented reality, 63 % ($n = 37$) and 65.5 % ($n = 38$) of the participants had slight knowledge about AVs and augmented reality applications, respectively. Results of other questions are shown in Figure 4.6.

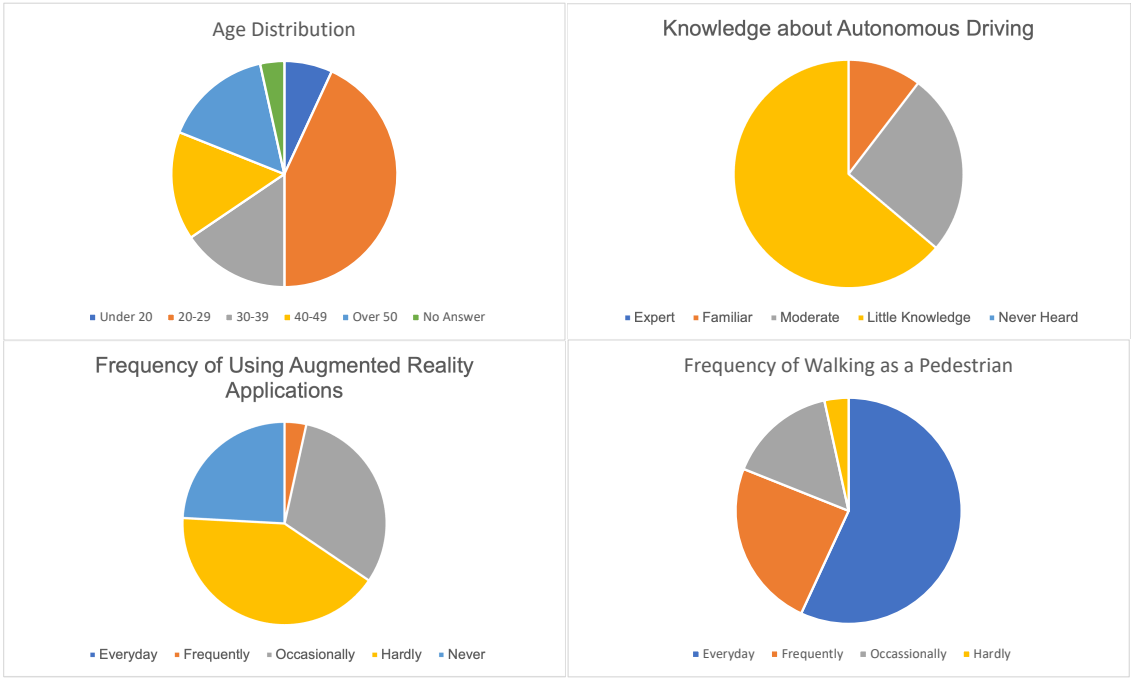



Fig. 4.5: Pie charts for results of demographic questions.

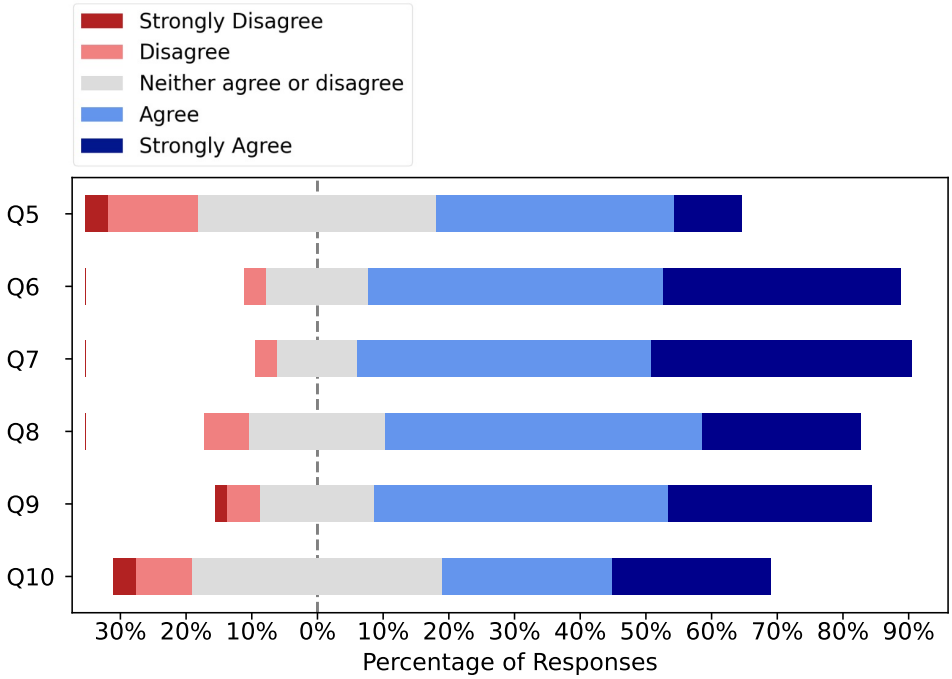



Fig. 4.6: Questionnaire results for the rest of questions.

## 4.4 User Study

After reviewing the answers to the questionnaires, the results showed that people were positive about utilizing this system. To evaluate how much can the system help pedestrians to understand the AV's intention in a certain scenario, we then conducted an empirical user study with a small group of participants.

### 4.4.1 Scenario Design

Although in our design, the AR application can work anywhere on the road and display many kinds of information, for user study, there needs to be a simple but convincing scenario that takes advantage of one or more kinds of information to validate this system. *stop_reason* is the most direct intention that a CAV can express. Therefore, the experiment design is based on this message.

The scenario is set at an intersection where there's no traffic signal. A pedestrian is going to cross the street when he finds that a vehicle is going to make a 90-degree turn and may have a conflict with him. In a conventional situation, he may wait at the roadside until the vehicle is reducing its speed to a very low level or even stopped, or the driver will make a gesture or eye contact with him to notify whether he can go or not. When it comes to AVs, without communication with the driver, this process may take more time because the pedestrian has no clue whether the vehicle is stopping or not. The figure in the specification section will illustrate this scenario.

But with the AR application, things may be different. The *stop_reason* should be powerful and convincing information for pedestrians to know that the vehicle is stopping, and the designated point of this stop will also appear in the AR scene. Autoware generates such information as soon as it detects the pedestrian will potentially conflict with the vehicle and makes plans in advance, therefore the pedestrian can see this information before the vehicle approaches. As a result, the total time that the pedestrian takes to

cross the road may be reduced.

As figure 4.7 illustrates, the CAV will run from point A and try to make a left turn at the intersection, while the pedestrian will start from point B and walk towards point C where he can start to make a crossing. Intending to obtain objective and quantitative results, a timer will record the time since the pedestrian starts to walk until he/she makes a move to cross. The timing is tested and adjusted in advance such that when a participant is walking at his normal pace and going to step down on the zebra line, he can notice that the vehicle is turning. For different participants, point A was set closer or further to the center of the intersection to minimize the error. As the route is fixed and the pedestrian appears in the same place every time, the CAV will generate a stop message that expects the vehicle to stop at the same point. There will be a human operator on the vehicle to prevent an emergency, he will only look at the screen of the PC that runs Autoware and won't give any hint to the pedestrian. After the experiment, several questions were raised to the participants, asking them about the experience.

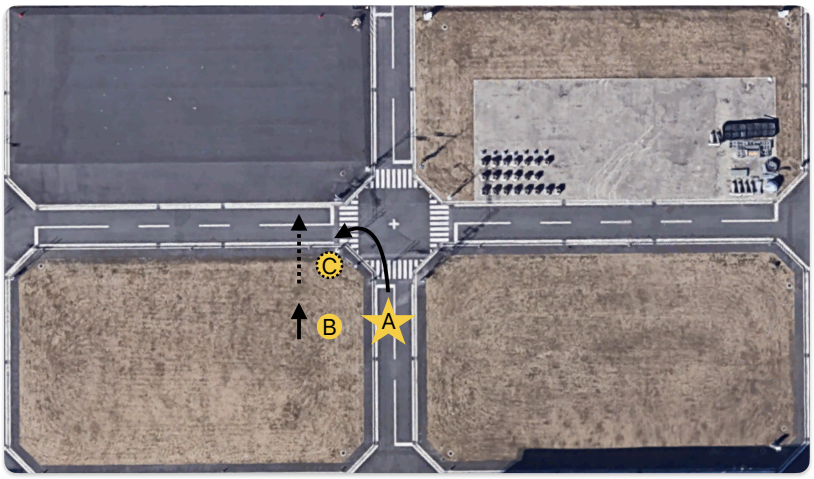



Fig. 4.7: The experiment field and scenario.

Four participants joined this experiment. They were told that the vehicle would approach them from behind and they were required to cross the road whenever they felt it was safe. The participants all had moderate knowledge of AVs. Besides, they were also shown the designs of the entities and principles of the AR application in advance. Every participant was assigned to complete the experiment six times, three times of which they were equipped with the AR device. For counterbalancing, the order of experiments for each participant was shuffled and different from each other.

After analyzing the data from the experiment, we had interviews with the participants to learn their feelings after using this system in the field.

### 4.4.2 Experiment Setup

The CAV was a Yamaha golf car that is capable of autonomous driving, it was equipped with a Velodyne VLP-16 LiDAR for localization and perception. The pedestrian takes an iPhone 12 as the AR device. The experiment was carried out in the experiment field in Kashiwa Campus, The University of Tokyo.

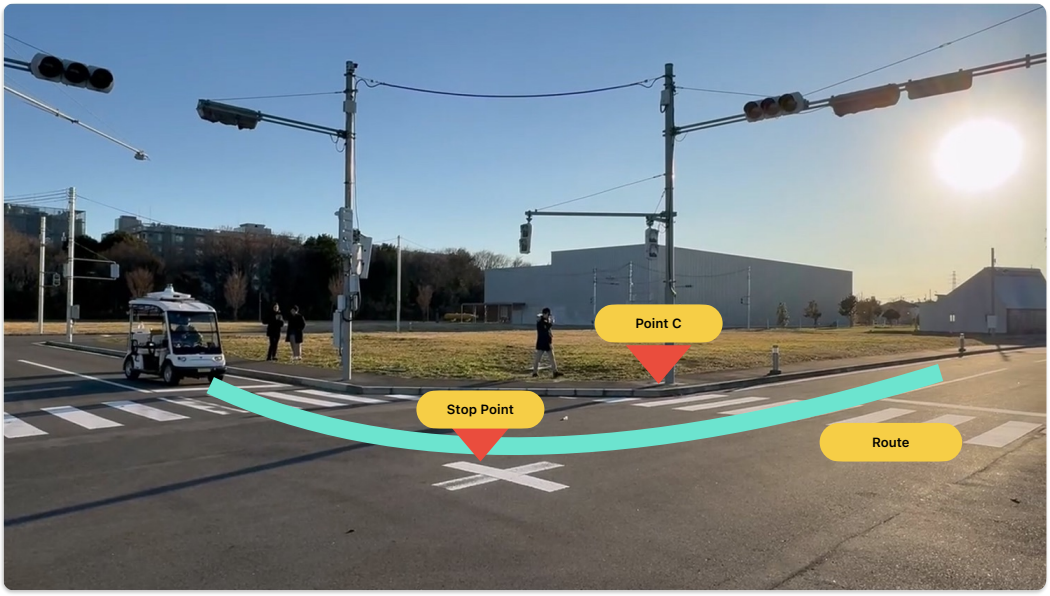



Fig. 4.8: Record of the user study.

| Participant No. | Time without AR (seconds) | Time with AR (seconds) |
|---|---|---|
| 1 | 8.46, 8.41 | 7.97, 7.49 |
| 2 | 7.37, 7.46, 6.84 | 7.21, 6.10, 6.18 |
| 3 | 7.53, 6.41, 7.06 | 7.36, 8.56, 5.42 |
| 4 | 7.29, 6.74, 6.59 | 8.06, 7.66, 6.12 |

Table 4.3: User study results.

### 4.4.3 Results

#### Timing Results

The experiment results are listed in table 4.3. For a better visualization, the order of results is different from the order of experiments. Note that for participant one, due to data loss of the timer, there are only four times of experiments recorded.

Summing up all data from the results by grouping them as experiments with AR and without AR, we obtained the average values of 7.28 and 7.1 with the standard difference of 0.67 and 1.00. The two-tailed P value for the paired t-test of this data is 0.61. By conventional criteria, this difference should not be considered significant.

#### Interview Results

However, we did notice that for the first 2 participants, the time was reduced by around 10 percent on average, which is apparent. A P value of 0.024 also shows a significant difference between experiments with AR and without AR, although the sample number is fewer to be statistically significant. In addition, we also found for participants 3 and 4, although using the AR device took them more time in the first two experiments, it got significantly better in the third time.

Based on the observation above, we interviewed the participants about their experiences

during the experiments. Three questions were raised, two of which are the same for all participants:

1. *Q11. Do you think the application increases the speed of your recognition of the vehicle's intention? Why?*
2. *Q12. Would you like to turn on such AR features if one day AR glasses are as ubiquitous as today's smartphones? Or are there any situations you can imagine where you definitely want or do not want such an application to show the vehicle's intention?*

Based on the participants' data in the experiment, a specific question was raised:

1. *Q13. The data suggests that the AR application has helped you to increase the speed to understand the vehicle's intention. Did you feel unaccustomed to the AR interfaces when you used the application by yourself for the first time? Can you tell me more about your experience?* This question was raised to participants 1 and 2.
2. *Q14. I noticed there's an increase in your reaction speed in the third time of your experiment with the AR device, can you tell me something about this?* This question was raised to Participant 3, as in the third time of the experiment, he took much less time to make the decision.
3. *Q15. The data suggests that the AR application has helped you little to increase the speed to understand the vehicle's intention. Can you tell me more about your experience?* This question was raised to Participant 4.

Towards Q11, participants 1 to 3 all gave positive answers:

1. *I can see the vehicle saying it's stopping even if it hasn't really stopped, it does accelerate my decision-making to cross the road. Compared to the normal case, I should always make sure that the car is stopped so I can feel safe to cross. Clear messages from the application saved a lot of work to tell if the car really wanted to give the road to me.*
2. *Yes. I think the application has a positive impact on the speed of recognizing vehicle intention. The application provides real-time updates on the movement of the vehicle, allowing me to make decisions faster. Sometimes it can be hard to determine if a vehicle is stopping, so it takes time to make decisions on our own. The application provides clear information about the vehicle's intention, which speeds up the decision-making process.*
3. *Yes, sure. The application helped me recognize the intentionion of the vehicle timely. I think the reason lies in the good visualization of showing the "Stop" text on the screen.*

Participant 4 didn't mention the acceleration in his decision-making, but he stressed that *I think instead of the increase in speed, I was more confident that the vehicle would stop.*

For the participant-specific question which asked about the direct experience of using the application, participants 3 and 4 both complained that they were not accustomed to the design and meaning of objects.

> *Since it's the first day I used this application, I was not accustomed to it.*

> *In the first time, I actually did not get the information shown in the screen. In the third time, I already got use to it and fast my reaction speed.*

Participants 1 and 2 also mentioned such unfamiliarity:

> *Even though I think the indicators were easy to understand and the application is*

*pretty user-friendly, I needed a short familiarization period, but it didn't take too long.*

*It happened that for example, I just recognized the "stopping" on the status panel of the vehicle but totally ignored the exist of the stop location sign.*

# Chapter 5

# Discussion

## 5.1 Latency Test

According to the test results, we can qualitatively expect that with the cellular network, the transmission of the information from the vehicle to the AR device won't take over 100 milliseconds in an area that has good coverage of the cellular network. In conclusion, we can expect a latency of around 100 milliseconds since the information is obtained by the subscriber module until it is displayed as AR objects on the AR application.

100 milliseconds sounds normal since usually in an ITS, a rate of 10 HZ is required for broadcasting cooperative awareness messages (CAM) [47]. For a vehicle that runs at a speed of 10 meters per second (36 km/h), this latency means that the AR objects displayed in the application will be at least 1 meter behind the vehicle. When the vehicle's speed is faster, this latency may have a larger impact on the application's visual effect, or even affect the pedestrian's recognition when there are multiple vehicles in a queue. But for scenarios such as intersections without signals, usually the vehicle speed won't be fast, that would be where this system can work at the best condition.

## 5.2 Questionnaire

According to the questionnaire results, the participants were positive toward the AR interface. Most participants believed the interface conveyed more information and made them feel safer.

Regarding questions about the sense of safety when encountering AVs (*Q5*), 46 % ($n = 27$) of the answers expressed concern due to the absence of a human driver. Meanwhile, 32.7 % of them neither agree nor disagree with this concern. The reason why a considerable number of participants gave a neutral answer may be that they didn't encounter a real autonomous vehicle, as one of the participants commented. In the future, we may need to have participants in the experiment field participate in further user studies.

Regarding our AR application's performance, people generally responded positively to our work. Over 70 % of them agreed or agreed strongly with the statements from *Q6* to *Q9*. This demonstrates that the system can effectively convey information from an AV and maintain pedestrian attention on the surrounding environment.

For *Q10*, the results showed that a considerable number of participants believed that the displayed information was sufficient. Thirteen participants provided in-depth feedback on this query. A subset expressed the desire for the system to present more details, including the distance between the vehicle and the pedestrian, the vehicle's intended destination, and indicators if the vehicle contains elderly passengers or infants. Conversely, some participants expressed concerns that the interface could become cluttered as the number of AVs in a given scenario increases. They emphasized the need for mechanisms to limit

the quantity of AR objects in such situations. While software implementation can readily address this, determining which elements to filter requires further exploration.

In summary, people tend to feel more secure with the AR interface that shows information about the connected autonomous vehicle's operations and intentions. But the types of information displayed should be selected so that it won't confuse the pedestrian.

## 5.3 User Study

### 5.3.1 Discussion on the Interview and Questionnaire Results

It can be shown from responses to Q11 that although the quantitative measurements did not speak strongly of the improvement in pedestrians' reaction time, they thought their confidence about the vehicle's intention was strengthened. As the third answer said, the "Stop" text let him make the decision faster, which reflects the result of Q9 in the questionnaire stage. This also converges with the Q6 that most people do feel an increased sense of safety towards the AV.

As for Q12, participants 2, 3, and 4 spoke positively of turning on this application. Participants 2 and 3 thought unsignalized intersections that have a small number of vehicles driving through is the best scenario. Participant 2 stressed that in a busy area that has many vehicles, turning on such a feature may just mess the view up. Participant 3 said he'd like this application when he was scared by the vehicle, a sudden horn e.g. Participant 4 preferred to see a longer route of the vehicle so that he could make a more confident decision. However, participant 1 prefers a clean view of the AR glasses without pop-up messages and he also thinks it would be annoying to turn on this application each time when needed. The answers showed the flexibility of an AR application to display any wanted information anywhere, corresponding to the result of Q8. And corresponding to the relatively large number of moderate ratings in Q10, it can be seen that although people accept the strength that this AR application brings, they are concerned that seeing such messages too often can lead to distraction or even make them feel annoyed. Different people may also want different kinds of information to make them feel more comfortable about the road.

### 5.3.2 Discussion on the Interview and Timing Results

According to the answers to Q13 to Q15, it was surprising that even though we've shown them the design of the AR concepts and the possible locations of their appearance, the participants still took time to get familiar with the application. This may relate to bad designs of the user interface which made the users don't know where to look in the beginning, despite the positive rating of Q9. This also reminds us that simulation experiments such as video watching and demo playing may not completely tell the truth. In addition, participant 4 also mentioned the problem of localization errors that made him make late judgments. Due to the private property of the experiment field, the VPS didn't work when the experiments so the application was working based on only GPS localization. Although the GPS worked well in the experiment field, the accuracy was not enough to support stable AR visualization all the time. Therefore, this problem should be solved if further work and verification needs to be done.

## 5.4 Summary

In conclusion, although the quantitative data did not speak strongly of the positive effect that the AR application brought to the pedestrians, from the interview we can understand that they did feel more confident and safer when facing a CAV on the road which is exactly our target at the beginning, this result also converges with that from the questionnaire survey.

The users also pointed out many challenges of this application that might potentially affect the reaction time in the experiments. For example, seeing many pieces of information about one or two AVs at an intersection without signals makes the pedestrian feel safe, but they don't want the same things on a busy road. The users' feedback also suggests that a plain design of the AR objects might cause a longer time of recognition. The AR framework should also be improved to work better in private fields like we've used.

## 5.5 Future Directions

From current observation and discussions, it is apparent that there are still many places in the system that can be improved. Regarding the AR application, the localization error within the experiment field of the campus should be fixed. This can be done by manually constructing a map of the field for the AR framework, it may be heavy but once it's finished, we can have much better localization and as a result, a better visual effect. Aggregating the data and managing the display of information from multiple vehicles so that they do not disrupt the user's recognition can also be an important direction if we want the application to be run anywhere. Making the application flexible to display a customed combination of AR objects may also improve the user's in-depth experience. Looking at the system, measuring the effect of network latency, and investigating different ways of communication should also be inspiring.

In terms of user study, adapting the AR application to AR glasses should let the users recognize the interfaces better and have a more immersive experience.

# Chapter 6

# Conclusion

In this study, we have designed and implemented a system that directly channels information from an autonomous driving platform to pedestrians via an AR application. Through our user study and questionnaire survey, we can say that people tend to feel more secure or confident with the AR interface that shows the intentions of a CAV.

Pedestrians' safety is always a concern in building an ITS with AVs. The broader implications of our work suggest that as autonomous vehicles become more prevalent, transparent communication mechanisms like the one we've developed will be essential in bridging the understanding gap between machines and humans. In the future, it will be beneficial to delve deeper into refining the design of the AR interface and improving the communication progress. Additionally, as urban environments possibly become more congested with AVs in the future, devising intelligent strategies to streamline and prioritize information display will be crucial. This ensures that pedestrians are not overwhelmed but are provided with the most pertinent information for their safety and decision-making.

# Publications

(1) Yiwei Cheng, Jin Nakazato, Ehsan Javanmardi, Chia-Ming Chang, and Manabu Tsukada, "Pedestrian-centric Augmented Reality Visualization of Real-time Autonomous Vehicle Dynamics" The Workshop on Intelligent Cloud Continuum for B5G Services in the IEEE International Conference on Cloud Networking 2023.

# References


[1] Long Chen, Yuchen Li, Chao Huang, Bai Li, Yang Xing, Daxin Tian, Li Li, Zhongxu Hu, Xiaoxiang Na, Zixuan Li, et al. Milestones in autonomous driving and intelligent vehicles: Survey of surveys. *IEEE Transactions on Intelligent Vehicles*, 8(2):1046–1056, 2022.

[2] Ricardo Roriz, Jorge Cabral, and Tiago Gomes. Automotive lidar technology: A survey. *IEEE Transactions on Intelligent Transportation Systems*, 23(7):6282–6297, 2022.

[3] Di Feng, Ali Harakeh, Steven L Waslander, and Klaus Dietmayer. A review and comparative study on probabilistic object detection in autonomous driving. *IEEE Transactions on Intelligent Transportation Systems*, 23(8):9961–9980, 2021.

[4] SAE International. Taxonomy and definitions for terms related to driving automation systems for on-road motor vehicles, 2021. Accessed: 2023/12/23.

[5] Jianqiang Wang, Heye Huang, Keqiang Li, and Jun Li. Towards the unified principles for level 5 autonomous vehicles. *Engineering*, 7(9):1313–1325, 2021.

[6] Jingchen Dai, Xiaokun Cara Wang, Wenxin Ma, and Ruimin Li. Future transport vision propensity segments: A latent class analysis of autonomous taxi market. *Transportation Research Part A: Policy and Practice*, 173:103699, 2023.

[7] Peng Jing, Yunhao Cai, Baihui Wang, Bichen Wang, Jiahui Huang, Chengxi Jiang, and Chenglu Yang. Listen to social media users: Mining chinese public perception of autonomous vehicles after crashes. *Available at SSRN 4011917*, 2022.

[8] Vinod Vasudevan and Mohammad Heidari Kapourchali. Self-assessment of deployment of connected and autonomous vehicle technologies using u.s. department of transportation framework: An illustration using alaska data. *Transportation Research Record*, 2677(3):1654–1664, 2023.

[9] Yu Asabe, Ehsan Javanmardi, Jin Nakazato, Manabu Tsukada, and Hiroshi Esaki. Autowarev2x: Reliable v2x communication and collective perception for autonomous driving. In *2023 IEEE 97th Vehicular Technology Conference (VTC2023-Spring)*, pages 1–7, 2023.

[10] Yuze Jiang, Ehsan Javanmard, Jin Nakazato, Manabu Tsukada, and Hiroshi Esaki. Roadside lidar assisted cooperative localization for connected autonomous vehicles. *arXiv preprint arXiv:2311.07913*, 2023.

[11] Carl Bergenhem, Erik Hedin, and Daniel Skarin. Vehicle-to-vehicle communication for a platooning system. *Procedia - Social and Behavioral Sciences*, 48:1222–1233, 2012. Transport Research Arena 2012.

[12] Radwa Ahmed Osman, Amira I. Zaki, and Ahmed Kadry Abdelsalam. Novel road traffic management strategy for rapid clarification of the emergency vehicle route based on v2v communications. *Sensors*, 21(15), 2021.

[13] Yan Li and Zhiheng Huang. Basics and applications of ai in adas and autonomous vehicles. *Advanced driver assistance systems and autonomous vehicles: From fundamentals to applications*, pages 17–48, 2022.

[14] Galina Sidorenko, Daniel Plöger, Johan Thunberg, and Alexey Vinel. Emergency braking with acc: How much does v2v communication help? *IEEE Networking*

*Letters*, 4(3):157–161, 2022.

[15] Sara El Hamdani, Nabil Benamar, and Mohamed Younis. Pedestrian support in intelligent transportation systems: challenges, solutions and open issues. *Transportation research part C: emerging technologies*, 121:102856, 2020.

[16] Fernando García, Felipe Jiménez, José Javier Anaya, José María Armingol, José Eugenio Naranjo, and Arturo De la Escalera. Distributed pedestrian detection alerts based on data fusion with accurate localization. *Sensors*, 13(9):11687–11708, 2013.

[17] Zhengjuan Zhou. Headsup: keeping pedestrian phone addicts from dangers using mobile phone sensors. *International Journal of Distributed Sensor Networks*, 11(5):279846, 2015.

[18] Mehrdad Bagheri, Matti Siekkinen, and Jukka K Nurminen. Cloud-based pedestrian road-safety with situation-adaptive energy-efficient communication. *IEEE Intelligent transportation systems magazine*, 8(3):45–62, 2016.

[19] Taehwan Hwang, Jaehoon Paul Jeong, and Eunseok Lee. Sana: Safety-aware navigation app for pedestrian protection in vehicular networks. In *2014 International Conference on Information and Communication Technology Convergence (ICTC)*, pages 947–953. IEEE, 2014.

[20] Quang-Huy Nguyen, Michel Morold, Klaus David, and Falko Dressler. Car-to-pedestrian communication with mec-support for adaptive safety of vulnerable road users. *Computer Communications*, 150:83–93, 2020.

[21] Karthik Mahadevan, Sowmya Somanath, and Ehud Sharlin. Communicating awareness and intent in autonomous vehicle-pedestrian interaction. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, CHI '18, page 1–12, New York, NY, USA, 2018. Association for Computing Machinery.

[22] Lik-Hang Lee, Tristan Braud, Pengyuan Zhou, Lin Wang, Dianlei Xu, Zijun Lin, Abhishek Kumar, Carlos Bermejo, and Pan Hui. All one needs to know about metaverse: A complete survey on technological singularity, virtual ecosystem, and research agenda. *arXiv preprint arXiv:2110.05352*, 2021.

[23] Wilbert Tabone, Yee Mun Lee, Natasha Merat, Riender Happee, and Joost De Winter. Towards future pedestrian-vehicle interactions: Introducing theoretically-supported ar prototypes. In *13th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, pages 209–218, 2021.

[24] Tram Thi Minh Tran, Callum Parker, Yiyuan Wang, and Martin Tomitsch. Designing wearable augmented reality concepts to support scalability in autonomous vehicle-pedestrian interaction. *Frontiers in Computer Science*, 4:866516, 2022.

[25] Shinpei Kato. "autoware, 2017.

[26] Yiwei Cheng, Jin Nakazato, Ehsan Javanmardi, Chia-Ming Chang, and Manabu Tsukada. Pedestrian-centric augmented reality visualization of real-time autonomous vehicle dynamics. 2023.

[27] Debargha Dey, Azra Habibovic, Bastian Pfleging, Marieke Martens, and Jacques Terken. Color and animation preferences for a light band ehmi in interactions between automated vehicles and pedestrians. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, CHI '20, page 1–13, New York, NY, USA, 2020. Association for Computing Machinery.

[28] P. Bazilinskyy, L. Kooijman, D. Dodou, and J.C.F. de Winter. How should external human-machine interfaces behave? examining the effects of colour, position, message, activation distance, vehicle yielding, and visual distraction among 1,434 participants. *Applied Ergonomics*, 95:103450, 2021.

[29] Pavlo Bazilinskyy, Dimitra Dodou, and Joost de Winter. Survey on ehmi concepts: The effect of text, color, and perspective. *Transportation Research Part F: Traffic Psychology and Behaviour*, 67:175–194, 2019.

[30] Adell Peters. This self-driving car smiles at pedestrians to let them know it' s safe to cross. *Fast Company*, 2016.

[31] Chia-Ming Chang, Koki Toda, Xinyue Gui, Stela H. Seo, and Takeo Igarashi. Can eyes on a car reduce traffic accidents? In *Proceedings of the 14th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, AutomotiveUI '22, page 349–359, New York, NY, USA, 2022. Association for Computing Machinery.

[32] Chia-Ming Chang, Koki Toda, Xinyue Gui, Stela H. Seo, and Takeo Igarashi. Can eyes on a car reduce traffic accidents? In *Proceedings of the 14th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, AutomotiveUI '22, page 349–359, New York, NY, USA, 2022. Association for Computing Machinery.

[33] Debargha Dey, Azra Habibovic, Andreas Löcken, Philipp Wintersberger, Bastian Pfleging, Andreas Riener, Marieke Martens, and Jacques Terken. 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*, 7:100174, 2020.

[34] Yi-Chih Tung, Zhi-Quan Zhan, Si-Han Peng, Chih-Hsiang Ho, and Cheng-Chang Chen. 5g smart pole and internet of thing use case. In *2022 IEEE 6th Information Technology and Mechatronics Engineering Conference (ITOEC)*, volume 6, pages 1794–1798, 2022.

[35] Vishal Chauhan, Chia-Ming Chang, Ehsan Javanmardi, Jin Nakazato, Pengfei Lin, Takeo Igarashi, and Manabu Tsukada. Fostering fuzzy logic in enhancing pedestrian safety: Harnessing smart pole interaction unit for autonomous vehicle-to-pedestrian communication and decision optimization. *Electronics*, 12(20), 2023.

[36] Ronald T Azuma. The road to ubiquitous consumer augmented reality systems. *Human Behavior and Emerging Technologies*, 1(1):26–32, 2019.

[37] Yourui Tong et al. An augmented warning system for pedestrians: user interface design and algorithm development. *Applied Sciences*, 11(16):7197, 2021.

[38] Marc Hesenius, Ingo Börsting, Ole Meyer, and Volker Gruhn. Don't panic! guiding pedestrians in autonomous traffic with augmented reality. In *Proceedings of the 20th international conference on human-computer interaction with mobile devices and services adjunct*, pages 261–268, 2018.

[39] Shengrong Lu, Yang-Han Lee, Hsien-Wei Tseng, and Cheng-Fu Yang. Research on non-line-of-sight collision avoidance warning using the vehicle-to-vehicle communication system in 5g mobile communication network. *Sensors & Materials*, 35, 2023.

[40] Xinzhou Wu, Radovan Miucic, Sichao Yang, Samir Al-Stouhi, James Misener, Sue Bai, and Wai-hoi Chan. Cars talk to phones: A dsrc based vehicle-pedestrian safety system. In *2014 IEEE 80th Vehicular Technology Conference (VTC2014-Fall)*, pages 1–7. IEEE, 2014.

[41] Wilbert Tabone, Riender Happee, Jorge García, Yee Mun Lee, Maria Luce Lupetti, Natasha Merat, and Joost de Winter. Augmented reality interfaces for pedestrian-vehicle interactions: An online study. *Transportation research part F: traffic psychology and behaviour*, 94:170–189, 2023.

[42] The ROS Community. Nodes. `https://wiki.ros.org/Nodes`, 2018. Accessed: 2024-1-4. Under the Creative Commons Attribution 3.0 license.

[43] The ROS Community. Topics. `https://wiki.ros.org/Messages`, 2018. Accessed: 2024-1-4. Under the Creative Commons Attribution 3.0 license.

[44] The ROS Community. Messages. `https://wiki.ros.org/Topics`, 2019. Accessed: 2024-1-4. Under the Creative Commons Attribution 3.0 license.

[45] Apple Inc. Tracking geographic locations in ar. `https://developer.apple.com/documentation/arkit/arkit_in_ios/content_anchors/tracking_geographic_locations_in_ar`, 2024. Accessed: 2024-1-7.

[46] Shuchisnigdha Deb, Lesley Strawderman, Daniel W Carruth, Janice DuBien, Brian Smith, and Teena M Garrison. Development and validation of a questionnaire to assess pedestrian receptivity toward fully autonomous vehicles. *Transportation research part C: emerging technologies*, 84:178–195, 2017.

[47] ETSI. Tr 103 300-1 - v2.2.1. `https://www.etsi.org/deliver/etsi_tr/103300_103399/10330001/02.02.01_60/tr_10330001v020201p.pdf`, 2021. Accessed: 2024-1-10.

# Acknowledgements

Over the past two years, I had the chance to delve into the captivating field of intelligent transport systems and autonomous driving. While my research ultimately took a different path from my initial fascination with technical V2X communication, I believe that this domain represents a promising glimpse into the future of our lives. The communication between autonomous vehicles and other road users is equally intriguing, although it necessitates further dedication to user studies and scenario construction. I am optimistic that our colleagues, Vishal and Shangkai, will continue to make significant strides in this field.

I would like to extend my sincere gratitude to every member of our lab for allowing me to share and implement my ideas freely. I am especially indebted to Prof. Tsukada, whose guidance during my initial year was instrumental in helping me find my research direction. I am equally appreciative of the invaluable support I received from two assistant professors – Prof. Javanmardi, who consistently provided unique insights and assistance with field experiments, and Prof. Nakazato, whose efforts contributed to my paper's development. I would also like to express my sincere thanks to Mr. Jiang for engaging in critical discussions regarding my research ideas. His insightful suggestions aided me in grasping the core principles of scientific research, bolstering my confidence in addressing them, following discussions with our professors. My gratitude extends to Prof. Chang and Ms. Gui from the Igarash lab for their professional guidance on the intricate subject of human-machine interaction.

Beyond the academic sphere, I want to acknowledge my friends outside the university for being a constant source of companionship in my daily life. Engaging in conversations with them has been a relief during moments of solitude. Exploring Japan with friends has also added color and joy to my life, and I am immensely thankful for those unforgettable travel experiences. Additionally, I am grateful for the vibrant entertainment culture in Japan and appreciate everyone who has shared their enthusiasm, contributing to the enrichment of my life and my living space.

Finally, I want to express gratitude to my parents who supported my decision to go abroad, although they don't want me to go far away. I treasure this love and trust and will continue my life with them.