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Using Virtual Reality Techniques to Investigate Interactions Between Fully Autonomous Vehicles and Vulnerable Road Users

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16. Abstract

At roadway ecosystems with frequent movement conflicts among vehicles, pedestrians, and other road users, a road user entering the location immediately triggers a vibrant exchange of informal or formal cues with other road users and the traffic environment to ensure safe and efficient movement for all the road users at that location and at that time. For such communication, the non-vehicle road users typically use informal communication mechanisms to interpret other road users' intentions for making movement decisions. In the prospective era of FAVs (fully autonomous vehicles) that self-drive in any environment and conditions), these informal communication mechanisms will become obviated because the FAV has no human driver.

As such, a new paradigm of communication among road users is needed in the FAV era to avoid misinterpretation of pedestrian actions and intentions that could lead to collisions. This is particularly important not only for pedestrians but also for all road users that are considered vulnerable to sustain serious injury or death if they collide with a vehicle.

This study first reviewed relevant literature on the interfaces for human-computer communication and the pedestrian-AV interaction. Then the study compared the demerits and merits of using virtual reality (VR) vs. augmented reality (AR) for simulating and analyzing FAV-VRU interactions. Next, the study developed a framework for studying FAV-VRU interaction using VR and AR tools and presented the two aspects of this framework: design of the simulation environment (including scenarios); and design of the experiment including the data collection protocol. This is done for a prospective future implementation because during the study period, persistent COVID concerns precluded full conduction of the framework using human subjects. Next, the study obtained and modified open-source resources to develop a simulation environment for the CAV-VRU interaction study, and established the problem setting and the simulation environment.

Overall, the full experimental framework, when implemented, can ultimately provide useful guidance to state and local agencies as they proceed to document their VRU safety assessments in compliance with the Infrastructure Investment and Jobs Act (IIJA).

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LIST OF ACRONYMS

ADA	Americans with Disabilities Act
ADS	Advanced Driving Systems
AR	Augmented Reality
BIL	Bipartisan Infrastructure Law
CAV	Connected and Automated Vehicle
eHMI	Electronic Human-Machine Interface
FAV	Fully Autonomous Vehicle
FARS	Fatality Analysis Reporting System
FHWA	Federal Highway Administration
GUI	Graphical User Interface
HMD	Head-Mounted Display
HMI	Human-Machine Interface
IIJA	Infrastructure Investment and Jobs Act
MADD	Mothers Against Drunk Driving
NHTSA	National Highway Traffic Safety Administration
NPC	Non-playable Character
ODD	Operational Design Domain
PCWS	Pedestrian Collision Warning Systems
SAA	Safe Systems Approach
SLAM	Simultaneous Localization and Mapping
UTAUT	Unified Theory of Acceptance and Usage of Technology
VR	Virtual Reality
VRU	Vulnerable Road User
VRU-SA	Vulnerable Road User Safety Assessment
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything

CHAPTER 1 INTRODUCTION

1.1 Study Background

1.1.1 Urban Road Ecosystems

An urban road traffic ecosystem consists of a collection of elements that constitute or share the roadway and its open spaces (Reyes-Muñoz & Guerrero-Ibáñez, 2022). Like most engineering systems, the ecosystem consists of physical elements (road users and infrastructure), a set of rules to guide the operations of each element, and an environment (in this case, physical space), and boundaries. The individual elements interact with each other to achieve various goals. The holistic nature of an urban ecosystem is reflected in the realization that the effect of the entire collection of all the vehicles and pedestrians combined is not the same as the sum of individual effects of these elements). In addition, every road user or other entity has specified goals and acts to maximize their utility, often selfishly. The road agency plays a unique arbiter role of ensuring that the sum of the system goals and the individual goals are maximized as much as possible within the physical constraints (road space), institutional constraints (road rules), and legislative constraints (ADA access and in some jurisdictions, priority). Figure 1.1 presents an example of a road ecosystem.

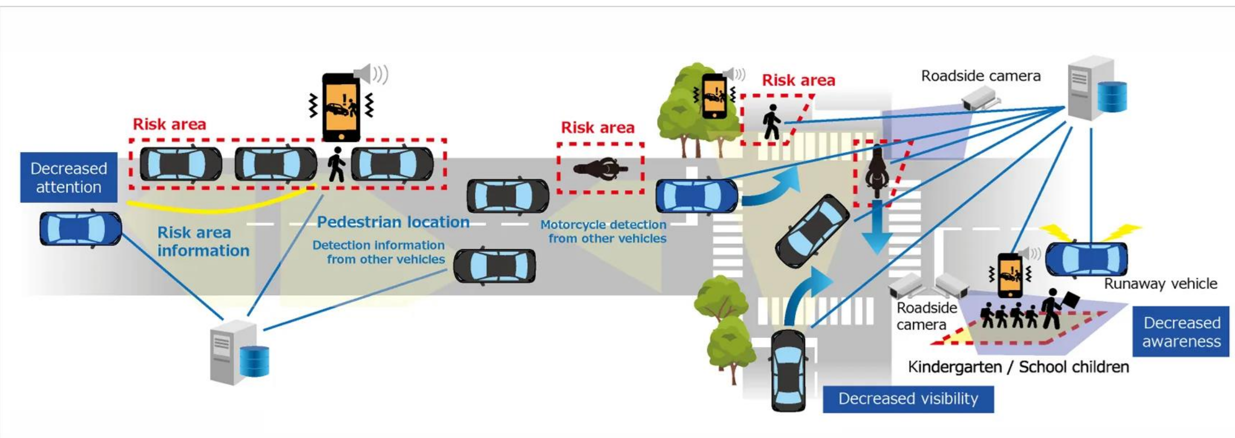

Figure 1.1. An example of a traffic ecosystem with VRUs (source: Honda Corporation, 2023)

1.1.2 Vulnerable Road Users

The physical elements include road users and road infrastructure, as follows:

- Protected road users
    - Four-wheeled vehicles of all classes (including traditional vehicles, fully autonomous vehicles (FAVs),
- Unprotected road users
    - Micromobility, exposed, and two-wheeled vehicles including bicycles, scooters, unicycles, and skateboards. These may be motorized (gasoline or electric) or

unmotorized. Also includes unprotected 4-wheel vehicles like recreational carriages, horses (the dominant travel mode of some communities), and recreational rickshaws,
    - Pedestrians, including the elderly, wheelchair users, and the visually- and auditory-handicapped,
    - Highway workers on foot in a highway work zone
- Road infrastructure
    - Traditional roadway infrastructure (such as traffic signals, streets roads), and
    - Communication infrastructure (such as roadside unit, cellular networks).

Of the above, the unprotected road users are of particular interest in this study. A vulnerable road user (VRU) is defined as an "individual who is at higher risk of injury or harm while using the road due to lack of protection or visibility, compared to motor vehicle occupants (Cambridge Systematics, 2023). Also, the FHWA (2022) defined a VRU as a nonmotorist that has a fatality analysis reporting system (FARS) person attribute code for pedestrian, bicyclist, other cyclist, and person on personal conveyance or an injured person that is, or is equivalent to, a pedestrian or pedal-cyclist as defined in the ANSI D16.1-2007 (See 23 U.S.C. 148(a)(15) and 23 CFR 490.205). FHWA also states that a VRU may include people walking, biking, or rolling and notes that a VRU includes a highway worker on foot in a work zone, given they are considered a pedestrian, and that VRUs do not include motorcyclists.

The FHWA (2022) advocates that state DOTs should adopt a "Safe System Approach" towards their VRUs. SAAs infers the adoption of roadway designs that emphasize "minimizing the risk of injury or fatality to road users; and that: takes into consideration the possibility and likelihood of human error; accommodates human injury tolerance by taking into consideration likely crash types, resulting impact forces, and the ability of the human body to withstand impact forces; and takes into consideration vulnerable road users. (23 U.S.C. 148(a)(9))." The FHWA (2022) also defines Vulnerable Road User Safety Assessment is an "assessment of the safety performance of a State with respect to vulnerable road users and the plan of the State to improve the safety of vulnerable road users as described under 23 U.S.C. 148(l). (23 U.S.C. 148(a)(16))."

In the United States, the Infrastructure Investment and Jobs Act (IIJA) (Pub. L. 117-58, also known as the "Bipartisan Infrastructure Law" (BIL)) required all States to develop a Vulnerable Road User Safety Assessment as part of their Highway Safety Improvement Programs (HSIP). In response to the IIJA, the state of Indiana developed a VRU Safety Assessment document (Cambridge Systematics, 2023) with the intent of examining the safety challenges experienced by bicyclists, pedestrians and micromobility users, and other users of non-motorized vehicles. Indiana's VRU Assessment, which reflected the state's commitment to road user safety, was developed in collaboration with partner state and local agencies and safety advocates and yielded set of VRU-targeted safety-enhancing strategies.

VRU safety assessment may consist of 4 steps:

- A review of literature regarding the factors, policies, infrastructure designs, efficacy of VRU-related initiatives, programs and policies, and the experience of road agencies at various levels of government regarding VRU safety. This could be done in both the current and prospective future (FAV) contexts.
- Network screening of serious and injuries fatality data for state and local roadways to

identify high-risk vulnerable road user areas, to characteristics, demographics, and contributing factors to VRU incidents including considerations of race, ethnicity, gender, age, and income were evaluated to facilitate the identification of disparities and

- Consultation organizations involved in safety of VRU, and local agency representatives to gather local knowledge and perspectives of vulnerable road user safety needs, challenges, and successes within different community contexts.
- Strategy Development – Insight gathered from the network screening analysis and local consultation with local agencies and safety interest groups including Mothers Against Drunk Driving.

VRU safety has become a national issue. This is because in recent years, VRUs have accounted for a growing share of all United States roadway fatalities (NHTSA, 2022). In 2021, every 71 minutes, a pedestrian was killed in a traffic crash, and a total of 7,388 pedestrians were killed that year (a 13% increase from 2020) and more than 60,000 pedestrians were injured nationwide. Compared with 2019, bicyclist fatalities increased 9.2% and pedestrian fatalities increased 3.9%. In the European Union, vulnerable road user (VRU) related collisions account for 46% of road traffic deaths and 53% of serious injuries (The EU Monitor, 2010).

1.1.3 Fully Autonomous Vehicles

SAE International (the erstwhile-named Society of Automotive Engineers), developed a set of guidelines to classify automated driving features, from Level 0 (no automation) to Level 5 (full automation). Figure 1.2 presents these levels vis-à-vis those established by the NHTSA. Figure 1.3 presents some details of each level of automation. On one extreme (Level 0), the human driver conducts all driving tasks, and the vehicle does not take over any aspect of driving. The vehicle may include driver assistance features such as blind-spot and lane-departure warnings. At Level 1, the vehicle can control one aspect of the driving task: either the steering or the speed, for example, cruise control and lane centering. At Level 2, the vehicle has both lateral and longitudinal control (the Advanced Driving System (ADS) controls both the steering and speed) but always requires full driver attention. At Level 3 (conditional driving automation), the driver does not drive the vehicle while the automated system is engaged, under certain conditions; however, the driver must be ready at any time to take over if the system becomes disengaged.

At the fully autonomous modes (Levels 4 and 5), there is no need for a driver. At Level 4, the vehicle can fully drive itself but is specific to its Operational Design Domain (ODD): it operates only within a specific geofenced area, and the vehicle disengages and comes to a stop on its own if it encounters a problem. Level 5 is fully self-driving and does not require human involvement. Unlike Level 4, Level 5 is not ODD specific because it can operate autonomously at all locations and under all conditions. The conceptual interior design of an FAV (Mercedes-Benz Massapequa, 2015) may be such that because of the seating arrangement, there may be no direct line of sight to the roadway ahead (Figure 1.4). This means that the FAV occupants may not even be aware of the VRUs and other pedestrians with whom they share the roadway. It may be possible for the interior design to include electronic monitors that show the roadway ahead or the environs of the roadway at any time.

Figure 1.2 SAE vs. NHTSA classifications of automated driving systems

				Automated Driving Systems (ADS)		
	Level 0 **No Automation**	**Level 1** **Driver assistance**	**Level 2** **Partial automation**	**Level 3** **Limited self-driving (conditional automation)**	**Level 4** **Full self-driving under certain conditions (high automation)**	**Level 5** **Full self-driving under all conditions (full automation)**
Vehicle	No automation.	Can assist driver in some situations.	Can take control of speed and lane position in certain conditions.	Can be in full control in certain conditions and will inform the driver to take control.	Can be in full control for the entire trip in these conditions and can operate without a driver.	Can operate without a human driver and need not have human occupants.
Driver	In complete control at all times.	Must monitor, engage controls, and be ready to take over control quickly at any moment.	Must monitor and be ready to take over control quickly at any moment.	Must be ready to take control quickly when informed.	Not needed	Not needed

Figure 1.3 Other descriptions of the levels of automation (Source: GHSA (2018))

Figure 1.4 The conceptual interior design of FAV (Mercedes-Benz Massapequa, 2015)

During the HDV-AV transition period (illustrated in Figure 1.5), it is anticipated that roadways will host traditional vehicles (that is, human-operated, or, Level 0), automated vehicles (Levels 1– 4), and fully autonomous (Level 5). After the transition period, all vehicles on the road will be fully autonomous:

The period of HDV-AV transition could be described as consisting of five phases:

- Phase I, low fraction of AVs to HDVs: up to 25% of vehicles in the traffic stream are AV.
- Phase II, low-to-medium AV-HDV fraction: 25-50% of vehicles in the stream are AV.
- Phase III, mid-to-high AVs-HDV fraction: 50%-75% of vehicles in the stream are AV.
- Phase IV, high AV-HDV fraction: 50%-75% of vehicles in the stream are AV.
- Fully autonomous phase (FAP) – all (100%) of vehicles in the stream are AVs.

These phases might consist of sub-phases depending on the percentage of each of the 3 higher levels of autonomy. At the early stages of the transition phase, L4-5 market penetration rates will be low and L1-2 will be dominant. As time goes on, the AV market penetration will increase gradually to a point where AVs (and higher levels of AV) will represent a higher fraction of the traffic stream.

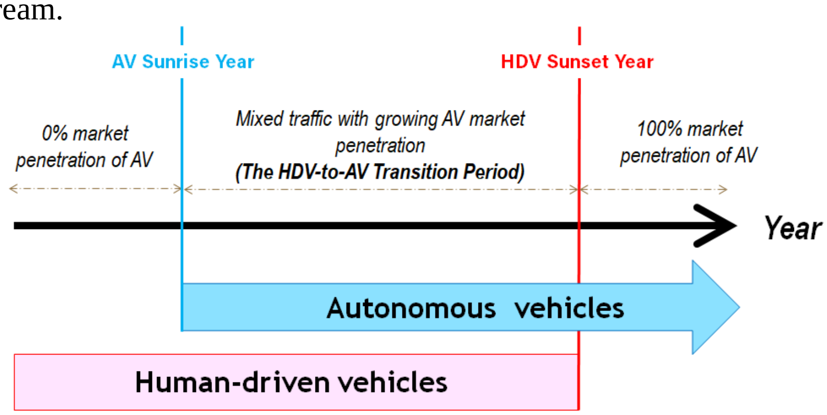

Figure 1.5 Timeline of Modal Distributions (adapted from Labi, 2019)

1.1.4 The Confluence of VRU and FAVs

Fully automated CAVs (FAVs) are designed not only to replicate the conventional mobility capabilities of existing vehicles but also to possess advanced capabilities enabling them to perceive and comprehend their driving environment. This includes the ability to undertake driving tasks with minimal or no human intervention.

While the prospective inception of FAVs is beneficial in terms of transportation mobility, travel efficiency, and a myriad of other beneficial impacts, it poses a safety concern. While the advent of CAVs presents a promising future, it also brings forth new challenges, particularly in the realm of safety. FAVs are generally unable to communicate directly with pedestrians and other road users, and this inability is considered particularly worrisome because of road users that are particularly vulnerable because of their age, height, movement speed and other factors. The traditional modes of interaction between VRUs and vehicles, characterized by informal communication methods such as eye contact, facial expressions, and gestures, may become obsolete as vehicle automation levels increase to the point where they become fully autonomous. Further, as CAVs gain higher levels of autonomy and market penetration, the VRU safety concerns become to take center stage.

1.2 Problem Statement

When VRUs use roadways, particularly at unsignalized intersections, their reliance on informal communication methods becomes critical. In these situations, the VRU depends on visual cues to interpret the intentions of vehicles and other road users in order to make informed and safe movement decisions. In the prospective era of FAVs, the dynamics of communication between vehicles and VRUs will undoubtedly become a critical safety factor. The advent of connected autonomous vehicles (CAVs) presents a promising future, enabling the vehicles to "talk" to each other or to the infrastructure. It is essential to establish a new communication channel specifically tailored to the unique requirements of VRUs. This involves leveraging the coordination between different traffic agents to create a seamless exchange of information, ensuring that CAVs and VRUs can effectively share roadway spaces with heightened safety and efficiency.

Considering these advancements, Figure 1.6 illustrates various communication methods between drivers and pedestrians, emphasizing the need for a redefined communication framework in the era of connected and autonomous vehicles. This shift not only underscores the transformative potential of CAVs but also underscores the importance of fostering a comprehensive understanding of the intricate interactions between different elements within the transportation ecosystem. As technology continues to shape the future of mobility, the establishment of effective communication channels between CAVs and VRUs stands as a critical step towards realizing a safer and more integrated transportation landscape.

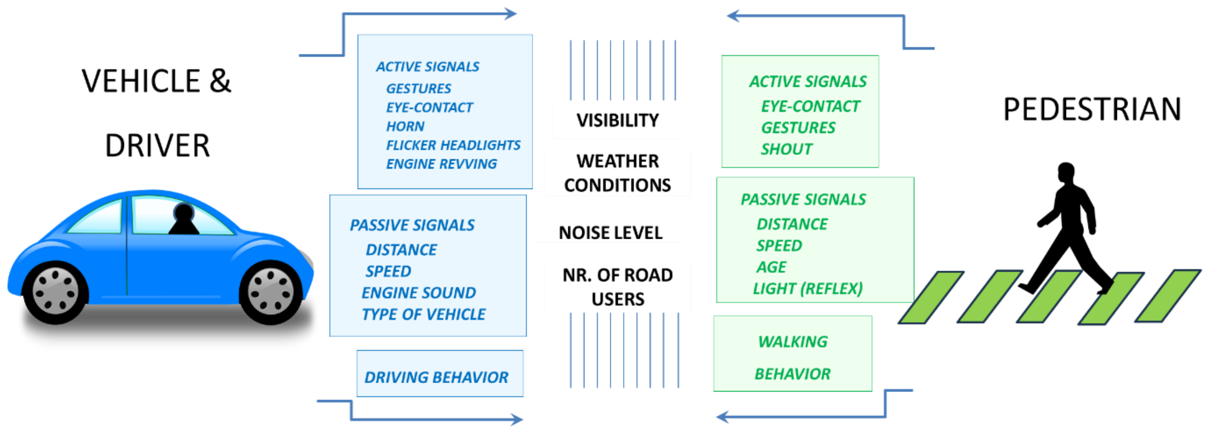

Figure 1.6 HDV-VRU Communication Channels (adapted from Lagstrom and Lundgren, 2015)

1.3 Study Objectives

The proposed research project uses virtual reality (VR) techniques to perform experiments in a simulated traffic environment (a virtual crosswalk) where participants will interact with a FAV that is equipped with specific external features. The objectives are tailored from recommendations from previous studies related to this topic (Tran et al., 2021; Deb, 2018). These are:

- Investigate VRU-related factors that affect their trust in automation road use behavior,
- Identify designs that facilitate VRU interaction of FAVs in terms of intended movements or behaviors at specific areas of the roadway,
- Evaluate the efficacy of Augmented Reality techniques compared to Virtual Reality techniques in addressing the pertinent issues related to FAV-VRU interaction.
- Establish an experiment environment (scenarios) and data collection protocol involving human subjects playing VRU roles.

This report develops input that could be used to help agencies develop their Safe Systems Approach (SAA) frameworks for VRUs, in the context of a prospective future of FAV operations. These SAA inputs addresses the identification of the underlying factors that contribute to crashes involving vulnerable road users in the FAV era. This assessment includes evaluation of existing infrastructure, road user behavior patterns, equity, and policies to understand the risks faced by these VRUs. The objective is to comprehend these challenges and to develop FAV-VRU (pronounced "fave-roo") policies and strategies to protect VRUs in the prospective era of FAVs.

1.4 Organization of the report

The report is organized as follows: Chapter 1 presents the study background, problem statement, study objectives, the key elements of the study framework, and the way the report is organized. Chapter 2 discusses VRU and FAV concepts and issues provided in the literature. Chapter 3 discusses the merits and demerits of virtual reality vs. augmented reality in analyzing FAV-VRU interactions. Chapter 4 discusses the experimental design and setup for a future experiment involving virtual reality equipment, modeled after a previous research study. Chapter 5 concludes the report and Chapter 6 presents a synopsis of the USDOT performance indicators accomplished in this study, and Chapter 7 lists the study's outputs, outcomes, and potential impacts.

CHAPTER 2. LITERATURE REVIEW

2.1 FAV-VRU Communication Interface

FAV-VRU communication may be viewed from the context of the wider field of human-computer communication or even wider, human-machine communication. For such communication to take place, the machine possesses a component (referred to as an "interface" that allows the human to communicate to the machine and vice versa. Human-machine interface (HMI) is by itself, a broad and fast-growing discipline.

In the current HDV era, there is little need for VRU interactions with the vehicle because the human driver is able to interact directly with the VRU through a variety of communication cues, gestures and sounds (Figure 1.6). In the prospective era of FAVs, safety concerns will motivate great need for such human-machine interaction.

2.2 Physical Infrastructure Area of Interest

Regarding the physical infrastructure area of interest, most studies investigated road crossings at intersections. Some of these were unsignalized and others were signalized (Jayaraman et al., 2018). Others investigated areas of interest that were undefined such as car parks and shared spaces (Weber, 2019).

2.3 Right of Way

In some countries and jurisdictions, the absence of crossing facilities, such as crosswalks, implies that Autonomous Vehicles (AVs) have the right-of-way. The presence of such facilities suggests that pedestrians have the right-of-way. In certain countries, vehicles must yield to pedestrians at crosswalks. Nevertheless, at most places, a crosswalk still presents a hazardous location, and approaching vehicles and pedestrians are encouraged to be vigilant (Deb et al., 2020).

2.4 Multiplicity of Vehicles and VRUs

In real life, there could exist any of several possibilities of the number of AVs and pedestrians in the environment in a specific instance of AV-VRU interaction:

- One to one: 1 VRU and 1 FAV
- One to many: 1 VRU and multiple FAVs
- Many to one: Multiple VRUs and 1 FAV
- Many to many: Multiple VRUs and multiple FAVs.

In experiments that involved CAVs rather than FAVs, past researchers have considered at least one of the above 4 contexts. In cases where multiple vehicles were considered 1 VRU and 1 FAV: in deciding whether to cross, participants were required to observe only one vehicle at a time (Tran et al., 2021). In most studies, the CAV-VRU interaction was one-to-one (Ackermans et al., 2020), and in a few, the road-crossing VRU interacted with multiple vehicles (Mahadevan et al., 2019 and Colley et al., 2020). Mahadevan et al. (2019) used an environment where there were multiple vehicles and multiple pedestrians. According to Tran et al. (2021), to date, there seems to exist no research efforts that addressed multiple pedestrians interacting with a single vehicle.

2.5 Road Environment Setup- The Factors

Environment setup for an FAV-VRU experiment involves the use of parameters that are adjusted to reflect the real situation on the ground. According to Tran et al. (2021), these parameters influence the decisions of both the pedestrian during their road crossing movements and the vehicle driver. In the prospective era of FAV operations, it is expected that these parameters will also influence the decisions of the FAV in its interactions with VRUs, some parameters to a larger extent and others to a smaller extent compared to the current HDV era. The factors can be categorized as follows (Rasouli & Tsotsos, 2020; Fuest et al., 2018; Mahadevan et al., 2018; 2019):

- Pedestrian-related factors
- Social factors
- Vehicle-related factors
- Traffic factors
- Natural environment factors
- Road design factors
- Interface factors

The pedestrian-related factors include type (walking, bicycling, etc.), age, disability status, trust in autonomy, and gender. Social factors include whether the pedestrians and a group familiar with each other, group size, and group behavior. The vehicle-related include noise, color, size, speed, acceleration, direction and the vehicle class (large truck, small truck, van or SUV, automobile, motorcycle). Other vehicle-related factors include the level of automation, vehicle driver's intention to yield to the VRU, driving behavior, communication, and the lateral and longitudinal distance to the VRU. Traffic related factors include light traffic conditions or dense traffic conditions, the number of vehicle, time headways between vehicles, and the direction of traffic. The environmental factors include time of day, ambient temperature, rain or show, and wind, nature of the street scene (for example, calm or chaotic), ambient noise, and lighting conditions. The road design factors include street width, pavement markings and delineations, and road condition. The interface factors include the efficacy of the interface communication.

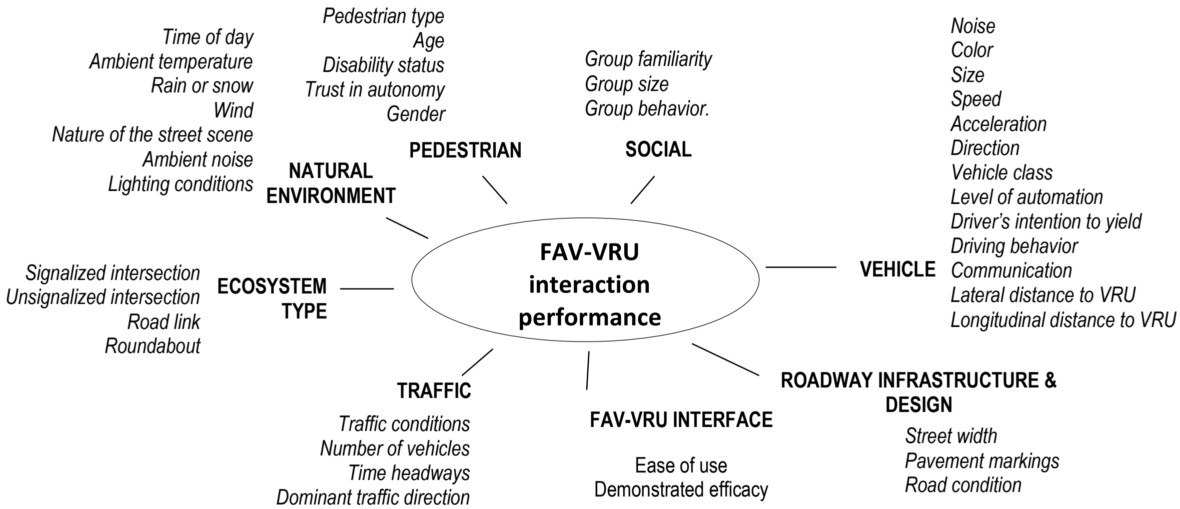

Figure 2.1 Factors affecting the performance of FAV-VRU interactions

2.5.1 Pedestrian Attributes

Researchers including Reyes-Muñoz et al. (2022), Dey et al (2022), Martínez-Buelvas et al. (2022), Li et al. (2023) and Morris et. al (2021) have studied and thrown much light on pedestrian behavior based on factors such as those illustrated in Figure 2.1: pedestrian type, age, disability status, trust in autonomy, gender, and other individual characteristics. We discuss a few below, in the context of the findings of these researchers.

Pedestrian Type: The type of pedestrian can be classified different types based on their behavior and characteristics: at a given location, regular (high familiarity with the area) vs. rare pedestrians (for example, tourists); able-bodied vs. disabled.

Age: Age significantly influences pedestrian behavior. Children may exhibit behaviors such as sudden crossings and lack of proper observation, while the elderly may move slowly and have difficulty judging vehicle paths and speeds. Also, older pedestrians tend to be more cautious when crossing streets.

Disability status: Individuals with disabilities such as blindness, deafness, or mobility impairments i.e., individuals who require assistive devices such as canes, crutches, or wheelchairs have unique needs and challenges when navigating road environments.

Trust in autonomy: This refers to road users' levels of trust in autonomous vehicles (AVs) and their willingness to interact with or use such technology. Trust levels may vary among different individuals and can influence their behavior on the road. Users' perceptions of the value of CAVs influence their trust, with trust generally increasing over time as individuals are exposed to CAVs.

Gender: Gender can also play a role in road user behavior, with studies indicating differences in attitudes and behaviors between men and women. For example, men may exhibit more risky behaviors and aggression, while women may be more cautious.

Other pedestrian-related attributes: Other categorizations of the pedestrian include their socioeconomic status, cultural background, personality traits, level of education, or past experiences. These factors can also influence road user behavior and attitudes towards road safety, technology acceptance, perceptions of traffic situations, and assessment of crossing risks. Pedestrian choices regarding crossing location and timing significantly affect crash risk, with many fatalities occurring in urban areas and non-intersections. Pedestrians may overestimate their visibility to drivers, leading to unsafe crossing decisions, and distracted walking may further exacerbate risks.

2.5.2 Social attributes

Schrauth et al. (2021) conducted a study and found that acceptance levels differed between groups, with pedestrians and cyclists showing slightly lower acceptance compared to car drivers. Understanding these factors is crucial for identifying groups more prone to maladaptive interactions with AVs and those less likely to accept policies facilitating AV mass introduction.

Certain road user groups, such as young drivers and cyclists, are more prone to engaging in risky behaviors, emphasizing the importance of road user risk profiling. However, risky road behavior has been rarely considered in research on AV acceptance (Deshmukh et. Al, 2023).

Additionally, Riaz and Cuenen (2019) focused on enhancing traffic safety for children, recognizing their limited ability to assess road environments. Their findings indicated that children performed better in familiar situations compared to unfamiliar ones. Social factors, particularly variations in cultural norms pose challenges for both current drivers and Vulnerable Road Users (VRUs) when traveling in unfamiliar locations. This challenge could extend to Autonomous Vehicles (AVs), assuming that vehicle control algorithms are universal across different cultural contexts.

2.5.3 Vehicle attributes

Windhager et al. (2008) and Klatt et al. (2016) addressed pedestrian perceptions of vehicle appearance and its impact on their behavior. The Windhager et al. study determined that cars are often perceived by pedestrians as have “power” and dominance. Klatt et al. (2016) expanded on this, finding that pedestrians tend to start crossing the road earlier in front of cars they perceived to be friendly-looking compared to dominant ones (often large ones). Also, vehicle size was found to influence pedestrian judgments of distance: larger vehicles were perceived to be closer and more threatening.

Schneemann and Gohl (2016)’s study showed that pedestrian behavior varies based on vehicle speed. At higher speeds of the vehicle, the pedestrian tends to focus on the vehicle; at lower vehicle speeds, pedestrians seek eye contact with the driver. Dey et al. (2022)’s findings suggest that pedestrians’ willingness to cross decreases as the car approaches, and in the “ambiguity zone,” pedestrians focus on the vehicle’s leading edge. In addition, the pedestrian considers vehicle-centric and driver-centric cues, and adjust their crossing-behavior accordingly.

Zimmermann et al. (2017) explored how an AV’s motion behavior influences pedestrians’ emotions and decisions. They also found that factors such as braking initiation and vehicle size impact pedestrian-AV interactions. It was asserted that effective communication is important, and that there exists the possibility that false or misleading information (often inadvertently) could be disseminated by the vehicles. Also, it was recognized that driver assistance technology problems could compromise the pedestrian safety.

2.5.4 Roadway infrastructure and design

Factors such as street width, pavement markings, and road conditions play crucial roles in pedestrian-vehicle interactions, particularly at non-signalized crosswalks. These factors can influence pedestrian behavior and affect the effectiveness of communication between pedestrians and AVs.

Street Width: The width of the street could impact pedestrian-vehicle interactions by influencing pedestrian perception of safety and the time needed for crossing. Rasouli et al. (2017) observed pedestrian behavior at non-signalized crosswalks and found that the structure of the street, including its width, influenced the timing of crossing events. Habibovic (2018) discovered that children, the elderly, and people with disabilities often experience limited mobility, leading to feelings of dependency and social exclusion. This can be attributed primarily poor street design, complex traffic environments, inaccessible public transportation, and the lack of convenient parking near destinations.

Pavement Markings: Clear and visible pavement markings indicate the designated crossing areas and thus could enhance communication of road user intents between pedestrians and AVs. Studies have shown that pedestrians often rely on pavement markings to determine safe crossing locations. When pavement markings are well-maintained and easily visible, pedestrians are more likely to use designated crosswalks. However, inadequate or faded pavement markings may lead to confusion and hesitation among pedestrians, impacting their willingness to cross. While specific studies focusing solely on the influence of pavement markings on pedestrian behavior may be limited, research on pedestrian safety and infrastructure design emphasizes the importance of clear markings in promoting safe crossing behavior. In recent years, there have been developments in prototype designs aimed at facilitating communication between AVs and other road users. These prototypes include light reflections on roads and pavements to convey messages and information. Organizations that support standardization such as the United Nations Economic Commission for Europe (UNECE), the Society of Automotive Engineers (SAE J3016TM), and the International Organization for Standardization (ISO, TC22/SC39/WG8) regularly carry out discussions on this topic.

Road Conditions: Road conditions, including factors like slippery surfaces due to rain or snow, affect the capabilities of both pedestrians and AVs. Poor road conditions could cause decreased traction and thus, longer stopping distances for vehicles, making it challenging for AVs to stop quickly in response to the presence of pedestrians. Rasouli et al. (2017) and other similar studies provided valuable insights into pedestrian behavior and the factors that influence communication between pedestrians and AVs at non-signalized crosswalks.

2.5.5 Traffic

The traffic sub-system of the overall ecosystem includes the vehicles, pedestrians, traffic infrastructure (signals), and communication infrastructure (WiFi, cellular networks, 4G, 5G, Bluetooth, and so on). Segregated traffic is the term used to describe the division of traffic streams or areas based on traffic characteristics or conditions, for example, where vehicle traffic is prohibited and pedestrian-friendly zones are protected (Mayhew, 2015).

2.6 General Thoughts

Lagstrom and Lundgren (2015) investigated the existence of a need to enhance a vehicle's ability to communicate with pedestrians in the era of automated driving and also examined the influence of external communication interface on AV-pedestrian interaction. Their study findings suggest that pedestrians need to know whether a vehicle in their path is in manual or automated driving mode, as they were unwilling to cross the road if they perceived that the AV's driver is inattentive. In the era of FAVs, such ambiguity will not exist, and VRUs will need to trust that the automation driving system will sense them and undertake appropriate maneuvers to avoid collision. In addition, to err on the side of caution, it will be useful for the VRU to be equipped with a connectivity device that can alert them of potential collisions based on a quick and real-time analysis of the speed, acceleration, and direction of each vehicles in the neighborhood of the VRU.

CHAPTER 3. VIRTIAL REALITY VS. AUGMENTED REALITY IN ANALYSING FAV-VRU DISCUSSIONS: MERITS AND DEMERITS

Augmented Reality (AR) and Virtual Reality (VR) represent distinct, albeit related, technological paradigms. AR functions by augmenting the physical realm with digital overlays, thereby enriching the user's interaction with and perception of their immediate environment. This enhancement of reality introduces an interactive and informative dimension to the user's experience. On the contrary, VR engenders a fully immersive experience by constructing a digital environment that supersedes the natural world. Through VR, users are transported into entirely computer-generated settings, enabling them to engage with synthetic realities.

3.1 AR Background

Augmented Reality (AR) serves as an innovative interface technology, augmenting human perception of the real world through the superimposition of contextual information in real-time (Ling, 2017). It is projected that the forthcoming industrial revolution will be characterized by a substantial reliance on AR devices and systems (Mahmood et al., 2018).

Historical exploration into AR dates back to 1960, coinciding with Ivan Sutherland (1968)'s pioneering creation of the head-mounted display (HMD). Initial AR systems, primarily experimental in nature, were designed for specialized applications such as maintenance and repair tasks (Henderson and Feiner, 2017). However, in recent years, AR has transitioned from research laboratories to widespread use across diverse sectors, including advanced driver-assistance systems (Wang et al., 2020), advertising (Jayawardena et al., 2023), education (Yuen et al., 2011), entertainment (Pucuhar and Coulson, 2015, manufacturing (Nee et al., 2012), medicine (Sielhorst eta l., 2006), smart cities (Yagol et al., 2018), social networking (Shu et al., 2018), and tourism (Cranmer et al., 2020). The expansion of AR applications is attributable to four significant technological advancements:

- The ubiquity of affordable visual sensors, such as smartphone cameras, has laid the groundwork for consumer adoption of AR technologies.
- Enhancements in environmental perception algorithms, notably visual Simultaneous Localization and Mapping (SLAM), have been crucial in integrating virtual content with real-world environments seamlessly.
- Progress in optics has been instrumental in the development of consumer-grade AR displays, making them more accessible to the general public.
- The evolution of multimedia techniques has diversified and enriched the content and presentation styles of AR applications, thereby enhancing user experience and engagement.

3.2 AR in Transportation Research

In the domain of transportation research, Augmented Reality (AR) is particularly aligned with Intelligent Transportation Systems (ITS), and more specifically, with the concept of connected vehicles (Mahmood et al., 2018). Growing vehicular traffic volumes that have led to road congestion and increased energy expenditures, has spotlighted the significance of cooperative driving techniques including "platooning." To realize cooperative driving, it is imperative to furnish human drivers with navigational guidance, collaboratively computed by an array of connected vehicles (Wang et al., 2020). AR has emerged as a sophisticated method for effective conveyance of such guidance to drivers. Furthermore, AR can serve as an ancillary source of information, augmenting drivers' situational awareness within the driving milieu. This information includes navigation details (Von Sawitzky et al., 2019) and information about the surrounding environment (Phan 2016), where AR can significantly contribute by presenting drivers with the most efficient routes derived from current traffic conditions; it also facilitates safer overtaking maneuvers by enabling drivers to visually "see through" slower-moving vehicles ahead.

The presence of multiple actors on the road, particularly vulnerable road users (VRUs) such as pedestrians, cyclists, and wheelchair users, underscores the importance of enhanced situational awareness for safety improvement. VRUs are often involved in urban traffic incidents, with the gravest outcomes often stemming from collisions with motor vehicles. Various advanced Pedestrian Collision Warning Systems (PCWS) have been developed to identify pedestrians through onboard sensors and notify drivers of their presence. Nevertheless, the challenge lies in effectively communicating such detected information to drivers without causing distraction or annoyance, particularly when false alarms occur. Recent research has focused on addressing this issue through the development of AR-based solutions (Phan, 2016; Abdi and Meddeb, 2018; Kim Et al., 2016; Kim et al., 2018), utilizing AR devices to create efficient and user-friendly interfaces for the dissemination of VRU detection information to drivers.

Exploring further, the potential of AR technology extends beyond vehicular use, promising enhancements in VRU safety. Innovations include the use of smartphone AR and AR glasses to alert pedestrians of approaching vehicles, AR devices mounted on vehicles for use by other road users, and AR applications for remote operators. The comprehensive review by Riegler et al, 2021) identifies numerous endeavors in this field, highlighting the broad potential contribution of AR technology in road safety and travel efficiency.

3.3 VR Background

Virtual Reality (VR) technology, as a sibling technology to Augmented Reality, engenders an immersive three-dimensional virtual environment. Within these virtual spaces, users are afforded the opportunity to navigate and interact with the surroundings to various extents. The conceptual foundation of VR can be traced back to the 1960s, epitomized by Sutherland's pioneering concept of the "Ultimate Display," which aimed to replicate the real world across all perceptible senses (Sutherland, 1965). Despite numerous endeavors over the past three decades to commercialize and mainstream VR technology (Kavanagh, 2017 and Van Goethem, 2020) many such efforts were transient or encountered substantial setbacks (Van Goethem, 2020). Nonetheless, these experiences have yielded valuable insights, allowing for the identification of both the challenges and advantages inherent to VR usage. Furthermore, advancements in computing and peripheral technologies have progressively enhanced the performance and affordability of VR systems. Anthes et al. (2016) provide an extensive overview of the technological developments in both hardware and software that have contributed to the resurgence of VR in recent years.

In the realm of transportation research, VR technology has found application as a potent tool for data acquisition. Specifically, driving simulators equipped with VR devices have been employed to gather diverse data related to human behavior, including driving patterns and pedestrian dynamics (Ambroz, 2005; Yu, 2013; Ihemedu-Steinke, 2017; Taheri, 2017). Additionally, VR has been used for data visualization purposes within the transportation sector. As outlined in Pack (2010), VR-integrated platforms such as "IntelliDrive" facilitate the visualization of intricately detailed data, encompassing geospatial, temporal, and categorical dimensions. This capability not only enables the exploration of vast data sets but also supports the extraction of actionable insights through data mining techniques. As for the participation of VRUs, VR technology has not been used much other than incorporating pedestrians into the virtual experiments (Lehsing and Feldstein, 2018).

3.4 Challenges of VR and AR

There exists great potential in using AR and VR techniques in the transportation domain. However, several challenges remain.

Hardware Limitations:
Hardware constraints present formidable barriers to the broad adoption of Augmented Reality (AR) and Virtual Reality (VR) technologies. The existing hardware is yet to attain a level of immersion that mirrors the natural human experience without compromises, as headsets and displays fall short in replicating the full field of view, resolution, refresh rate, low latency, and the comfort required for extended use. Moreover, the processing capabilities are currently inadequate to support fully photorealistic and interactive virtual environments, particularly when accommodating a large number of users simultaneously. Additionally, the cost of high-performance graphics cards remains prohibitive for the average consumer.

Software Development Challenges:
The development of software for AR and VR technologies entails considerable difficulties. Crafting immersive virtual landscapes and accurately overlaying digital content onto the real world demands advanced programming skills, alongside robust frameworks and platforms. Software solutions must effectively synchronize inputs from various devices, sensors, interfaces, platforms, and engines to deliver cohesive and intuitive user experiences, minimizing latency and errors.

User Adoption and Comfort:
The widespread acceptance and comfort level with AR and VR technologies are hindered by several factors. Users frequently report motion sickness, eye strain, disorientation, and anxiety, particularly when using lower-quality hardware and software. Moreover, apprehensions regarding privacy, data management, potential health ramifications, and addiction are significant obstacles to mainstream adoption.

Privacy and Security Concerns:
Privacy and security issues represent critical challenges for AR and VR technologies. These technologies require extensive data collection and sensor usage, creating immersive experiences that could jeopardize users' information and safety if not properly managed. Key concerns include the risk of surveillance, susceptibility to hacking, potential for manipulation, exposure of sensitive data, and the overarching issue of data ownership and control.

Developing Realistic and Immersive Environments:
The endeavor to create authentically realistic and immersive environments is fraught with challenges. Achieving a level of photorealism, spatial presence, physicality, and social richness essential for making virtual spaces feel genuinely believable and immersive is a tall order. Current hardware and software capabilities are often inadequate for realizing these aspirations, particularly in more extensive and complex virtual experiences.

3.5 Past work

Significant work has been done in the study of pedestrian behavior in real or simulated environments. Bhagavathula et al. (2018) shed much light on the comparison of pedestrian behavior in real and virtual environments. Camara et al. (2020) investigated the interactions between pedestrian and AVs using VR. Chen et al. (2020) compared behavior towards AVs and HDVs in the context of traffic gap acceptance, and de Clercq et al. (2019), studied the effect of HMIs on pedestrian crossing behavior in an environment of AVs. Deb et al. (2017) studied the efficacy of VR in facilitating pedestrian safety studies and others that did similar work include Nuñez Velasco et al. (2019). Deb et al. (2018) used a VR experiment and reported on pedestrian suggestions for AV external features. Similarly, Tabone et al. (2021), Meyer and Beiker (2019)'s work included perspectives on VRU and AV interactions. Dey et al. (2020) proposed a classification taxonomy related to AV HMI design. Dietrich et al. (2020) investigated implicit sound communication of urban AVs as related to pedestrian crossing behavior. Siuhi and Mwakalonge (2016) studied challenges and opportunities of smart mobile applications. Other studies on AV and pedestrian communication include Fuest et al. (2020), Hollander et al. (2019), More et al., (2019), Koojiman et al. (2019), Hudson et al., 2019), Lee et al., 2019). Others include Lee at al. (2020), Othersen et al. (2018), Lee et al (2021). Studies that used VR to study pedestrians' interactions with vehicles and AVs in specific contexts of application, include Stadler et al. (2019), Stanney et al. (2003), Schmidt et al. (2020), and Wang et al. (2019).

CHAPTER 4. DEVELOPING AN ENVIRONMENT TO ASSESS CAV-VRU INTERACTIONS

4.1 Problem Setting

Within the experimental framework, our objective is to replicate situations wherein vulnerable road users find themselves crossing unsignalized streets with an approaching vehicle that operates as a fully autonomous car (Figure 4.1). Consequently, the challenge arises as the road user is deprived of the conventional means of communication, such as facial expressions and eye contact, traditionally relied upon to engage with human-driven vehicles, given the automated nature of the forthcoming vehicle in this scenario.

Figure 4.1 Pedestrian crossing the street in front of an FAV (Ford Media Center, 2017)

4.2 Simulation Environment

To investigate pedestrians' behavioral responses towards FAVs equipped with different external features, Unity is used to construct the virtual environment and expose participants to the scenario with HTC Vive Pro headset which are equipped with movement tracking sensors and eye trackers (Figure 4.2). Unity is a powerful and widely used game development engine that has become a cornerstone in the creation of interactive digital experiences. Unity provides a versatile platform for designing and building video games, simulations, virtual reality (VR), augmented reality (AR), and other interactive applications. In Unity, we constructed a city as one completed game scene based on the Westdrive repository (Nezami et al., 2020; 2021). The scene also includes pedestrians, trees, buildings, traffic lights and seating benches (Figure 4.3).

(a) CCAT's HTC VR headset

(b) Demonstration of Simulated Testing Environments (from Deb et al., 2017)

Figure 4.2 Equipment in the experiment and the simulated environment

Figure 4.3 Demonstration of the simulated urban environment (from Nezami et al., 2020)

There are two essential parts in the scenario when we constructed the simulated environment, which are the static environment and the dynamic objects. The static setting mirrors a vast cityscape, including a sizable urban expanse comprising 93 residences, extensive roadways and pathways spanning kilometers, approximately 10,000 smaller items, and roughly 16,000 trees and plants, across an expansive territory totaling about 230 hectares. Many of the 3D objects used were acquired from the Unity® asset store without cost. Figure 4.3 presents an example of the simulated urban environment. However, the configuration of the urban setting outlined in this context is highly customizable within the editor, facilitated by an integrated mesh separation tool (Nezami et al., 2020).

This flexibility extends to modifying the dimensions, shapes, and quantities of individual buildings, streets, cars, pedestrians, and all other assets featured in the Unity® Editor's graphical user interface (GUI). In terms of the dynamic objects, there are six internally developed components. These components comprise a Path Manager designed for the creation and manipulation of pathways utilized by both pedestrians and cars. Augmenting this is the Car Engine script, empowering cars to operate autonomously, and a Car Profile Manager facilitating the customization of distinct profiles for varied vehicles. These profiles include parameters such as the maintained distance between vehicles, engine sounds, and car colors.

Furthermore, the simulation platform provides capabilities to customize the simulated pedestrians and their properties, which are tasked with managing simulations and source points for dynamic characters as they follow their assigned routes. Adding another level of complexity is the Experiment Profile Manager. In this module, flexible configuration of detailing routes, audio files, and scripted events along the designated path are feasible to the users.

Notably, the City AI in the Westdrive project functions as a standalone entity within the Unity editor's GUI, offering the capability to define fixed routes and spawn points for both pedestrians and cars. These non-playable characters (NPCs), encompassing pedestrians and cars, adhere to these designated routes, contributing to the dynamic simulation. Importantly, if visual alterations to characters are desired, an external tool becomes necessary, ensuring a comprehensive and customizable approach to character aesthetics and behavior.

Figure 4.4 illustrates the collaborative efforts of different functions within the toolkit to enable the integration of spawned cars, pedestrians, and various experimental setups into a cohesive scene. Activating experimental profiles initiates the procedural controller, which oversees the start and end of the experiment and generates the ego vehicles and background traffic. Concurrently, this action activates both the car and pedestrian, which are responsible for introducing non-player-controlled cars and pedestrians into the scene.

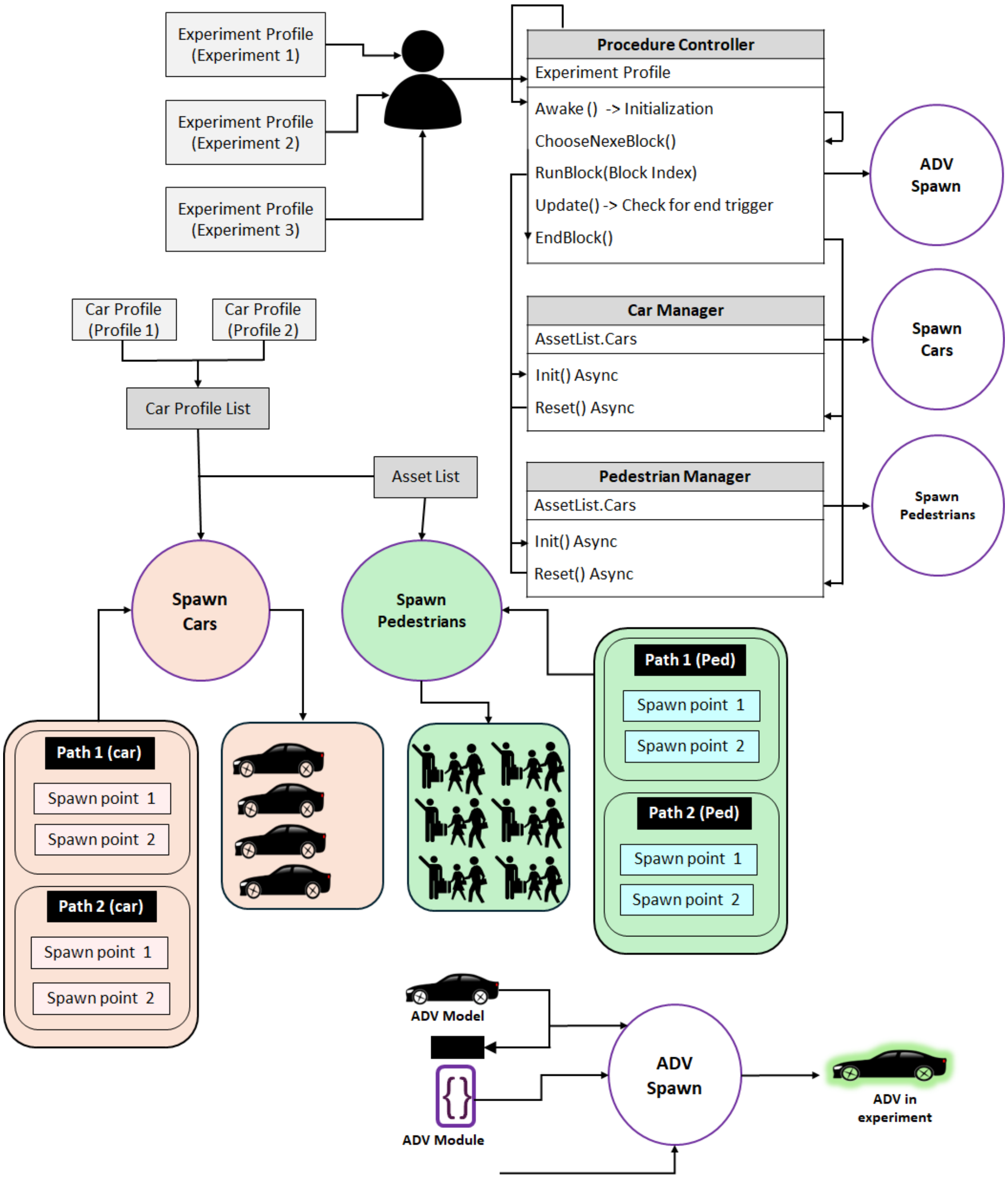

Figure 4.4 Diagram outlining the AI functionalities within the simulated urban environment (modified from Nezami et al., 2020)

CHAPTER 5. DEVELOPMENT OF AN EXPERIMENT DESIGN

5.1 Overview of the scenario design

The scenario is design is intricately aligned with the exploration of the three fundamental research areas:

1. Identify use-cases of CAV–VRU interaction using the VR platform:
    a. Road crossings without traffic lights
    b. Car parking lot
2. Configuration of the experimental scenarios considering the factors of pedestrian behavior:
    a. Right of Way: Examine the effect of unsignalized and signalized crossing walks on the certainty and trust of the VRU
    b. The number of VRUs and CAVs in the environment:
    Only investigate one-to-one interactions (specifically, even there are multiple surrounding vehicles, the participant only need to interact with only one vehicle at a time)
    c. Interaction Modalities:
        i. Visual: demonstrating using dynamic external features of the autonomous vehicle. When the FAV intend to yield, an animation showing a green moving icon will be play on the windshield of the FAV.
        ii. Auditory: speech indicating yield of vehicle (controlled ambient sound since the efficiency may be affected by the surrounding noise)
        iii. Haptic: warnings can be sent through joystick to simulate the phone vibration.
        iv. Combination of several modalities.
3. The metrics that could be used to evaluate CAV–VRU interaction in VR environment:
    a. Presence questionnaire: this measures the perception of involvement and immersion
    b. Implement naturalistic walking (to ensure participants' safety)
        i. General reactions and objectively measured metrics
        ii. NASA-TLX (workload)
        iii. Perceived comfort and safety
        iv. Self-Assessment Manikin (emotions)

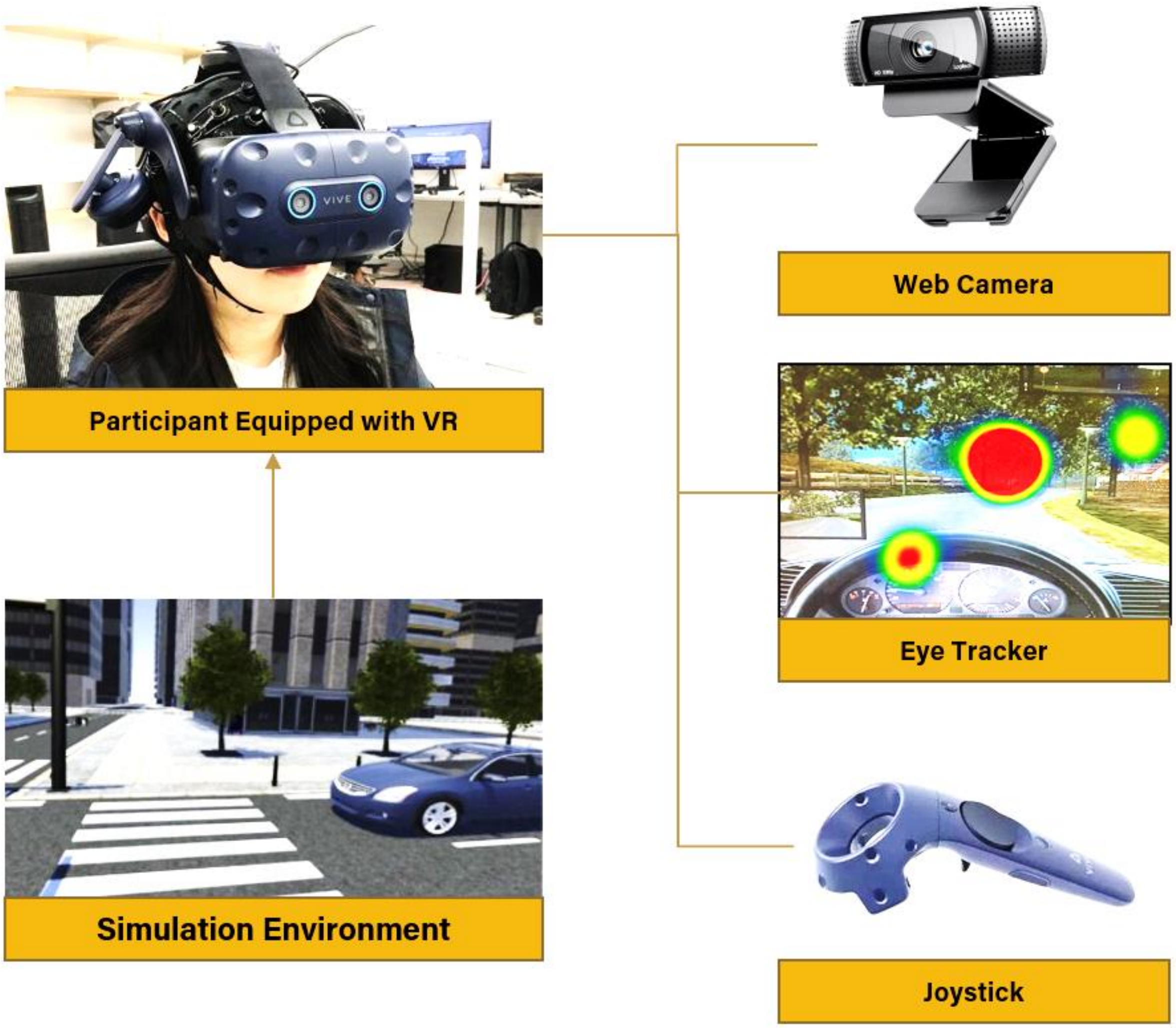

Figure 5.1 Data collection schema

5.2 Experiment Procedures

The initial phase of the experiment involves recruiting a varied group of volunteer participants. Each participant will receive an explanation of the experiment's purpose and procedures upon initial contact and again before the experiment commences. They will be informed that the experiment evaluates their interaction with autonomous vehicles (AVs) in a simulated environment. Participants will be reminded of the importance of confidentiality and that the study focuses on their interactions with AVs rather than their general behavior.

Participants will first view a brief instructional video outlining the experiment's procedure, along with an introduction to the monitoring devices to be utilized. Upon agreement to participate, each participant will be given a screening questionnaire to assess qualifications, including inquiries about motion sickness history, mental or physical impairments, and regular medication usage.

Additionally, participants aged 65 and above will undergo a phone interview to assess memory impairment prior to their visit to the test center.

Participants complete the pre-experiment survey which asks participants' sociodemographic characteristics, individual characteristics, travel behavior, and their interaction with various forms of everyday automation before they come to the test center to participate in the driving simulator experiment. On completion of the survey, the participant will be asked to provide an email address or phone number, which will be used to identify participants' completion of the survey later when they come to the test center. The participant can also opt to complete the pre-experiment survey, Wechsler Logical Memory Scale, and screening questionnaire after they come to the test center. Pre-experiment survey takes approximately 10-15 minutes to complete. The participant will schedule a time for participation using an online portal or by contacting the TEST Center through email or phone.

The participant reports to the test center at their scheduled time and complete the VR experiment. Two supervisors (from key personnel) will be assigned to each scheduled experiment. Supervisor 1 is responsible for communication with subjects during experiment runs and he/she is unaware of the experimental condition assigned to participant. Supervisor 2 is responsible for assigning the experimental condition and technical support, and he/she is of similar gender as the subject is. Before the experiment, the subject will be provided complete details about the experiment procedure, biosensor devices and other equipment used during the experiment by Supervisor 1. Then, the participant will be asked by Supervisor 1 to sign an informed consent form for their participation in this study. Before coming for the experiment, the participant needs to take the following preparatory actions: simple hair care (no hair products), no medication for at least 8 hours prior to the experiment, no caffeinated beverage or food at least 8 hours prior to the experiment, no nicotine, alcohol, or other drugs at least 8 hours prior to the experiment.

After consent is obtained, the participant will fill out a baseline Trust in Automation questionnaire. Depending on the randomly assigned condition, the participant will a random sequence of the scenarios. First, the participant will view a short introductory video that will explain the functionality of autonomous vehicles, including the general capabilities and limitations of the technologies, and the ADS they will be interacting with during the simulator portion of the experiment. A practice session will be provided to the participant to make him/her familiar with the control of the equipment. During the practice run, the participant will be asked verbally if he/she is feeling motion sickness. In this step, we will make sure that participants who feel motion sickness symptoms (such as dizziness and nausea) while equipping the VR headset and interact with the simulated environment. If the participant does not show signs of simulator sickness following this familiarization drive, the participant will then fill out another Trust in Automation questionnaire, as well as two other measures focused on their acceptance of the technology (i.e., the Usefulness & Satisfaction Survey and the Unified Theory of Acceptance and Usage of Technology [UTAUT] questionnaire adapted for autonomous vehicles). After the surveys, the participant will be required to complete 3 experimental sessions. After each run, the participant will be asked to fill out their third Trust in Automation survey, their second batch of acceptance surveys with the ADS, and the Mental and Temporal Demand subscales of the NASA Task Load Index, and a Simulator Sickness Questionnaire after third run. Web cameras will be used to record participants' behavior during the experiment. The participant stays at the TEST Center for about 15 to 30 minutes or until he/she feels comfortable before driving back in the real-world; or they can ask someone to pick him/her up. The purpose is to avoid the possibility that participants may not be adequately recalibrated to real-world driving. The total experiment time required at the test center does not exceed three hours.

5.3 Data collection

- *Pre-experiment survey*
    - Sociodemographic characteristics: Gender, income, age, education, household size, household vehicles, etc.
    - Individual characteristics: self-reported knowledge of AV, attitude toward AV, annual mileage
    - Automation Complacency Potential

- *VR experiment*
    - Experiment scenario settings: Traffic conditions, information characteristics.
    - Participant behavior: overall crossing time, hesitation time. Mid-experiment survey data: Trust in Automation survey, Acceptance surveys (Usefulness & Satisfaction Survey and UTAUT questionnaire adapted for AV), self-assessed workload scales (Mental and Temporal Demand subscales of the NASA Task Load Index), and the Simulator Sickness Questionnaire.
    - Physiological data: Video recordings of facial expressions, eye tracker data.

CHAPTER 6. CONCLUDING REMARKS

Fully autonomous vehicles (FAV) or Level 5 automation vehicles can perform driving tasks in any environment and under all conditions without input from human drivers. However, they can lead to other challenges during real world implementation. Specifically, communication methods between vulnerable road users (pedestrians, bicyclists) and FAVs may change ultimately, which may lead to misunderstanding of intentions and cause more collisions.

When road users enter the road network, they initiate a constant exchange of information with the traffic environment and other road users around them in order to be ready to respond immediately. Road crossing pedestrians and bicyclists generally rely on informal communication methods, eye contact, facial expression and gestures, to interpret intentions of other road users and make decisions based on the information.

With FAVs, these informal communication approaches cannot be realized. Hence, it is necessary to understand the interactions between these road users and FAV and design proper external features of FAV to establish efficient communication method.

This study first carried out a review of literature on the interfaces for human-computer communication and the pedestrian-autonomous vehicle interaction. Then the study compared the demerits and merits of using virtual reality vs. augmented reality in analyzing FAV-VRU discussions. Next, the study developed an environment to assess CAV-VRU interactions, describing the problem setting and the environment for the simulation. Next, the study developed an experiment design procedure, including an overview of the scenarios, the experiment procedures and the proposed data collection for a prospective human factors study in future.

Overall, the study details and results can provide some useful guidance to state and local agencies as they go about documenting their VRU safety assessments in compliance with the Infrastructure Investment and Jobs Act (IIJA).

CHAPTER 7 SYNOPSIS OF PERFORMANCE INDICATORS

7.1 USDOT performance indicators I

Two (2) transportation-related courses were offered annually during the study period that was taught by the PI and a teaching assistant who are associated with the research project. One of these was a newly developed course that was inspired and directly associated with this CCAT research. One graduate student and one (1) post-doctoral researcher (subsequently designated a Visiting Assistant Professor) participated in the research project during the study period. One (1) transportation-related advanced degree program (a doctoral program) utilized the CCAT grant funds from this research project, during the study period to support the graduate students.

7.2 USDOT performance indicators II

Leadership Development Performance Indicators: This research project generated 3 academic engagements and 2 industry engagements. The PI's held positions in 2 national organizations that address issues related to this research project.
Education and Workforce Development Performance Indicators: The methods, data and/or results from this study were incorporated in the class content of several versions (Fall 2022, Spring 2023, and Fall 2023) of the following courses at Purdue University's undergraduate civil engineering program: (a) CE 299 (Smart Mobility), an optional undergraduate-level course, and (b) CE 398 (Introduction to Civil Engineering Systems), a mandatory undergraduate course. The students in these classes will soon be entering the workforce. Thereby, the research helped enlarge the pool of people trained to develop knowledge and utilize the technologies developed in this research, and prospectively, to put them to use when they enter the workforce.
Collaboration Performance Indicators: There was collaboration with other agencies, and one (1) agency and at least four (4) academic institutions provided matching funds.

The outputs, outcomes, and impacts are described in Chapter 7.

CHAPTER 8. STUDY OUTCOMES AND OUTPUTS

8.1 Outputs

8.1.1 Publications, conference papers, or presentations

None.

8.2 Outcomes

The outcomes of this project are the prospective changes in agency policy, design, programs and initiatives to protect road users at road intersections in the impending era of autonomous vehicles (and farther out in the future, fully autonomous vehicles).

8.3 List of impacts

According to the U.S. Federal Highway Administration in 2022, road traffic safety remains a key priority and strategic goals. This is important in the current time when vehicle and pedestrian volumes continue to grow. The impacts of this project are the effects of outcomes on the transportation system characterized by the confluence of fully automated vehicles and vulnerable road users sharing the same right of way.

- Using the material contained in this report, state and local transportation agencies could be placed in a better position to develop their VRU Safety Assessment as is mandated by the IIJA legislation. The societal benefits of the VRU-SAs being developed nationwide include improved roadway safety, reduced fatalities, improved VRUs' travel efficiency, and reduced adverse community impacts of emerging transportation technologies on the most vulnerable road users.
- The information provided in this report, will hopefully help build motivation for city road agencies to provide infrastructure to protect VRUs.
- The study FAV-VRU safety framework, experimental setup, and considerations discussed in this report, can help state and local agencies prepare their VRU Safety Assessments that is required by national legislation. The effect of their adoption of these materials can potentially improve the operation and safety of large-volume urban intersections as AVs continue to increase in both their market penetration and levels of autonomy.
- The conduction of the study by 4 graduate students and the incorporation of the research material in transportation-related courses in Purdue graduate and undergraduate curricula, will help increase the pool of people trained to develop knowledge and utilize new technologies and put them to use. The VR equipment purchased using the grant funds will improve the physical resources towards future workforce training regarding new technologies. This will increase the body of knowledge and technologies.
- The graduate students that worked on this project will enter the workforce in 2024 to help support the workforce that will implement and/or improve the methods developed in this study.

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