IDK: An Interaction Development Kit to design interactions for lightweight autonomous vehicles

by

Jerry Wei-Hua Yao

B. Des., National Taiwan University of Science and Technology (2016)

Submitted to the Program in Media Arts and Sciences,
School of Architecture and Planning,
in partial fulfillment of the requirements for the degree of
Master of Science in Media Arts and Sciences

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Author: ____

Program in Media Arts and Sciences
August 9th, 2019

Certified by: ____

Kent Larson
Principal Research Scientist
Thesis Supervisor

Accepted by: ____

Tod Machover
Academic Head, Program in Media Arts and Sciences

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Abstract

Various studies have demonstrated that privately owned cars will become significantly less prevalent in the city in the next 10 to 15 years. Other efficient alternatives for mobility platforms within the city are in demand around the world. One example is the emergence of the PEV (Persuasive Electric Vehicle), an agile autonomous bike-sharing platform (*M. Lin, 2015*). Based on this trend, it is reasonable to anticipate that increasingly more mobility systems of different forms will emerge in urban areas in the future. These new mobility systems might not necessarily be similar to cars; they may instead be a new class of social robot that could blend into the city more seamlessly. Moreover, when there is no longer a driver within each vehicle, designing human-machine interface (HMI) that is simple for users to process will be more important than ever. For example, if a pedestrian encounters a lightweight autonomous vehicle for which it is apparent that no one is in the vehicle, how can the pedestrian understand the intention of the vehicle? And how can we, as designers, make this more intuitive and seamless?

This thesis presents IDK, which is an Interaction Development Kit equipped with essential tools to help facilitate the design and prototyping process. IDK could be physically installed in PEVs, thereby enabling designers and developers to prototype human-machine interactions in a rapid and intuitive manner. This thesis also identifies multiple situations that a lightweight autonomous vehicle may encounter while navigating through streets and proposes a range of interactions that can tackle these problems. All prototypes from this thesis are based on the latest version of the PEV as an interactive platform. The proposed interactions are evaluated through outdoor testing as well as indoor exhibitions to determine how people respond to these new norms of communication. My hope is that the results of this thesis will provide useful insights for designers and developers who seek to develop interactions that allow humans to seamlessly interact with lightweight autonomous vehicles.

Thesis Advisor: Kent Larson
Title: Principal Research Scientist

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Advisor: ____

Kent Larson
Principle Research Scientist, MIT Media Lab
Thesis Supervisor

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Reader: ____

Cynthia Breazeal
Associate Professor of Media Arts and Sciences
MIT Media Lab

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Reader: ____

Colleen Emmenegger
Director of People Centered Automation
UCSD Design Lab

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Chapter 1

Introduction

1.1 The trend of future cities and transportation

As the world has become increasingly more environmentally aware, countries and cities around the world have begun to introduce measures to reduce carbon emissions. It is evident that human activities are responsible for most of the increase in greenhouse gases over the last 150 years [1]. In the United States, the most significant source of greenhouse gas emissions from human activity is from burning fossil fuels, of which about 28% was from transportation [2] (Figure 1-1). Furthermore, despite the densification and urbanization of cities, roads in the United States continue to be predominantly occupied by solo drivers [3]. This is both uneconomical and detrimental to the environment. To tackle this problem, cities around the world have begun to shift their current transportation platforms to be more environmentally friendly. For instance, Paris has started to restrict the access of all privately owned cars to its city center on the first Sunday of every month to improve overall air quality and to grant pedestrians access to more public space, thereby creating a more human-centric environment for the citizens [4]. Mexico City has also introduced a similar policy, which helped limit smog levels in the city. Other cities such as Madrid, Berlin, and San Francisco are also adopting various approaches to reduce the number of personally owned cars on their roads. Research by Stanford economist Tony Seba even predicted that nearly no one in the U.S.'s main cities will own a conventional car by the end of 2030 [5]. Instead, most travelers in U.S. cities will be served by on-demand, autonomous, electric rideshares, since using electric rideshare services will be four to 10 times cheaper per mile than purchasing a new car [6]. Modern transportation in the city is currently experiencing major changes due to transformative transportation technology. The shift towards on-demand hire basis autonomous vehicles has unfolded in stages, enabling a more eco-friendly environment and improving the efficiency of people's day-to-day activities.

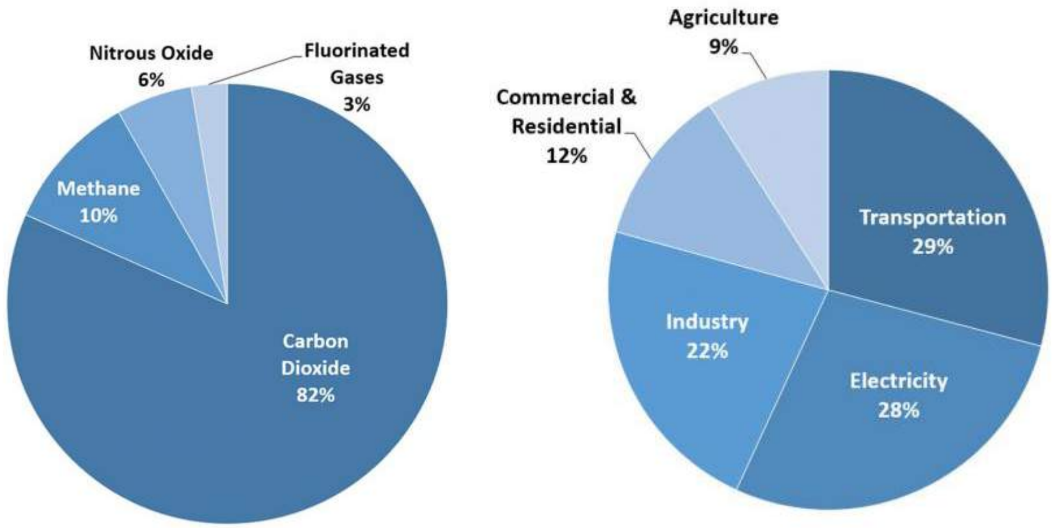


Figure 1-1: Global carbon emissions from fossil fuels [1].

1.2 The emergence of micro-mobility

Metropolitan cities around the world are facing an epidemic of pollution and congestion caused by rapid urbanization as well as the overuse of personally owned cars [8]. To mitigate the situation, many countries have considered alternatives that could enable city dwellers to navigate the city more efficiently. The term micro-mobility was coined in the late 2010s and refers to a solution to last-mile transportation in dense urban areas [9]. This new category is now represented by various types of lightweight transportation such as docked and dockless bike-sharing systems, electric bikes, and electric scooters [10]. For instance, Chinese bike giant Mobike introduced the very first dockless bike in 2015 and completely changed the mobility pattern in Asia. In 2018, the prevalence of micro-mobility experienced tremendous growth due to the emergence of electric scooters. Lime and Bird, two pioneering U.S.-based companies developing electric scooters, had become popular in the San Francisco within a year. Every city has its own transit desert [11], regardless of how extensively the public transportation system was planned. Micro-mobility thrives to fulfill this gap [12], offering a more flexible option for populations in underserved areas and increasing access to public transportation.

Moreover, the emergence of micro-mobility has also caused city governments to rethink the infrastructure of cities. In most cases, the infrastructure and transportation networks in current cities are designed to accommodate cars. It is potentially dangerous to have forms of vehicles other than conventional cars on the same road, particularly when some of them are lightweight and vulnerable. As more people have begun to commute within the micro-mobility system, policy-makers have begun to re-design cities' infrastructure by making it more human-centric and all mobility friendly.

Recognizing the potential and benefits of micro-mobility systems, academic institutes as well as industry giants have also begun to exhibit interest in revolutionizing the urban mobility pattern. Thus far, the market has been dominated primarily by electric scooters and shared bikes, but they are certainly not the only forms. Based on these trends, it is reasonable to anticipate that more micro-mobility systems will be entering into the urban areas in different forms in the near future. The new mobility systems might not necessarily resemble cars; they may instead involve a new class of social robot that could blend into the city more seamlessly.

1.2.1 PEV (Persuasive Electric Vehicle)

The PEV (M. Lin, 2015) is an ongoing research project initiated by the MIT Media Lab [13]. It is a low-cost, agile, shared-use autonomous bike that can be either an electrically assisted tricycle for passenger commutes or an autonomous carrier for package delivery (Figure 1-2). The PEV is the next generation of micro-mobility; it not only provides a healthy and sustainable mobility option but also implements autonomy technology in addition to current conventional micro-mobility systems. It is certain that the ubiquity of open-source autonomy technology represents a major shift in the micro-mobility industry. We may expect that new mobility platforms in the future will share critical functions such as lightweight, shared-use, and autonomous drive.

Our vision for PEV is that riders will request the PEV through a mobile application, and the nearest available PEV will arrive autonomously to meet the rider. The rider can either choose to operate the PEV themself or use the PEV to deliver packages autonomously. When the trip is complete, the PEV will simply proceed to its next mission.

Figure 1-2: First prototype of the PEV (Persuasive Electric Vehicle).

1.3 Designing human-machine interfaces for PEV

The scope of human-machine interface (HMI) that this thesis discusses refers to how people and automated systems interact and communicate with each other through a collaborative approach. In the case of PEVs, in which there is no longer a driver inside a vehicle who would be the main conduit of information transactions between the vehicle and its surroundings, designing intuitive mediums that allow vehicles to convey its intention to pedestrians has become more critical than ever. For example, if a pedestrian and a PEV encounter an intersection in the street, how does the PEV express its intention and communicate with the pedestrian? How do we, as designers, design interactions that are sufficiently straightforward for humans to understand the machines without any learning curve? Could we translate the interactions that humans have with each other into new interfaces to start a potential conversation with the machines?

Additionally, we started to see more research emphasis on the interactions between the vehicle and the pedestrian nowadays, thereby evidencing the importance of building suitable HMIs. Enabling everyone to understand the intention of the vehicle is even more critical for PEV, since it is used for last-mile transportation within the city and has a closer relationship with humans relative to other micro-mobility systems. Since PEV is emerging in the human-inhabited environment, all of the people around it must be able to interact with them, not merely the drivers themselves.

Furthermore, no protocols have been established yet for the lightweight autonomous vehicle to interact with people external to the vehicle; since the interaction is about humans and the machines, making the interactions human-centric is also an essential factor.

1.4 Introducing IDK and its contribution

This thesis presents IDK, an Interaction Development Kit that could be physically installed in the PEV, thereby enabling designers and developers to rapidly prototype human-machine interfaces into the vehicle. IDK aims to facilitate the human-machine interaction design and prototyping process. It provides a modularized system that is equipped with the essential tools to build interactions for lightweight autonomous vehicle (LAV), allowing designers and developers to examine potential ideas in a rapid and intuitive manner. This version of IDK is designed to be directly installed into the PEV; however, it could also be scaled and transformed into different variants to fit in other forms of LAVs. This thesis also identifies multiple situations that a LAV would encounter while navigating a city. It introduces a series of interactive solutions that have been built by an IDK to tackle the problems, suggesting new communication methods for LAVs to interact with the drivers and pedestrians in the city.

In addition, this thesis also provides a series of interactions that are developed through IDK as examples of how humans could interact with PEV and make the interactive experiences more intuitive and seamless. The results of this thesis are evaluated by multiple groups of people from diverse backgrounds, including professionals from the automobile industry, professors researching autonomous vehicles, and city dwellers who are interested in having more LAVs deployed in their cities. The qualitative user study and quantitative analysis data will provide insights for designers and developers who seek to design human-machine interactions for their own lightweight autonomous mobility platforms. The Interaction Development Kit described in this thesis, as well as the lessons learned from the design and testing prototypes, could potentially assist in building human-machine interactions for the next generation of micro-mobility systems.

1.5 Overview of this thesis

This thesis is organized as follows:

Chapter 2 discusses previous research upon which this research draws. It elucidates the human-machine interactions between people and conventional cars as well as different forms of micro-mobility systems. It also introduces prior research in an endeavor to observe social behavior while deploying a new mobility platform in the city. By accounting for insights from prior research, it identifies possible directions to focus on and build on top of the previous research.

Chapter 3 describes the approaches deployed to design human-machine interactions for PEVs by building an Interaction Development Kit. It presents the necessary sensors that are required to function lightweight autonomous vehicles and illustrates the design and engineering work performed to build the prototypes.

Chapter 4 presents multiple interactive experiences that are built through the Interaction Development Kit and explains the inspiration as well as the purpose behind each design.

Chapter 5 presents user study experiment and an online web platform to collect user feedbacks. By understanding users' needs, it is possible to design real human-centric experiences. This chapter also concludes the evaluation from user testing and discusses user data analysis.

Chapter 6 concludes the contribution of the IDK system, and chapter 7 proposes the future works that we are planning to implement after completing this thesis.

Chapter 2

Related Works

This chapter first examines multiple human-machine interaction-related research on automobiles and robots. Most of the existing research focuses on the HMI development of conventional vehicles or autonomous cars; the studies seldom concentrate on the research for lightweight autonomous vehicles, since they are not prevalent yet. However, it is critical to learn from the experience of the HMI design in cars and translate these interactions to fit the next generation of micro-mobility systems.

2.1 AEVITA: Vehicle-to-pedestrian communication

Pennycooke et al. [15] aim to enable the pedestrians to understand the intentions of autonomous vehicles by utilizing the AEVITA system (Autonomous Electric Vehicle Interaction Testing Array) to design biomimetic vehicle-to-pedestrian communication protocols. AEVITA proposed a pair of mechanical eyes that could be deployed on the CityCar platform [16], an autonomous electric vehicle developed at the MIT Media Lab. The AEVITA system introduced a pair of mechanical eye gadgets to understand the intentions of people who are outside of the vehicle (Figure 2-1). If any pedestrians are identified, color-coded LEDs could change from green to yellow and red to acknowledge pedestrians or send messages to them. This demonstrated the vehicle's capability of human recognition and conveys its intentions through directed contextual messages. In addition to LED signals, the directional speakers on the vehicle could point towards pedestrians, acknowledging to them that it is safe to cross the streets.

AEVITA has three communication layers that is uses to cover the simplified spectrum regarding how humans and autonomous vehicles could communicate with each other.

- Recognition system
    - Demonstrates its capability to recognize pedestrians on the streets;

- Announcement system
    - Announces the intention of the vehicle through directional speakers to initiate interpersonal conversation;
- Body language system
    - Uses sensors and actuators on the CityCar platform to create basic mechanical movements to express the intentions of the vehicle.

AEVITA is one of the few studies in the early 2010s that focused on the external interactions of vehicles rather than the internal interactions, which also motivates my research interest in this thesis and design. The successful implementation of AEVITA can help to alleviate robotic vehicle operational anxiety among those who have no choice but to navigate the same spaces with autonomous vehicles.

In the field of human-vehicle interaction design, the Interaction Development Kit that this thesis presents is most closely related to AEVITA's concept. However, while AEVITA successfully introduces a new communication platform between pedestrians and autonomous vehicles, some of the suggested mediums might not be sufficiently straightforward for micro-mobility platform, as the new mobility platform might no longer be the shape of a conventional car. Furthermore, the color codes of LEDs as well as the mechanical movements might not be able to be sustained over time. Communication and informal rules are in constant flux, and the rules must take cultural context into account as well. While using visual signals to communicate with pedestrians might be a good approach, it could also be ambiguous sometimes. For example, in the United States, when a driver encounters a pedestrian at an intersection, the driver often blinks the car's headlights twice to signal that it is safe for the pedestrian to pass. Nevertheless, there are drivers in South American countries who use the same cue to express that they are going to start driving and the pedestrian should hold. Even under the same culture context, the visual signals could still remain equivocal to pedestrians as their interpretation to the signals differs from one another. Therefore, while designing these types of human-machine interactions, particularly in the case of mobility platforms, investigating current patterns in the context is extremely crucial.

Sharing the same goal of allowing people inside and outside the vehicle to have better user experiences with the mobility platform, we learned from experiences of AEVITA and designed a new approach tailored to the emerging micro-mobility platforms in the United States and East Asia (Japan, Taiwan).

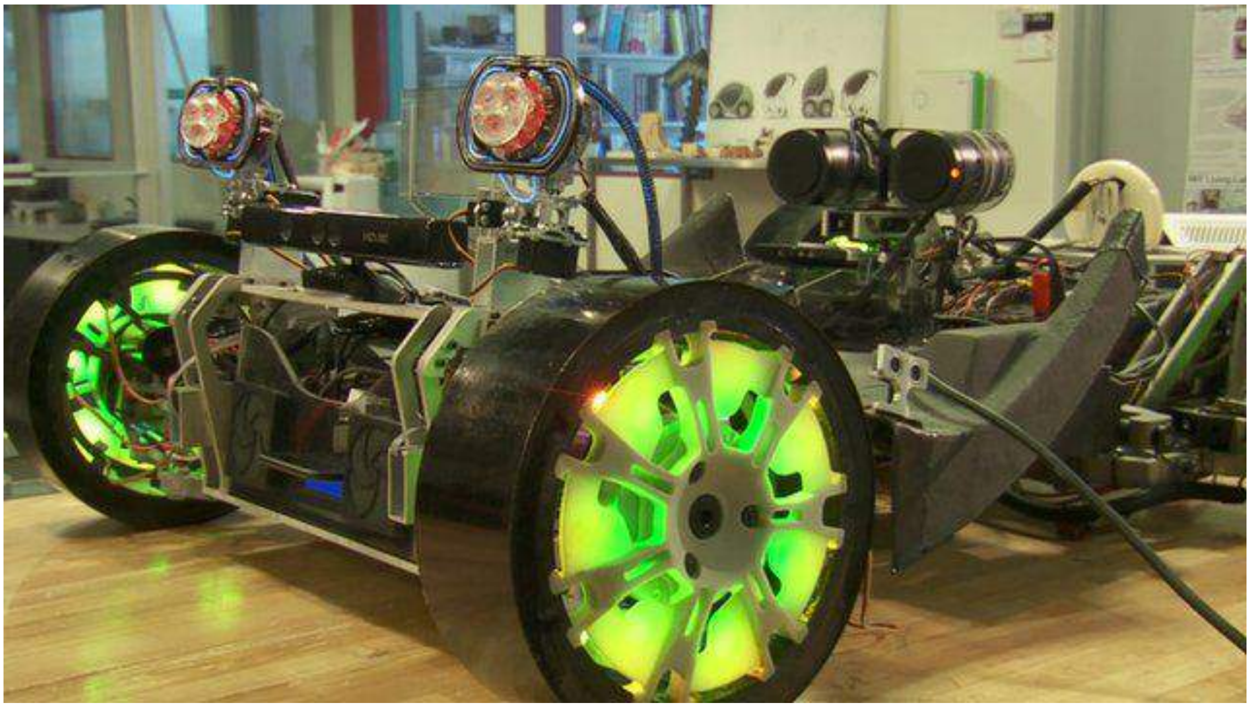


Figure 2-1: Prototype – AEVITA on a 1/2 scale CityCar [10] platform.

2.2 Human-vehicle interaction research

Micro-mobility systems and conventional self-driving cars would frequently encounter similar problems on the streets, since they are both a new form of mobility system entering into the urban area. For example, both platforms must interact with other users of the road as well as human-operated vehicles [17]. This section discusses multiple approaches that the automobile industry has proposed, with a special focus on providing a better understanding of the role of human interactions with autonomous vehicles (AVs).

- Interactions between AVs and drivers

- In a level four or five autonomous vehicle, the driver no longer needs to pay attention to the road. They might be deeply engaged in other activities; therefore, regaining a distracted driver's attention could be challenging. Merat et al. [18] conducted studies on drivers' ability to handle conditions when a car's automated system reverts to manual control. The results indicated better performance overall when control was transferred after six minutes. The studies highlight the importance of how an effective human-machine interfaces could increase the safety level of a driver while using an autonomous vehicle.

- Interactions between AVs and pedestrians

  - Jafary et al. [17] suggest that walking could become more pleasant in the future because on-street parking will disappear. Pedestrians can truly feel safe while walking on the street, as the AV exhibits a higher success rate in detecting pedestrians relative to human-operated vehicles [19]. In terms of conveying the vehicle's intentions to pedestrians, the automobile industry has offered examples in the following paragraph.

    Audi launched a new HMI design for its concept car Aicon in 2017 [20]. The Aicon car was equipped with more sophisticated LED headlights to serve as the eyes of the vehicle (Figure 2-2). The new headlights could adapt shapes to resemble wide pupils or squinted eyes for an aggressive look. Similarly to AEVITA [15], the Aicon also makes "eye contact" with pedestrians and follows them in the vicinity of the vehicle by changing the LED patterns. In addition, it uses animations on its display to warn pedestrians and cyclists of emergencies. In terms of the lighting design, it visualizes statuses of the vehicle such as platooning, urban driving, and slow-speed driving by utilizing horizontal LED strips. This is a more subtle and well-polished means to exchange information between humans and vehicles. However, while using headlights as a pair of eyes is an interesting function, it does not display the difference between human-tracking or vehicle-tracking, thus making it more difficult to create customized interactions to fit into different contexts.

Mercedes-Benz [21] also removes the headlights on its F 015 series by replacing the front and back portion of the vehicle with massive clusters of LED pixels. This new feature serves more purposes than merely lighting up the road ahead. It adds a color-coded lighting design. For example, the light turns white if the car is in the human-operated mode and switches to blue if the car is under autonomous mode. This would require a short amount of time for people to learn; however, if the color codes are not standardized across different companies, it could become exceptionally confusing for the pedestrians. On the other hand, one design decision that Mercedes made was relatively straight-forward. The rear LED strips of the vehicles could be used to scroll messages such as “SLOW” or “STOP” to communicate with the drivers or vehicles behind it. When emergencies occur, the easiest approach might be the most effective.

The F 015 series also introduced a new approach by using projection to project the information on the floor to communicate with pedestrians (Figure 2-3). For example, when the autonomous vehicle is intended to signal to the pedestrian to cross the road, it projects a sidewalk pattern on the floor and uses the projections to engage in several interactions with pedestrians. This project was eventually terminated, as there are certain physical limitations and constraints involved in the current projection technique, and it is not economical to put expensive projection gadgets in a vehicle if the scalability does not meet the standard. However, as one of the leading companies in the automobile industry, Mercedes kept pursuing the idea of “human-centric” as its future insight.

Figure 2-2: HMI eye contact interaction for Audi Aicon.

Figure 2-3: Image projection interaction from Mercedes-Benz.

- Interactions between AVs and other transportation platforms

    - Aside from driver and pedestrian interactions, autonomous vehicles also need to cohabit with other transportation networks involving bicycles, scooters, or other autonomous vehicles in the city. Hobert et al. [22] introduced research concerning two emerging technologies in the automotive domain: vehicle-to-vehicle communication (V2V) and vehicle-to-infrastructure communication (V2X), which enable sensing and maneuvering, the two main features that permit the creation of AVs. Hobert divides autonomous driving into three categories: close-distance, urban, and freeway use cases; he analyzes the requirements for safe and efficient operations. However, the problem for bicycles and scooters is that they are not linked to these networks due to their size, thereby leaving a gap of 40 to 60% of road users [22]. Companies such as Tome and Trek are working on bicycle-to-vehicle (B2V) interaction [23] that attach beacons on bikes to transmit information and enhance the safety of travel for cyclists. Predictably, future mobility platforms are likely to have similar sensors integrated into their systems, allowing each vehicle to talk to others to mitigate dangers on the road and advance towards a Cellular Vehicle-to-Everything (C-V2X) scenario.

2.3 Ghost driver-pedestrian behavior studies

While designing human-machine interactions for an autonomous vehicle, one important factor is to understand the reactions and behaviors that pedestrians exhibit when they encounter one in their cities. Emmenegger et al. [24] conducted an interesting wizard-of-Oz experiment by disguising the driver as a car seat to forge the impression of an autonomous vehicle (Figure 2-4). The study was operated at the campus of University of California San Diego as well as downtown La Jolla to examine the interactions pedestrians may display while crossing the street in front of an autonomous vehicle. The results indicated that over 90% of the participants (N=67) did not discover the missing driver and continue their day normally. Rothenbücher et al. [25] conducted another pedestrian behavior study with an autonomous vehicle; while encountering an autonomous vehicle, participants chose to cross the street when the autonomous vehicle stopped; when the car started to move into the crosswalk gradually as if it was going to cross, the participants took this cue and stopped to let the vehicle pass. In the survey questionnaires, 12 out of 13 interviewees described their experience with the autonomous vehicle as “safe,” “smooth,” and “deliberate.”

Social factors also play a significant role when pedestrians make decisions. Rasouli et al. suggested that the *group size* of the pedestrians changes one’s behavior [26]. When crossing as a group, pedestrians tend to be more negligent and pay less attention on the crosswalk. It often results in a shorter gap between humans and vehicles. Group size could also impact the way pedestrians comply with traffic laws. Lefkowitz et al. observe that individuals in a group are less likely to follow someone who is breaking the laws [27], and the driver tends to hold while encountering a group of pedestrians as opposed to individuals. Studying the norms of pedestrians and drivers on the streets enables our design to be more natural. We must observe the current behavior that pedestrians and drivers engage in and translate these experiences into a new language that machines can perform.

Figure 2-4: Example of Wizard of Oz experiment to disguise the driver [24].

In short, this chapter reviews multiple human-machine interaction studies that have been conducted by both the automobile industry and academic institutes. Learning from the lessons regarding human-car interactions and translating these experiences to fit the scope of micro-mobility system is a crucial part of this thesis. We have learned about the AEVITA platform Pennycooke et al. [15] developed and design interaction protocols that are more up to date. We also reviewed the HMI research by Mercedes-Benz and Audi to learn how to improve lighting design for mobility platforms. Last but not least, we have studied pedestrians' behavior through research conducted by Rothenbücher et al.

Chapter 3

IDK: System development

3.1 Overview of IDK system

Figure 3-1: The latest generation of PEV platform with IDK+.

This chapter elaborates upon the development of the Interaction Development Kit (IDK) as well as the hardware development process of the PEV [13]. We present three different versions of the IDK system in this chapter: IDK Lite, IDK Standard, and IDK+. Each version provides different levels of interactions that developers could design based on their needs. The latest IDK system is built on top of the PEV and could be easily installed at the rear part of the vehicle (Figure 3-1). Over the past two years, the PEV has undergone several hardware system and prototype upgrades; the key design goal for each alteration is to incorporate more human-machine interactive functions into PEV and grant more accessibility for designers, developers, and users. Based on our research, we have identified the five core principles of PEV and the future micro-mobility system as follows:

- **Lightweight**
  - The new generation of the micro-mobility system must be agile and able to move dynamically in the urban areas.
- **Shared use**
- **On-demand**
- **For passengers and logistic purposes**
  - To maximize the usability of the vehicle, when the PEV is not operated by humans, it could also be used to deliver packages and cargo.
- **Autonomy and electric driving**

To design more HMIs for PEV while ensuring these core principles are reached, we built an Interaction Development Kit (IDK) that modularizes all of the essential tools to function the vehicle and design interactions via the system. IDK allows designers and developers to rapidly design and prototype interactions for PEV. The latest system could be divided into four layers:

- **Perception layer**
  - This layer is equipped with sensors such as LiDAR and a camera vision system that allows the vehicle to perceive the world.
- **Vehicle-to-Pedestrian (V2P) layer**
  - The V2P layer focuses on the hardware required to build interactions for people external to the vehicle.
- **Vehicle-to-Rider (V2R) layer**
  - V2R layer targets the necessary hardware that operates the interactions between the vehicle and the rider.
- **Power management layer**

3.2 Introducing the PEV hardware system

This section introduces the basic sensors that enable PEV to maneuver (Figure 3-2). To design an autonomous micro-mobility system while maintaining the functions of bicycle, we have opted to place an electric bike motor in the middle of the bike frame to function the system. The other motor is for the steering purpose; we install the steering motor at the conjunction between left and right linkage. We also utilize a high-torque servo motor to control the brake of the bike (Figure 3-3). As for the autonomy part of the PEV, we have applied LiDAR (Figure 3-1) on top of the PEV, which allows it to perceive the world.

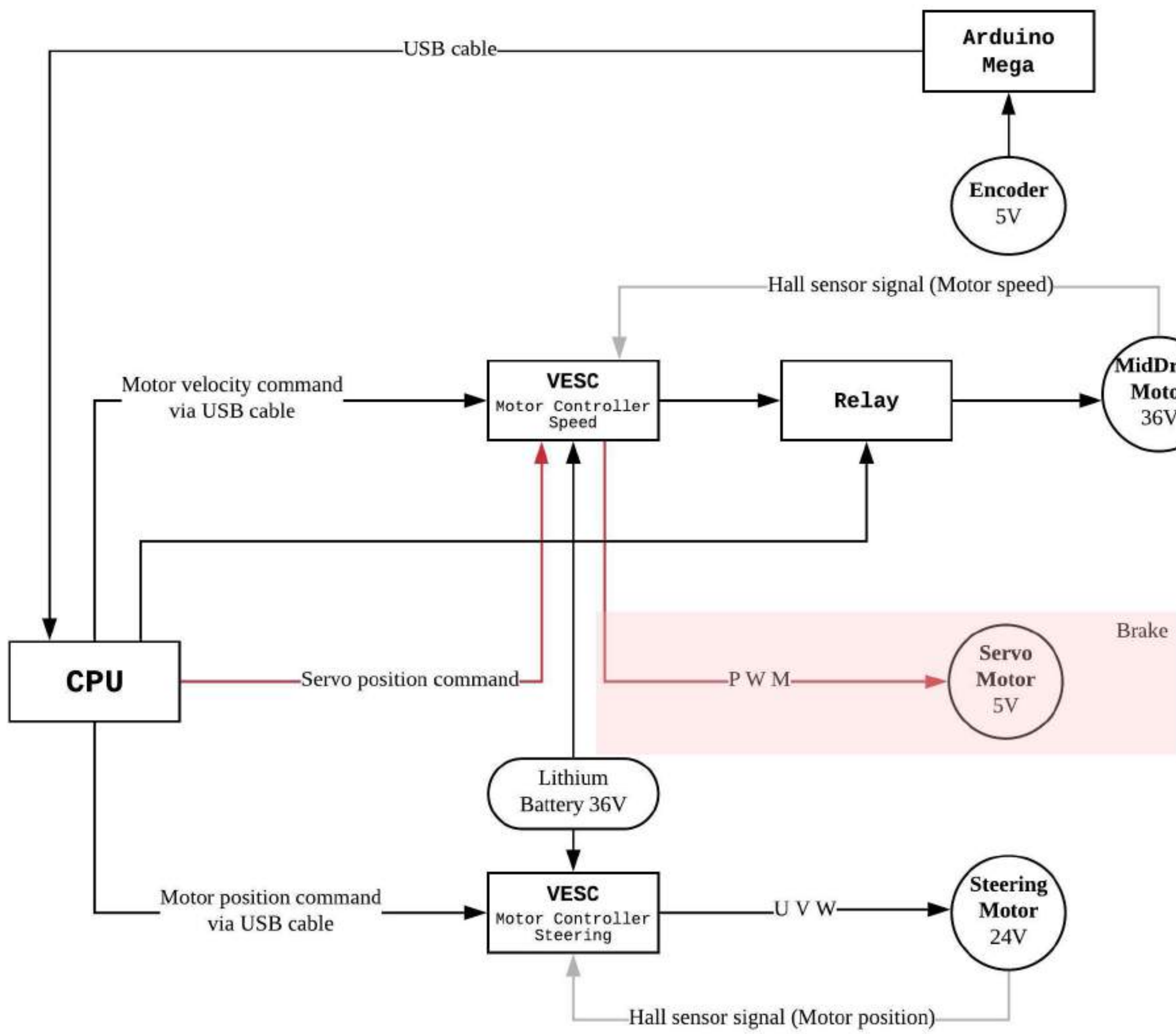


Figure 3-2: PEV control and navigation diagram.

Figure 3-3: High torque motor to control bike brake.

3.3 IDK hardware system development

Learning from the experience of building previous PEV prototypes, we realized the importance of building a modular system to function the PEV. Having a modularized system would give designers and developers greater flexibility while making changes to the PEV.

Currently, there are four different versions of PEV distributed at the research institutes around the world. We often visit these places to conduct on-road testing in the city and adapt the system to enable more human-machine interactions. However, each version of PEV is slightly different from one another depending upon the time when it was built. It makes it even more difficult for developers to update or design new functions for the vehicle before physically going onsite and seeing the vehicle. With the IDK system, developers and designers around the world could remotely make changes on this portable system and rapidly prototype the experience on any version of PEV. While going to different cities for demonstrations or outdoor testing, all we have to do is carry this compact system with us and simply install it in the PEV. The IDK system not only facilitates the interaction design and prototyping process for designers but also enables the development across different vehicles to be more seamless and efficient.

3.3.1 IDK Lite

IDK Lite is the most basic version of IDK system, it provides elementary sensors that allow designers to build human-machine interactions for the lightweight autonomous vehicles. As Figure 3-4 illustrates, we attempted to modularize all of the basic sensors such as LiDAR, mid-drive, and steering motors that function the PEV into different units on the very first prototype of IDK. We combined each sensor with its MCU (Microcontroller unit) into a small box and placed these different units on separate layers at the front part of PEV (Figure 3-5). We also centralized the power supply by building a module to power most of the sensors in one unit.

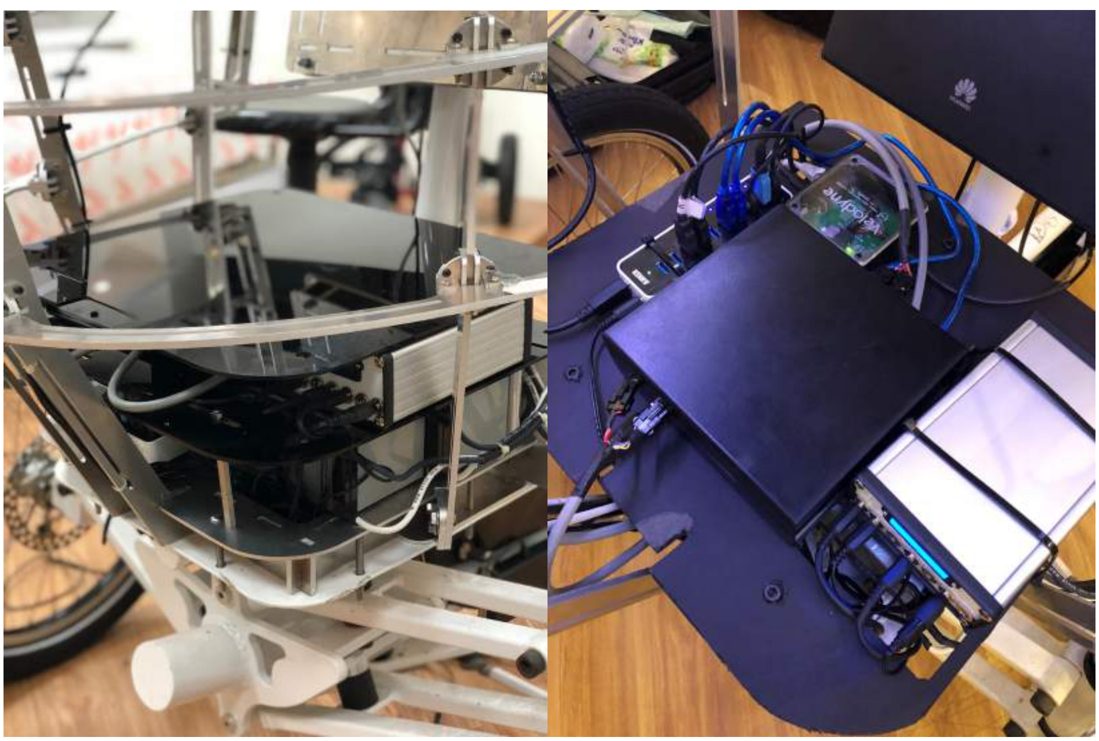


Figure 3-4: IDK Lite tested and installed on PEV.

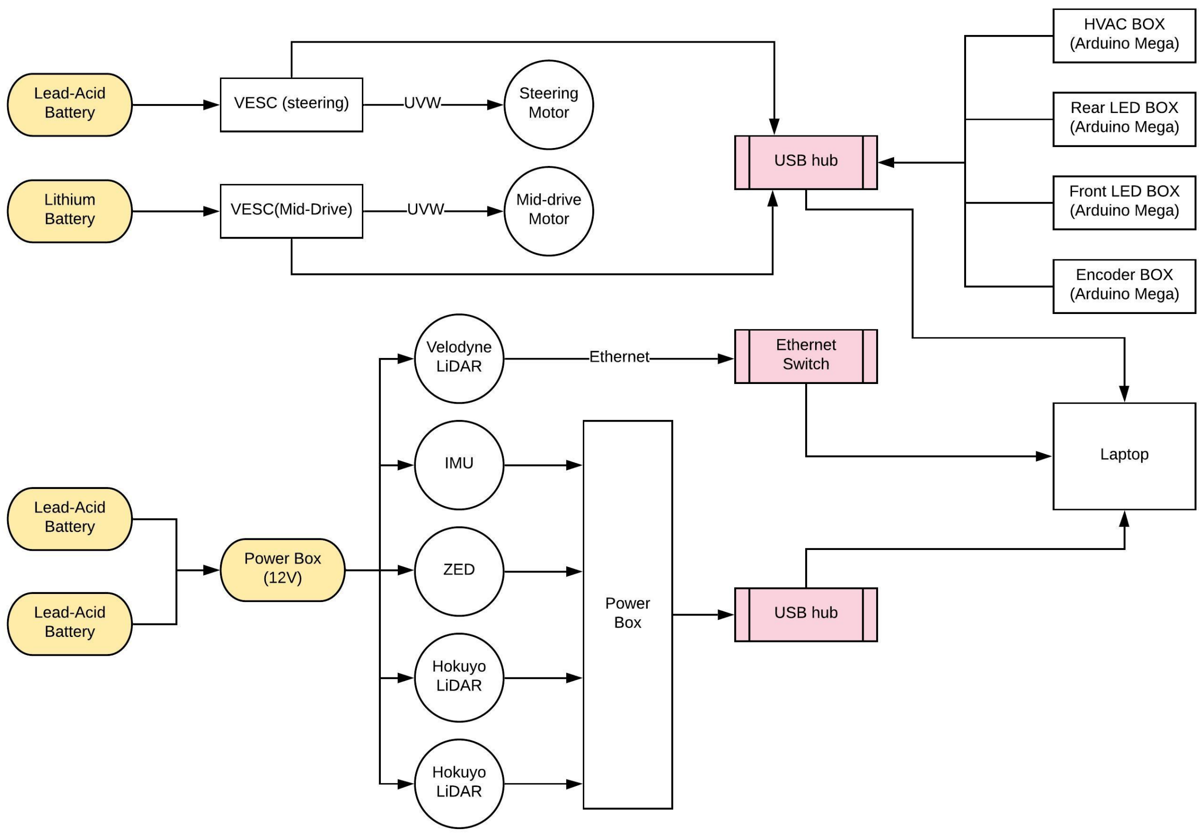


Figure 3-5: IDK Lite: System layout.

However, this version of prototype could only support very basic functions that allow PEV to move and avoid obstacles; not many interactions could be developed through this version of IDK due to the limited sensors that we could access. Moreover, the system itself is physically clumsy, since it requires both a lithium battery as well as a lead-acid battery to power the entire system.

3.3.2 IDK Standard

Building upon the IDK Lite, we added more human-machine interface-related sensors in the 2nd version of IDK, IDK Standard. Sight and hearing are the two common senses that humans use to interact with mobility platforms on the streets. We built a camera vision system and embedded the system in a Jetson TX2 (computing device) that communicates with the laptop. As the system became computationally heavy, we intended to separate the computing device into two units: One master laptop controls the navigation and operation part of PEV, while the TX2 serves as a slave device that listens to the Master device. This version of IDK enables PEV to read the basic facial expression of a pedestrian by the embedded vision system. It also provides multiple servo motors that allow designers to design mechanical interactions. For example, in this version of IDK, we design a pair of mechanical eyes that track the postures of pedestrians and follow them to start potential conversations.

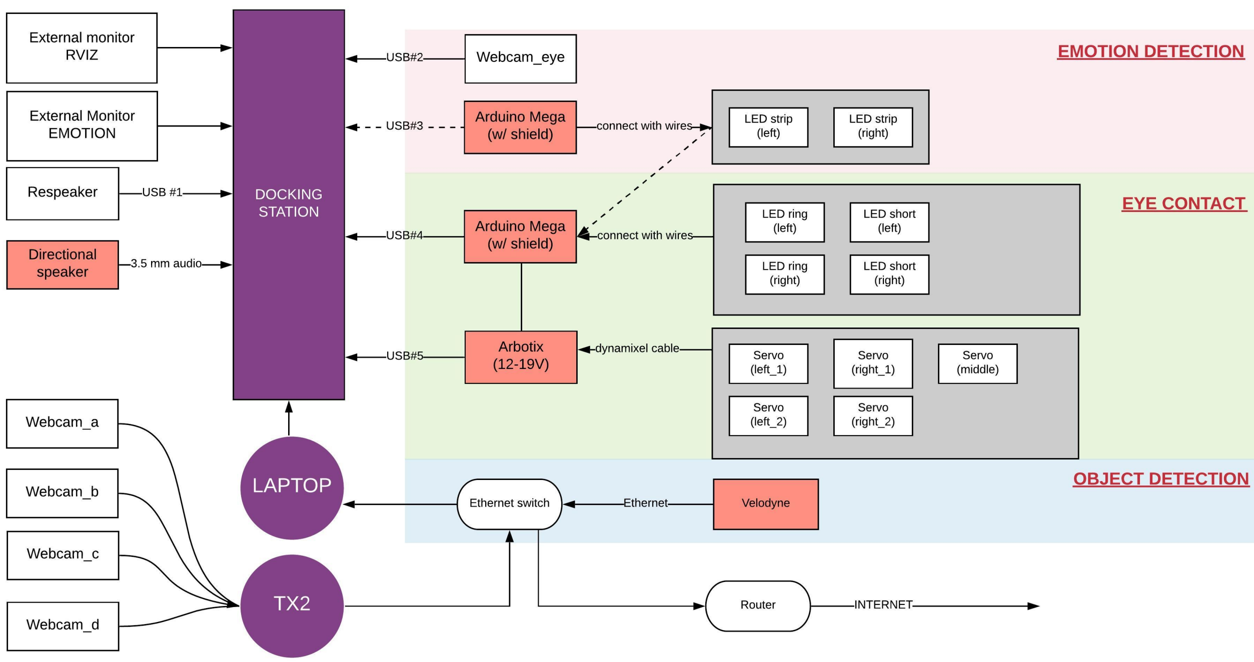


Figure 3-6: IDK Standard: system layout.

Compared to the IDK Lite, IDK Standard has a clearer system structure that allows developers to access the desired sensors. While designing the IDK Standard, we divided the system into two major layers: the control and HMI layer. The control layer is equipped with essential sensors and placed at the lower part of the vehicle. The HMI layer contains the sensors that we need to prototype the human-machine interactions on PEV. To maximize the use of space, the HMI layer was designed to fit the front part of the PEV and could be easily mounted inside the vehicle (Figure 3-7).

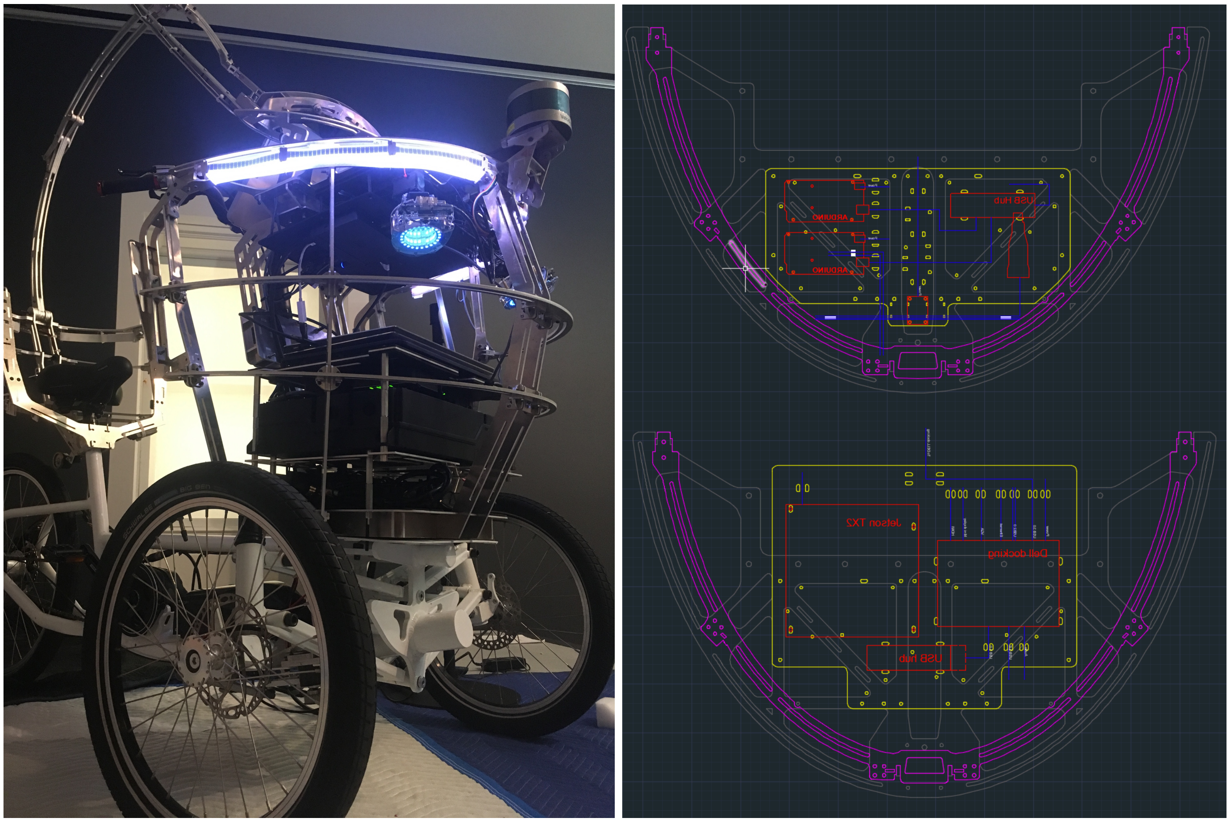


Figure 3-7:System designed to be mounted in the front part of PEV.

Starting from 2D design allows us to optimize the space we use and enable the system to be well-organized and compact.

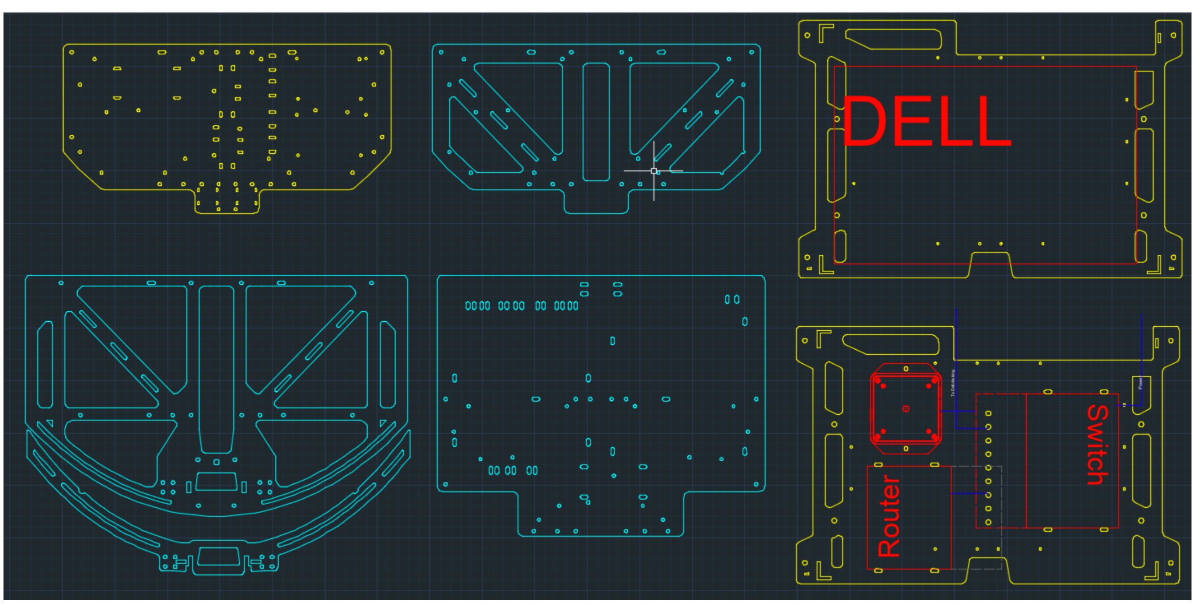


Figure 3-8: IDK Standard system layout.

IDK Standard was built for the *Reimaging Future Mobility* Exhibition at the Cooper Hewitt Smithsonian Design Museum in New York City. We built multiple HMI projects with this version of IDK system and showcased the PEV for three months (2018.12 – 2019.3).

Due to the constraints of the museum, we could only use domestic power during the exhibition. We redesigned the power management system for PEV by removing the power module from the first version of IDK and changing it to AC supply.

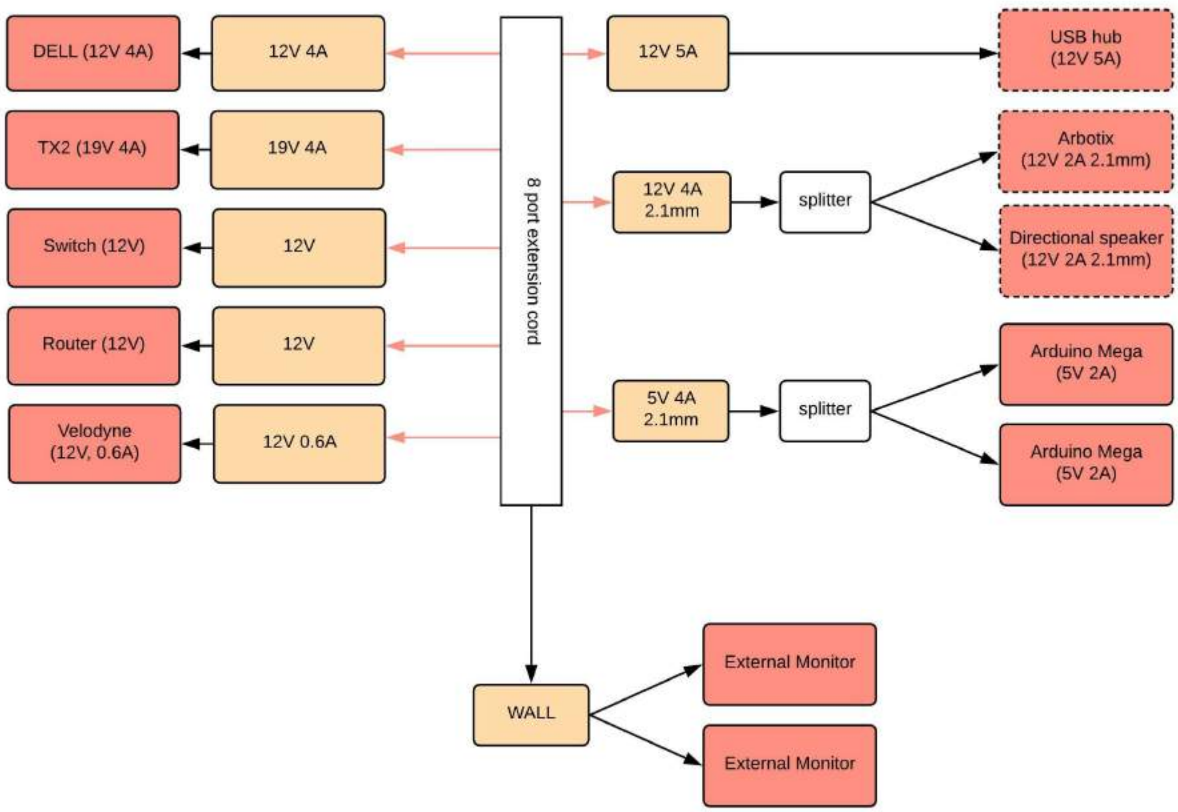


Figure 3-9: IDK power management diagram using domestic power.

3.3.3 IDK Plus

IDK Plus (IDK+) is the most recent edition of IDK. We installed and tested this system on the latest version of PEV. This version is equipped with a more comprehensive hardware system (perception, camera vision, air conditioning, directional speaker, GPS, IMU, etc.), which allows designers to build interactions in different forms of output, including sight, hearing, and touch. Unlike with previous versions of IDK, we decided to move the system from the front to the rear part of the PEV (Figure 3-10). Aside from aesthetic purposes, changing the location of the IDK system enables developers to quickly access the system and make changes immediately.

Figure 3-10: IDK+ installed on the latest PEV (design).

Relative to previous versions, IDK+ is more compact and powerful and grants more accessibility for designers. This version also provides two sets of Arduino Camp (with 6 Arduino Megas embedded) that are pre-connected to ROS (Robot Operating System) and serve as a medium to create V2P (Vehicle to Pedestrian) as well as V2R (Vehicle to Rider) interactions. While designing interactions with the Arduino unit, all developers need to do is simply connect the desired sensors by applying new shields and programming the Arduino. We also add two HVAC units (Heating, ventilation, air conditioning) in the IDK+ system for developers to build V2R interactions with air as an output.

IDK+ also provides a clearer mechanical structure relative to previous versions; we designed the system as different portable modules that could be easily installed in the PEV. The systems can be divided into four different layers: the perception and control layer, V2P layer, V2R layer, and power management layer. The perception layer contains two LiDAR units and a camera vision system that allow PEV to perceive the world. The control layer utilizes a mid-drive motor, steering motor, and servo motor to move the vehicle. The V2P layer functions with hardware such as LEDs, directional speaker, and a projector that allow the vehicle to interact with people external to the vehicle. The V2R layer provides sensors for designers to design interactions between the vehicle and the rider in the PEV.

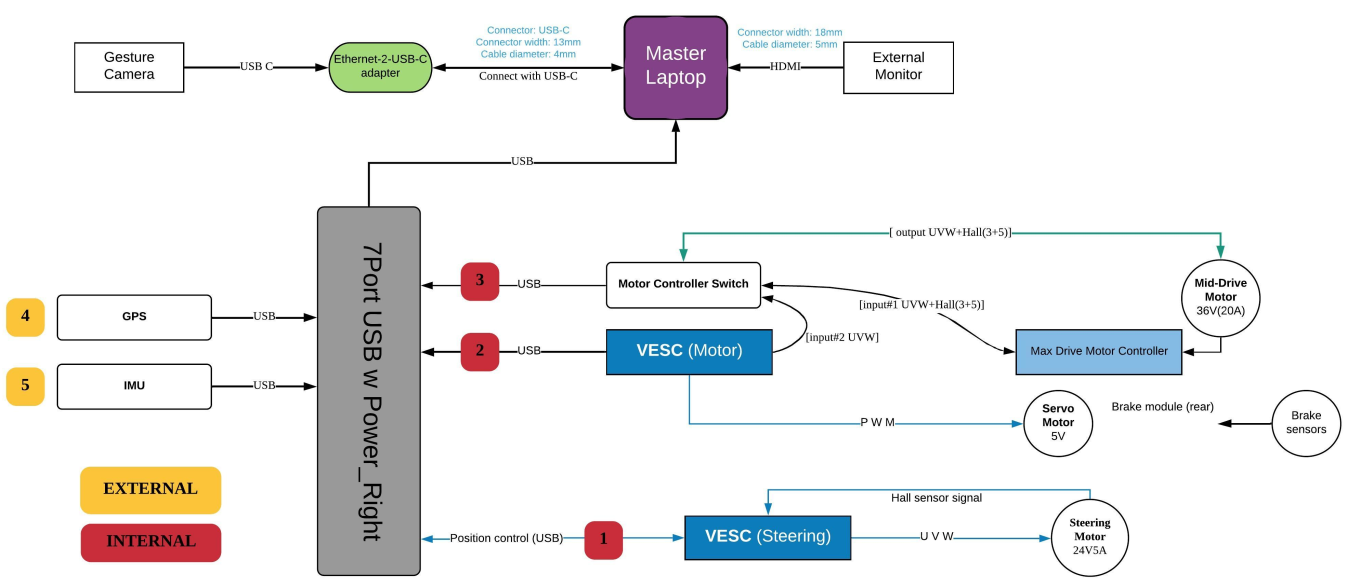


Figure 3-11: IDK+ perception and control layer.

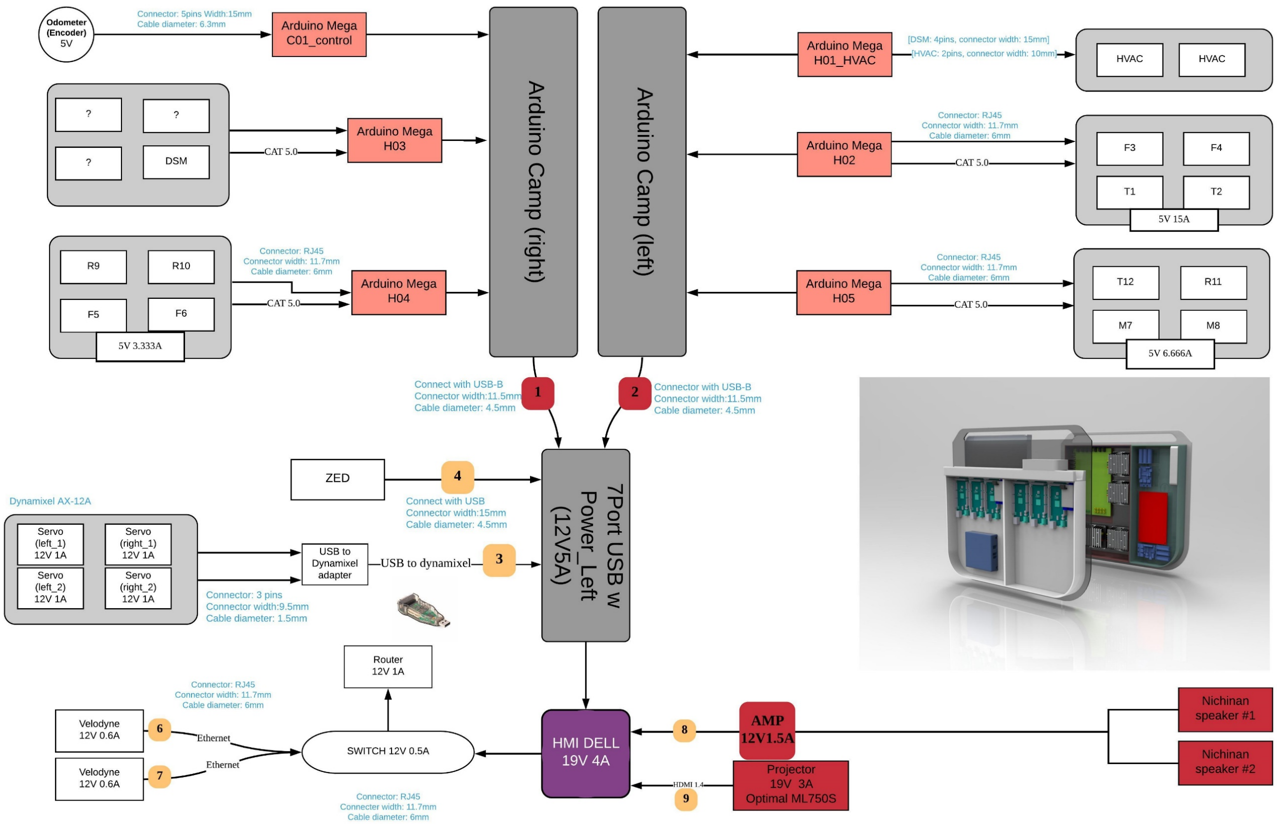


Figure 3-12: IDK+ V2P and V2R layer.

Lastly, we designed a modular battery management system (BMS) for IDK+. The BMS is equipped with a wide range of power supply that allows designers to use it without hazard. The system uses 36V power input and provides six sets of 5V, 12 sets of 12V, four sets of 19V, four sets of 24V, and an additional 36V power output. It could be troublesome for designers without prior electrical engineering knowledge but who wish to utilize different sensors to design interactions for machines. The BMS aims at providing a safe, intuitive, and centralized power management system for interaction designers, bridging the gap between design and electrical engineering while facilitating the design process seamlessly. All designers need to do is to plug in the compatible power supply without worrying about damaging the system. Figure 3-13 illustrates the layout of the BMS.

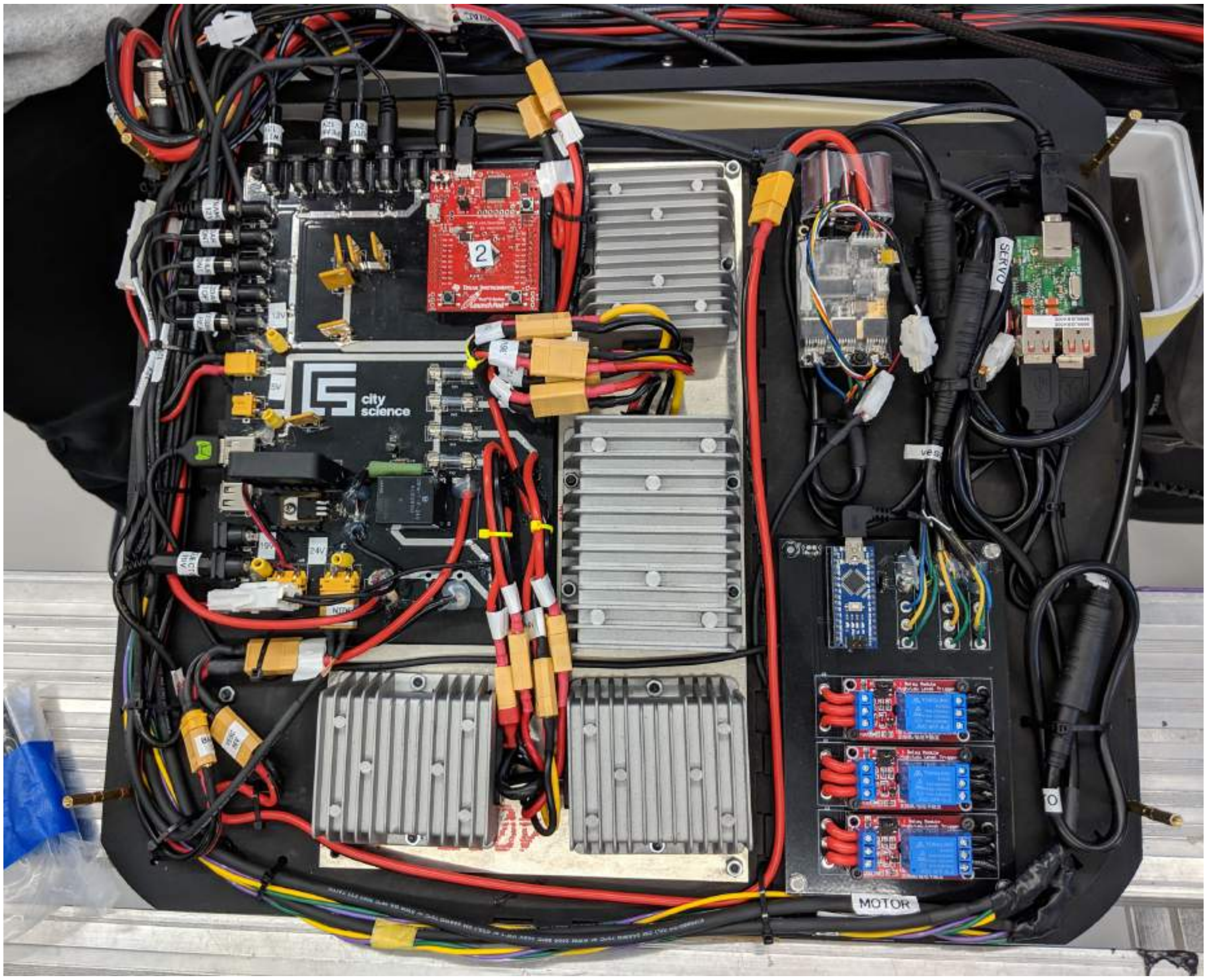


Figure 3-13: The battery management system in IDK+.

3.4 PEV and IDK+ integration

After building the IDK+ module, we installed the system in the latest version of PEV and started building human-machine interfaces with it. Besides providing more hardware sensors for designers to design interactions, the design goal of IDK+ also aims to provide developers and designers more access to the system. That is why we place the system at the rear part of the PEV, allowing developers to utilize the system in a plug-and-play manner. Since the IDK system is tailored to fit the PEV, we also must consider the aesthetic value as well as the functionality while designing the system. The previous versions of IDK were embedded in the PEV; therefore, it takes up space that we can use as a storage place in the vehicle. However, the IDK+ was designed as an add-on device that could be attached at the rear part of the PEV. Not only does this design alteration free up more space in the vehicle, but it also provides an extra storage layer that allows users to use PEV for delivery purposes.

Figure 3-14: The IDK+ and latest PEV integration.

However, moving the system from the front to rear makes the electrical wiring slightly harder than before, since the batteries are still placed in the front part of the vehicle. We took extra time to calculate the power that each sensor drains and chose the most compatible cables for each unit. Considering that our users, interaction designers, and developers might not necessarily have an electrical engineering background, we need to ensure that our system is robust and safe enough for them to use by allocating the optimal wirings for the vehicle. The diagram illustrates the wirings of integrating the IDK+ with the PEV.

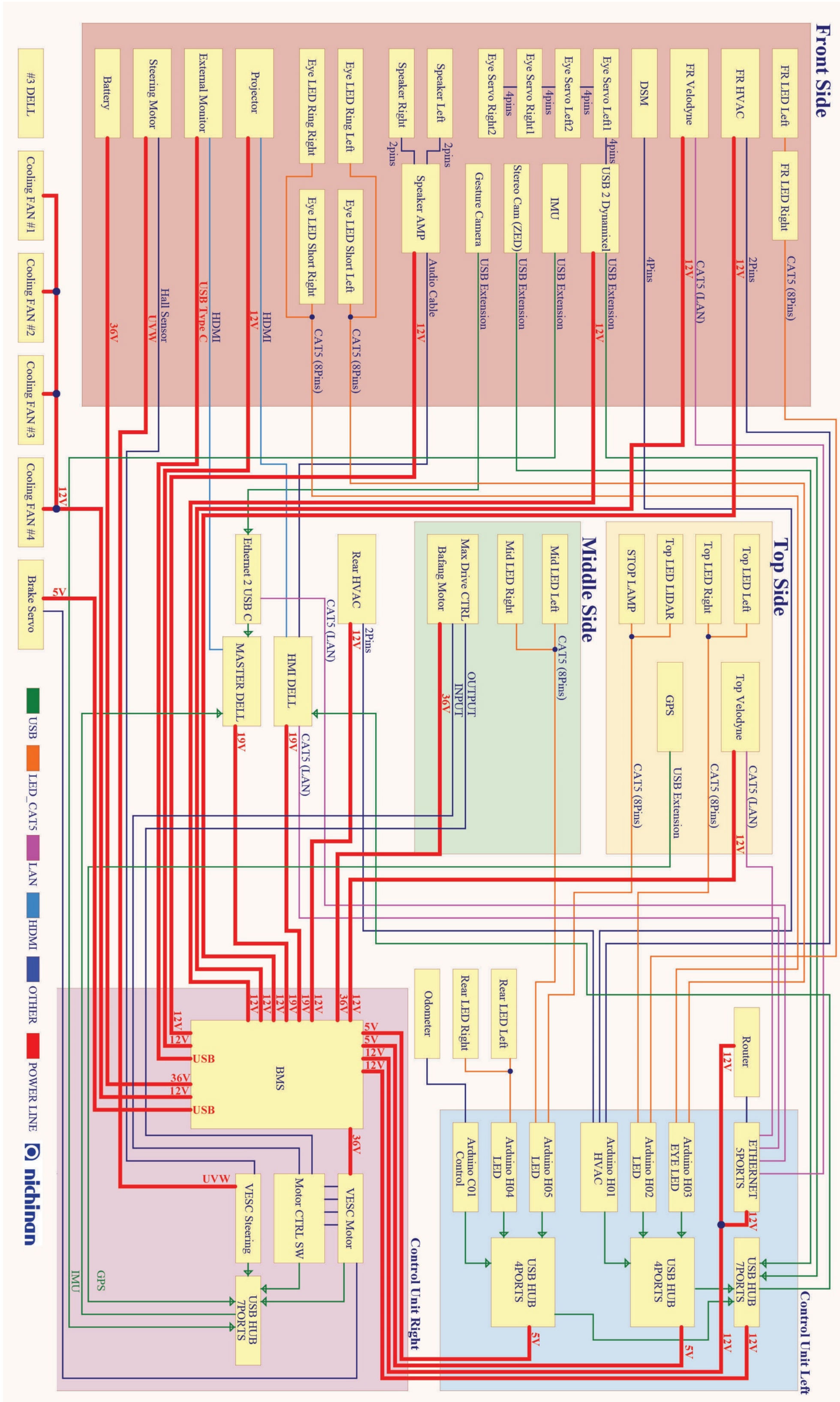


Figure 3-15: The IDK+ wiring diagram.

Figure 3-16: The IDK+ installed in the rear part of the PEV.

In summary, this chapter introduces three different versions of the Interaction Development Kit: IDK Lite, IDK Standard, and IDK+. IDK Lite supports the highly basic functions that allow the PEV to move and avoid obstacles, IDK Standard enables developers to build more human-machine interfaces by providing more hardware options, and IDK+ equips it with the most comprehensive hardware layouts, with multiple modules that allow the designers and developers to design V2P (Vehicle-to-Pedestrian) as well as V2R (Vehicle-to-Rider) interactions. IDK+ also introduces a modular battery management system that is safe and easy for designers to use while designing interactions for machines.

Chapter 4

Human-machine interface design

4.1 Overview of HMI design

This chapter introduces multiple human-machine interface (HMI) suggestions that we designed for PEVs utilizing different versions of IDK. Based on test pilots of PEVs in the city, we have identified multiple scenarios that require HMI intervention. The design goal for all of the HMI examples introduced in this chapter is to suggest potential approaches that could potentially enable riders and pedestrians to interact with PEVs in a more pleasant and natural manner. This chapter also identifies definite constraints and problems that PEVs would encounter in the city and suggests various HMI solutions that could potentially address these problems.

4.2 Vehicle-to-pedestrian (V2P) interaction for PEV

PEVs function primarily on bike lanes in the city, which means that it is essential to design interactions that are sufficiently seamless and easy to understand to allow the vehicles convey their intentions to the pedestrians. To define the problems and necessary interactions, we have initiated research concerning different scenarios that PEVs would encounter while navigating various types of bike lanes in the Cambridge and Boston area (Figure 4-1). Considering the complexities of real-life scenarios, we cannot purely rely on a computer or an algorithm to determine what is important or safe for users. That is why we took the opportunity while we were showcasing the PEV at the Cooper Hewitt Design Museum and interviewed 30 people to identify their concerns regarding lightweight autonomous vehicles, taking advantage of human knowledge and extracting all of the information that pedestrians think is relevant to them. One major concern of the interviewees is the collision problem; 22 out of 30 interviewees expressed concern about the safety issue, since PEVs navigate bike lanes and are even closer to the pedestrians relative to cars. For example, when a pedestrian and a PEV encounter each other at an intersection, how does the PEV signal to the pedestrian that it is safe for them to walk cross the street? How does the pedestrian understand the intention of the PEV?

Figure 4-1: Scenarios of PEV piloting in the urban areas.

After identifying the problem, we then began to design HMIs that enable the PEV to convey its intentions to the people external to the vehicle, rendering the interactions more straight-forward and pleasant.

4.2.1 PEV headlights design

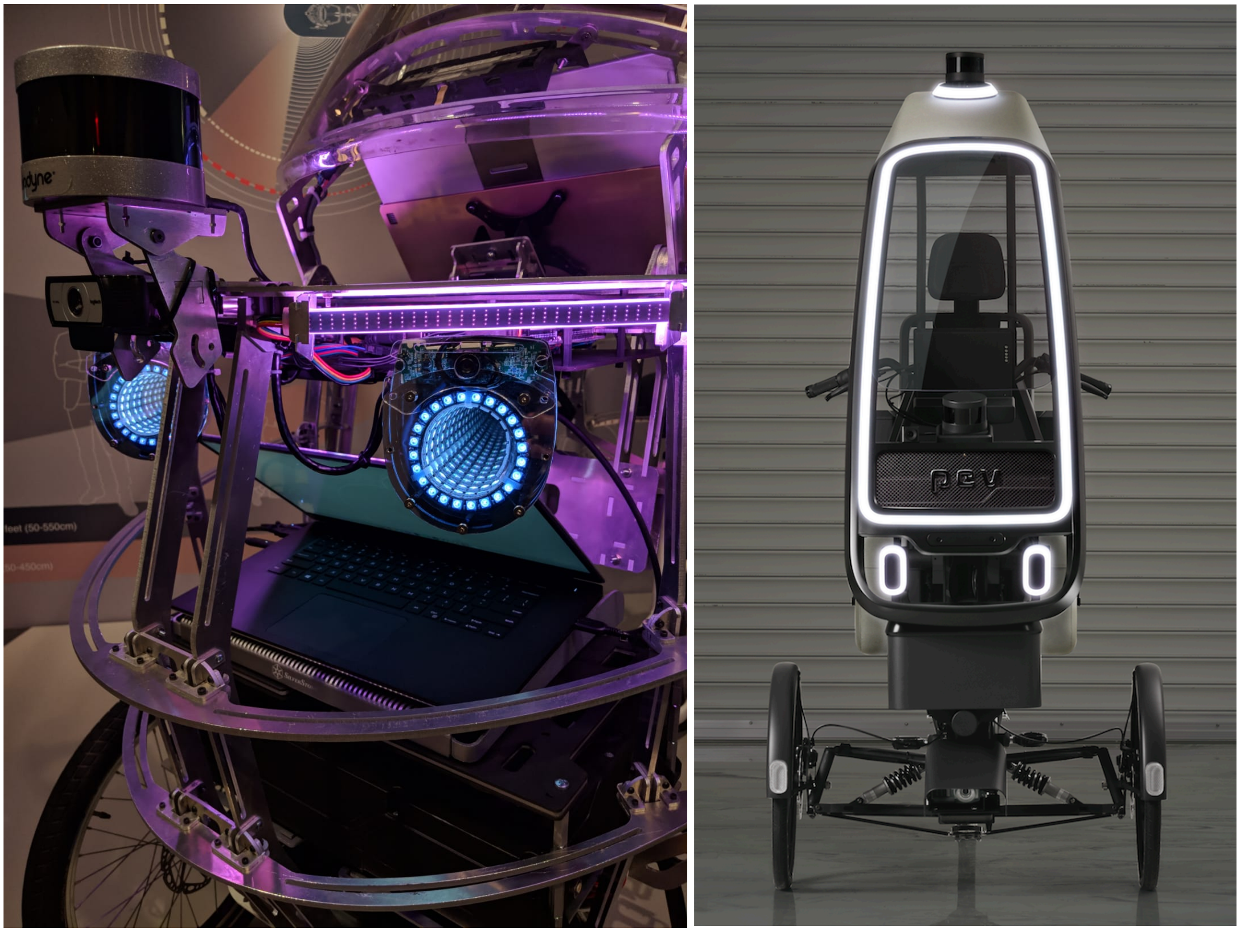


Figure 4-2: Mechanical Eye on PEV built by IDK Standard (left) and IDK+ (right).

We designed a pair of mechanical eyes that serve as PEV headlights and use different light signals and mechanical movements to convey the PEV's intentions to the pedestrians. As Figure 4-2 illustrates, we have used the IDK Standard and IDK+ to build two different versions of the headlights. Both versions of the headlights share some similar functions:

- Eye contact
    - In places frequently accessed by pedestrians and cyclists, the right-of-way is typically dynamic and negotiated through tacit interactions, beginning with individual acknowledgment of the presence of others. Using a webcam and computer vision techniques that are embedded in the IDK system, the PEV uses

eye contact to acknowledge surrounding individuals as a means to establish a basic level of trust and to convey its intention to the pedestrians.

- Facial expression and pose detection
  - The IDK allows developers to use human facial expression as an input to design HMIs, possibly providing more features that engage humans and machines in the future. Using a webcam and computer vision, the PEV determines the basic facial expressions of its human collaborators and detects their postures as an input; this can potentially enable future PEVs to interact with people in a natural, sociable, and intuitive manner.

- Object detection
  - Locational awareness of people and objects surrounding the vehicle is critical for the safety and navigation of autonomous robots. The PEV uses LiDAR to maintain a live perspective of its surroundings and to determine its path and prevent collisions.

The first version of mechanical eyes that were built by IDK Standard were showcased at the Cooper Hewitt Smithsonian Design Museum in New York. We received an immense amount of positive feedback regarding utilizing the headlights to communicate with the pedestrians. The visitors expressed that having the headlights as PEV's eyes characterized the PEV and could possibly make the vehicle more approachable. However, aside from creating eye contact with humans, we think that the mechanical eyes should be able to translate more interactions that pedestrians typically have with human drivers. Therefore, we began to work on the second version of PEV headlights using IDK+ and to create more mechanical movements based on how pedestrians generally communicate with drivers on the street.

For example, when we attempt to communicate with drivers on the street, one of the interactions that we might have is making eye contact with the drivers in the vehicle, and the drivers sometimes express their intentions by waving to the pedestrians or by using certain gestures to signal to the pedestrians that it is safe for them to pass by. Some drivers tend to blink the car's headlights quickly as a cue to inform pedestrians that they are going to allow the pedestrians to cross the streets. Taking these interactions as references, we designed a new version of headlights for the PEV. By default, the PEV always prioritizes pedestrians and stops to let them cross the street. While detecting pedestrians, the mechanical eyes on the PEV point in the direction of pedestrians to make eye contact with them first; they start moving the eyes to signal to pedestrians to cross the street, as if they were a driver waving to them. The mechanical eyes also flash a green light quickly, along with a movement to signal that it is safe for pedestrians.

The new headlights were developed by IDK+ and applied on the latest PEV. With the built-in directional speaker in IDK+, the developers could easily use the speakers as an output to design more interactions. Our approach entails embedding the speakers in the headlights and using the headlights to point to the pedestrians and convey PEV's intention with them.

Figure 4-3: Mechanical Eye with embedded speakers built by IDK+

Moreover, since the IDK+ also functions as a vision system and pose detection, we utilize human posture as an input to stop the vehicle. The pedestrian could simply wave to the PEV as though waving to a taxi, and the PEV would stop immediately in front of the pedestrian if it is available.

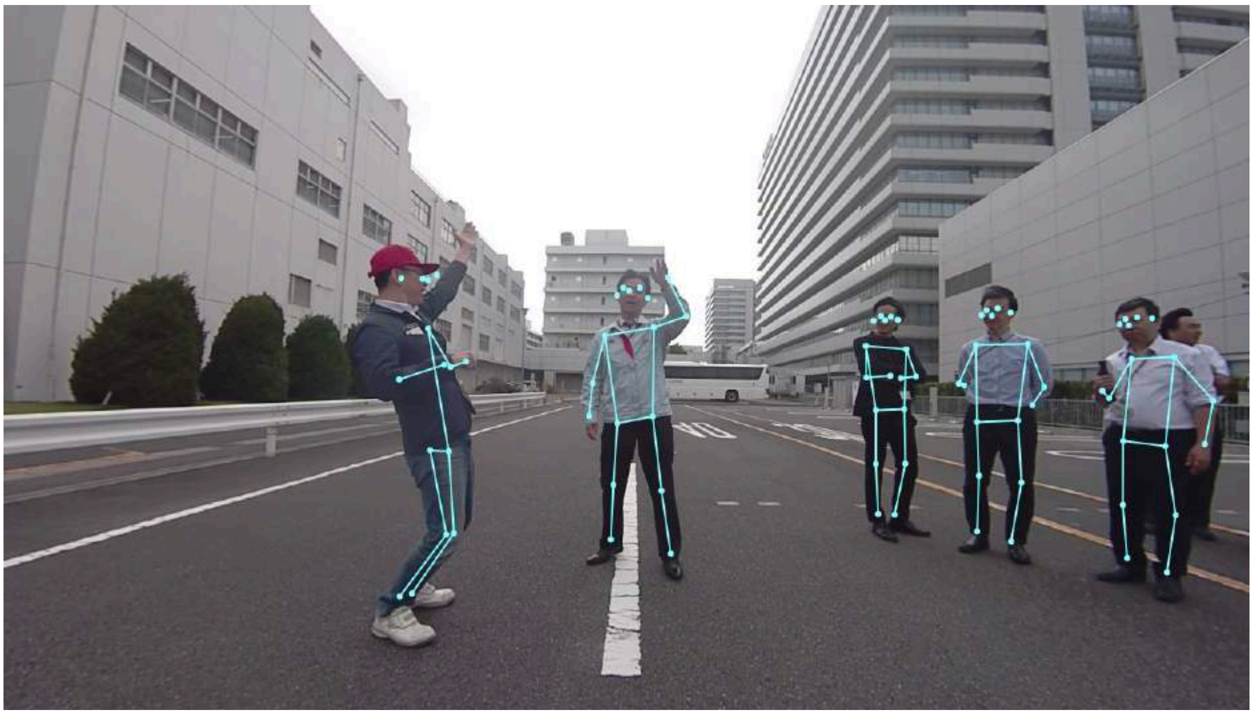


Figure 4-4: Pose detection utilizing IDK+

Figure 4-5: Pedestrians wave to stop the available PEV

4.2.2 Light signals design for PEVs

Figure 4-6: Lighting design built by IDK Lite (left) and IDK+ (right)

One of the features we provide in the IDK system is the visual signals design. This could be used if the developers seek to design a visual cue that allows pedestrian to observe from a distance. Utilizing IDK Lite allows designers to quickly prototype the color of LED through the embedded Arduino modules. The first generation of PEV, which functions with the IDK Lite system, provides two LED strips as outputs for designers to build interactions.

However, after running testing on the street and observing the performance of the LEDs, we determining out that there were not many visual interactions that could be made due to the limited LED outputs, and it was sometimes difficult to see the lightings from the side of the PEV, since the LEDs were only placed in the front and rear part of the vehicle. Therefore, we added more LEDs while designing the latest version of PEV and provided more modules in the embedded IDK+ system to allow designers and developers to color-code different parts of the lighting system.

The latest version of PEV functions with 10 LED strips in total and could be designed to handle different scenarios. The lights also represent different modes of the PEV. The PEV flashes breathing white lights when it is on default mode or operated by a human, and the lights turn to blue if it is in the autonomous mode. If the PEV detects pedestrians who want to cross the street, it stops and flashes a green light to signal that it is safe for the pedestrians to pass by. While the PEV is navigating on the streets and detects obstacles, the LED strip on top of the vehicle flashes a red light to signal that the PEV has detected them and will hold or re-route to avoid the obstacles. There are two sets of LED strips built in the windshield, chassis, and the rear part of the vehicle that could be used as direction indicators. These LED strips flash when the PEV is about to alter its direction, allowing people to see the signs from any angle.

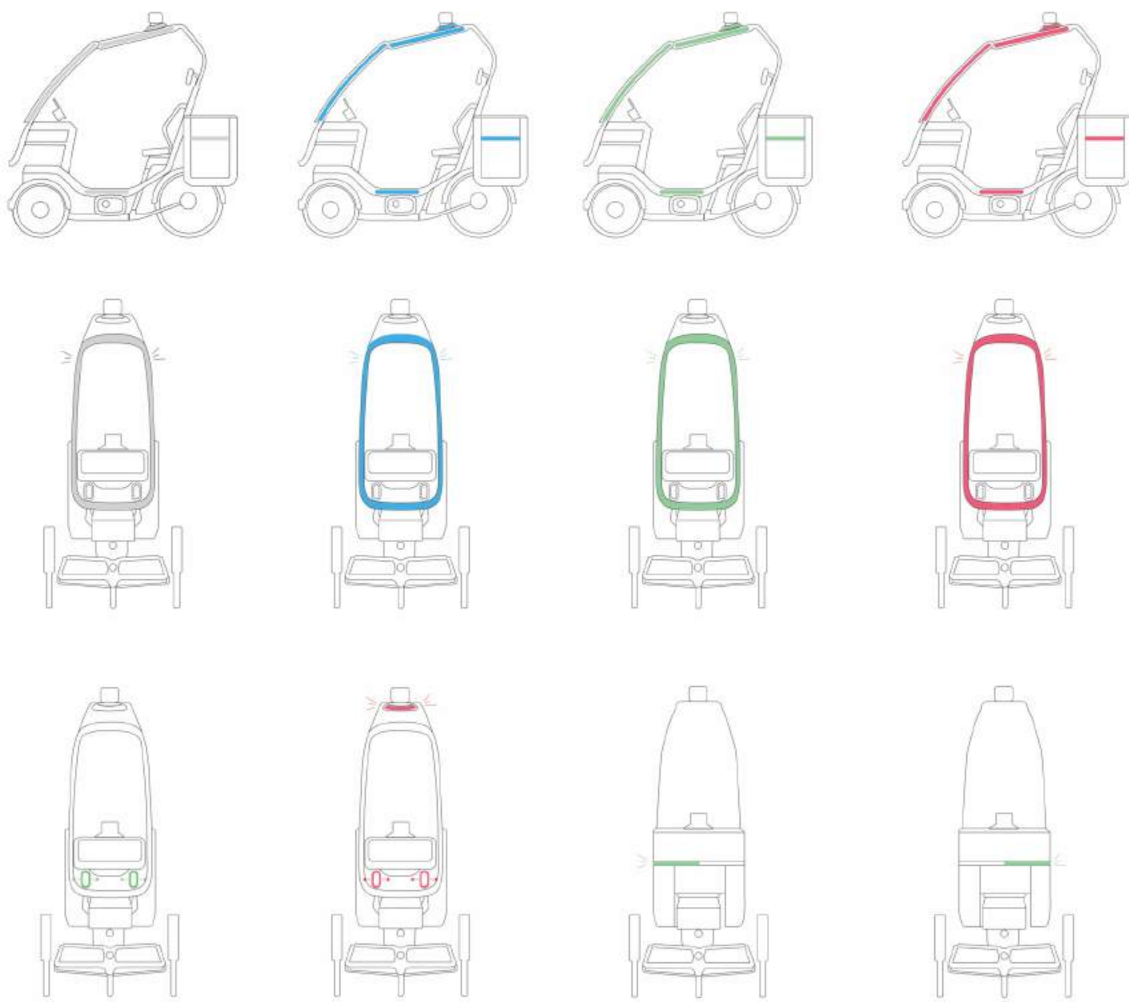


Figure 4-7: PEV light signals

4.2.3 Projection interaction

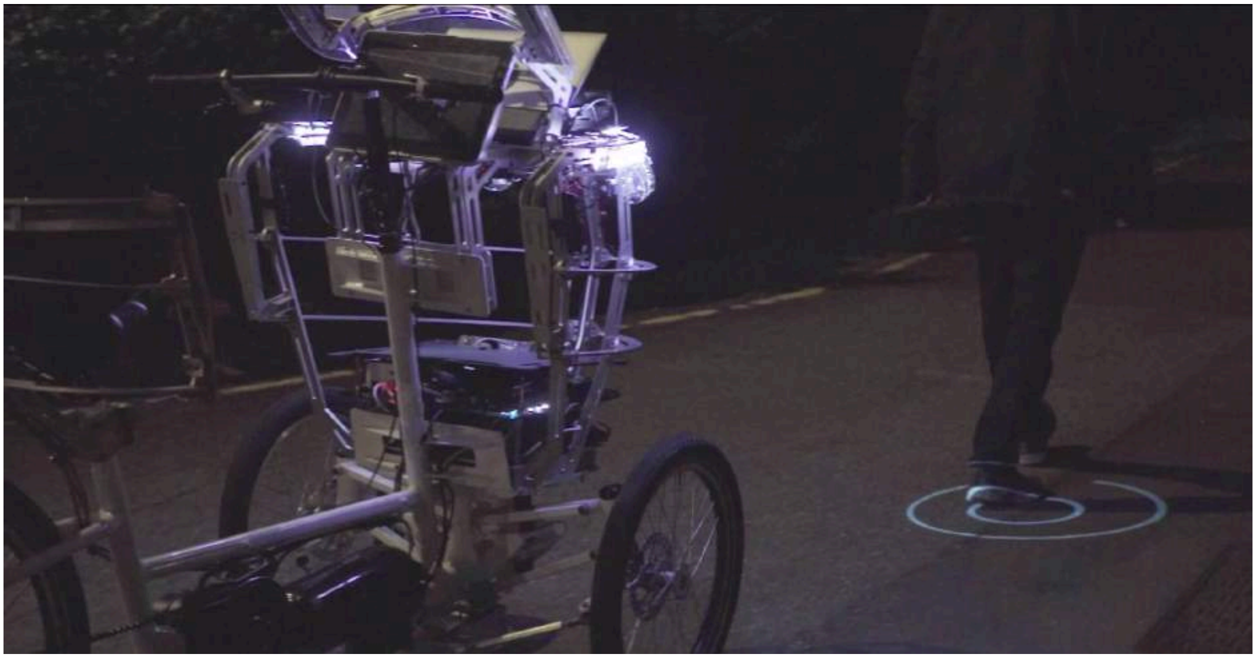


Figure 4-8: PEV utilizing projection to interact with a pedestrian.

During the night, when visibility is relatively lower than the day, designing interactions tailored to night time to enhance pedestrians' sense of security might be an effective approach for designers. For example, we have utilized IDK Standard, which is equipped with an embedded projector and a LiDAR and builds interactions with the system. When a PEV detects a pedestrian, it projects a rippling circle on the floor and matches the location of the pedestrian. We attempt to use projection as a signal to the pedestrian indicating that the PEV is aware of their existence, potentially building trust between the pedestrian and the machine.

While designing this interaction, we have utilized the data, Costmap [29], from LiDAR as an input. In general, Costmap is a fundamental concept in autonomous robotics. It represents the difficulty of traversing different areas of the map. The data is used to guide a route-planning algorithm to identify efficient and safe routes across the ground. While the data represents how a robot perceives the world, it is still relatively abstract to the pedestrians. For example, when LiDAR detects obstacles, it generates a 2D map in its software (Figure 4-9), which is how a robot understands the existence of the obstacles. We extract the center point of each obstacle that the LiDAR detects and apply a new layer of an image on top of it. We can then project these images onto the floor and map the images with the obstacles, thereby bringing the robotic world into real life through data visualization.

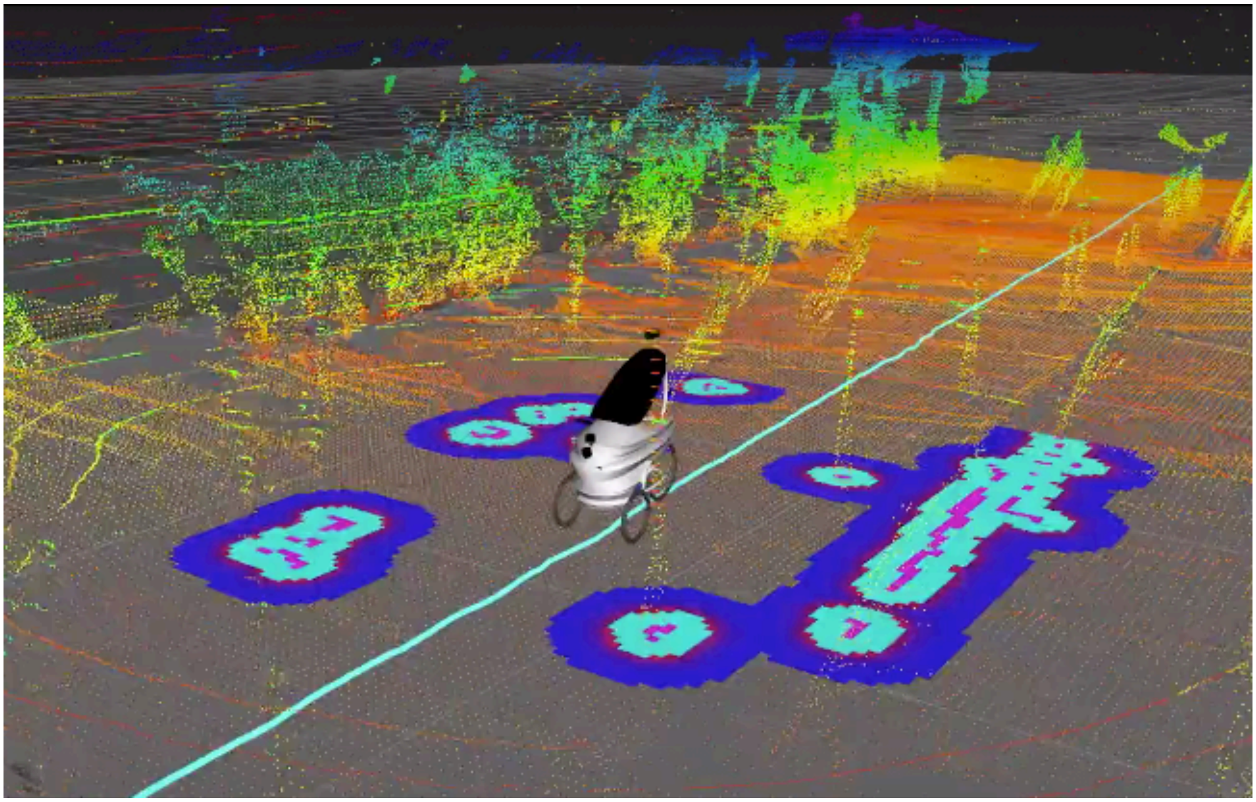


Figure 4-9: LiDAR detects obstacles

Furthermore, we can also visualize the intention of a robot through different projection patterns. One approach that we have attempted involves visualizing the direction of the PEV by projecting different arrows on the ground (Figure 4-10). This could potentially be used as a new means for pedestrian to communicate with the PEV. For example, if the PEV detects a pedestrian at an intersection, it projects an arrow onto the ground signaling that it is safe for the pedestrian to cross the street. Aside from using the data from LiDAR, it is also possible for developers to utilize the computer vision system in IDK Standard and use human posture as an input to design more projection interactions (Figure 4-11).

Figure 4-10: Projection showing the intention of the PEV.

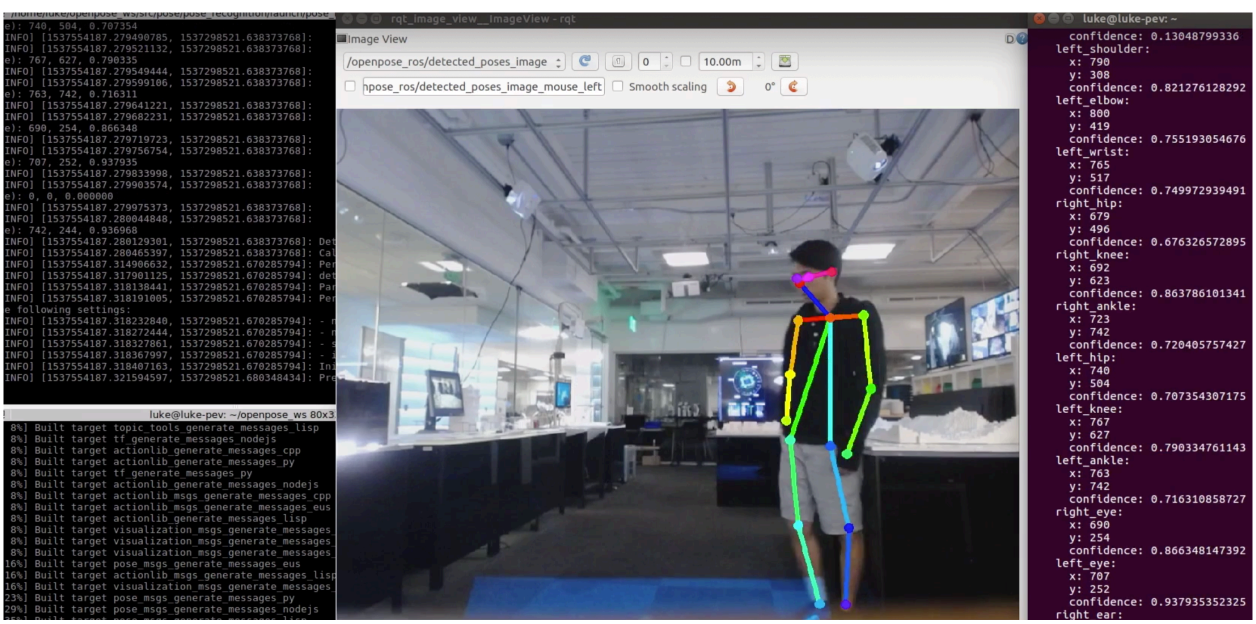


Figure 4-11: Using human posture as an input to design projection interactions.

4.3 Vehicle-to-Rider (V2R) interaction for PEV

Aside from V2P interactions, we have also designed various vehicle-to-rider interactions that might be able to improve the overall user experience between the riders and the PEV. This section introduces a mobile application that riders can use to summit a PEV, a driver state monitor that detects a rider's facial features and could potentially be used as an input to create interactions and different modes that the PEV offers to the riders.

4.3.1 PEV mobile application

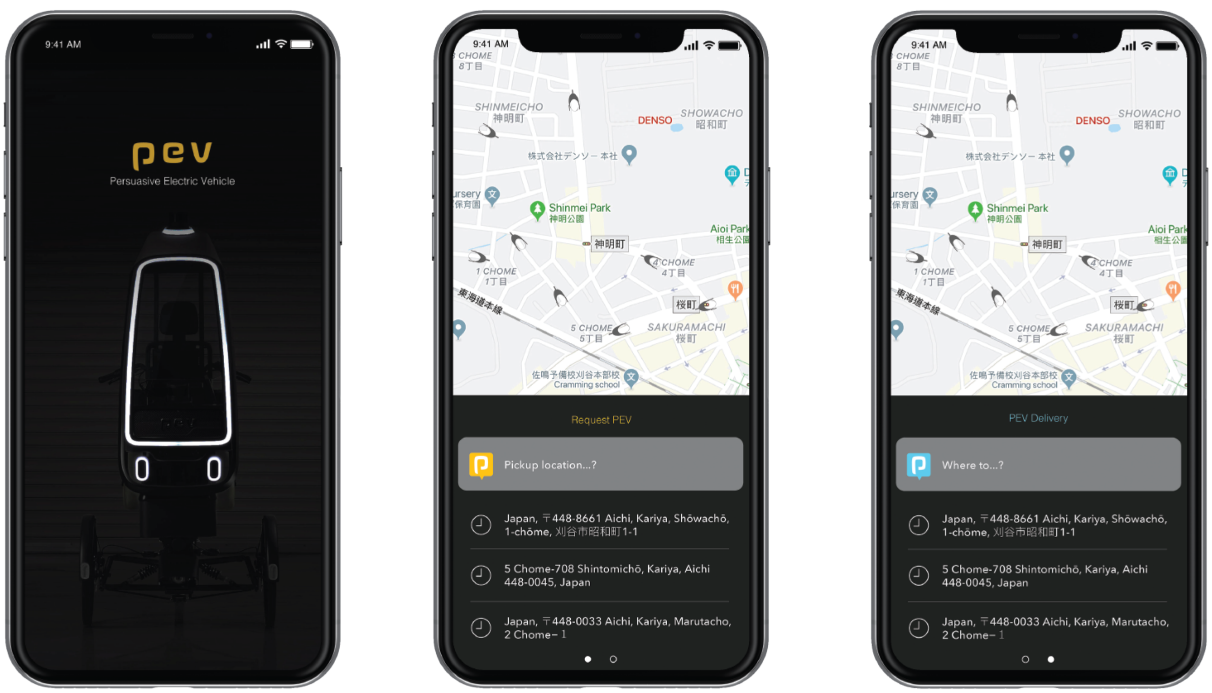


Figure 4-12: PEV mobile application.

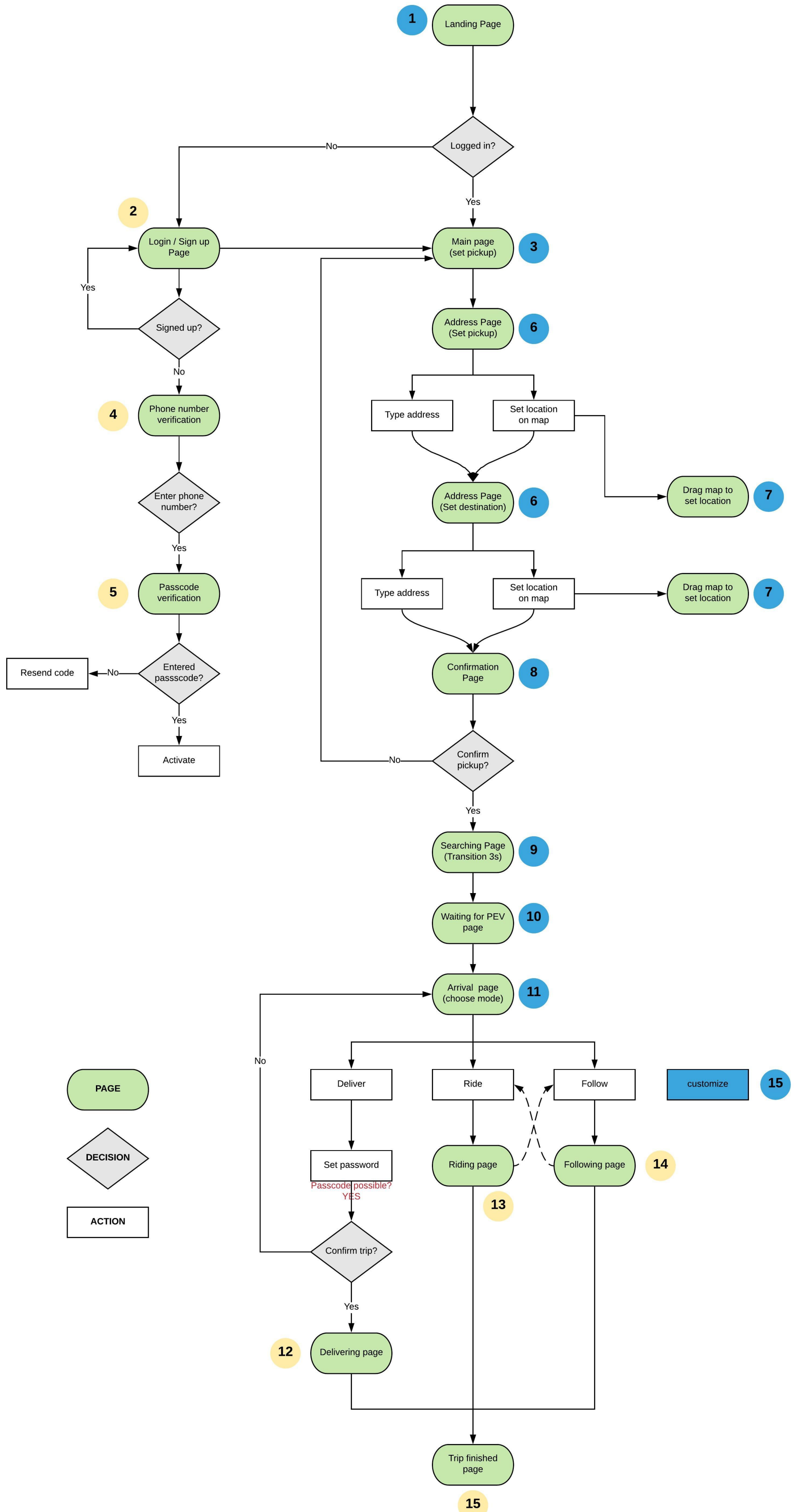
In terms of V2R interaction, the mobile application is essential for the riders to interact with their PEVs. The PEV has two main use cases: A rider can request a PEV and operate the vehicle independently, or a rider can request a PEV and use it for logistic purposes (Figure 4-12). While designing the application, we must account for both of the experiences and design interfaces that match these two scenarios.

- **User experience - Request a PEV:**

After a rider logs in to the PEV mobile application, they will be directed to the main page of the application. The main page displays the available PEVs nearby and asks the rider for their pick-up location. The rider can choose to type in the address to set the pick-up location or click on the small location icon next to the address field and set their location by moving the pins on the map. We have designed this step as a duo-verification for the riders, since the GPS in phones might not be accurate at all times.

After setting up the pick-up location, the rider must set up the destination as well. Even for the riders who have an open-goal destination (uncertain where the destination will be), we still ask the rider to enter an estimated destination, since it is necessary to ensure that the rider summons a PEV that has sufficient power remaining to complete the trip. After setting up the destination, the rider can click on the "confirm pick-up" button, and the system will assign a compatible PEV to the rider. While the rider is waiting for their PEV, the mobile application displays the information for an upcoming PEV. The rider will see a designated color on their screen. When the PEV arrives, having a designated color allows riders to quickly identify their vehicle.

However, we know that riders are unpredictable. It is possible that the rider may change their mind upon the arrival of the PEV. This is why we decide to allow the rider to choose their trip purpose only when the PEV arrives. When the PEV arrives, the rider can choose between three modes: Riding mode, Delivery mode, and Following mode. Riding mode allows riders to operate the PEV themselves, and delivery mode requires riders to set up a passcode to unlock the compartment and uses the PEV to deliver packages autonomously.



1
Landing Page
Logged in?
No
Yes
2
Login / Sign up Page
3
Main page (set pickup)
Yes
Signed up?
No
6
Address Page (Set pickup)
4
Phone number verification
Type address
Set location on map
Enter phone number?
Yes
Drag map to set location
7
Address Page (Set destination)
6
5
Passcode verification
Type address
Set location on map
Drag map to set location
7
Resend code
No
Entered passscode?
Yes
Confirmation Page
8
Activate
No
Confirm pickup?
Yes
Searching Page (Transition 3s)
9
Waiting for PEV page
10
Arrival page (choose mode)
11
No
PAGE
Deliver
Ride
Follow
customize
15
DECISION
Set password
Riding page
Following page
14
Passcode possible? YES
13
ACTION
Confirm trip?
Yes
12
Delivering page
Trip finished page
15

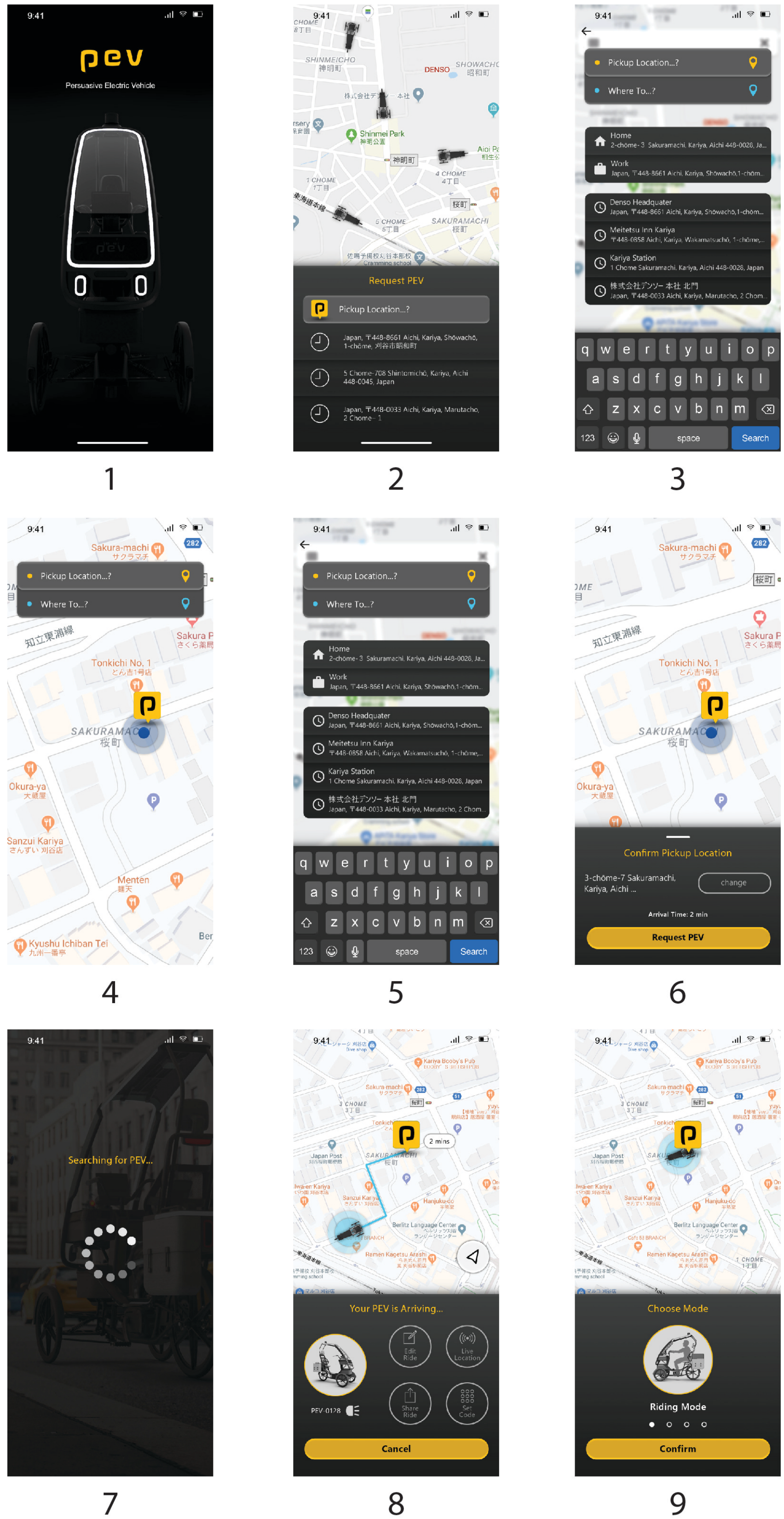


Figure 4-13: PEV mobile application design.

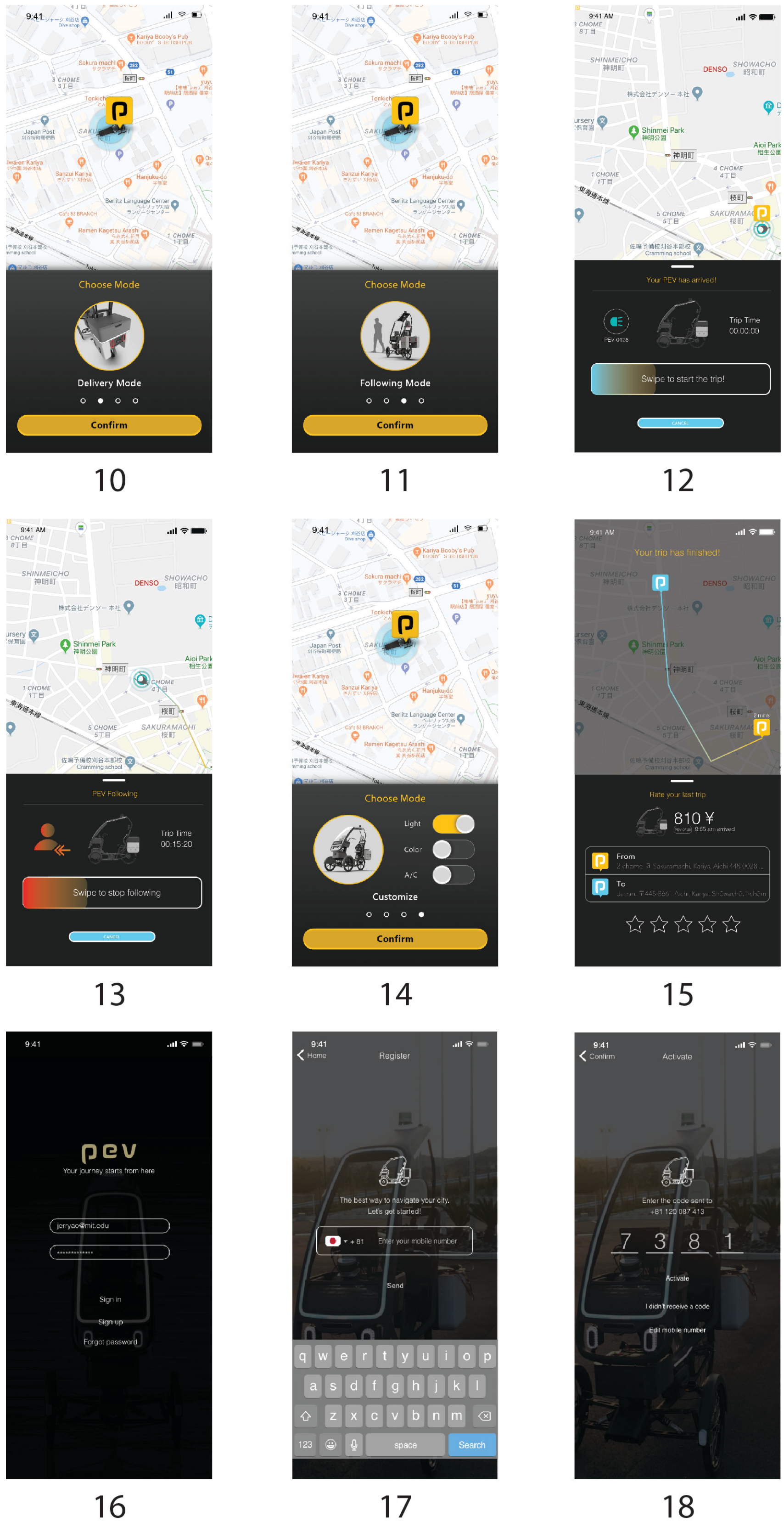


Figure 4-14: PEV mobile application design.

4.3.2 PEV following mode

Figure 4-15: PEV following mode: PEV follows a rider using IDK Standard system.

In IDK Standard, we incorporated ultra-wideband sensors, a radio technology that can use a very low-energy level for short-range, high-bandwidth communications across a large portion of the radio spectrum[30]. We have utilized this sensor to design a function that enables the PEV to follow a rider. Riders can simply attach an ultra-wideband sensor on their clothing and activate the following mode via PEV mobile application. After changing to the following mode, the PEV will seamlessly follow the person who wears the sensor. We have designed this function to allow riders to use the PEV to carry groceries or packages for them.

We have tested this function on the PEV and determined that people sometimes worry that the PEV could not catch up to a human's speed and keep turning their head to check whether the PEV is still following them. Therefore, we set a standard distance between the human and the PEV to ensure that the PEV remains within the vicinity of the rider. When the rider stops walking, the

PEV will remain one meter away from the rider. If the rider walks too fast (distance between human and the PEV > three meters) so that the vehicle cannot catch up, then the vehicle emits a beeping sound to remind the rider that they are too distant. Although this function was tested on PEVs, it could also be scaled and transformed to fit in different scenarios as well. One of the developers, Y. Chiang, utilized this function to design an autonomous golf cart that follows the player on the golf course [31].

4.3.3 Rider state monitor

Figure 4-16: A rider testing rider state monitor (RSM) in the PEV

The rider state monitor (RSM) is a module provided by our sponsor company, Denso Corporation; it is essentially a camera embedded with the face detection technique. We incorporated the RSM into the latest IDK+ system, allowing developers to use a human's facial features as an input to design interactions for lightweight autonomous vehicles. In the case of PEVs, we have utilized the RSM module to detect different angles of the rider's head. There are three different motions of humans that we use as input data: Yaw, Pitch, and Roll. We map the rider's head motion to the headlights of PEV; therefore, when a driver rides in a PEV and looks around to view the city, the PEV's headlights match the angle and position of the driver's head, as though it was an extended version of the driver.

The RSM module also detects subtle features on the human's face. For example, the module could also detect the distance between the rider's eyelids. We can also use this as an input; when the RSM detects that the rider is yawning or falling asleep, we could activate the air conditioning unit and gently generate wind toward their face and wake them up. This might not be the most ideal solution to regain a rider's attention, and it certainly requires more research. However, utilizing these tools in the IDK+ system can allow designers to quickly prototype an interactive experience, thereby increasing the odds of identifying the most promising human-machine interfaces.

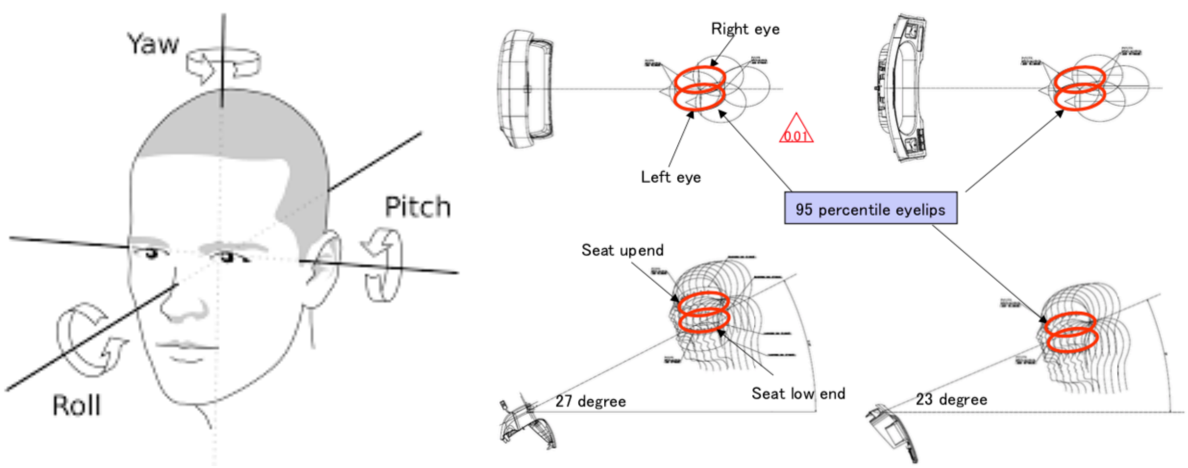


Figure 4-17: RSM detects human's face features

4.3.4 Thermal seat design

Figure 4-18: Thermal seat prototype

In the IDK+ system, we added two HVAC units (heating, ventilation, air conditioning) that allow designers to use air as an output to design interactions. For example, we designed a thermal seat for the PEV. We connected the cushion layer of the seat to the HVAC unit at the rear part of the PEV. The rider can use the PEV mobile application to turn on the air conditioner; the seat will then release cool air to cool down the seat as well as the rider, thereby enhancing the comfort level and riding experience for the rider. For future development, we are planning to embed vibration motors into the cushion and combine it with the RSM module to build more interactions.

If the RSM module detects that the rider is not paying attention to the road for a period of time that might potentially cause accidents, we can blow air from the HVAC unit and activate the vibration motors under the seat to regain the rider's attention. For future seat design, we can also replace the rigid frame with an intricate structure, detect users' body temperature, and generate proper airflow from the biotic pipes inside the seat cushion, rendering the seat more ergonomic.

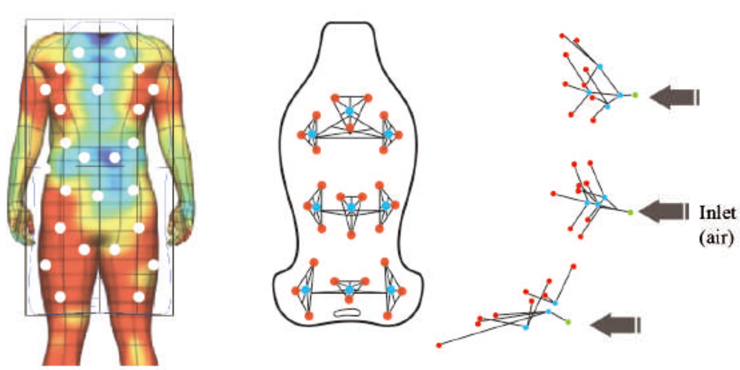


Figure 4-19: Thermal seat design and how to activate air conditioner in the PEV

Chapter 5

User Study

5.1 Overview of user study

The user study primarily focuses on two realms:

- The user experience of human-machine interactions with PEVs:
  - As we hope to deploy the PEV in the urban area someday, having feedback from industry experts is truly helpful to improve our design. Therefore, we invited 10 executives from various departments (R&D, design, engineering, and vehicle dynamics) of Denso Corporation, one of the largest automobile components manufacturing companies in the world, to test the V2P and V2R interactions that we designed for the PEVs. After experiencing all of the interactions, we asked the participants to complete a post-study survey through a web platform, providing their feedback on these interactions and indicating how we should improve these interactions to deploy PEVs in the real world and interact with customers (riders).
- The usability and accessibility of IDK systems:
  - We conducted a group discussion and interviews with six people, including two software engineers, two electronics engineers, one mechanical engineer, and one interaction designer, who have been involved in the development of PEV during the past three years. We explained different versions of the IDK systems (IDK Lite, IDK Standard, IDK+) in the discussion process and shared how the IDK system will facilitate the interaction design process for the PEV. Based on each version of the system, we asked the participants to provide feedback regarding how the system could be improved for future development.

5.2 User experience of HMIs for PEV

Figure 5-1: Testing field of user study session

The user study was held at the headquarters of Denso Corporation in Kariya City, Japan. To perform the user study session in a safe and controllable environment, Denso Co. has provided us with a small testing field (Figure 5-1) that the company uses to test their autonomous vehicle projects. Fifteen participants (13 men and two women) were recruited for the user study session. The age of the participants ranges from 25 to 59 years old. Upon each session, we explained the testing scenarios to the participants, informing the HMIs about what they will experience before conducting the demonstrations.

In the user study sessions, we performed various HMI experiments as follows:

1. **Mobile app hailing**

We presented the PEV mobile application to the participant and asked the participant to summon a PEV from point A (a randomly selected location in the testing field) to point B (the current location of the participant).

2. **Visual signal**

After sending the request through the mobile application, the PEV starts moving from point A towards the participant (point B). Meanwhile, the lights on the PEV change from a breathing white light (default mode of PEV) to a blue light (autonomous mode). During the journey, we ask a developer from our team to stand in a designated location to represent an obstacle. When the PEV sees the developer, the LED on top of the vehicle flashes a red light, signaling that the PEV has noticed the obstacle; the PEV then avoids the obstacle and resumes its journey. When the PEV arrives at the location of the participant, the light changes from blue to green, signaling that it is available and ready for the rider.

3. **Eye contact**

While the PEV is moving from point A to point B in autonomous mode, it will avoid the obstacles and resume its journey. However, if the obstacle is a human, then the eyes on the PEV will point in the direction of the human and make eye contact with them. We asked another developer from our team to demonstrate this scenario to the participant.

4. **Pedestrian gesture interaction**

When the PEV is navigating towards the destination, we ask the participant to wave and stop the PEV. We do not instruct the participant regarding how to wave, as we would like to study the most natural way that people will behave if they want to stop a PEV.

5. **Riding experience and thermal seat**

After the PEV arrives at the location that the participant sets, we ask the participant to ride the PEV from point C to point D. In this session, the PEV provides various levels of electric assistance to make the ride more seamless and pleasant. We also turn on the HVAC system (air conditioning unit) for the participant and demonstrate the thermal seat function in the PEV.

6. Following mode

After the participant arrives at point D, we ask a developer from our team to demonstrate the following mode for the participant. We instruct the participant regarding how to change the PEV from Electric Assist Mode to Following Mode via the mobile application. After the participant switches the PEV to Following Mode, the PEV starts following behind a developer in the testing field.

7. Audio cue

While demonstrating the following mode, the developer will walk at a different speed. When the developer walks too fast (distance between human and the PEV > three meter), and the vehicle cannot catch up, the PEV emits a beeping sound to signal that the developer is too distant.

Figure 5-2: User study session in the Denso Corporation headquarter.

5.3 Post-study survey

We have designed a web platform that allows the participants to provide feedback about each interaction that they have with the PEV during the demonstrations. The post-study survey was formulated to collect participants' feedback for future development and improvement purposes. The survey contains the following questions with images to recall participants' memories:

1. **Mobile app hailing**

   Is the user interface clear and easy to use?

2. **Arrival visual signal**

   Is the visual signal easy to understand?

3. **Eye contact**

   Is it helpful for pedestrians to understand the PEV through the mechanical eyes? Is the process easy to understand?

4. **Pedestrian gesture interaction**

   Is this a good method to stop the PEV? Is the visual and audio expression clear?

5. **A-B direct pick-up**

   Is the vehicle motion smooth?

6. **Thermal seating**

   Does thermal seat provide additional comfort for the rider?

7. **Following mode**

   Is this a good means for rider to interact with the PEV?

8. **Buffering distance**

   In following mode, is the distance between rider and the PEV appropriate?

9. Following mode audio cue

Is this an informative signal to remind the rider to walk more slowly?

Based on each interaction, the participant could choose "like" (thumbs up) or "dislike" (thumbs down) on the survey platform (Figure 5-3). If they like the interaction, the survey directs the participant to the next questionnaire. If they dislike the interaction, a pop-up window appears to allow the participant to type in their feedback. After answering every question in the survey, the webpage guides the participant to the last page, which allows the participant to review all of their feedback (Figure 5-4). The interactions that they liked will be highlighted, whereas the other interactions that they disliked are faded. The last step involves asking the participant to provide their basic information such as age and gender. The result of the survey is then sent to the backend library for future analysis.

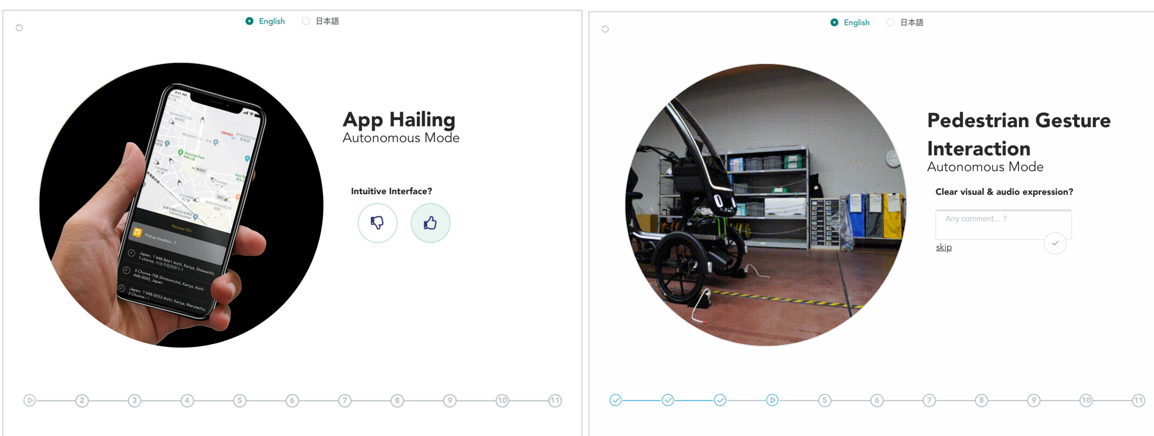


Figure 5-3: Post-study survey for participant to provide feedbacks

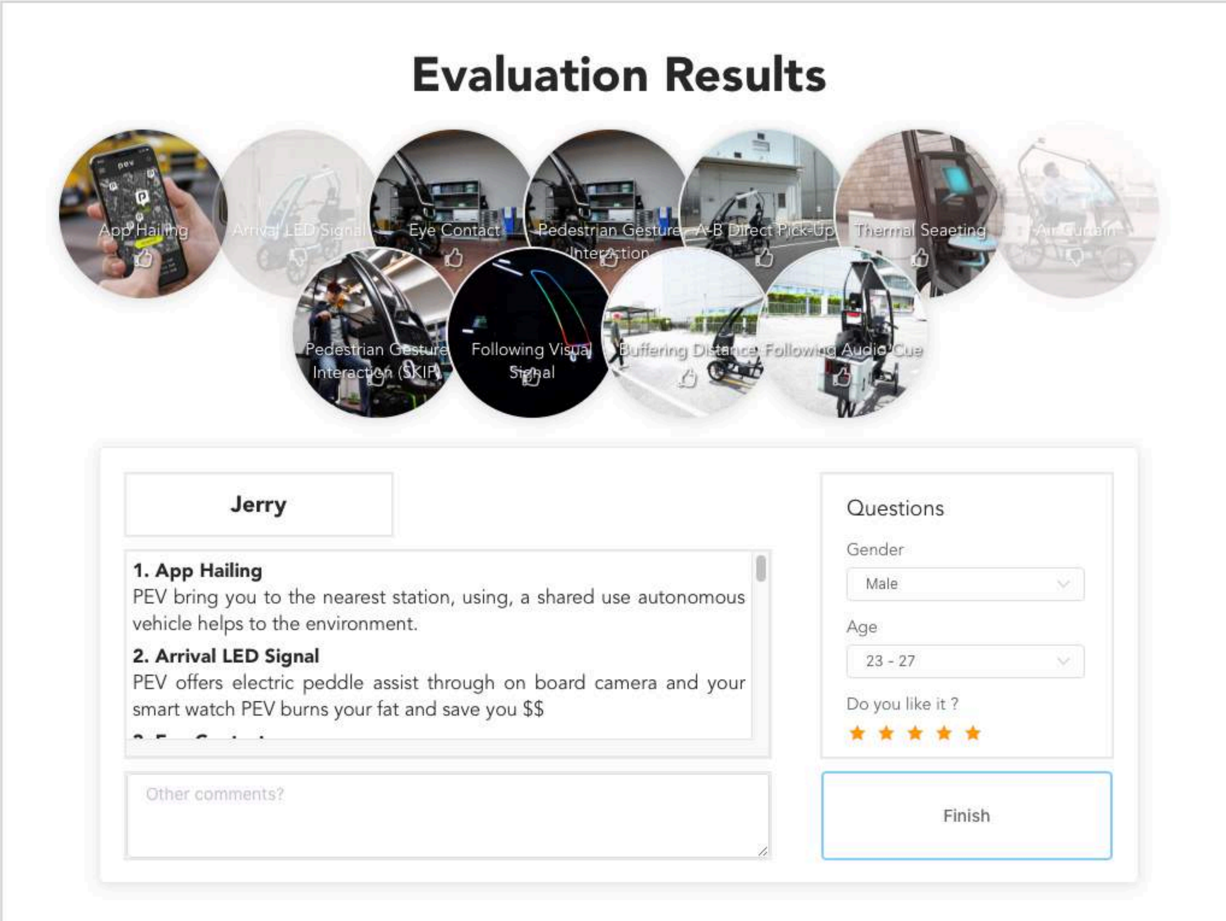


Figure 5-4: Last page of post-study survey for participants to review

5.4 Post-study survey result

Mobile app hailing	Arrival visual signal	Eye contact	Pedestrian gesture interaction	A-B direct pick-up
73% (11)	**40%** (6)	**86%** (13)	**60%** (9)	**33%** (5)

Thermal seating	Air curtain	Following mode	Buffering distance	Following mode audio cue
66% (10)	**60%** (9)	**60%** (9)	**53%** (8)	**60%** (9)

Figure 5-5: Post-study survey result

Figure 5-5 illustrates the result of the user study session. Fifteen participants filled in the post-study survey; therefore, 15 is the highest score of each item. Overall, utilizing the PEV's headlight as a pair of eyes to make eye contact and transmit information with the pedestrians gained the most positive feedback from the participants; 86% of the participants believed that this is an effective approach to initiate interactions between humans and machines. However, some participants suggested that the mechanical movements of the eyes should be more obvious. In the daytime, the lighting effects on the PEV are not as obvious as during the night; pedestrians would need the eye movements to understand the intentions of the PEV. Only 33% of the participants liked the A-B direct pick-up demonstration, since the vehicle motion did not perform well. We did not consider the weather factor while determining the speed of the PEV. The weather was windy on the day we conducted a user study session; therefore, the PEV was navigated against the wind, and the speed was therefore slower than usual.

The visual signals of the PEV were also not sufficiently visible. Most of the participants indicated that the LEDs on PEV are not sufficiently bright for the daytime. While determining the brightness for all of the LED strips on the PEV, we were concerned that the power cable might not be able to sustain such a high current; therefore, we decided to lower the brightness of all of the LEDs and ensure that the system is safe. After the user study session, we updated the power system and changed all of the power cables to the ones that can sustain a high current and increase the brightness level of LEDs.

In the case of V2R (Vehicle-to-Rider) interaction, the participants expressed that our mobile application was easy to use. The interface was clear and self-explanatory; 60% of the participants believed that the following mode is an important function for the PEV, as it gives the city dwellers a new option to interact with the mobility system. Some of the participants noted that the following mode would be extremely helpful if the PEV was deployed in a theme park; the visitors could use the PEV as their assistant to help them carry their bags throughout the theme park. However, the participant also indicated that the distance between the rider and the PEV should be even closer (less than two meters); 60% of the participants believed that the audio cue for following mode is an effective approach. However, they suggested that we change the beeping sound to a more characteristic and friendly sound that fits the vehicle's image better. The participants also enjoyed the thermal seat and air curtain function in the PEV. Considering that the weather in Japan is hot and humid, utilizing the HVAC system is an effective means to increase the comfort level of the rider.

5.5 Discussion on usability and accessibility of IDK systems

In addition to the user study on the HMIs that we designed for the PEV, we hosted another internal group discussion for the developers who have been involved in the development of PEV over the past three years. The participants included two software engineers (hereafter referred to as S1 and S2), two electronics engineers (E1, E2), one mechanical engineer (M1), and one interaction designer (D1). The participants were between 22 and 25 years old.

During the discussion, we discussed each version of the IDK system (IDK Lite, IDK Standard, and IDK+) and noted that we should improve the systems in the future. Among the participants, S1 and D1 have experience with developing interactions with all three versions of IDK. S2 and M1 have experience with utilizing IDK Standard and IDK+, while E1 and E2 only have experience working with the latest IDK+ system.

In the case of IDK Lite, all of the participants believed that the system is too cumbersome, as it takes up almost the same space as IDK Standard but only provides exceptionally limited hardware for developers to design interactions. IDK Lite could be utilized by those developers who only seek to have highly basic functions for their lightweight autonomous vehicle, such as map building, autonomous driving, obstacle avoidance, etc. However, we need to make the system as light and compact as possible. E1 and E2 suggest removing the lead-acid batteries and replacing them with a new power management system. M1 thinks that this version is not sufficiently modular is therefore difficult for developers to access.

In the case of IDK Standard, S1, S2, and D1 believe that it is a good idea to separate the HMI layer and the control layer. M1 thinks that we should add another layer that focuses on the perception part (LiDAR and computer vision system) of the system. Separating the system into the HMI, control, and perception layer allows designers, firmware engineers, and software engineers to divide tasks more clearly, and it also facilitates the debugging process. S1 notes that it is difficult to access to the system when we attach the system in the front part of the PEV.

In the case of IDK+, all participants expressed that the system structure is clearer compared to the previous versions. The new mechanical structure also makes it easier for developers to access the desired sensors. D1 notes that it is an effective approach to embed a battery management system in the IDK+. It enables designers who are not familiar with the electronics to utilize the system more easily. S1 and S2 believed that it is a good idea to consolidate all Arduino systems into one modular unit; it allows software engineers to quickly utilize the sensors without trouble. E1 and E2 stated that it is possible to change the Arduino Mega to a smaller version once we finalize the system.

Chapter 6

Conclusion and contribution

6.1 Conclusion

This thesis discusses the emergence of lightweight autonomous vehicles such as PEVs in urban areas and the need to design interactions between humans and these new mobility platforms. Many are familiar with the term SDK (Software Development Kit); it is essentially a set of software tools and programs used by developers to create applications for specific platforms. We have presented the IDK, a modular Interaction Development Kit equipped with essential tools to help facilitate the design and prototyping process in designing human-machine interfaces for lightweight autonomous vehicles. Using PEV as our platform, the IDK could be physically installed in the PEV, enabling designers and developers to prototype HMIs in a rapid and intuitive manner. There are three different versions of the IDK system that we present in this thesis: IDK Lite, IDK Standard, and IDK+. Each version provides different levels of interactions that developers could design based on their needs.

We also proposed a range of V2P (Vehicle-to-Pedestrian) and V2R (Vehicle-to-Rider) interactions that are built by the IDK system. To evaluate these interactions, we conducted user study sessions with Denso Corporation, a leading company in the automobile components manufacturing industry, to collect feedback from industry experts. The evaluation demonstrates that there are effective approaches and many challenges when designing interactions for new mobility platforms. We hope that these new communications mean that what we designed as well as the user analysis data collected in the evaluation session could be used as suggestions and provide useful insights for those designers and developers who seek to design interactions for their own lightweight autonomous vehicles.

6.2 Contribution

The IDK that this thesis presents enables designers and developers to experiment with prototypes of human-machine interface in a rapid, straightforward, and iterative manner. The IDK introduces a new approach for designers and developers to designing interactions on micro-mobility systems; it provides a new tangible interface that embodies the concept of SDK and transports the concept from a virtual tool to a physical embodiment, facilitating the human-machine interface design and prototyping process.

This thesis also illustrates the concerns that inhabitants of cities have about lightweight autonomous vehicles and their expectations of the new micro-mobility platform through interviews. Based on the interview results, this thesis suggests a series of interactions as potential solutions to address users' concerns. The HMI solutions that we suggested in this thesis are evaluated through indoor exhibitions as well as outdoor testing; we invited experts from automobile industries and academic research institutes to provide feedback on the interactions. We then analyzed their feedback to determine what does and does not work, thereby improving our design and ascertaining the most promising interactions. This data could potentially provide insights for other developers intending to design the next generation of micro-mobility systems for cities, helping them to build interactions that truly matter to the users.

Chapter 7

Future work

7.1 Future work

This thesis suggested various means for humans to interact with PEVs as examples of how to design HMI for micro-mobility systems. It also raised multiple questions that are worth researching further. One of the major problems we found during user evaluation sessions was the relatively poor visual signals on our vehicle. Due to the physical limitations of the chosen LEDs and cables, the LEDs could not reach the desired brightness level, making it difficult for pedestrians to distinguish lighting signals during the daytime. A possible next step would be to deploy superior electrical systems and more compatible sensors to make the visual signals more discernible in daylight.

The IDK systems presented in this thesis were installed and tested on PEVs; however, these modular systems could also be scaled and transformed into different variants to fit in other forms of LAVs. Depending on the purpose of the LAVs, the interactions required will vary; the designers and developers could use IDK systems as a starting source and tweak the systems to build the most desirable interactions for their vehicles. For example, if there were developers seeking to utilize the IDK system to build interactions for a delivery robot (Figure 7-1), certain sensors could be replaced in the IDK system to best fit the needs of the vehicle. Delivery robots usually need to be lightweight and low-cost; thus, utilizing expensive LiDARs might not be an economical solution. In this case, the developers could choose to enhance the camera vision systems in the IDK and install radar and ultrasonic sensors for additional safety.

Figure 7-1: Amazon delivery robot

To further test the scalability and usability of the IDK system, we will collaborate with other designers and developers who are developing LAVs and install the system in their products. We hope to test our system on different platforms to discern its capabilities and potential problems.

The IDK system could also be used as an educational tool to teach students around the world how to program this portable system and build their own autonomous robots. We could use the basic IDK Lite to teach students the fundamental sensors that make an autonomous vehicle function. After the students become familiar with the system, we can provide IDK Standard and IDK+ to introduce the different levels of interactions that they could build for their vehicles. The vehicle does not necessarily need to be a bike; the platform could be a scooter, a wheelchair, an arbitrary form of robot, and others. With the IDK system, it is just a matter of dressing the system in different clothes and encouraging students to use their imagination to design the next generation of micro-mobility systems. We hope this approach will help facilitate the development of micro-mobility systems and the identification of the most promising alternatives for future mobility platforms.

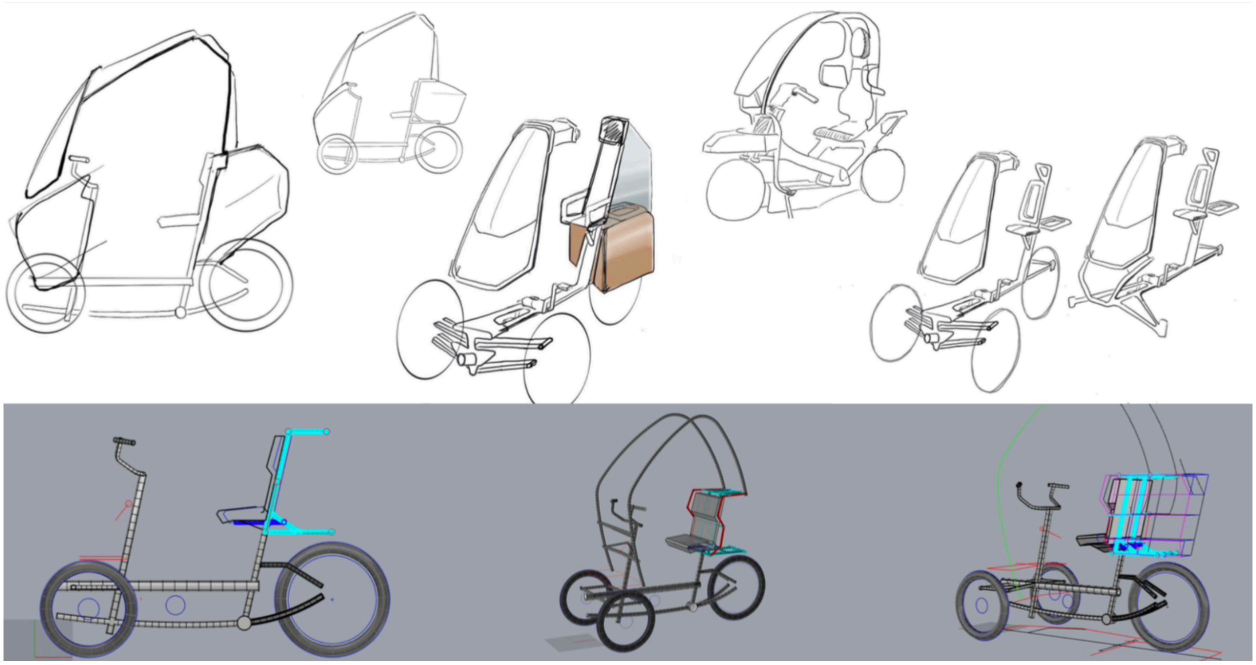


Figure 7-2: Utilizing the IDK system in different forms of vehicles.

Lastly, when we conduct user study sessions in the future, we must consider the study structure and gender ratio. The preliminary interview that we did at Cooper Hewitt museum was not well-structured; we asked the visitors about their concerns with LAVs without providing examples and scope for them to consider, thus the feedbacks that we acquired were too general and imprecise. Another factor that could affect the user study precision is the time. The user studies that we conducted at Denso Corporation were relatively short, which greatly limited the use of our system and the feedback we received. The gender ratio of the participants was unbalanced as well: we recruited 15 participants, only two of which were female. To collect more objective feedback, we must conduct the user study sessions more carefully in the future. We hope that this thesis provides useful insights for readers and raises questions that encourage them to pursue research in this field. We believe that, as technology becomes increasingly advanced, more people will become interested in designing new LAVs that could be deployed in cities as a more efficient alternative to conventional cars.

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