Autonomous Vehicles with Visual Signals for Pedestrians: Experiments and Design Recommendations

by

Henry Kan Chen

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Autonomous Vehicles (AV) or Automated Driving Systems (ADS) are the future of transportation and they are poised to transform the ways people travel. While ADS promise to enhance traffic safety and efficiency, many challenges remain. One of these is the disruption of communications between road users. Today, drivers play a critical role in promoting traffic cooperation by sharing their intention using active signals such as eye contact or hand waves. However, these signals will be missing from a driverless vehicle. Researchers and regulatory agencies recognize that the lack of this communication channel could be a new threat for road safety and therefore are calling ADS designers and manufacturers to find ways to communicate ADSs state of operation and intent to other traffic actors, such as human drivers, cyclists, and pedestrians. However, one key question remains and is hampering the development of an ADS lighting standard, namely: which form of visual signal is best for communicating ADS intentions.

As such, this thesis attempts to answer this question. It presents the findings from four successive human-subject experiments that assess visual signals in terms of visibility, intuitiveness, persuasiveness, and usability. While only six different types of visual signals are compared and contrasted in this study, the experiment methodology proposed in this thesis is novel and could be used by future researchers to evaluate other visual signals. Furthermore, these experiments revealed a wealth of design recommendations for ADS visual signals, which will be thoroughly discussed.

Altogether, we hope this work would contribute to the establishment of an international ADS light standard, one that will engender trust from users, thus taking another step toward the maturation of automated driving.

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Dedication

To God Almighty, the Creator of the Universe and my trusted good Father in heaven, nothing is possible without You. Thank You for these two plus years of study. In all my limitations, I gave my best and wish to dedicate this work to You. Also, to my parents, Jie Wei Huang and Si Jian Chen, who sacrificed so much to bring me to Canada so that I can become who I am today. Finally, to my late grandparents, who I miss dearly, I will always remember your love and cherish the memories of you.

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Glossary

Autonomoose An autonomous driving research platform at the University of Waterloo, Canada xiv, 11, 50, 51

ego A vehicle in the autonomous state of operation such that it is fully controlled by its software 52, 56, 57

illuminance The total luminous flux incident on a surface per unit area; measured using a light meter 28, 31, 58, 86, 93

interACT A multi-institutional and multi-national European project "working towards the safe integration of AVs into mixed traffic environments [27]" 7, 8

JOSM a software tool created in Java for editing OpenStreetMap 50, 52

lanelet A set of GPS waypoints representing a road lane 50, 52

waypoint A GPS coordinate representing an point on earth 11, 50, 51

Abbreviations

ADS Automated Driving Systems iii, 8, 13, 20

ANOVA Analysis of Variance 31, 44

app Smartphone Application 18, 29, 38, 40

AV Autonomous Vehicles iii

AVIP Autonomous Vehicle Interaction with Pedestrians 9

AVOD Aggregated View Object Detector 15, 50

eHMI external Human Machine Interfaces 7, 8

GRE Working Party on Lighting and Light-Signalling 7

ISO International Organization for Standardization 2, 7

LiDAR Light Detection and Ranging 11

NHTSA US National Highway Traffic Safety Administration 1

OSM OpenStreetMap 52

RGB Red, Green, and Blue 11, 17

ROS Robotics Operating System 12, 55

S.E.M. Standard Error of the Mean 31, 42

SAE Society of Automotive Engineers International 2, 7, 8, 26

UNECE United Nations Economic Commission for Europe 7

V2X Vehicle to Infrastructure 8

WISE Waterloo Intelligent System Engineering 11, 54

WRESTRC Waterloo Region Emergency Services Training and Research Centre 50, 58

Chapter 1

Introduction

Autonomous Vehicles (AV) or Automated Driving Systems (ADS) are the future of transportation and they will soon appear in neighbourhoods near you. The potential benefits of autonomous vehicles for society are enormous such as reduction of traffic accidents and fatalities. According to the US National Highway Traffic Safety Administration (NHTSA), "human choices are linked to 94 percent of serious crashes on the U.S. roadways during 2016 [1]," and they believe that many of those crashes can be prevented by eliminating human errors and mistakes through the promotion of vehicle technologies such as autonomous driving [2]. Making the same argument for Canada, that implies ADS could prevented many of the 1,679 traffic fatalities and 112,479 injuries in 2017 [6]. Combining with the Conference Board of Canada's findings that autonomous vehicles can reduce travel time, fuel cost, and road congestion, the total benefits of autonomous driving for Canadian societies could be 65 billion dollars every year [19]. For these reasons, autonomous driving technologies are recognized as one of the most impactful technologies of the 21st century. Hence, developed societies around the world are incentivized to expedite the driverless transformation of their transportation system.

However, the reality is that societies and the autonomous driving technologies are not ready for mass adoption; and ironically, safety is among the top concerns that are keeping autonomous vehicles off our streets. In a 2017 voluntary safety guideline, the NHTSA outlined 12 safety elements that autonomous vehicles should consider: 1) System safety, 2) Operational design, 3) Object and event detection and response, 4) Fallback and minimal risk condition, 5) ADS testing and validation methods, 6) Human Machine Interface, 7) vehicle cybersecurity, 8) Crashworthiness, 9) Post-Crash ADS behaviour, 10) Data recording, 11) Consumer education and training, and 12) Regulations. Specific to the Human Machine Interface element, the NHTSA is urging "ADS designers and manufacturers to consider the need to communicate information regarding the ADS's state of operation to traffic actors, such as human drivers, cyclists, and pedestrians, with whom the ADS may have interaction, and to consider how this information should be communicated [2]."

Indeed, one of the safety challenges for ADS is the disruption of communications between road users. Today, drivers play a critical role by sharing their intention with road users by using active signals such as eye-contacts or hand-waves [10]. Studies have shown these signals are necessary for traffic cooperation and safety [32]. However, they will be missing from a driverless vehicle, and there is a need for an alternative communication method. In recognition of this, universities, autonomous vehicle manufactures, and regulatory agencies from around the world are working to address this communication gap. Most notably, the Society of Automotive Engineers International (SAE) started a task force, J3134, dedicated to this effort. In their latest update, released on December 2018, they recognized signal lights, displayed in the front of a vehicle, as a promising way to communicate intention. They also found a turquoise colour marker light can be used to indicate a vehicle is operating in self-driving or ADS mode. However, they also identify many knowledge gaps in this research field, most notably the chairperson of the SAE J3134 task force posed the question: "which form of visual signals, such as flashing or sweeping, is best for communicating an autonomous vehicle's intention [43]?"

Therefore, this thesis is centered around answering that question. Working under the hypothesis that there exist visual signal designs that could effectively communicate an autonomous vehicle's intention to pedestrians, this thesis argues that these signals should be visible, intuitive, persuasive, and usable. Hence, it proposes 4 successive and novel human-subject experiments and asks 12 complementing research questions in order to evaluate visual signals according to those qualities. By doing so, it constructs an elaborate answer to the SAE research question and offers several practical design recommendations for building an effective autonomous vehicle visual signal system. Moreover, this thesis also addresses two related research questions: 1) how pedestrians will behave at crosswalks in the context of autonomous driving? and, 2) how can an autonomous vehicle engender trust with pedestrians? Table 1.1 provides an overview of the experiments and research questions examined in this thesis.

Ultimately, we hope this work will contribute to the improvement and development of several international autonomous vehicle communication lighting standards, such as the released SAE standard on "Automated Driving System Marker Lamp (J3134_201905) [44]", the International Organization for Standardization (ISO) standard on "Ergonomic Aspects of External Visual Communication From Automated Vehicles to Other Road Users (ISO/TR 23049:2018) [15]", and two related ISO standards under development: "Ergonomic Design Guidance for External Visual Communication From Automated Vehicles to Other

Road Users (ISO/NP TR 23735) [16]" and "Methods for Evaluating Other Road User Behavior in the Presence of Automated Vehicle External Communication (ISO/AWI TR 23720) [17]."

Study	Experiments	Research Questions
Phase 1	1 (Visibility)	RQ1: What visual signal pattern is most notable in a pedestrian's peripheral vision? RQ2: Where to mount a visual signal to enhance its peripheral visibility?
	2 (Intuitiveness)	RQ3: How would a pedestrian react to different visual signals intuitively? RQ4: How would a pedestrian react to different visual signals after training? RQ5: How long does it take for a pedestrian to interpret and react to different visual signals?
Phase 2	3 (Persuasiveness)	RQ6: What visual signals would encourage or deter a pedestrian from crossing in front of an approaching autonomous vehicle? RQ7: What visual signals would encourage or deter a pedestrian from crossing in front of a stationary autonomous vehicle? RQ8: How does repeated exposure to visual signals influence a pedestrian's crossing decision? RQ9: How does familiarity and trust of an autonomous vehicle influence a pedestrian's crossing decision?
Phase 3	4 (Usability)	RQ10: How does a pedestrian identify and recognize an autonomous vehicle? RQ11: Can pedestrians notice a visual signal on an autonomous vehicle? If so, what do they think about it? RQ12: Will pedestrians react differently to an autonomous vehicle equipped with visual signals?

Table 1.1: Study Overview - Experiments and Research Questions

Chapter 2

Literature Review

Overall, this thesis contributes to the research fields of Pedestrian Behaviour and Autonomous-Vehicle-and-Pedestrian Interaction. Specifically, it attempts to discover the most effective way for an autonomous vehicle to communicate its intention to pedestrians; and, it investigates how pedestrians make crossing decisions when facing an autonomous vehicle, exploring influencing factors such as cognition and trust.

In this chapter, we will outline the prominent and state-of-art research in those fields. The sections are structured using the literature framework outlined by Rasouli *et al* in their paper "Autonomous Vehicles That Interact With Pedestrians: A Survey of Theory and Practice" [47]. Combining the survey of Rasouli *et al* and a review of the latest literature, this chapter provides the necessary background knowledge for the rest of the thesis.

2.1 Pedestrian Behaviours at Crosswalks

Fundamentally, Rasouli *et al* argued pedestrian behaviours at crosswalks are determined by 8 main influencing factors [47]: 1) **Physical Context** such as road structure, traffic signal, and lighting conditions; 2) **Dynamic Factors** such as vehicle speed, gap acceptance, and communication; 3) **Traffic Characteristics** such as vehicle size, traffic volume, and law enforcement; 4) **Social Factors** such as social norms and group size; 5) **Demographics** such as gender and age; 6) **Abilities** such as speed and distance judgement; 7) **Personal State** such group size and attention; and finally, 8) **Personal Characteristics** such past experience and culture. The authors added that the first 3 of these factors pertain to the environment and the others to pedestrians. These factors are intertwined and they work together to formulate a crossing decision in the pedestrian's mind in a fraction of a second [12]. These influencing factors and their inter-dependencies are captured in Figure 2.1, which demonstrates the complexities of pedestrian decision making and that relatively little is known about how pedestrians behave in the context of autonomous driving. The following sections examine some of the influencing factors impacting the interaction between pedestrians and both autonomous and conventional vehicles.

2.1.1 Vehicle Speed and Distance

Vehicle distance and speed are powerful *dynamic factors* influencing pedestrian behaviours [49]. Namely, the distance separating the vehicle and the pedestrian is known as the "gap", which can be "distance gap" (in meters) or "time gap" (in seconds)[1]. It is recognized as the "dominant factor" influencing pedestrian crossing decisions [8], [53]. The minimum distance gap pedestrians are willing to accept before deciding to cross is known as gap acceptance [66]. Studies reveal gap acceptance is highly dependent on social, cultural, and demographic factors. For example, pedestrians in India and Germany have different gap acceptance [53].

Another factor affecting pedestrian behaviour is Time-to-Collision (TTC), which incorporates both distance gap and vehicle speed into consideration [66]. The minimum TTC pedestrians are willing to accept ranges from 3-7 seconds [11]. However, studies have shown the estimate of TTC is often inaccurate because it is difficult for pedestrians to accurately estimate vehicle speed, and therefore, distance gap is still preferred by pedestrians [53].

2.1.2 Traffic Signal and Zebra Crossing

Physical structures such as traffic signals and zebra crossings also have major impacts on pedestrian behaviours [38]. For example, Tom *et al* found pedestrians are more complacent at an intersection equipped with traffic signals; "they check traffic for vehicle on 69.5% of the time compared 86%, if the intersection was not signalized" [60], [47]. Moreover, zebra crossings can cause a pedestrian to feel entitled to the right way, though to a lesser degree than a signaled crossing, it is still a powerful influencer of their behaviours [58].

[1] The terminology Distance Gap is from the SAE standard on driving performance measures and statistics (J2944) [42]. It is also referred to as Gap Distance in literature such as [8]. We followed the SAE standard in this thesis.

2.1.3 Gender and Age

Demographic factors such as gender and age also impacts pedestrian crossing behaviours in many ways. Namely, studies show female and male pedestrians have different levels of risk-tolerance, law-compliance, and attention at crosswalks [25], [65]; particularly, male pedestrians tolerate shorter distance gap than female pedestrians at crosswalks [9] and female pedestrians are generally more law-bidding and attentive to traffic situations [60].

Pedestrians belonging to different age groups also have different crosswalk behaviours. Namely, elderly pedestrians tend to have slower movements and are less able to accurately assess vehicle speed and TTC of fast-moving vehicles at a distance [12]; consequently, elderly pedestrians have longer gap acceptance [9] and are generally more cautious at crosswalks [23].

2.1.4 Group Size and Attention

Another powerful factor influencing pedestrian crosswalk behaviour is group size. Many studies have shown a group of pedestrians are more careless and inattentive than individual pedestrians [22], [47], which causes them to also move slower and accept shorter gaps [11], [62], [24]. In addition, a pedestrian also likely to imitate the behaviours of those around them, unless some individuals are blatantly breaking the law, like crossing on the red light [30], [47].

Moreover, a preoccupied and distracted pedestrian often display signs of inattentional blindness, in which they fail to notice their visible surroundings. For example, pedestrians distracted by mobile phones often experiences this and exhibit symptoms of irregular walking trajectory and speed [26].

2.2 Autonomous Vehicle and Pedestrian Interactions

In the previous section, we examine influencing factors that impact pedestrian behaviours at a crosswalk. The implied context of those studies is pedestrian interactions with human-operated vehicles. While much of the findings are transferable, pedestrian interaction with autonomous vehicles introduces many challenges and unknowns. Specifically, the disruption of pedestrians-driver communications is recognized to be the most problematic because it could create traffic chaos and make the transition to autonomous vehicles more challenging [7].

2.2.1 Pedestrian and Driver Communication

Traditionally, it is believed that drivers play a critical role to facilitate traffic safety by communicating their intention to pedestrians using non-verbal communication cues such as eye-contacts and gestures [10]. In fact, some studies argued "majority of pedestrians expects communication from drivers and search for their eye contacts [57]," and that eye contact is a powerful form of communication that promotes traffic cooperation and rule compliance [20]. Moreover, Ren *et al* observed that "pedestrian's stare can influence drivers' behaviours by causing them to decelerate earlier, which increases TTC and promotes crosswalk safety [48]." Hence, many researchers believed autonomous vehicles will need to find alternative means to correspond with pedestrians. Failing to do so, Lundgren *et al* argued, will lead to a decrease of pedestrian confidence and trust of AV [32]. In particular, Lagstrom *et al* identified four important messages autonomous vehicles need to communicate to pedestrians. 1. whether the vehicle is driving autonomously; 2. whether the vehicle noticed the pedestrian; 3. whether the vehicle will yield; and, 4. when the vehicle intends to drive [29].

However, a recent interACT study conducted in Greece contradicts these findings. Namely, it observes at high density un-signalled urban crossings, the role of explicit communications such as eye contacts are limited; they are only required in interactions when the implicit body and movement cues are unable to resolve the traffic situation in question [40]. Camara *et al* agreed and argued:'in the context of autonomous driving, some human communication styles such as eye contact do not play a major role in pedestrian crossing behaviors, and that the motion pattern and behavior of vehicles are more important [5].'

Despite these contradictory findings, the automotive industry and regulatory agencies agree some forms of autonomous vehicle intention communication are necessary. Namely, the SAE, the ISO, and the United Nations Economic Commission for Europe (UNECE) are all working on an external signal lamp standard for automated driving [44], [15]. The SAE J3134 task force and the UNECE Working Party on Lighting and Light-Signalling (GRE) are devoted to investigate the signalling requirements. Hence, this thesis builds on this consensus and aims to contribute to the agencies' efforts.

2.2.2 Autonomous Vehicle Intention Communication Interfaces

Many intention communication interfaces or external Human Machine Interfaces (eHMI) concepts have been tested to communicate the intentions of autonomous vehicles. For example, Clamann *et al* designed a pioneering LCD based communication display in front of a vehicle for pedestrians to see. Even though the system did not significantly change pedestrian behaviour during experimentation, the study revealed many important design considerations for an AV intention communication system. Namely, it needs to be interpretable at a distance and within the limited time as the vehicle approaches the pedestrian, and it needs to be scalable to an urban environment where there will many cars, pedestrians, and interference [8]. Alternatively, Mercedes-Benz and Mitsubishi are separately proposing to use laser projections to communicate with pedestrians. Namely, they conceptualize that an autonomous vehicle can project a zebra crossing on the road for pedestrians to cross on, or the vehicle can project the direction of travel on the road for pedestrians to see [36], [37]. The effectiveness of these designs is unknown because they have not been tested. To make the autonomous vehicle more personable, Pennycooke *et al* prototyped the AEVITA moving eye system that mimics a driver's eye-contact with a pedestrian [46]. While it is unknown how pedestrians will interact with such a system, it demonstrates the possibility of using gaze-tracking technology for intention communication. Moreover, Mahadevan *et al* compared multiple intention communication interfaces such as an LED strip, a speaker, and a mobile phone with Vehicle to Infrastructure (V2X) technology. In the end, the study ranked visual signals, such as LED strips, as the best option for communicating vehicle intention [33].

Interestingly, a recent interACT study shows cultural factors have significant influences on the pedestrians' interpretation of eHMI. Namely, Weber *et al* showed in a virtual reality study that "pedestrians in Germany and the United States can better understand the vehicle's intention through eHMI; whereas, the benefit of eHMI are not recognizable in China." Consequently, the authors conclude that "eHMI should only be used in safe states of the AV, such as when yielding [61]."

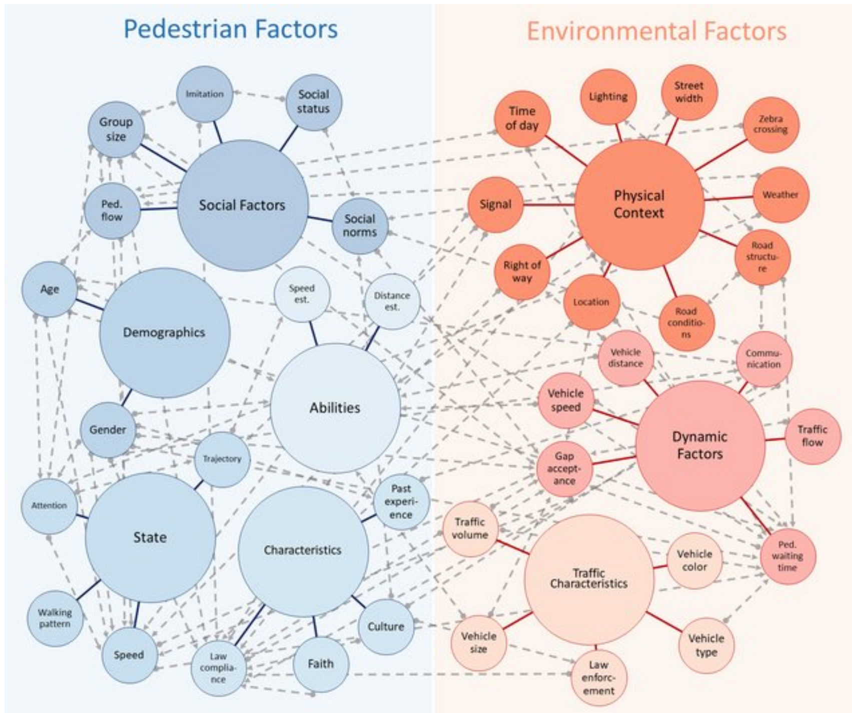
2.2.3 Autonomous Vehicle Visual Signals Concepts

Visual Signals have long been used on conventional vehicles to communicate driver intention; similarly, the automotive industry is embracing the idea that autonomous vehicles can also use visual signals to communicate their intentions. Specifically, the SAE J3134 task force recommended that the colour of blue-green, as known as Turquoise, should be used for ADS lamps. They reasoned this unique colour will minimize interference with existing automotive signals. Further, they recommended that a single solid marker lamp should be used to denote an ADS is in the automated state of operation. However, they added "more research are needed to determine how to communicate ADS intentions with visual signal [43]."

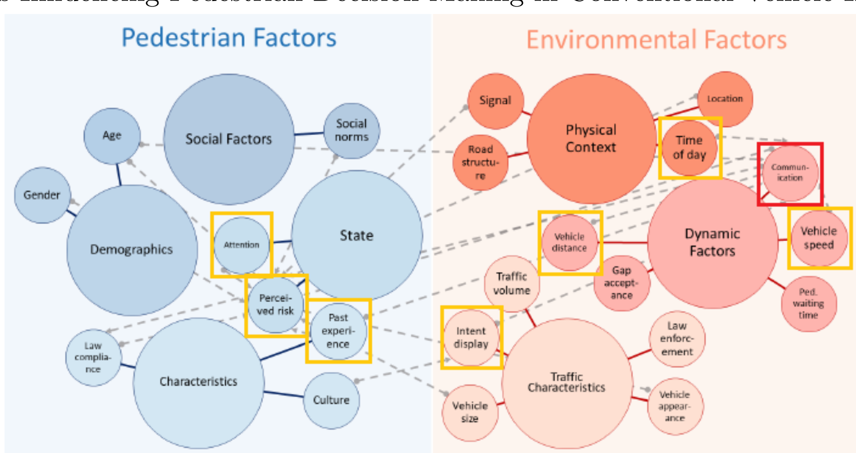
Lagstrom *et al* was among the first to investigate this subject. Namely, they designed and built the Autonomous Vehicle Interaction with Pedestrians (AVIP) visual signal system which communicates vehicle intention by displaying different light patterns on an LED strip mounted at the top of a vehicle's windshield. To evaluate whether the system is "understandable and helpful", the authors asked 9 participants to observe the AVIP system on an approaching vehicle, supposedly autonomously driven, and interviewed them about their interaction experience. Ultimately, the authors reported that the system can "increase pedestrian's willingness to cross and make the crossing experience more pleasurable" [29]. Since then, more studies have investigated the subject. For example, Ford and Virginia Tech conducted an observational study to evaluate the effectiveness of AV visual signals on public streets. Namely, the authors equipped a vehicle with an LED signalling system that also used light signal patterns to communicate vehicle intentions. Then, disgusting the driver as a car seat, they drove the vehicle on various public streets at Arlington, Virginia, signalling the vehicle's intention at crosswalks and intersections, they observed most pedestrians did not notice the vehicle and that their behaviours were not affected by the visual signals [55]. Given the novelty of this research field, there is a lack of explanations on what caused the discrepancy in the two results and explain their design implications for autonomous vehicle visual signals. Hence, this thesis will attempt to fill those research gaps.

2.2.4 Autonomous Vehicles and Pedestrian Trust

This thesis also investigates the little-known research field of Autonomous Vehicle and Pedestrian Trust. Namely, Jayaraman *et al* use the uncertainty reduction theory (URT) to explain pedestrians' trust of an autonomous vehicle is proportional to their knowledge of about it; and, in a road-crossing scenario, the two key pieces of information that will boost a pedestrian's trust of an autonomous vehicle are the vehicle's driving behaviour and whether the crosswalk is signed [28]. However, the latest robotics trust researchers also suggest that a user's trust of a robot is not entirely dependent on its performance [52], rather on its perceived capabilities [50]. For these reasons, we hypothesize that a pedestrian's trust of an autonomous vehicle is less dependent on observed behaviour, but rather on the pedestrian's knowledge about the autonomous vehicle's capability. We will explore this hypothesis in Experiment 3.



(a) Factors Influencing Pedestrian Decision Making in Conventional Vehicle Interactions



(b) Factors Influencing Pedestrian Decision Making in Autonomous Vehicle Interactions. The red and yellow boxes represent the primary and related topics of investigations in this thesis.

Figure 2.1: Factors Influencing Pedestrians Behaviours as depicted by Amir Rasouli and John Tsotsos, 2018. "The circles represent main influencing factors and their sub-factors, and the dash lines represent their known inter-dependencies and the direction of influence [47]."

Chapter 3

Visual Communication System Prototype

In the literature review chapter, we discovered visual signals, or lights, is the most promising interface for communicating autonomous vehicle intention to pedestrians. In this section, we will examine the making of a programmable visual signal system for the autonomous vehicle owned by the Waterloo Intelligent System Engineering (WISE) lab, called Autonomoose.

3.1 The Autonomoose platform

The Autonomoose is Canada's first complete autonomous driving research platform. The vehicle is based on a 2014 Lincoln MKZ hybrid sedan and it is equipped with Light Detection and Ranging (LiDAR), inertial, GPS, and camera sensors. The vehicle's software architecture, typical of ADS, consists of five major components: perception, mapping, planning, vehicle control and supervision [69], [54].

- The **Perception** layer is responsible for identifying the vehicle's position and tracking other objects in the environment, such as cars, pedestrians, road signs, and etc. The input to this layer are LiDAR data and camera Red, Green, and Blue (RGB) images. The output includes 3D bounding boxes and an occupancy grid.
- The **Mapping** layer, called Map Server, localizes the perceived objects on a map of lanelets, which are GPS waypoints representing road lanes.

- The **Planning** layer includes a Behaviour Planner, which designs the maneuver to be executed, and a Local Planner, which implements the maneuver as a trajectory for the vehicle to follow. The planning layer takes the outputs from the perception and mapping layers. It outputs the planned trajectory for the next few seconds.

- The **Vehicle Control** layer executes the planned trajectory by controlling the vehicle's steering, braking, and throttle actuators.

- The **Supervision** layer monitors the vehicle's hardware and software performance and makes sure that all systems are operating as designed. It is also responsible for alerting the driver about any failures that would require them to take over control of the vehicle.

Altogether, the Autonomoose is capable of operating in Level 3 autonomy. The challenge for our project is to build a visual communication system that seamlessly integrates with this ADS.

3.2 Hardware

The two main design considerations for the visual communication system are compatibility and customizability. Specifically, since our goal is to create a fully integrated visual communication system for the Autonomoose ADS, it is important for the system to be compatible with the Robotics Operating System (ROS), which is the environment that the Autonomous software stack operates on. The second consideration is customizability, as the system needs to be able to display a variety of the visual signal patterns. We will discuss both the ROS integration process and the visual signal patterns in detail later in this chapter.

3.2.1 Arduino

Arduino is an open-source electronic platform that provides inexpensive and flexible computing for a wide range of applications. The platform is usually comprised of a hardware microcontroller board and an open-source software environment, called The Arduino IDE, which allows users to write customized applications, in the C and C++ programming languages, for Arduino boards [4]. Moreover, the Arduino IDE provides a software library that supports many hardware and environments, such as ROS. As such, we decided to base our visual communication system on the Arduino platform.

Specifically, we choose to use the Arduino Uno microcontroller board. The Uno board is one of the most popular Arduino boards. It is based on the ATmega328P microcontroller with a 16 MHz clock. It has 14 configurable digital input/output pins and 6 analog inputs. The digital pins operate at 5 volts and each can provide or receive a recommended 20 mA. It is also comes with a built-in USB Type B connector that functions as the interface to the Arduino IDE and an external power source. Alternatively, the board can be powered through its 2.1 mm center-positive female power jack, accepting 7-12V DC [3].

3.2.2 LED Strip

Next, we need a light source for our system. Inspired by the stage lights at my church, we selected the WS2815 Light-Emitting Diode (LED) for our system. The WS2815 is a versatile RGB LED that can emit a full range of 256^3 colours. Having been arranged on a flexible circuit strip, each WS2815 LED pixel can be individually programmed and controlled as a whole to display any visual pattern a programmer may conceive. The LED strip, which requires a 9.5-13.5V DC power source, can be powered from a vehicle's cigarette lighter plug, which outputs 12V DC; it also requires a control voltage of 0-6V DC, which means it is compatible with Arduino Uno's digital output pins. Moreover, its data transmission rate and switching time, 300 ns and 120 μs, respectively, also meets our design requirements. The only potential drawback is the luminous intensity of the LED, see Table 3.1. Assuming all three colours are emitting simultaneously, the combined intensity of a WS2815 LED is between 1.95 - 3.5 candela (cd) per pixel. The ADS marker lamp in our system contains 8 LED pixels emitting up to 28 cd of light. Without taking into account factors impacting photometry, such as obstructions and viewing angles, our marker lamp meets the photometry requirements, 2.5 - 300 cd in daytime and 0.5 - 125 cd in nighttime, specified in the SAE standard of "Automated Driving System Marker Lamp (J3134_201905) [44]."

Emitting Colour	Wavelength (nm)	Luminous Intensity (cd)
Red	620-625	0.3-0.6
Green	515-525	1.5-2.5
Blue	465-475	0.15-0.4

Table 3.1: Visual Communication System Prototype - WS2815 Luminous Intensity

3.2.3 Impedance Matching

Impedance is the opposing force in an electric circuit that inhibits the flow of current. In a DC circuit, impedance is equivalent to the circuit's resistance, while in an AC circuit, impedance would also include the circuit's capacitance and inductance. Impedance matching is the practice of equalizing the load circuit impedance with that of the source circuit. For our application, the source circuit is the Arduino UNO circuit board, whereas the load circuit is the WS2815 LED strips that connect to Arduino's digital output pins. By matching the impedance of the two circuits, we can maximize power transfer and reduce circuit noise. This is especially important for high frequency applications, like ours, to reduce data transmission error and increase transmission efficiency. Hence, by trial and error, we added a 300 ohm resistor in series in between the Arduino digital output and the LED strip and found it was effective to reduce data transmission overshoot by 24.3%. Figure A.1 in Appendix A illustrates the noise reduction effect of impedance matching on a visual signal control circuit.

3.3 Software

3.3.1 Rosserial

Rosserial is a protocol that allows embedded hardware to communicate directly with ROS. In particular, the rosserial_arduino is ROS package that enables communication with Arduino boards. For example, by running the rosserial package along the Autonomoose software stack, an Arduino UNO board will appear as a ROS node on the stack and it can easily exchange data with other nodes using ROS topics. This package simplified the task of Arduino ROS integration and gave us the ability to write customized programs separately in both platforms that can exchange data with each other. We will discuss some of those programs in the following sections. Finally, two versions of Rosserial are available, a stable python version, a faster experimental C++ version. For the sake of stability, we choose to use the python stable version.

3.3.2 ROS_vState_Publisher

The main purpose of this ROS node is to compute the gap between a stationary pedestrian and the experiment vehicle. Initially, we attempted to measure the distance using ground markings and measuring tape but this method is time consuming and prone to misinterpretation. Then, we attempted to estimate the distance using the vehicle's 3D pedestrian detector - Aggregated View Object Detector (AVOD). However, we observed that AVOD sometimes fails to detect a stationary pedestrian, thus making it unsuitable for our application. Finally, we devised a way of measuring distance using coordinate frames.

The following is a summary of the key coordinate frames specified by ROS [14], [35].

- **base_link frame** is a moving coordinate frame attached to a mobile robot. A coordinate is expressed relative to a robot's body, using the where convention X represents forward, Y represents left, and Z represents up. On the Autonomoose research vehicle, the base_link frame is attached directly at the center of the rear axle. As the robot moves, the base_link frame changes to reflect its orientation and heading.

- **odom frame** is a fixed coordinate frame tied to a robot's startup position. As the robot moves, its position relative to the odom frame is computed using an odometry source, such as inertial measurement unit (IMU), wheel odometry, or visual odometry. The odom frame can yield a continuous path of a robot's trajectory, which is a useful reference that allows a robot to sense and act on its local surroundings. However, the odom frame is not a good long-term reference of position because odometry drifts will result in large error.

- **map frame** is also a fixed coordinate frame tied to a robot's startup position; however, its coordinates are defined relative to a global coordinate system, such as a map. As the robot moves, a localization component computes its position in map frame according to new sensor observations. The map frame has the benefit of eliminating odometry drifts, which make it a reliable long-term reference of the robot's position. However, it is susceptible to sensor delay, making it less desirable for local sensing and acting.

For our purposes, we determined the best way to compute the distance gap is to initialize the vehicle at the location where pedestrians will be standing, and because the map frame gives an accurate measurement of the distance between the pedestrian (at the frame origin) and the vehicle, we can get the distance gap by simply observing the vehicle location in the map frame. To do so, we utilize the ROS **tf** package, which tracks coordinate frames and the transformations between them over time. By invoking the *tf.TransformListener()* function, we are then able to transform the vehicle's current position from base_link frame into map frame, which yields the vehicle's position as 3 numbers representing longitude, latitude, and elevation. Moreover, by assuming the test area as being flat, we computed the distance gap as the Euclidean distance of longitude and latitude. This ROS node then broadcasts the results, in meters, using a ROS topic, which the ROS_Subscriber Arduino program will subscribe to and utilize as information for Experiment 1.

3.3.3 ROS_Light_Controller

This ROS node is the key component that integrates the visual signalling system with the rest of the Autonomoose software stack. It performs two keys functions: to understand the vehicle planned behaviours and to broadcast the corresponding instructions to control the visual signals. Namely, this program examines three parameters to understand what the vehicle is doing. The most important of the three is the vehicle's planned maneuver, which is broadcast by the behavioral_planner topic as an integer value representing the vehicle's maneuver: 0 - track_speed, 1 - decelerate_to_stop, 2 - stop, 3 - yield, 4 - park_vehicle, 5 - lead_vehicle_follow, and 6 - emergency_stop. In addition, the program also examines the distance of the next intersection and the current vehicle speed to determine the corresponding visual pattern. Specifically, as the autonomous vehicle approaches and is within 102.6 meters of an intersection[1], if vehicle maneuver is 1 - decelerate_to_stop, the visual signal will be commanded to show the *approaching* pattern. Then, when the vehicle is stopped (2 - stop) at the intersection, the visual signal will display the *resting* pattern. Finally, when the vehicle maneuver is 0 - track_speed and the vehicle is moving pass the intersection, the visual signal will displaying the *caution* pattern. We will examine these visual patterns in each experiment. Table 3.2 provides a summary of the relationship between vehicle behaviour and visual signal output. The visual signal control messages are broadcast as an integer by a topic called *led_control*.

Vehicle Maneuver	Distance to Intersection (m)	Vehicle Speed (km/h)	Visual Signal Controller Output
0 - track_speed	> 100	40	0 - OFF
1 - decelerate_to_stop	< 100	< 40	1 - approaching
2 - stop	0	0	2 - resting
0 - track_speed	< 0	> 0	3 - starting

Table 3.2: Visual Communication System Prototype - Relationship Between Vehicle Behaviour and Visual Signal

[1]The crosswalk in Experiment 3 is about 2.6 meters before the interaction.

3.3.4 Arduino programs

In this section, we will discuss the Arduino programs written for this study. All of the programs listed below are written using the Arduino IDE and in the C programming language. Every program is designed to run on an Arduino UNO board, utilizing its full capabilities within the hardware limitations. For example, the LED_Control program runs on a dedicated UNO board to animate light patterns on a WS2815 LED strip; similarly, another program, ROS_Subscriber, runs on a dedicated UNO board to communicate with the ROS stack. Moreover, combinations and variations of these programs were used for the different experiments. The summary below provides an overview of these programs. We will describe in later chapters about how they are used for different experiments.

- **LED_Control**: This program controls the WS2815 LED strip through the Arduino IDE FastLED library. Control messages are transmitted serially to the light strip through the Arduino's digital output pins, and every message contains instructions for what pixels the strip should display. By updating these instructions every 100 to 250 ms, this program can produce a variety of static and dynamic light patterns on the LED strip. Examples of the patterns include blinking, expanding, and shrinking. These patterns will be described for each experiment as required.

  The LED colours are programmed using the following RGB colour codes.

  - Red - RGB decimal code of 204,6,5 (HEX code of #CC0605)
  - Green - RGB decimal code of 51,165,50 (HEX code of #33A532)
  - Amber - RGB decimal code of 255,191,0 (HEX code of #FFBF00)
  - Turquoise - RGB decimal code of 0,255,239 (HEX code of #00FFEF)

- **ROS_Subscriber**: This program turns the Arduino into a ROS subscriber node to retrieve relevant information from the Autonomoose ROS stack for the experiment. For example, it can subscribe to the ROS_vState_Publisher node to get vehicle position information, or the ROS_Light_Controller node to know what light patterns to display. The refresh rate is 10 ms.

- **ROS_Publisher**: Similarly, this program turns Arduino into a ROS publisher node, which publishes information from the Arduino to the Autonomoose ROS stack. The main use of this program is for data logging, such that the ROS stack can record and examine how a physical event relates to the components on the stack. For example, when a pedestrian is crossing, the event is recorded by a researcher pressing a button connected to the Arduino and the signal is then published as a ROS message. This program was used in Experiment 3 of the study.

Both the ROS_Subscriber and ROS_Publisher programs depends on the Arduino IDE ROS library.

- **Main_COMM**: This is the main processing program for both Experiment 1 and Experiment 2. It performs the following functions.

  1. To communicate with an Arduino HC-06 Bluetooth module, which is setup to receive participant inputs from a smartphone device.
  2. To communicate serially with the UNO running the LED_Control program and to send commands on what light patterns to display.
  3. To execute pre-programmed test scenarios for the experiment.
  4. To record and log experiment results for analysis.

3.3.5 Smartphone Applications

To assess participants' reaction to the visual signals, two Android Smartphone Application (app) were developed to capture and transmit their response to an Arduino board. The apps were developed using the MIT App Inventor platform. They were designed and tested on an Xiaomi Mi 5 Android smartphone. The apps' layout was optimized for its 5.15 inches screen. The same smartphone was used during the study. Figure A.2 in Appendix A shows sample screenshots of the apps. The apps' main function is to capture participants' input from the screen and transmit the input to the Arduino using the smartphone's builtin Bluetooth transceiver. The transmission messages are encoded using the ASCII format. An Arduino UNO board running the Main_COMM program will receive the messages by its HC-06 Bluetooth module. A 250 ms delay was imposed between each transmission to allow for transmission delay and Arduino processing. The apps were used in Experiment 1 and Experiment 2 of the study.

3.4 Installation and Integration

This section discusses how we attached the visual communication display on the research vehicle, connecting the hardware and software components and ultimately producing an integrated prototype for later experiments.

3.4.1 Mounting

In general, we identified two locations where we wished to mount the visual signals—top of the windshield and above the grill in the front of the vehicle. In preparation for later experiments, the mountings must hold the signals in place and keep them facing the participants, even when the vehicle is moving. To accomplish this, we designed an aluminum mounting rack to enclose the flexible light strips. The enclosure is built with a 3/4 inch or 1.905 cm aluminum U-channel, cut to 125 cm in length, which is the span of the top windshield. Two 5 inches zinc corner brackets are fastened to the vehicle's roof equipment rack. Then, we fasten the enclosure to the other end of the corner bracket using screws and bolts, thus placing the visual signal enclosure directly above the top windshield.

To attach the light strips to the enclosure, we placed the signal wire at the bottom of the enclosure, padding it with anti-static foam and a layer of black rubber tape, and glued the signal strips on top of the rubber tape. To weather-proof the design, the light strips are covered by transparent tape, the ends of the enclosure are sealed with electrical tape and the entire u-channel was further sealed with a layer of transparent tape. The holes in the back of the u-channel enclosure where wires exit were also plugged and sealed with electrical tape. See Figure 3.1 for illustration.

(a) Aluminum Mounting Rack

(b) Assembled Signal System

Figure 3.1: Visual Communication System Prototype - Mounting of Signals above the Windshield

The front signal mounting did not require an aluminum enclosure; instead, we utilized the existing channels on the grill of the vehicle, slotting anti-static foams to fill the gaps, placing black rubber tape on top, and installing the signal strips on top of the tape. Electrical wires for the visual signals were run underneath the hood and then along the edge of the window to merge with the wires from the top light strips. Electrical tape was also used to seal off the ends of the light strip to prevent water-damage. The whole installation assembly was also taped on both ends for added security. See Figure 3.2 for illustration.

(a) Anti-Static Foams Slotted in the Grill

(b) Assembled Signal System

Figure 3.2: Visual Communication System Prototype - Mounting of Signals in front of the vehicle

3.4.2 Integration

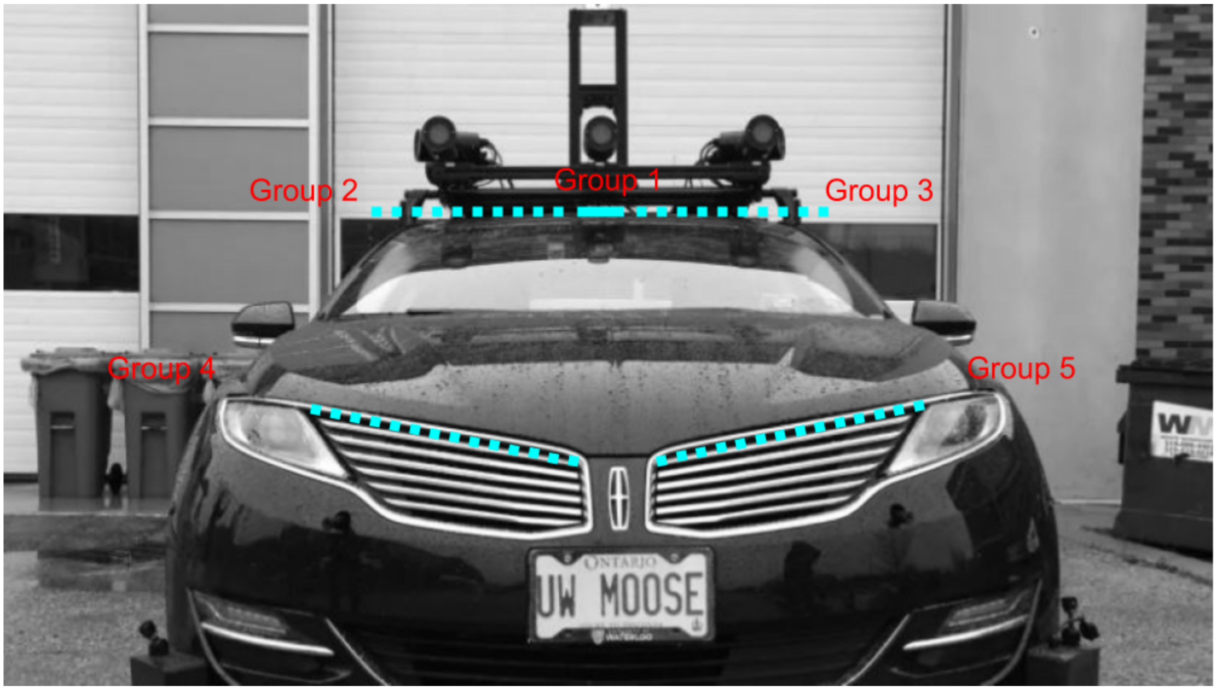
After mounting the visual signals, we proceeded to integrate the signals with the vehicle. First, we connected the light strips' voltage and ground wires to a 2 port wiring terminal block, which is connected to 12V cigarette plug power adapter that draws power from the vehicle's 12V DC auxiliary power. Then, we connected the light strips' data wires to the LED_Control Arduino board and we joined the Arduino ground with the light strip and vehicle groups. This provides a common reference point for the entire system and is crucial for the system to work. Finally, we connected the Arduino boards to the vehicle's computer using USB, thus allowing the vehicle software stack to communicate with the Arduino and light strips. As such, the integration of the visual system is complete.

3.5 System Overview

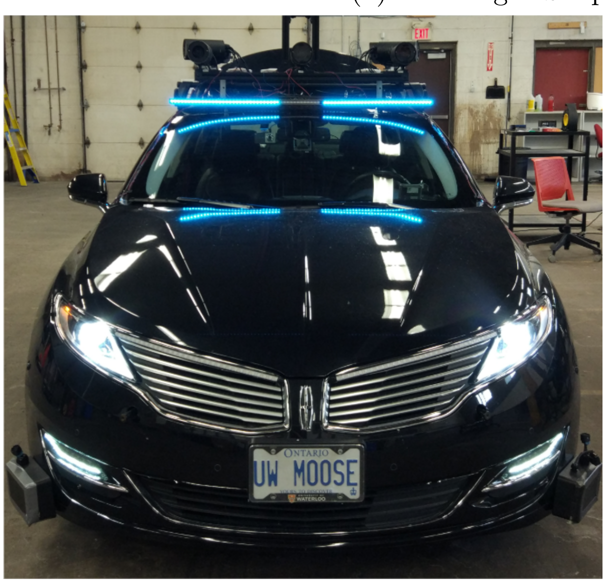
In this section, we will give an overview of the visual communication system. It serves as a reference for subsequent phases of the study, which utilize different parts of this system. In general, 5 groups of light strips were installed on the vehicle. Group 1 is designed as an ADS marker light. It is comprised of an LED strip, 13.28 cm long with 8 LED pixels spread evenly on the strip. The marker light communicates whether an ADS is operating in autonomy mode or self-driving mode. Group 2 through 5 are intention communication signals. Each group consists of an LED strip, 53.12 cm long with 32 LED pixels spread evenly on the strip. While the groups share identical designs, they can be programmed individually to display different visual patterns. These signals are the subjects of our experiments. Furthermore, each LED pixel draws a maximum of 60 mA, so in total, 136 pixels could draws a maximum of 8.16 A. This is within the max, 20 A, current capacity of the vehicle's auxiliary power port. Lastly, Group 2 and 3 differs from group 4 and 5 only by their mounting location. Table 3.3 provides an overview of the system physical and electrical properties. Figure 3.3 illustrates the layout of the visual signals and their appearance.

LED Strip	Pixel Counts	Length (mm)	Max Current (Amp)	DC Power (Volt)
Group 1	8	132.8	0.48	12
Group 2	32	531.2	1.92	12
Group 3	32	531.2	1.92	12
Group 4	32	531.2	1.92	12
Group 5	32	531.2	1.92	12
Total	136	233.8	8.16	12

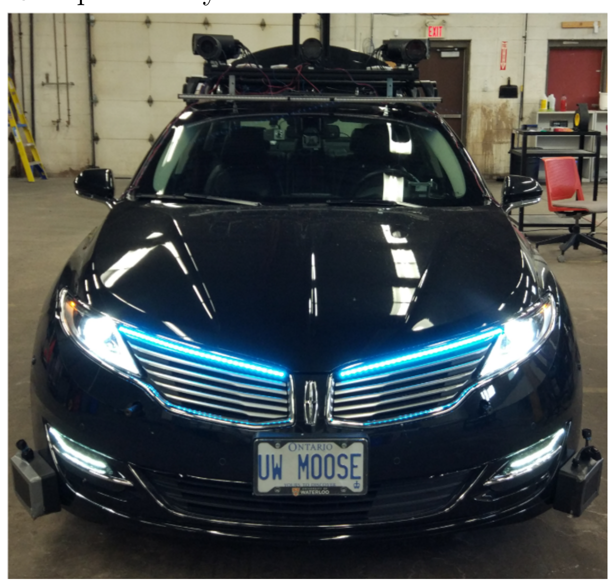
Table 3.3: Visual Communication System Prototype - Physical and Electrical Properties of Visual Signal Groups



(a) LED Light Strip Groups and Layout



(b) Top Mounted Lights (Group 2 and 3) Showing Solid Turquoise Pattern



(c) Front Mounted Lights (Group 4 and 5) Showing Solid Turquoise Pattern

Figure 3.3: Visual Communication System Prototype - Overview

Chapter 4

Phase 1: Visual Signal Designs

This chapter focuses on the design of an intention-communication visual system for autonomous vehicles. In particular, we seek to understand what design features would promote visibility and intuitive understanding by pedestrians. Note that the key is to make design decisions for the signals which have the best chance to be understood and accepted by pedestrians. Communication is a conduit for conveying the intention of the vehicle and in our case the communication channel is visual.[1] We designed and conducted two novel experiments to gain insights into those topics. This chapter will examine them separately, discussing the research questions, methods, and results. As far as we know, the two experiments are unique and original. We hope the findings in this chapter can serve as a useful reference to the design and standardization of autonomous vehicle visual signals going forward.

4.1 Background Information

In this section, we will provide some background information to give context for the experiments.

[1] This contrasts with achieving mutual beliefs of intention between intelligent systems and users through the communication of linguistic dialogues, though the aim is the same: to establish common ground.

4.1.1 Historical Context

Fundamentally, the main reason for communicating vehicle intention is to make the vehicle's movement predictable, and visual signals has been used for that purpose for over a century. In 1914, silent film star and automotive inventor, Florence Lawrence, invented the first "signalling arm" to communicate whether an automobile will turn or stop [45]. Shortly after, "Red tail lamps and yellow brake lights" were introduced in 1915 and "flashing turn signal" were added in 1940 [63]. Ever since, visual signals have been evolving with automobiles, signal lamps are now indispensable for every automobile. In fact, visual signals are part of our common knowledge such that people from around the world intuitively recognize that blinking turn signals signify a vehicle intends to turn, and illuminated brake lights signify a vehicle is about to stop. Some may even argue that the modern traffic system is built on people's shared understanding of visual signals; the traffic system could not function safely and smoothly without them.

However, as discussed in the literature review chapter, there are currently no visual signals to communicate a vehicle's stop and go intentions to pedestrians in front of the vehicle. While drivers currently perform that communication, the challenge for autonomous vehicle signal designers is to fill that gap, while keeping in mind the design constraints.

4.1.2 Design Constraints

The proliferation of automobiles in the 20$^{\text{th}}$ century spawned the invention of many automotive signals; similarly, the rise of autonomous vehicle in the 21$^{\text{st}}$ century could also bring about a new wave of signal inventions. However, the challenges this time are not technical; rather, they are integration and coordination. Today, it is estimated that there are over 1 billion vehicles on the road, one quarter of which are in the United States and one-third in China [64]. As such, the migration to autonomous driving is poised to take a long time, and thus, autonomous vehicles joining the traffic system must adhere to its rules and cope with road users' expectations. Hence, following are some design considerations for autonomous vehicle visual signals.

First, autonomous vehicle visual signals should comply with regulations and restrictions of colour. For example, in U.S. and Canada, the red and blue signals are mostly reserved for the police department; red signal is used by the fire department; green is used by emergency service vehicles; and amber is often used by construction and utility vehicles. While regulations could change to accommodate autonomous vehicle, it is important for signal designers to respect these restrictions to foster traffic harmony. Second, visual signals should align with people's expectations. For example, people naturally react to red traffic lights by stopping and green signal by accelerating. Hence, an effective visual signal must respect these mental models and not contradict them. Third, autonomous vehicle visual signals must not interfere with existing signals. It is self-explanatory why a visual signals should not have dual meanings. Finally, to facilitate standardization and globalization, autonomous vehicle signals should be universal. This means an effective visual signal should comply with all the above constraints regardless of jurisdiction or culture, and be, at least to some extent, the same or similar across all jurisdictions. While this is not an exhaustive list, we will use these restrictions as guidelines for designing the visual signals for the experiment in the next section.

4.2 Experiment 1: Visibility Study

4.2.1 Research Questions

The focus of this experiment is to discover design features that could enhance a visual signal's visibility, which we measure by how well it can be seen in a pedestrian's peripheral vision. Specifically, we explore a situation where pedestrians are crossing a street without looking for oncoming vehicles. It is a situation made worse by the increased usage of electronic devices, as pedestrians are increasingly being distracted by tasks such as texting or video streaming [26]. We feel this is an important crosswalk hazard that autonomous vehicles need to address and that a solution could be to attract pedestrians' attention with visual signals before they cross. Namely, we hypothesize that some visual signal patterns will be more prominent in a person's peripheral vision, and they are desirable because they can potentially warn a pedestrian even when he/she is not looking directly at the signal. To validate this hypothesis, we conducted a novel experiment to answer the following research questions.

- RQ1: What visual signal pattern is most notable in a pedestrian's peripheral vision?
- RQ2: Where to mount a visual signal to enhance its peripheral visibility?

4.2.2 Experiment Signals

In this experiment, we selected three unique patterns of visual signals for testing. Each pattern has a unique feature that impacts its visibility, and we mounted the signals in two different locations for examination. We choose to use Turquoise for the colour of visual signals because it is the recommended colour for autonomous vehicle signals [44]. The following are more details about the three signal patterns and Figure 4.1 depicts the signal patterns.

- **Solid**: a static signal pattern that resembles a vehicle's stop light or a traffic light. This kind of signal is simple and straight-forward to implement. It is the most commonly used pattern for traffic signals.
- **Blink**: a dynamic signal pattern that flashes ON and OFF. For this experiment, the pixels on our LED light strip flashes continuously at 2 Hz[2].
- **Chase**: a dynamic signal pattern that exhibits horizontal movements. For this experiment, two parallel LED light strips span the width of the vehicle; when looking directly at them, the pixels on both light strips turn ON one-by-one, expanding from the center to the outside of the vehicle. Once reaching the end, all pixels turn OFF at once and the pattern repeats continuously at 4 Hz.

The focus of this experiment is on how signal patterns can affect visibility. Specifically, the Blink and Chase signals represent two broad classes of dynamic signal patterns: the flashing pattern and the sweeping pattern. In this experiment, we will investigate how these two classes of patterns, along with the Solid pattern, impact visibility (RQ1). At the same time, we will examine how mounting location, top of the windshield or the front bumper, impacts visibility (RQ2). Altogether, we tested the following six signals and they are displayed using the corresponding light strips.

E1-S1:	Top Solid Turquoise	(LED light strip groups 2 and 3)
E1-S2:	Front Solid Turquoise	(LED light strip groups 4 and 5)
E1-S3:	Top Blink	(LED light strip groups 2 and 3)
E1-S4:	Front Blink	(LED light strip groups 4 and 5)
E1-S5:	Top Chase	(LED light strip groups 2 and 3)
E1-S6:	Front Chase	(LED light strip groups 4 and 5)

[2]As reference, SAE specified a flashing rate of 1 to 2 Hz for vehicle turn signals [41].

(a) Solid

(b) Blink (2 Hz)

(c) Chase (4 Hz)

Figure 4.1: Basic Autonomous Vehicle Visual Signal Patterns

The meaning of a visual signals often originates from its colour and movement. For example, for a static signalling system like a traffic light, its colours give its meaning. On the other hand, for a dynamic visual signal like Blink and Chase, its meaning comes from its movement. We will investigate specifically the meaning they convey in the next section;

4.2.3 Location and Time

The experiment was conducted at parking lot B beside the University of Waterloo Engineering 5 building. An area of approximating 25 x 15 meters was sectioned off with pylons for the experiment, which took place over 9 days in various time slots between 10:00 am to 10:30 pm. During those times, we encountered various weather conditions including sunny, cloudy, and night. The diversity of conditions was expected and desirable because it resembled the conditions visual signals must eventually operate in. However, we also recognize the outdoor brightness can greatly impact the visibility of visual signals. Hence, we took illuminance measurements before each trial to quantify the experiment results. In particular, the measurements were taken using the same smartphone light sensor and by the same method of placing the smartphone face up so its light sensor points toward the sky. These practices ensure consistency in the illuminance measurements, thus allowing for comparable interpretations of experiment results.

4.2.4 Participants

In total, 31 participants (22 males and 9 females) between 18 and 44 years old were recruited for the study. They were recruited on the University of Waterloo campus using computer science department mailing-lists and recruitment posters around the campus. 29 of 31 participants (93.5%) received some level of college and university education. 25 of 31 participants (80.6%) hold a valid driver's license; 11 of 31 participants (35.5%) own a motor vehicle; and, 23 of 31 participants (74.2%) have at least 1 years of driving experience. When asked to estimate the average number of times they cross a street each day, 5 (16.1%) said 0-5 times, 16 (51.6%) said 6-10 times, 6 (19.4%) said 11-15 times, 2 (6.5%) said 16-20 times, and 2 (6.5%) said 20 or more times. Finally, 21 of 31 participants (67.7%) rated themselves 6 or higher on a 7-point Likert scale indicating a high level of willingness to adopt and accept new products or innovations. Each participate received $20 Canadian as appreciation for participation in both experiments.

4.2.5 Methods and Procedures

This experiment mimics a street-crossing situation, where a pedestrian crosses a street without checking for vehicles. It starts by having the study vehicle display one of the experiment signals and drive toward a crosswalk. A participant is waiting and trying to detection the vehicle or its visual signals using their peripheral vision. Upon detection, the distance between the vehicle and the participant, called **distance gap**, is recorded. Hence, by comparing the distance gap produced by different visual signals, assuming a larger distance gap represents better visibility, we can infer which visual signal has better visibility. Similarly, by comparing the gap produced by different visual signals mounted at different vehicle locations, we infer the impact of mounting location on visibility. The following is the detailed procedure of Experiment 1.

1. A researcher briefs the participant about the experimental procedure and their role and guides them to the experiment location.

2. The experiment consists of 28 test trials and two practice trials. Each of the trials differ in three ways from each other[3]:
   - Participant location: a participant could be standing at either 1 or 3 meters away from the imaginary crosswalk.
   - Vehicle location: the vehicle could be approaching either from the left or right side of the pedestrian.
   - Signal types: the vehicle could be displaying no visual signal or one of six experiment signals.
3. Participants are randomly assigned to 4 possible study locations, 1 or 3 meters from the crosswalk and with vehicle approaching either from left or right.
4. At each location, participants first do the baseline test, without any visual signal, followed by 6 test trials with experiment signals appearing in random orders.
5. Prior to starting the baseline test, the participant did 2 practice trials, with and without any visual signal, to familiarize with the experimental procedure.
6. Each trial followed the experimental steps below:
   - The autonomous vehicle is parked out-of-sight of the participant.
   - The participant stands at the study location, keeping their head straight looking parallel to the crosswalk and not turning either side. They are instructed to use their peripheral vision to scan for the vehicle or any visual signal; they are also instructed not to focus on anything to avoid tunnel-vision.
   - As the study vehicle approaches the crosswalk at 5 km/h, it displays one of they experiment signals. The vehicle is manually driven by a qualified researcher.
   - A research assistant is standing near the participant as a safety precaution.
   - When the participant spots the vehicle or a visual signal, they say ‘STOP’.
   - At which point, the research assistant use the custom-build app to send a signal to the vehicle to mark the location of detection[4].
   - Upon receiving the signal, the vehicle turns off the visual signal and calculates the **Distance Gap** between it and the participant, recording the result.

[3]Figure 4.2 illustrates the difference in participant and vehicle locations

[4]We did not let the participant operate the app to avoid potential distraction.

- Moreover, the participant is asked to describe the signal pattern they saw. The research assistant records the answer and does not tell the participant whether they were correct.
- The vehicle returns to the start location and the trial ends.

7. The experiment ends after all the trials have been completed. The order of trials were randomized.

Experiment 1 takes approximately 45 minutes to complete. The participant takes a five minutes rest and Experiment 2 proceeds afterward.

Figure 4.2: Experiment 1 - Illustration of the Difference in Participant and Vehicle Locations

4.2.6 Results

In total, 28 participants completed the experiment and generated valid results. Regarding RQ1, the experiment reveals that dynamic visual signals, like Blink and Chase, are more visible in peripheral vision than a Solid visual signal. This finding is consistent with previous optometry research that suggest peripheral is good at detecting motion [59]. Specifically, participants detected the Blink and Chase signals at an average of 7.95 meters and 7.99 meters, which are significantly better the average distance gaps of the Solid Turquoise signal of 5.84 meters. Using the Analysis of Variance (ANOVA) test, the difference between the groups are ($F(1,498) = 13.96$, $p < .001$, $\eta^2 = .031$) and $F(1,520) = 14.8$, $p < .001$, $\eta^2 = .032$), respectively[5]. There are no significant difference among the results produced by Blink and Chase signals ($F(1,0.2) = .007$, $p = .934$, $\eta^2 < .001$).

Regarding RQ2, this experiment also found that mounting location does not significantly impact visual signals' visibility. Namely, Solid visual signals mounted at the top of the windshield and at the front of the vehicle have an average distance gap of 5.7 meters and 5.98 meters, respectively ($F(1,4) = .116$, $p = .734$, $\eta^2 < .001$); Blink visual signals mounted at the top of the windshield and at the front of the vehicle have an average distance gap of 8.03 meters and 7.87 meters, respectively ($F(1,1) = .041$, $p = .841$, $\eta^2 < .001$); Chase visual signals mounted at the top of the windshield and at the front of the vehicle have an average distance gap of 7.78 meters and 8.21 meters, respectively ($F(1,11) = .322$, $p = .571$, $\eta^2 =.002$). Moreover, we found on average that visual signal visibility is not significantly impacted by where pedestrians are standing, 1 meter or 3 meters from the crosswalk and whether the vehicle is approaching from the left or from the right ($F(3,72) = 2.05$, $p = .106$, $\eta^2 = .009$). Table 4.1 shows the average distance gaps obtained in various test conditions. Standard Error of the Mean (S.E.M.) is calculated by dividing the variance by sample size and taking the square-root of the result. Figure 4.3 illustrates these findings graphically.

Impacts of Brightness

Moreover, the experiment confirms that visual signal visibility is highly susceptible to external influence such as outdoor brightness, measured as illuminance. Specifically, we grouped the results into three conditions according to the average brightness level in which the experiment trials were performed. The three conditions are: 1) sunny condition - Lux higher than 10,000 (N=11); 2) overcast condition - Lux between 1,000 - 10,000 (N=6); and 3) nightfall condition - Lux below 1,000 (N=8). Figure 4.5 illustrates the difference in brightness conditions. Then, as expected, we found the visual signals are most salient in nightfall and least visible in bright sunlight. However, we are also surprised to discover that the visibility advantage of dynamic signals vanished during nightfall and sunlight

[5] To account for any potential difference in participants' visual abilities, we performed additional ANOVA tests by normalizing the distance gaps against the participants' baseline gaps. These tests revealed the same results.

Average	Baseline No Signal	E1-S1 Top Solid Turquoise	E1-S2 Front Solid Turquoise	E1-S3 Top Blink	E1-S4 Front Blink	E1-S5 Top Chase	E1-S6 Front Chase
1 meter from Right:	8.67 (±0.77)	5.04 (±1.26)	6.04 (±1.18)	7.70 (±1.14)	7.84 (±1.10)	7.73 (±1.01)	7.90 (±1.19)
1 meter from Left:	8.71 (±0.70)	5.14 (±1.15)	4.74 (±1.06)	6.80 (±1.10)	7.65 (±1.13)	6.86 (±1.11)	7.58 (±1.08)
3 meter from Right:	9.63 (±0.67)	5.94 (±1.11)	6.46 (±1.15)	9.19 (±1.01)	8.44 (±1.03)	8.63 (±0.97)	9.17 (±1.01)
3 meter from Left:	9.60 (±0.70)	6.67 (±1.24)	6.67 (±1.23)	8.42 (±1.12)	7.54 (±1.16)	7.88 (±1.18)	8.19 (±1.09)
Gap Average:	9.15 (±0.35)	5.70 (±0.59)	5.98 (±0.57)	8.03 (±0.55)	7.87 (±0.55)	7.78 (±0.53)	8.21 (±0.54)

Table 4.1: Experiment 1 - Average Distance Gaps of Visual Signals in Various Test Conditions (in Meters) and S.E.M. in brackets (N=28)

conditions. Namely, there were no significant difference in the distance gaps between the six experiment signals, ($F(5,5) = .187$, $p = .967$, $\eta^2 = .005$) and ($F(5,14) = 1.62$, $p = .161$, $\eta^2 = .053$), in nightfall and sunlight condition respectively. Further, Blink, Chase, and Solid Turquoise signals are looked the same regardless of where they are mounted. The advantage of dynamic signals over Solid signal is only significant in overcast condition, ($F(5,166) = 14.12$, $p < .001$, $\eta^2 = .213$). Table 4.2 shows the average distance gaps obtained in different illuminance level. The baseline corresponds to the gap the participant sighted the vehicle. Figure 4.4 illustrates these findings graphically.

Identification Accuracy

Analyzing participant responses to what they think they saw, it seems like pedestrians can differentiate the experiment visual signals in their peripheral vision. For all six experiment signals, participants were able to accurately identify them between 50% to 76% of the time, suggesting these are not random guesses. Moreover, identification accuracy is particularly high for experiment signals E1-S2, E1-S3, and E1-S4 with over 70% accuracy. Ignoring the mounting position of the visual signals, participants' identification accuracy for the Solid, Blink, and Chase signal is 66%, 73%, and 51%, respectively. While it is tempting to conclude these signals are more recognizable, it is also possible that some participants

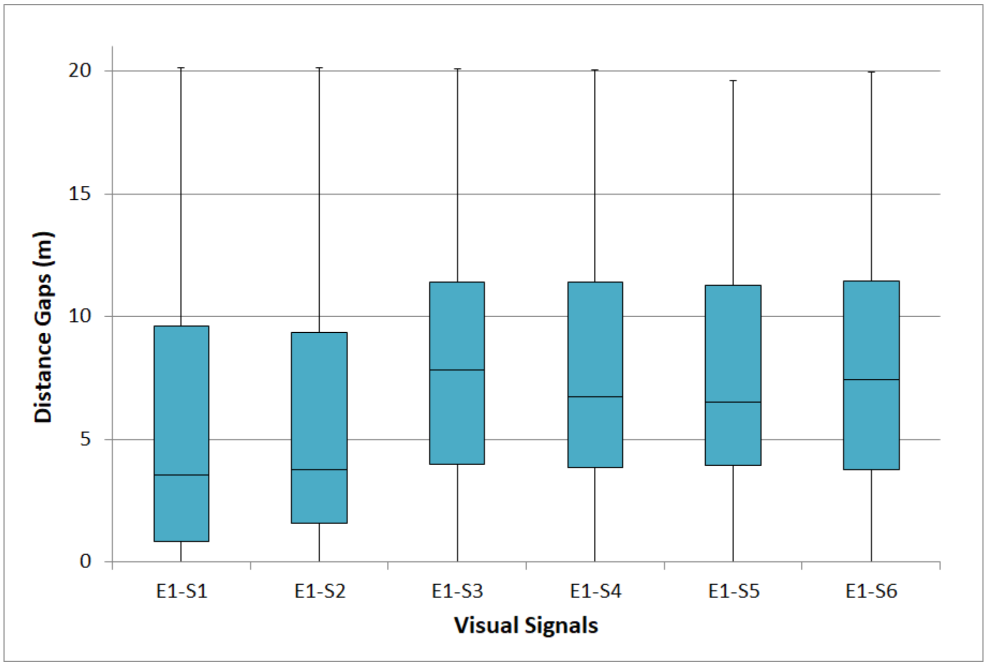


Figure 4.3: Experiment 1 - Visual Signal Visibility Measured as Average Distance Gaps (in Meters)

Average	Baseline No Signal	E1-S1 Top Solid Turquoise	E1-S2 Front Solid Turquoise	E1-S3 Top Blink	E1-S4 Front Blink	E1-S5 Top Chase	E1-S6 Front Chase
Sunny Condition:	6.23 (±0.69)	1.08 (±0.46)	1.52 (±0.50)	2.86 (±0.73)	1.98 (±0.65)	2.56 (±0.58)	2.92 (±0.65)
Overcast Condition:	10.12 (±0.46)	3.16 (±0.48)	3.51 (±0.45)	7.41 (±0.60)	6.77 (±0.50)	6.82 (±0.56)	7.26 (±0.52)
Nightfall Condition:	11.29 (±0.57)	13.69 (±0.86)	13.66 (±0.88)	13.83 (±0.91)	14.48 (±0.79)	13.92 (±0.82)	14.51 (±0.88)

Table 4.2: Experiment 1 - Average Distance Gaps of Visual Signals in Various Illuminance Level (in Meters) and S.E.M. in brackets (N=11,6,8)

made educated guesses that they would see the front-mounting visual signals before the top-mounting ones, and that Blink signals are more familiar than Chase.

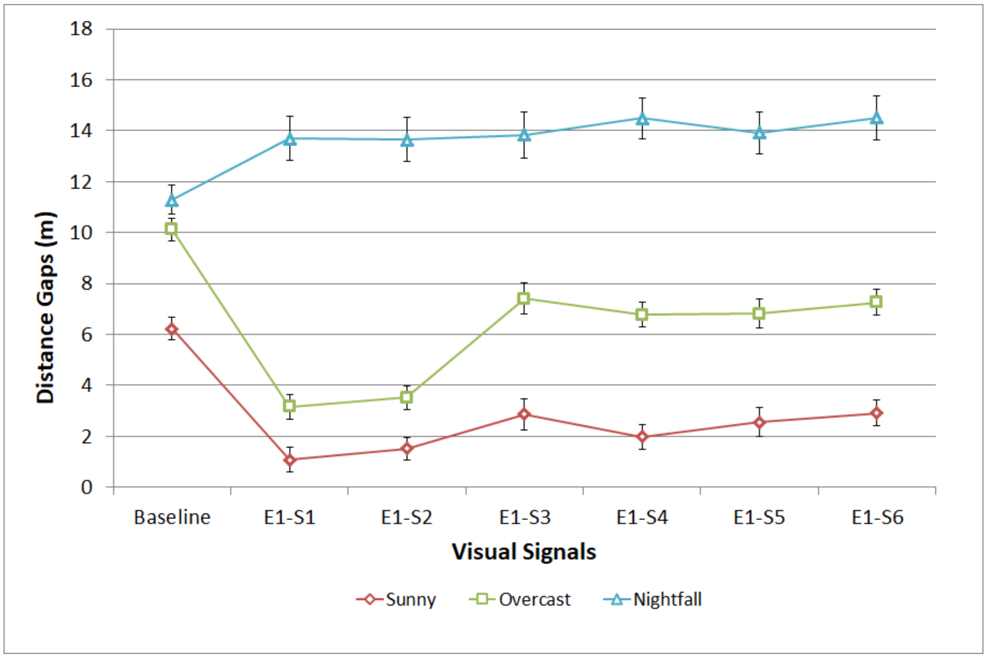


Figure 4.4: Experiment 1 - The Impact of Illuminance Level on Visual Signal Visibility Measured as Average Distance Gaps (in Meters) and S.E.M. as Error bars

(a) Sunny Condition - Lux > 10,000

(b) Overcast Condition - Lux between 1,000 - 10,000

(c) Nightfall Condition - Lux < 1,000

Figure 4.5: Experiment 1 - Illustration of the difference in Outdoor Brightness Conditions

4.3 Experiment 2: Intuition Study

4.3.1 Research Questions

The goal of this experiment is to learn the cognitive impact of visual signal patterns. Previous studies found that people use mental models to represent the causal relationships between what they observe and its consequence [29]. Similarly, we believe people have developed mental models about visual signals, which influence their street-crossing behaviours. For example, pedestrians have learn to cross when the *walk* signal is shown. In some instance, the influence of such a mental model is so prevalent, people are using it as a mental shortcut to cross without checking the traffic situation [58]. However, in contrast, mental models for autonomous vehicle visual signals are less clear. Upon seeing a novel signal, pedestrians would not know immediately what to do; instead, we hypothesize their mind would attempt to associate the signal with a model they know in order to decide what to do. The process of association could both conscious and unconscious; however, we believe there will be salient signal features that would trigger certain common associations. It is the goal of this experiment to discover how those associations operate, thus learning how to map design features to potential pedestrian actions. These could then be effective choices for the design of autonomous vehicle visual signals. In addition, we will try to qualify the cognitive demand of visual signal features in terms of decision time, arguing a pedestrian would take less time to act on an easy-to-associate signal and take more time on an a complex signals. Finally, we will investigate whether mental models can be taught by demonstration. In summary, we ask the following research questions.

- RQ3: How would a pedestrian react to different visual signals intuitively?
- RQ4: How would a pedestrian react to different visual signals after training?
- RQ5: How long does it take for a pedestrian to interpret and react to different visual signals?

4.3.2 Experiment Signals

Six unique signal patterns were examined in this experiment. Some of the signals were derived from the literature and others were conceived and designed by the research team. Whatever the case, they have distinct features that are designed to communicate whether an autonomous vehicle will yield or not. Similar to Experiment 1, we used the LED light strips mounted above the windshield to display the visual signals; the front mounting light strips were not used because mounting location is not the focus of this experiment. Moreover, a green and red solid signal was used as baseline signals to measure participants reaction time. Altogether, the visual signals for this experiment can be divided into 4 groups.

- **Baseline**: the **Solid Red** and the **Solid Green** signal in this group resemble those on a traffic light. The red signal indicates a pedestrian should stop and the green signal indicate a pedestrian can go. For the regulatory and practicality reasons these colours are not good choices for autonomous vehicle visual signals. However, they are useful baselines for understanding how pedestrian would react to visual signal.

- **Solid**: this group consists of a **Solid Amber** and a **Solid Turquoise** signal. The Amber signal resembles the ready to stop signal on a traffic light; consequently, we expect most pedestrian to interpret it as a warning to yield. On the other hand, Turquoise signals are uncommon and it is unclear how a pedestrian may interpret them. Both signals are evaluated in this experiment.

- **Dynamic**: this group consists of the same dynamic signals in Experiment 1. Namely, the **Blink** signal that flickers ON and OFF continuously and the **Chase** signal that extends from the center of the vehicle outward. In this experiment, we are interested in investigating the flashing and sweeping characteristics of the two signals, thus understanding how pedestrians will interpret them in a crosswalk situation. Both signals use the Turquoise colour.

- **Perceptual**: this group consists of two visual signals that are correlated to vehicle movement - the **Expanding** and the **Shrinking** signals. They are novel and are inspired by the door that opens and closes depending on a person's proximity from it [34]. For the Shrinking signal, its LED pixels turn OFF successively as the autonomous vehicle approaches a crosswalk, turning OFF the last pixel exactly when the vehicle stops; for the expanding signal, its LED pixels turn ON successively as the autonomous vehicle accelerates from rest, eventually filling the entire light bar. These signals translate the vehicle's movement into visual cues in order to accentuate pedestrians' awareness of the vehicle movement, thus allowing pedestrians to make informed crossing decisions with ease. For this experiment, the pixels on our LED light strip flashes continuously at 0.3 Hz. Both signals use the Turquoise colour.

Altogether, we tested the following 6 of visual signals and 2 baseline signals; they were displayed using LED light strip groups 2 and 3. Figure 4.6 depicts these signals.

E2-B1: Baseline Solid Red

E2-B2: Baseline Solid Green

E2-S1: Solid Amber

E2-S2: Solid Turquoise

E2-S3: Blink Turquoise

E2-S4: Chase Turquoise

E2-S5: Expanding Turquoise

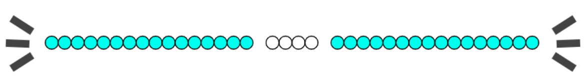
E2-S6: Shrinking Turquoise

(a) E2-B1: Baseline Solid Red

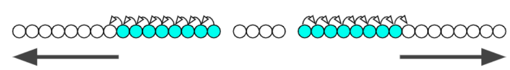
(b) E2-B2: Baseline Solid Green

(c) E2-S1: Solid Amber

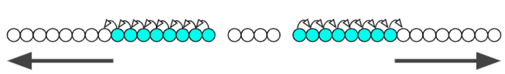
(d) E2-S2: Solid Turquoise



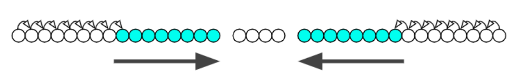
(e) E2-S3: Blink Turquoise (2 Hz)



(f) E2-S4: Chase Turquoise (4 Hz)



(g) E2-S5: Expanding Turquoise (0.3 Hz)



(h) E2-S6: Shrinking Turquoise (0.3 Hz)

Figure 4.6: Experiment 2 - Depictions of Featured Visual Signals

4.3.3 Location and Participants

This experiment is conducted at the same location as Experiment 1 and with the same participants.

4.3.4 Methods and Procedures

This experiment also mimics a street-crossing situation, where an autonomous vehicle is approaching a crosswalk and a pedestrian needs to decide whether it is safe for them to cross the road. The focus of this experiment is to determine how the above experiment signals would make a pedestrian feel; do they produce a feeling of easiness or a feeling of uncertainty? We can deduce the pedestrian's feelings by observing whether they decide to cross the road or not. The experiment is conducted in three parts.

Part 1 measures a participant's baseline reaction time to a visual signal. This involves showing a randomized sequence of 12 baseline signals: six E2-B1 and six E2-B2. Participants are asked to react immediately to the signals using the handheld application in Section 3.3.5. They press the *GO* button upon seeing the Solid Green signal and press the *STOP* button upon seeing the Solid Red signal. The participants make their choice using a smartphone with a custom-designed app and their decision and time to decision are captured by the Arduino board communicating with the smartphone.

The second part of the experiment is similar to the first, except it consists of two trials and a randomized sequence of 18 experiment signals shown to the participants each time. The signal sequence is comprised of 6 experiment signals each appearing 3 times. Participants had no prior knowledge of the meaning of the signals; upon seeing the signals, they were asked to decide as quickly as possible whether they feel comfortable crossing the road. Again, they indicated their choice by pressing the *GO* and *STOP* button on a smartphone app. In the first trial, the vehicle was *parked* in front of the simulated crosswalk and the participants were instructed to make their crossing decision in that context. In the second trial, the vehicle was parked 17 meters away[6] from the front of the vehicle to the crosswalk and the participants were instructed to make their decision by imagining the vehicle is *approaching* at 40 km/h. The second trial investigates a supplementary research question of how participants would interpret the visual signals of a 'moving' compared to that on a stationary vehicle. This trial was not conducted with a moving vehicle because the

[6] The theoretical stopping distance for a vehicle traveling at 40 km/h on a dry road with a 0.7 coefficient of friction and using 1 second as reaction time is about 20 meters calculating from the rear axle of the vehicle or 17 meters from the front of the vehicle [18].

timing error resulting from the vehicle's movement would have prevented us from getting a consistent measurement of the participants decision time; doing the trial with a stationary vehicle is also beneficial for isolating the visual signals from other influencing factors such as the vehicle's movement. Therefore, we asked participants to use their imagination for trial 2. Majority of the participants in Part 2 experienced trial 1 (parked vehicle) before trial 2 (approaching vehicle). Part 2 is to answer RQ3.

Finally, Part 3 of the experiment is identical to Part 2, except we gave participants a 2-minute training on what the signals meant. We showed the participants the visual signals and described them using the following adjectives in order to help them remember.

E2-S1: Solid Amber - 'caution'

E2-S2: Solid Turquoise - 'calm'

E2-S3: Blink Turquoise - 'danger'

E2-S4: Chase Turquoise - 'hand wave'

E2-S5: Expanding Turquoise - 'accelerating'

E2-S6: Shrinking Turquoise - 'decelerating'

Majority of the participants in Part 3 experienced trial 2 (approaching vehicle) before trial 1 (parked vehicle). Part 3 to answers RQ4 and altogether Experiment 2 investigates RQ5. The following is the detail procedure of Experiment 2.

1. A researcher briefs the participant about the experimental procedure and their role in the experiment.

2. The participant stands at one of the experiment locations, which is 3 meters away from the vehicle's path of travel and at either the left or right side of the vehicle.

3. The experiment consists of 5 test trials and 1 practice trial. They are grouped into the three parts as mentioned above.

    - Part 1: a baseline trial to record the participant's reaction time. The trial consists of a randomized sequence of 12 baseline signals, with each baseline signal appearing 6 times.
    - Part 2: two experiment trials to examine the participant's reaction to visual signals without prior knowledge of the signals' meaning.

- Part 3: two experiment trials to examine the participant's reaction to visual signals after learning about the signals' meaning.

4. The three parts were conducted sequentially.

5. Each of the experiment trial in Part 2 and Part 3 consists of a randomized sequence of 18 experiment signals, with each experiment signal appearing 3 times.

6. The participants are assigned randomly to one of the experiment locations.

7. Prior to Part 1, the participant did a practice trial to get acquainted with the experiment and the app they will be using. Figure A.2 (c) shows a sample screenshot of the app and it is described in Section 3.3.5. The results are not recorded.

8. Prior to Part 2, we gave the participants a preview of the 6 experiment signals, the preview of each signal lasted about 3-5 second. This is done so the participant would not be overwhelmed during the test.

9. Prior to Part 3, we gave the participant a 2 minutes training of the experiment signals, explaining their intended meaning.

10. Each Part 2 and Part 3 consists of a trial with the vehicle stopped in front of the crosswalk, and a trial with the vehicle parked 17 meters away from the crosswalk[7]. For the latter case, the participant is instructed to imagine the vehicle is approaching the crosswalk at a speed of 40 km/h.

11. Each trial followed the experimental steps below:

    - The participant stands at the experiment location looking at the vehicle and hold a smartphone running the custom designed Android app connected with the visual signal system on the vehicle.
    - The participant presses the *READY* button to begin the trial.
    - The vehicle displays a randomly-selected visual signal and starts an internal timer.
    - The participant interprets the signal and presses either the *GO* or *STOP* button on the app to indicate whether they will cross the street or not.

[7]Figure 4.7 illustrates the vehicle positions

- The vehicle turns off the visual signal and stops the timer upon receiving the participant's decision. It records the participant's decision and time to make the decision.
- The vehicle waits 3 seconds and displays another randomly-selected visual signal.
- This process repeats until all the signals have been shown in the trial, thus ending the trial.
- The participant then moves to the other experiment location and is offered a two-minute break.

12. The experiment ends after all 5 trials are completed.

Experiment 2 takes about 45 minutes to complete. Since Experiment 1 and Experiment 2 are designed to be independent experiments, hence they are administered in random order to avoid unintended learning.

(a) Stopped in Front of the Crosswalk

(b) 17 meters away from the Crosswalk supposedly Approaching

Figure 4.7: Experiment 2 - Illustration of Experimental Vehicle Positions

4.3.5 Results

In total, 17 participants completed the experiment and generated valid results, which included 612 intuition tests for Part 2 and 612 learned tests for Part 3. Of the total 1224 tests, 11 (0.899%) were discarded due to recording errors. In summary, we found distinct patterns in how participants react to visual signals, which seems to confirm our hypothesis that pedestrians share certain mental intuitions about visual signals and use them, rather consciously or subconsciously, to guide their street crossing behaviours. Namely, for the intuition tests in Part 2, we found that the E2-S3 Blink and E2-S4 Chase signals consistently induce participants to decide Not to Cross, 84.0% and 90.10% of the time, respectively. Similarly, the E2-S2 Solid Turquoise, E2-S5 Expanding, and E2-S6 Shrinking signals are also effective to convince participants to Cross. However, some signals can also be ambiguous, such as the E2-S1 Solid Amber signal, in which participants decided 47% of time to cross and 53% of the time not to cross. Table 4.3 shows a summary of the participants' intuitive reactions to visual signals.

Now, for the learned tests in Part 3, we found that participants can learn to react differently to visual signals after receiving the necessary training. Namely, they learned to Not to Cross on the E2-S1 Solid Amber signal and E2-S5 Expanding signal, 94.12% and 72.55% of the time, respectively. However, training was not sufficient to overcome participants' intuition of not crossing to a E2-S4 Chase signal. Although the percentage dropped, 61.39% of the time, participants still decided they will not cross at the signal. Table 4.4 shows a summary of the participants' learned reactions to visual signals.

Number of	E2-S1 Solid Amber	E2-S2 Solid Turquoise	E2-S3 Blink	E2-S4 Chase	E2-S5 Expanding	E2-S6 Shrinking
Valid tests:	100	101	100	101	101	101
Cross Decisions:	47 (47.0%)	77 (76.24%)	16 (16.0%)	10 (9.90%)	80 (79.21%)	81 (80.20%)
Not Cross Decisions:	53 (53.0%)	24 (23.76%)	84 (84.0%)	91 (90.10%)	21 (20.79%)	20 (19.80%)
Aggregate Reaction:	Ambiguous	Cross	Not Cross	Not Cross	Cross	Cross

Table 4.3: Experiment 2 - Participants' Intuitive Reactions to Visual Signals (as Percent of Valid Tests) (N=17)

Finally, the experiment revealed the decision time required for participants to deliberate on the visual signals. On average, participants took 2.5 and 2.6 seconds to decide on the E2-S1 Solid Amber and E2-S4 Chase signals, respectively; also, they took 2.8 and 2.9 seconds to decide on the E2-S2 Solid Turquoise and E2-S3 Blink signals; finally, they took 3.0 and 3.1 seconds to interpret the E2-S5 Expanding and E2-S6 Shrinking signals. The average S.E.M. of decision time in part 2 is 0.14 second. A shorter decision time could indicate that a visual signal demands less mental effort to process, with a longer decision time being more strenuous. However, the decision time could also been impacted by animation time of

Number of	E2-S1 Solid Amber	E2-S2 Solid Turquoise	E2-S3 Blink	E2-S4 Chase	E2-S5 Expanding	E2-S6 Shrinking
Valid tests:	102	102	102	101	102	100
Cross Decisions:	6 (5.88%)	90 (88.24%)	33 (32.35%)	39 (38.61%)	28 (27.45%)	79 (79.0%)
Not Cross Decisions:	96 (94.12%)	12 (11.76%)	69 (67.65%)	62 (61.39%)	74 (72.55%)	21 (21.0%)
Aggregate Reaction:	Not Cross	Cross	Not Cross	Not Cross	Not Cross	Cross

Table 4.4: Experiment 2 - Participants' Learned Reactions to Visual Signals (as Percent of Valid Tests) (N=17)

the visual signals. Namely, the E2-S5 Expanding and E2-S6 Shrinking signals take longer to animate and that could be why participants take longer to interpret them.

Moreover, comparison of the decision time between the intuition and learned tests revealed that the decision time for the E2-S1 Solid Amber decreased from 2.7 seconds for the intuition tests to 2.3 seconds for the learned tests, suggesting perhaps, the training had removed the ambiguity and confusion about the signals. A similar observation can be made for the E2-S5 Expanding signal, which training also disambiguated: the participant decision time decreased from 3.2 seconds to 2.8 seconds. Coincidentally, the decision time for both signals reduced by about 0.4 seconds, which could be interpreted as a tangible benefits of training. However, training can have an opposite effect on decision time. Namely, decision time for both the E2-S3 Blink and E2-S4 Chase increased 0.4 and 0.5 seconds, suggesting it required more mental effort to distinguish the two similar signals from each other. The average SEM for the learned tests in Part 3 is 0.15 second. Table 4.5 shows a summary of the participants' intuitive and learned decision time and standard error for each visual signal.

Furthermore, the vehicle's position, whether it is parked at the crosswalk or supposedly approaching at 40 km/h, did not significant change participants reactions and decision time to the visual signals ($F(1,283921) = .124$, $p = .725$, $\eta^2 < .001$). Rather, we observed participants' decision time was quicker in trial 2, compared to trial 1, regardless of the vehicle's position. Specifically, decision time was on average 0.4 seconds quicker for the intuition tests and 0.3 seconds quicker for the learned tests. We believe this is caused by participant's increased familiarity with the visual signals.

Finally, the average reaction time for baseline E2-B1 Solid Red and E2-B2 Solid Green signals is 1.3 seconds. When performing the ANOVA statistical test, the 11 test results (0.899%) that were discarded due to recording errors was assumed to the participant's baseline reaction time. The ANOVA test confirms that there exists significant interaction between training and decision time, (F(5,8603) = 3.8, $p < .01$, $\eta^2 = .015$); and, decision times are significantly different for each visual signal, (F(5,11992) = 5.3, $p < .001$, $\eta^2 = .021$)[8]. The reaction times in the above discussions and tables are not normalized.

The results for Experiment 1 and Experiment 2, and the standard ANOVA are discussed in Chapter 7.

Decision Time	E2-S1 Solid Amber	E2-S2 Solid Turquoise	E2-S3 Blink	E2-S4 Chase	E2-S5 Expanding	E2-S6 Shrinking
Combined Average:	2.5 (±0.11)	2.8 (±0.10)	2.9 (±0.10)	2.6 (±0.10)	3.0 (±0.11)	3.1 (±0.12)
Intuitive Case:	2.7 (±0.14)	2.9 (±0.14)	2.7 (±0.12)	2.3 (±0.11)	3.2 (±0.17)	3.2 (±0.18)
Learned Case:	2.3 (±0.16)	2.6 (±0.14)	3.1 (±0.17)	2.8 (±0.15)	2.8 (±0.14)	3.0 (±0.16)
Difference:	-0.4	-0.3	+0.4	+0.5	-0.4	-0.2

Table 4.5: Experiment 2 - Participants' Intuitive and Learned Decision Time to Visual Signals (in Seconds) and S.E.M. in brackets (N=17)

4.4 Qualitative Study

Prior to Experiment 1 and Experiment 2, a researcher welcomed each participant and asked them to sign a consent form and to fill out a pre-study questionnaire. The questionnaire collected basic demographic information about the participant, including age, gender, education, and years of driving experience. Moreover, it also asked participants to estimate the number of times they cross a street per day, their attitude toward technology adoption, and their knowledge and impressions of autonomous vehicles. The questionnaire was completed on Google Forms using an Apple iPad.

[8]To account for any potential difference in participants' reaction time, we performed additional ANOVA tests by normalizing the decision time against the participants' baseline reaction time. These tests revealed the same results.

Upon completing Experiment 1 and Experiment 2, each participant is asked to complete a post-study questionnaire, which assessed their experience with the visual signals and whether the experiments changed their impression of the autonomous vehicle. The post-study questionnaire was also delivered using Google Forms and they were completed by the participants within 24 hours of the experiment. Moreover, an onsite interview was conducted with the participants to explore those same questions; we also made audio recordings of the interviews. In Chapter 7, we use these qualitative data to better interpret the experimental results.

4.4.1 Questionnaire Results

In total, we received 31 responses to the pre-study questionnaire and 27 responses to the post-study questionnaire. We asked the following questions in the post-study questionnaire to assess participants' impression of the visual signals and below is a summary of their responses.

- *What is your overall impression of the visual signals?* 10 of 27 (37.0%) participants answered good, 8 (29.6%) answered very good, 2 (7.4%) answered excellent, 5 (18.5%) answered fair, and 2 (7.4%) answered poor. Participants' overall impression of visual signals are positive.

- *Where do you think the visual signals should be installed?* 14 of 27 (51.9%) participants preferred the front of the vehicle and the rest (48.1%) preferred the top of the windshield.

- *What types of visual signals do you think are easiest to notice?* 22 of 27 (81.5%) participants answered flashing (Blink), 10 (37.0%) answered fast sweeping (Chase), 3 (11.1%) answered slow sweeping (Expanding and Shrinking), and 2 (7.4%) answered Solid. Some participants choose multiple signals. Overall, flashing signals seem to be the most noticeable.

- *Do you think an autonomous vehicle should communicate its intention?* and *Do you think an autonomous vehicle should use visual signals to communicate its intention?* All of the participants answered Yes to both questions.

- *What types of visual signals do you prefer to see on an autonomous vehicle?* 23 of 27 (85.2%) participants preferred flashing signals, 8 (29.6%) preferred fast sweeping signals, 9 (33.3%) preferred slow sweeping signals, and 6 (22.2%) preferred Solid signals. Some participants preferred multiple signals. Overall, flashing signals (Blink) seem to be the most preferable, possibly because it is also the most noticeable.

- *What do you like or don't like about the proposed visual signals?* Some common grievance against the visual signals include "they are not bright enough and difficult to see in daylight," "the flashing light and fast sweeping light looked similar in peripheral vision," "it is hard to associate this particular 'blue' solid light with anything immediately," and "the purposes of various types of sweeping light are not clear." Some commendations for visual signals include "you can immediately associate fast sweeping or slow sweeping motion of light with fast or slow speed of the vehicle" and "flashing Light is a good option to make people aware that a car is approaching." Finally, some suggestions include "visual signals are very easy to ignore among all the traffic signals and surrounding lights" and "do not want the vehicle to produce a large amount of light which would be very uncomfortable for the pedestrian."

Moreover, we asked the following questions in both the pre-study and post-study questionnaire to assess whether the experiments affect participants' impression of autonomous vehicles. Below is a summary of their responses.

- *Overall, what is your impression of autonomous vehicles?* Prior to the experiments, 14 of 31 (45.2%) participants answered very good, 12 (38.7%) answered good, 3 (9.7%) answered excellent, and 2 (6.5%) answered fair. After the experiments, 11 of 27 (40.7%) participants answered very good, 9 (33.3%) answered good, 4 (14.8%) answered excellent, and 3 (11.5%) answered fair.

- *Overall, do you think fully autonomous vehicles are ready to roam our streets?* Prior to the experiments, only 1 of 31 (3.2%) participants answered 6 or higher on a 7-point Likert scale indicating that they think autonomous vehicles are ready. After the experiments, 4 of 27 (14.8%) participants answered 6 or higher.

Overall, it seems like participants' impression and confidence of autonomous vehicles was not affected by the experiments. When we asked participants to *explain whether the visual signals changed your opinion about autonomous vehicles,* 18 participants responded, 12 of them (66.7%) answered "No." Their responses include:"type of visual signals should be reduced and simplified," "not being able to understand the signals," and "confusions caused by the lack of signal standards." In contrast, 6 of 18 (33.3%) participants suggested that the visual signals changed their opinion about autonomous vehicles. Their responses include:"the visual signals gave greater confidence by communicating what the vehicle's next decision is going to be," "they might make me trust more the future of autonomous vehicles," and "the visual signals made me feel more comfortable because its interacting with pedestrians."

Chapter 5

Phase 2: Visual Signals and Automated Interactions

In this chapter, we discuss whether an autonomous vehicle can use visual signals to influence pedestrian road-crossing behaviour. In particular, we focus on two crosswalk scenarios in which pedestrians interact with an autonomous vehicle at a crosswalk and they must decide whether they will cross street. This chapter is the center-piece of this thesis because it seeks to validate the effectiveness of an intention-communication system. In particular, we conducted a novel autonomous vehicle-to-pedestrian communication experiment using a real self-driving vehicle. As far as we know, we are the first in the field to conduct such an experiment involving human participants and a fully automated autonomous vehicle. As a result, we hope the findings in this study can reveal new insights about autonomous vehicle and pedestrian interaction involving visual signals, and that it will encourage more similar studies in the future.

5.1 Background Information

Fundamentally, the purpose of a visual signal is to communicate an autonomous vehicle's intention so that pedestrians can cooperate accordingly. As such, the effectiveness of a visual signal can be measured as the likelihood of a pedestrian complying with the visual signal in an expected way. For example, if a pedestrian should decide whether to cross a street or not based on a visual signal, a 50% compliance rate would indicate the signal is completely ineffective because it constitutes a random guess, whereas, a 95% compliance rate would indicate the signal is highly effective. This investigation is at the core of many autonomous vehicle visual signal studies [47]. While different methods have been used in these studies, they can be grouped into three categories.

1. **Conceptual Approach**: In this approach, participants must decide what they will do in hypothetical scenarios. For example, researchers may ask participants to visualize they are at a crosswalk and a vehicle is approaching and showing various visual signals, which will be demonstrated to the participants using pictures or videos. Then participants will decide what they will do in those situations [33]. The advantage of this method is that it is simple and quick-to-implement. It is a great way for concept validation because many designs can be validated in a short amount of time. However, it lacks realism and the results could misrepresent reality. As a result, conceptual experiments alone are often insufficient.

2. **Simulation Approach**: This is a virtual testing approach in which participants are immersed in a virtual environment where they interact with virtual vehicles and visual signals. To increase the realism of the test, researchers use tools such as high-fidelity videos, surround sounds, or even virtual reality [28]. The ultimate purpose is to solicit naturalistic response from participants in the scenarios they are subjected to. The advantage of using the simulated approach is that the test environment can be fully controlled and the test scenarios will be consistent for every study participant. However, the drawbacks are that it takes a long time to setup the simulation and participants may still feel disconnected from the situation.

3. **Wizard-of-Oz Approach**: This is a holistic testing approach in which participants interact with a vehicle equipped with a prototype of the visual signals. For this kind of experiment, participants must believe the vehicle is operating autonomously because they often behaves differently with a human-operated vehicle. As such, researchers will use different techniques, such as disguising the driver as a car-seat, to hide the driver from the participants. A well-disguised vehicle can convince 87% of participants that it is self-driving [51]. This is by far the most realistic testing method of visual signals and hence why it is the most popular [21]. However, we wonder can we do better and do this experiment with an actual self-driving vehicle?

5.2 New Experimental Method

Intuitively, we believe an autonomous vehicle and pedestrian interaction experiment should be done with an actual autonomous vehicle. However, there are many technical and practical limitations that would make such an experiment impractical. For example, an autonomous vehicle may be limited by its capabilities, there may not be a suitable test location, there are safety risks that need to be addressed in order to ensure participant safety, and finally since there is no precedent the experimental method will need to be invented. Nonetheless, we believe the benefit of conducting such an experiment outweighs the challenges. Therefore, we took on the challenge and the following sections discuss how we realized such an experiment.

5.2.1 Vehicle

To execute the experiment, an autonomous vehicle must perform three main tasks: 1) self-drive to a predetermined location, 2) localize the participant and determine their relative location, and finally 3) execute the necessary maneuvers and output the corresponding visual signals. To meet these requirements, we leveraged the Autonomoose research vehicle, which is currently capable of conditional self-driving by following a lanelet of GPS waypoints. We construct such a lanelet using the JOSM - Java OpenStreetMap Editor. Figure 5.3 illustrates the basic design of our experiment scenario. The vehicle follows the red lanelet to where the participant is waiting. Upon arriving, it is important for the vehicle to know where the participant is and its proximity to the participant. There are two ways to get that information: 1) we can use the vehicles perception system (in our case, AVOD) to detect the participant and estimate their distance and 2) we can leverage the vehicle's Map Server and calculate the distance to the next intersection, assuming there exists a crosswalk and a participant will be waiting there. In actual traffic situations, the latter approach is not practical. Pedestrians can cross anywhere. However, it is the preferred and most reliable method for our experiment, because AVOD is susceptible to errors. Finally, we developed the ROS_Light_Controller node to control the autonomous vehicle signal lights. The node was discussed in Section 3.3.3. In this way, the Autonomoose vehicle is made ready for the experiment. Figure 5.1 is a picture of the Autonomoose on the test track.

5.2.2 Location

Next, we selected the test track at the Waterloo Region Emergency Services Training and Research Centre (WRESTRC) as the location for our experiment. The test track is a private two-lane ring road connected to a 4-way intersection. It has the advantage of being in a fenced and restricted area, where there are few pedestrians and vehicles on it. As

Figure 5.1: Experiment 3 - Autonomoose Research Vehicle on the Test Track

a result, we can run our experiment with little interference. Second, we have a detailed GPS waypoints map of the entire test track. The Autonomoose vehicle's navigation system depends on it; in fact, the experiment scenarios are built largely using the map. Figure 5.2 shows the test track and the GPS waypoints in blue.

Figure 5.2: Experiment 3 - GPS Map of Test Track at WRESTRC

5.2.3 Scenarios

In total, we designed two autonomous scenarios for our experiment.

1. **Drive-By Scenario**: the ego [1] vehicle approaches the crosswalk where a pedestrian is waiting, the vehicle is travelling at 40 km/h, when the vehicle is 100 meters away, it displays a visual signal indicating its intention to drive pass the crosswalk, keeping the speed, it passes the crosswalk after 10 seconds, thus ending the scenario.

2. **Stop-and-Go Scenario**: the ego vehicle approaches the crosswalk where a pedestrian is waiting, the vehicle is travelling at 40 km/h, when the vehicle is 100 meters away[2], it displays a visual signal indicating its intention to stop at the crosswalk, keeping the speed for 5 seconds, when it reaches 48 meters of the crosswalk[3], it decelerates while continuing to displayed the visual signal, and then finally coming to a full stop in front of the crosswalk. The ego vehicle displays another visual signal indicating it is at rest and is waiting, then after 10 seconds, it displays a third signal indicating it is about to drive. After another 10 seconds, the vehicle finally accelerates, driving pass the crosswalk and ending the scenario.

The implementations of the above scenarios can be split into two parts: ego behaviour and visual signal control. In particular, the ego behaviour is largely determined by the information stored in OpenStreetMap (OSM) maps. In particular, the ego is programmed to follow a planned lanet starting from the start point and finishing at the end point. Along the way, it is also programmed to adhere to the speed limit of the lanelet, which is 40 km/h in our case, and obey all regulatory elements stored in the map, such as stop signs and stop lines. Therefore, we created two OSM maps representing the two experiment scenarios, in which they share the same start and end point and lanelet information for consistency. However, we removed the stop line and stop sign in one of the map, so the ego would drive pass the crosswalk without stopping. Figure 5.3 illustrates the design of the Stop-and-Go scenario in JOSM. The ego vehicle is shown to the left at the start location, the green circle to the right is the end location, the red line marks the lanelet path the ego will follow. The pedestrian is standing at the imaginary crosswalk to the right of the third red trigger point along the path, at which place is a stop line and a stop sign. These stop elements are removed from the map for the Drive-By scenario. In addition, the

[1] ego denotes a vehicle in autonomous operation under the control of its software stack.

[2] The crosswalk is about 2.6 meters before the intersection.

[3] Studies have shown when a vehicle approaches a crosswalk, it typically reaches its highest speed at 40-50 meters before the crosswalk [57].

ROS_Light_Controller[4] node controls the prototype visual signal system and synchronizes it to the ego's behaviour. While the OSM map does not control the visual signals, the red trigger points in Figure 5.3 illustrates the visual signals' expected behaviours. The first trigger point, 100 meters from the crosswalk, indicates where the ego displays the approaching visual signal; the second trigger point, 48 meters from the crosswalk, is where the ego starts deceleration; the third trigger point is where the ego stops and display the 2-resting visual signal. After 10 seconds, the vehicle displays the 3-starting visual signals before finally accelerating and driving pass the crosswalk[5]. From the first trigger point to the third, the approaching visual signal displays for 5.5 seconds before ego start to brake and 6.5 seconds after. Finally, a maximum speed limit of 40 km/h was chosen to match the intended speed limit of Experiment 4.

Figure 5.3: Experiment 3 - Design of the Automated Stop-and-Go Scenario

[4]See Section 3.3.3.

[5]Visual signal behaviours are summarized in Table 3.2.

5.2.4 Testing and Safety

Simulations

We extensively tested the above experiment scenarios in simulations before actual implementation on the vehicle. In particular, we tested the vehicle's behaviour in the WISE lab's AV simulator, which is powered by the Unreal engine. Moreover, we validated the visual signals' operation using ROS tools such as rviz, rqt, and ROSbag, thus ensuring the signals integrate successfully with the vehicle's software stack and behaviours.

Field Test

Having validated the soundness of experiment scenarios in simulation, we implemented them on the vehicle and calibrated the scenarios in a field test. For example, we adjusted the ego's starting location to allow for a smooth initial acceleration; we adjusted where the first signal is triggered to give participants more time to decide; and, we adjusted how long the vehicle will stop at the crosswalk in the Stop-and-Go scenario. Moreover, the Shrinking visual signal[6] requires synchronization with the vehicle's deceleration, thus we tuned the signal controller to start the shrinking signal when the vehicle is 100 meters away and to turn OFF the signal precisely at the moment when the vehicle comes to a full stop at the crosswalk. Altogether, these calibrations ensured the vehicle can perform the experiment scenarios accurately so that consistency is achieved between every trial[7].

Safety

In addition to technical considerations, safety is the utmost important consideration for a fully autonomous experiment. Namely, we are obligated to ensure participants are never in a dangerous situation even if the self-driving system fails. For this reason, we kept pedestrians at least 3 meters away the vehicle's lane of travel and positioned a researcher beside them to ensure they keep the distance. Moreover, when the vehicle was operating autonomously, a qualified safety driver was in the driver's seat and ready to take control of the vehicle at anytime.

[6] Described in Section 4.3.2.

[7] In reality, neglectable maneuvering and signalling differences exist between multiple runs of even the same scenario.

5.2.5 Data Collection

Due to safety reasons, we did not allow pedestrians to physically cross in front of the vehicle. Instead, we devised two arm signals for participants to indicate their intentions. Namely, they learned to extend their right arm in front of their body, pointing their fingers across the street, to indicate their willingness to cross; and, while in that position, they learned to bend their elbow, pointing their fingers to the sky, to indicate they are not willing to cross.

To record the participant's decision, a researcher in the vehicle presses an electronic button every time the participant's arm position changes. The button is connected to an Arduino board, and every time it is pressed, it sends a signal to the vehicle's ROS software stack, which time-stamped and logged the signal. So, the participant's decision is recorded with other relevant data, such as the vehicle's position, current maneuver, and the visual signal state. These information are then automatically saved in a log file, which we use for analysis. Moreover, we created external video recordings of every experiment trials. Namely, a video camera on a tripod, records the crosswalk, the participants and the vehicle approaching for each experiment trial. Moreover, we made ROSbag recordings of some of the trials for future analysis.

5.2.6 Evaluation

The impact of visual signals are evaluated using the metrics of **Distance Gap**[8] and **Stop Crossing Time**. Namely, the Distance Gap measures the separation between the ego vehicle and the crosswalk where a participant is crossing. As the vehicle approaches, the distance gap decreases. With everything being equal, except the use of visual signals, we compare the distance gap at the moment when the participant decides not to cross. Hence, we quantified the impact of visual signals on participants. Now, if the vehicle is already stopped at the crosswalk, the distance gap is zero and we assumed a participant will continue to cross as long as the vehicle remains stationary. However, at t_{signal}, after the vehicle were stationary for 10 seconds, we programmed the vehicle to display a visual signal to indicate its intention to accelerate. Unaware of the signal's meaning, we record when or if the participant decides to stop crossing t_{stop}. The difference between t_{signal} and t_{stop} is referred to as Stop Crossing Time, which we compare between trials using different visual signals in order to determine the signals' impact.

[8]See Section 2.1.1 for additional details.

5.3 Experiment 3: AV Interaction Study

5.3.1 Research Questions

Having acquired the capability of conducting a fully autonomous vehicle pedestrian interaction experiment, we proceed to investigate the impact of visual signals on pedestrian road-crossing behaviour. Specifically, we investigated two common crosswalk situations in which a pedestrian needs to decide whether they will cross or not: 1) when an autonomous vehicle is approaching the crosswalk, and 2) when an autonomous vehicle is stopped at the crosswalk. In general, we hypothesize there are visual signals that could encourage or deter participants' crossing preference in the two scenarios. Hence, this experiment seeks to discover those signals and understand what design features make them effective. In addition, we hypothesize the novelty of an autonomous vehicle could have significant impacts on pedestrian behaviours. Hence, we undertook two supplementary investigations to determine whether knowledge and familiarity with an AV would make pedestrian more trustful, and whether pedestrian behaviours would change through repeated interactions with an AV and its visual signals. In summary, this experiment tries to answer the following research questions.

- RQ6: What visual signals would encourage or deter a pedestrian from crossing in front of an approaching autonomous vehicle?
- RQ7: What visual signals would encourage or deter a pedestrian from crossing in front of a stationary autonomous vehicle?
- RQ8: How does repeated exposure to visual signals influence a pedestrian's crossing decision?
- RQ9: How does familiarity and trust of an autonomous vehicle influence a pedestrian's crossing decision?

5.3.2 Experiment Signals

In this experiment, we examined six visual signals appearing in three unique situations[9]. The first situation pertains to the Drive-By scenario where the ego is approaching and signalling its intention to stop; the second situation also pertains to the Drive-By scenario

[9]Figure 5.4 illustrates the three Experimental Situations

but the ego is signalling its intention to pass the crosswalk without stopping; and, the third situation pertains to the Stop-and-Go scenario where an ego is stopped and intends to start moving again. Similar to Experiment 2, we only used the LED strips above the windshield to display the visual signal. Below is a summary of the visual signals used in each situation[10].

- **Approach-and-Stop**: In this situation, the ego wants to encourage pedestrians to cross and attempts to communicate its intention with a **Solid Turquoise** or a **Shrinking** signal. The two signals are identical to those in Experiment 2. However, the Shrinking signal is calibrated to synchronize with the ego's deceleration; namely, all LED pixels on the light strip are lit when the ego first reaches within 100 meters of the crosswalk, and the lit portion starts to shrink inward, turning OFF one pixel at a time, and until the last LED pixel is OFF at the exact instance when the vehicle comes to a full stop[11]. We choose these signal patterns because they were effective in Experiment 2 to prompt participants to cross.

- **Approach-and-Pass**: In this situation, the ego wants to deter pedestrians from crossing and attempts to communicate its intention with a **Solid Amber** or a **Blink** signal. Similarly, these signals are identical to the ones in Experiment 2 and we choose them because they are effective in Experiment 2 to deter pedestrians from crossing.

- **Stop-and-Start**: In this situation, the ego is at rest and attempts to warn pedestrians of its intention to move. Hence, it also uses the **Solid Amber** or the **Blink** signal to prompt pedestrians to wait and yield.

In essence, this experiment tries to find visual signals to represent whether an ego vehicle is approaching or starting. However, it does not examine the case when the ego vehicle is resting. Instead, we just use the **Solid Turquoise** signal to represent that state and assume the stationary position of the ego will be self-explanatory. Below is the list of 6 of visual signals and 3 baseline signals we tested; they were displayed using LED light strip groups 2 and 3. Figure 5.5 depicts these signals.

E3-B1: Baseline No Signal Stop

E3-S1: Solid Turquoise

[10]Note: The term *scenario* in this chapter refers to the autonomous vehicle's automated maneuvers; the term *situation* refers to test conditions in which participants are subjected to.

[11]The stopping maneuver takes about 12 seconds to complete.

E3-S2: Shrinking Turquoise

E3-B2: Baseline No Signal Pass

E3-S3: Solid Amber

E3-S4: Blink Turquoise

E3-B3: Baseline No Signal Start

E3-S5: Solid Amber

E3-S6: Blink Turquoise

5.3.3 Location and Time

The experiment was conducted on the test track of WRESTRC. It took place over six days and between the hours of 9:00 am to 5:00 pm. Similar to Experiment 1, we encounter a diverse range of conditions that could impact the visibility of visual signals; hence, we also took illuminance measurements to frame our interpretation of results.

5.3.4 Participants

Twenty-two participants (14 males and 8 females) between 18 and 44 years old participated in the study. They were recruited on the University of Waterloo campus using computer science department mailing-lists and recruitment posters around the campus. The participants had no prior knowledge of the study and have not participated in any of the previous experiments. 21 of 22 participants (95.5%) received some level of college and university education. 14 of 22 participants (63.6%) hold a valid driver's license; 5 of 22 participants (22.7%) own a motor vehicle; and, 20 of 22 participants (90.9%) have at least 1 years of driving experience. When asked to estimate the average number of times they cross a street each day, 6 (27.3%) responded 0-5 times, 9 (40.9%) said 6-10 times, 4 (18.2%) said 11-15 times, 2 (9.1%) said 16-20 times, and 1 (4.5%) said 20 or more times. Finally, 14 of 22 participants (63.6%) rated themselves 6 or higher on a 7-point Likert scale indicating a high level of willingness to adopt and accept new products or innovations. Each participant received $20 Canadian as appreciation for participating in the experiment; they were also reimbursed for the travel expense to the experiment location.

(a) Approach-and-Stop Situation - Ego Stopping and Participant Indicating Decision to Cross with a Straight Arm Signal

(b) Approach-and-Pass Situation - Ego Driving Pass and Participant Indicating Decision to Not Cross with a Bend Arm Signal

(c) Stop-and-Start Situation - Ego Stopped in front of the Crosswalk and Participant Indicating Decision to Cross with a Straight Arm Signal

Figure 5.4: Experiment 3 - Illustration of Experimental Situations

5.3.5 Methods and Procedures

Combining all the components above, this experiment consists of 2 test runs, and each test run consists of 6 trials. In every trial, the autonomous vehicle is programmed to execute either the *Drive-By* or the *Stop-and-Go* scenario, in which the vehicle displays either no visual signal or one of experiment signals pertaining to its situation. Based on those visual signals, study participants decide whether they will cross the road and they indicate their choices by using arm signals. Table 5.1 summarizes the visual signals used in a typical test run. The order of the trials and the usage of visual signals in each situation are randomized. Stop-and-Go scenarios tested two experiment situations sequentially: *Approach-and-Stop*

(a) E3-S1: Solid Turquoise

(b) E3-S2: Shrinking Turquoise (sync with ego's deceleration)

(c) E3-S3/E3-S5: Solid Amber

(d) E3-S4/E3-S6: Blink Turquoise (2 Hz)

Figure 5.5: Experiment 3 - Depictions of Featured Visual Signals

and *Stop-and-Start*. The test results for each trial are logged and compared in order to quantify the impact of visual signals on pedestrian crossing behaviour (RQ6, RQ7).

Scenarios	Trials	Ego Approaching visual signals	Ego Resting visual signals	Ego Starting visual signals
	1	Baseline - OFF	Baseline - OFF	Baseline - OFF
Stop-and-Go	2	Solid Turquoise or Shrinking	Solid Turquoise	Solid Amber or Blink
	3	Solid Turquoise or Shrinking	Solid Turquoise	Solid Amber or Blink
	4	Baseline - OFF	N/A	N/A
Drive-By	5	Solid Amber or Blink	N/A	N/A
	6	Solid Amber or Blink	N/A	N/A

Table 5.1: Experiment 3 - Trials and Visual Signals in a Typical Test Run

Moreover, we conducted two test runs consecutively to examine whether participants can learn to interpret the visual signals through repeated exposures (RQ8). And finally, we randomly split the participants into two groups and took one of the groups on an autonomous ride around the test track before the experiment. Then, by comparing the crossing behaviour between these two groups of participants, we examined whether familiarity with the autonomous vehicle will cause pedestrians to trust or distrust the autonomous vehicle more (RQ9). The following is the detailed procedure for Experiment 3.

1. A researcher welcomes the participant and briefs them about the experimental pro-

cedure.

2. The participant signs a consent form and fills out a pre-study questionnaire.

3. If the participant is part of the control group, they are offered to take an autonomous ride in the research vehicle around the test track.

4. Afterward, the participant stands at the start location at the entrance of the experiment crosswalk, which is about 7 meters away from experiment vehicle's lane of travel. The vehicle approaches from the right hand of the participant.

5. The experiment consists of 12 test trials and 2 practice trials. The test trials are divided into 2 test runs and administered sequentially.

6. Each test run consists of 6 test trials. The order of the test trials are randomized and the order of the visual signals used in the trials are also randomized. Table 5.1 shows an example of a test run.

7. For each test trial, the experiment vehicle may perform either the *Drive-By* scenario or the *Stop-and-Go* scenario.

8. Prior to starting, the participant does 2 practice trials of the Stop-and-Go scenario, with and without visual signals, to get acquainted with the experiment procedure. The results are not record.

9. The experiment steps for the **Drive-By** scenario is as follows:

    - The participant stands at the start location and lets the research assistant know they are ready.
    - The research assistant radios the researcher in the vehicle, who activates the automated scenario.
    - The vehicle accelerates to 40 km/h and drives toward the crosswalk.
    - When the vehicle is 100 meters away from the crosswalk, it displays either no visual signal (baseline), the Solid Amber signal (E3-S3), or the Blink signal (E3-S4).
    - At the same time, the participant takes 2 steps forward and stops, holding their right arm straight to indicate they are crossing.
    - As the vehicle approaches, the participant is instructed to bend their arm at any time to indicate they wish to stop crossing.

- The researcher in the vehicle monitors the participant's arm position and records their intention using an electronic button connected to an Arduino board and the vehicle's ROS system.
- The vehicle drives past the crosswalk at 40 km/h and the scenario ends.

10. The experiment steps for the **Stop-and-Go** scenario is as follows:
    - The participant stands at the start location and lets the research assistant know they are ready.
    - The research assistant radios the researcher in the vehicle, who activates the autonomous scenario.
    - The vehicle accelerates to 40 km/h and drives toward the crosswalk.
    - When the vehicle is 100 meters away from the crosswalk, it displays either no visual signal (baseline), the Solid Turquoise signal (E3-S1), or the Shrinking signal (E3-S2).
    - At the same time, the participant takes 2 steps forward and stops, holding their right arm straight to indicate they are crossing.
    - When the vehicle is 48 meters away from crosswalk, it decelerates and continues to display the visual signals.
    - The vehicle comes to a graduate stop in front of the crosswalk.
    - The participant is instructed to bend their arm at any time to indicate they wish to stop crossing.
    - The researcher in the vehicle monitors the participant's arm position and records their intention using an Arduino electronic button connected to the vehicle's ROS system[12].
    - Once the vehicle comes to a full stop, the vehicle starts a 10 second timer and displays either no visual signal (baseline) or the Solid Turquoise signal (E3-S1).
    - At the same time, the participant again holds their right arm straight to indicate they are crossing[13].

[12] The recorded event allows determining the Distance Gap at which the pedestrian decided to stop crossing.

[13] Out of 102 Approach-and-Stop trials, we observed only 4 cases (3.92%) in which a participant decided to cross again before the vehicle came to a full stop. All four cases occurred when visual signals were used to communicate the vehicle's intention. Nonetheless, we assumed these cases are the exceptions; therefore, we zeroed the calculation of stop Crossing Time to the moment when the vehicle came to a full stop.

- After the 10 seconds, the vehicle displays either no visual signal (baseline), the Solid Amber signal (E3-S5), or the Blink signal (E3-S6).
- The participant again is instructed to bend their arm at any time to indicate they wish to stop crossing.
- The researcher in the vehicle again records the participant's intention using an Arduino electronic button, which allows calculating the Stop Crossing Time[14].
- After another 10 seconds, the vehicle accelerates and drives pass the crosswalk.
- The scenario ends.

11. The experiment ends after all 12 trials in 2 test runs are completed.

The experiment took approximately 90 minutes to complete. Note that letting the participant signal crossing intention by hand rather than actually crossing has two important reasons. First, it would be impractical to let a participant cross continuously until they decide not to cross; yet we want to establish the precise point during a situation when they change their crossing decision. Second, crossing in front of a vehicle, especially during the Approach-and-Pass scenarios would be potentially risky. Our experimental design addresses both issues.

5.3.6 Results

In total, 19 participants completed the experiment and generated valid results for the approach Approach-and-Stop and Approach-and-Pass situations, which included 102 test trials and 99 test trials for each situation, respectively. Also, 14 participants generated valid results for the Stop-and-Start situation, completing 77 test trials. Some test trials were omitted due to technical issues, and 21 of the 278 (7.55%) of test trials contained ambiguous timestamps, either duplicate or missing, which was manually disambiguated by the researchers using the experiment videos. Accordingly, by analyzing the results of these trials, we found that visual signals, such as E3-S1 Solid Turquoise, E3-S2 Shrinking, E3-S3 Solid Amber, and E3-S4 Blink, cannot encourage or deter a pedestrian from crossing in front of a moving vehicle; however, the E3-S5 Solid Amber and E3-S6 Blink signals were able to prompt the participants to yield to the vehicle. Table 5.2 summarizes the average Distance Gap participants are willing to accept in the Approach-and-Stop and

[14] The Stop Crossing Time is the time elapsed from when the vehicle came to a stop until the pedestrian signalled the decision to stop crossing.

Approach-and-Pass situations. It shows that the E3-S1 Solid Turquoise signal had the intended effect on participants to accept a shorter distance gap, and the E3-S3 Solid Amber and E3-S4 Blink increased distance gap as intended. These results are encouraging but they are not statistically significant, (F(5,87) = 0.26, p = .933, η^2 = .007). Table 5.3 summarizes the average Stop Crossing Time for the Stop-and-Start situation. Given the autonomous vehicle is programmed to accelerate at 20 seconds, it shows that participants will stop crossing at 14.79 and 15.76 seconds, respectively if the vehicle warns them about the impending start using the E3-S5 Solid Amber and E3-S6 Blink visual signals. In the baseline trials, without visual signals, majority of participants kept crossing until the vehicle moved at 20 seconds; however, the average baseline stop crossing time is 18.84 because three of the participants decided in 4 different occasions to stop crossing before the vehicle moved[15]. These are statistically significant results, (F(1,207) = 19.62, p < .001, η^2 = .286) and (F(1,127) = 12.31, p < .001, η^2 = .191), that demonstrate the effectiveness of autonomous vehicle visual signals in a Stop-and-Start situation[16].

	Approach-and-Stop			Approach-and-Pass		
	Baseline No Signal	E3-S1 Solid Turquoise	E3-S2 Shrinking	Baseline No Signal	E3-S3 Solid Amber	E3-S4 Blink
Gap Average:	33.72 (±1.01)	31.15 (±0.94)	33.98 (±1.00)	30.87 (±1.00)	31.36 (±0.95)	34.44 (±1.02)

Table 5.2: Experiment 3 - Average Minimum Distance Gaps Measured in the Approach-and-Stop and Approach-and-Pass Situations (in Meters) and S.E.M. in brackets (N=19)

Impacts of Trust

To investigate how personal experience impacts trust, the 19 participants were divided into two groups: 9 received a ride in the autonomous vehicle and 10 did not. Comparison of distance gaps between the two groups revealed significant differences in their crossing

[15]Based on the experiment videos, two of the participants seem to be trying to guess what the vehicle will do and the other may have gotten confused about the arm signal.

[16]To account for any potential difference in participants' gap acceptance, we performed additional ANOVA tests by normalizing the distance gaps against the participants' baseline gaps for each scenario. These tests revealed the same results.

	Baseline No Signal	Stop-and-Start E3-S5 Solid Amber	E3-S6 Blink
Time Average:	18.84 (±0.82)	14.79 (±0.80)	15.76 (±0.78)

Table 5.3: Experiment 3 - Average Stop Crossing Time Measured in the Stop-and-Start Situations (in Seconds) and S.E.M. in brackets (N=14)

behaviour, (F(1,3325) = 10.69, p < .01, η^2 = .051)[17]. This showed that the participants with the autonomous ride experience became more risk-tolerant. Regardless of whether visual signals are used, participants tolerated on average a shorter Distance Gap of 8.15 meters over the six trials in both the Approach-and-Stop and Approach-and-Pass situations. Some robotics studies suggest that people's trust for a robot increase with their awareness of the robot's design capabilities [50]. Hence, one possible explanation of our results is that participants gained confidence about the vehicle's ability as they saw how the vehicle drove itself around the test track, thus increasing their trust of the vehicle and increasing their willingness to accept a shorter and riskier distance gap before crossing the street. Table 5.4 summarizes the average distance gap for the two groups of participants and for both the approach situations. Figure 4.4 illustrates these findings graphically. Regarding the Stop-and-Start situation, there was no significant differences in Stop Crossing Time, (F(1,23) = 1.65, p = .203, η^2 = .022). Table 5.5 summarizes the Stop Crossing time for the Stop-and-Start situations.

Impacts of Learning

Moreover, 17 of the 19 participants had repeated encounters with the visual signals. Namely, they experimented all six trials in Table 5.1 in random order twice. However, comparison of Distance Gaps and Stop Crossing Time between the two runs revealed no significant difference in the participants' crossing behaviours, (F(1,3) = .011, p = .915, η^2 < .001) and (F(1,9) = .068, p = .413, η^2 < .01), thus suggesting that repeated exposures to visual signals had not resulted in any meaningful learning. Further investigations are required to study whether even more exposures will have any meaningful impact. Table 5.6

[17]The impact of AV ride on participants' gap acceptance is significant when comparing all six visual signals groups together. The impact is not statistically significant when comparing the visual signal individually.

Average	Approach-and-Stop			Approach-and-Pass		
	Baseline No Signal	E3-S1 Solid Turquoise	E3-S2 Shrinking	Baseline No Signal	E3-S3 Solid Amber	E3-S4 Blink
Group with AV Ride:	29.50 (±1.40)	25.47 (±1.26)	29.08 (±1.39)	29.54 (±1.36)	26.12 (±1.28)	30.03 (±1.33)
Group without AV Ride:	37.23 (±1.44)	35.92 (±1.38)	37.85 (±1.41)	32.29 (±1.47)	35.78 (±1.37)	39.13 (±1.56)
Difference:	-7.72	-10.45	-8.77	-2.76	-9.66	-9.10

Table 5.4: Experiment 3 - Average Distance Gaps of AV Ride and No Ride Group in the Approach-and-Stop and Approach-and-Pass Situations (in Meters) and S.E.M. in brackets (N=10)

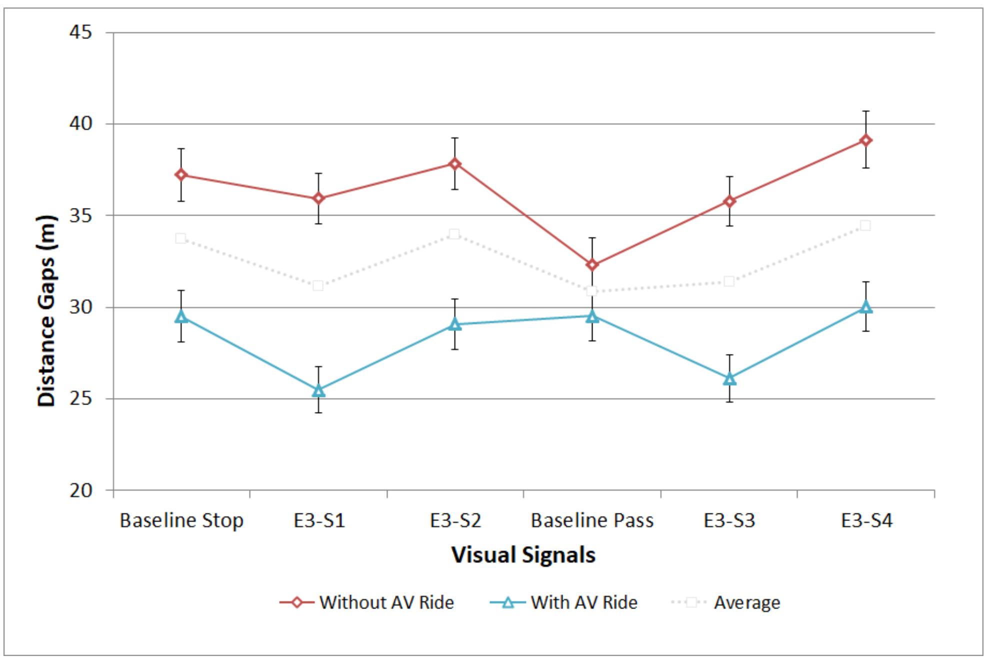


Figure 5.6: Experiment 3 - The Impact of trust on Pedestrians' Crossing Distance Gaps in the Approach-and-Stop and Approach-and-Pass Situations (in Meters) and S.E.M. as Error bars

summarizes the average distance gap for the two runs and for both the approach situations, and Table 5.7 summarizes the Stop Crossing time for the two runs of the Stop-and-Start

Average	Approach-and-Pass		
	Baseline No Signal	E3-S5 Solid Amber	E3-S6 Blink
Group with AV Ride:	18.21 (±1.14)	14.33 (±1.14)	15.15 (±1.08)
Group without AV Ride:	19.46 (±1.18)	15.21 (±1.13)	16.38 (±1.12)

Table 5.5: Experiment 3 - Average Stop Crossing Time of AV Ride and No Ride Group in the Stop-and-Start Situation (in Seconds) and S.E.M. in brackets (N=7)

situation.

Average	Approach-and-Stop			Approach-and-Pass		
	Baseline No Signal	E3-S1 Solid Turquoise	E3-S2 Shrinking	Baseline No Signal	E3-S3 Solid Amber	E3-S4 Blink
Run 1:	33.73 (±1.55)	30.85 (±1.39)	34.12 (±1.51)	29.28 (±1.5)	29.78 (±1.36)	33.18 (±1.54)
Run 2:	30.68 (±1.48)	29.01 (±1.35)	33.60 (±1.5)	33.09 (±1.6)	29.19 (±1.35)	34.28 (±1.56)
Difference:	-3.05	-1.84	-0.52	3.81	-0.59	1.10

Table 5.6: Experiment 3 - Average Distance Gaps of Repeated Runs in the Approach-and-Stop and Approach-and-Pass Situations (in Meters) and S.E.M. in brackets (N=10)

5.4 Qualitative Study

Similar to the Phase 1 Qualitative Study, a pre-study questionnaire was given the participants prior to Experiment 3. The questionnaire collected the same demographic information about participants as in Phase 1, and it is also delivered on Google Forms using an Apple iPad. Similarly, the post-study questionnaire was given to assess participants' experience with the visual signals and to determine whether the experiment changed their impression of the autonomous vehicle. It is also delivered using Google Forms and completed within 24 hours of the experiment. Moreover, we also conducted an onsite interview

Average	Approach-and-Pass		
	Baseline No Signal	E3-S5 Solid Amber	E3-S6 Blink
Run 1:	19.49 (±1.18)	14.84 (±1.28)	15.86 (±1.15)
Run 2:	18.19 (±1.14)	14.38 (±1.26)	15.59 (±1.14)

Table 5.7: Experiment 3 - Average Stop Crossing Time of Repeated Runs in the Stop-and-Start situation (in Seconds) and S.E.M. in brackets (N=14)

with the participants to explore the same questions; we also made audio recordings of the interviews. In Chapter 7, we use these qualitative data to better interpret the experimental results.

5.4.1 Questionnaire Results

In total, we received 22 responses to the pre-study questionnaire and 18 responses to the post-study questionnaire. We asked the following questions in the post-study questionnaire to assess participants' impression of the visual signals as well as their impression of the experiment. Below is a summary of their responses.

- *What is your overall impression of the experiment?* 10 of 18 (55.6%) participants answered very good, 7 (38.9%) answered excellent, and 1 (5.6%) answered good.
- *Can you guess what the vehicle was going to do during the experiment? Please explain.* 16 participants responded, 11 of 16 (68.8%) indicated they can guess the vehicle's intention. Specifically, 3 (18.8%) said they inferred the vehicle's intention by its movement or speed. 7 (43.8%) said they used lights as indicators of the vehicle's intent[18].
- *Did you notice the visual signals that the vehicle used? If so, please describe them.* 15 participants answered the question and they all noticed the visual signals. Their responses include: "I noticed but could not interpret what they mean," "the signal have different colors and different frequency," "the visual signal flashing indicated

[18] One participant said they relied on both movement and light.

that the vehicle was about to start moving or come to a halt," "I needed the attendant to point them (visual signals) out to me after the first two trial runs," and "I noticed the visual signal. Every time the vehicle stops and the visual signal changes, I know that 'it's time to pass!' After several seconds when the signal changes again (i.e. from steady light to blinking), I will stop going across and keep observing."

- *Can you guess the meaning of the visual signals? Please elaborate.* 15 participants responded, 12 of them (80.0%) guessed correctly that the visual signals are meant to communicate the vehicle's intention, but their interpretations of the signals varied. Some notable comments include:

  flashing blue lights mean the vehicle will not stop and yield, and solid blue mean the vehicle will stop, "when colour of lights change, the state of vehicle will change. Lights flashing reminds people to be careful and do not cross," "the progress bar visual signal gave a countdown timer of sorts to indicate that the vehicle was going to stop," and "the signals represent a decision or a change of state: stop movement, start moving or continue moving." 3 of 15 (20%) participants did not know or misinterpreted the purpose of the visual signals. One of them thought:"it means the vehicle detected me."

- *What is your overall impression of the visual signals?* 5 of 18 (27.8%) participants answered good, 5 (27.8%) answered very good, 5 (27.8%) answered excellent, 3 (16.7%) answered fair, and no one answered poor. Participants' impression of visual signals are positive.

- *How would you rate the visual signals?* 7 of 18 participants (38.9%) rated the visual signals 6 or higher on a 7-point Likert scale indicating they are useful.

- *Do you think an autonomous vehicle should communicate its intention?* and *Do you think an autonomous vehicle should use visual signals to communicate its intention?* 16 participants responded and all of them answered Yes for both questions.

Moreover, we asked the following questions in both the pre-study and post-study questionnaire to assess whether the experiments affect participants' impression of autonomous vehicles. Below is a summary of their responses.

- *Overall, what is your impression of autonomous vehicles?* Prior to the experiments, 11 of 22 (50.0%) participants answered very good, 7 (31.8%) answered excellent, and 4 (18.2%) answered good. After the experiments, 8 of 18 (44.4%) participants answered very good, 6 (33.3%) answered excellent, and 4 (22.2%) answered good.

- *Overall, do you think fully autonomous vehicles are ready to roam our streets?* Prior to the experiments, 6 of 22 (27.3%) participants answered 6 or higher on a 7-point Likert scale indicating that they think autonomous vehicles are ready. After the experiments, 3 of 18 (16.7%) participants answered 6 or higher.

When we asked participants to *explain whether the visual signals changed your opinion about autonomous vehicles,* 16 participants responded, 4 of them (25.0%) suggested "No." Their main concern is "not being able to understand the signals." In contrast, 12 of 16 (75.0%) participants suggested that the visual signals changed their opinion about autonomous vehicles. Some of their responses include: "I think it's a great idea if the visual signals can communicate just like the traffic light to pedestrians," "it makes me feel more comfortable to walk or cross the road as pedestrian," "visual signals probably helps us to predict the action of the vehicle," "they would definitely make it a lot easier for pedestrians and even other drivers to feel safe around them," and "they reinforced my positive opinion about autonomous vehicles." However, it is surprising to see fewer participants thought autonomous vehicles are ready to roam our street after the experiment. As one of the participants explained, this is likely caused by an increase of awareness of the current state of the self-driving technology. He said: "seeing that the lack of communication ability between pedestrians (and cyclists) and autonomous vehicles made me realize that we are perhaps farther away than I previously thought from having autonomous vehicles safely in our city streets."

Chapter 6

Phase 3: Visual Signals on Public Road

This chapter examines what happens when visual signals are used in real-traffic situations; specifically, we focus on pedestrians' intersection with, and feelings toward, an autonomous vehicle equipped with visual signals. In particular, we conducted a Wizard-of-Oz experiment with an autonomous vehicle on a public road. We took the most influential visual signals from Phase 1 and Phase 2 of the study and used them to interact with actual pedestrians. By analyzing video recordings of the interactions and pedestrians' written feedback, we hope to provide insights about the role of autonomous vehicle visual signals in actual traffic situations.

6.1 Experiment 4: Public Road Study

6.1.1 Research Questions

Like the other experiments in the overall study, this experiment examines a situation where one or more pedestrians meet an autonomous vehicle at a crosswalk. However, unlike the other experiments, the focus of this experiment is on the pedestrians in naturalistic setting, rather than the signal designs and their influence in a controlled environment. Hence, this experiment takes a qualitative approach by observing pedestrians interaction with an autonomous vehicle with its visual signals. We recorded and analyzed their reactions and also asked them directly in a questionnaire to get their opinions. By doing so, we hope to learn from the pedestrians' perspective on how to build visual signals that are useful and appealing. Moreover, this experiment may reveal insights on how pedestrians may interact with autonomous vehicle at the outset of autonomous vehicle proliferation. The research questions for this experiment are summarized below.

- RQ10: How does a pedestrian identify and recognize an autonomous vehicle?
- RQ11: Can pedestrians notice a visual signal on an autonomous vehicle? If so, what do they think about it?
- RQ12: Will pedestrians react differently to an autonomous vehicle equipped with visual signals?

6.1.2 Experiment Signals

Four visual signals were selected for this experiment based on the results of the previous experiments; the signals represents four operating states of the autonomous vehicle.

- **Ego in ADS mode**: In this state, an autonomous vehicle is operating normally. In accordance with the recommendation of SAE, we choose a **Solid Turquoise Marker** light to represents the vehicle is in self-driving or ADS mode [44]. This perhaps will be a distinguishing feature of autonomous vehicles going forward .
- **Ego is decelerating**: In this state, an autonomous vehicle is braking and decelerating toward a crosswalk. We choose the **Shrinking** signal from Experiment 3 to represent this state.
- **Ego is stopped**: In this state, an autonomous vehicle is stationary and not intending to move. We choose the **Solid Turquoise** from Experiment 3 to represent this state.
- **Ego to accelerate**: In this state, an autonomous vehicle is stationary but intending to accelerate. The signal is meant to warn pedestrians of its impending action and to yield to the vehicle. We choose the **Blink** signals from Experiment 3 to represent this state.

The maneuvers of the autonomous vehicle in this experiment are choreographed. It features an autonomous vehicle driving toward a crosswalk, decelerating to a full stop, waiting and then displaying a warning visual signal for at least 5 seconds before finally accelerating and driving pass the crosswalk if no pedestrians are on it. Table 6.1 summarizes the usage of the experiment signals in accordance with the choreographed maneuvers. Figure 6.3 depicts the experiment signals.

Ego Maneuvers	Corresponding Visual Signals
Approaching	Solid Turquoise Marker
Decelerating	Shrinking Turquoise
Stopped	Solid Turquoise
To Accelerate	Blink Turquoise

Table 6.1: Experiment 4 - Vehicle Maneuvers and Corresponding Visual Signals

6.1.3 Location and Time

The experiment was conducted on the University of Waterloo Ring Road, which is an open public road, at the crosswalk outside the Carl A. Pollock Hall (CPH). Figure 6.1 illustrates the experiment route, the experiment vehicle starts from the Earth Science Museum (ESM), turns around at the parking lot beside the Douglas Wright Engineering (DWE) building, and returns to where it started it. The vehicle stops twice along the route and interacts with pedestrians at the crosswalk outside CPH. A stationary camera and a drone camera were set up at the crosswalk to record the experiment. The experiment took place on an overcast morning between 9:00 am and 11:30 am; these were the ideal conditions to enhance signal visibility. Moreover, we choose to experiment on the Ring Road because of the abundance of pedestrians. It was also a convenient location because it is under the jurisdiction of the University of Waterloo campus police and safety office, so we can work with them to ensure pedestrian safety.

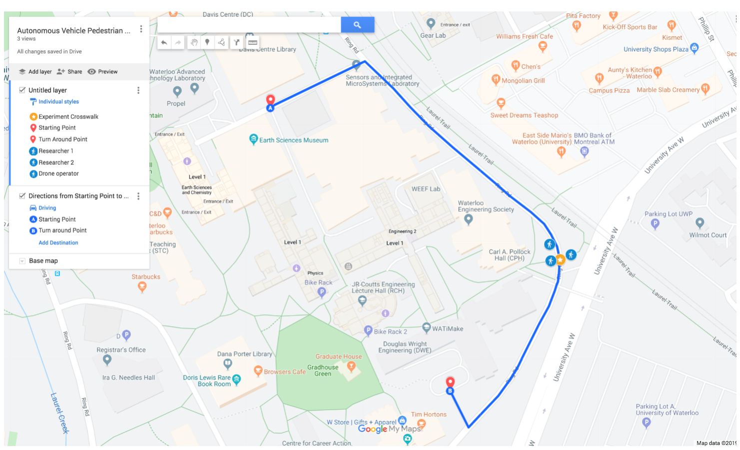


Figure 6.1: Experiment 4 - Test Route on University of Waterloo Ring Road

6.1.4 Participants

The participants in this experiment are actual pedestrians at the experiment location, and they may participate in the study in two ways. First, a pedestrian may voluntarily participate in a questionnaire study to share their experience about the interaction with the study vehicle. This group of participants are at least 17 years of age and must be legally able to give consent to participate in the study. On the other hand, a pedestrian may involuntarily participate in an observational study by encountering the study vehicle and having the interaction recorded and analyzed. This kind of study is common and it does not violate the normal expectation of privacy in a public place. Nonetheless, we posted signs along the experiment route and on the study vehicle to inform pedestrians about the experiment and that the videos are being recorded. We also posted instructions with the signs about how to withdraw from our study and have any personal recordings removed.

Fifteen participants (14 males and 1 female) between 17 and 24 years old participated in the questionnaire study. 14 of 15 participants (93.3%) received some level of college and university education. 14 of 15 participants (93.3%) holds a valid driver's license and have at least 1 years of driving experience; 4 of 15 participants (26.7%) own a motor vehicle. When asked to estimate the average number of times they cross a street each day, 2 (13.3%) said 0-5 times, 4 (26.7%) said 6-10 times, 6 (40.0%) responded 11-15 times, and 3 (20.0%) said 20 or more times. Finally, 9 of 15 participants (60.0%) rated themselves 6 or higher on a 7-point Likert scale indicating a high level of willingness to adopt and accept new products or innovations. Each participant received $5 Canadian as appreciation for participation in both experiments.

Seven of fifteen participants interacted with the autonomous vehicle without visual signals, they are referred to as the **baseline group**. The other 8 interacted with the vehicle with visual signals, they are referred to as the **experiment group**. The age, gender, and education demographics of the two groups are similar. Only 1 person in the baseline group does not hold a driver's license. Both groups have similar number of years of driving experience with the exception of 1 person in the baseline group having zero experience and another person in the experiment group having 7 years of driving experience. Overall the baseline group has more daily street crossing experience than the experiment group, 57.1% crossing between 11-15 times compared to 50.0% between 6-10 times, respectively. The baseline group seems to be more willing to adopt new technologies as well, 71.5% rated themselves 6 or higher on a 7-point Likert scale compared to 50.0% of the experiment group.

6.1.5 Methods and Procedures

This experiment is a field study involving a Wizard-of-Oz autonomous vehicle interacting with pedestrians on the University of Waterloo Ring Road. To conceal the driver from the pedestrians, we tinted the vehicle's windows and windshield using Gila Scratch Resistant Xtreme Limo Window Tint, which is the darkest film in the company's product line, allowing only 2.5% Visible Light Transfer. In Ontario, it is not legal to operate a vehicle with a tinted windshield; however, we obtained a special permission from the University of Waterloo campus police and safety office to do so for this experiment. This allowed us to carry out the intended investigations without exposing the public to undue risks. As far as we know, we are the first in the field to use this Wizard-of-Oz experiment method; we hope it can be another tool for future researchers in the field. Figure 6.2 illustrates how the autonomous vehicle look with a tinted windshield.

Disguised as a self-driving vehicle, the vehicle makes a total of 12 runs from the Earth Science Museum (ESM) to the Douglas Wright Engineering (DWE) building, crossing the experiment crosswalk outside CPH 24 times. Before the experiment, we had identified braking locations along the route, 30 meters before the crosswalk, at which place the driver will activate a decelerating visual signal and the vehicle will gradually stop. The deceleration time is choreographed to be 5 seconds. Once the vehicle is stopped, the driver waits for pedestrians to cross, and after 5 seconds, he activates the To-Accelerate visual signal to prompt pedestrians to yield. Finally, when the crosswalk is clear, the vehicle accelerates and passes the crosswalk. Before the experiment, the Wizard-of-Oz driver practiced these maneuvers to gain proficiency and ensure consistent execution between each trial.

The first 6 runs are baseline trials in which the vehicle does not use visual signals to communicate its intention; the next 6 runs are test trials in which visual signals are used. By comparing and contrasting pedestrian reactions between the baseline and test trials, we infer whether the visual signals affected pedestrian behaviours (RQ12). In addition, two researchers at the crosswalk invited pedestrians who crossed paths with the vehicle to complete a questionnaire about their experience. Their answers are used to determine the appeal and usability of the visual signals (RQ10 and RQ11).

6.1.6 Privacy

Given the fact that this experiment involves filming on a public street, the following precautions are taken, in accordance with the recommendations of the University of Waterloo

Figure 6.2: Experiment 4 - the Wizard-of-Oz Autonomous Vehicle with Tinted Windshield

Ethics Office and the Office of the Privacy Commissioner of Canada, to ensure pedestrians' expectations of privacy are met and respected.

- Signs were posted along Ring Road, at the crosswalks, to inform pedestrians about the study and about the possibility of being filmed.
- Signs were posted on the sides of the vehicle to informing pedestrians that filming is in progress.
- A privacy information letter was prepared and posted along with the signs at the crosswalks to explain how the video recordings will be used and secured. Researchers also had hard copies of the information sheet for anyone who asked.
- The recordings are secured and accessible by study researchers only for analysis. Pedestrians are given the option to remove their image from the recordings.
- No recordings or images of pedestrians will be published without their written consent.

6.1.7 Data Collection

In order to better analyze the impact of visual signals, we made a video recordings of the pedestrian-vehicle interaction from 3 different angles: vehicle, ground, and air. These videos are an essential part of this experiment as they allow us to analyze pedestrian behaviours from different perspectives, so we can better infer their emotions and feelings about the visual signals.

1. The **Vehicle** angle gives a first-person perspective of the experiment from the vehicle's point of view. The videos are recorded using one of the autonomous vehicle's on-board cameras, namely the center front camera. These videos do not show the vehicle's body nor visual signals, but they provide a close-up view of the pedestrian as they cross in front of the vehicle.

2. The **Ground** angle gives a third-person perspective of the experiment. These videos are recorded using a stationary camera located around 20 meters from the crosswalk. They give a full view of the vehicle as it approaches the crosswalk and captures the entire crosswalk where pedestrians are crossing. Most of the videos capture the front of the vehicle and visual signals, thus allowing us to correlate the pedestrian's reaction to signals.

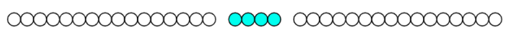
3. The **Aerial** angle gives a bird's-eye view of the experiment. A DJI Mavic Air drone records the experiment from the air directly above the crosswalk, flown by a licensed operator. From this angle, pedestrians and vehicles can be represented by bounding boxes moving on a 2D plane. They are recorded for future work where we plan to mathematically model the pedestrians' paths.

In addition, we made ROSbag recordings of each experiment trial, capturing vehicle sensor data for future analysis.

6.1.8 Results

Questionnaire Results

We asked the following questions to both the baseline and experiment groups of pedestrians and below is a summary of their responses.



(a) Approaching - Solid Turquoise Marker

(b) Decelerating - Shrinking (sync with ego's deceleration)

(c) Stopped - Solid Turquoise

(d) To Accelerate - Blink (2 Hz)

Figure 6.3: Experiment 4 - Depictions of Featured Visual Signals

- *Did you notice the black Lincoln vehicle at the crosswalk? What can you recall about it?* 6 of 7 pedestrians (85.7%) from the baseline group noticed the vehicle and 5 (71.4%) recalled roof-mounted cameras as the most noticeable feature. In contrast, all the pedestrians in the experiment group noticed the vehicle, in which 4 of 8 (50.0%) recalled cameras, 2 (25.0%) recalled sensors, and 4 (50.0%) recalled lights (P14, P21, P22, P24). Two of the pedestrians (P21, P24) recalled both cameras and visual signals. They wrote: "it had a bar of LED lights and several cameras" and "lots of cameras on the roof, and blue LED light bar above the windshield", respectively[1].

- *Do you feel comfortable and safe crossing in front of the vehicle?* On a 7-point Likert scale, 4 of 7 (57.2%) baseline group pedestrians answered 6 or higher indicating they felt comfortable; compared to the 4 of 8 (50.0%) of the experiment group pedestrians who said they felt comfortable. There was no substantial difference between the two groups.

- *Did you notice any visual signal on the Lincoln? If so, please describe them.* Expectantly, none of the pedestrians in the baseline group noticed the signals; but, 4 of 8 (50.0%) experiment group participants did (P14, P21, P22, P24)[2]. Two of the pedestrians (25.0%) described the signals as light bar and three (37.5%) mentioned blue colours. For example, P24 mentioned both: "a blue led light bar. It was flashing, not sure what it meant."

[1] P22 mentioned in another question that there are "blue lights on top."

[2] P14 answered "No" to this question but he indicated in another question that he saw a "unique design blue lighting," so we included him in the count

- *Are the visual signals noticeable? and Did the visual signals make you feel comfortable and safe?* On a 7-point Likert scale, only 1 of 8 (12.5%) pedestrians, P22, in the experiment group answered 6 or higher indicating the visual signals are noticeable and they made him felt comfortable and safe. Most of the other participants either did not notice the visual signals or had neutral feelings about them.

- *What do you think are the purpose of the visual signals?* Out of the 4 (50%) pedestrians who saw the visual signals, P14 wrote: "to warn pedestrians to be alert when crossing"; P21 wrote: "to indicate the intentions of the vehicle"; P22 wrote nothing; and P24 wrote: "to communicate the car's intentions." It is encouraging to see the pedestrians who saw the signals somewhat understood its purpose.

- *What are the visual signals communicating to you?* The 4 pedestrians who recalled the visual signals did not know what they meant.

- *Overall, what is your impression of autonomous vehicles?* 6 of 7 (85.7%) pedestrians in the baseline group and 6 of 8 (75.0%) of the pedestrians in the experiment group said very good or excellent. There are no important difference between the two groups.

- *Can you share what do you know about autonomous vehicles?* Pedestrians seem to have very different understandings about autonomous vehicles. Some common responses are "they drive themselves", "Tesla has some", they use "sensors and cameras", and "they are the future".

- *Overall, do you think fully autonomous vehicles are ready to roam our streets?* On a 7-point Likert scale, 1 of 7 (14.3%) pedestrian in the baseline group and 2 of 8 (25.0%) pedestrians in the experiment group answered 6 or higher indicating they think the autonomous vehicle is ready.

- *Please comment on any aspect of this crossing experience.* P21 in the experiment group asked: "Why wouldn't the light just be red yellow or green? I remember seeing some weird blue green colour."

Observation Results

In total, we drove the autonomous vehicle 12 times around the experiment route and passed the experiment crosswalk 24 times. Table 6.3 and Table 6.2 summarizes the results from the 12 experiment passes and 12 baseline passes with and without using visual signals, respectively. Each pass is further divided into two scenarios in which the autonomous vehicle is decelerating as it approaches the crosswalk or stopped at the crosswalk. The tables refer to the autonomous vehicle as Ego. For each pass and scenario, the tables show the total number of pedestrians crossing paths with the Ego, the total number of pedestrians who looked at the Ego, and the total number of pedestrians who reacted to the situation and changed their crossing behaviours. They also report the number of pedestrians distracted by various activities while crossing; the activities include looking at a handheld device (most common), reading, or taking off a jacket. An asterisk (*) symbolizes there was another vehicle waiting at the crosswalk, which could have influenced pedestrians' crossing behaviours. The results are obtained by reviewing video recordings of the experiments; the primary source of information is derived from the ground level recordings. Figure 6.4 is a snapshot of the ground level video of Pass 18 in which the Ego is stopped at the Crosswalk waiting for a pedestrian to cross.

Passes	Weather	Ego is Decelerating				Ego is stopped			
		Total Crossed	Total Looked	Total Reacted	Dis-tracted	Total Crossed	Total Looked	Total Reacted	Dis-tracted
1	Sunny	5*	2	0	0	2	1	0	0
2	Sunny	3*	2	3	0	2	2	1	0
3	Sunny	1	0	0	0	-	-	-	-
4	Sunny	1	1	1	0	2	1	0	2
5	Overcast	-	-	-	-	1	0	0	0
6	Sunny	4	0	0	1	-	-	-	-
7	Overcast	-	-	-	-	-	-	-	-
8	Overcast	5	0	0	2	2	1	1	0
9	Overcast	-	-	-	-	-	-	-	-
10	Overcast	11	0	0	0	2	0	1	0
11	Sunny	4*	3	0	0	-	-	-	-
12	Sunny	3	1	0	1	4	0	0	1
Average		37	9 (24.3%)	4 (10.8%)	4 (10.8%)	15	5 (33.3%)	3 (20.0%)	3 (20.0%)

Table 6.2: Experiment 4 - Observations of Pedestrian Vehicle Interaction at Experiment Crosswalk without Visual Signals

Overall, most of pedestrians in the experiment videos exhibited inattentiveness and carelessness. Namely, out of the 52 baseline group pedestrians who crossed paths with

Passes	Weather	Ego is Decelerating Total Crossed	Total Looked	Total Reacted	Dis-tracted	Ego is stopped Total Crossed	Total Looked	Total Reacted	Dis-tracted
13	Overcast	1	1	0	0	-	-	-	-
14	Overcast	-	-	-	-	-	-	-	-
15	Overcast	3	0	0	0	-	-	-	-
16	Overcast	2	1	1	0	-	-	-	-
17	Overcast	-	-	-	-	-	-	-	-
18	Overcast	2	1	0	0	1	1	0	0
19	Overcast	2	2	2	0	5	4	4	0
20	Rain	2	0	0	0	4	1	0	0
21	Overcast	5	1	0	0	25	4	2	0
22	Overcast	1	1	1	0	34*	6	4	5
23	Overcast	20	4	0	0	4	1	0	0
24	Rain	-	-	-	-	3*	3	0	1
Average		38	11 (28.9%)	4 (10.5%)	0 (0.0%)	76	20 (26.3%)	10 (13.2%)	6 (7.9%)

Table 6.3: Experiment 4 - Observations of Pedestrian Vehicle Interaction at Experiment Crosswalk with Visual Signals

the autonomous vehicle, only 14 (26.9%) looked directly at the vehicle. Similarly, out of the 114 experiment group pedestrians who crossed paths with the vehicle, only 31 (27.2%) looked directed at the autonomous vehicle. Comparing the reactions of those who looked, 7 of 14 (50.0%) baseline group pedestrians changed their crossing behaviours after looking at the autonomous vehicle. Namely, 4 (28.6%) hesitated before crossing, 2 (14.3%) yielded to the vehicle, and 1 (7.1%) jogged across the crosswalk in front of the waiting vehicle; we did not observe any noticeable change of crossing behaviours among the other pedestrians. Similarly, 14 of 31 (45.2%) experiment group pedestrians changed their crossing behaviours after looking at the autonomous vehicle with visual signals. Namely, 3 (9.7%) hesitated before crossing, 3 (9.7%) yielded to the vehicle, 4 (12.9%) jogged across the crosswalk in front of the waiting vehicle, and 4 (12.9%) stopped after crossing and took photos of the vehicle.

Examining some of these interactions in details, we see in Pass 19, when the autonomous vehicle was waiting at the crosswalk and signalling its intention to accelerate, a group of 4 pedestrians saw the Blink signal and immediately started to jog across the crosswalk,

Figure 6.4: Experiment 4 - a snapshot of Pass 18 showing the ego at the crosswalk and waiting for a pedestrian to cross

seemingly trying to get out of the vehicle's way[3]. While it seems like the pedestrians have understood the visual signals and are cooperating with the vehicle, it is also possible that they are being courteous and trying to let the vehicle pass. As in the case of Pass 2, we also observed a pedestrian who jogged across the crosswalk even when the autonomous vehicle was not communicating with any visual signal. In both cases, the pedestrians were the last ones on the crosswalk. We will further discuss these observations in Chapter 7.

In another example, we observed visual signals had no effect on some pedestrians. For example, in Pass 21, when the vehicle used the Blink signal to notify a group of nearby pedestrians that it was about to accelerate, the pedestrians looked at the vehicle and proceeded normally to enter the crosswalk and cross the street[4]. It is not clear whether the pedestrians did not understand the signals or choose to ignore them. Nonetheless, there are evidence to suggest that pedestrians generally can recognize an autonomous vehicle and take notice of its visual signals. For instance, in Pass 22, two of the pedestrians exhibited excitement when they saw the autonomous vehicle displaying the Blink signal, thus they paid close attention and took photos of the vehicle as they crossed[5]. Although

[3]See Figure 6.5 for a snapshot of the ground level video of Pass 19.
[4]See Figure 6.6 for a snapshot of the ground level video of Pass 21.
[5]See Figure 6.7 for a snapshot of the ground level video of Pass 22.

it is unclear whether their behaviours were induced by the visual signals, such enthusiasm was not observed during baseline passes.

Figure 6.5: Experiment 4 - a snapshot of Pass 19 showing the ego at the crosswalk signalling its intention to accelerate, and a group of pedestrians started to jog across

Figure 6.6: Experiment 4 - a snapshot of Pass 21 showing the ego at the crosswalk signalling its intention to accelerate, and a group of unyielding pedestrian entering the crosswalk

Figure 6.7: Experiment 4 - a snapshot of Pass 22 showing the ego at the crosswalk signalling its intention to accelerate and a pedestrian taking Photo of the vehicle

Chapter 7

Discussion

The overarching purpose of this thesis is to answer the question posed by the chairperson of the SAE J3134 task force on Automated Driving Systems Lamps:'which form of visual signals, such as flashing or sweeping, is best for communicating an autonomous vehicle's intention[43]?' In previous chapters, we attempted to find the answer with 4 novel experiments by looking at the question from the perspectives of visibility, intuitiveness, persuasiveness, and usability. In this chapter, we attempt to synthesize the quantitative and qualitative findings and to construct a coherent argument for improving the designs of autonomous vehicle visual signals.

In addition, this chapter will discuss the four novel experimental methods, their benefits and drawbacks. By doing so, we hope to improve the experiment methodology so future researchers can build on them to evaluate visual signals. Finally, this chapter ends by discussing the implications of the findings and some ideas for future work.

7.1 Experimental Findings

Altogether, we asked 12 research questions in this thesis to understand how autonomous vehicles may use visual signals to better communicate with pedestrians. Each of the 4 sections below discusses the findings of an experiment, answering its research questions, and offers practical design recommendations for autonomous vehicle visual signals based on the results.

7.1.1 Designing for Visibility

In Experiment 1, we evaluated three visual signal patterns, **Solid**, **Blink**, and **Chase**, according to their peripheral visibility. In general, we believe visibility should be measured this way because pedestrians often do not look directly for vehicles when they cross a street; a visual signal with good peripheral visibility may therefore catch their attention even when they are not looking. In general, this experiment shows that a visual signal involving movement, like the Blink and Chase signals, is more visible than a static signal pattern, like Solid Turquoise. So, a general implication to RQ1[1] is that autonomous vehicles should use movement patterns that involve flashing or sweeping to enhance peripheral visibility. However, a closer examination of the results in relation to outdoor brightness revealed another answer. Namely, we discovered that the visual advantage of moving signals only exists in overcast conditions, when the illuminance level is between 1,000 - 10,000. Whereas, in sunny and nightfall conditions, the peripheral visibility of the three tested signal patterns are about the same. Moreover, it was also discovered during daytime when the illuminance level is above 1,000, participants were able to spot the moving experiment vehicle before the visual signals. This finding was surprising but open-end interviews suggest that the size of vehicle is a possible cause for this phenomenon. Because peripheral vision is not good at detecting details [56], this is why it can detect the larger vehicle before the smaller visual signals. Therefore, combinations of the findings suggest that visual signals will not be helpful for a distracted pedestrian who is not paying attention, except at nighttime, when the visual signals could warn the pedestrian of the vehicle's presence well before they see it physically. Now, it is possible these findings would change by increasing the size and brightness of the visual signals being tested. In fact, that could be investigated in future studies(see Section 7.3.1). Nonetheless, the visual signal system used in this study already span the width of the vehicle. By further increasing its physical appearance, visual signal designers will need to consider the trade-off between functionality and vehicle aesthetics.

In response to RQ2[2], the experiment suggests the mounting location of the visual signals has little impact on the signals' visibility. Open-end interviews suggest that this again is caused by the low accuracy of peripheral vision. A participant said it is difficult to tell because the top mounted visual signals are so close to the front mounted ones; another pointed out he had spotted the reflection of the top-mounted visual signals on the vehicle's hood. Although it is possible to create more separation by mounting the visual signals at the back of the rear-view mirrors or at the bottom of front bumper, the existing findings suggest it will make little difference in visibility. In addition, designers

[1] RQ1: What visual signal pattern is most notable in a pedestrian's peripheral vision?

[2] RQ2: Where to mount a visual signal to enhance its peripheral visibility?

should consider the trade-off between mounting location, signal size, and practicality. For example, there is limited space behind the rear-view mirrors which limits signal size; and signal lights mounted close to the road surface will be prone to obstruction by dirt and debris. Furthermore, some participants mentioned sunlight reflections off the vehicle's chrome grill impacted the signals' visibility. All of these findings lead us to think that it is best to mount autonomous vehicle visual signals near the top of the windshield to minimize visual interference [3].

In summary, autonomous vehicle manufacturers and visual signal designers should examine the following design recommendations.

- R1: Use moving or static visual signal patterns, such as Blink, Chase, and Solid, to enhance autonomous vehicle visibility during nighttime.
- R2: Place vehicle signals near the top of the windshield to minimize visual interference.

7.1.2 Designing for Intuitiveness

One of the obstacles of introducing a new vehicle signal is the education of the public. It is simply not enough to install a visual communication signal on an autonomous vehicle and expect pedestrians to understand its meaning. However, it is also true that it is expensive to educate the public and time-consuming for an idea to spread. Therefore, we designed Experiment 2 in an attempt to discover mental models of visual signal patterns shared by the public, in which we argue should be leveraged in the designs of autonomous vehicle visual signals to promote fast adoption. Experiment 2 answered RQ3[4] by examining how participants react intuitively to the six novel autonomous vehicle signals: **Solid Amber**, **Solid Turquoise**, **Blink**, **Chase**, **Expanding**, and **Shrinking**. In doing so, we discovered that more than 3/4 of participants react intuitively to Solid Turquoise, Expanding, and Shrinking signals by crossing, and to Blink and Chase signal patterns by Not crossing. Hence, there seems to exist certain properties about those signals that cause people to react this way and indeed post-experiment interviews reveal them. Namely, some participants revealed they had associated the "fast" frequency of the Blink and Chase signals, 2 Hz and 4 Hz, with urgency and danger; whereas, they associated the "slow" frequency of the Expanding and Shrinking signals, 0.25 Hz, with calm and peace. Hence, this is likely

[3] Lagstrom *et al* also advocated to mount autonomous vehicle visual signals near the top of the windshield [29].

[4] RQ3: How would a pedestrian react to different visual signals intuitively?

why they reacted the way they did. Moreover, participants revealed that colour was the main determining factor for how they perceive the solid signal pattern. Namely, some participants interpreted the Amber colour as warning not to cross, while others proceeded to think that the vehicle is about stop. This confusion is reflected in their ambiguous reactions to the Solid Amber signals. On the other hand, the Solid Turquoise signal is novel to most participants, but surprisingly, the vast majority of them perceived the colour to be calm and mellow, thus deciding it was OK for them to cross.

Next, we examined RQ4[5] by attributing meanings to the six vehicle signals and training the participants to react to them accordingly. In doing so, we discovered that training resolved the confusion about the Solid Amber signal and gave new meaning to the Expanding signal; specifically, participants learned, against their intuition, Not-to-Cross at those signals. However, training was not able to overcome participants' intuition about the perceived danger of the Chase signal. Apparently, participants tend to be risk-averse; they are not willing to risk their lives against their intuition. Such actions would require an extraordinary amount of trust on the visual signal, which evidently was not acquirable in two minutes of training.

Regarding RQ5[6], the experiment showed that participants intuitively react swiftly to Blink and Chase visual signals, perhaps due to our given instinct to avoid danger. However after training, the two solid signals became easiest to interpret and decision time decreased by 453 milliseconds, which confirms that our minds are quicker to process colour than movement [39]. On the other hand, decision time to Blink and Chase signals increased by 433 milliseconds after training, reflecting the confusion participants had about the two signals. Finally, participants generally take longer to react to the slow moving Expanding and Shrinking signals, namely, 440 milliseconds longer compared to the Solid signals, suggesting the animation speed of visual speeds should be considered in the design of visual signals. To put the discussion in context, a vehicle moving at 40 km/h will cover 5 meters of distance in 450 milliseconds. Hence, if a slow-moving visual is used to encourage pedestrians to cross, it is harmless for pedestrians to take longer to decide. The danger lies in using a slow-moving signal to deter pedestrians from crossing because if the pedestrians are already in motion and walking toward a crosswalk, the slower decision will give them less time to react and increase their risk of colliding with the vehicle; visual signals designers should avoid this mistake.

In summary, autonomous vehicle manufacturers and visual signal designers should examine the following design recommendations.

[5] RQ4: How would a pedestrian react to different visual signals after training?

[6] RQ5: How long does it take for a pedestrian to interpret and react to different visual signals?

- R3: Use fast-moving visual signal patterns to communicate urgency and danger to deter pedestrians from crossing.
- R4: Use slow-moving visual signal patterns to communicate calm and safety to encourage pedestrians to cross.
- R5: Do not use slow-moving visual signal patterns to deter pedestrians from crossing; it may endanger them.
- R6: Validate any visual signal pattern with pedestrians' intuition; do not work against it.
- R7: Use solid visual signal patterns to reduce pedestrians' cognitive load and to make their crossing decision easier.

7.1.3 Designing for Influence and Trust

In Experiment 3, we conducted a first-of-kind autonomous vehicle and pedestrian interaction study with a fully automated vehicle. The findings could be the most reliable indication of how pedestrians and autonomous vehicles may interact in reality. By conducting the experiment, we answered RQ7[7] and showed that visual signals can convince a pedestrian to yield to a stationary autonomous vehicles at a crosswalk. Specifically, we found a static visual signal like Solid Amber is just as effective as a dynamic signal like Blink at influencing pedestrians behaviour; post-experiment interviews reveal two potential explanations for this phenomenon. First, some participants indicated that it was the sudden transition from the Solid Turquoise signal to Solid Amber or Blink signal that communicated to them "the vehicle is about to do something different." Therefore, they reacted by changing their action from crossing to stop. Secondly, some participants also indicated that they were able to react to the visual signals simply because they can see them better in close proximity.

Moreover, the experiment answered RQ6[8] and showed that visual signals can not convince a pedestrian participant to cross in front of an approaching vehicle. This is probably the case because visual signals are not enough to overwrite vehicle speed and distance as the dominating factors influencing a pedestrian's crossing decision [49]. Nonetheless, given

[7]RQ7: What visual signals would encourage or deter a pedestrian from crossing in front of a stationary autonomous vehicle?

[8]RQ6: What visual signals would encourage or deter a pedestrian from crossing in front of an approaching autonomous vehicle?

that all 36 test runs in this experiment were performed in bright sunny conditions, with an average illuminance level at 26,753, we cannot say for certain how pedestrians would have reacted if they can see the visual signals better, such as in nightfall conditions. This can be a topic of investigation for future studies (see Section 7.3.1). Nevertheless, as in the case of Experiment 1, environmental factors, such as outdoor brightness, will continue to challenge the effectiveness of visual signals. Designers and engineers will need to find the right balance between visibility and aesthetics for their application.

To investigate RQ8[9], participants interacted with the same set of vehicle signals in two repeated test runs. Although, at the end, we found no significant evidence of learning in pedestrians' crossing behaviours, some participants were able to accurately described the visual signals during interviews, suggesting that there is some level of learning intellectually and that pedestrians may eventually learn to react to the signals given enough time and exposure. Hence, we recommend to repeat this experiment with 5 or more repeated interactions.

Finally, the experiment answered RQ9[10] and revealed that a person who witnessed a properly-behaving autonomous vehicle in action is more likely to trust in the vehicle's technical capability and tolerate more risk when crossing a street in front of such an approaching vehicle. Participants explained their behaviours during interviews suggesting they believe the vehicle will stop for them. Indeed, in accordance with previous robotics trust studies, it appears that trust is engendered through perceived capabilities [50]. Evidence would suggest that pedestrians will learn to trust autonomous vehicles more as their interaction increases. This finding is encouraging for the proliferation of autonomous vehicles. However, it is also concerning because some studies suggest people have the tendency to over-trust a robot and can act irrationally because of it [52]. We also observed some evidence of over-trust in Experiment 3. For example, the E3-S3 Solid Amber was supposed to warn participants of an approaching autonomous vehicle and prompt them to stop. The group of participants that did not receive an autonomous ride seem to have understood the signal and complied. However, for the group of participants who "trusted" the vehicle, the signal seems to have the opposite effect; it appears that participants had assumed both the E3-S3 Solid Amber signal and the E3-S1 Solid Turquoise meant that the vehicle had seen them and will stop for them, which was not the case. Assumption like this and overconfidence in autonomous vehicle could have catastrophic consequence for pedestrian safety in real traffic situations. Therefore, we recommend not to use static signal patterns like E3-S3 Solid Amber to deter pedestrians to cross because they are prone to mental

[9] RQ8: How does repeated exposure to visual signals influence a pedestrian's crossing decision?

[10] RQ9: How does familiarity and trust of an autonomous vehicle influence a pedestrian's crossing decision?

biases and misjudgements. Instead, we suggest using a moving visual signal pattern like Shrinking to encourage more careful deliberation before crossing.

In summary, autonomous vehicle manufacturers and visual signal designers should examine the following design recommendations.

- R8: Incorporate an abrupt change of visual signal patterns on a stationary vehicle to suggest to pedestrians that the vehicle is about to accelerate.
- R9: Avoid using statistic visual signal patterns to deter pedestrians to cross.

7.1.4 Designing for the Public

To investigate RQ10[11] and RQ11[12] of Experiment 4, we recruited pedestrians who interacted with the autonomous vehicle to complete a questionnaire. The pedestrians were divided into two groups, the *baseline* group who did not see the visual signals, and the *experiment* group who saw the visual signals. We discovered important differences in how they identify and recognize an autonomous vehicle. Namely, in the absence of visual signals, 71.4% of pedestrians recalled cameras as the most salient feature of the autonomous vehicle; whereas in the experiment group, equal percentage of pedestrians (50.0%) recalled cameras and visual signals as salient features[13]. Overall, this finding affirms the SAE recommendation for autonomous vehicles to use a marker light to indicate it is in ADS mode [44]. We can image this will become increasingly important as automated driving technologies mature and the size of external sensors and cameras decrease. Perhaps one day, a visual signal will be the only distinguishing feature between an autonomous and a conventional vehicle. Nonetheless, the questionnaire also revealed that today's pedestrians are not ready for autonomous vehicle visual signals. In particular, only half of pedestrians noticed the visual signals in our experiment, only 12.5% thought they were noticeable, and none of them knew what the signals meant. It is encouraging, however that most of them guessed correctly that the visual signals are for communicating the vehicle's intention. These findings can possibly explain why we did not observe significant behaviour change in pedestrians who saw the visual signals. Comparing with the findings of Experiment 3, where visual signals demonstrated significant influence on participant crossing behaviours in some situation, we believe the lack of knowledge and attention are the reasons why

[11]RQ10: How does a pedestrian identify and recognize an autonomous vehicle?

[12]RQ11: Can pedestrians notice a visual signal on an autonomous vehicle? If so, what do they think about it?

[13]Two of the pedestrians (25.0%) recalled both cameras and visual signals.

visual signals are not effective in Experiment 4. Namely, Experiment 3 participants were asked to watch the autonomous vehicle with the visual signals. Hence, they were engaged in the crossing task and paid close attention to the visual signals. We believe that this allowed them to notice the visual signal pattern change and to react accordingly. This is in stark contrast compared to the real traffic situations in Experiment 4, in which most pedestrians were unaware of the visual signals and not paying close attention to the traffic situation. This leads us to believe that in order for visual signals to be effective in real-traffic situations, pedestrians need to, at least, be educated about the signals' existence, so they can look for them and hopefully react to them. Section 7.3.9 discusses future research that could enable visual signalling system to better acquire pedestrian attention. In the meantime, this experiment suggests public education is still an important aspect of an effective autonomous vehicle visual signalling system.

In addition to administering the questionnaires, we observed pedestrian behaviours in 24 crosswalk interactions to see whether visual signals affected pedestrian crossing behaviours (RQ12[14]). As discussed in the results Section 6.1.8, we observed 2 unique behaviours among the pedestrians who interacted with the visual signals, namely speeding up to cross and taking photos of the vehicle. These behaviours seem to suggest the pedestrians are cooperating with, and enthusiastic about, the autonomous vehicle and its visual signals. However, those behaviours seem to be the exception rather than the norm, which we also attributed to pedestrians' lack of knowledge and attention to the visual signals. In addition, observations of the interaction also reveal the strong presence of herd behaviours among pedestrians. Namely, in a group crossing situation, most pedestrians do not brother to look at the traffic if there are one or more pedestrians already in the crosswalk. Pedestrians seem to share an unspoken crossing code of conduct. Namely, they seem to reason if I am the first one to enter a crosswalk, it is my responsibility to look for traffic and ensure my own safety; however, if someone else is already on the crosswalk, it is safe for me to enter because their presence implies safety. Finally, if I am the last person on the crosswalk I need to look to check if it is still safe, because if drivers are getting impatient, I need to get off the crosswalk quickly. This code of conduct seems to describe the majority of the pedestrian crossing behaviours we observed in this experiment[15]. In general, the majority of the studies in the pedestrian-AV-interaction field deal with interaction with a single pedestrian. This experiment reveals the need to conduct autonomous vehicle interaction studies with multiple pedestrians. Section 7.3.2 discusses this need.

In summary, autonomous vehicle manufacturers and visual signal designers should ex-

[14] RQ12: Will pedestrians react differently to an autonomous vehicle equipped with visual signals?

[15] Majority of the pedestrians who interacted with the autonomous vehicle seem to be university students; therefore, this road crossing code of conduct may or may not be the same for other demographic groups.

amine the following design recommendations.

- R10: Develop and use standardized visual signals given the potential of pedestrians being confused by the signals.
- R11: Use marker lamps, such as those recommended by the SAE, to differentiate an autonomous vehicle from a manually-operated one.
- R12: Educate the public about the existence of visual signals and their meanings.

7.2 Experimental Methods

7.2.1 Experimenting with Mind and Sight

At the outset of Experiment 1, we choose to conduct the experiment outdoors for two main reasons: 1) to test the visual signals in conditions that mimic their intended operating environment, and 2) to leverage the vehicle's GPS positioning system for obtain accurate distance gap from the participants. However, there are expected and unexpected drawbacks for doing this experiment outdoors. As we already discussed in Section 4.2.6, visual signals are highly susceptible to light interference. That includes ambient light interference, which we accounted for by quantifying the results using illuminance measurement. However, we also experienced an unexpected interference from visual signals coming from other vehicles in the parking lot. Namely, during one of the experiment trials, a construction vehicle entered the parking lot and flashed its amber warning signal, which became so salient in the participant's peripheral vision that we had to pause our experiment. Because of reasons like these, one may argue it is better to experiment indoors where the environment can better be controlled. While that is true, we found the following drawbacks during our assessment of running an indoor experiment. First, the indoor space must be large enough for the experiment, perhaps at least 25 x 15 meters. Second, the space must have adequate ventilation, especially if the experiment vehicle runs on an internal combustion engine. This is very important for preventing carbon monoxide build-up. Finally, researchers must find an accurate and reliable indoor positioning method to calculate the distance gap between the pedestrian and vehicle. Since GPS positioning technology has poor performance indoors, researchers could consider alternative Lidar, vision, or radio frequency indoor positioning methods [67], [68].

One of the objectives of Experiment 2 is to discover mental models of visual signals shared among pedestrians. While the experiment succeeded in finding some of the salient visual signal patterns that most pedestrians intuitively understood, there are certainly more to be discovered. For example, we would recommend testing with different frequency of the blink and chase signals as we discovered frequency of signal has a major influence on the perceived meaning of signals. Moreover, future studies can use the proposed methodology here to test the Side-to-Side Sweeping signal pattern, which have been featured in other recent studies [13], [55]. In addition, we recognize this experiment could be performed in a lab environment using a conceptual or simulation approach, as discussed in Section 5.1. Even though the participants would lose the realism of seeing the visual signals on an actual autonomous vehicle, more visual signals can be tested and the participant sample size could increase. It is a trade-off researchers can consider for their purpose.

7.2.2 Experimenting with Autonomous Vehicles

In Experiment 3, we conducted a first-of-kind visual signal pedestrian interaction experiment with an fully autonomous vehicle. As we discussed in Section 5.3.6, participants' perception of autonomous vehicles have tangible impact on how they react to visual signals. Consequently, it could be the case that pedestrians would react differently to an autonomous vehicle in a simulator and even an Wizard-of-Oz vehicle. As one of the participants put it "I know it is an autonomous car and it will make a solid decision on stop or go... I am relying on machine's logic"; if such a logic represents the prevailing sentiment in people's perception of autonomous vehicles vs human drivers, we feel visual signals pedestrian interaction studies should be conducted using actual autonomous vehicles.

In addition, there are at least one procedural and one technical improvement we can make to the experiment. Namely, the execution procedure can be improved by eliminating the manual loading of autonomous scenarios between each trial. We need to implement a software based selection method without the need to reload the scenario. This was inefficient because at times the load procedure would cause the vehicle to lose its fix on the GPS signal and it is time-consuming to re-establish alignment. By making this improvement, we could have maximized the participant's time and completed more test runs to investigate the learning impact of visual signals. Secondly, we need a better recording method to register participants' decisions into the vehicle's ROS system. Originally, we built a pair of Android Radio Frequency transceivers for the purpose. The idea was that the research assistant would use a 9V battery powered transmitter to send the participants' decision directly to the autonomous vehicle equipped with a receiver. However, we eventually discovered the transceivers were unreliable in open-field and over a long distance. As a result, we decided use the current manual solution because of its superior reliability, despite the drawback of operator input delay which we assumed to be the same over all the trials.

Moreover, as Rasouli *et al* observed that pedestrian communication studies involving autonomous vehicles generally have limited sample size, 10 or less, and the demographics of participants typically lack diversity [47]. While we tried to overcome these shortcomings by conducting Experiment 3 with 22 participants and recruiting campus wide, 4 of our participants (18.2%) turned out to be keenly interested in autonomous vehicles; and, upon their request, we granted two of them a ride in the autonomous vehicle before the experiment. While it is unknown whether their interests would impact their crossing behaviours, we feel future studies should consider recruiting participants outside a university campus, perhaps in a public area such as a shopping mall. This could increase the diversity of participants to better represent general pedestrians.

7.2.3 Experimenting in the Wild

In Experiment 4, we conducted a field study with an autonomous vehicle driven by a Wizard-of-Oz driver on a public road. One of the challenges we encountered during the experiment was a traffic jam. In particular, the University of Waterloo Ring road is extremely busy near the top and the 30 minutes mark of the hour when students are arriving to go to class. As a result, our experiment was interrupted on few instances by vehicular traffic waiting in front of the experiment crosswalk for pedestrians to cross, thus forcing us to stop up the road and wait for the traffic to clear before approaching. Moreover, there were 5 instances during the experiment where another vehicle was arriving or leaving the experiment crosswalk when the autonomous vehicle was also present. Even though the experiment videos suggest they had minimal impact on pedestrian behaviours, we believe this aspect of the experiment can be improved by enforcing some temporary traffic controls to make sure the crosswalk is free of vehicles before the experiment vehicle arrives. Finally, for the questionnaire study, 8 of 15 (53.5%) participants were not able to complete the questionnaire at the experiment location because of time constraints. They subsequently completed the questionnaire afterwards within 36 hours of the experiment, with two exceptions of participants who completed the questionnaire around 48 hours and 54 hours after the experiment. Therefore, it is conceivable that those participants had forgotten some aspects of the interaction such as the appearance of the autonomous vehicle or the visual signals. Therefore, we recommend that future research should insist participants complete the questionnaire at the experiment location.

7.2.4 Statistical Analysis

To make sense of the experimental results, we used the statistical tool of Analysis of Variance (ANOVA), which helps us find out whether the test results produced by different independent variables are statistically similar or not. For example in Experiment 3, we use a single-factor ANOVA to determine whether distance gaps produced in trials involving different visual signals are statistically different. In Experiment 2, we use two-factor ANOVA to determine whether decision time is influenced by the factors of visual signals and participant training; the analysis also reveals whether the two factors interact or influence each other.

In general, these analysis methods return P-values; using a threshold of 0.05 (5%), we consider P-values less than 5% to denote two groups of results are significantly different from each other. We used the word **significant** in the results sections of chapter 4 through 6 to denote that statistical significance. Moreover, we calculated Eta Square (η^2) to denote effect size [31]. The usage of this analysis method aligns with the standard approach of this research field.

7.3 Future Work

There are many opportunities to expand on this work. In addition to the experiment improvements, this section outlines some additional research ideas and potential first steps to realize them.

7.3.1 Signals

In this study, we examined six visual signal patterns according to four dimensions of effective visual signal communication—visibility, intuitiveness, persuasiveness, and usability. While these six visual signal patterns are meant to be representative, there are more that can be examined. For example, both the Blink and Chase signals at lower frequency of 0.5 Hz and 2 Hz, the side-to-side sweeping signal in literature [13], [55], and a Blinking pattern that flashes at higher frequency as the vehicle approaches a crosswalk are all potential candidates that could reveal new design insights for autonomous vehicle visual signals. Moreover, visual signal intuition studies can be scaled to focus groups and even large scale international surveys using videos.

In addition, we feel there needs to be more research on how to increase signal visibility, particularly in bright sunny conditions. In fact, existing vehicle signals could be studied in order to learn potential design features that could increase autonomous vehicle visual signals' visibility and aesthetics.

7.3.2 Group Interaction

A mostly unexplored research area in this field is autonomous vehicle interaction with pedestrians in a group. As Experiment 4 revealed, herd behaviours among pedestrians are prevalent in everyday crosswalk situations. Therefore, a pedestrian intention communication system must be effective in group interactions. In general, we hypothesize that the key to effective group communication is through its leader, which in a crosswalk situation, seems to be the first pedestrian in front of the group. Hence, future research could repeat Experiment 3 with a group of pedestrians. It will reveal important insights about how visual signals can communicate effectively to a group of pedestrians. We should aim to interact with a border demographics of pedestrians and increase the number of interactions.

7.3.3 Multiple Vehicle Scenarios

Just as it may be useful to further study the interactions between pedestrians in order to decide how best to design the signalling conventions of autonomous vehicles, so too will it be important to consider scenarios where multiple autonomous vehicles may be present together in the environment, each of which is interacting with pedestrians. Whether pedestrians could cope well with several signalling efforts at once is an interesting question. While currently pedestrians share the road with multiple cars, perhaps for autonomous vehicles the addition of activity such as chasing or blinking will be more challenging to experience. Additional experiments with more than one autonomous vehicle in the environment may be valuable to conduct.

7.3.4 Multi-Context Signalling

As discussed in Section 2.1.2, physical structures and contexts such as zebra crossings, mid-blocks, road markings, urban vs rural settings, and signaled rail-crossings can significantly impact pedestrians' crossing behaviour. Therefore, we believe it would be beneficial to study how autonomous vehicle visual signals can be used in those contexts to communicate with pedestrians.

7.3.5 Analyzing differences between types of pedestrians

In our experiments, we gathered data about the gender and age of pedestrians. It would be worthwhile to delve further into an analysis of the responses received along these two axes. In order to produce a more in-depth study, likely we will need a larger number of samples and also ones where there is less of an imbalance between the genders and certainly a larger percentage of older adult participants. Considering pedestrians with assistive needs (e.g. canes or wheelchairs or even parents with baby carriages) will be important to examine as well, in order to better understand the requirements of each class of pedestrian.

7.3.6 Learning more about user preferences

Just as researchers designing to support gestures on mobile phones have at times explored ahead of time how people tend to interpret different hand motions, so too would it be possible for us to operate with some focus groups, aiming to discover typical intuitions for signals such as Blinking and Chasing, to then determine whether the signal choices proposed by our studies end up matching those innate preferences.

7.3.7 Examining light intensity as a factor

While our studies examined choice of colour and pattern of projection (Solid, Blinking or Chasing), another factor to fine-tune might be the actual brightness of the signal and whether for instance a dimming of lights may serve to convey an intention to stop.

7.3.8 Prior user knowledge and confidence

In Experiment 4, we discovered that participants who had the opportunity to ride in the autonomous vehicle tended to acquire important confidence in the vehicle's ability to properly stop for pedestrians. This suggests that a natural tendency for risk aversion can be moderated by this education regarding the vehicles. In a similar vein, researchers who understand exceedingly well what these vehicles are capable of and where they have limitations may end up being instead more reluctant to simply trust that the communication between the vehicle and pedestrians can unfold without problems. All of this may simply suggest that there are fundamental differences between classes of users and their reactions and interpretations. Designing future experiments to take this tendency into account may be of value.

7.3.9 Intelligent Signalling

The next major step for autonomous vehicle intention communication could be intelligent signalling. For example, our system could be integrated with a glance recognition feature, so it can recognize when a pedestrian is looking at it and it can change its visual patterns to signify its intention. Moreover, our system could also learn to recognize the leading pedestrian in a group, so that it directs its communication to that individual. It can further be integrated with a pedestrian path prediction system, so it can attempt to communicate with the pedestrian who had the greatest probability of collision.

Chapter 8

Conclusion

The future of autonomous driving is here. As societies migrate toward self-driving, companies like Waymo and Tesla are leading the way and we could soon encounter one of their autonomous vehicles at a crosswalk near us. To prepare for that day, this thesis examined how an autonomous vehicle can use visual signals to communicate its intention to pedestrians at crosswalks; the goal is to make such interactions safe and pleasant for all stakeholders. So accordingly, this thesis produced twelve visual signal design recommendations aimed to maximize a visual signal's visibility, intuitiveness, persuasiveness, and usability. The recommendations are listed in Table 8.1. In doing so, we provided some answers to the research question posed by the chairperson of the SAE J3134 task force: "which form of visual signals is best for communicating an autonomous vehicles intention [43]," thus addressing one of the major knowledge gaps in the field of Autonomous Vehicle and Pedestrian Communication [47].

Moreover, this thesis presented 4 novel experiment methodology for evaluating ADS visual signals, which includes a first-of-kind visual signal communication experiment with a fully automated vehicle. In doing so, we demonstrated the feasibility of such methodology and we showed that an autonomous vehicle can indeed influence pedestrian behaviours with visual signals by communicating its intention to accelerate.

Furthermore, the experiments revealed new insights about how pedestrians could behave at crosswalks in the autonomous driving era. For instance, we learned pedestrians' crossing behaviours are heavily influenced by their personal experience and perception of autonomous vehicles, and the lack of knowledge about autonomous vehicle signals could be one of the main reasons for their non-cooperative behaviours. All of these findings suggest the importance of educating the public about autonomous driving today, so the technology can engender public trust and acceptance in the future. Table 8.2 and Table 8.3 summarize the findings of each experiment.

In conclusion, it is important for autonomous vehicles to communicate their intentions to pedestrians in order to promote safety, traffic cooperation, and public trust. While much more can be learned, we hope that this work will contribute to the global effort of making autonomous vehicles safer and more socially acceptable, thus helping to realize the potential of this technology to reduce traffic fatalities and injuries. This is the reason why we work hard to make autonomous transportation a reality.

Study	Experiments	Design Recommendations
Phase 1	1 (Visibility)	R1: Use moving or static visual signal patterns, such as Blink, Chase, and Solid, to enhance autonomous vehicle visibility during nighttime. R2: Place vehicle signals near the top of the windshield to minimize visual interference.
	2 (Intuitiveness)	R3: Use fast-moving visual signal patterns to communicate urgency and danger to deter pedestrians from crossing. R4: Use slow-moving visual signal patterns to communicate calm and safety to encourage pedestrians to cross. R5: Do not use slow-moving visual signal patterns to deter pedestrians from crossing; it may endanger them. R6: Validate any visual signal pattern with pedestrians' intuition; do not work against it. R7: Use solid visual signal patterns to reduce pedestrians' cognitive load and to make their crossing decision easier.
Phase 2	3 (Persuasiveness)	R8: Incorporate an abrupt change of visual signal patterns on a stationary vehicle to suggest to pedestrians that the vehicle is about to accelerate. R9: Avoid using statistic visual signal patterns to deter pedestrians to cross.
Phase 3	4 (Usability)	R10: Develop and use standardized visual signals given the potential of pedestrians being confused by the signals. R11: Use marker lamps, such as those recommended by the SAE, to differentiate an autonomous vehicle from a manually-operated one. R12: Educate the public about the existence of visual signals and their meanings.

Table 8.1: Design Recommendations for Autonomous Vehicle Visual Signals

Study	Experiments	Research Questions
Phase 1	1 (Visibility)	*RQ1: What visual signal pattern is most notable in a pedestrian's peripheral vision?* Findings: Flashing and sweeping signal patterns are more visible than static ones in overcast conditions. *RQ2: Where to mount a visual signal to enhance its peripheral visibility?* Findings: Mounting location, top of the windshield or the front bumper, does not impact visibility.
	2 (Intuitiveness)	*RQ3: How would a pedestrian react to different visual signals intuitively?* Findings: Fast-moving signals deter pedestrians from crossing; slow-moving and static Turquoise signals encourage crossing; a static Amber signal is ambiguous. *RQ4: How would a pedestrian react to different visual signals after training?* Findings: Training taught pedestrians to cross on a static Amber signal, and not to cross on a slow-expanding signal; however, it could not overcome pedestrians' tendency to avoid fast-moving signals. *RQ5: How long does it take for a pedestrian to interpret and react to different visual signals?* Findings: Intuitive reactions to fast-moving signals are quickest (average 2.5 sec); Learned reactions to static signals are quickest (average 2.45 sec); reactions to slow-moving signals are slowest regardless of training (average 3.1 sec).

Table 8.2: Phase 1 Research Questions and Summary of Findings

Study	Experiments	Research Questions
Phase 2	3 (Persuasiveness)	*RQ6: What visual signals would encourage or deter a pedestrian from crossing in front of an approaching autonomous vehicle?* Findings: Visual signals did not significantly change pedestrian behaviour when vehicle is approaching. *RQ7: What visual signals would encourage or deter a pedestrian from crossing in front of a stationary autonomous vehicle?* Findings: A change of visual signal appearance prompted pedestrians to stop crossing. *RQ8: How does repeated exposure to visual signals influence a pedestrian's crossing decision?* Findings: The impact was not obvious with limited exposure. *RQ9: How does familiarity and trust of an autonomous vehicle influence a pedestrian's crossing decision?* Findings: After a ride in the AV, pedestrians accepted shorter distance gaps.
Phase 3	4 (Usability)	*RQ10: How does a pedestrian identify and recognize an autonomous vehicle?* Findings: Visual signals and cameras are the most recognizable features on an autonomous vehicle. *RQ11: Can pedestrians notice a visual signal on an autonomous vehicle? If so, what do they think about it?* Findings: While pedestrians noticed the visual signals, they do not know how to interpret or react to them. *RQ12: Will pedestrians react differently to an autonomous vehicle equipped with visual signals?* Findings: While some pedestrians seem to be cooperative and enthusiastic about an AV with visual signals, the signals did not engender significant behavioural change.

Table 8.3: Phase 2 and Phase 3 Research Questions and Summary of Findings

References

[1] The National Highway Traffic Safety Administration. 2016 fatal motor vehicle crashes: Overview. Technical report, U.S. Department of Transportation, 10 2017.

[2] The US National Highway Traffic Safety Administration. Automated driving systems 2.0: A vision for safety. Technical report, The U.S. Department of Transportation, 09 2017.

[3] Arduino. Arduino uno rev3. https://store.arduino.cc/usa/arduino-uno-rev3. Accessed: 2019-10-09.

[4] Arduino. What is arduino? https://www.arduino.cc/en/Guide/Introduction. Accessed: 2019-10-09.

[5] Fanta Camara, Oscar Giles, Ruth Madigan, M Rothmller, PH Rasmussen, SA Vendelbo-Larsen, Gustav Markkula, Yee Mun Lee, Laura Garach, Natasha Merat, and C Fox. Filtration analysis of pedestrian-vehicle interactions for autonomous vehicle control. In *15th International Conference on Intelligent Autonomous Systems (IAS-15) workshop on Robot Perception of Humans*, 06 2018.

[6] Transport Canada. Canadian motor vehicle traffic collision statistics: 2017. Technical report, Minister of Transport, 2017.

[7] Stephen M. Casner, Edwin L. Hutchins, and Don Norman. The challenges of partially automated driving. *Commun. ACM*, 59(5):70–77, April 2016.

[8] Michael Clamann, Miles Aubert, and Mary Cummings. Evaluation of vehicle-to-pedestrian communication displays for autonomous vehicles. In *Transportation Research Board 96th Annual Meeting*, 2017.

[9] John Cohen, E. J. Dearnaley, and C. E. M. Hansel. The risk taken in crossing a road. *Journal of the Operational Research Society*, 6(3):120–128, 1955.

[10] Debargha Dey and Jacques Terken. Pedestrian interaction with vehicles: Roles of explicit and implicit communication. In *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, AutomotiveUI '17, pages 109–113, New York, NY, USA, 2017. ACM.

[11] Charles M Dipietro and L Ellis King. Pedestrian gap-acceptance. In *Paper sponsored by Committee on Characteristics of Traffic Flow and presented at the 49th Annual Meeting*. Highway Research Record, 1970.

[12] Aurlie Dommes and Viola Cavallo. The role of perceptual, cognitive, and motor abilities in street-crossing decisions of young and older pedestrians. *Ophthalmic & physiological optics : the journal of the British College of Ophthalmic Opticians (Optometrists)*, 31:292–301, 05 2011.

[13] Stefanie M. Faas and Martin Baumann. Yielding light signal evaluation for self-driving vehicle and pedestrian interaction. In Tareq Ahram, Waldemar Karwowski, Stefan Pickl, and Redha Taiar, editors, *Human Systems Engineering and Design II*, pages 189–194, Cham, 2020. Springer International Publishing.

[14] Tully Foote and Mike Purvis. Rep 103: Standard units of measure and coordinate conventions. https://www.ros.org/reps/rep-0103.html. Accessed: 2019-10-18.

[15] International Organization for Standardization. Standard: Road vehicles - ergonomic aspects of external visual communication from automated vehicles to other road users (ISO/TR 23049:2018). https://www.iso.org/standard/74397.html, 2018. Accessed: 2019-12-07.

[16] International Organization for Standardization. Standard: Road vehicles ergonomic design guidance for external visual communication from automated vehicles to other road users (ISO/NP tr 23735). https://www.iso.org/standard/77988.html, 2019. Accessed: 2020-01-01.

[17] International Organization for Standardization. Standard: Road vehicles methods for evaluating other road user behavior in the presence of automated vehicle external communication (ISO/AWI TR 23720). https://www.iso.org/standard/76749.html, 2019. Accessed: 2020-01-01.

[18] Lynn B Fricke, 1899-. Traffic accident investigation manual Baker J. Stannard (James Stannard), and Ill.). Traffic Institute Northwestern University (Evanston. *Traffic accident reconstruction : volume 2 of the Traffic accident investigation manual.*

Evanston, Ill. : Northwestern University, Traffic Institute, 1st ed edition, 1990. Includes bibliographical references and index.

[19] Barrie Kirk Paul Godsmark Gill, Vijay and Brian Flemming. Automated vehicles: The coming of the next disruptive technology. Technical report, The Conference Board of Canada, 03 2015.

[20] Nicolas Guguen, Sebastien Meineri, and Chlo Eyssartier. A pedestrians stare and drivers stopping behavior: A field experiment at the pedestrian crossing. *Safety Science*, 75, 06 2015.

[21] A. Habibovic, J. Andersson, M. Nilsson, V. M. Lundgren, and J. Nilsson. Evaluating interactions with non-existing automated vehicles: three Wizard of Oz approaches. In *2016 IEEE Intelligent Vehicles Symposium (IV)*, pages 32–37, June 2016.

[22] W. Andrew Harrell. Factors influencing pedestrian cautiousness in crossing streets. *The Journal of Social Psychology*, 131(3):367–372, 1991.

[23] W. Andrew Harrell. Precautionary street crossing by elderly pedestrians. *The International Journal of Aging and Human Development*, 32:65–80, 01 1991.

[24] W. Andrew Harrell and Tami Bereska. Gap acceptance by pedestrians. *Perceptual and Motor Skills*, 75:432–434, 07 1992.

[25] Carol Holland and Roslyn Hill. The effect of age, gender and driver status on pedestrians' intentions to cross the road in risky situations. *Accident; analysis and prevention*, 39:224–37, 04 2007.

[26] Ira Hyman, S. Boss, Breanne Wise, Kira Mckenzie, and Jenna Caggiano. Did you see the unicycling clown? inattentional blindness while walking and talking on a cell phone. *Applied Cognitive Psychology*, 24:597–607, 07 2009.

[27] The interAct project group. About interact. https://www.interact-roadautomation.eu/about-interact/, 2019. Accessed: 2019-12-01.

[28] Suresh Kumaar Jayaraman, Chandler Creech, Lionel P. Robert Jr., Dawn M. Tilbury, X. Jessie Yang, Anuj K. Pradhan, and Katherine M. Tsui. Trust in av: An uncertainty reduction model of av-pedestrian interactions. In *Companion of the 2018 ACM/IEEE International Conference on Human-Robot Interaction*, HRI '18, pages 133–134, New York, NY, USA, 2018. ACM.

[29] Tobias Lagström and Victor Malmsten Lundgren. Avip - autonomous vehicles' interaction with pedestrians - an investigation of pedestrian-driver communication and development of a vehicle external interface. Master's thesis, Chalmers University of Technology, Gothenborg, Sweden, 2015.

[30] M Lefkowitz, Robert Rogers Blake, and Jane Srygley Mouton. Status factors in pedestrain violation of traffic signals. *Journal of abnormal psychology*, 51 3:704–6, 1955.

[31] Timothy Levine and Craig Hullett. Eta squared, partial eta squared, and misreporting of effect size in communication research. *Human Communication Research*, 28:612 – 625, 10 2002.

[32] Victor Malmsten Lundgren, Azra Habibovic, Jonas Andersson, Tobias Lagström, Maria Nilsson, Anna Sirkka, Johan Fagerlönn, Rikard Fredriksson, Claes Edgren, Stas Krupenia, and Dennis Saluäär. Will there be new communication needs when introducing automated vehicles to the urban context? In Neville A. Stanton, Steven Landry, Giuseppe Di Bucchianico, and Andrea Vallicelli, editors, *Advances in Human Aspects of Transportation*, pages 485–497, Cham, 2017. Springer International Publishing.

[33] Karthik Mahadevan, Sowmya Somanath, and Ehud Sharlin. Communicating awareness and intent in autonomous vehicle-pedestrian interaction. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, CHI '18, pages 429:1–429:12, New York, NY, USA, 2018. ACM.

[34] Patrizia Marti. Perceiving while being perceived. *International Journal of Design [Online]*, 4(2), 2010.

[35] Wim Meeussen. Rep 105: Coordinate frames for mobile platforms. https://www.ros.org/reps/rep-0105.html#coordinate-frames. Accessed: 2019-10-18.

[36] Mercedes-Benz. Overview: Mercedes-benz f015 luxury in motion. https://www.mercedes-benz.com/en/mercedes-benz/innovation/research-vehicle-f-015-luxury-in-motion/. Accessed: 2019-11-25.

[37] Mitsubishi. Mitsubishi electric introduces road-illuminating directional indicators. https://www.mitsubishielectric.com/news/2015/pdf/1023.pdf, 2015. Accessed: 2019-11-25.

[38] R. L. Moore. Pedestrian choice and judgment. *Journal of the Operational Research Society*, 4(1):3–10, 1953.

[39] Konstantinos Moutoussis and Semir Zeki. Functional segregation and temporal hierarchy of the visual perceptive systems. *Proceedings. Biological sciences / The Royal Society*, 264:1407–14, 11 1997.

[40] Dimitris Nathanael, Evangelia Portouli, Vassilis Papakostopoulos, Kostas Gkikas, and Angelos Amditis. Naturalistic observation of interactions between car drivers and pedestrians in high density urban settings. In Sebastian Bagnara, Riccardo Tartaglia, Sara Albolino, Thomas Alexander, and Yushi Fujita, editors, *Proceedings of the 20th Congress of the International Ergonomics Association (IEA 2018)*, pages 389–397, Cham, 2019. Springer International Publishing.

[41] Society of Automobile Engineers International. Standard: Flashers (J1690_199608). https://www.sae.org/standards/content/j1690_199608/, 1996. Accessed: 2019-12-11.

[42] Society of Automobile Engineers International. Operational definitions of driving performance measures and statistics (J2944_201506). https://www.sae.org/standards/content/j2944_201506/, 2015. Accessed: 2019-12-23.

[43] Society of Automobile Engineers International. Standard: Automated driving system (ADS) marker lamp (J3134_201812). https://wiki.unece.org/download/attachments/75531441/AVSR-02-20e.pdf?api=v2, 2018. Accessed: 2019-11-25.

[44] Society of Automobile Engineers International. Standard: Automated driving system (ADS) marker lamp (J3134_201905). https://www.sae.org/standards/content/j3134_201905/, 2019. Accessed: 2019-12-07.

[45] John Paul. Florence lawrence: Automotive inventor and the worlds first movie star. https://www.historicvehicle.org/florence-lawrence-automotive-inventor-worlds-first-movie-star. Accessed: 2019-10-24.

[46] Nicholas Pennycooke. Aevita : designing biomimetic vehicle-to-pedestrian communication protocols for autonomously operating & parking on-road electric vehicles. Master's thesis, Massachusetts Institute of Technology, 03 2013.

[47] A. Rasouli and J. K. Tsotsos. Autonomous vehicles that interact with pedestrians: A survey of theory and practice. *IEEE Transactions on Intelligent Transportation Systems*, pages 1–19, 2019.

[48] Zeheng Ren, Xiaobei Jiang, and Wuhong Wang. Analysis of the influence of pedestrians eye contact on drivers comfort boundary during the crossing conflict. *Procedia Engineering*, 137:399–406, 12 2016.

[49] Malte Risto, Colleen Emmenegger, Erik Vinkhuyzen, Melissa Cefkin, and Jim Hollan. Human-vehicle interfaces: The power of vehicle movement gestures in human road user coordination. In *Proceedings of the 9th International Driving Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design: driving assessment 2017*, pages 186–192. University of Iowa, 11 2017.

[50] Alessandra Rossi, Patrick Holthaus, Kerstin Dautenhahn, Kheng Lee Koay, and Michael L. Walters. Getting to know pepper: Effects of people's awareness of a robot's capabilities on their trust in the robot. In *Proceedings of the 6th International Conference on Human-Agent Interaction*, HAI '18, pages 246–252, New York, NY, USA, 2018. ACM.

[51] D. Rothenbcher, J. Li, D. Sirkin, B. Mok, and W. Ju. Ghost driver: A field study investigating the interaction between pedestrians and driverless vehicles. In *2016 25th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN)*, pages 795–802, Aug 2016.

[52] Maha Salem, Gabriella Lakatos, Farshid Amirabdollahian, and Kerstin Dautenhahn. Would you trust a (faulty) robot?: Effects of error, task type and personality on human-robot cooperation and trust. In *Proceedings of the Tenth Annual ACM/IEEE International Conference on Human-Robot Interaction*, HRI '15, pages 141–148, New York, NY, USA, 2015. ACM.

[53] S. Schmidt and B. Frber. Pedestrians at the kerb – recognising the action intentions of humans. *Transportation Research Part F: Traffic Psychology and Behaviour*, 12(4):300 – 310, 2009.

[54] A. C. Serban, E. Poll, and J. Visser. A standard driven software architecture for fully autonomous vehicles. In *2018 IEEE International Conference on Software Architecture Companion (ICSA-C)*, pages 120–127, April 2018.

[55] John Shutko, Teryn Bray Bray, Andy Schaudt, Shane McLaughlin, and Vicki Williams. Evaluation of av external communication in the wild. https:

//wiki.unece.org/download/attachments/75531441/AVSR-02-23e.pdf?api=v2, 2018. Accessed: 2019-11-25.

[56] Hans Strasburger, Ingo Rentschler, and Martin Jttner. Peripheral vision and pattern recognition: A review. *Journal of Vision*, 11(5):13–13, 12 2011.

[57] Matus Sucha. Road users strategies and communication: driver-pedestrian interaction. In *Transport Research Arena (TRA) 5th Conference: Transport Solutions from Research to Deployment*, 2014.

[58] Matus Sucha, Daniel Dostl, and Ralf Risser. Pedestrian-driver communication and decision strategies at marked crossings. *Accident; analysis and prevention*, 102:41–50, 03 2017.

[59] M.P.S. To, B.C. Regan, Dora Wood, and J.D. Mollon. Vision out of the corner of the eye. *Vision Research*, 51(1):203 – 214, 2011.

[60] Ariane Tom and Marie-Axelle Grani. Gender differences in pedestrian rule compliance and visual search at signalized and unsignalized crossroads. *Accident Analysis & Prevention*, 43:1794–801, 09 2011.

[61] Florian Weber, Ronee Chadowitz, Kathrin Schmidt, Julia Messerschmidt, and Tanja Fuest. Crossing the street across the globe: A study on the effects of ehmi on pedestrians in the us, germany and china. In Heidi Krömker, editor, *HCI in Mobility, Transport, and Automotive Systems*, pages 515–530, Cham, 2019. Springer International Publishing.

[62] Alexandra Willis, Nathalia Gjersoe, Catriona Havard, Jon Kerridge, and Robert Kukla. Human movement behaviour in urban spaces: Implications for the design and modelling of effective pedestrian environments. *Environment and Planning B: Planning and Design*, 31:805–828, 11 2004.

[63] Burkard Wördenweber, Jörg Wallaschek, Peter Boyce, and Donald D. Hoffman. *Automotive Lighting and Human Vision*. Springer International Publishing, 2007.

[64] Worldmeters. Car facts. https://www.worldometers.info/cars. Accessed: 2019-10-24.

[65] Dana Yagil. Beliefs, motives and situational factors related to pedestrians self-reported behavior at signal-controlled crossings. *Transportation Research Part F: Traffic Psychology and Behaviour*, 3:1–13, 03 2000.

[66] Kai Yun Yang, Feng Jiang, Pingge Jiang, Renran Tian, Michele Luzetski, Yaobin Chen, Rini Sherony, and Hiroyuki Takahashi. Pedestrian behavior analysis using 110-car naturalistic driving data in usa. In *23rd International Technical Conference on the Enhanced Safety of Vehicles (ESV)*, 2013.

[67] F. Zafari, A. Gkelias, and K. K. Leung. A survey of indoor localization systems and technologies. *IEEE Communications Surveys Tutorials*, 21(3):2568–2599, thirdquarter 2019.

[68] Lingling Zhu, Aolei Yang, Dingbing Wu, and Li Liu. Survey of indoor positioning technologies and systems. In Shiwei Ma, Li Jia, Xin Li, Ling Wang, Huiyu Zhou, and Xin Sun, editors, *Life System Modeling and Simulation*, pages 400–409, Berlin, Heidelberg, 2014. Springer Berlin Heidelberg.

[69] W. Zong, C. Zhang, Z. Wang, J. Zhu, and Q. Chen. Architecture design and implementation of an autonomous vehicle. *IEEE Access*, 6:21956–21970, 2018.

APPENDICES

Appendix A

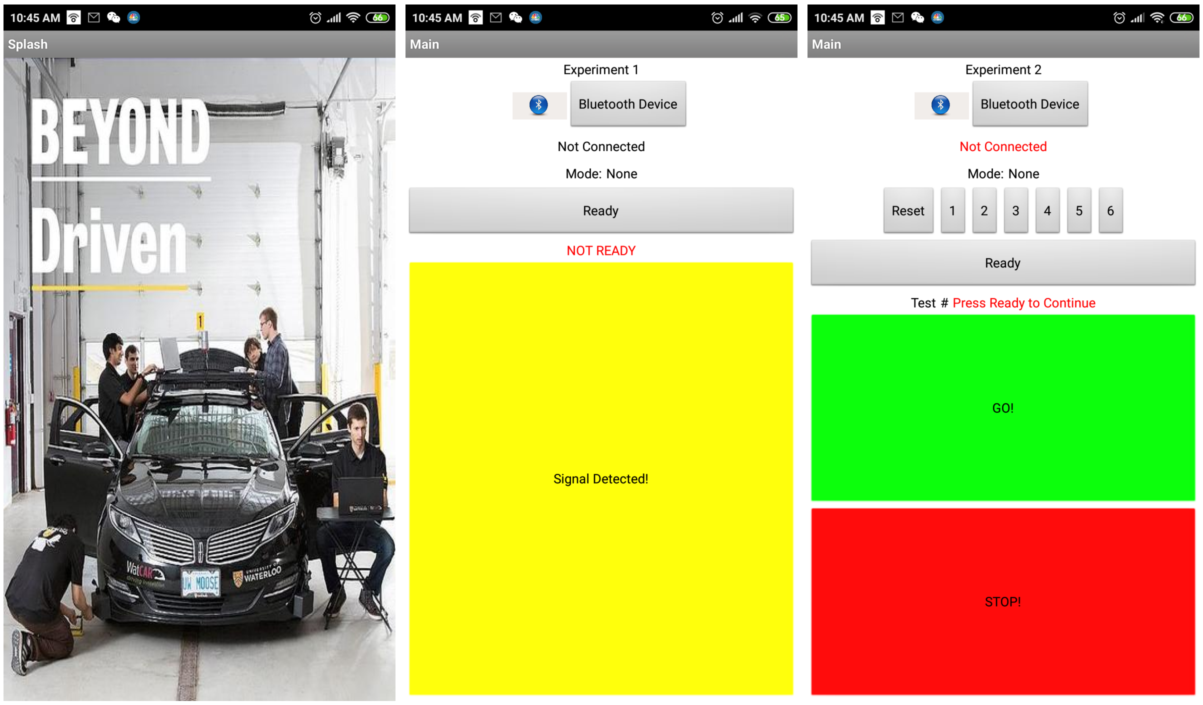
Visual Communication System Prototype Design Artifacts

Reference for Section 3.2.3 - Impedance Matching

(a) Control Signal Before Impedance Matching (b) Control Signal After Impedance Matching

Figure A.1: Appendix A - Noise Reduction Effect of Impedance Matching on a Visual Signal Control Circuit

Reference for Section 3.3.5 - Smartphone Applications



(a) Splash Screen (b) Experiment 1 APP (c) Experiment 2 APP

Figure A.2: Appendix A - Screenshots of Android Handheld Applications used during Experiments