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### Virtual Reality based Study to Analyse Pedestrian Attitude towards Autonomous Vehicles

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## Virtual Reality based Study to Analyse Pedestrian attitude towards Autonomous Vehicles

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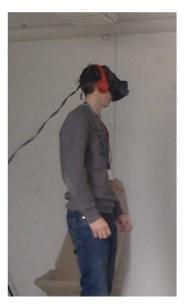






Figure 1: Virtual reality method to study pedestrian attitude towards autonomous vehicles: (left) A participant wearing the virtual reality headset and taking part in the experiment; (right) the virtual worlds used in the experiment as seen through participant's eyes.

#### **ABSTRACT**

What are pedestrian attitudes towards driverless vehicles that have no human driver? In this paper, we use virtual reality to simulate a virtual scene where pedestrians interact with driverless vehicles. This was an exploratory study where 15 users encounter a driverless vehicle at a crosswalk in the virtual scene. Data was collected in the form of video and audio recordings, semi-structured interview and participant sketches to explain the crosswalk scenes they experience. An interaction design framework for vehicle-pedestrian interaction in an autonomous vehicle has been suggested which can be used to design and model driverless vehicle behaviour before the autonomous vehicle technology is deployed widely.

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#### **KEYWORDS**

Autonomous vehicles (AVs), self-driving car, virtual reality (VR), pedestrian-vehicle interaction, implicit interaction, interaction design (IxD), Human-Computer Interaction (HCI), Human Machine Interaction

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#### 1 INTRODUCTION

HS Automotive Inc. predicts global sales of nearly 21 million driverless vehicles (AVs) in 2035 [2]. Almost all major automotive manufacturers are investing heavily in the autonomous vehicle research. The market for autonomous vehicles is expected to reach nearly US\$77 billion by 2035 [3]. McKinsey&Co. estimate that self-driving vehicles would eliminate 90% of the vehicle accidents in the United States and save upto US\$190 billion of the expenses related to damages and health costs, while also saving thousands of lives [35].

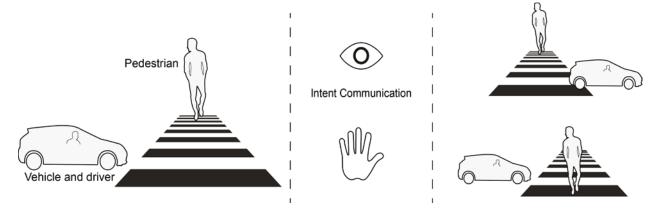


Figure 2: Interaction between pedestrians and vehicles at a crosswalk: a) A pedestrian and a vehicle approach the crosswalk, b) the pedestrian makes eye-contact with the driver and communicates intent using body movement and gestures, c) the driver indicates not giving way and crosses the crosswalk while the pedestrian waits or the driver indicates giving way and waits for the pedestrian to cross the road.

Safer vehicles also mean lower insurance costs on a vehicle. Driverless vehicle technology will make traffic much more efficient and streamlined, reduce congestion, efficiently use road space, save fuel and increase roadway capacity. For example, autonomous technology allows sensing and predicting the leading vehicles' acceleration and braking patterns. Such insights would allow for smoother acceleration and braking in vehicles, thus leading to fuel saving and less wear-and-tear. Driverless vehicles can also detect lanes and intersections to make efficient route choices and coordinate platooning, thus increasing the road capacity [9] by an estimated 273% [33].

Autonomous vehicles do not require a human in the driving loop of the vehicle. The vehicle will possess the ability to sense the environment around them and navigate without human input. When such autonomous vehicles encounter pedestrians, it is essential that the vehicle is able to convey their status and intent to the pedestrians in an effective and efficient manner. This is particularly important to ensure that autonomous driving systems does not compromise the safety of the pedestrians and also of the passengers inside the vehicle. Autonomous vehicles are certain to be designed and programmed to avoid hitting people, but it is also necessary to communicate this to the pedestrians to avoid unexpected reactions from the pedestrians. Currently, the technology for vehicles to cruise autonomously is being heavily researched, but how an autonomous vehicle would interact with pedestrians is relatively unclear. Hence, the study of autonomous vehicle interaction with pedestrians is indispensable. Pedestrian behaviour and their perception of vehicles in different situations can be a starting point of the investigation — to design the interaction between the autonomous vehicles and pedestrians.

#### 1.1 Problem statement

Research shows that pedestrian-driver interaction at a crossroad relies heavily on eye-contact between the pedestrian and the human-driver [25, 26]. Other signals such as gaze, body movements and posture helps the driver understand pedestrian's intent and in turn helps the pedestrian understand the driver's intention [26]. There

is a tacit transaction taking place at road crossings where the pedestrian and driver interact to decide about who crosses the road first. The pedestrian can deduce the intention of the driver based on the driving behaviour without explicit communication between the two. The purpose of this study is to understand how a pedestrian would perceive vehicle behaviour in a situation where no driver is present. The pedestrian might have to rely on other factors to understand vehicle intention. This insight about pedestrian behaviour could be used to design interactions for autonomous vehicles. The following research question has been framed:

How does lack of a human driver in a vehicle, influence pedestrians' interpretation of vehicle behaviour under different visibility conditions?

#### 1.2 Virtual Reality experiment

Pedestrian attitude towards autonomous vehicle can be studied used using a VR method (Figure 1). VR is defined as a computergenerated environment where a user can experience a virtual world without being actually there. VR has been shown to be immersive and inducing presence [5] [30]. First advantage of using VR for the experiment is that the vehicle behaviour is controlled by a computer, similar to an autonomous vehicle. Secondly, in the VR experiment the participants who act as the pedestrians do not have a driver to communicate intent unlike an experiment in the realworld where it would be necessary to have a driver. Driverless vehicles are not yet available for the purpose of the experiment due to lack of prototypes and also due to legal legislations that require all vehicles to have a human driver behind the steering wheels. The virtual scene was set in an urban scenario as majority of the accidents between vehicles and pedestrians happen in urban areas[1].

Pedestrian fatalities account to 15% of all the fatalities in traffic accidents [1]. Crossing the road is an event that can result in accidents involving pedestrians. The negotiation between the pedestrians and the vehicles to cross the road takes place at crosswalks (Figure

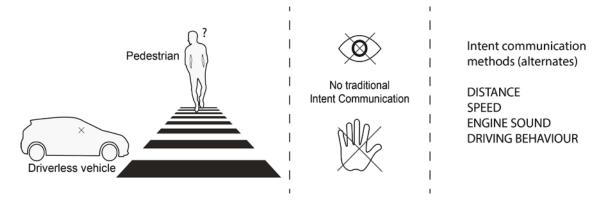


Figure 3: Interaction between pedestrians and driverless vehicles at a crosswalk: a) A pedestrian and a driverless vehicle approach the crosswalk, b) no driver in the vehicle results in failure to communicate intent using traditional methods like eye or hand gestures. c) possible alternative methods to communicate vehicle intent.

2). Hence, the crosswalk scene can be used for the VR setup. Pedestrians are able to cross the road even without any communication with the driver in certain scenarios, for example, when the driver of a vehicle cannot be seen (like at night or during bad weather [24]). Two extreme situations can be used to clearly distinguish the environmental conditions and get a better understanding about how people perceive a vehicle approaching them in low visibility conditions. A research conducted by Schneemann and Gohl [27] shows that a human driver's interaction with a pedestrian starts about 60 meters before the crosswalk in a 50 km/h zone, or starts 30 meters before the crosswalk in the 30 km/h zone. Another study mentions average stopping time, distance from which a driver starts to decelerate etc [11]. Results from these studies can be adopted to model the vehicle behaviour in the VR experiment.

#### 2 BACKGROUND

#### 2.1 Autonomous Vehicles

An autonomous vehicle (AV) is a vehicle capable of sensing [32] and understanding its environment and navigating around without the need of a human input. Advanced control systems interpret sensory information from a variety of technologies like radar, laser light, GPS and computer vision to identify navigation paths, other vehicles [36], pedestrians, obstacles and signages.

#### 2.1.1 Classification of Autonomous vehicles

. SAE International, an automotive standardization body, classifies autonomous vehicles into six different levels as follows [8, 23]:

- Level 0 No automation: the driver is in control of the vehicle and responds to the automated systems in the vehicle.
- Level 1 Driver assistance: the automated system and the driver share the driving responsibility. The driver is expected to take full control of the vehicle at any moment.
- Level 2 Partial automation: the system takes full control of the vehicle operation. The driver must monitor the driving at all times and be prepared to take control of the vehicle.
- Level 3 Conditional automation: The driver can disengage from driving tasks and the vehicle will inform the driver to take over the driving control in some limited time.

- Level 4 High automation: vehicles operate autonomously for entire trips and driver attention is not required. Humanassistance is supported only in specific circumstances.
- Level 5 Full automation: fully autonomous system where the vehicle's performance is equal to human driver in any driving scenario. No driver assistance is required at any stage of the vehicle operation.

In this paper, 'driverless vehicles' and 'fully autonomous vehicles' refer to Level 5 autonomous vehicles where a human is not required in the driving loop of the vehicle.

#### 2.2 Pedestrian-Vehicle Interaction

Interaction between pedestrians and drivers starts well before the actual event of crossing as reported by Schweizer et al. [28] and Varhelyi [34]. Drivers also make their decision (to yield/cross) at least 40-50 meters before the crosswalk. A driver's reaction to yield after spotting a pedestrian trying to cross a road is generally by smooth and slow deceleration of the vehicle depending on the clarity of the pedestrian's intentions. Schmidt and Färber [26] showed that pedestrian's intention to cross a road is conveyed by their body language. Body language can include head, leg and body movements (like turning of the body etc). Schweizer et al. [28] and Scherer [25] further confirm the existence of a mutual gaze behaviour during the interaction process.

#### 2.2.1 Task analysis for vehicle-pedestrian interaction.

Task analysis [17] of pedestrian interaction with a normal car at a crosswalk situation gives an insight into standard pedestrian behaviour. There is a breakdown in this behaviour when the pedestrian encounters an autonomous vehicle. The task analysis is as follows:

- (a) both pedestrian and vehicle approach the crosswalk,
- (b) pedestrian makes eye-contact,
- (c) driver makes eye-contact,
- (d) driver indicates not giving way,
- (e) pedestrian waits,
- (f) vehicle crosses,
- (g) pedestrian crosses

At step c, an alternate trajectory is also possible,













Figure 4: Existing or conceptual solutions for interaction between vehicles and pedestrians: (upper row – left to right) Semcon's Smiling Car concept uses smile to communicate vehicle intent; AutonoMI concept tracks the pedestrian's position on the street by glowing directed LED lights on the vehicle body.; AVIP (Automated Vehicle Interaction with Pedestrians) prototype developed by Viktoria Swedish ICT uses an LED strip to communicate vehicle intention to pedestrians. (bottom row) Mercedes's 'The F 015 Luxury in Motion'concept uses LED displays on the vehicle body, F 015 uses projectors and LED displays to communicate. The projectors are able to display informative messages based on the situation. Nissan IDS Concept using LED display in front of the vehicle and LED indicator lights around the body.

- (d) driver indicates giving way,
- (e) driver waits,
- (f) pedestrian crosses,
- (g) vehicle crosses

In the scenario, the intent communication between the driver and pedestrian happens during steps b and c — which is identified as a crucial point where a tacit communication between the driver and the pedestrian takes place (Figure 2).

However, no tacit communication can take place in the case of driverless vehicles. This is a breakdown in this traditional pattern of interaction between vehicles and pedestrians (Figure 3). The traditional process of intent communication which relies on eye contact and body gesture stalls. However, Rothenbücher et al. [24] notes that pedestrians are highly capable of interacting with vehicles, in situations like night time and poor weather, when the driver cannot be seen by a pedestrian. This might suggest the presence of cues, other than the tacit communication between the driver and the pedestrian, that a pedestrian may use to tackle the situation.

#### 2.3 Existing solutions

Concepts for autonomous vehicle's interaction with pedestrians have been developed and prototyped by few companies and research institutes. Most of the concepts involve some form of visual communication— either in the form of LED displays or projectors.

Smiling Car (Figure 4) is a concept developed by Semcon, where a self-driving car interacts with pedestrians by smiling. When the vehicle detects a pedestrian, a display in front of the car lights up to depict a smile trying to communicate that the car will stop for the pedestrian [29]. Mercedes's F 015 Luxury in Motion (Figure 4) communicates with pedestrians using LED displays outside its body. F 015 lets the pedestrian know that the car has noticed them and illuminates their path with projected lights to guide them [19]. The projectors are also able to display informative messages according to the situation (Figure 4, bottom row). AEVITA [22] concept developed at Massachusetts Institute of Technology (MIT) uses directional speakers and headlamps along with illuminated wheels that change colour based on proximity of the pedestrians to communicated with the pedestrians. A concept developed at ISIA Roma Design Institute called AutonoMI [12] uses light pointing towards the pedestrian following them across the crosswalk - indicating that they have been spotted (Figure 4). Nissan IDS Concept [21] is a solution that indicates the pedestrian being spot using LEDs around the body along with explicit visual feedback messages(Figure 4). AVIP — Automated Vehicle's Interaction with Pedestrians (Figure 4), developed at Swedish Victoria ICT consists of a strip of LEDs placed on top of the wind shield outside the vehicle[18]. Other concepts proposed from Viktoria Swedish ICT involve LED grills, LED wind shields and laser projections on the road.

#### 2.4 Human Cognition

Interaction between vehicles and pedestrians can be analysed at cognitive level. An approach to design interaction for autonomous vehicle could be by understanding human cognition with respect to autonomous systems, especially in the case of action and intention recognition. Nilsson et al. [20] suggest two different cognitive methods relevant to human interaction with autonomous systems.

Nilsson suggests that autonomous vehicles can be considered as inanimate objects which move. Heider and Simmel [14] demonstrate that people tend to interpret moving inanimate objects similar to person-like actions. The study showed that people interpret moving triangles and squares as animated beings that have individual personalities. The second method is a neuroscience study by Thill et al. [31] which points the importance of embodiment and morphological similarities in social interactions; meaning that humans might be able to understand behaviour of human like robots but not necessarily of all automated systems.

Two important branches of cognitive science can be used to understand autonomous vehicles' user experience. First, the extended and distributed views of cognition [6, 15] where autonomous system is seen as an extension of the human mind. In extended cognition, the external objects play a significant role in the cognitive process. 'The Extended Mind' [6], a thought experiment, illustrates how environment and external stimuli gets coupled with the mind. In case of autonomous vehicles, the vehicle is an external object which becomes an extension to the mind and the cognition is distributed and understood in terms of interaction with the automated system. The other branch is social cognition where two or more autonomous systems co-regulate their coupling such that they retain their autonomy and their relational dynamics lead to form an autonomy of its own [7]. According to social cognition, both humans and the autonomous vehicles are treated as two independent systems that act and behave independently but together create an understanding of their own, retaining their individuality.

#### 2.5 Implicit interaction

Implicit Interaction [16] is a paradigm that facilitates communication without the use of explicit input and output. Making something that is invisible in day-to-day life very obvious and using the same to convey intentions is a challenge. Implicit Interaction does this by placing humans in the forefront and putting technology in the background. One approach to achieve this in interaction design is to understand human-human interaction and then translate and apply these interactions to new human-product interactions [16]. As discussed in section 2.4 about cognition, an autonomous vehicle is also an independent system similar to a human being. Human-like actions and behaviour by the autonomous vehicle might be better understood by the people. This idea is also postulated by Rothenbücher et al. [24] who raises the perspective that pedestrians are able to cross the roads at crosswalks without any communication with the driver of a car. The possible explanations the researcher suggests for such a behaviour is the human ability to pick up implicit cues from the driving pattern of the human driver in situations like adverse weather, night, low-light conditions and decide whether (and when) to cross the road. In such situations, explicit methods of communication (Figure 2) between a pedestrian and a car driver using eye-contact and hand gestures fail and the decisions are based on vehicle attributes like speed, sound and driving behaviour (Figure 3).

#### 3 PURPOSE

The purpose of the study is to understand the pedestrian interaction process with a vehicle when there is no human-driver present, in

order to design interactions for autonomous vehicles. To derive insights on how a vehicle should behave around a pedestrian who intends to cross the street, we expose the pedestrian to different vehicle behaviours under different weather conditions. First, we examine how the pedestrian perceives a vehicle without a human-driver. The vehicle behaviour is modelled on human-driving behaviour based on the human cognition and implicit interaction theories discussed above. Here, the aim is to validate if the participants could relate the driverless vehicle to human driving behaviour. Finally, we examine the cues taken into consideration by the pedestrian to understand the vehicle behaviour. Out of this, key aspects governing the vehicle-pedestrian interaction can be identified. These insights can be used to design and model vehicle-pedestrian interaction for an autonomous vehicle.



**Figure 5: The study using virtual reality:** a) The HTC Vive VR headset used for the experiment. b) A person wearing the headset and participating in the experiment.



Figure 6: Crosswalk scene as seen through participant's eyes during the experiment.





Figure 7: Environmental factors as seen in the VR scene. (left) Clear sky with ample daylight; (right) Low visibility condition resulting from rain and fog at night time.

#### 4 METHODS

#### 4.1 Participants and location

Fifteen people (10 males and 5 females) took part in the study. Of the total 15 people, 12 participants were from Sweden and 3 were from the Asian sub-continent (2 Chinese and 1 Indian). The study was conducted individually with each participant. All the experiments were held in a 5x5 room where the VR device (HTC Vive, Figure 5a.) used for the experiment was installed and configured. The participants are introduced to the purpose of the experiment and acquainted to the VR headset and the task was described as follows:

The virtual scenario you will see is an urban street and you are at a crosswalk. Your task is to cross the road making sure that it is safe to cross. A car is approaching from your left-side and you are required to understand the intention of the car and cross the road. There are six different situations.

Following the description of the task, the participants were made familiar with the VR and audio headset and asked to walk around in the virtual scene to get familiar with the virtual world. Once the participants got accustomed to the virtual world, they were presented the six situations in a random order. Each experimental situation is followed by a semi-structured interview where the participants are also asked to sketch on a white board and explain the vehicle's behaviour as it approached them. The three vehicle behaviours and two environmental factors result in a total of six situation that each participant was exposed to. Once the participants are done with the six situations, they are asked a few more questions regarding the whole experiment. The participants were not made aware that the vehicle is autonomous/not, however the question is raised during the final interview. This was done to avoid the participants from having any preformed notions or expectations from an autonomous car, as the form and shape of a prospective autonomous vehicle is still undefined.

#### 4.2 Experimental Design

Pedestrian attitude towards autonomous vehicle was be studied used using a VR method. The six situations used in the VR experiment are the result of permutation and combination of the two

environmental factors and the three vehicle behaviour patterns. Two environmental conditions were simulated as seen in Figure 7. The first situation was a bright day with ample daylight and clear visibility, while the second situation was a low visibility condition resulting from rain and fog at night time. The extreme situations could help better understand about how people perceive a vehicle approaching them in low visibility conditions. A crosswalk situation (Figure 6) in an urban setting was developed using Unity, a cross-platform game engine, that provided features to render the virtual environment for the purpose of the experiment. The game engine simulated the video and audio for the VR scene. The virtual scene was set in an urban scenario. In the experiment, the participants stood at the beginning of the crosswalk (as shown in Figure 6), ready to cross the road. A vehicle approached the crosswalk from the pedestrian's left hand side and the participants were asked to cross the road safely. The experiment had three different vehicle behaviours (Figure 8) as described below:

(1) the vehicle accelerates and attains a speed of 60 km/h; at a distance of 60 metres from the crosswalk the vehicle decelerates reaching a speed of 30km/h and then further decelerates coming to a complete stop,

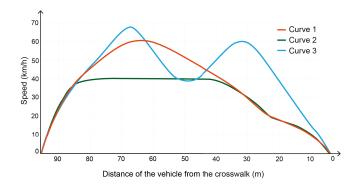


Figure 8: Speed-Distance graph showing the different vehicle behaviours used for the experiment. The distance shown is the distance from the crosswalk. Each vehicle starts from a stop at 100 meters from the crosswalk and stops 7—10 meters before the crosswalk.

- (2) the vehicle accelerates and attains a constant speed of 30 km/h; at a distance of 30 meters from the crosswalk the vehicle decelerates to a complete halt,
- (3) the vehicle accelerates and reaches 70 km/h; the vehicle then decelerates to 40km/h and then accelerates to 60 km/h before finally decelerating to a complete stop,

In all the situations the vehicles started from a standstill at a distance of 100 meters from the crosswalk. The lack of driver in the virtually simulated car was the closest feasible option to a real driverless car.

Table 1: The six experiment situations

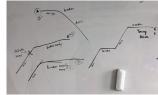
Situation	Weather condition	Driving behaviour
A	Bright and clear	Curve 1
В	Poor visibility	Curve 1
C	Bright and clear	Curve 2
D	Poor visibility	Curve 2
E	Bright and clear	Curve 3
F	Poor visibility	Curve 3

#### 4.3 Methods of analysis

Qualitative methods were primarily used to assess the data. The data consisted of audio and video footages of participant's reaction to the experiment situations and their responses to the interview questions. The participant's eye-view in the virtual world was recorded and matched to the participant's reaction in the real world to help understand their behaviour. The responses to the semi-structured interview were aggregated to find the similarities and differences in participant's understanding of the different scenarios. Participants also shared their understanding of vehicle behaviour in different situations by drawing sketches on a whiteboard. The participants were also asked to think-aloud during the complete study.

- Video recording All the proceedings of the study was recorded on video to capture the participant's reaction to different situations. The interviews were also captured.
- (2) VR situation recording What the participant sees in the virtual world during the experiment changes according to his/her movement. Participant's eye-view of the virtual world was recorded and mapped with the video footage to better understand their movements and responses.
- (3) Semi-structured interview Every situation in the experiment was followed by a semi-structured interview to understand the participant's perception of the situation. A set of questions were formulated which sequentially became more specific. This was done to avoid leading questions and get unbiased views from the participants on each of the situations. The questions in proper sequential order were as follows:
  - 1) "What influenced your decision to cross/not cross?"; 2. "Were you able to see the vehicle? (Optional question based on the scenario)"; 3. "What do you think the vehicle was trying to do?"; 3.1 "Was the vehicle intention clear?"; 3.2 "How did you understand it?"; 4. "Can you describe the vehicle behaviour as





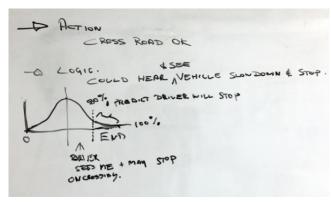


Figure 9: Examples of participant's sketches on the white-board. The participants were asked to draw the vehicle behaviour as it approached: (top row) Photograph of curves used by participants to explain the vehicle behaviour in different situations. The six curves represent the six different situations of the experiment. (bottom row) A participant explaining a situation using graph and going in detail while drawing.

- it approached the crosswalk?" 5. "Can you sketch and explain the vehicle behaviour on the white-board?"
- (4) Sketches on whiteboard As part of the semi-structured interview, the participants were asked to sketch[10] how they understood the vehicle's behaviour while it was approaching the crosswalk. They were asked to think-aloud during this process and explain their drawings in detail.
- (5) Post-experiment semi-structured interview After the six situations, the participants were asked the following set of questions to assess their views on the overall experiment.

  1) "Which scenarios were uncertain for you as a pedestrian? Why?"; 2) "How did you infer vehicle intention in low visibility compared to normal visibility?"; 3) "Which was the most comfortable situation as a pedestrian? Why?"; 4) "Do you think the vehicle was human-driven or autonomously driven in any of the situations? Why do you think so?" 5) "Do you think driverless autonomous vehicles would/should behave differently than human-driven vehicles?"

#### 4.4 Consent

The participants were made aware that they were being recorded on video and audio, that will be used only for the purpose of the study. The purpose of the study was explained as to understand pedestrian attitude towards different vehicle behaviour in different weather conditions. A consent form was signed as acknowledgement.

Table 2: Participant's perception of the car

Participant recognised that there is no driver and	
the vehicle is self-driven	13
(during the experiment + during interview)	
Participant unsure how the vehicle was moving	1
Participant assumed a human driver in the car	1
Total	15

#### 5 RESULTS

In this paper, people's attitudes towards autonomous vehicles was studied using the VR method. The VR method proved to be an effective method to study people's attitudes towards autonomous vehicles. The participant's perception of the vehicle in the VR experiment was studied. Comfort levels of the participants were determined under different circumstances. The co-relation between driving behaviour and vehicle perception was observed. Weather and culture was also taken as an important parameter for the analysis of participant's attitudes towards autonomous vehicles. Finally, attempts were also made to understand people's expectations from an autonomous vehicle.

#### 5.1 Effectiveness of the of the VR situation

Participants showed signs of hesitation, stepping back and hesitating while trying to complete the task of crossing the road. Participants were also expressive with their body language trying to express their trust and comfort level in a situation by making subtle body movements like leaning forward and backward and occasionally changing position to move to a more comfortable position in the virtual world. In certain occasions, people had to be prompted to stop walking in order to avoid walking into walls but one participant did manage to walk into a wall during the experiment. The participants made remarks on the virtual environment like "It's crazy that I feel a bit of cold just because it's raining" and "Oh it's raining and it's night" and "The moon is up! Wow! And it's actually snowy" confirm the effectiveness of the VR experiment.

#### 5.2 Vehicle perception by the participants

Eight participants were quite observant during the experiments and explicitly mentioned that there is no driver in the car and hence difficult to make the crossing decisions as they cannot get any confirmation from a driver. They postulated that the car might be self-driven. During the post-experiment interview session, the participants were asked "Do you think the vehicle was human-driven or autonomously driven in any of the scenarios?". Five participants converged to the notion that the vehicle is autonomous and lacks a human driver. One participant assumed the presence of a human-driver in the car, while one participant was unsure about how the vehicle was moving and could not reach any conclusion. 13 people were convinced that the vehicle is self-driven.

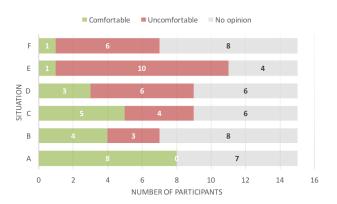


Figure 10: Comfort levels of the participants under different situations: The participants were most comfortable in situation A and most uncomfortable in situation E.

# 5.3 Comfort levels of the participants determined participant behaviour under different circumstances

The participants immersed completely in the situation trying to cross the road, walking freely in a natural manner. Video footage shows them occasionally reaching the end of the room very close to the wall or walking into it. Participant's body language revealed occasional signs of hesitation and discomfort when the car arrived. Table 1 shows the comfort levels of the participants in different situations. Ten people described Situation E to be very uncomfortable and labelled it as 'young driver' and 'reckless driving'. People remarked the vehicle behaviour in situation E and F as "This driver is crazy, I am not going to cross the road" and "I think he is out on a joy-ride." Out of the 15 participants in the experiment, no one was comfortable with situation E and only one person found situation F to be comfortable. Eight participants found situation A to be very assuring describing the behaviour with positive phrases like 'clear intention', 'slowed down', 'smooth', 'vehicle spotted me and acknowledge by slowing down' and 'good feedback'. No one was uncomfortable with situation A, but 3 people were uncomfortable in the situation B which is the same driving behaviour in bad weather conditions. Mixed reactions were observed with Situation C where the car is already slow while approaching the crosswalk. Five people were comfortable with the situation and four participants categorized it as a bad driving behaviour. They remarked that "I felt that the driver had spotted me earlier but reacted to slow down the vehicle very late" and "The reaction was late and I was bit confused". More people were comfortable in situation A and B (8 and 4 respectively) compared to situation C and D (5 and 3 respectively) while in situation E and F the comfort levels were very poor (0 and 1 respectively). Situation E and F were the two most uncomfortable situations with 10 and 6 people reporting it to be uncomfortable. Situation A and B fared better with only 0 and 3 people reporting it to be uncomfortable; while situation C and D was uncomfortable to 4 and 6 people respectively.

## 5.4 Weather as a determining factor of participant behaviour

According to the participants the weather played an important role in their decision making to cross the road. Table 1 shows that all participants preferred clear and bright conditions over the rainy and foggy weather. They quoted that "Like when it is daytime" and "clear weather is much easier to cross". Participants tend to be more careful in situation B, C and F and said that "I was cautious". The participants remarked that "I saw the lights of the vehicle in the dark" and "I waited for the car to stop completely in rainy and foggy conditions". Participants emphasized the importance of sound during poor visibility by saying that "Sound from the vehicle was 80% of the decision making" and "I could hear the car accelerating and decelerating". The participants remarked that under bad weather conditions they "had to actively look for a vehicle in the direction of sound but it was not always clear." All participants could hear the vehicle before seeing them in the poor weather conditions. In the sketches, the participants marked the point where they saw the vehicle for the first time; the curve before that point was drawn based on the sound from the vehicle. While all the participants were cautious in bad conditions; a few participants were comfortable to cross the road after getting the first glimpse of the vehicle lights.

More participants felt comfortable in clear weather than in bad weather conditions for the same driving behaviour as evident from Table 1. Similarly, more people were uncomfortable in bad weather conditions than in clear conditions except in situation E and F. In situation E and F, the participants were more uncomfortable in clear conditions than in bad weather. 10 participants felt uncomfortable in situation E (clear weather) while only 6 felt uncomfortable in situation F (same vehicle behaviour in bad weather).

### 5.5 Co-relation between driving behaviour and vehicle perception

When the participants were asked "Do you think the vehicle was human-driven or autonomously driven in any of the situations?" unanimously everyone agreed that situation E is human-driven behaviour remarking it as 'reckless and carefree driving'. They remarked that "an autonomous vehicle would never drive itself like that". Situation E and F was considered as rash driving or a young driver. The term 'young driver' was used by many people to indicate that the driver does not know how to drive properly and is careless. People were angry and uncomfortable with the driving behaviour in situation E and F. The participants suggested that situation A and B were very good representation of how autonomous vehicle would behave and situations C and D representing autonomous vehicle behaviour to some extent. People remarked that autonomous vehicles 'would stop like situation A where the vehicle would 'perfectly slow down and come to a stop smoothly.' In situation C, people identified that the initial speed of the vehicle was slower than situation A and that the vehicle was cruising at a constant speed. However, the participants were unable to get any information from the vehicle behaviour if it will stop and hence few participants were confused until very late when the vehicle decelerated. The slow cruising speed in situation C was considered comfortable and acceptable by a few people.

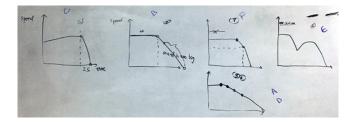


Figure 11: Sketches by a participant from the Asian subcontinent for all the situations [A-F]. The similarity in curves is attributed to the difference in perception of vehicles and traffic in different cultures.

The change in speed of the vehicle was attributed to the vehicle spotting the pedestrian in all situations. People were comfortable when the vehicle lowered it's speed early such as in situation A and felt uncomfortable when the change in speed happened very late such as in situation E. People's expectations of a good driving behaviour meant that the vehicle would show clear and timely intentions like in situation A and not behave impulsively (such as in situation E).

## 5.6 Cultural differences influenced participant response to vehicle behaviour

Three participants in the experiment were from the Asian subcontinent, two from China and one from India. These participants had a very relaxed attitude while crossing the road— always waiting for the vehicle to come to a complete stop before walking. Occasionally, they would also dash across the crosswalk. Their judgement about the vehicle behaviour was casual. When these participants were asked to draw and describe the experiment situations (Figure 11), they drew similar sketches for different situations and were unable to tell the differences between them. Their instinct was to cross the road at the earliest or else wait for the vehicle to stop completely and then decide to cross the road. They were not interested in what the vehicle was doing until it came to a stop. The participants were also unable to make out if the speed of the vehicle in a certain situation was greater than the other. They were very relaxed and did not try to understand the vehicle intentions in great detail. During the interview the following remarks "I waited for the vehicle to stop and then cross the road" and "When the vehicle stopped then I decided that I can cross the road" were made. The participant attitude towards vehicle was evident by the following statements, "Until the vehicle stops I am not supposed to cross" and "I would not step on the road until the car stops and gives me permission to cross the road".

### 5.7 Analysis of people's expectations from an autonomous vehicle

People expect vehicles to communicate the intention clearly and sometime before it reaches the crosswalk. People expect an autonomous vehicle to behave like a 'good human-driver', who is always alert of the surroundings, accelerates and decelerates the vehicle smoothly and does not make any impulsive driving manoeuvres. Most importantly, the pedestrians do not want to know

weather a vehicle is self-driven or human-driven. A participant remarked that "I am used to human drivers and if an autonomous vehicle is similar to a human then I don't have to worry about if a vehicle is autonomous or not". People described good driving behaviour as slow and calm, quoting "That is how I would drive a vehicle, in a controlled manner. I would expect an autonomous vehicle to do the same". Few people suggested that a visual feedback whether they have been spotted by the vehicle at the crosswalk would be an assuring piece of information.

#### 6 DISCUSSION

#### 6.1 Reflection on methodology

The work demonstrates the use of VR to conduct research in autonomous vehicle interaction. The method simulates different vehicle behaviours under different weather conditions in a virtual environment. Video footage confirms that the VR scene was immersive and induced presence. The interviews reveals that the approach works well and the people relate the car in the virtual situation to be autonomous. This method is more effective compared to car simulators where the participants sit in a model vehicle and view digitally rendered situations on a screen. VR is also cheaper than the Wizard-Of-Oz approaches [24] used to study interaction between pedestrians and autonomous vehicles. In Wizard-of-Oz techniques, the participants are exposed to a system and often times the subjects are curious and excited about the system which seems out of place. In a VR simulation, the participants interact naturally with the environment they are exposed to and do not engage with the system due to curiosity and fascination. The VR setup also allows the freedom to recursively iterate the experiment factors which would be very time-consuming using other methods. Moreover, in this particular experiment design, a virtual setup was considered closest to an autonomous vehicle behaviour under the rationale that both are governed by a computer. 13 out of the 15 participants were fully convinced that the vehicle in the virtual scene was autonomous. The VR experiment was immersive and can serve the purpose as an alternative to study real-world autonomous vehicles.

#### 6.2 Insights on pedestrian behaviour

The purpose of the study was to understand pedestrian behaviour in different situations when they are unable to spot a driver in the vehicle. In the absence of a driver, it was observed that people actively tend to get intentional cues by observing the vehicle movement and passively get information by sound. Bogdan and Sundblad [4] used cues to communicate awareness information to people. In our experiment, people were able to guess the vehicle behaviour (the speed and changes in speed) by observing it. Sound was particularly important when the visibility was low. People understood the presence of a vehicle and it's driving pattern but most people were actively looking for a visual confirmation of the vehicle in the direction of the sound in poor weather conditions. The pedestrians were able to overcome the lack of communication with a driver by interpreting the vehicle behaviour through sound and vision. When the vision was poor, implicit cues such as the auditory signal from the vehicle helped form the first impression of the driving behaviour in the minds of the pedestrians. Glimpses of the vehicle

helped people get further assurance in form of conformation to the audio cues.

It was found that people understood the driving behaviour in terms of a human-driven vehicle. This leads to the idea that people interpret and expect the vehicle to have person-like actions. For example, situation E was compared to a 'young driver' and situation A was considered to be representative of how a 'good driver' would drive the vehicle. People described situation A as "That is how I would drive a vehicle" and suggested that an autonomous vehicle would drive like that. They linked the vehicle behaviour to their own driving patterns. People also tried to understand and interpret the behaviour of the vehicle and react according to it. In situation E, people stepped on the road when the vehicle made the first deceleration but hesitated and stepped back when the vehicle accelerated again. This demonstrates how the pedestrian's mind identifies the vehicle as an autonomous entity and decides to react to the vehicle's behaviour. In the real-world, humans and autonomous vehicles can be expected to interact with each other and create a relational dynamics of their own.

It is also clear from participant interviews that pedestrians do not want to know if a vehicle is autonomous or not. People today are used to understanding the human driving behaviour and react to it accordingly. Introducing a new pattern will be an overhead on the pedestrians forcing them to learn a 'new language' to understand autonomous vehicles, which is not advisable. People relate vehicle behaviour to human-like driving patterns. The participants expected an autonomous vehicle to behave like a 'good human driver'. Autonomous vehicles behaviour could be modelled based on a good human driver. This can be done by using real-life driving data to create mathematical models of good driving behaviour. An autonomous vehicle when it behaves like a good human driver would solve two problems. First, the pedestrians are already familiar with the driving behaviour of an AV and will interact with it intuitively. Second, the pedestrians will not have to be worried about if a vehicle is autonomous or not. This also means that the autonomous vehicles will blend with the existing vehicles in the traffic.

A participant made a very interesting remark by saying that "I am used to human drivers and if an autonomous vehicle is similar to a human then I don't have to worry about if a vehicle is autonomous or not. And also if you are not used to human drivers, then you should be, otherwise you are dead. If you want to live, you have to be able to react to human drivers". This sums the reality of the situation that no matter how safe autonomous vehicles become, the pedestrians have to react to human-drivers who can be very unpredictable. Assuming that human drivers always behave in a sane manner would be a grave mistake. It is necessary that pedestrians are able to react to human drivers until the time when all the human-driven vehicles are replaced by autonomous vehicles. This does not seem like something happening in immediate future. Hence, it is furthermore important that the autonomous vehicles behave like a 'good human driver'.

#### 6.3 Implication for design

Important cues that pedestrians use to understand a vehicle on the road have been identified. In absence of a human-driver, the

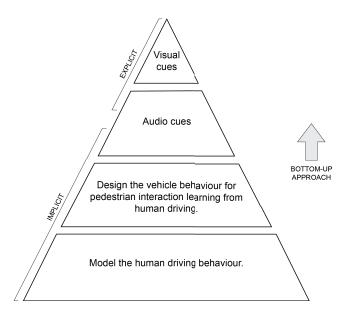


Figure 12: Bottom-up framework to design vehiclepedestrian interaction for autonomous vehicles

pedestrians take into consideration the following cues to assess whether it is safe to cross the road.

- Audio Cues engine, tire and braking sounds gave information regarding what the vehicle is doing. With electric vehicles, which are silent, artificial audio cues can be used to communicate the vehicle status.
- Driving patterns the acceleration and deceleration pattern
  of the vehicle can be picked by the pedestrian to understand
  vehicle intent. This can be communicated both visually and
  by audio. People understand and decipher the acceleration
  and deceleration sounds from the vehicle. The visual movement of the vehicle also conveys this information.
- Visual feedback explicit information from the autonomous vehicle that a pedestrian has been spotted.

Based on the above factors, a design framework (Figure 12) to develop the interaction for vehicle-pedestrian is as follows:

- (1) Model good driving behaviour based on real driving data.
- (2) Understand how a human driver shows intention by changes in the speed of the vehicle. Factors involved: initial speed of the car, deceleration pattern until the car halts and distance from the crosswalk.
- (3) Add audio cues: Since modern electric cars are relatively silent it would be a good idea to artificially add some audible noise (for example: engine sounds)
- (4) Visual cues using LED display etc. to convey information such as the pedestrian has been spotted or the car is giving way etc.

The first 3 aspects would be implicitly understood by a person without having to actively engage and trying to read information. Visual cue is an explicit way of communicating intent that would be particularly beneficial in harsh weather conditions and also could

be used to provide positive affirmations like the pedestrian has been spotted etc.

#### 6.4 Implications of Cultural Difference

The most important aspect of cultural difference is that how majority of the people in a specific geographic area interact with a vehicle. Peoples approach towards vehicles and traffic change and evolve along with the evolution of culture. A quick user research elucidated the fact people in Sweden have the 'Human first, vehicles later' approach while crossing the road. This is also evident in day-to-day life in Sweden where vehicles almost always yield to the pedestrians. This behaviour is also evident in countries like Finland and Germany. However, in countries like China and India people follow the 'Vehicle first, humans later' approach. For example, In India pedestrians wait to cross the road or weave their way across the road through traffic. This is one of the major reasons why the Asian participants in the experiment waited for the car to stop before crossing and remarked that "car stops and gives me permission to cross". There has been some research[13] which studies the differences in human gestures for interaction with traffic across different cultures.

This raises a few very important questions regarding design of interaction for autonomous vehicles. First, can similarities be drawn among cultures to form a design framework which is applicable across the globe? This would mean that autonomous vehicles would have the same behaviour all over the world and would be understood by everyone equally well. Second, if a vehicle is designed to adapt to different cultures, how can we draw lines to decide the vehicle's behavioural transition from one culture to another. Would it be enough for vehicles to have a behavioural pattern for a group of countries grouped together culturally? How specific should an autonomous vehicle adapt to the local culture? Third, if a vehicles travels through the 'cultural borders', how would it make the transition from one behaviour to another? Finally, in countries like India, where people make it a habit to weave through the traffic; an autonomous vehicle would remain perpetually stuck at a point on the road, always yielding for the pedestrians.

#### 6.5 Limitations

Several limitations are noted here. First, all the participants were employees in the automotive industry and might include people who were particularly aware of autonomous vehicle technology. This could be addressed by replicating the study with participants from diverse backgrounds. Second, the experiment used very limited speed-profiles for the vehicle. The behaviour of the vehicle was also not optimized according to real-data but rather taken from earlier research conducted on stopping behaviour of vehicles [11][27]. This limitation could be addressed in future work. Finally, the VR experiment forced the pedestrian to always stand at a crosswalk and anticipate the approaching vehicle. This was partially due to the limitation of the VR technology. This can be addressed by changing the experiment situations and also with progress in the VR technology.

#### **6.6 Future Prospects**

Future research could use VR to optimize mathematical models to define behaviour patterns in autonomous vehicles to communicate intent with a pedestrians. For example, a car travelling at 60km/h should slow down differently than a car travelling at 40km/h. Various aspects like the change in speed, distance from where the speed should change should differ according to initial condition of the vehicle. It is also important that intent is communicated by the vehicle on-time according to the situation. The speed-profile of the vehicle could be changed iteratively to study the behaviour of the pedestrians. This could involve collecting data from real-life driving situations to develop the mathematical models and test them using VR techniques. VR would be a very quick way to test and qualify new models. It would be of interest to study how weather affects pedestrians' perception of vehicles and traffic. Although the pedestrians are exposed to a similar vehicle conditions, they perceive and react differently in different environmental conditions. As seen, culture also has an impact on how pedestrians understand vehicles. Research could be done to understand the cultural differences and similarities and understand how to accommodate these differences. Would it be required that the vehicles in different places have different behaviour adapting to the culture/region? All these scenarios involving weather, variable vehicle behaviour etc can be easily simulated on a VR environment demonstrating the flexibility and strength of the methodology used in the work.

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