TEENAGE CYCLISTS' PERCEPTION TOWARDS AUTONOMOUS VEHICLES AND ITS ASSOCIATED TRAFFIC INFRASTRUCTURES

by

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ABSTRACT

TEENAGE CYCLISTS' PERCEPTION TOWARDS AUTONOMOUS VEHICLES AND ITS ASSOCIATED TRAFFIC INFRASTRUCTURES

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Background: Cycling is a cost-effective means of transportation. Many teenagers cycle to go to schools and ride in neighborhoods. Cyclists are more vulnerable to injuries and fatalities than motor vehicle drivers. With the implementation of autonomous vehicles (AVs), interactions between AVs and road-users are expected to be safer. It is most likely that current young people will be the ones to use these vehicles and interact with them. However, very few past studies have focused on cyclist-AV interaction, with little to no attention toward the teenage cyclist population.

Objectives: This study is aimed at examining teenage cyclists' perceptions of AVs and identifying supporting infrastructures or communication interfaces necessary for them to interact with AVs.

Methodology: A virtual focus group study with 20 participants (12 females aged 13-17-years) was conducted in four groups. Each group had three to five participants attending a one-hour session and were presented with simulated pictures of potential designs for infrastructures and interfaces. Participants rated the designs and answered multiple surveys to express their cycling behavior, perceptions toward AVs, and expected infrastructures and modes for cyclist-AV interaction.

Results: Teenage cyclists were receptive towards AVs and believed that AVs would be safer. However, they would like to have more spacious lanes for cyclists and physical barriers separating AVs and cyclists. They preferred visual interfaces with familiar icons to be more effective for interfaces; nevertheless, they recommended both visual and audible interfaces to ensure cyclists' attention and include the need of visually and audibly impaired populations.

Conclusions: Future researchers and stakeholders will be benefited from the methodology and outcomes of this research**.** Further research can test these designs in a simulated environments or real-world environments to get realistic responses from cyclists and for the establishment of universal designs.

CHAPTER 1: INTRODUCTION

Public opinion and perception of autonomous vehicles (AVs) from different regions and by different road users, specifically in the United States, show a combination of positive and negative attitudes. Road safety is an important concern and AVs are expected to reduce fatalities of vulnerable road-users like cyclists on urban roads. Bicycling represents an important mode of transport in many countries, especially in urban areas (Pucher, Buehler, and Seinen, 2011). Bicyclists are defined as riders of two-wheel non-motorized transport, powered by pedals (National Center for Statistics and Analysis, 2019).

According to the European Commission (2018), bicycles are frequently used by adolescents and teenagers. Teenagers are young people whose ages fall within 13 to 19-years. They can cover larger distances by cycling compared to walking; this makes cycling an attractive, inexpensive, and accessible transportation mode (Ghekiere et al., 2015). Teenagers who regularly choose cycling as their mode of transport have better cardiovascular health, physical fitness (Andersen et al., 2011), and lower body mass indexes (Bere et al., 2011). Even with these positive effects of cycling (Oja et al., 2011), the overall safety of cyclists has continued to elicit concerns as this vulnerable population is not physically secured like drivers of vehicles.

Teenagers are more likely to use cycling for schools and work and thereby ride within the community using minor roads. Statistics show bicyclist fatalities on minor roads are significantly higher for teenagers (44 percent) compared to bicyclists aged 20 and older (28 percent) (Insurance Institute of Highway Safety, 2018). AVs are expected to make the overall traffic system safer for the vulnerable populations like teenage cyclists. However, these are still under experimentation for their safe interaction with different road-users under different traffic infrastructures. As the teenage cyclists will be the users of this future vehicle technology, it is important to understand teenage cyclists’ perceptions of these vehicles and their expectations for changes in infrastructure and for the addition of communicating interfaces on these vehicles while interacting with them on roads.

According to the National Center for Statistics and Analysis (NCSA), there has been a general downward trend in traffic fatalities over the past 40 years. However, bicyclist fatalities increased by 2.3 percent between 2017 and 2018 (NCSA, 2020). Furthermore, the number of bicyclist fatalities (857) reached to its highest in 2018 since 1990 (NCSA, 2019). Although these numbers seem low compared to motorcyclist and pedestrian fatalities, they are very alarming due to the increase in nature of cyclist deaths. Seventy-nine percent of bicyclist fatalities, happened in 2018, was from motor vehicle crashes in urban areas (NCSA, 2020). According to the NCSA report, 60 percent bicyclist fatalities occurred at locations with no intersections, 29 percent occurred at intersections, and 11 percent occurred at locations shared with other road users. Fifty percent of the fatalities occurred in the dark (50 percent) than in daylight (46 percent), dusk (2 percent), and dawn (2 percent). Ninety nine percent of bicyclist fatality occurred from single-vehicle crashes. It was most likely for bicyclists to be struck by the front of the vehicles, approximately for 82 percent of the fatal crashes. Light trucks (SUV, pickup, and van) were involved in 45 percent vehicle crashes which killed bicyclists. Males suffered 5 times higher injury rate, per million people than females and fatality rate per million people was 7 times higher for males than females. Involvement of alcohol, either for the vehicle driver or for the bicyclist, was found in 37 percent of all fatal bicyclist crashes. Bicyclists aged 15 to 24-years old have the highest rate of injuries (553 per million people).

Most of the traffic crashes are the result of human errors; therefore, the introduction of AVs with appropriate safety gadgets and sensors will reduce traffic accidents and drastically decrease the number of deaths and injuries suffered by bicyclists (NHTSA 2019). Researchers are investigating how AVs can prevent traffic collisions with other vehicles, cyclists, and pedestrians. They are trying to identify communicating interfaces to help the interaction between AVs with vulnerable road-users (Deb et al., 2016; Deb et al., 2018). To improve bicyclist safety, particularly for teenagers, the incorporation of AVs could potentially account for and prevent bicyclist-vehicular accidents. The primary research questions and hypotheses (H) for the current research are as follows:

Research Question 1. *What are the perceptions of teenage cyclists about AVs?*

The research hypotheses relative to this research question are:

H_{1A}: Teenage cyclists will show positive attitudes and a high level of trust toward AVs.

H_{1B}: Teenagers will be more willing to accept these vehicles due to the knowledge about AVs and their operations.

H_{1C}: Male’s teen cyclists will be more positive toward the AVs compared to female teen cyclists.

Research Question 2. *What type of traffic infrastructure would a teenage cyclist like to see to interact with AVs?*

The research hypotheses relative to this research question are:

H_{2A}: Teenagers will want to see separate and designated lanes for AVs in existing infrastructures.

H_{2B}: Teenagers will feel safer with AVs compared to traditional vehicles in traffic environments.

Research Question 3. *What effect does the type of communicating interfaces have on the attitudes of teenage cyclists concerning their interactions with AVs?*

The research hypotheses relative to this research question are:

H_{3A}: Teenagers will show positive attitudes toward communicating interfaces.

H_{3B}: Teenagers will prefer visual communicating interfaces more than the audible communicating interfaces.

H_{3C}: Teenagers will be more willing to interact with AVs through mobile applications and sensors.

CHAPTER 2: LITERATURE REVIEW

The review of literature for this study investigated both conceptual and empirical evidence. The conceptual aspects dwell on varied ideas from scholars, given different aspects of the research and the empirical dimensions focus on findings from fieldworks and experiments conducted on the subject matter. An extensive literature review was performed using ScienceDirect, Google Scholar, and TRID websites. The review of literature was focused on (1) Cyclist's interaction with conventional vehicles; (2) autonomous vehicles; (3) cyclists' perceptions of autonomous vehicles; and (4) issues on cyclists' interaction with autonomous vehicles; (5) traffic infrastructures supporting autonomous vehicles; and (6) communicating interfaces supporting AV-cyclist interactions. The objectives of this literature search were to identify the gaps in research regarding teenage cyclists' perceptions of autonomous vehicles and effective modes of interaction with autonomous vehicles.

2.1 Cyclists Interaction with Conventional Vehicles

Cyclists have a high risk of suffering from severe injuries in the event of a crash, especially when bigger vehicles are involved (Aarts and van Schagen, 2006; Rosén, Stigson, and Sander, 2011). The Scholes et al. study (2018) posits that bicycle riders are susceptible to deaths from crashes, and this occurs mainly in urban areas which are densely populated and are dense with high traffic flows (Cantisani et al., 2019). The reasons for traffic collisions are based on the facts that vehicles and cycles share the same network of roads and facilities in the city and their paths often cross at various intersections.

Morrison et al. (2019) identified three categories of cycling facilities: cycle paths, cycle tracks, and cycle lanes. According to them, cycle paths are part of public roads specifically designed for both cyclists and pedestrians. In contrast, cycle tracks, are exclusively made for cyclists; they are contiguous to roads but physically delineated from vehicular traffic and also detached from sidewalks. Dill and Carr (2003) categorize them as Class 1 (Bike paths) facilities or off-street amenities used exclusively by cyclists and other non-vehicular modes. Cycle lanes represent the most common visible facilities for cycling in the city; they are lanes located directly on the road designated by conspicuous markings, signage, striping, or physical barriers such as bollards. Dill and Carr, (2003) designate them as Class 11 (Bike lanes) facilities or on-street amenities that use the same infrastructure as motorized traffic but are exclusively reserved for cyclists. Other amenities in their ranking include bike boulevards, “sharrows”, and signed bike routes which are shared with vehicles. Bike/cycle lanes are perceived as the most popular among others for being more convenient than bike paths, coupled with their capacity to provide some protection from vehicular traffic (Nuworsoo et al., 2012). However, studies found that cycle lanes are less acceptable on account of direct and constant negotiations with vehicles (Duc-Nghiem et al., 2018) and lead to frequent bicycle-vehicle clashes (Allsop et al., 2015; Wall et al., 2016). It is estimated that off-street facilities are usually expensive and need more space, and therefore are easier to build in rural or semi-urban areas with low population. While on-street facilities are cheaper, the need for space poses a challenge in the busy and compact city, since they share the same limited space with vehicles and sidewalks (Dill and Carr, 2003).

Another important factor that can be considered as a possible cause for vehicle-cycle collisions in a zero-automated context is the human error. Human drivers are subject to the law of nature, and consequently are prone to commit errors, blunders, and misjudgments on account of factors such as distraction, confusion, fatigue, stress, bottled-up aggression, influence of drugs, alcohol, and other psychoactive substances (Vissers et al., 2016). The notion of expectations by the human driver about the presence of other road users can create errors in their decisions

(Räsänen and Summala, 2000; Houtenbos, 2008; Herslund and Jørgensen, 2003). For example, Räsänen and Summala, (2000) found that, at an intersection, drivers may not expect to find a cyclist approaching, while Herslund and Jørgensen (2003) study revealed that drivers may not see a cyclist approaching. In general, drivers' failure to sight or detect cyclists is attributed to the fact that their attention is focused mainly on other approaching cars and not on other less visible and less threatening road users like cyclists (Herslund and Jørgensen, 2003).

An additional factor implicated for road collision involving cyclists is in the event of misunderstanding of a non-verbal communication cue between a human driver and a cyclist. This is usually applied when traffic rules are ambiguous or the traffic situation is complex (Schramm, Rakotonirainy, and Haworth, 2008). Non-verbal communication comprises the use of blinkers and light signals such as brake lights, to signal the intentions of the vehicle driver, and also eye contact, head movement or nodding, and hand gestures to signal the intentions of the cyclist (Lundgren et al., 2017). A wrong reading or interpretation of a non-verbal cue either by the human driver or the cyclist can lead to a collision (Westerhuis and De Waard, 2016). Autonomous vehicles can address the human errors by resuming human driver control from the driving task.

2.2 Autonomous Vehicles

The Society of Automotive Engineers (SAE) has developed a six-level automation in 2016: Level 0 (no driving automation); level 1 (driver assistance); level 2 (partial driving assistance); level 3 (conditional driving automation); level 4 (high driving automation); and level 5 (full driving automation) (Coppola and Morisio, 2016; SAE, 2016; Zmud et al., 2016; Center for Automotive Research, 2017). Level-5 automation is seen as the default level for categorizing a vehicle as fully autonomous. AVs aids the operation of vehicles without a human driver, unlike the traditional vehicle that is entirely operated by humans (Shladover, 2018).

It is expected that automation technologies will have beneficial impact on cycling. For example, promoting the safety of cyclists by programming safety systems into automated cars that aid in sighting cyclists, limiting the speed of the automated car or installing Intelligent Speed Assistance to void one of the major triggers of fatalities among cyclists, and implanting emergency braking systems to avert collisions with cyclists and pedestrians (Woolsgrove, 2018). Nikolas (2019) adds that the extra space offered on the road by less-capacity automated vehicles can be exploited to create infrastructure for cyclists and pedestrians.

2.3 Cyclists' Perception of Autonomous Vehicles

Very few studies have been carried out in the field of vulnerable road users and AV interaction across America and Europe (Vissers et al., 2016). Blau (2015) examined the effect of automated vehicles' presence on cyclists' and pedestrians' perceptions, preferences, and behavior towards bicycle/pedestrian infrastructure using a survey study. The survey involved a total of 767 adult participants drawn from student, faculty, and staff populations at Ohio State University in the United States. Results show that about 80% of the sample preferred the same cycle infrastructure in both traditional and automated situations, while about 20% preferred the same intersection infrastructure for both traditional and automated settings. However, respondents preferred more secured cycle/pedestrian infrastructures with the increase in traffic flow, velocity, and road size. Specifically, in an automated situation at Street Type 1 (a quiet, two-lane residential street with slow traffic and few vehicles), respondents preferred no cycle infrastructure above others. In the case of Street Type 2 (a moderately busy, three-to four-lane street with average driving speed no more than 35 miles per hour), a significant majority of respondents preferred buffered bike lane, cycle track or bike path. In relation to Street Type 3 (a major, 4 lanes plus boulevard with numerous traffic driving over 35 miles per hour), the most popular choice of respondents were elevated cycle track, at-grade cycle track, or bike path. It is evident that, street type had effect on cyclists' preferences, but vehicle type also had a minor effect on infrastructure preferences. For traditional vehicles, preference for protected, horizontally separated facilities increased with each Street Type. However, for automated vehicles, preferences for protected, horizontally and vertically separated facilities increased with different Street Type. Therefore, it can be said that Blau's study reflects a cautious attitude of cyclists and pedestrians toward AVs.

Botello et al. (2019) examined the state of knowledge about automated and connected vehicles regarding issues with infrastructure planning for cyclists and pedestrians during AV development and implementation in the United States. Using a semi-structured interview of experts in industry, academia, and government, they found positive results in favor of Connected/automated vehicle (C/AV) development and deployment. There was a consensus among respondents about the positive effect from cyclists and pedestrians on C/AV adoption. A significant majority of interviewees expressed hope that C/AV technology will be safer and more reliable than human drivers. Furthermore, a 65% of respondents reported that if the space saved on roadways from AV implementation were converted to bike lanes or pedestrian paths, the widened gulf between vehicles and vulnerable road users would offer more protection to cyclists and pedestrians. However, respondents agreed on two negative consequences of C/AV's interaction with cyclists and pedestrians, such as overestimation of the car's abilities during the transitional period by drivers, cyclists and pedestrians. This is coupled with the fact that cyclists and pedestrians may find it difficult to know the difference between C/AVs and human-driven vehicles. A second but minor negative report by respondents concerns the fear that a greater attraction to car travel due to C/AVs deployment may lead to a reduction in travel using the bike or foot.

Most of the studies carried out in the field of automation were focused on safety implications of automated vehicles in relation to cyclists and pedestrians. Some of them evaluated the safety impressions of cyclists and pedestrians in the course of interacting with shuttle buses or WEpods in Gelderland, Netherlands (Crawford et al., 2017; Rodriguez et al., 2017; Tafidis et al., 2019). WEpods were the world's first self-driving electric shuttles that was implemented by Dutch public transportation system. The major focus of these studies was a comparison of the crossing behavior of the sample at un-signalized intersections with that of conventional vehicles. Through the use of face-to-face interviews, focus groups, and on-line surveys they found varied responses with respect to reliance and trust in the pods and perceived safety of the pod. Specifically, compared to conventional vehicles, cyclists and pedestrians felt safer when relating with self-driving pods. Incidentally, at un-signalized intersections, cyclists reported feeling less safe with the WEpods during interaction than conventional vehicles. In terms of expectation, it was found that cyclists' and pedestrians' expectation is that the WEpods will always stop for them to cross the road even when other road users violate traffic rules. It was also found that cyclists and pedestrians who relied on non-verbal cues, such as eye contact and gestures with human drivers, preferred to cross at dedicated facilities in the presence of WEpods than respondents who did not depend on such communication cues. Overall, two reasons were found to be responsible for the confidence in WEpods included automated technology and the low operational speed of the WEpod.

Crawford et al. (2017) investigated the issue of trust in automotive vehicles in the course of interactions with cyclists and pedestrians in the United Kingdom, based on a trial or experimental model. Using data from 134 adults, they found that trust ratings on automated vehicles by cyclists were significantly high. The trust rating was actually predicated on the safety measures configured into the car system, especially the fact that the car had the capacity to stop for an approaching cyclist. Consequently, participants rated it better than the human driven car. They found no statistically significant differences in ratings of trust provided by cyclists and pedestrians, irrespective of age or driving experience. However, trust ratings seemed to be more of the outcome of the cars' features, such as movement and noise than the perceived risk of a scenario. Additionally, participants expressed the view that more trial should be conducted to give people more opportunity to know how the automated car works, before they invest more trust in the system.

Tafidis et al. (2019) examined how automated vehicles can affect the safety of cyclists and the level of severity of accidents between cyclists and cars. The study was conducted in the city center of Hasselt, Belgium, a medium-sized city whose city center is characterized by narrow one-lane streets shared by cyclists and cars. Findings of the study show that automated vehicles have the capacity to improve network performance and boost road safety for cyclists in urban areas. In terms of safety of cyclists, the results showed that cyclists were safer in the environment of automated vehicles despite the challenges of interaction. Additionally, they found that the introduction of automated vehicles in the road network minimized the total number and severity level of accidents. It was also confirmed that majority of accidents occurred at road intersections. This result is expected because intersections present an intricate and knotty traffic situation where various kinds of road users converge. Furthermore, the total number and severity level of accidents between cars and cyclists decreased while minor improvements were observed in the traffic performance of cyclists. Among different types of accidents, the one that had the most positive impact was rear-end collisions, where researchers found a substantial reduction in occurrence.

Few experimental studies on automation have been carried out; these include Levine and Morton (2015) and Marjan et al. (2020) studies. The Levine and Morton's (2015) study summarizes results from a Federal Highway Administration (FHWA) funded Exploratory Advanced Research (EAR) Program. This research evaluated the potential of a hypothetical automated vehicle to boost access to and use of available rapid-transit rail services. The researchers asked participants the likelihood that the presence of pedestrians, cyclists, and other transit users in larger number would affect traveler's perceptions leading them to change mode of transit. One hundred and fifty people from each of the four Chicago neighborhoods (Evanston, Skokie, Pilsen, and Cicero in Illinois, U.S.A) participated in the study. Three levels of use (e.g., current level of users, a few more users, and a lot more users) were represented in the survey images for the transportation and urban design improvements. The results show that the specific improvements included an automated, fixed-route community shuttle serving the transit station; bicycle lanes, bike paths, bike racks, and bike signals; and streetscape changes, such as more trees, wider sidewalks, and better lighting. The positive response to improvements in cycling facilities suggests that there is substantial potential for growth for this transport mode when the relevant and recommended facilities are installed.

Marjan et al. (2020) investigated differences in expectations and behavioral intentions of cyclists when interacting with automated cars on the one hand and manually driven cars on the other hand. They used a photo experiment to conduct a survey with 35 participants, (above 18 years and with cycling experience), at the Delft University of Technology, who evaluated car-bicycle interactions from the point of view of the cyclist. A total of thirty photos were presented to the participants. This study is based on the possibility of misinterpreting the intention of cars and over-reliant expectations of automated cars with respect to spotting or sighting the cyclist.

Findings revealed statistically significant differences in relation to cyclists' evaluation of being sighted by the automated car, the automated car's reaction to them, and their own reaction to the automated car. A significant majority of participants expressed more confidence in the human-driven car than the automated car. Participants held a restrained and cautious attitude toward automated cars as they did not expect to be sighted by them better than human driven cars. There was no difference between traditional vehicles and AVs with respect to the certainty of cyclists that the automated car would stop for them. The participants showed more confidence in the ability of the traditional car to stop for them than the automated car. However, based on the varying priority settings presented to participants, it was seen that when the cyclist had priority on the road the participants expressed more confidence of being sighted by the automated car as opposed to the traditional car. On the reverse, in settings where the cyclist did not have priority on the road, the participants expressed confidence in the ability of the manually driven car to sight them than the automated car.

This review has revealed that although there are more positive perceptions of the automated vehicle than negative perceptions, it is noteworthy that cyclists expressed a cautious attitude in their interaction with automated vehicles.

2.4 Issues on Cyclists' Interaction with Autonomous Vehicles

The interaction between an AV and a cyclist is complicated due to the issues of detecting cyclists effectively and taking safe actions by AVs. It is expected that automated vehicles will enhance the safety of cyclists as they do not over-speed, beat traffic lights, or commit errors associated with human drivers (Vissers et al., 2016). However, understanding the intention of autonomous vehicles by cyclists presents a daunting challenge (Marjan et al., 2020). Research in this direction has raised issues over the interaction between automated vehicles and non-automated road users in the transition period. One such issue is the expectation and corresponding behavior of cyclists in contact with AVs. According to Maarten et al., (2018), it is vital to detect cyclists and pedestrians in order to prevent crashes and maintain the flow of traffic. A major challenge is how to ensure that cyclists are able to identify different types of vehicles, ranging from manually driven vehicles to fully automated vehicles. A similar concern is how to ensure that cyclists are aware of what to expect from each of these different vehicles (Vissers et al., 2016). Different levels of automated vehicles operate differently, some of them requires human input and through monitoring while others require least to no human driver input. The inability to identify the exact type of vehicle in a contact situation will definitely affect the expectations of the cyclist, sometimes with negative consequences.

An additional issue is related to behavioral adaptation of the cyclist; a consistent positive performance of an automated vehicle may result in cyclists becoming too over-confident with the system leading to complacency among them (Vissers et al., 2016). For instance, the certainty that an automated vehicle will stop for them to cross the road may eventually result in careless or risky behaviors while crossing roads. Which, in turn, may affect their safety since automation has its limitations (Schoettle and Sivak, 2014; Millard-Ball, 2016). Non-verbal communication cues are used in the interaction between cyclists and manually-driven car drivers. In the automation context, as important as informal non-verbal cues are, they will be dispensed with computer-controlled technology. Making eye contact or nodding the head will become dysfunctional as the driver is not really in control and will be totally useless in the absence of an occupant (Vissers et al., 2016). An outstanding issue considered in the interaction between cyclists and the automated car is that all cyclists are not the same with respect to their age, skill, and behavior. Since all cyclists do not behave or react the same way, it may be problematic to program automation that interacts with them in a typical way (Vissers et al., 2016).

In summary, autonomous vehicles can reduce cyclist-related collisions and provide opportunity for wider infrastructure for this vulnerable population. However, it is important for the future cyclist population, teenage cyclists, to be involved in the design of (a) infrastructures required to support these vehicles along with conventional vehicles on the road and (b) substitute interpersonal communication of human drivers to provide cues to cyclists.

2.5 Traffic Infrastructures Supporting Autonomous Vehicles

Aside from the foregoing challenges facing automated vehicles, a major challenge confronting the technology is an environmental one: traffic infrastructure. Infrastructure is used to describe various navigational aids and gadgets that are instrumental in the operations of different types of transports. Since AVs are computer driven (to a great extent), it requires special infrastructure, rather than the conventional ones. Notably, the present traffic infrastructure suits human-driven vehicles and it is supposed that, at least, some modifications and adaptation would need to be undertaken in order to accommodate automated vehicles (Zhang, 2016). Some researchers posit that a fully autonomous vehicle should be able to utilize its own internal technology and navigate while still using the conventional infrastructure (Pilli-Sihvola et al., 2015), while some opine that no major infrastructural alterations are needed in current roads in the short and medium terms ((Alonso et al., 2017). The fact remains that some degree of investment in infrastructure is needed, due to the fact that automated vehicles are expected to interact with the surrounding environments and non-automated road users (Brendan et al., 2017).

A number of researchers have identified two broad categories of infrastructure—physical and digital infrastructure. The physical infrastructure includes the roads, road signs, road markings, communication infrastructure, dedicated lanes, lay-bys, video/cameras for monitoring traffic, speed cameras, traffic detection communication, etc. These are components of the geographical space used by vehicles (Alonso et al., 2017; Gicquel, 2015; King, 2013; Townsend, 2016). From a design and implementation perspective, the Catapult Transport Systems (2017) identified eight different infrastructural adaptations to support automated vehicles: traffic management measures, road markings, safe harbor areas, role of service stations, car parking, Automated Demand Responsive Public Transport Vehicles, crossings and junctions, and bridge structures. Additional infrastructures that require modification and adaptation to accommodate AVs include pavement structure, road surfaces, parking lots, service stations, roundabouts, bridges, and drainages (Brendan et al., 2017; Yuyan et al., 2019).

The digital infrastructure includes digital maps, sensors, advanced communication and positioning technologies (Alonso et al., 2017; Gicquel, 2015; Townsend, 2016;) for the purpose of sensing the surrounding environment, sourcing, processing, transmitting of information, quality control, security, and data protection. In order for these infrastructures to function optimally for AVs, manufacturers need ample and exhaustive data from field studies and experiments (Cara et al., 2017). While all these technologies may not be readily available at the onset, the most essential and relevant infrastructure that enhances safety, efficiency, and performance for autonomous vehicles need to be identified and prioritized within the context of automation level (Ryan et al., 2018). Authors posit that the constant sharing of information between autonomous vehicles and infrastructure can help to identify road hazards and establish a systematic interchange of information beneficial to all road users. Incidentally, it may be easy for automated vehicles, in sync with infrastructure, to interact with other automated vehicles (due to inter-connectivity), and identify manually-driven vehicles (due to their size) and vulnerable road users ahead of time.

However, detection and prediction of intention of unpredictable vulnerable road-users is not as simple as it is with AVs and even manually driven vehicles.

Many recent studies have suggested that basic traffic infrastructure such as road signs and lane markings are pivotal before deployment of C/AVs on public roads (Lu et al.,2019; Nitsche et al.,2014; Rad et al., 2020). However, the idea of dedicated lanes for automated vehicles has been mooted as a strategy to enhance deployment of AVs. A dedicated lane is described as one of the existing lanes of a motorway on which only automated (partially or fully automated vehicles with or without connectivity) are allowed (Rad et al., 2020). These are lanes separated from other traffic lanes or lanes specifically separated for automated vehicles. According to these design ideas, the lane dedicated to automated vehicles is usually the fastest lane of the motorway, which might be a lane added to existing ones or an already existing lane reserved for automated vehicles (Rad et al., 2020). It is reported that dedicating a lane to automated vehicles has the potential to improve traffic performance, although the effectiveness of dedicated lanes depends on the penetration rate of automated vehicles in traffic (Rahman and Abdel-Aty, 2018; Xiao et al., 2019). The introduction of AVs into the road network requires the addition of an enabling technologies phase. This will be responsible for the development of enabling technologies, e.g. Vehicle to Vehicle or other infrastructures (V2X) communication protocols, and message sets that support automation algorithms, as well as usage of Highly Automated Driving (HAD) maps and the realization of complementary Advanced Driver Assistance Systems (ADAS) functions. Implementation of these enabling technologies will be expensive and difficult to establish (Lu and Blokpoel, 2017).

In other studies, dedicated lanes (DLs) have been shown to improve traffic efficiency (Xiao et al., 2019; Amirgholy et al., 2020), and traffic safety (Rahman and Abdel-Aty, 2018). Liu et al., (2020) adds that implementing dedicated lanes for automated vehicles can also improve fuel efficiency, and that this is more evident at low Market Penetration Rates (MPR). Some other studies have reached similar and different results with respect to the implementation of dedicated lanes and the effect on throughput; however, it is shown that deployment of dedicated lanes can cause shock wave formations or bottlenecks due to mandatory lane changes (Talebpour et al., 2017; Princeton and Cohen, 2011).

Other important factors regarding infrastructure design for AVs included separation or barriers between lanes. According to the National Automated Highway System Consortium (1997), there are three kinds of separation on the road as follows:

Virtual barrier. A paint stripe between normal lanes and dedicated lanes. Fundamentally, it is a paint stripe that is used to demarcate between normal lanes and automated lanes. This type of demarcation would offer little or no partition or protection between normal lanes and automated vehicles.

Buffer zone. A spatial separation between normal lanes and DLs ranging from 2 to 14 feet. Additionally, this type of separation offers no positive protection for either manual or automated vehicles in cases of accidents or encroachment of reprobate vehicles.

Physical barrier. A barrier such as a concrete block. Dimensions of such a barrier should be investigated further. Safety requirements, physical dimension (i.e., shape, width, height, buffer areas), and construction material for physical barriers have not yet been investigated and measured. Many issues would be involved in this investigation including liability, cost, emergency response, etc.

The first two separation types, virtual barrier and buffer barrier, are classified as soft separation while the physical barrier is classified as hard separation. Soft separations are lines marked on the road that separate automated and manual traffic, while hard separation are barriers that more clearly demarcate roads between automated and manual vehicles. Overall, hard separation has proven to be more effective due to the fact that it restricts and prevents the vehicles from crossing the separation. They are also important for reasons of safety and efficiency (Awan et al, 2018). Additionally, due to fewer interactions, drivers are not so influenced by the acts of C/AV drivers in other lanes (Yang et al., 2019). However, hard separations have some disadvantages. Even though hard separations more clearly demarcated between automated and manual traffic, peak hour is a difficult time to operate this kind of separation. In addition, during emergency situations, it is very difficult for C/AVs to exit the dedicated lanes urgently with hard separations such as guardrails. Another demerit of hard separation is that drivers feel too restricted or fenced in in the course of driving (Varaiya, 1995; Rad et al., 2020). With respect to other road users such as teenage cyclists, these separations will prove to be pivotal in relation to safety. Virtual barriers and buffer zones may not be as safe for teenage cyclists as physical barriers, because the demarcations are not so neat. Virtual barriers and buffer zones imply that lanes are shared between or among various road users which suggests that there is interaction, though minimal. With physical barriers, cyclists are safer to ride, as they have less influence and interaction with other road users including automated and manual vehicles.

Each one of these separation kinds has positive or negative effects on flow of traffic, behavior of driver, and efficiency of traffic flow and safety. On a general note, Carreras et al. (2018) identified five levels of infrastructure support for automated vehicles named as Infrastructure Support for C/AVs levels.

Level E. Conventional infrastructure without digital information that can support the automated vehicles (AV). AVs are just required to identify road geometry and road signs.

Level D. Provision of a digital map with static regulatory information. Digital map data is available with static road signs. Map data could be complemented by physical reference points (landmarks signs). Traffic lights, short term road works and VMS need to be recognized by AVs.

Level C. Provision of all relevant digital information in digital form. All dynamic and static infrastructure information is available in digital form and can be provided to AVs.

Level B. The infrastructure senses complete traffic situations at a microscopic level by specialized sensors. The Infrastructure is capable of perceiving microscopic traffic situations and providing this data to AVs in real time.

Level A. Automated vehicles are able to optimize the overall traffic flow with the aid of the infrastructure which is capable of traffic perception for the purpose of microscopic traffic management. Based on the real-time information on vehicle movements, the infrastructure is able to guide AVs (groups of vehicles or single vehicles) in order to optimize the overall traffic flow.

Yuyan et al., (2019) identify the need for incident and roadwork communication devices for emergency situations in traffic. They recommend the establishment of harmonized readable emergency signs and barriers/cones and the establishment of electronic communication on the road for the purpose of providing real time information. They also identify the need for inter-connectivity of vehicles, the environment, and other vulnerable road users such as cyclists and pedestrians. Consequently, they highlight the need for sensors such as in-roadway sensors made up of loop detectors and magnetic detectors, and over-roadway sensors made up of radars, cameras, ultrasonic devices, etc. These sensors are crucial for traffic management, control, and safety.

Erdelean’s (2019) recommendation for infrastructure include both digital and physical infrastructure, as exemplified in test sites from different countries in the world. The digital infrastructure includes cameras, HD maps, radar and roadside sensors for traffic flow, weather information, localization systems, various measurement systems, etc. The physical infrastructure includes Road markings, Road edges delineation, and markings of road types. Mocanu & Nitsche, (2014) identified several intelligent infrastructures provided by various projects including COBRA (Cooperative Benefits for Road Authorities), SEAMLESS (Seamless Traffic Data Dissemination across urban and inter-urban Networks), RAIDER (Realizing Advanced Incident Detection on European Roads), and QUATRA (Software and Services for the Quality Management of Traffic Data). COBRA provides 3 bundles of infrastructure to improve traffic in urban centers. Bundle 1 comprises events on the road aimed at warning about road works, warning about traffic jams ahead, and notification about hazardous sites on the road. Bundle 2 is about signage and speed aimed at providing in-vehicle signage, workable speed limits, and adapting speed limits. Bundle 3 is concerned with information provision, aimed at providing guidance and information on parking, traffic information using different modes, and mappings of itinerary. The aim of SEAMLESS is to use harmonized data systems to enable easy distribution of information in urban and inter-urban networks.

The Traffic Light Phase Assistant is designed to announce traffic light time to road users. It announces and alerts drivers before the light turns red and provides drivers with advice on speed in regard to the driver's current speed and distance to the traffic light. Provision of road information is targeted at easy traffic information in urban and inter-urban roads with in-vehicle devices. The instrument provides information to drivers on choice of route in the city. The device also provides information to drivers about weather conditions, speed, delays or traffic jams, etc.

Many smart driving technologies are decentralized, in the sense that they do not require any communication with the infrastructure (i.e., V2I) to work. In general, under normal operational conditions, certain smart driving technologies, e.g., lane departure warning and lane keeping, will require clear lane marking and traffic signs, because they rely on sensing of these objects to determine surrounding environments. Other technologies, such as adaptive cruise control and blind spot monitoring, do not require any specific infrastructure as they are vehicle-based features and only rely on sensing of surrounding vehicles but not particular infrastructure. The technologies that will require the most infrastructure changes are traffic sign recognition, automated assistance in roadwork and congestion, auto-valet parking, and driverless cars. Table 1 summarizes studies that have suggested new or modified infrastructure for the implementation of AVs.

Table 1: Summary of literature review based on supporting infrastructure of AVs.

Study Reference	**Focus of infrastructure**	**Results**
Botello et al., 2019	Infrastructure on communication, built environment, land use	•Mode separation for easy flow of traffic •Prioritization of detection infrastructure
Crawford et al., 2018	Intersection infrastructure	•High potential for trust •Cyclists are cautious but have high trust
Alonso et al., 2017	Physical infrastructure, digital infrastructure	•Improved road signs and markings •Development of digital mapping •Development of digital speed limits
Catapult Transport System, 2017	Road Markings and Signage, Safe harbor areas, Crossings and Junctions	•Development road signs and markings • Design of safe harbor areas on high-speed roads •Mounting of sensors and V21 Communication gadgets •Mounting of signal-controlled junctions and crossings
Lyon et al., 2017	Communications infrastructure	•Installation of sensors •Traffic signals to communicate directly with AVs •Making signages compatible with AV development •Provision for AV/Cyclist communication via mobile device
Blau, 2015	Intersection infrastructure	•Building of buffered bike lanes or cycle tracks •Building of elevated cycle tracks on busy roads •Installation of technology to aid detection of cyclists at major intersections via audio and visual devices
Kockelman et al., 2017	General traffic infrastructure	•Roadway capacity improvement •Autonomous intersection management •Dynamic traffic assignment approach
Woolsgrove, 2018	Technology for cycles and vehicles	•Intelligent Speed Assistance installation •Automatic Emergency device •Braking for cyclists, • Blind spot detection for large vehicles
Ryan et al., 2018	Traffic technology	•Well-maintained lane-marking technologies.

Study Reference	Focus of infrastructure	Results
		•Developing universal lane-markings, signage, and traffic signals across all states
Yuyan et al., 2019	General traffic infrastructure	•Upgrading of traffic signs and road markings •Provision of digital communication with sensors •Strengthening of pavement structure to avoid potholes and cracking •More flexible designs for parking •Provision of safe harbor areas •Provision of segregated infrastructure including bridges, tunnels, and underpasses
Tafidis et al., 2019	Road infrastructure	•AVs improve traffic flow in urban areas •Optimization of crosswalk locations •Provision of cycling facilities •Provision of road corner radius to enhance traffic flow

2.6 Addition of communication interface to autonomous vehicle and teenage cyclist.

The inclusion of communication interfaces between automated vehicles and teenage cyclists is essential for interaction purposes and safety. Communication interfaces are simply the connection of different road users through technology, such that vehicles can communicate with cyclists and the traffic environment.

Bieshaar et al., (2017) posits that automated vehicles should have the capacity to communicate among themselves through electronic systems, but this communication cannot not be accomplished with other vulnerable road users such as cyclists. Therefore, there is a need for communication interfaces to facilitate interaction between automated vehicles and cyclists in order to ensure overall traffic safety. The Bieshaar et al. study proposes a holistic approach that is composed of a vehicle-based communication system, an infrastructure-based communication system, and a mobile device-based communication system. They reiterated that very little research study has been carried out on detection of cyclists as compared to work on detection of pedestrians using communication interfaces.

In order to detect vulnerable road users such as cyclists, and avoid dangerous situations in traffic, several projects have been undertaken to achieve communication between automated vehicles and other road users (Deb et al., 2018, Fang et al., 2017, Kohler et al., 2012, Volz et al., 2016). The goal of these innovations is to establish a communication link among vehicles, between vehicles and the environment, as well as other road users such as cyclists and pedestrians. The research proposed the use of body-worn sensors by cyclists for detection purposes. Smart devices like Wi-Fi-enabled smartphones can be used as communication gadgets with capacity to connect vehicles with cyclists in traffic. The study anticipates a future when vehicles, cyclists and the environment are integrated such that vehicles are equipped with electronic maps, sensors, and Internet connection; cyclists are equipped with smartphones and smartwatches; and the traffic environment is equipped with sensors, such as laser scanners or cameras located at urban intersection points.

Ryan et al., (2018) posit that communication in traffic is essential as data is shared among road users for the purpose of safety of all. They affirm that certain communication technologies such as traffic signal coordination, variable speed limits, and traffic detection at signalized intersections are helpful in terms of sensing the traffic environment and sharing data with vehicles. For example, such sensors can help to warn automated vehicles about the presence of cyclists around them and collision-prone road conditions.

Researchers, engineers, and auto-manufacturers have developed different means of communication between automated vehicles and vulnerable road users to facilitate their interactions in traffic environments (Benderius et al., 2017; Deb et al., 2018; Florentine et al., 2016; Vissers et al., 2016). A laser projected zebra crossing can be used in front of an automated vehicle, when it detects a pedestrian or cyclist crossing the road, to show that the vehicle is giving way to the road user (Vissers et al., 2016). Past research has suggested implanting displays and speaker systems in automated vehicles regarding safe and unsafe crossing conditions, including positive and negative signals. These signals enable the interpersonal communication for vulnerable road users with automated vehicles the way they used to be with the drivers of conventional vehicles.

Florentine et al. (2016) and Benderius et al. (2018) studies have utilized a speaker system to capture pedestrian attention by playing music or alerting messages, and a LED light strip with changing light color and sequence to provide different signals. Deb et al. (2018, 2020) evaluated a number of communicating interfaces including visual and/or audible features. Visual features were displayed on the hood of the vehicle, included flashing text (“BRAKING” and “WALK”) in green, an animated white pedestrian silhouette, a flashing smile in green, a red upraised hand, and a stop sign. Audible features included a horn sound, music, and a verbal message (“safe to cross”). While most of these studies focused on pedestrians’ crossing performances in front of an autonomous vehicles, de Clercq et al. (2019) and Hudson et al. (2018) studied interface effects on perceived safety duration and preference, respectively. Similarly, Stadler et al. (2019) evaluated a communicating interface with respect to its effectiveness, efficiency, and user satisfaction, when utilized to assist pedestrians in crossing the street in front of an autonomous vehicle. Both pedestrians and cyclists are considered to be vulnerable road users, not protected with physical structure of motor vehicles. They are unpredictable in their traffic behaviors as they cannot be strictly controlled by traffic rules like motor vehicle users. Therefore, a similar communication system can be designed for cyclist population with a standardized approach to benefit both pedestrians and cyclists.

However, despite the advantage of communication technologies and interfaces to enable inter-connectivity of road users with autonomous vehicles and infrastructures, there are still challenges. Vissers et al., (2016) has highlighted the facts that bad weather reduces the power and efficiency of sensors and software encounters difficulties with respect to sighting or sensing pedestrians and cyclists. The Wi-Fi signal-based communication using smart-phone and smart-devices can be disrupted based on signal quality, device quality, and users' acceptance toward using these devices. The assisting device requirement can be expensive and can create added burden of distraction on cyclists for using them while continuing with their cycling task. Traffic information with presence of vulnerable road users and traffic speed, volume, and hazard conditions can be useful for highway or interstate road settings with less obstructions. However, these information boards will not be useful in crowded urban settings mostly used by cyclist population due to the obstructions and lack of space. Therefore, the most convenient approach is to install an alert system in the autonomous vehicles to create signals and warn vulnerable road users like pedestrians and cyclists. The literature review on communicating interface design for AV-cyclist communications are summarized in Table 2.

Table 2: Summary of interface design supporting AV-cyclist communications.

Study References	**Focus of infrastructure**	**Results**
Bieshaar et al., 2017	Communication technology	• Mobile device-based communication system • Cycles with smartphones and smartwatches
Alonso et al., 2007	Communication technology	•Vehicle to Pedestrian/Cyclists Connection (V2P)
Ryan et al., 2018	Communication technology	• Traffic signal coordination • Variable speed limits • Traffic detection at signalized intersections
Vissers et al., 2016	Communication technology	• Laser projection to project a zebra crossing before AVs •Implementation of a smile on AVs to enable detection of pedestrian or cyclist head and eye movements towards the automated car
Deb et al., 2020	Communication Technology	•Visual and/or audible features for Pedestrians

CHAPTER 3: METHODOLOGY

A mixed method incorporating quantitative and qualitative approaches was used in this research. The quantitative method was undertaken through the use of questionnaires while the qualitative method was operated by the use of focus group discussion. Focus group research is a method of collecting qualitative data by engaging a small number of people in an informal group discussion or discussions (Wilkinson, 2004). The objectives of these studies are to (1) understand teenage cyclists' perceptions toward autonomous vehicles; (2) identify the changes required in cyclist infrastructure to successfully implement autonomous vehicles; and (3) investigate the needs for communicating interfaces to interact with autonomous vehicles.

3.1 Survey Instruments

Survey instruments were selected based on the literature review and research questions to be investigated in this study. The online questionnaires for cyclists and pedestrians, akin to the approach used by similar studies, comprised of their demographics (Blau, 2015; Deb et al., 2017; Piao et al., 2016), behavior while walking or cycling (Deb et al., 2017; Useche et al., 2018), and personal innovativeness (Agarwal and Prasad, 1998), Likelihood scale for adoption of AVs (Bloom et al., 2017), Anxiety questions concerning AVs (Hewitt et al., 2019), cyclist receptivity questionnaire toward AVs (Deb et al., 2017). These surveys were designed specifically for this study based on standard and validated survey tools. Table 3 shows the list of survey tools used in this research, number of survey items for each of them, and references for valid tools. The demographics section provided information about the respondents in relation to their age, sex, education, residence, cycling experience, etc. The cycling behavior section of the questionnaire seeks to evaluate respondents' behavior while using the cycle. The personal innovativeness scale aims to estimate respondents' willingness to accept autonomous vehicles and supporting changes in traffic environments. The Likelihood questions determine whether cyclists will adopt to the changes from implementing autonomous vehicles. The anxiety questions evaluate how concerned the respondents would feel riding alongside AVs and about the safety consequences of AV's system failure. Additionally, the cyclist receptivity questionnaire aimed to examine if the teenage cyclist will accept the concept of AVs sharing roads with them. Survey items were also used to collect data on cyclists' preference of different modes to interact with AVs. These responses can help researchers effectively designing platforms for cyclist-AV communication.

Table 3. List of survey tools used in the study.

Survey Tool (Likert Scale)	**Number of Survey Items**	**References**
Demographics Questions	9	
Cyclist Behavior Questionnaire (7-point)	17	Useche et al., 2018
Likelihood Questions for accepting AVs (7-point)	4	Bloom et al., 2017
Personal Innovativeness Scale (7-point)	4	Agarwal and Prasad, 1998
Anxiety Questions (5-point)	4	Hewitt et al., 2019
Cyclist Receptivity toward AVs (7-point)	10	Deb et al., 2017
Cyclists' Perception on Cyclist-AV Interaction (7-point)	10	Developed for this study

3.2 Ethical Consideration

Participant recruitment and data collection were started upon the approval of the study from the Institutional Review Board (IRB) at the University of Texas at Arlington. Participants were assured that the data is for academic purposes only and will not be used for any other purpose.

3.3 Study Population

The population of the focus group study is the teenage cyclists from the United States. The participants were informed and recruited through emails, social media postings, and billboard communications. One of the basic requirements to be included in the study was that the respondent must have adequate internet connection to participate in the required survey and discussion forums. Another requirement was that each respondent must be an English speaker and have no visual or hearing challenges of any sort. The most important criterion was that each respondent must be an experienced bicyclist who uses the cycle, at least once a week.

Table 4. Demographic information for participants (N=20)

Demographics	**Level**	**Number (Percentages)**
Gender		
	Male	8 (40)
	Female	12 (60)
Race		
	Caucasian or White	1 (5)
	African American	9 (45)
	Asian	9 (45)
	Multiracial	1 (5)
Education		
	Middle School	8 (40)
	High School	12 (60)
Age		
	13-14 years	11 (55)
	15-17 years	9 (45)
Duration of weekly cycling trip		
	<15 min.	10 (50)
	15-30 min.	6 (30)
	>30 min.	4 (20)
Frequency of Weekly cycling trip		
	<2	14 (70)
	3-4	6 (30)
Reason for cycling		
	To play with friends	6 (30)
	For Exercise	14 (70)
Knowledge of cycling rules		
	Strongly agree	2 (10)
	Agree	11 (55)
	Neutral	4 (20)
	Disagree	3 (15)
	Strongly disagree	0 (0)

Five focus groups of three to five teenagers, totaling 20 participants, participated in this study. Data were collected from two different age groups: 13 to 14 years and 15 to 17 years. The number of participants was limited due to reasons of time and resources. However, this number was in consonance with such studies that investigate the behavior of road users (Botello et al., 2019; Hagenzieker et al., 2019).

Most of the participants were female (60%) and most of them were in their younger teenage years (under 17 years of age). They were more likely to be in high school. The respondents also comprised of different racial groups, such as Caucasian or White, African American, Asian, and Multiracial. Majority of the participants (70%) reported that they cycle less than twice a week and the rest of them cycle more than twice. The primary reason of their cycling was likely to be for exercise versus leisure. Half of the teenage participants typically cycle for more than 15 minutes a week. Most of the participants stated that they had sufficient knowledge about cycling rules and laws. Table 4 shows the summary of demographics information for the study population.

3.4 Design of Focus Group Discussion

Following the questionnaire, respondents participated in different focus group discussions. However, due to Covid-19 restrictions and the protocol of social distancing, the discussions were entirely virtual. The respondents were divided into two age groups as follows: 13 to 14 and 15 to 17 years old. The segmentation is appropriate because although they are all teenagers, all of the age groups may not exhibit the same attitude and behavior. The first group of teenage cyclists (13 to 14-years-old) may not be as experienced as their older counterparts and may still bear and exhibit significant marks of childhood in their behavior. The second group (15 to 17-years-old) may have completely passed through the period of childhood but may still retain aspects of childish behavior.

The three groups were scheduled to have five respondents each making a total of 15 respondents. Initially, we planned for three replications for each group, meaning that 15 respondents will be involved for each group. A total of nine virtual focus-group discussions were proposed. However, due to different issues such as tardiness, unavailability of participants, and for technical issues with virtual meetings, data was collected from five groups with a total of 20 participants. The discussions lasted for one hour for each group; the time was long enough to cover all the subjects discussed and minimal enough not to bore the respondents. All the discussions were documented with the aid of audio and video recordings. The questions for the focus group discussion were well structured and the same instructions and same protocol were posed to each group. Since the groups were not homogeneous, we expected that results of the discussion would be varied. In addition to the questions, simulated pictures of automated vehicles' supporting infrastructure and interacting signal designs were presented to the group for discussion. This was in concordance with earlier studies that used such an approach to collect realistic data (Crawford et al., 2018; Hagenzieker et al., 2019; Howard and Dai, 2014; Motamedi et al., 2020). They stated their different views for each design based on the pictures. Furthermore, the respondents made their ratings on the supporting infrastructure and interacting signal designs using survey questions.

3.5 Focus Group Study Protocol

The focus group participants were introduced to the subject of discussion and given the first set of survey questionnaires which included the demographic, cyclist behavior questions, likelihood questions for Autonomous vehicles being helpful, personal innovativeness, anxiety questionnaire, and cyclist receptivity questionnaires. They were asked to pause the survey after answering these survey items and to join the first discussion on infrastructure designs. The researcher displayed pictures of six potential infrastructure design to the participants using share screen scheme of the virtual meeting platform and provided a brief description of each design without creating any bias about their usefulness. The participants were asked to discuss the pros and cons of each infrastructure design given that these teenage cyclists will share roads with autonomous vehicles. When they finished the first discussion (15-minute long), they were asked to continue with the paused survey. At this phase of the survey, participants were asked to rate each infrastructure design considering their interaction with and without AVs on roads.

Following the survey, they joined the second discussion where pictures of potential interacting signals were shared with them. The teenage cyclists were asked to discuss the pros and cons of these interacting signals, for three safe and four unsafe crossing conditions, presented on a display mounted on an approaching autonomous vehicle. After their discussion (15- minute long), they were asked to continue with the survey to rate and rank each of these interacting signals to express their preference for communicating with autonomous vehicles. They also answered survey items regarding their preference for modes of interaction with autonomous vehicles. After these surveys, participants were allowed to leave the study. An Amazon e-gift card of $10 was emailed to each of the participants in appreciation for their time and contribution. The flow chart of the protocol is shown in Figure 1.

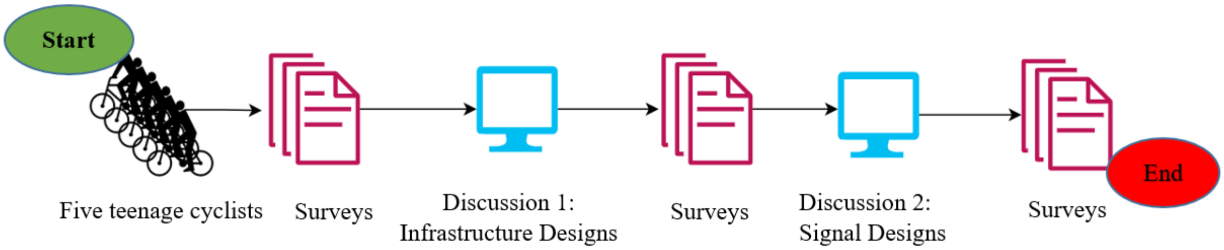
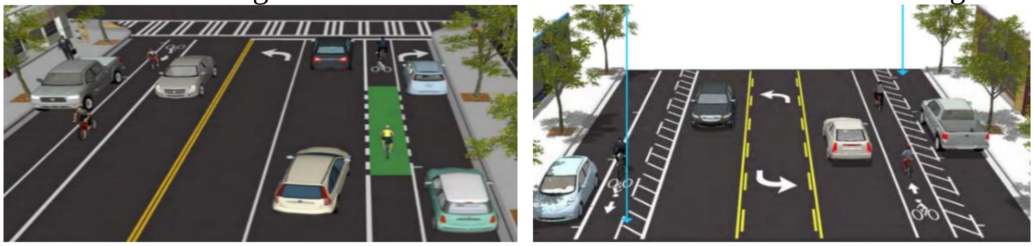


Figure 1. Protocol for focus group study

3.5.1 Potential Infrastructure Designs

The infrastructure designs that we shared with our participants are listed below (see Figure 2), in sequence. In these designs, the cyclists are sharing roads with autonomous vehicles (AV). Different designs show different lane structures, markings, clearance, and separation styles.

Infrastructure Design #1 Infrastructure Design #2



Infrastructure Design #3 Infrastructure Design #4

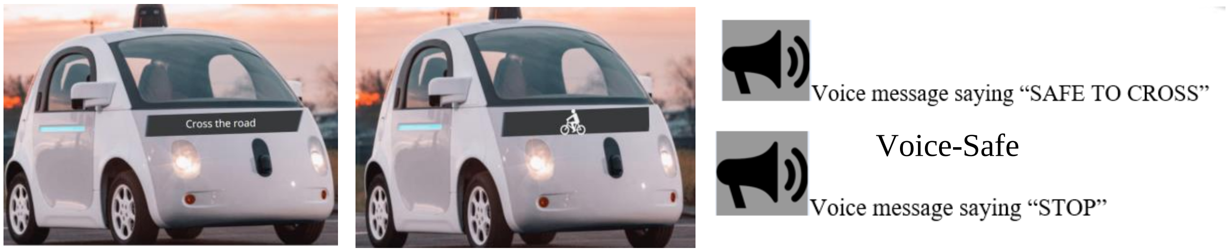
Infrastructure Design #5 Infrastructure Design #6

Figure 2. Potential designs of traffic infrastructures for autonomous vehicle sand cyclists
Sources: KOA Corporation (2015); National Association of City Transportation Officials. (n.d.)

In infrastructure design #1, the cyclists are sharing lane with autonomous vehicles with no markings for cyclists. There are no clearances between the cyclists and the parked vehicle lanes. If someone comes out of the vehicle, the cyclist must stop and wait for the passenger to move out of the way. In infrastructure design #2, the cyclists are sharing lane with autonomous vehicles with marked space for cyclists. There is clearance of three feet between the cyclists and the parked vehicle lanes. For infrastructure design #3, there is a separate lane for the bicyclist, and they are separated by the markings. There is clear difference between the vehicle and cyclist lane. Infrastructure design #4 has clear separation and markings for the vehicle and bicycle lane. It has clearance between the parked vehicle and bicycle lanes. Infrastructure design #5 has physical barriers separating vehicle and bicycle lanes. However, these barriers are not continuous; sometimes the cyclist can ride in the vehicle lane. Infrastructure design #6 has separate lanes for cyclists and vehicles. This design has a continuous physical barrier that cannot be crossed over by either cyclists or the vehicles.

3.5.2 Potential Designs for AV-Cyclist Interactions

In this study a number of potential communicating signals were proposed for both safe and unsafe crossing conditions of AV-teenage cyclist interactions. The signals were designed for AV-cyclist interactions at a crosswalk while a cyclist has to cross the road in front of an approaching autonomous vehicle. The signals were designed to be appeared on a display mounted in the front of an autonomous vehicle. The safe designs inform teenage cyclists that it is safe to cross the roads. These interacting signals can be a flashing text showing “Cross the road”, a flashing cyclist image shown on the display, or a voice message frequently saying “Safe to Cross”. The unsafe designs indicate that it is unsafe for cyclists to cross the road. These interacting signals can be a flashing text showing “Do not Cross”, a flashing image displaying ‘no cycling’ sign, upraised Hand-unsafe or a voice message frequently saying “Stop”. Potential designs for interacting conditions are shown in Figure 3.



Voice-Safe

Text-Safe Cycle Image-Safe Voice-Unsafe

Cycle Image-Unsafe Text-Unsafe Upraised Hand-Unsafe

Figure 3. Potential designs of cyclist-autonomous vehicle interactions

3.6 Data Analysis

Analysis of data was performed to calculate both descriptive and inferential statistics; while descriptive statistics showed the result of inquiry as it is, inferential statistics was used to make inferences about the result of an inquiry. In terms of descriptive statistics, averages and standard deviations were used to summarize participant survey responses on cyclists' behavior, personal innovativeness, likelihood of being beneficial, anxiety of sharing the road with AVs, receptivity toward AVs, and their perceptions on the mode of interaction with AVs.

For the focus group discussion data, a comprehensive transcription was created based on notes and audio recordings. Participants' ID and their comments were recorded onto one Excel file separating four groups. All comments regarding potential designs were coded based on the factors which were hypothesized to be influential from the literature review, such as safety, separation type, space, marking, and other factors like collision and crossover option. For example, the comment "I'll not feel comfortable with the stripe of paint only" was coded as 'separation' and the comment "there was no sign to understand where the cyclists will go" was coded as marking. After debriefing the entire transcription, the comments were reorganized, with the comments from all four groups summarized in one Excel sheet. The comments from all four groups with the same code were organized together and highlighted in the same color. The number of responses for each code was then counted and the percentage of responses for each code was calculated.

The averages and standard deviations of rating survey responses helped us to identify participants' preferences for different interface designs. For the ranking survey, the frequency and percentages were calculated to find the most favorable and least favorable designs. The associations were investigated for these ratings and rankings with demographics and other constructs collected using survey tools.

Analysis of variance (ANOVA) and regression analyses were conducted appropriately to find influence of demographic factors and of different scale scores on participants' perception and receptivity of AVs and on their ratings and ranking scores for proposed designs. Post-hoc analyses were performed for significant effects at 95% confidence intervals in order to present inferential statistics.

CHAPTER 4: RESULTS AND DISCUSSIONS

The data were analyzed using Statistical Product and Service Solution SPSS vs. 27. Both Descriptive and inferential statistics were calculated to test the hypotheses and answer each research question. The results are followed by discussions in the following sections. Descriptive statistics were found to understand overall cyclist behavior, their perception of AVs, expectations from these vehicles, and ways to interact with them. Further analyses were performed to find the effect of demographics variables on these measures and association between cyclists' preferences for supporting (i) infrastructures and (ii) interacting interfaces with their (a) cycling behavior, (b) cyclist receptivity of AVs, (c) personal innovativeness, (d) likelihood, and (e) anxiety.

4.1 Descriptive Statistics of Pre-Discussion Surveys

4.1.1 Cyclist Behavior Questionnaire

The factors collected using this behavior questionnaire are cyclists' *error and violation*, *aggressive behaviors,* and *positive behaviors*. Each item is coded as 1(very infrequently or never) to 7 (very often or always). A higher score means that participants are more supportive to the statement. Mean and standard deviations are given in the tables below for each survey items. These behaviors have implications for the safety of the cyclist and other road users. Such behaviors include approaches to crossing the road, braking, relating with other road users. and using of gadgets in the course of cycling. The results of the inquiry are presented below in Table 5:

Most of these questions were risky behaviors in terms of *errors and violations* and *aggressiveness*. Most of the scores were below 3 (neutral point is 4) which indicates that teenage cyclists understand the traffic rules and follow them while cycling on the road. Only two statements under risky behaviors showed higher scores: however, still below the neutral point 4. These are the behaviors very common in inexperienced and teenage cyclist populations. The teenagers stay on their bikes while crossing a road and they like to listen to the music while cycling for recreation or exercise. These results confirm that teenagers may think that they are well aware of most of the traffic rules, they still need to learn about more to confirm their safety and safety of other road users. Aside from these statements on risky behaviors, few statements (positive behaviors) represent acceptable and responsible behavior in traffic. The participants, on average, rated them with higher scores (above the neutral point 4). The results indicate that, generally, the teenage respondents were against violating traffic rules, but also were more in favor of the questionnaire statements that focused on complying with respectable traffic attitudes or behavior, all for the sake of their personal safety. These results are consistent with self-reported behaviors from other road users in past studies (Deb et al., 2016; Granie et al., 2013) which showed people mostly shows positive behaviors on the road.

Table 5: Means and standard deviations for cyclist behavior questionnaire items.

Cyclist Behavior Questionnaire toward AVs: 7-point Likert Scale (N=20)	**Mean (SD)**
Errors and Violations (reverse-scaled)	
I go against the direction of traffic	2.35 (1.57)
I cross over from the bicycle lane into the motor vehicle traffic lane	1.85 (1.37)
I cross roads when it appears to be a clear crossing, even if the traffic light is red	2.60 (1.90)
I cross the road without looking properly	1.55 (1.15)
I brake suddenly to where I almost cause accidents	2.30 (1.78)
I fail to notice the presence of pedestrians crossing when turning	1.65 (0.88)
I do not brake on a “stop/yield” and come close to colliding with road-users	1.80 (1.24)
I unintentionally hit a parked vehicle	1.45 (0.83)
When crossing roads, I stay on my bike instead of getting off and walking	3.75 (2.22)
I cycle alongside friends and hold their hand/mess with them while cycling	1.30 (0.47)
I talk over phone while cycling	1.70 (1.30)
I listen to audio (news or music) while cycling	3.85 (2.37)
Aggressive Behaviors (reverse-scaled)	
I yell at other road users if they do not follow the rules.	1.35 (0.93)
I cycle around other road-users and “cut them off”, forcing them to brake	1.35 (0.93)
Positive Behaviors	
I try to move at an appropriate speed to avoid sudden collision or braking	5.45 (1.47)
I usually keep a safe distance from vehicles and other road users	5.95 (0.95)

Cyclist Behavior Questionnaire toward AVs: 7-point Likert Scale (N=20)	Mean (SD)
Errors and Violations (reverse-scaled)	
I always use designated area to cycle and to cross.	5.70 (1.38)

For each of the three factors in the cyclist behavior questionnaire, a subscale score was calculated by taking averages of the all the item scores under each factor. For all the subscales, except the positive behavior one, a lower score means safer cyclist behavior. The composite score for cyclist behavior was calculated by adding together the three subscale scores, considering *error and violation* and *aggressive behavior* items as reverse scaled. These scores were later used to find their influences on teenagers' perception of AVs and to determine the association between participants' choice of infrastructures and communicating interfaces with their cyclist behavior, for subscale scores and for composite scores.

4.1.2 Personal Innovativeness

The personal innovativeness (PI) scale is used to evaluate respondents' willingness to accept and adopt new technology in a general sense (Agarwal and Prasad, 1998). Personal innovativeness is the individual's propensity to act or react towards an object or idea. Items in the PI scale are coded from 1 (strongly disagree) to 7 (strongly agree). The higher score means that respondent is more supportive to the statement. For all the items, except for the third one, a higher score means more willingness to accept sharing roads with autonomous vehicles. Mean and standard deviations are presented in Table 6. Most of the scores are higher than the neutral point 4 and for the reverse-scaled item, the score is lower than the neutral score 4. These results show that teenage cyclists were not cautious about trying out new technologies. They would be enthusiastic in embracing new deployment of AVs on the road. This means the respondents mostly agree to explore new technologies and would appreciate the deployment of AVs on the road given that they will safely share roads with them. This finding can be supported by previous research

(Hartman and Samra, 2006; Park and Lee, 2011), which have found teenagers being significantly interested in accepting and adopting new technologies.

Table 6: Means and standard deviations for personal innovativeness scale items.

Personal Innovativeness Scale Items: 7-Point Likert Scale (N=20)	**Mean (SD)**
If I heard about a new technology, I would look for ways to experiment with it	5.40 (1.19)
Among my peers, I am usually the first one to try out new technologies	4.20 (1.54)
In general, I am hesitant to try out new technologies (**reverse-scaled**)	3.25 (1.21)
I like to experiment with new technologies	5.60 (1.31)

A personal innovativeness score was calculated by averaging responses for each item, considering the third item as reverse scaled. This score was used to find its influence on teenagers' perception of AVs and to determine the association between participants' choice of infrastructures and communicating interfaces with their personal innovativeness.

4.1.3 Likelihood Questionnaire

The likelihood of how participants feel about AVs and their safety and failures can be used to estimate respondents' views about adopting these vehicles. Four questions were specifically designed for this study based on questionnaire used in Bloom et al. (2017). The likelihood questionnaires were answered on a 7-point Likert scale with 1 (very unlikely) to 7 (very likely). The results are presented in Table 7.

Table 7: Means and standard deviations for likelihood questionnaire items.

Likelihood: 7-point Likert Scale (N=20)	**Mean (SD)**
What is the likelihood of you identifying an AV on the road?	4.50 (1.28)
How likely do you think using AV will lead to fewer crashes with cyclists?	5.15 (1.60)
How likely do you think AV will lessen severity of crashes with cyclists?	5.00 (1.49)
How likely do you think AV will free more space for cyclists?	5.20 (1.28)

The scores reveal that participants have higher comfort sharing roads with autonomous vehicles. The teenage cyclists have strong feelings that the deployment of AVs to the road will reduce the number of crashes they encounter while riding their bicycle. However, they showed comparatively a lower score (but higher than the neutral value 4) for identifying an autonomous vehicle on the road. This result is reasonable as these vehicles are not on the road yet and they are still under investigation regarding their designs and appearances. Therefore, there is not enough information available to be able to identify these vehicles on the road. This is to say that a higher number would have problems identifying an AV on the road. This result is important as correctly sighting AVs can have influence on cyclist’s comfort sharing roads with them. If a cyclist cannot sight an AV properly, they may not know how to act towards it, and this may result in confusion and discomfort. However, with respect to the likelihood of crashes with cyclists, respondents mostly believed that AVs would lead to fewer crashes, reduce the severity of crashes with cyclists, and make more space available to cyclists on the road. The fourth question about freeing space for cyclists implies that there will be less frequency of contact with vehicles that eventually will reduce the number and severity of crashes.

A likelihood score was calculated by averaging responses for each item. This score was used to find its influence on teenagers’ perception of AVs and to determine the association between participants’ choice of infrastructures and communicating interfaces with their likelihood of adopting AVs.

4.1.4 Anxiety Scale

The survey items of anxiety scale were developed based on a valid questionnaire used by Hewitt et al. (2019). This scale can be used to measure respondents’ attitude and concern towards autonomous vehicles. Anxiety represents an individual’s concerns about an object or situation. The questions were designed around four conditions: riding side- by-side with an AV, performance of AVs in poor weather conditions, performance of AVs at night, and the possibility of AV's system failure. The results of the inquiry are exhibited in Table 8.

Table 8: Means and standard deviations for anxiety scale items.

Anxiety Questions: 5-point Likert Scale (N=20)	**Mean (SD)**
How concerned would you be about riding alongside an AV?	3.25 (0.97)
How concerned would you be about AV's performance in poor weather?	2.75 (0.97)
How concerned would you be about AV's performance in the night?	2.70 (1.42)
How concerned would you be about consequences of AV's system failure?	1.90 (1.07)

The anxiety questionnaires were answered on a 5-point Likert scale from 1 (very concerned) to 5 (not at all concerned). The results show that for the first three statements, respondents were not concerned; they scored above the neutral value (2.5). It can be said that teenagers were not anxious about riding alongside AVs, and they were not anxious toward AV's performance in poor weather or at dark. These results support other findings regarding teenagers being positive about AVs implementation; hence, would be comfortable with riding side by side with AVs, using AVs in poor weather, or at night. Nevertheless, a lower score for the fourth items indicates that teenage cyclists were very anxious about AV's system failure and consequences led by the failure. In summary, the anxiety scale scores show that a higher number of teenagers were not anxious about using AVs irrespective of the condition. However, as these vehicles are still under development and investigation for safety, teenage cyclists are not quite ready to ignore AV's system failures and consequences.

An anxiety score was calculated by averaging responses for each item. This score was used to find its influence on teenagers' perception of AVs and to determine the association between participants' choice of infrastructures and communicating interfaces with their anxiety regarding AV implementation.

4.1.5 Cyclist Receptivity towards AVs

This construct was investigated to evaluate cyclists' behavioral intention to cross the road in front of an approaching AV. The survey items were designed based on three factors: *safety*, *interaction*, and *compatibility* with existing infrastructure. Nine statements were developed based on Deb et al.'s (2017) pedestrian receptivity questionnaire toward AVs. This inquiry is important because it shows how respondents are receptive toward the new technology and their willingness to interact with it. The results are presented in Table 9.

Table 9: Means and standard deviations for items on cyclist receptivity toward AVs.

Cyclist Receptivity toward AVs: 7-point Likert Scale (N=20)	Mean (SD)
S. I would feel safe to share road with AVs	5.10 (1.33)
S. I would feel more comfortable doing other things while sharing roads with AVs	4.50 (1.50)
S. AVs will always make the right decision	3.95 (1.50)
S. My parents, family, and friends would trust AVs	4.15 (1.35)
S. I would feel comfortable if my parents, family, and friends trust AVs	5.75 (1.33)
I. It would be difficult to communicate with AVs (**reverse-scaled**)	5.15 (1.18)
I. It would take more effort to understand the intention of an AVs (**reverse-scaled**)	4.95 (1.19)
C. Existing road design, lanes, and signals will support AVs	4.30 (1.56)
C. AVs will easily and correctly communicate their intention with cyclists	4.20 (1.51)

Note: S-*Safety*, I-*Interaction*, and C-*Compatibility*

The cyclist receptivity questionnaires were answered on a 7-point Likert scale with 1 (strongly disagree) to 7 (strongly agree). The results show a discrepancy with respect to the views and beliefs of respondents on cyclists' receptivity towards AVs. For most of the *safety* statements, participants believed that AVs would make the roads safer. It is reasonable to feel confident while sharing roads with AVs, but it can be counted as over-confidence to be engaged in other activities while sharing road with AVs, hence the lower score from the respondents compared to the first item. The lower score on the third item (lower than the neutral value 4) indicates that participants would not trust these vehicles always making correct decisions. Automated vehicles with limited safety features being involved in fatal crashes must have influenced their responses. The examples are Tesla's crash in California in 2018 and Uber's crash in Arizona in 2018. Furthermore, fourth and fifth *safety* statements are about trust of family and friends on AVs. A low score in fourth item explains that participants' family and friends are not yet ready to accept AVs; however, a higher score on the fifth item shows that opinion of family and friends would have a great influence on teenagers' receptivity toward AVs. The issue of trust involving family and friends is anchored on a suggestion that teenage cyclists would require some encouragement and support from close relatives to ride alongside AVs and interact with them.

For the statements regarding *interaction* with AVs, two reverse-scaled items, the higher scores indicate that respondents found it to be difficult interacting with these vehicles and understanding their intentions at an intersection. This report is hinged on the relationship between human controlled cycles and computer-controlled AVs. This result confirms and validate the purpose of the current research to identify supporting infrastructures and communicating interfaces for teenage cyclists and AV interactions.

The last two survey items in this questionnaire are based on *compatibility* factor and about respondents' perceptions on existing traffic infrastructure being adequate for AVs. Although the scores are higher than the neutral value, comparatively lower scores than some of the safety and interaction items strengthen the objective of this research as many participants still believe that current traffic infrastructure is inadequate for AVs. These results imply that in order to make teenage cyclists comfortable and receptive toward AVs, it is important to make changes or modifications in current infrastructure and incorporate a platform for effective cyclist-AV interactions.

For each of the three factors in the cyclist receptivity questionnaire, a subscale score was calculated by taking averages of the all the item scores under each factor. For all the subscales, except the interaction one, a lower score means more receptivity. The composite score for cyclist receptivity was calculated by adding together the three subscale scores, considering interaction items as reverse scaled. These scores were later used to find their influences on teenagers' perception of AVs and to determine the association between participants' choice of infrastructures and communicating interfaces with their cyclist receptivity toward AVs, for subscale scores and for composite scores.

4.2 Summary of Questionnaire Data

The questionnaires discussed in the above section explain teenage cyclists' cycling behavior and their knowledge about cycling, their attitudes toward autonomous vehicles, their concerns about the functionality of AVs, and their perceptions toward adopting these vehicles. All the composite scores and subscale scores, for appropriate cases, are presented for each of the questionnaires in Table 10.

Table 10: Summary of teenage cyclists' perceptions toward AVs

	Mean (SD)	
Questionnaires	**Subscale Scores**	**Composite Score**
Cyclist Behavior	Errors and violations [E&V]: 2.18 (0.69) Aggressive behaviors [A]: 1.35 (0.61) Positive behavior [P]: 5.70 (1.00)	2.17 (1.40) [P- E&V- A]
Personal Innovativeness (PI)		4.61 (2.31)
Likelihood		4.96 (1.02)
Anxiety		2.65 (0.95)
Cyclist Receptivity	Safety [S]: 4.49 (0.99) Interaction [I]: 5.05 (1.00) Compatibility [C]: 4.25 (1.45)	3.69 (2.64) [S+C-I]

4.3 Influence of Demographics Factors on Perceptions of AVs

Analysis of Variance (ANOVA) was conducted to determine the influence of age groups (2 levels: 13–14 and 15-17), gender (2 levels: Male and Female), education level (2 levels: middle-school and high-school), duration of cycling per day (3 levels: <15 min, 15-30 min, and >30 min), frequency of cycling per week (3 levels: 0-2, 3-4, and >4) and reason for cycling (2 levels: play with friends and exercise) on each of the composite scores and subscale scores for cyclists' personal innovativeness, likelihood, anxiety, and receptivity towards AVs. The ANOVAs revealed significant influence of gender on compatibility score [*F-statistics* (*df* : 1, 19), *p-value* = 6.220, 0.023]. Female teenage cyclists [μ= 3.61, SD= 1.21] were more concerned about interacting with AVs with existing infrastructures as compared to their male counterparts [μ= 5.13, SD= 1.38]. No other factors had any significant influence on cyclists' perceptions toward AVs.

ANOVA was also conducted to test the influence of cyclists' knowledge of cycling rules (rated from strongly disagree to strongly agree on a 5-point scale) and cycling behaviors on their perception and receptivity of AVs. Results show that cyclists' *safety* perception is significantly influenced with their knowledge of cycling rules [*F-statistics* (*df* : 1, 19), *p-value* = 4.002, 0.027]. The participants who reported to have better knowledge of cycling rules and regulations were found to be more confident about AVs being safe and were comfortable sharing roads with AVs. This result is not consistent with earlier results obtained in studies involving adult respondents that showed a lot of concerns and skepticism about safety with automated vehicles (Casley et al. 2013; Piao et al. 2016; Advocates for Highway and Auto Safety, 2018). In Piao et al.'s (2016) study, only a quarter of respondents expressed belief that AVs would be safer than conventional vehicles. The opinion poll, conducted by Advocates for Highway and Auto Safety (2018), showed adult participants' skepticism about AVs being capable of providing safety on the road. In Casley et al.'s, (2013) and Schoettle and Sivak's (2014) studies, a majority of respondents negatively evaluated AVs on safety. In the present study, the belief of respondents that AVs will reduce both the frequency and severity of crashes on the road may be attributed to their inadequate experience with AVs. As teenagers, their knowledge about technology led them believe that technology brings ease and speed in services and the same is applicable with AVs. There was no significant association found for other factors considered in analyses.

Answering Research Question #1

The summary shown in Table 10 confirms that teenagers are well aware of the cycling rules and shows mostly positive behaviors on the road. The first research question of the study was "*What are the perceptions of teenage cyclists about AVs?*" Based on the composite scores for personal innovativeness and likelihood, it can be said that teenagers are most likely to be excited willingly accept AVs on the road and they will get adopted with the changes without much hesitation. These results are in line with previous studies with adult road-user populations (Deb et al., 2017; Schoettle and Sivak, 2014). Although the composite score for anxiety was above the neutral value (3), teenagers were not ignorant about the concerns of correctly identifying an AV on the road and having consequences of AV's system failure. Therefore, their responses were not overwhelmingly positive. In case of cyclists' receptivity towards AVs, teenagers were, on average, positive about AVs being safe and compatible with existing infrastructures. However, they found it to be more difficult to interact with AVs compared to the drivers of traditional vehicles.

These results satisfy our hypothesis **H_{1A}** [teenage cyclists will show positive attitudes and a high level of trust toward AVs]. As there was a small difference in ages for two age groups, teenagers did not show any significant differences in their perceptions of AVs based on the age groups. However, the knowledge of cycling rules was found to have significant association with participants' safety perceptions of AVs. Therefore, it can be said that the second hypothesis **H_{1B}** [teenagers will be more willing to accept these vehicles due to the knowledge about AVs and their operations] is also satisfied based on teenagers with proper knowledge of traffic rules feeling safe around AVs. The results of gender having influence on compatibility score satisfies the third hypothesis **H_{1C}** [Male teen cyclists will be more positive toward the AVs compared to female teen cyclists] in that male teenagers are more willing and ready to share existing infrastructures with

AVs compared to female teenagers. For females, there must be some changes or addition of new infrastructures to make them feel safer around AVs.

4.4 Cyclist Perception on Cyclist- AV Interaction

The questions on traffic infrastructures and communication interfaces were developed and used to evaluate respondents’ views on cyclist-AVs interactions as well as ways to improve their experience of interactions. The infrastructure refers to both physical and digital types. Ten statements were provided contingent on sensors, visual and auditory signals, cycle lanes, road markings, dedicated lanes, etc. These statements represent respondents’ opinions on requisite facilities that would enhance interaction between cyclists and AVs. The results of the inquiry are presented in Table 11.

Table 11: Means and standard deviations of items for cyclist perception on cyclist-AV interaction.

Cyclists’ Perception on Cyclist-AV Interaction: 7-point Likert Scale (N=20)	**Mean (SD)**
Cycle lanes should be broadened for detection purposes	5.70 (1.03)
New road markings should be placed to separate and direct vehicles and cyclists	6.05 (0.95)
New signs should be provided to warn cyclists at intersections	6.30 (0.57)
Dedicated lanes and parking spaces will help to reduce cyclists-AV contacts	6.05 (0.82)
Pickup/drop off areas should be provided to avoid collision with cyclists	5.90 (0.91)
Using a smart mobile phone app with sensors will reduce collision while cycling	4.65 (1.46)
AVs should have auditory signals to alert cyclists	5.65 (1.35)
AVs should have visual signals to alert cyclists	6.05 (1.05)
Cycles should have sensors to interact with automated vehicles	5.65 (1.23)
Cycles should have sensors to interact with traffic signs	5.45 (1.43)

These survey items were answered on a 7-point Likert scale with 1 (strongly disagree) to 7 (strongly agree). In terms of physical infrastructures, respondents provided their views with respect to cycle lanes, road markings, signs at intersections, pickup/drop off areas, and dedicated lanes as seen in the first five survey items. Most of the respondents agreed that road markings should be broadened for purposes of detection of cyclists by AVs. The implication is that broadening cycle lanes will further reduce contact between cyclists and AVs, which leads to cyclist safety. Majority of respondents agreed with the proposition that new road markings are needed to separate and direct AVs and cyclists. This is an indication that the current road markings are not adequate for implementing AVs with regard to cyclist safety. A large number of respondents were positive to the statement that new traffic signs should be provided at intersections to warn cyclists about the presence of AVs on the road. This suggestion indicates that current signage systems at intersections are not adequate with respect to alerting cyclists about the presence of other road users such as AVs. Based on the anxiety score, participants were worried about detecting AVs on the road. Through the new signage system, they will be able to learn about the presence of AVs on the road and take appropriate actions in their traffic environments. A high number of respondents agreed that dedicated lanes and parking spaces will help to reduce contact between cyclists and AVs. In addition, AVs are most likely to be carrying passengers from one place to another and less likely to be using parking services, designated pickup/drop off areas should be provided for them to avoid collisions with cyclists. This suggestion is based on either inexistent or inadequate pickup/drop off zones for AVs to avoid crossing over cyclist lanes. The establishment of these physical facilities will help reducing the possibilities and frequencies of contact between AVs and cyclists. The respondents are concerned about their contacts and collisions with AVs and would like such situations to be minimized with proper spacing, separation, signage, and necessary designated lanes.

The last five statements are for cyclists' preferred mode of interaction with AVs. Respondents demonstrated their concerns regarding communication with AVs and suggested for supporting digital infrastructures. The identified digital infrastructures from literature review include sensors and signals facilitating cyclist-AV interactions. Most of the statements are focused on AVs and cyclists having sensors as interacting platform, and AVs having auditory and visual signals to explain their intentions (brake, stop, go, change direction, etc.) on roads. Participants overwhelmingly rated these statements with higher scores. Teenage cyclists are concerned about their interactions with AVs, and they would feel more comfortable sharing roads with AVs if both cyclists and AVs are equipped with sensors. Teenage cyclists would also like to see auditory and visual signals from AVs to understand their intentions on the road. However, when they were asked about using a mobile application to get assistance in reducing AV-cyclist collisions, their responses were not as enthusiastic as were for other statements. Many of them believe that using a smart mobile phone app equipped with sensors is effectual; however, some of them also did not agree to this statement. This indicates that teenagers are not completely in agreement that the mobile app will be helpful avoiding collisions, not causing further distractions leading to collisions.

4.5 Focus Group Discussion on Infrastructure Designs

In this section, the data obtained through the focus group are presented and analyzed. With the aid of simple percentages or frequency counts, respondents' views about factors affecting perception about traffic infrastructure designs for AVs were coded and grouped into six categories. They are (1) perception of safety, (2) separation between cyclists and AVs, (3) space between lanes, (4) road markings, (5) collision, and (6) crossing lanes. These categories were based on six (6) designs showing different types of infrastructure for vehicles and cyclists on the road. In different group discussions, some major factors were prominent among the feedback from respondents. Table 12 summarizes these factors, above mentioned, their frequencies and percentages, and examples of verbatim statements.

Cyclists' perception of safety. Safety was one of the most important factors for most of the respondents. A high frequency count of 87 responses (representing 32.46%) included safety with AVs on the road. From their survey results it was found that respondents believe cyclists will be safer while riding alongside AVs. However, they had doubts and concerns regarding identifying an AV and about AV's system failure. These concerns could be explained by outcomes of their discussions.

Table 12: Factors influencing cyclists' perception on traffic infrastructure design for AVs.

Factors	Frequency (Percentage)	Example of Verbatim
Cyclists' perception of safety	87 (32.46%)	"I think that cyclists will have enough safety with autonomous vehicles on the road."
Soft/hard separation between cyclists and AVs	79 (29.48%)	"I like how there is a separating line between AVs and cyclists; I think it makes the design safer." "The design with a median between the AV lane and the cyclist lane is the safest one."
Additional space between lanes	36 (13.43%)	"There is more space between the cyclist lane and the car lane, but there is still nothing stopping AVs from driving into the cyclist lane." "I like space between lanes as clearance and to have more room for cyclists."
Markings for AVs and cyclists	26 (9.70%)	"Autonomous vehicles may need lanes with some kind of markings or signs (stripes) to differentiate them from normal vehicles." "Cyclists should have designated lanes with signs to let them know where they should go."
Collisions	22 (8.21%)	"If there is no separation and cyclists do not pay much attention, there can be collisions with AVs."
Crossover to other's lanes	18 (6.72%)	"Without a physical barrier cyclist may crossover to AV lanes as we do not always see people following the rules."

According to infrastructure design 1 and 2 there were no separate lanes for cyclists and were little to no space for them. For design 3 and 4, there were separate lanes for cyclists, separated by road markings only; there was no barriers or raised platform to obstruct road users from crossing over lanes. Designs 5 and 6 had separate cyclist lanes and hard separations with physical barriers to obstruct motor vehicles from crossing roads. Although teenagers were positive adopting these vehicles, they are still not confident about their safety sharing the same lanes or different lanes, separated with markings only, with these vehicles.

Soft/hard separation between cyclists and AVs. With respect to soft and hard separation between cyclists and AVs, a high frequency count of responses (79, representing 29.48%) included this factor in their discussions. The participants favored the infrastructure designs 3, 4, 5, and 6 because there were soft and hard separations between cyclists and autonomous vehicles. However, they all preferred the infrastructure design 6 as the best in terms of safety because there was a solid and continuous barricade separating the cyclist path and the autonomous vehicle lane.

Additional space between lanes. A frequency count of 36 responses (representing 13.43%) reasoned that AVs may need additional space between lanes with special markings to keep them separated from vehicles. They believe that cyclists need designated lanes for proper direction and making turns. They would also like to see additional space between lanes for infrastructure designs 1, 2, and 3. According to designs 5 and 6, there are clear demarcations for cycle lanes which represents an improvement to the other four designs. Consequently, additional spaces between the teenage cyclists and AVs on the road would be appreciated as an improvement in the road infrastructure. The respondents think that with designs having sufficient spaces would make teenage cyclists comfortable riding safely alongside AVs. Reynolds et al. (2009) stated that with improvements in traffic infrastructure and successive promotion of a safety culture can drastically decrease crashes, injuries, and fatalities.

Markings for AVs and cyclists. In relation to markings on the road, a frequency count of 26 responses (representing 9.70%) were recorded. Respondents advised that the markings for AVs should be different from the normal vehicles where it is possible. In addition, there should be markings on the road for cyclists to guide them on where to cycle. According to design 3, there are clear markings for cyclist' lanes which represents an improvement to the first and second designs. However, despite this improvement, respondents did not think the design had sufficient features that autonomous vehicles would drive safely.

Collisions. In the aspect of collisions on the road, a frequency count of 22 responses (representing 8.21%) included this factor in their discussions. The infrastructure design 1 without any separate lane and without clear marking was viewed by the respondents as not safe with high chance of crashes between cyclists and autonomous vehicles. Although the autonomous vehicles will have sensors to detect the presence of any object around it, they believe it is safer to have all roads marked to demarcate the cyclist lanes from the vehicle lanes. However, they reasoned that nonseparation of lanes and distraction on the part of cyclists can lead to collision on the road. This is because, in the design 5, although there are obstructions between the vehicle and cycle lanes, the barricades did not cover the entire section of the road. As a result, vehicles and cycles would have to share the road at some point which may lead to accidents.

Crossover to other's lanes. An insignificant frequency count of 18 responses (representing 6.72%) reasoned that in the absence of physical barriers on the road, there is a tendency for cyclists to cross over to AV lanes since people do not comply with traffic rules. The respondents noted that if there are no soft or hard separation between the bicycle and autonomous vehicle lanes, the tendency of road users, especially cyclists, violating the rules by crossing over will be high. This may lead to collision or crashes between the autonomous vehicles and cyclists. In the case of a cyclist crossing over to AV lanes, a large majority of the participants were in agreement that design 6 will prevent cyclists from doing this. Although most of the participants stated that they follow traffic rules, but they do not trust other road users following the rules like them.

4.6 Rating of the Infrastructure Designs

After their discussion, participants responded to a rating survey for infrastructure designs comparing autonomous vehicles with traditional vehicles while sharing roads as cyclists. The mean and standard deviation of these ratings are presented in the Table 13.

Table 13: Ratings for infrastructure designs.

Designs		**Ratings: Mean (SD)**
Infrastructure Design 1	With traditional vehicles	2.90 (1.17)
	With *autonomous* vehicles	3.32 (1.00)
Infrastructure Design 2	With traditional vehicles	2.35 (1.09)
	With *autonomous* vehicles	2.74 (1.15)
Infrastructure Design 3	With traditional vehicles	1.90 (1.05)
	With *autonomous* vehicles	2.22 (1.31)
Infrastructure Design 4	With traditional vehicles	4.10 (1.02)
	With *autonomous* vehicles	4.47 (0.84)
Infrastructure Design 5	With traditional vehicles	3.25 (1.02)
	With *autonomous* vehicles	3.84 (0.90)
Infrastructure Design 6	With traditional vehicles	4.75 (0.91)
	With *autonomous* vehicles	4.74 (0.56)

For all of the infrastructure designs, participants rated those with higher scores while AVs on the road as compared to the traditional vehicles on the road. Teenagers reiterated through these ratings that they trust the safety features of AVs for safer interactions. However, there was no significant difference in their ratings for traditional vehicles and AVs. This result is reasonable as the teenage participants do not have enough information on AVs to trust them unconditionally. Participants showed diverse responses for their discussion-based opinions and for ratings regarding most-favored and least-favored designs. This can be due the reason that participants were not rating the features comparing them against one another but for comparing AVs against traditional vehicles.

Answering Research Question #2

The second research question for this study was "*What type of traffic infrastructure would a teenage cyclist like to see to interact with AVs?*" Results from questionnaire items for cyclists' perceptions on AV-cyclist interactions (see Table 11), focus group discussion on potential infrastructure designs (see Table 12), and ratings on these infrastructure designs (see Table 13) confirm that teenagers want traffic infrastructures with few specific features: spacious lanes; separated lanes for cyclists and AVs, most preferably with physical barriers; markings and signage for AVs and cyclists; necessary designated places for pickup/drop offs. These results satisfy hypothesis $\mathbf{H_{2A}}$ [teenagers will want to see separate and designated lanes for AVs in existing infrastructures]. Ratings presented in Table 13 show that teenage cyclists will feel safer with AVs compared to traditional vehicles. However, no significant difference was found between cyclists' perception of AVs and traditional vehicles based on pair-wise comparisons. Therefore, no statistical evidence can be provided for the hypothesis $\mathbf{H_{2B}}$ [teenagers will feel safer with AVs compared to traditional vehicles in traffic environments].

4.7 Focus Group Discussion on Interface Designs

Factors that were pronounced in the second focus group discussion were (1) ease of understanding, (2) appeals attention, (3) disabilities (visual/audible)/illiteracy, and (4) familiarity with design. The frequency counts for using these factors along with their percentage and example of verbatim are presented in Table 14.

Ease of Understanding. The term *ease of understanding* was prominent in teenagers' discussions; 78 (41.94%) was the highest frequency (percentage) of using this factor. Some of the respondents opined that text would be easy to read and comprehend, while some stated that the symbol with a cyclist marked with red for one of the unsafe conditions would be most confusing. They argued that the cyclists would understand it as a symbol indicating that cycling is prohibited in that area.

Appeals Attention. The next term that featured in their focus group discussion was *appeals attention* with 43 (23.12%) frequency (percentage). In their discussion, the respondents were diverse in views. Some said that the voice will get their attention faster, while others opposed it with an argument that if someone is listening to music or on a call while riding, they might not hear the voice message. Similarly, many participants believed that flashing visual signals will catch their attention, while others were concerned about people not looking at the vehicles to see the signals on time.

Table 14: Factors influencing cyclists' perception on interface design for AVs.

Factors	**Frequency (Percentage)**	**Example of Verbatim**
Ease of Understanding	78 (41.94%)	"The interacting signal design #1 is "Do not cross the road." When you see it you know exactly what to do." "No cycling sign is confusing as this can be interpreted as no cycling is allowed in this road."
Appeals Attention	43 (23.12%)	"I like the voice, because I think that would really help get people's attention immediately." "People may not listen to the voice messages when they are listening to the music or talking over mobile phones."
Disabilities (visual/audible)/Illiteracy	42 (22.58%)	"People with visual impairment or low visibility may not see or read the sign." "People who do not know English will have troubles with text messages."
Familiarity with Design	23 (12.37%)	"Upraised hand is a universal design; everybody knows what it means."

Disabilities (visual/audible)/Illiteracy. Participants used *disability and illiteracy* concepts for 42 times. While discussing about interface designs with visual and audible signs, participants were very thorough and inclusive about considering needs of disabled and illiterate populations. They also wanted the features to be standard and universal which can be easily, correctly, and immediately interpretable. There are many people who cannot read English or takes time to read, there are also people with visual impairment or low visibilities, and people with hearing disabilities. The designs should be effective enough to satisfy everyone's needs.

Familiarity with Design. Familiarity with designs was another important factor that participants mentioned quite frequently (23 times). The designs that are familiar to the participants were easy for them to interpret. For example, almost all of the participants understood what an upraised hand stands for and how to act in front of an AV showing a red-colored upraised hand. An image with bicycle sign was also easy for them to understand; however, its opposite sign just with a red mark on cyclist image created confusions. This sign was designed for indicating an unsafe condition. Nevertheless, participants familiar with similar type of signs for 'no crossing' or 'no pedestrian in this area' accepted this sign for no cycling in this area rather than understanding an unsafe crossing condition.

4.8 Rating of the Interacting Signal Interfaces.

The participants were shown different interacting signal interfaces (see Figure 3) during the second discussion session. These interacting signal interfaces depicts safe and unsafe signals with text, symbols, and voice messages, displayed in front of AVs. The results are presented in Table 15.

Table 15: Rankings for interface designs.

Communication Interfaces	**Ranking (Percentages)**	
	Most Favored	Least Favored
Text-Safe	35	30
Text-Unsafe	15	35
Cycle Image-Safe	45	30
Cycle Image-Unsafe	35	25
Upraised Hand-Unsafe	30	0
Voice-Safe	20	40
Voice-Unsafe	20	40

The interacting signal interfaces were ranked based on the percentage of responses for most favored and least favored designs. The cycle image-safe got the most favored ranking for the highest number of participants (45%) as participants are used to seeing this symbol and found it to be the best way to convey a message for safe crossing conditions. The cycle image-unsafe gained support from 35% of the respondents; this response was low because some of the respondents argued during discussion that the symbol might convey 'no biking' on the road instead of a momentary halt. Furthermore, there were diverse opinions about using text for the safe and unsafe crossing conditions, even during the focus group discussions. The text-safe was preferred by 35% of respondents as it was easy to see, read, and understand. However, 30% of the participants chose it as their least favored signal as they mentioned that there are teenage cyclists who do not understand English, do not have patience to read a text displayed on AVs, and may have impaired or low visibility to be able to see and read the message. Next, one-third of the respondents ranked the upraised hand-unsafe as their most favorite. According to the participants, they are familiar with the red upraised hand-unsafe at pedestrian crossings. Notably, none of the participants ranked this interface as their least favorite.

For both the safe and unsafe voice messages, participants were consistent in their rankings; 20% ranked them as most favored while 40% ranked them as least favored. In different focus group discussions, the respondents mentioned that voice messages may not be the best interacting interfaces as most teenage cyclists listen to music with earbuds on while cycling. As a consequence, they would not hear a voice message from AVs when sharing roads with them. In analysis of the data, linear regression analyses were performed to find associations between participants' ratings and rankings of infrastructures and interfaces with demographic factors and with scale scores. However, no significant associations were found. Low participant numbers must have been the reason for not finding significant influence of cyclists' behavior and receptivity of AVs on their choice of designs.

In summary, most of the participants agreed that a combination of visual and audible interfaces, especially with the symbols (cycle-safe and upraised hand-unsafe) and voice messages (safe and unsafe) would be the best options for cyclist-AV interactions.

Answering Research Question #3

The third research question of this study was "*What effect does the type of communicating interfaces have on the attitudes of teenage cyclists concerning their interactions with AVs?"* Results presented in Table 11 for cyclists' perceptions on cyclist-AV interactions, in Table 14 regarding factors of importance from focus group discussion, and in Table 15 for interface ranking show that teenagers were very positive about installing communicating interfaces on AVs. Teenage cyclists would like to interact with AVs with the aid of communicating interfaces in order to understand AVs intentions on the road. They believe that communicating interfaces on AVs will make cyclist-AV interaction safer and will increase cyclists' confidence levels towards adopting these vehicles and interacting with them on the roads. This finding satisfies hypothesis **H_{3A}** [teenagers will show positive attitudes toward communicating interfaces].

Most of the teenagers liked the visual interfaces with familiar symbols. They thought that visual interfaces will appeal their attention and will be easier to understand with universal symbols. Additionally, teenagers use headphones for listening to music while cycling which will prevent them from hearing the voice messages. This finding satisfies the hypothesis **H_{3B}** [teenagers will prefer visual communicating interfaces more than the audible communicating interfaces].

In the case of teenagers' preference of mode for interacting with AVs, they have chosen communicating interfaces and sensors on AVs and cycles over mobile phone applications.

Hypothesis $\mathbf{H_{3C}}$ [teenagers will be more willing to interact with AVs through mobile applications and sensors] was made based on teenagers' inclination toward using technologies like smartphones and different mobile applications. However, teenagers were more concerned about their safety and being distracted by mobile application rather than being warned by them. This finding did not satisfy hypothesis $\mathbf{H_{3C}}$.

4.9 Limitations

This study had a number of methodological limitations for participant recruitment due to the Covid-19 and winter storm situations. The IRB approval was delayed due to the reason with limited employees and the need to be cautious about direct interaction with participants at any phase of the study. As face-to-face interaction between teen participants were not possible, this study was performed virtually. Many sessions were not completed successfully due to technical difficulties. For example, sometimes participants were not able to join meetings, hear researchers, or use their microphones properly to contribute to discussions. Furthermore, recruitment of teenage participants aged from 18-19-years was difficult. The researcher targeted UTA student populations for this age group. As students are mostly on virtual classes, they may not have seen the fliers. It was also difficult with younger participants as they were not willing to participate to avoid another virtual meeting added to their schedule. Additionally, the researcher was affected by the winter storm and was not able to run focus group discussions due to power outages for the researcher as well as for participants. Future research should follow the methodology and questionnaires developed and used in this study to recruit more participants and explore additional outcomes.

CHAPTER 5: CONCLUSIONS

There is an overwhelming enthusiasm in transportation researchers and vehicle manufacturers to commercialize autonomous vehicles (AVs) and implement them in existing traffic infrastructure. Whiles AVs have potentials to enhance traffic safety by reducing human errors, their implementation in traffic systems can create a huge change in road-users' behaviors regarding their interaction with these new-technology and computer-controlled vehicles. Therefore, researchers should continue performing receptivity and acceptance research to promote knowledge of AVs and awareness about them in all levels and types of populations. Research should also be performed on universal and supporting infrastructure and interface designs to facilitate interaction between AVs and different road-user groups.

This study included teenage cyclists who will be the actual users of these future vehicles. This research investigated teenage cyclists' overall perceptions toward fully autonomous vehicles (AVs). With respect to safety, it has been estimated that a majority of accidents occur due to human error which provides a reason and incentive for the development of AVs. In this study a most of the teenage cyclists were confident that AVs will provide safety on the road. This is against the backdrop of numerous accidents and crashes involving cyclists and conventional vehicles.

The research findings also identified factors that are connected to teenage cyclists' perceptions about AVs. For infrastructure designs, such factors include safety, separated and spacious lanes with markings and directions for cyclists and vehicles, contact with AVs, cyclists not following rules and crossing-over lanes traffic behavior. In case of communicating interface designs, factors like ease of understanding, attracting attention, familiarity with designs, and inclusion of needs for disabled and people with English illiteracy were important for teenagers. Manufacturers and transportation researchers should consider these results and design the AVs accordingly. Future studies can investigate the feasibility and preference for the reported designs in a simulated experimental study to collect more realistic responses from cyclists. Responses from other vulnerable road-users need to be considered as well toward developing universal designs. The methodology and results of this study are therefore will be useful to all researchers investigating road-user safety concerning their interactions with AV

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