Designing an Inclusive Mobile App for People with Disabilities to Independently Use Autonomous Vehicles

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ABSTRACT

Autonomous vehicles (AVs) could potentially provide independent mobility to people with physical and sensory disabilities. It is critical to understand the needs of people with disabilities and design interfaces specifically for accessible interaction before, during, and while ending an AV trip. Using a *research-through-design* approach, we identify needs and explore design concepts for a smartphone application to allow people with disabilities to use AVs independently. Through 20 individual interviews, 12 monthly meetings with a group of people with disabilities and transportation advocates, and design prototyping, we develop design concepts for accessible smartphone control of an AV trip. Our work contributes a set of interaction needs for accessible AV interaction, design concepts centered on confidence and control developed in partnership with people with disabilities, and a discussion of an accessible co-design process that other designers can learn from to create accessible automotive user interfaces.

CCS CONCEPTS

• **Human-centered computing → Accessibility design and evaluation methods**; **Human computer interaction (HCI)**; *Mobile computing*.

KEYWORDS

autonomous vehicles, accessibility, mobile interfaces, participatory design

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1 INTRODUCTION

Autonomous vehicles (AVs) could potentially provide people with disabilities similar experiences of independence and control that able-bodied drivers have today [1]—traveling anywhere at any time, listening to whatever you want, and having a comfortable space all to yourself for just a moment. Previous work has estimated that AVs could allow a 14% increase in travel for people with conditions that prevent them from driving [22]. To achieve this vision, AVs must have communication and control interfaces that are accessible to all people, regardless of their ability and communication preferences.

However, developing accessible AVs will require automotive designers to reconsider how people interact with and control a vehicle. As stated by Riggs and Pande "*simple acts of getting in and out of the vehicle might pose difficulties for people with disabilities.*" [32, pg. 2] Accessibility needs to be fundamental to the design of new AVs and AV services. This includes interactions such as controlling doors and ramps, setting a destination, adjusting climate controls, seat positions, and windows, requesting assistance, and asking the vehicle to make small adjustments such as pulling up to a different spot on the curb upon arrival at the destination. These requirements and the motivation to serve people with varying physical or sensory disabilities provide new opportunities for the design of inclusive automotive user interfaces.

Recently, the automotive user interface community has developed a focus on accessible AVs through inclusive mobility design workshops [17, 36] and projects that develop AV interface designs, such as for people with autism spectrum disorder [31]. Recent interface design examples include accessible center-stack displays [7, 25]. Previous works have also suggested that smartphone applications and their accessibility features can provide inclusive interfaces for people with disabilities to interact with autonomous vehicles [2, 11, 19, 25]. However, there is limited work designing a detailed smartphone application that supports accessible interaction throughout the end-to-end trip experience and prototypes the interfaces to a high degree of fidelity. Moreover, while prior works often engage people in a small number of co-design sessions, working with people with disabilities throughout a long-term design process over many months can allow more opportunities to discover new user needs through iterative design discussions and allows people with disabilities to provide more guidance on the designs of new interfaces for accessible interaction with AVs.

In our work, we take a *research-through-design* approach [39] to explore new design concepts for accessible mobile interfaces for inclusive AV interaction. We use a co-design process that includes 20 interviews with people with physical and sensory disabilities and transportation advocates, 12 monthly online community meetings, and design prototyping activities to surface new needs around accessible interfaces for autonomous vehicles. Our work contributes to the growing literature around people with disabilities' needs for AVs, strengthening previous findings and documenting new needs across the end-to-end trip experience. Our work also contributes high-fidelity design concepts that address users' needs for control, confidence, and situational awareness in AVs. Finally, we provide reflections on a long-term co-design process that other designers may build upon when creating accessible automotive user interfaces.

2 RELATED WORK

2.1 Autonomous vehicle perceptions

As AVs become technically feasible, understanding perceptions on their utility and safety is important for designers to consider when creating new AV interfaces. Among the general driving population, early work from a 2014 survey of drivers in the US, UK, and Australia found that people were relatively optimistic about AVs but have significant concerns about their safety and security [35]. In more recent work, Hewitt et al. [23] developed the Autonomous Vehicle Acceptance Model and found concern about the safety of highly autonomous vehicles. In addition to the general driving population though, it is necessary to characterize people with disabilities' perceptions so that such designs are inclusive.

In a survey of 516 people with visual impairments, Brinkley et al. [11] found that the respondents were generally positive about AVs but concerned about safety. Kassens-Noor et al. [27] provide an excellent review of previous work (see Table 1 on pg. 388), showing how opinions differ between people with different disabilities. People with mobility impairments, for example, viewed AVs more negatively [5] than those with non-motor disabilities [28]. Kassens-Noor et al. further explore this difference through an intercept survey of bus riders, with 40% of the respondents having some disability, finding that people with mobility impairments reported less willingness to use an AV compared to people with visual impairments [27]. In contrast, Cordts et al. [15] found that people with physical disabilities were generally positive about AVs assuming that they were accessible. In general, research on people with disabilities' perceptions of AVs suggests that they think AVs could increase mobility, but that they have reservations about safety and accessibility. Our work seeks to understand people's perceptions and design AV interfaces specifically for their accessibility needs.

2.2 Accessibility Needs for Autonomous Vehicles

Prior work has explored people with disabilities' mobility needs to inform how AVs and AV interfaces can be designed to be more inclusive, centering on the needs for control, awareness, and accessible interfaces. Foundational work by Brewer & Kemeswaran [9] highlights people's *need for control* of their experience as a key to enabling independent mobility for people with visual disabilities. The authors further their understanding of users' needs around the ride experience by describing how aspects of rideshare services—drivers helping passengers in and out of vehicles or drivers leaving vocal turn-by-turn directions on to let people know where they are on the route—help disabled users build trust, confidence, and independence in their mobility [10]. These core ideas of control and confidence are found in other areas such as the desire of riders to choose their preferred route [12].

Previous work has also found that helping people maintain awareness during an AV ride will be important to foster trust and confidence in the ride. Surveying people with vision impairments, Brinkley et al. [11] found that people were concerned about traveling in an AV without knowing their immediate surroundings. Respondents also mentioned concerns about the AV leaving them before they had confirmed that they were in the right location. In separate works, Brewer & Kameswaran [10] and Carvhalo et al. [12] highlight people's desire for situation awareness cues, such as by announcing landmarks along the route.

Across various studies, people with disabilities express the need to receive information and control the vehicle through various means. Work from Amanatidis et al. [2] suggests that conventional multimodal interfaces (with which users probably have experience) would lead to more inclusive and accessible AV interaction. Huff et al. [25] highlight the need to consider interface controls, specifically using different modalities such as speech and touch, and to control vehicle interfaces from the backseat during a ride. The authors also suggest opportunities for mobile app interfaces that include multiple input modalities [25]. Brinkley et al. [11] show similar findings with their participants, suggesting a desire to use smartphones to control and communicate with an AV. In addition, Carvalho et al. [12] distilled from focus groups, interviews, and co-design sessions a hierarchical set of user needs that placed the personalization of the AV interfaces as a top priority. Such personalization can be realized by using people's personal smartphones where they have enabled their preferred accessibility features. Throughout these examples, opportunities for smartphone-based interfaces are echoed and suggest that the smartphone should be considered in accessible interactions with AVs as they provide visual, audio, and haptic interactions and leverage existing accessible technologies familiar to many people with disabilities [19]. Our work looks to build on these suggestions and develop a smartphone-based application in detail to enable control of and facilitate confidence in AVs.

2.3 Design Engagements with Disability Communities

Our community workshops draw on accessible participatory design approaches. Participatory and co-design methods aim to center the perspectives of those least likely to have their voices heard or their needs met by traditional design processes [30, 34]. Non-designers offer the expertise of their own lived experience to meaningfully inform design outcomes. Previous research in the space of accessible participatory design has focused on developing service robots to interact with and guide those who are blind and low vision through a building [3], designing assistive smart devices with children with autism [20], imagining socially assistive robots with older adults diagnosed with depression and their therapists [29], and building an augmentative and alternative communication (AAC) device for nonverbal communication [38]. Other work makes methodological contributions centered on ensuring that those with disabilities drive the design process [16], given the known power discrepancies between the researcher and the subject [37]. Galliers et al. [21], for example, describe employing people with aphasia as consultants who participate in game-playing activities and hands-on prototype interaction.

Building on this tradition, there has been a growing body of research taking up participatory methods to examine the needs of people with disabilities in the context of AVs. Dicianno et al. [18] conducted a systematic review of the scientific literature on autonomous vehicles for people with disabilities and found that there is an unmet need to focus on the entire travel journey and to approach the engineering process in an inclusive way, considering the needs of diverse disability groups. Their work argues that accessibility for autonomous vehicle interaction should be considered during the design and development phase. As an example, Brewer & Kemeswaran [9] led a series of focus groups with 15 people with vision impairments, with each session including a design component that asked participants to develop voice-based and tactile solutions for using an AV. Participants explored ideas like conversational route planning and orientation systems, but also highlighted concerns over whether the controls would work consistently in such a high-stakes collaborative human-machine operating environment. Colley et al.'s work [13, 14] focuses on addressing the lack of inclusive design for external vehicle communication. They conducted a workshop with people with visual impairments focused on vehicle-pedestrian communication [13], learning that high content messaging and communication between vehicles is preferred. Huff et al. [25] describe the participatory development of a low-fidelity prototype of a HMI for AVs with a visually impaired co-designer. Carvalho et al. [12] similarly drew out a set of user needs and design concepts for a mobile app and an external HMI from their co-design engagements with older adults and blind and low-vision users, focusing on developing accessible autonomous ridesharing experiences through what they call an ecosystem of technologies (e.g., a mobile application, a web application, an in-vehicle human-machine interface, an external human-machine interface, and the vehicle interior design). Extending this research, we present a long-term participatory study leveraging mobile technologies to establish standards of control across AV vehicle types with and for users with a diverse set of disabilities. We chose to do a long-term participatory engagement to involve community members throughout the app design process and position them as active members who can suggest ideas and critique the design over time. Extended engagement also gives community members more control over the final design outcomes [6]. Furthermore, a long-term deployment matches the timeline of a full, high-fidelity app design project and would allow our team time to determine needs and design numerous features across the entire trip experience (e.g. ordering, boarding, riding, existing, rating).

3 METHODS

Our team began by convening a group of disability and transportation advocates in a year-long series of online group meetings to develop our core concept for a smartphone app-based communication and control system to allow people with disabilities to independently take autonomous vehicle trips. Community members were recruited via an email advertisement sent by our University Transportation Research Consortium whom had many connections with local community members. In parallel with our community meetings, we also conducted a series of individual interviews with 20 people with disabilities and transportation advocates to understand their current mobility challenges and thoughts on future AV services. The results of both the interviews and community meetings informed our design prototyping.

3.1 Online Community Meetings

We convened 12 monthly community meetings with a set of invested wheelchair users, people who are blind or have low-vision, and transportation advocates for people with disabilities and older adults located in the US. Community members were initially recruited via an email advertisement sent by our University Transportation Research Consortium. Community members also invited people from other organizations that they were members of to participate as interviewees or as community meeting members. A number of interview participants joined later community meetings. Community meetings ranged between 8–15 attendees and included people with different disabilities. Meetings were held online over Zoom video conference and lasted 1 hour each on a weekday during times when a majority of community members could join. The meeting time was updated quarterly based on community member and design team member preferences.

The primary objective of each meeting was to discuss features of the smartphone application and to receive feedback on the design concepts. The first author acted as facilitator during meetings and began each meeting with a update on what feature designs had been completed and what features were scheduled to be discussed in the meeting. Presentation slides of the agenda and guiding questions were screen shared. Meetings during the first few months focused on discussion topics ranging from the needs of different users, to the safety and security of autonomous vehicles, to pricing models for autonomous vehicles services. As the design concepts for the mobile application formed, later meetings focused on showing community members the design concepts and receiving feedback. Student design team members led discussions around the application interfaces. Design sketches and mockups were presented using screen sharing and verbally described. Community members observed the demonstration and gave verbal or written feedback. The student facilitator also could simulate a user test by asking people to speak out what they would press on the screen or say to a voice system and then control their local copy of the prototype to show the app's proposed response. Our typical meeting agenda had iterations of features discussed in prior meetings shown to confirm appropriate changes had been made before moving on to discussion around new features. Across all meetings, design team members wrote notes on people's feedback and proposed design changes in a shared document and, when relevant, annotated the design concept directly in the app design tool, Figma.

3.2 Individual Interviews

Our team conducted individual semi-structured interviews with 20 people (10 M, 10 F; aged between early 20's – mid-70's). This included 14 people who are blind / low-vision, three wheelchair users, two advocates for accessible transportation, and one person with arthritis & diabetes. Interview participants were recruited from our first three community meetings and through snowball sampling. The interviews were conducted over online video conference and lasted 45–60 minutes. Participants reviewed a voluntary informed consent form prior to the interview and gave their written or verbal consent. Each interview was recorded and machine-transcribed to help accurately capture participants' thoughts and support qualitative analysis. The participants volunteered without compensation.

The objectives of the interviews were to learn about people's experience with current transportation before, during, and after their ride, their thoughts about autonomous vehicles, and to gain feedback on initial ideas for the design of a smartphone app interface to interact with autonomous vehicles. The study team used affinity diagramming to review and make sense of the interview transcripts, drawing out themes related to mobility challenges, perspectives on autonomous vehicles, and feedback on the smartphone app design concepts. These themes were used to define a set of needs for the smartphone control and communication app and served as inspiration for the initial design.

3.3 Design Prototyping

Our iterative design prototyping complemented interviews and community meetings as a way to understand the needs of people with disabilities and the requirements for a smartphone app for independent mobility in autonomous vehicles. The design team consisted of 28 student designers and four faculty advisors. The 28 students worked in phases throughout the project timeline (due to graduations and shifting student responsibilities). Students worked in subteams focused on touchscreen interface design, voice design, user research, and testing. The team also worked with an industry partner, Propel IT, who supported the team with one project manager and two app developers. During the early stages of our design work, the team used storyboards to explore different user scenarios and possible interface ideas such as unlocking and opening doors, checking their current location on the road, opening windows, and being notified of technical issues with the car. The app features and user flows were broken into five main phases:

(1) On-boarding & personal settings
(2) Ordering a ride
(3) Pickup & boarding
(4) During the ride
(5) Drop off & exiting the vehicle

Detailed app features were created for each phase and were categorized as elements for controlling car/ride features such as requesting a car, opening doors, and changing climate controls or for communication and information, such as alerting the rider to issues at a pickup location or providing details about the ride such as speed, direction, route, and local landmarks. As screens were developed, style guidelines were developed to define accessible elements such as typeface, buttons, sliders, and informational text.

Touchscreen prototypes were developed in Figma[1], a collaborative online design tool that allows the creation of graphics and simple interactive prototypes. The interactive design prototypes were then developed into functional applications for Android and iOS to test on-device interactivity and, importantly, screen reader interactions using Android TalkBack and iOS VoiceOver. Prototyping of voice user interface concepts was done using Voiceflow[2], an online tool to create tree-based voice interfaces. The touchscreen and voice user interface prototypes went through two major design iterations, where the first iteration helped to define the major features and interaction modalities, and the second iteration focused on refinements to specific interaction interfaces. As part of the design work, our team performed internal accessibility audits based on checklists from the Web Content Accessibility Guidelines (WCAG) 2.1[3]. These audits were done to find well-known accessibility issues, such as low-contrast or color issues, text size issues, and text alternatives for image-based interfaces.

4 FINDINGS ON USER NEEDS

We include our findings from both the interviews and the community meetings together as critical user needs were discovered during both activities. An important aspect of *research-through-design* is that many user needs findings can come to light when a design concept is presented to a user, allowing them to engage with the idea and imagine the preferred future that it may bring [39]. Our findings first highlight the current mobility challenges facing our stakeholders and their perceptions and opinions on autonomous vehicles in general. We then document more specific needs regarding the various stages of independently riding in autonomous vehicles, including pickup and boarding, in-car information and controls during the ride, and drop off and exiting.

4.1 Current mobility challenges

Many disabled people must endure inconvenient situations when traveling by road. Of the people we spoke with, only two wheelchair users had their own vehicles with modified controls that allowed them to travel independently. The other wheelchair users and blind & low-vision participants we spoke with relied on car rides from family and friends, shared ride services (Uber/Lyft), accessible paratransit, and public transportation. Car rides from family and friends were generally viewed positively, but were seen to provide less independence than other modes. Across other services, blind/low-vision users and wheelchair users used different mobility options at different times. Blind / low vision participants reported using mixed public transit, paratransit, and ridesharing services such as Uber and Lyft to meet their travel needs. However, wheelchair users only reported using wheelchair accessible paratransit and public transit. We discuss the challenges across these services and associated user needs for accessible AV services.

4.1.1 Challenges with rideshare services. Among the wheelchair users we spoke with, none had used a rideshare service as there

[1]https://www.figma.com/
[2]https://www.voiceflow.com/
[3]https://www.w3.org/TR/WCAG21/

were no accessible vehicles in their cities[4]. Thus, wheelchairs users felt they were kept from independent mobility via ridesharing due to lack of availability, despite many stating they would value the option.

While blind/low-vision users reported fewer issues with accessing ridehsaring services, interviewees and community group members who traveled with guide dogs did report being turned away from shared ride services on occasion. Although drivers are legally required to allow guide dogs, our users noted drivers likely did not want to take on the burden of cleaning from allowing a dog in their vehicles. Users discussed filing complaints with service providers, receiving refunds, and rebooking rides, which affected their travel timeline and caused frustration at being denied service despite legal protections. From these findings on challenges with rideshare services, we identified the need to know that there are adequate vehicles available and that they will not be denied service based on their use of animal support or assistive devices.

4.1.2 Challenges with paratransit service. While many users appreciated accessible paratransit, they also reported challenges and frustrations with services in their area. One specific challenge raised by many was that paratransit trips must be scheduled 24 hours in advance. This reduced flexibility and spontaneity in their travel and required them to plan well in advance. The 24-hour requirement also meant that users could not rely on these services for urgent matters where they would need a ride in a few hours.

Long trip times and variable drop off times were also reported as common frustrations by participants. As paratransit services in users' region were shared wheelchair accessible vans and minibusses, a trip often required multiple pickups and drop-offs throughout a ride. People reported trips that were highly variable in length and somewhat unpredictable, with some lasting multiple hours even though the distance traveled from the start to the end point would take significantly less time as a direct trip. Users reported having to plan to arrive at an appointment over an hour early to accommodate for the variability in travel time. Unfortunately, people also reported that even when planning in extra time to arrive, they might be late anyway. Such issues turned seemingly simple trips for something like a haircut or visiting a friend into an almost full-day event. Furthermore, such variability reduced the control people felt they had over their mobility. Although paratransit is a critical form of accessible transportation, users reported the need for more dynamic and spontaneous travel. Based on challenges in trip planning, users sought ways to estimate their trip time and help them get to their destinations on time. In general, users emphasized the need to have more control over their mobility.

4.2 Perception of autonomous vehicle services

Overall, interviewees and community group members were optimistic about AVs and their ability to provide more flexibility and control in their travel. Users spoke about AVs taking them directly to their final destination (unlike public transportation) and taking more trips for enjoyment, such as to recreation centers, to see friends and family, or even just to enjoy the experience of driving, such as on a winding road. Having said this, many participants also had reservations about the safety of AVs. Users wanted to know how the vehicles would be proven safe and how they could trust that the vehicles would not be susceptible to hacking. Although our design work assumes that AVs will be safe and that digital communications will be secure, we note that such concerns are important to address as part of the total AV experience. For the purposes of our mobile application, we took comments on safety, trust, and assurance to further motivate the need for riders to understand what was happening during the ride and to have clear communication about the state of the ride and the vehicle.

4.3 Autonomous vehicle trip needs

We had many discussions with community members and interviewees about their needs before, during, and at the end of a ride in an autonomous vehicle—with particular focus on how users could receive support if there was no driver to help them.

4.3.1 Before the ride. Users wanted to set their preferences to ensure that they would receive a vehicle that is appropriate for their needs. Wheelchair users, in particular, discussed wanting to know about a vehicle's ramp width and location (e.g., side or rear ramp), the height of the vehicle, and the height of the doorway. Other users stated that they would be comfortable sharing information about their disability with the service, but only if it had the purpose of changing the vehicle interaction (e.g., in-car interfaces). Lastly, users wanted the ability to select their preferred vehicle type (e.g., size). Seeing eye dog users were concerned about knowing that their dog could ride in the vehicle with them and knowing that the seat could be adjusted to let the dog lie on the floor[5]. Conversely, other users noted that some riders might be allergic to dogs or sensitive to strong odors such as lingering food or strong air fresheners.

4.3.2 Boarding. Many users, and particularly blind or low-vision people, were concerned about getting into the correct vehicle. One low-vision interviewee recounted a time when they got into the wrong vehicle at the airport, noting that this is already a problem when many vehicles are similar. Users discussed the need to find the car and ensure that they were in the correct vehicle. Ideas that came up during interviews and in the community meetings included flashing the car's lights, honking the car's horn, and having a QR code that a user could scan to confirm that they were at the correct car. People also discussed modeling current rideshare behavior, where the car could confirm who they are by name. Wheelchair users stated concern about how they would know their wheelchair was secured before the ride, especially without assistance from another person.

4.3.3 During the ride. Users discussed wanting to be informed of route status and diversions. For blind users, having a sense of where they were was important, such as the road they were traveling on or what landmarks were around. Many people noted they often knew a route from the vehicle movement, thus any diversion from the route (e.g., not making a left to go up the hill) would put people at a loss for where they were, reducing their trust in the car and the

[4]At the time of writing, Uber (https://www.uber.com/us/en/ride/uberwav) and Lyft (https://help.lyft.com/hc/e/articles/115013081668-wav-rides#regions) have some drivers with wheelchair accessible vehicles in select cities, however not in the region of our interviewees and community group.

[5]Guide dogs are trained to lay on the floor of the vehicle when traveling.

accuracy of their final destination. Blind participants appreciated when rideshare drivers kept verbal turn-by-turn directions on to help them know the route. Similarly, people discussed wanting to choose which way their car drove so that they could maintain a mental model of where they were going during a drive. Knowing where they were on a route would also help riders avoid accidentally travelling to drop-off locations that may have similar names but be in different areas (e.g., 1st Street vs. 1st Avenue). Overall, people desired information that would provide them situational awareness throughout their drive. Our users also said that they wanted multiple interfaces, such as through screenreader ready touchscreen interfaces and voice controls, for interacting with in-car features. Finally, to feel safer, many of our users desired the ability to signal for help or to pull the car over if needed, such as in a medical emergency or if something seemed wrong with the car.

4.3.4 After the ride. A major concern for our users was knowing about their drop-off location and the state of the sidewalk when they get out of the vehicle. For example, navigating a construction zone or icy sidewalk can be challenging. For wheelchair users, it was important to know if the sidewalk was clear, if a curb cut was nearby, or if there are things blocking the sidewalk such as trashcans or cars parked on the curb. For low vision and blind users similar information would be useful in addition to information about other obstacles, such as bike racks or bollards, that they should navigate around. In some cases, our users wanted the ability to change their drop-off location in the moment. However, users noted that just having the information can be enough to prepare them to navigate safely. From these conversations, we learned that users need detailed information about their drop-off location to help them navigate the sidewalk or to make a decision to choose another drop-off location.

Blind users also discussed needing assistance to their final destination. Many current paratransit services offer door-to-door assistance where a human will help guide a rider to their final destination after exiting the vehicle. Our blind interviewees also mentioned that rideshare drivers would often guide them to their final destination even though this is not required as part of their service. Low-vision and blind users noted that after leaving a vehicle, they will need a description of where to go to get to the destination itself.

5 DESIGN CONCEPT

Our final design concept was driven by users' need for control of their ride experience and to maximize their confidence and independence during their travel. Our design work was guided by a set of key assumptions:

- Autonomous vehicles will operate without any intervention from the passenger (SAE Level 5 Autonomy [26])
- Autonomous vehicles will be safe for passengers
- Most rides will occur in shared ride vehicles
- A variety of vehicle sizes and types are available with ample vehicles having wheelchair ramps available
- Vehicles will have secure digital communications allowing users' phones to communicate with the car interfaces

5.1 Design Principles

(1) **Prioritize control** - Many people with disabilities have little control over their transportation today. While users will not be able to control the car's movements, we can provide control of as many non-driving aspects as possible. Ensure that riders verify when to take the next step in a ride sequence.
(2) **Provide ample information to promote user's confidence** - The application should provide information to give the user a full understanding of the situation and help the user develop confidence in traveling independently. Rather than hide information, allow users to select what information they prefer to receive.
(3) **Provide information to help users understand the surrounding environment** - Offering information about where someone is in the world through various forms can help build confidence in the car's operations.
(4) **Provide multiple interfaces to control features and receive information from the car** - Vehicle control interfaces should be accessible through touchscreen, using a screen reader, and through voice-based interfaces.
(5) **Provide a means for users to get assistance** - Helping users feel more in control includes knowing that they can get help if needed. Provide interfaces for requesting assistance.

Below, we discuss the key features that our team designed with community members to make AVs accessible. Key accessible interface features are shown in Figures 1A-L and the full app design is provided in Appendix A in the supplemental materials.

5.2 Before the ride

5.2.1 Vehicle selection settings. Riders can set parameters to ensure that an AV service will match them with an appropriate car, shown in Figure 1A. Toggle switches allow users to select support handles, low-height vehicles, wheelchair accessible vehicles, mobility scooter mounts, and preferences for pet-free vehicles [6]. Wheelchair users in our community meetings helped define parameters to ensure that a wheelchair-accessible vehicle could accommodate their wheelchair including settings to define their wheelchair as manual or powered, set the ramp width, and define the height of the door opening (detail shown in Appendix A, Figure 1).

5.2.2 Route selection and time estimates. To give riders control over the drive, our app allows them to choose the route they would like to take, shown in Figure 1B and Appendix A, Figure 2. While many rideshare services assume that riders may not care about their route, providing disabled users with control allows them to better know how they will get to their destination. This is especially important for blind users, who may rely on the turns of the vehicle to help them know where they are along a route. Selecting a preferred route can also give users confidence that they are going to the right location. As part of route selection, estimated arrival times are provided as an important feature for disabled users who often

[6] Pet-free vehicles were somewhat contentious among the group as people with seeing eye dogs worried they could be denied service, however others in the group were allergic to dogs. This feature should be considered a preference and not a hard filter. People with seeing eye dogs should never be denied service; however, if a fleet has some cars reserved as pet-free, then these might be sent first if available.

use ride services that cannot accurately estimate their trip time. Trip estimates allow our users to feel confident that they will reach their destinations on time.

5.2.3 Accessible pickup checking and adjustment. Because not all locations allow riders to board easily (particularly for wheelchair users), our team and community group also considered a feature that could alert a user that their location may not be accessible, and could suggest more accessible pick up locations such as a curb cut within half a block of the user, shown in Figure 1C and Appendix A, Figure 3. We imagine that such a feature could be enabled based on 3D maps that include curb cuts and loading zone areas and crowdsourced through rider feedback [33] (see Section 5.5.3).

5.3 Boarding

5.3.1 Find and confirm vehicle. The app provides multiple ways to help riders confidently find and confirm the correct car. Our community group suggested buttons to flash the car's lights, honk the horn, shown in Figure 1D. Riders can also scan a QR code on the side of the vehicle, shown in Appendix A, Figure 4.

5.3.2 Opening doors, deploying a ramp, verifying departure. To give users control over their boarding, we designed an interface to allow users to select and open any door, shown in Figure 1E. During community meetings, users discussed putting groceries in the trunk or opening the door for other passengers as important. For users with a ramp-equipped vehicle, the app indicates where the ramp is located with a wheelchair icon. As the ramp deploys, the progress is shown and a schematic view indicates where users can safely wait, shown in Appendix A, Figure 5 "Boarding - Opening". After the users have boarded, the app shows that any wheelchair harnesses are secured via a check mark. When the user is ready, they press a button to close the doors, Appendix A, Figure 5 "Boarding- Confirm". To begin the ride, users *press* and *hold* a "start ride" button, adding an extra layer of assurance that the rider is ready to have the car drive away, shown in Appendix A, Figure 5 "Start Ride".

5.4 During the ride

5.4.1 Ride information for situation awareness. To help riders feel confident during the ride, the interface provides information to support their situation awareness. Spoken and visualized turn-by-turn directions allow riders to keep track of their journey. Major landmarks are shown periodically to provide users anchors to where they are, shown in Figure 1F. A box with speed and cardinal direction is provided on the top left of the screen and is screenreader accessible so blind users know they are heading the correct way. Any trip updates such as changes in estimated time to arrival are communicated immediately. Finally, a 360° camera button in the lower right of the screen opens a view from the vehicle's cameras to gives riders, especially those with mobility limitations, the ability to see around the outside of the vehicle and situate themselves (see Appendix A, Figure 6 for detailed screens).

5.4.2 Touchscreen vehicle interface controls. Since users may not have physical access to in-car controls such as heating and cooling, windows, seat controls, and lighting, we provide access to these features via the "Control Panel" button shown during the ride in Figure 1F. This opens a panel with the car's state and buttons along the bottom of the phone to control climate, windows, lighting, and seating, shown in Figure 1G. Users first choose what they want to control, which seat they would like to control, and then specify the settings using screenreader accessible buttons or sliders, such as the example slider to control the fan speed shown in Figure 1H. Most controls are placed closer to the bottom of the phone to allow easier access. Appendix A, Figures 7 & 8 show details of controls for climate, windows, seating, and lighting.

5.4.3 Voice-based vehicle interface controls. A microphone button located on the right edge of the Control Panel, shown in Figures 1G & 1F, allows users to give voice-based commands such as "*raise the temperature,*" "*change the fans to feet and head,*" and "*roll down the front windows.*" Community members requested voice features be available even when not holding their phone by using a wake word (e.g., "*Ok, Google*" or "*Hey, Siri*"). Through lightweight testing during our community meetings, we developed a structure where voice commands could include all the information ("*Turn my seat warmer on high*") or could expose information and help users fill in details (Rider: "*Change the temperature*", App: "*OK, what temperature would you like to set to?*", Rider: "*70 degrees*").

5.4.4 Emergency actions. A key aspect for making people feel confident riding in an AV was knowing that they could get help, pull the vehicle over, or report issues with the vehicle during the ride. An "emergency actions button" is placed on the lower left of the ride detail page (Figure 1F). Pressing the button gives riders quick access to emergency actions, shown in Figure 1I. Each item includes a reiteration of the action to be taken and button-based confirmation to help riders avoid accidentally activating an emergency response, shown in the lower part of Figure 1I and in Appendix A, Figure 9. We envision these features to connect to outside services such as the AV service provider or first responders via a phone call or through text message depending on the rider's preferred form of communication.

5.5 Ending the ride

5.5.1 Identifying drop off point issues and rerouting. Users wanted the car to avoid obstacles such as construction zones, icy sidewalks, or walkways in disrepair at the drop off. We imagine that an AV can use its sensors to identify these hazards and the app can provide a visual alert of the issue, shown in Figure 1J. Users can also use the 360° camera button in the lower right of Figure 1J to look outside the car to view the sidewalk before opening the doors. If the user deems the location to be difficult to navigate, they can choose a new drop-off location, shown in detail in Appendix A, Figure 10.

5.5.2 Exiting the vehicle. Once users reach their destination, they can control when to open the doors. This gives them time to collect their belongings and get ready to exit. A wheelchair ramp will be deployed if equipped on the vehicle and used by the rider (see Appendix A, Figure 11 for details.) The application then waits for the rider to verify that they are done with the ride and that they are comfortable with the car leaving by using the the "End Ride" confirmation button in Figure 1K. We discussed this sequence throughout community meetings and interviews and designed the interaction to ensure that the rider knows they are in the right place before the car departs. One motivating story for this feature was told by a blind user whose rideshare driver dropped them off a block away from their house but drove off before the rider noticed.

5.5.3 Feedback on ride and drop off. Once the rider has confirmed the end of their ride, they are presented with a feedback page, shown in Figure 1L. Although collecting feedback on service quality is common practice, the community group came up with a feature to rate the drop-off location to help other riders find accessible pickup and drop-off locations (based on their own accessibility needs). A rider can also report issues such as poor sidewalk conditions or obstacles via a free response input. We imagine that over time such data can help map accessible pickup and drop-off locations and can be used by municipalities to improve the accessibility of sidewalks.

6 DISCUSSION

6.1 Extending the foundation of needs for accessible AVs

Similar to prior work on people with disabilities' perception of AVs [15], we found that the people we spoke with were generally optimistic about the prospect of AVs contributing to increased mobility for people with disabilities, though many had reservations about safety and security [11, 23]. One of the most important findings that we replicate and extend to include people with visual or mobility disability is Brewer & Kemeswaran's [9] identification of *control* as a key element in promoting accessible interaction. Our work adds further justification for prioritizing control by people with disabilities as a key element of accessible design for AVs, and suggests even simple design elements like adjusting interior climate settings, selecting route options, and verifying when to move forward in the ride process can foster more confidence in the experience with an AV. Through our user engagements and design work, we provide further support for using mobile interfaces as an accessible and desirable way to interact with AVs [2, 11, 19, 24]. Our community members were generally positive about smartphone interfaces because of their current accessibility and familiarity [12].

Our needfinding replicates findings around supporting users during the beginning and end of their trip [10] in ways similar to how rideshare or accessible paratransit works today, such as helping people get to accessible pickup and drop-off points. We also find that providing information to support people's situational awareness [8] was discussed as an important aspect for inspiring trust in the vehicle. A key feature co-designed here was providing information on local landmarks alongside turn-by-turn directions (see Figure 1F and Appendix A, Figure 6), similar to ideas expressed in [10, 12]. Furthermore, our community group helped identify new features to support situational awareness, such as providing 360° camera access from the car (accessed via a button in Figure 1F) and alerting riders to obstacles at pickup or drop-off locations (see Figures 1C & 1J).

Finally, our work highlights building confidence through accessible means of assistance as a primary design feature. As with prior work showing safety to be a primary concern for people with disabilities [23, 28], we too had many discussions with community group members and interviewees around safety. Together, we designed a set of emergency actions (Figure 1I) that would allow riders to know they could request help and pull the vehicle over. While our group discussed that such features hopefully would not be used often, consideration for adverse events was an important aspect of providing users with a feeling of control of their ride experience and could help address the need to feel safe throughout a ride.

6.2 Reflections on co-design processes for inclusive design

Our long-term engagement with invested stakeholders builds on the growing set of research using participatory design approaches to develop accessible AVs [9, 12–14, 25]. Hosting entirely online sessions was generally more inclusive for our participants, as many have mobility challenges making in-person events harder to attend. Online engagement allowed people from different communities outside of our city to join us and provide perspectives on mobility in different areas. Long-term, repeated interactions with the group also contributed to a sense of conviviality and an openness to share opinions during the meetings as people began to get to know each other. By engaging over many iterations and seeing the design evolve, our community members could take more agency in guiding the design. Over time, they began to directly suggest changes to the visual and interactive elements, for example defining certain controls to be buttons or sliders or describing where information displays should be placed on the screen. We found that quick prototype testing with design artifacts led to increased identification of new needs and deeper discussion around new accessible design concepts. Our meetings also often featured debates among community members about how a feature might be designed or what information was important to share. Furthermore, people began to empathize with each other and think about features for one another based on their abilities (e.g., a wheelchair user considering how a blind user might navigate the sidewalk). Overall, other design groups should consider maintaining long-term relationships to help community members engage deeply and collaboratively guide design outcomes.

Our long-term engagement was not without it's challenges. On occasion, a design team member did not sufficiently describe a visual design, making it hard or impossible for a low-vision or blind community member to understand. As these community members became more comfortable with our team they would often ask for more description, however some members may have felt they could not contribute to the discussion. Scheduling all community members for a shared time was also challenging and people who missed meetings needed more background on previously made design decisions. While a design team member or a community member could often explain the rationale of a feature, this did require extra time during the meeting, reducing time spent on new design discussions.

Finally, our long-term engagement with the community group allowed the design team to consider other ways to have a collective impact on disability rights. Our community group conversation often brought up topics related to the general design of AV services. This included things like pricing, security, and availability. As our group included people with knowledge on collective action, this led to ideas for the design team to participate in activities such as engagement with local or national policy makers and to share

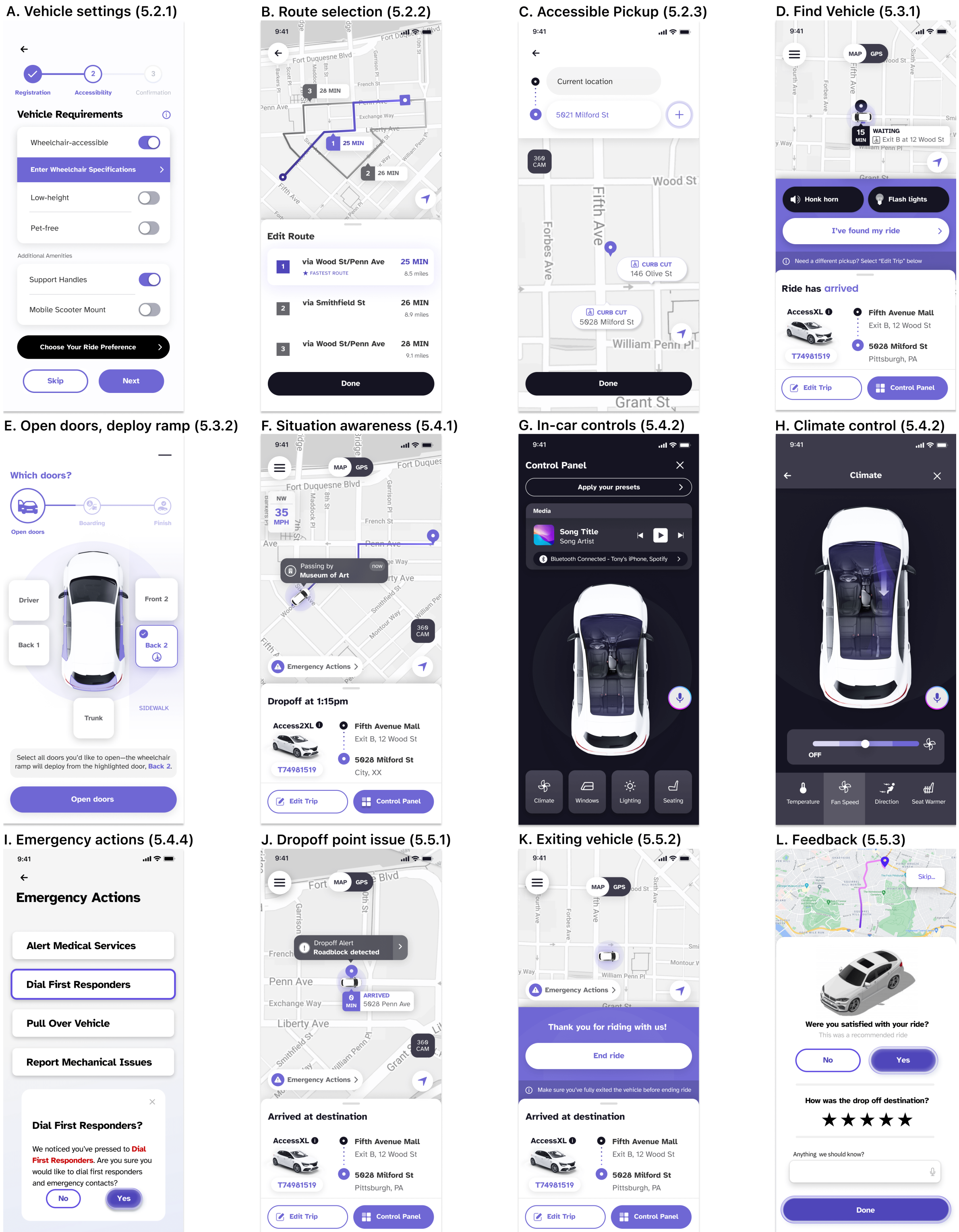

Figure 1: Key app interfaces to allow people with disabilities to confidently interact with AVs as they order a ride, find an accessible pickup location, enter the vehicle, maintain situation awareness on the road, control climate and comfort settings, and end the ride.

knowledge on our processes with other advocacy organizations working on new mobility technologies.

6.3 Limitations & Future Work

While our work made strides to include people with varying disabilities, more perspectives are needed. Our interviewees and community members were predominantly blind, low-vision, or wheelchair users excited about AVs. Future work should include more people with hearing disabilities, cognitive disabilities, and multiple disabilities. Furthermore, our community members lived mostly independently. However, there are more opportunities to consider *interdependence* as a key feature of accessible design [4]; future work should include the voices of people who need support from another person during daily tasks, as well as caretakers.

From a design perspective, our concepts were limited to accessibility features of mobile devices, though there are opportunities to further explore accessible in-vehicle interfaces. Novel interface design could serve as an important backup if a smartphone interface is not available. Furthermore, while the speech-based system flows may be conceptually accessible, many speech-to-text systems are not suited for those with accents or with a speech impediment. Thus, speech-based systems will remain limited to the technical capabilities of the speech-to-text engine.

Finally, our online sessions and the choice of design tools sometimes limited our ability to receive design feedback during community meetings. For example, Figma does not produce screen reader-ready designs, and we were limited to developing working apps to test these functionalities. This slowed our progress and concealed issues that would have likely been found through quick iteration and testing. We had similar issues with the voice prototyping platform, Voiceflow, finding that the speech-to-text capabilities were not accurate. Instead, we simulated testing with a human over video conference. Designers looking to employ long-term engagements with people with disabilities should consider using tools that allow for early prototype testing that still leverage accessibility features such as screen readers or voice input.

7 CONCLUSION

Automotive user interface designers should take an accessibility-first approach to ensure that autonomous vehicles deliver on the promise of independent mobility for people with disabilities. Our collaborative *research-through-design* work provides an example of an inclusive design process that helped extend our knowledge of people with disabilities' needs for confident control over their ride experience and generated concepts for accessible smartphone-based communication with AVs. This work offers designers insights from our collaborative process, as well as concrete needs and high-fidelity design concepts co-developed with community members to enable more independent mobility for all.

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