Journal of Urban Technology

ISSN: 1063-0732 (Print) 1466-1853 (Online) Journal homepage: www.tandfonline.com/journals/cjut20

Increasing Access to Transit: Localized Mobile Information

Aaron Steinfeld, Leslie Bloomfield, Sarah Amick, Yun Huang, Will Odom, Qian Yang & John Zimmerman

To cite this article: Aaron Steinfeld, Leslie Bloomfield, Sarah Amick, Yun Huang, Will Odom, Qian Yang & John Zimmerman (2019) Increasing Access to Transit: Localized Mobile Information, Journal of Urban Technology, 26:3, 45-64, DOI: 10.1080/10630732.2019.1614896

To link to this article: https://doi.org/10.1080/10630732.2019.1614896

Published online: 01 Jul 2019.

JOURNAL OF URBAN TECHNOLOGY
2019, VOL. 26, NO. 3, 45–64
https://doi.org/10.1080/10630732.2019.1614896

Routledge
Taylor & Francis Group

Increasing Access to Transit: Localized Mobile Information

Aaron Steinfeld [a], Leslie Bloomfield[a], Sarah Amick[a], Yun Huang[a], Will Odom[a], Qian Yang[b], and John Zimmerman [b]

[a]Robotics Institute, Carnegie Mellon University, Pittsburgh, United States; [b]Human-Computer Interaction Institute, Carnegie Mellon University, Pittsburgh, United States

ABSTRACT
While several studies note the challenges that people with disabilities face when using public transit, little work has investigated how mobile transit information apps affect accessibility. To address this gap, we recruited transit riders who are blind, who have low vision, who use mobility devices, and who have no disabilities. We asked them to use a transit information app, *Tiramisu*, for 21 days during their regular travel. We observed participants struggling with a number of barriers that had previously been reported. However, the localized transit information also removed barriers to travel; we observed participants engaging in less preplanning and more opportunistic travel. We also identified new opportunities to improve transit use through mobile information.

KEYWORDS
Disability; transit; mobile; crowdsourcing; field study

Introduction

Improving access to transit for people with disabilities presents a wealth of opportunities for emerging technologies to help people live independently, gain and maintain employment, and experience a better quality of life (Livingstone-Lee et al., 2014; National Council on Disability, 2015; Steinfeld et al., 2017). While much of this research has focused on addressing the needs that arise from individual disabilities (e.g., Carmien et al., 2005; Guentert, 2011; Landau et al., 2014; Livingstone-Lee et al., 2014; Sánchez et al., 2013; Tomitsch et al., 2008), some research argued for improving transit through the use of universal design, a design philosophy that encourages developers to create services that benefit users both with and without disabilities. Universal design is "the idea of crafting the built environment to reduce the undesirable impact of real and metaphorical barriers in order to facilitate social participation" (E. Steinfeld and Maisel, 2012: xi).

Previous research shows that poor access to information poses significant barriers to transit, especially because people with disabilities are less adaptable to problems in the environment (Livingstone-Lee et al., 2014; National Council on Disability, 2015; A. Steinfeld et al., 2012). The rapid adoption of smartphones has given rise to a host of transit information apps that provide immediate access to transit information. Most use the current time and the phone's location to reduce the returned data to include only

CONTACT Aaron Steinfeld steinfeld@cmu.edu Robotics Institute Carnegie Mellon University, 5000 Forbes Ave, Pittsburgh, PA 15213, USA.

information about the immediate area, reducing users' efforts to find the information they most likely want. These apps may provide new opportunities for universal design to address transit barriers, thereby increasing accessibility.

Our work investigates how transit apps, and the information they provide, might lower such barriers. Our study had two goals. First, we wanted to understand the impact of transit apps that localized information. Second, we wanted to identify design opportunities for smartphones to lower accessibility barriers, via universal design or disability-specific designs, across the entire "travel chain" (Iwarsson et al., 2000) from planning, to boarding, to disembarking, to arriving at the desired destination. To this end, we conducted a field study with transit users who had visual impairments, mobility disabilities, and no disabilities. We asked them to use a transit app called *Tiramisu* for three weeks, after which we did ride-along interviews in which we took the bus with them as they demonstrated and recounted the impact of the localized transit information.[1]

In this paper, we provide an overview of the literature, study details, findings that replicate previous studies, and findings that are novel to this study. Finally, we provide a discussion of opportunities for smartphones to support accessible transit. The latter should be viewed as a continuum of inclusion because people with certain severe disabilities are unable to travel independently even with significant assistance from a smartphone.

Related Work

Research on accessible transit generally falls into one of two categories: (1) formative research using surveys and focus groups, or (2) novel technical systems. Researchers have investigated the needs of many types of transit users, including deaf, blind, deaf-blind, cognitively impaired, mobility impaired, and elderly/frail individuals (e.g., Azenkot et al., 2011; Barbeau et al., 2010; Mitchell and Suen, 1998; A. Steinfeld et al., 2010; E. Steinfeld et al., 2010). We found the three groups most often addressed by the accessible transit literature were people with visual, mobility, and cognitive disabilities.

The formative research generally focuses on identifying barriers to successful use of transit services; however, many of the novel technical papers also detail barriers. The National Council on Disability's 2015 *Update* offers a synthesis of many studies and provides one of the most complete reports of barriers across the United States (National Council on Disability, 2015). The report notes that, between 2005 and 2015, the number of people with disabilities using public transit increased faster than the number of people without disabilities. It attributes this increase to changes made by many transit services, such as annunciators that announce and display the name of the next stop and new bus designs that better accommodate mobility devices. Continuing barriers it lists include:

- *Getting to stops*: due to infrastructure such as missing curb cuts and sidewalks, or due to temporary changes like construction
- *Boarding*: due to buses passing by without stopping, non-functioning ramps/lifts, buses that did not identify themselves to riders who are blind when stopping, or buses that did not have space to take on and secure a mobility device

- *Disembarking*: due to non-functioning annunciators and/or drivers who did not announce stops, or drivers who did not remember a passenger who asked to disembark at a specific stop when boarding.

The report listed drivers (operators) as a critical failure point due to an unwillingness to follow the rules or due to union contract rules that seemed in conflict with legal requirements. The report encouraged riders with disabilities to keep detailed records of service problems, including the location, time of day, route number, and vehicle number. This seems to be an unrealistic request for many people with disabilities. Interestingly, our review revealed no technical systems focused on addressing drivers as a problem or creating new systems for drivers to help them improve their performance.

Research on transit users with cognitive and visual disabilities notes additional challenges. Studies show that transit services often provide information such as pamphlets that only show entire routes and maps of the whole system. Riders must navigate these artifacts to extract the specific details they need for their own travel, which presents a barrier for many, including those with cognitive disabilities (Carmien et al., 2005). Personal points-of-interest (PPOI) are particularly important to transit users with visual and cognitive disabilities. These users typically memorize a specific sequence of PPOIs that connect their origin to their destination in a set of short, repeatable links (Carmien et al., 2005; Guentert, 2011). Changes, which can arise from construction or a failure to disembark, can move these users away from their PPOIs and have a devastating effect.

Researchers have addressed aspects of these challenges with novel technical systems. To help with planning, several systems generate personalized maps. Two systems displayed personalized routes that address the specific needs of a user (Karimi et al., 2013; Narzt, 2013). Others, focused on riders who are blind, employed embossed diagrams and Braille. These maps could help with planning, and when used for travel, they did not overload a user's aural channel; their hearing remained available to help them find their PPOIs (Azenkot et al., 2011; Landau et al., 2014). Other planning systems focused on audio, even using recorded audio of different locations to help users select general points of interest when planning (Sánchez et al., 2013).

Transit users with visual impairments often struggle to find a specific stop on the sidewalk. Work by Campbell and colleagues (2014) used crowdsourcing to collect more detail on where stops are located and the types of poles used to support bus-stop signs. This helped several participants in their study find specific stops. New work by the *Route2Me* team is testing wireless beacons to provide precise localization at bus stops to address this need (Alvarado et al., 2018). Riders with visual and cognitive disabilities also struggle to know when to disembark, and several studies share detailed descriptions of their coping mechanisms, such as sitting up front and pestering a driver (Campbell et al., 2014). A few systems addressed this problem, including *HapticTransit*, which provided a vibration when it was time to pull the "next stop" cord (Jacob et al., 2011), and *TAD*, a system that alerted riders or their caretakers when they deviated from their planned route (Barbeau et al., 2010; Bolechala et al., 2011).

Need for Replication

One challenge with accessible transit research is recruiting participants who make up only a small percentage of all public transit users and may have a very low frequency of use. For example, research on the impact of low floor buses recorded approximately 1,000 riders boarding and exiting transit vehicles. Of those 1,000, only four had an observable mobility disability and none used a wheelchair (Hwangbo et al., 2015). Because of the challenge in recruiting, many formative studies and technical evaluations are carried out with very few participants (e.g., Chamorro-Koc et al., 2015—one participant; Rodger et al., 2016—four participants; Sanchez et al., 2013—five and six participants; Campbell et al., 2014—six participants). In addition, almost all of the studies investigate only a single metropolitan area that has topographic, infrastructure, culture, and weather properties that do not generalize to other cities. Because of these issues, there is a great need for accessible transit studies that replicate the findings of other studies in different cities and among participants with different disabilities in order to reveal insights and interventions that generalize across transit systems and users.

Transit Information and Universal Design

Transit information apps seem to be a perfect target for universal designs that address the information barrier. Interestingly, a review of 22 transit apps found widespread accessibility barriers (National Center for Accessible Media, 2012), which were primarily centered on poor support for screen-readers. Another review of 159 apps revealed limited support for people with cognitive disabilities (Livingstone-Lee et al., 2014). Only seven of the apps offered valuable features to this user group. Notably, apps developed for a mainstream audience are not uniformly poor. For example, *HopStop* offered an accessible trip-planning option that was also relevant to riders with strollers or suitcases. *OneBusAway* now includes crowdsourced details about transit stop accessibility features (Campbell et al., 2014). Google *Street View* is regularly used by people with disabilities to scout routes ahead of trips, and it has also been used as an information source for crowdsourced markup of bus stop infrastructure details (Hara et al., 2015).

It is sometimes unclear when to incorporate universal design and focus on solutions for all riders and when to make devices and apps for individual disabilities. In the saturated market of transit information apps, design is what sets many apps apart. Positive customer reviews, news articles, and awards often stem from novel design elements or slick interfaces. Animations, creative approaches to support novel interfaces, and heavy reliance on maps can be made accessible, but many developers do not take this step (e.g., National Center for Accessible Media, 2012).

Longevity presents a different problem. Like many other software markets, apps may disappear or lack ongoing support when small development teams shift focus, disband, or get acquired. Apps designed to serve specific disabilities are at additional risk due to their smaller user base and limited revenue opportunities. For example, many of the apps that were reviewed based on their value for users with disabilities are no longer available (e.g., Livingstone-Lee et al., 2014; National Center for Accessible Media, 2012).

Universal design addresses both of these issues. First, highlighting knowledge about successful universal design approaches can help interaction designers serve the needs of people with disabilities when developing innovative information solutions. Second, universal design broadens the user base and therefore limits exposure to the problems associated with small user populations. The more inclusive the design effort, the fewer people whose needs are not recognized or considered (Arenghi et al., 2016).

One approach is to identify transit information that has imbalanced informational value. For example, real-time information has clear value to riders of all abilities and may lead to greater use of transit by the general public (e.g., Brakewood et al., 2014; Brakewood et al., 2015), but it is considerably more valuable to riders with disabilities due to challenges in easily altering travel plans. Related work has shown that people with disabilities emphasize information that supports reliable and timely travel more than people without disabilities do (Verbich and Ahmed, 2016; Waara et al., 2015).

Field Study

Method

To meet our goals, we chose to conduct a field study where we could observe and probe participants on their use of mobile transit apps. We recruited paid participants from three different populations. We included people with visual impairments, including four who were blind (BL) and two with low vision (LV). We also recruited four people who used a mobility device (MD), such as a wheelchair or electric scooter. While only involving these two populations limits generalizability to universal design, we chose to focus on visual and mobility disabilities because these two groups have different information needs and challenges and have also been the focus of much previous accessible transit research (National Council on Disability, 2015). In addition, these two groups were the focus of the design effort for *Tiramisu* (A. Steinfeld et al., 2010, 2012; Zimmerman et al., 2011), the mobile app we used for our study. We limited MD to wheeled devices, as these users have unique spatial and information needs. For example, canes can be stowed and most cane users do not need deployment of vehicle door ramps. We chose to not include transit riders with cognitive disabilities both to help constrain the scope of this study, and because we assumed their needs were less likely to be met by current commercial transit apps or by the current version of *Tiramisu*. Finally, we recruited four people with no disability (ND) from the general public to identify breakdowns and solutions with universal impact. None of these participants was an older adult with a disability and all owned a smartphone.

Recruitment of people with disabilities was not tightly bound to specific medical classifications or ability thresholds because we wanted to attract input from a wide range of people. Our approach was to focus on behaviors and practices rather than medical details because the former are more relevant to the act of using public transit. While the number of participants in each class was small, previous work on accessible transit has effectively worked with small numbers.

Table 1 provides details of our participants, including their user classification, the type of smartphone they owned, and a list of any online or mobile transit information apps or services they used prior to the study. Participants who did not already own an Android or iPhone smartphone (including one participant with a Windows phone) were provided with an iPhone 5c to use for the duration of the study. We chose to lend participants an iOS device rather than an Android device because VoiceOver was the preferred screen-reader for users with visual impairments at the time of this study. All participants provided informed consent and were assigned a user code to protect their anonymity.

Table 1. Study participants and summary of their individual and collective use of the app during the 21-day duration of the study (Participants 1-LV and 4-ND had no data because we could not extract their log files)

Class	n	Part ID	Personal Phone	Apps Used Prior to Study	Sessions	Traces	Spots	Next Stop
Blind (BL)	4	1-BL	iPhone	*Tiramisu*	178	7	0	0
		2-BL	None		438	6	2	4
		3-BL	iPhone		829	39	0	4
		4-BL	iPhone		74	0	0	0
Low Vision (LV)	2	1-LV	iPhone		*could not extract data from logs*			
		2-LV	Android	*Transit App, Google Maps, Tiramisu*	994	23	0	0
				BL & LV Mean (n = 5)	503	15.0	0.4	1.6
Mobility Device (MD)	4	1-MD	Windows		2847	11	3	0
		2-MD	iPhone	*Tiramisu*	269	11	0	0
		3-MD	iPhone	*Google Maps*	82	0	0	0
		4-MD	None		442	15	3	0
				MD Mean (n = 4)	910	9.3	1.5	0.0
No Disability (ND)	4	1-ND	Android	*Google Maps*	263	6	0	0
		2-ND	None		2034	35	0	2
		3-ND	iPhone	*Google Maps*	335	9	0	0
		4-ND	None		*could not extract data from logs*			
ND Mean (n = 3)					877	16.7	0.0	1.6
Mean for all participants (n = 12)					732	13.5	0.7	0.8
Mean for all non-study users on the transit app					580	1.7	1.8	n/a

Three of 17 participants did not complete the study, and they do not appear in our list of 14 participants in Table 1. One participant without a disability never responded to scheduling requests for the post-study interview. In addition, we dropped two participants from the study—one MD and one BL—because they never successfully learned to use the iPhone we lent them.

Data Collection and Analysis Methods

For the field study, we provided each participant with a copy of the *Tiramisu* transit app. We asked participants to use the app for three weeks, and then we did a ride-along to observe how they used the app and to probe them on how it had affected their experience of using public transit.

We conducted pre- and post-, semi-structured interviews that typically lasted 30 minutes. Preliminary interviews prompted participants to describe their current use of public transit, where and how they obtained transit information, and their most common difficulties using public transit. Participants were then given a tutorial of *Tiramisu* and instructed to use the app during their routine commutes over the following three weeks. For those participants who received an iPhone to use for the study, we also provided a basic overview of iOS and how to use VoiceOver.

Post-interviews occurred at least three weeks after the pre-study interview. For the post-interview with a ride-along, the participant and a researcher boarded, rode a short distance, and disembarked together. The ride-along allowed the researcher time to observe how the participant interacted with the app and to prompt the participant to recall his or her experience using the app. In this way, researchers could tailor questions, and participants were primed and better equipped to recall specific experiences that were affected by their use of *Tiramisu* over the previous three-week period. Following the ride-along, the researcher conducted a second semi-structured interview that prompted participants to describe the ways in which they used and interacted with the app, and how this use affected or changed their public transportation experience.

All interviews were recorded, transcribed, and coded to capture trends concerning common rider experiences related to transit use, information gathering, common barriers, and design issues related to *Tiramisu*. Transcribed interviews were read and analyzed in team meetings. The team also generated affinity diagrams to draw out themes. Findings were later discussed and oriented around the Travel Chain (i.e., pre-planning, finding the bus stop, boarding, and disembarking: Iwarsson et al., 2000) to see the impact of mobile transit information across the transit experience and to identify other design opportunities for smartphones to lower barriers to using public transit. This analytical lens places priority on issues and barriers early in the Travel Chain. Breakdowns that occur early in the chain generally have a cascading impact on accessibility. Thus, fixing a downstream problem without addressing an upstream issue generally has no effect.

Study Context: Tiramisu *System Overview*

Tiramisu provides riders with access to arrival times for individual stops. In addition, unlike most other transit information systems, *Tiramisu* allows transit riders to share location traces and fullness information from their smartphones, thus improving transit information through crowdsourcing of arrival times and vehicle load. In our study, the main interaction flow presented users with a map showing nearby stops (See Figure 1A). When they selected a stop, the app showed a list of arrival times for all transit vehicles within a 90-minute window: those that should have passed within the previous 30 minutes and those that should arrive within 60 minutes (See Figure 1B). The app showed three types of arrival estimates. When a user was on a vehicle and sharing a location trace, the system showed "rider real-time," which used machine learning to estimate when the specific bus would arrive. When no user was sharing a location trace, but the specific trip (this vehicle at this time) had previously shared traces, the app displayed a "historical" estimate based on arrival history.

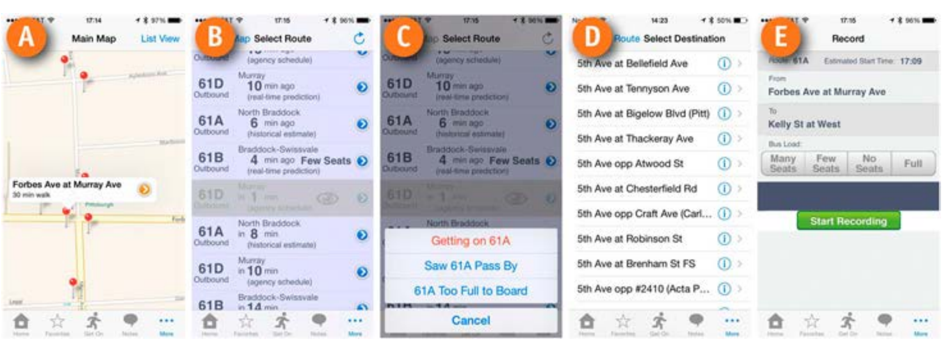

Figure 1. Screenshots: (A) Map allows stop selection. (B) Select route list allows user to select a trip. (C) Dialog allows user to indicate they want to start a trace (subsequently proceed to screenshot (D)) or to spot a bus passing by (or too full to get on). (D) Destination allows user to set a destination, where their trace will stop. (E) Record allows user to indicate fullness and to start a trace.

When no real-time or historical information was available, the app showed the arrival time based on the transit service's printed schedule.

When users selected one of the upcoming vehicles, they saw a popup dialog (See Figure 1C). This allowed them to do one of three things. They could indicate that they were boarding this bus, this bus passed by, or this bus passed by and was too full to board. The second two options offered additional ways for users to crowdsource real-time information.

When users indicated they were boarding this bus, they next selected a destination stop (See Figure 1D). Then, they rated the bus fullness upon boarding and selected "record" to share a location trace (See Figure 1E). The app used the indicated destination to automatically stop sharing location information as the vehicle approached the desired stop.

The app collected and displayed vehicle fullness information, something generally not found on other online or mobile information services. Previous research shows that transit riders want to know when an upcoming bus is too full to board (Yoo et al., 2010). The same study claimed this information might especially benefit people using mobility devices, such as a wheelchair. They speculated that this information would be broadly valuable for people who use a mobility device and required use of a specific area on the transit vehicle to secure their device when commuting. (For more details on the design and rationale, please see A. Steinfeld et al., 2012; Zimmerman et al., 2011).

The publicly available version of *Tiramisu* was designed to keep users anonymous. However, we were able to identify participants in this study by having them submit a report through the app during their preliminary interview that included their participant ID. We then searched the log file for a report with this code. We used this information to find each participant's unique *Tiramisu* ID in the server logs, thus allowing analyses of actual app use. We limited log analyses to the first 21 days of use to eliminate practice and decay effects for participants who did not have a prompt follow-up interview due to scheduling challenges. Log data could not be extracted for 1-LV or for 4-ND. Therefore, these participants are absent from the quantitative analyses. When the app was deleted and reinstalled, it produced a new unique ID within the logs. Because of this, we could not associate an individual log file with these participants.

Findings

Participants explained that localized arrival information, i.e., scheduled and estimated real-time arrival information that was filtered and organized by the current time and current location, had a significant impact on their transit service experience. While previous work showed access to mobile information consisting of real-time arrival information had a positive benefit on accessibility, our study observed benefits from primarily showing localized schedule data. Use of the app allowed participants to spend less time preplanning, to engage in more opportunistic travel, and to discover new travel options for the trips they often take. Participants discussed a number of barriers when trying to use the transit service effectively, some of which could be addressed through additional features in a transit app.

One of the main reasons we chose *Tiramisu* for the study was its ability to crowdsource real-time information and to offer information about how full the vehicles were. However, during the course of the study, participants shared that they did not obtain enough real-time information or fullness information to affect their use. Previous studies of *Tiramisu* use showed that the amount of real-time data available ranged from 0.3 to 8.8 percent, depending on location, day of the week, and time of day (Tomasic et al., 2015). All participants said that real-time information was very valuable. They all wanted more real-time data to reduce uncertainty when using public transit, and they felt that real-time data would also improve their access to transit.

Below we detail the findings across the travel chain, identifying issues and features specific to *Tiramisu* where appropriate.

Trip Planning

All participants said that they typically engaged in pre-planning for a trip. This was particularly true for participants with visual and mobility disabilities, especially when they travelled to a new destination. Participants used several strategies. The participants who used a mobility device said that they often called the transit agency to gather information about the infrastructure for specific stops. This information is generally not available online, in printed schedules, or in mobile transit apps (with the exception of *OneBusAway* in Seattle: Campbell et al., 2014; Hara et al., 2015). Participants with visual impairments always called the transit service as a first step in making their travel plans. The service agents helped participants select the routes, times, and stops that best fit their needs. Mobility device users and participants without disabilities also planned using published schedules and online route planning tools, such as Google's transit search. All participants complained about the time and effort needed to plan. One coping strategy many employed was to memorize the schedule for trips they frequently took. Having to use the call center was viewed as particularly cumbersome. It forced participants to plan quite early because the call center had limited weekday hours and did not operate during evenings or weekends.

Access to localized arrival information on a smartphone reduced the need to plan or to plan as far ahead for an anticipated trip. This created more flexibility for the trips they often took. Participants, especially those with visual impairments, really enjoyed this change in behavior, especially waiting to plan until close to travel time. 2-BL's experience represents that of many participants: "[With *Tiramisu*] I never had to call Port Authority to find out when my T was coming. I felt like I could just pick up and go when I wanted to go."

Access to mobile arrival information also affected how participants executed their plans. Many, especially participants with visual impairments, felt compelled to confirm their plan during execution by seeking confirmation from transit drivers or from other riders. This generally worked, but sometimes would lead to errors. With mobile information, they could rely on the device for confirmation, such as looking at upcoming stops to confirm the vehicle would go where they desired. They often felt this was more reliable than confirmations from drivers and other riders.

> I had to go to [place] last week and someone told me beforehand to take the 61C. So I caught a 61 and I thought I had to get off at a certain stop, but the bus driver said no, get off at this different stop. So I used Tiramisu to double-check that. (3-BL)

Interestingly, one MD participant regularly used several different online sources, including the *Tiramisu* app, to confirm that a plan would work. The participant needed to find the same information from several sources before trusting it.

In addition to reducing the need to engage in detailed planning, access to mobile information reduced barriers to opportunistic travel in a variety of ways. Both participants without disabilities and participants with visual impairments changed their behavior for short trips. For these, participants previously felt uncertainty about when to wait for a bus that might not come for up to 30 minutes, and when to simply walk the distance of a few transit stops. Access to mobile information made it much easier to determine when it was worthwhile to walk.

> There's a stop where I ride the bus on Craig St. and there are certain buses that stop there and I only go a short distance, like three or four blocks. So I check to see if there's a bus coming, and if there isn't then I just walk. So that's nice. I do that at different stops, check if there's a bus coming so I can plan to walk or go to a different bus stop. That to me is really helpful. (1-LV)

Interestingly, we did not observe this change in participants who used a mobility device. Due to the effort needed to load into and unload out of a transit vehicle, these participants reported that they rarely used public transit for short trips.

Access to mobile information also made it possible for some participants to deviate from their plans or react to an unfolding situation. For example, participant 3-ND found that they were unexpectedly ready to go home, but that they were not close to their planned departure stop. (3-ND: "There was an instance where I was in an unfamiliar place and I was walking and I checked, and there was a bus due, so I found the stop and caught the bus.") This ability to deviate from a plan also worked when they experienced breakdowns, such as missing a planned departure.

> Used [*Tiramisu*] to find the schedule after I missed my T coming back from my dentist appointment last week. They were running really late, so I had to check Tiramisu to know which next one I was catching and where I had to go to wait, because it was raining. So I was able to just go sit in the coffee shop for 20 minutes and come back. (2-BL)

The additional ability to learn about a new area reduced anxiety about trips and reduced planning. (1-LV: "It's also helpful if I go to an area that I don't know very well and I don't know exactly where the bus stops are, and I use it to find the bus stops.")

While not a focus of *Tiramisu*'s design, some participants used the app to discover new travel options for trips they often took. This often involved selecting the best route from several routes travelling near their destination.

> Every now and again I would click a stop and see what buses were due there, but that was kind of infrequent because I know the schedules enough in my head to know that they're going to come at this time. The most helpful thing was comparing routes. The other app that I use didn't have all the routes listed, so I know that the 68, 67, and 69 are all traveling the same path, so if I see that the 67 is running five minutes behind, and the 68 is running about seven minutes behind, it gives me an idea about whether or not I missed my bus or if it's running late and I'm okay. This is under my regular stop where I leave work every day. (2-LV)

In this case, the participant had memorized the schedule for the route regularly used and then could use the app to see if another trip had a better fit.

The map interface within *Tiramisu* is intended for sighted users to quickly indicate their desired departure stop in order to see arrival times. Interestingly, one participant without a disability used this interface to investigate and compare several stops nearby regularly used stops. In doing so, she discovered routes she had not used previously that travelled near her desired departures and destinations. This discovery led to an increase in the number of travel options and created a sense of increased access to travel by public transit. (4-ND: "I would use where I'm located to see other bus routes that I didn't know about which I liked.") Participants found this particularly useful in avoiding a transfer; the use of two buses for a single trip.

> I knew the bus that went from Squirrel Hill down to Liberty versus the one that I would've taken. I would've had to transfer in East Liberty, but I took a different bus because I used the map to look at different bus stops surrounding and it'll tell you what buses go there. (4-ND)

Almost all participants shared an unmet desire for route planning within a transit app. Occasionally they would be on the go and want to travel somewhere new. They wanted to search for destinations and get plans to compare, and they wanted this integrated into a transit information app.

Reaching and Using Stops

Prior research reported that people with disabilities face many barriers getting to and waiting for vehicles at transit stops. This includes finding information about infrastructure (e.g., if a stop has a curb cut or a sidewalk) and having buses pass them by without stopping. Our participants shared similar stories. Several participants who used mobility devices spoke about encountering stops they could not access due to a lack of a curb cut, disrepair of a sidewalk, and cars parked in ways that made it impossible to leave a stop and board a vehicle. Participants with visual impairments also talked about parked cars and hazards around stops that made them difficult to use. While an app cannot change infrastructure, accessible information can help a rider find alternatives. One problem not mentioned in prior literature that most of our participants mentioned was knowing if a stop was in use. Several told stories of waiting at a stop where no bus came and only learning later that vehicles had been detoured.

Similar to prior research, our participants with disabilities spoke about transit vehicles passing them by. Participants with visual impairments spoke about the challenge of finding the bus stop sign. They wanted to stand close to the stop to more clearly signal their intention to board. Unexpectedly, participants with low vision found the map view in *Tiramisu* to be helpful because it shows the approximate location of a stop in relation to the streets and intersections.

> I would use [*Tiramisu*] to see where nearby stops are. Sometimes I can't read an intersection sign, can't find the bus stop. Especially at night. Just being able to see what my options are … being able to look on the map and see where there's a point and knowing that a bus stop is there, and then clicking on the point and showing me the stop. That's very handy. (2-LV)

Participants who used a mobility device spoke about buses passing by and the uncertainty in knowing if the driver had not noticed them, or if the driver had noticed them and the bus had been too full for them to board. Similar to previous research, they expressed an ill regard for the drivers who did not stop, speculating that these drivers often see them but are avoiding the work of relocating current riders, and loading and securing their chair. (Aide for 2-MD: "And we've had drivers pass us up, cause they don't want [2-MD] on the vehicle. Cause she'll take up five spaces, and then five people couldn't sit there. And they don't like losing all those seats.")

Participants without disabilities also mention the problem of buses passing by without stopping. In discussing this point, they hinted at the challenge of conveying the intention to board. The mobility device users and participants without disabilities talked about trying to make eye contact, waving to the driver, and/or moving closer to the bus stop sign as the vehicle approaches as some of the things they would do. The intention to exit a vehicle can be explicitly expressed; riders pull a cable to signal to the driver that they wish to disembark at the next stop. However, for boarding, there appeared to be no explicit way to express this intention and no way for the driver to communicate why they might not be stopping.

Boarding

Similar to previous research, our participants who used a mobility device spoke of barriers to boarding. Drivers would often say the bus was too full for their mobility device. Sometimes other riders would contradict the driver.

> I had another bus driver who claimed the bus was too full, but then the people were like "Oh we can move!" So another girl who was getting on the bus got on and told people to move, and I got on, and it wasn't packed that much. So she was just too lazy to do it I guess. (3-MD)

Like previous research, our participants spoke of problems with securing their mobility devices. They claimed that the drivers would unquestioningly follow the transit agency's guidelines and ignore their insights on how to secure their device without damaging it or their need to have access to a grab-bar on a specific side.

> The bus driver was kind of ignorant because she told us that I need to sit on the right side of the bus, instead of behind her, and that I'm not allowed to tell the passengers to move, so I have to sit behind her. (2-MD)

This left the participant in the uncomfortable position of looking backwards for the trip.

Similar to previous research, our participants with visual impairments spoke of trouble knowing if the bus they desired was the one that had just arrived. Some buses would announce their route, but most did not, forcing participants ask other riders or the driver. In addition, they sometimes had trouble finding the entrance to a bus. These participants also identified a challenge with the app after boarding. *Tiramisu*'s crowdsourcing interaction to start a location trace required a bus fullness rating before the trace could start, and they had no easy way to infer how full the bus might be.

> The status of the seats doesn't mean that much to me, because most of the time I am given the front seat. Once I get on, it's hard unless I hear a lot of people, for me to judge the fullness of the bus. (3-BL)

In discussion of the *Tiramisu*-specific fullness data, participants with visual impairments said the driver always helped them get a seat, so fullness did not affect their use. Participants who used a mobility device said that what they really wanted to know was if there was space for them on the bus, and they did not immediately recognize fullness as a proxy for this information.

Riding and Exiting

Previous research states that riders with visual impairments struggle to know when to disembark. Often the annunciator that speaks the name of the upcoming stop would not work, or the general noise of the bus would make it hard to hear. Interestingly, we heard this same complaint from our participants with mobility disabilities and without disabilities. They spoke of the challenge of seeing out the windows, especially in the evenings, or of sitting or standing such that they could not easily see the screen showing the upcoming stop name or see through a window. Participants with visual impairments often relied on drivers to let them know when they had arrived at their desired stop, but sometimes the drivers forgot.

Interestingly, two of our participants with visual impairments discovered a hidden feature of the app. A previous version of *Tiramisu* had a button users could press when sharing a location trace that would show the name of the upcoming stop. This feature was removed as it was sometimes inaccurate and it caused a large drain on the phone's battery, something reviewers in the app stores had complained about. In disabling this feature, the developers had simply made the button invisible. However, VoiceOver read the alt text, communicating to these participants that the button was there, and enabling them to hear the name of the upcoming stop. These two participants really liked this feature, using it multiple times during the 21-day study (See Table 1).

> I really used the app the most to find out what stop I was near. That was my most functional use of the app. When I was on a bus I could click "what stop is next" and that was the most helpful feature. (2-LV)

Analysis of Behavior Logs

We present data from the behavioral logs only to provide evidence that the participants used the system enough to provide informed feedback. On average, participants used the system more than a typical *Tiramisu* user (See Table 1). During the 21-day study window, participants used the app an average of 10.8 (5.5 SD) days (See Table 1). They accessed arrival information an average of 732 (862 SD) times across these days. There were no significant differences between participant classes for days used, number of sessions, or location traces shared. To check the issue of small sample sizes, we also ran power analyses and computed the least significant *n*. These were all high (348, 139, and 119, respectively). There were too few cases of "spots" and "next stop" interactions to warrant any statistical analyses.

To better calibrate the experience of our participants to a typical *Tiramisu* user, we analyzed the *Tiramisu* logs over the seven months we recruited and collected data on our participants. We collected daily totals for sessions, traces, and spots. We divided these by the daily number of active devices and multiplied by 21 to get an estimate of how our participants' activity compared to the general *Tiramisu* population (See Table 1). Our participants accessed arrival information (sessions) and shared location traces at a higher rate than non-study *Tiramisu* users. They spotted less. Participants with visual impairments used the app at levels comparable to the general *Tiramisu* population while those with mobility disabilities used the app more frequently.

Discussion

The results of this research can inform the design of mobile transit information apps in three dimensions. First, we found that providing localized transit information increased accessibility for all users. Participants were able to reduce their planning of journeys, make more opportunistic trips, and find new travel options. Second, the study replicated prior research about the barriers that transit riders with disabilities face and reinforce previous findings on how riders without disabilities can benefit from mobile transit information. Our participants discussed issues they had navigating to stops and boarding the correct bus that were similar to research findings from other communities. Third, our research uncovered a number of opportunities for universal design methods to improve experiences across all rider classes. Though it is challenging to provide value to users with specific disabilities while still retaining broader appeal and utility, we believe we have succeeded with our current approach. Examples of success on this front are rare, so evidence from a longitudinal study, such as this, are important for the non-academic audience as justification for universal design in future software products.

The collected results provide valuable new insights and reveal opportunities for mobile services that can improve people's public transit experiences. The logs showed that most of the participants used *Tiramisu* extensively, indicating that their qualitative feedback was generally well-informed and indicative of people who are experienced with a mobile information system. Below, we detail opportunities for phones and transit apps to increase access to transit across the travel chain.

Planning

Transit apps with localized arrival information can significantly affect access to transit service. In our study, the biggest benefit of this information came from reducing planning efforts and shortening the timeline related to planning participants' journeys. The app decreased the need for reliance on limited customer service availability to obtain necessary travel information. Participants indicated that localized information also helped them discover new travel plans. Our participants who used mobility devices and those without disabilities reduced their reliance on paper schedules and online lookups, using the mobile app almost exclusively. We believe this increase in access to relevant information is fully responsible for the increase in opportunistic travel. Systems that provide real-time arrival information would magnify this effect and make opportunistic travel even more accessible.

Participants' requests for trip planning helped us see that most apps overly focus on the back end of the planning link in the travel chain. They help people arrive at stops on time, but they assume everyone knows the stops and buses that they need to complete their trip. While planning travel to a new destination is infrequent relative to a daily commute, it is a valued and often overlooked feature for transit apps.

We were surprised by one participant without disabilities who used the map to discover new ways for getting to frequent destinations. Participants with disabilities did not have this experience, and we suspect that they might spend less time exploring the app due to increased effort to navigate it, especially for riders with visual impairments who must listen to the text being read. A more intelligent app could learn people's regular commutes and make suggestions based on their location and time of day, exposing them to the best option for the given time/place.

Some transit apps seem to unintentionally support the two disability groups that we studied. However, we do not think current designs would work for most users with cognitive disabilities. The information is too dense and un-personalized for this group, which typically depends on a linked set of personal points-of-interest for navigation (Livingstone-Lee et al., 2014).

Arriving at Stops and Boarding

Many people with and without disabilities are challenged when navigating to stops in time to ride and effectively board the correct bus. While many structural problems, such as missing curb cuts, will not be solved with information technology, there is value in knowing about potential barriers prior to arrival. Access to new information and better communication with the transit service via a smartphone could help all users.

Existing transit apps seem disconnected from the operational state of the associated transit service. The *OneBusAway* service has addressed part of this problem by crowdsourcing critical information about stops that make them easier to find and easier to select using descriptions of what infrastructure is available. Crowdsourcing works well for this purpose because infrastructure information is mostly static and can persist for years.

Our participants' stories of standing at stops that were out of service would not be changed by *Tiramisu* or even apps like *OneBusAway* that log stop infrastructure. There is a need for more dynamic information about stops, such as whether they are in service. Most transit services make this information available on their websites, but it is rarely scraped by transit apps and the data is usually not available in the transit feeds that most services provide to third-party apps. The ability to add live detour information to feeds would likely be acted on by transit app developers who must compete for customers.

Similarly, the need to express the intention to ride, in order to ensure that the desired bus pulls over and stops, would also benefit all riders. However, this seems to be a more complex challenge than adding stop detour information. Future versions of *Route2me* may address some of these needs by pairing high-precision localization with transit information feeds (Alvarado et al., 2018), thereby allowing users to indicate the desire to board by approaching the bus stop sign just prior to vehicle arrival. This feature would be especially beneficial to those with visual impairments.

Likewise, riders could use their current phone to signal a bus to stop, similar to pressing the call button on an elevator. For example, some airport parking lots have a button that will illuminate a light at the top of the shelter so shuttle drivers know a customer is waiting. One challenge would be how to communicate this to drivers without added infrastructure. A simple solution would be to electronically pull the "next stop" alert cord on the bus. However, this misses the opportunity to let the driver know that an upcoming passenger has a disability. Communicating this information to drivers can emphasize the importance of pulling very close to the curb. The system could also request that current passengers vacate spaces reserved for those with disabilities before the bus arrives, taking this responsibility that drivers seemingly do not wish to have and placing it on the passengers. The unintended consequence is that it might train drivers to only stop when requested, thus making transit less accessible for anyone without a smartphone.

Disembarking

While the challenge of disembarking has been well documented for users with visual and cognitive disabilities, our study showed that other riders would also benefit from an app that provides information about exactly when to disembark. One study participant who is blind said that this hidden feature of *Tiramisu* had the greatest impact on the transit experience. Current smartphones have the ability to accurately sense their location, so transit app developers would just need to add an announcement of the approach to the destination stop as a new feature. The consequences for all users would be that they could free their attention during their travel from constantly monitoring their location and the time differential to their destination. This universal design feature would lower anxiety about missing a destination for all riders, and it would have a significant impact on users with cognitive or visual disabilities who can easily suffer a complete breakdown in travel when they miss their planned point to disembark. Based on the experience of the *Tiramisu* team, this may require new algorithms that use less battery power on the phone than what is currently available.

Disability-Specific Designs

Through our review of the literature and upon reflection on our study, we see one clear opportunity for transit apps to provide new services and features that would be more disability-specific. Both transit users with visual disabilities and cognitive disabilities typically memorize a sequential collection of personal points-of-interest that make up a specific trip before traveling; these points connect a departure location to a final destination. Current transit apps offer no method for users to input, record, or capture their linked set of PPOIs such that the user and/or the PPOIs can be monitored. The research system TAD demonstrated the benefits of monitoring the traveler and alerting their caretaker when they deviate from their travel plan (Barbeau et al., 2010; Bolechala et al., 2011). We also see value in a service that can monitor the PPOIs, or even a subset of the PPOIs, such as those within a transit station, so that users could be alerted ahead of time that their planned route was not available or would require a detour.

Conclusion

This study is intended to build support for new technology solutions and frame future research. Our findings, in conjunction with prior work, demonstrate the value of mobile transit information to people with disabilities. However, it is still important to remember that full accessibility is best served by a mix of service provider commitment, barrier-free environments, and effective information technology.

Now that real-time information is becoming more widely available across transit systems, validating that real-time information at a large scale and in an accessible form leads to better travel experiences and more robust use of local transit services. Our study was somewhat limited by our sample not fully representing the wide variation of people with disabilities, especially those with cognitive disabilities. Larger recruitment efforts, complete with more robust coverage of assistive technologies, would enhance understanding of this area.

Another key focus during large-scale data analyses will be to see if this study's finding that localized transit information helps all user groups can be confirmed at scale. This result would support the premise that universal design can effectively support the needs of a wide range of users. Moreover, it will be interesting to see if this information enables people with disabilities to experience transit in ways similar to those without disabilities.

Geolocation Information

The data for this research was collected in Pittsburgh, Pennsylvania, United States.

Note

1. We chose to use the *Tiramisu* app for two reasons. First, the Port Authority of Allegheny County, the public transit service provider in Pittsburgh where we were running the study, did not offer real-time arrival information for the buses at the time of this study. They did not have an Automatic Vehicle Location System (AVL) that continuously collected the locations of all the vehicles in service. Several studies have shown that access to this information significantly improves the user experience with transit (Brakewood et al., 2014; Ferris et al., 2010). *Tiramisu* employed a crowdsourcing approach to address the lack of an installed AVL service. It allowed transit riders to share location traces, collaboratively producing real-time information for other riders. Transit is integral to Pittsburgh, a mid-sized city in the US state of Pennsylvania, because there is limited parking downtown, hilly terrain, and a full spectrum of weather. Second, we had access to the *Tiramisu* usage logs and could observe how often individual participants used the app during the course of the study.

Acknowledgments

The authors would like to thank Shree Lakshmi Rao for her assistance during pilot testing and Elizabeth Carter for her editing assistance. The contents of this paper were developed under a grant from the National Institute on Disability, Independent Living, and Rehabilitation Research (NIDILRR grant number 90RE5011). NIDILRR is a Center within the Administration for Community Living (ACL), Department of Health and Human Services (HHS).

Notes on Contributors

Aaron Steinfeld is an associate research professor in the Robotics Institute at Carnegie Mellon University. He leads research on accessible and advanced transportation, inclusive technologies, and human-robot interaction.

Leslie Bloomfield is an interaction designer for industrial internet of things applications at National Instruments in Austin, Texas.

Sarah Amick is a software developer at MUST, Copenhagen.

Yun Huang is an assistant professor at the iSchool in Syracuse University. She co-directs the SALT lab, focusing on social computing systems research.

William Odom is an assistant professor in the School of Interactive Arts and Technology at Simon Fraser University. He leads research on domestic computing and methods for design-oriented human-computer interaction.

Qian Yang is a PhD student and design researcher at Carnegie Mellon's HCI Institute. She designs various machine learning systems and develops toolkits for designers to better ideate feasible, meaningful, and creative AI-enhanced user experiences.

John Zimmerman is a professor at Carnegie Mellon's HCI Institute. He does research on user experience design, service design, and interaction with intelligent systems. He develops new technology to innovate healthcare, education, public services, and domestic life.

Disclosure Statement

In accordance with Taylor and Francis policy and our ethical obligations as researchers, we are reporting that some authors have financial and/or business interests in a company that may be affected by the research reported in the enclosed paper. We have disclosed those interests fully to Taylor and Francis, and we have in place an approved plan for managing any potential conflicts arising from this involvement.

Funding

The contents of this paper were developed under a grant from the National Institute on Disability, Independent Living, and Rehabilitation Research [NIDILRR grant number 90RE5011]. NIDILRR is a Center within the Administration for Community Living (ACL), Department of Health and Human Services (HHS). The contents of this paper do not necessarily represent the policy of NIDILRR, ACL, or HHS, and you should not assume endorsement by the Federal Government.

ORCID

Aaron Steinfeld http://orcid.org/0000-0003-2274-0053
John Zimmerman http://orcid.org/0000-0001-5299-8157

References

A. Alvarado, A. Chong, Y. Kojitani, E. Orellana, E. Vadai, L. Zhang, G. Flores, R. Manduchi, and E. Miller, "RouteMe2: A Cloud-Based Infrastructure for Assisted Transit," in *Transportation Research Board Annual Meeting* (Washington DC, USA: January 7–11, 2018).

A. Arenghi, I. Garofolo, and A. Laurìa. "On the Relationship between 'Universal' and 'Particular' in Architecture," in H. Petri, J. Darzentas, and T. Walsh, eds, *Universal Design 2016: Learning from the Past, Designing for the Future* (Amsterdam: IOS Press, 2016).

S. Azenkot, S. Prasain, A. Borning, E. Fortuna, R. E. Ladner, and J. O. Wobbrock, "Enhancing Independence and Safety for Blind and Deaf-blind Public Transit Riders," in *Proceedings of the 2011 Annual Conference on Human Factors in Computing Systems—CHI '11* (Vancouver, Canada: May 7–11, 2011).

S. J. Barbeau, P. L. Winters, N. L., Georggi, M. A. Labrador, and R. Perez, "Travel Assistance Device: Utilising Global Positioning System-enabled Mobile Phones to Aid Transit Riders with Special Needs," *IET Intelligent Transport Systems* 4: 1 (2010), 12–23.

A. J. Bolechala, R. G. Miltenberger, S. J. Barbeau, and M. E. Gordon, "Evaluating the Effectiveness of the Travel Assistance Device on the Bus Riding Behavior of Individuals with Disabilities," in *Transportation Research Board 90th Annual Meeting* (Washington DC, USA: January 23–27, 2011).

C. Brakewood, S. Barbeau, and K. Watkins, "An Experiment Evaluating the Impacts of Real-Time Transit Information on Bus Riders in Tampa, Florida," *Transportation Research Part A: Policy and Practice* 69 (2014), 409–422.

C. Brakewood, G. S. Macfarlane, and K. Watkins, "The Impact of Real-Time Information on Bus Ridership in New York City," *Transportation Research Part C: Emerging Technologies* 53 (2015) 59–75.

M. Campbell, C. Bennett, C. Bonnar, and A. Borning, "Where's My Bus Stop? Supporting Independence of Blind Transit Riders with StopInfo," in *Proceedings of the 16th International*

ACM SIGACCESS Conference on Computers and Accessibility—ASSETS '14 (Rochester, NY, USA, October 20–22, 2014).
S. Carmien, M. Dawe, G. Fischer, A. Gorman, A. Kintsch, and J. F., Sullivan, "Socio-Technical Environments Supporting People with Cognitive Disabilities Using Public Transportation," *ACM Transactions on Computer-Human Interaction* 12: 2 (2005) 233–262.
M. Chamorro-Koc, L. Stafford, and B. A. Adkins, "Seamless Journeys: Enhancing Accessibility to Work Through Digital Technologies for People with Mobility-Related Impairments," in *Proceedings of the 6th IASDR (The International Association of Societies of Design Research Congress)* (Brisbane, Australia, November 2–5, 2015).
B. Ferris, K. Watkins, and A. Borning, "OneBusAway: Results from Providing Real-time Arrival Information for Public Transit," in *Proceedings of the 28th International CHI Conference on Human Factors in Computing Systems* (Atlanta, GA, USA: April 10–15, 2010).
M. Guentert, "Improving Public Transit Accessibility for Blind Riders," in *The Proceedings of the 13th International ACM SIGACCESS Conference on Computers and accessibility—ASSETS '11* (Dundee, Scotland, October 24–26, 2011).
K. Hara, S. Azenkot, M. Campbell, C. L. Bennett, V. Le, S. Pannella, R. Moore, K. Minckler, R. H. Ng, and J. E. Froehlich, "Improving Public Transit Accessibility for Blind Riders by Crowdsourcing Bus Stop Landmark Locations with Google Street View: An Extended Analysis," *ACM Transactions on Accessible Computing (TACCESS)* 6: 2 (2015) 5:1–5:23.
H. Hwangbo, J. Kim, S. Kim, and Y. G. Ji, "Toward Universal Design in Public Transportation Systems: An Analysis of Low-Floor Bus Passenger Behavior with Video Observations," *Human Factors and Ergonomics in Manufacturing and Service Industries* 25: 2 (2015) 183–197.
S. Iwarsson, G. Jensen, and A. Ståhl, "Travel Chain Enabler: Development of a Pilot Instrument for Assessment of Urban Public Bus Transport Accessibility," *Technology and Disability* 12: 1 (2000) 3–12.
R. Jacob, P. Mooney, B. Shalaik, and A. Winstanley, "HapticTransit: Tactile Feedback to Notify Public Transport Users," *International Journal of Digital Information and Wireless Communications (IJDIWC)* 1: 3 (2011) 238–252.
H. A. Karimi, L. Zhang, and J. G. Benner, "Personalized Accessibility Maps (PAMs) for Communities with Special Needs," in *Proceedings of the 12th International Conference on Web and Wireless Geographical Information Systems (W2GIS'13)* (Banff, Canada, April 4–5, 2013).
S. Landau, H. Subryan, and E. Steinfeld, "Interactive Wayfinding for the Visually Impaired," *EG Magazine* 11 (2014) <https://segd.org/interactive-wayfinding-visually-impaired> Accessed February 22, 2019.
S. A. Livingstone-Lee, R. W. Skelton, and N. Livingston, "Transit Apps for People With Brain Injury and Other Cognitive Disabilities: The State of the Art," *Assistive Technology* 26: 4 (2014) 209–218.
C. Mitchell and S. L. Suen, "Urban Travel, Intelligent Transportation Systems, and the Safety of Elderly and Disabled Travelers," *Journal of Urban Technology* 5: 1 (1998) 17–43.
W. Narzt, "Facilitating Utilization of Public Transportation for Disabled Persons by an Open Location-Based Travel Information System for Mobile Devices (VIATOR)," in Proceedings of UBICOMP 2013—7th International Conference on Mobile Ubiquitous Computing, Systems, Services and Technologies (Zurich, Switzerland, September 8–12, 2013).
National Center for Accessible Media, *Accessibility Review of Transit-Related Applications* (Boston, MA, USA, Carl and Ruth Shapiro Family National Center for Accessible Media at WGBH, 2012) <ncam.wgbh.org/file_download/152> Accessed December 3, 2018.
National Council on Disability. *Transportation Update: Where We've Gone and What We've Learned*. (Washington DC, USA, National Council on Disability, 2015) <http://www.ncd.gov/publications/2015/05042015/> Accessed December 3, 2018.
S. Rodger, J. Vines, and J. McLaughlin, "Technology and the Politics of Mobility," in *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems—CHI '16* (San Jose, CA, USA, May 7–12, 2016).
J. Sánchez, M. de B. Campos, M. Espinoza, and L. B. Merabet, "Accessibility for People Who Are Blind in Public Transportation Systems," in *Proceedings of the 2013 ACM conference on Pervasive*

and ubiquitous computing adjunct publication—UbiComp ‘13 Adjunct (Zurich, Switzerland, September 8–12, 2013).
A. Steinfeld, R. Aziz, L. Von Dehsen, S. Y. Park, J. Maisel, and E. Steinfeld, “Modality Preference for Rider Reports on Transit Accessibility Problems,” in *Transportation Research Board Annual Meeting* (Washington DC, USA, January 10–14, 2010).
A. Steinfeld, J. L. Maisel, and E. Steinfeld, *Accessible Public Transportation: Designing Service for Riders with Disabilities* (Abingdon: Routledge, 2017).
A. Steinfeld, J. Zimmerman, A. Tomasic, D. Yoo, and R. Aziz, “Mobile Transit Rider Information via Universal Design and Crowdsourcing,” *Transportation Research Record: Journal of the Transportation Research Board*, 2217 (2012), 95–102.
E. Steinfeld, M. Grimble, A. Steinfeld, S. L. Rao, and A. Tran, “Identifying Accessibility Problems in Existing Transit Systems, “ in *TRANSED 2010: 12th International Conference on Mobility and Transport for Elderly and Disabled Persons* (Hong Kong, China, June 2–4, 2010).
E. Steinfeld and J. Maisel, *Universal Design: Creating Inclusive Environments* (Hoboken, NJ: Wiley, 2012).
A. Tomasic, J. Zimmerman, C. Garrod, Y. Huang, T. Nip, and A. Steinfeld, “The Performance of a Crowdsourced Transportation Information System,” in *Transportation Research Board 94th Annual Meeting* (Washington, DC, USA, January 11–15, 2015).
M. Tomitsch, R. Schlögl, T. Grechenig, C. Wimmer, and T. Költringer, “Accessible Real-World Tagging through Audio-Tactile Location Markers,” in *Proceedings of the 5th Nordic Conference on Human-Computer Interaction Building Bridges—NordiCHI ‘08* (Lund, Sweden, October 20–22, 2008).
D. Verbich and E. G. Ahmed, “The Pursuit of Satisfaction: Variation in Satisfaction with Bus Transit Service among Riders With Encumbrances and Riders With Disabilities Using a Large-Scale Survey from London, UK,” *Transport Policy* 47 (2016), 64–71.
N. Waara, K. Brundell-Freij, R. Risser, and A. Ståhl, “Feasible Provision of Targeted Traveler Information in Public Transportation: Segmentation Based on Functional Limitations,” *Transportation Research Part A: Policy and Practice* 74 (2015) 164–173.
D. Yoo, J. Zimmerman, A. Steinfeld, and A. Tomasic, “Understanding The Space For Co-Design In Riders’ Interactions With A Transit Service,” in *Proceedings of the 28th International Conference on Human Factors in Computing Systems—CHI ‘10* (Atlanta, GA, USA: April 10–15, 2010).
J. Zimmerman, A. Tomasic, C. Garrod, D. Yoo, C. Hiruncharoenvate, R. Aziz, N Ravi Thiruvengadam, Y. Huang, and A. Steinfeld, “Field Trial of *Tiramisu*: Crowd-Sourcing Bus Arrival Times to Spur Co-Design,” in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (ACM: New York, 2011). 1677–1686.