Outdoor Wayfinding and Navigation for People Who Are Blind: Accessing the Built Environment

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Abstract. People who are blind use a range of tools and training to optimize their travel in the built environment. However, changes in the built environment have brought new challenges for blind mobility. Developments in technology, whether used by the person who is blind or designed within the built environment offer ways to overcome mobility challenges. Technology used by a person who is blind includes GPS units, ultrasonic detectors, and smartphone applications that offer travel system information. Technology designed to increase accessibility to the built environment includes accessible pedestrian signals, smart paint, talking signs, autonomous vehicles, integrated travel systems, and devices that communicate between the pedestrian and the built environment.

Keywords: Blind · Visual impairment · Pedestrian · Built environment · Accessibility · Orientation · Mobility

1 Introduction

1.1 Incidence of Visual Impairment

A person with a visual impairment includes people with a mild visual impairment (visual acuity of about 20/60) to people who are classified as blind (visual acuity 20/200 or worse) [1]. A person who is classified as blind might have useful but blurry vision, clear vision but a severely limited field of view, have only light perception, or have no vision at all [1]. All of these situations will impact a person's ability to travel effectively. Globally, it is estimated that 39 million people are blind and 246 million have low vision [2]. In the United States, in 2013, 2.3% of the population (or 7,327,800 people) were estimated by the American Community Survey as having a visual impairment [3]. It is estimated that there are 480,000 Canadians who are blind or who have low vision [4]. The majority of people with a visual impairment travel through a range of environments and use a range of tools to do so. While some might rely heavily on a human guide or a dog guide, most travel independently using learned skills and some combination of tools. These skills and tools are employed for both mobility (allowing one's self to move effectively in an environment) and orientation (knowing where one is within an environment).

M. Antona and C. Stephanidis (Eds.): UAHCI 2017, Part III, LNCS 10279, pp. 320–334, 2017.
DOI: 10.1007/978-3-319-58700-4_27

1.2 Mobility

Most tools used by people who are blind are used to detect objects in the environment and surfaces changes such as drop offs. The most commonly used mobility tool is a long cane or white cane. As the most commonly used mobility device, the long cane has seen little change in decades. When the modern long cane was developed in the 1940s, aluminum was chosen as the shaft material. More recently, canes are also made of carbon fiber and fiberglass. Canes can have solid shafts or be folded into 4 or 5 segments for easier carrying and storage when not in use. Current long cane users can also choose from a variety of cane tips. Some are designed for longer use, some for easier use in long grass or rough terrain, and others for easy use in snow. In general, however, the cane is only as effective as the person wielding it.

Since the primary goals of cane use are obstacle and drop off detection, recent research has delved more deeply than in the past into how cane and user characteristics impact these two outcomes. For drop off detection, younger users are better than older users [5], constant contact is better than two point touch [6], preferred cane technique does not make a difference [7], and cane length is not a factor unless approximately 10% longer than the prescribed length [8, 9]. Heaviness and flexibility of the cane shaft is a factor on drop off detection but is differentially impactful according to which common cane technique is being employed [10]. For obstacle detection, constant contact is better than two point touch [11], but a cane's length or the width with which it is swung is not a factor [12].

Beyond the white cane, there have been a range of technologically based devices developed over the years designed to improve the mobility of people who are blind. Many have used ultrasonic waves and provided auditory or vibrotactile feedback about objects in the environment [13]. Some of these devices were worn on a person's body, some attached to a cane, and some were held in a person's hand. Few of these have seen widespread adoption. Those still in production and limited use are the Sonic Pathfinder, the Hand Guide, the Miniguide, and the K Sonar [13].

1.3 Orientation

In order to optimally get from one place to another independently, a person who is blind needs to be able to locate him or herself within that environment. For many years the only way to accomplish this was to build up a repertoire of landmarks on a traveled route or within a defined area. More recently, GPS based devices have seen greater use. An early version linked a GPS unit with a braille based computer called a BrailleNote. Later devices incorporated the GPS and interaction unit into one for smaller and easier to use devices. Devices currently under widespread use include the Trekker Breeze, the Trekker Maestro, or a GPS unit within a smartphone. Depending on the accuracy of the GPS unit, travelers who are blind are now able to locate themselves according to streets, intersections, or addresses. Many people who are blind have used GPS devices to virtually explore the area around them, looking for specific locations, or to simply observe their environment as a person who is sighted might. Many GPS units allow for routes to be remembered and recalled or planned ahead of time to make travel more efficient.

But all of these devices used by a person who is blind, whether simple tools or technological marvels, place the onus of responsibility for travel on the traveler, with no adaptations of the built environment.

2 The Built Environment

People who are blind travel in all environments. They walk on sidewalks, cross streets, shop in malls, use buses, fly on airplanes, and generally travel as any other independent person does. By virtue of having limited or no sight, people with a visual impairment sometimes need a different way of getting information readily available to other pedestrian through vision. Historically, one of the main sources of useful information for a person relying on sound for navigation in an urban setting was the flow of traffic. Traffic flow can tell a person whether a street is one way or two way, how wide a street is, how close a person is to an intersection, and how close a person is to the street. All of these bits of information, combined with knowledge of how a city is laid out, allows a person to determine approximately where they are and perhaps even what direction they are walking. This process was used by people who were blind for decades and many skills taught by orientation and mobility (O&M) specialists were developed to take advantage of the usefulness of traffic flow information.

In the past 20 or so years, significant changes have been made to the typical environment in which a person who is blind will travel. Intersections have grown larger due to increased traffic flow, corners are more rounded to provide a greater turn radius for large vehicles, signals are increasingly linked to create platooning, intersections are more commonly actuated so that traffic signals react to the presence or lack of vehicles, and there are new and more complicated intersection geometries in use.

2.1 Impacts of Changes in the Built Environment on People Who Are Blind

One of the earlier changes to the built environment that impacted pedestrians who are blind was the creation of wheelchair ramps. These ramps were necessary to allow wheelchair users the ability to easily move between the sidewalk and street without having to deal with large level changes. However, once these ramps were becoming more prevalent, it was evident that pedestrians who were blind would often walk into the street without realizing it [14]. Detectable warnings in the form of truncated domes were developed to address this issue [15–18] (see Fig. 1). These surface treatments indicate the boundary between the walking surface and the road surface but do not provide any sort of alignment information. Countries other than the United States employ a secondary surface treatment that indicates where a crossing point exists and that provides some alignment information (see Fig. 2).

Fig. 1. Detectable warnings as commonly installed on a wheelchair ramp.

Fig. 2. Surface treatments used to guide pedestrians

When a pedestrian who is blind is at a legal crossing place, the traditional cue for determining when to begin crossing is the surge of traffic moving parallel with the pedestrian's intended line of travel. However, if no traffic is available, if the environment is noisy, or if the pedestrian has a problem perceiving the traffic, this cue might not be available. The solution for this issue of accessibility is the provision of accessible pedestrian signals (APS) [19]. This solution provides a pushbutton on each corner of an intersection that a pedestrian pushes when they wish to cross a street. At the appropriate time in the traffic cycle, which would be when the visual walk signal is lit for that pedestrian, an auditory signal is produced that indicates that the visual walk signal is lit. Many forms of APS also provide a vibrotactile signal so that a pedestrian who is deafblind can access the information. Note that the APS system does not indicate whether it is safe to cross, but only that the visual walk signal is lit: the same information available to a sighted pedestrian [20].

The need for additional guidance and access to information has become more necessary with the increase in actuated intersections. Before intersection actuation, intersections would cycle through regular intervals of one street and then the other street having a green traffic signal. As intersections have grown larger and traffic signal cycles have become more complex, keeping track of the cycle of traffic phases has become more difficult for pedestrians who are blind [21, 22]. At many larger urban intersections, both streets that meet at the intersection might have a traffic phase where vehicles proceed straight through the intersection, plus dedicated phases where traffic is only allowed to turn left, plus many other combinations of vehicular movement patterns. With the addition of traffic actuation, where the presence or length of a given traffic phase depends on what vehicles are queued in which lane, there might not be a regular pattern of traffic phases or lengths. If a pedestrian cannot visually perceive what the traffic is doing, the sequence of cycles may be difficult to ascertain. This is compounded by larger intersections where traffic that is turning from across the intersection might sound like it is proceeding straight, since those vehicles must move forward some distance before they begin their turn. In this situation, it is easy for a pedestrian who is blind to confuse a turning traffic movement with a parallel surge of traffic. The existence of an APS is designed to address this set of issues.

One of the latest developments in the built environment that is impacting the independent travel of pedestrians who are blind is the use of more complex intersection geometries. From the 1990s to the 2000s, this issue was focused on the increased building of roundabout intersections. Roundabouts present a particular problem to people who are blind because traffic does not have to stop and because walking paths

Fig. 3. A roundabout showing curved sidewalks and roadways with crossing facilities

and roadways are generally curved, often obscuring where crossing points are [23] (Fig. 3).

When crossing at a roundabout, a pedestrian who is blind must either determine that a large enough gap exists between vehicles to allow a crossing, cross in front of a stopped vehicle, or force a vehicle to stop. Determining that a large enough gap exists is easily done if traffic volume is light but if traffic is heavy, a pedestrian might not have a large enough gap for quite some time. In these cases, it has been shown that the longer a pedestrian is forced to wait, the more risk they are willing to assume in their crossing decisions [24].

If a pedestrian is not able to determine that a large enough gap exists between vehicles, the pedestrian needs to identify when a vehicle stops to allow the pedestrian to cross. However, a vehicle simply stopping does not provide the same amount of information to a pedestrian who is blind as it does to a pedestrian who is sighted. The driver might be looking at other traffic in the roundabout or be stopping for some reason unrelated to the pedestrian. If there are two lanes of traffic, a stopped vehicle in the first lane might auditorily mask the sound of an approaching vehicle in the second lane [25]. In cases where gaps are not easily identified and the pedestrian is unsure of yielding vehicles, there are some behaviors pedestrians can engage in that maximize yielding. The most effective behaviors are holding up a palm toward approaching vehicles or taking a single step into the roadway [26–28]. However, these strategies do not provide absolute safety and many pedestrians who are blind will not feel confident in using such strategies.

Some efforts that have been made to provide access to roundabouts for pedestrians who are blind include using tabled crossings that force vehicles to slow and, at roundabouts with higher traffic volumes, Pedestrian Hybrid Beacons (PHBs) that provide a red light for vehicles when a pedestrian pushes a pushbutton. These environmental modifications have been shown to increase yielding and access [29] but are not in widespread implementation. Nonetheless, even more complex geometries have already been developed that require new and different access innovations. Many newer intersection geometries such as a

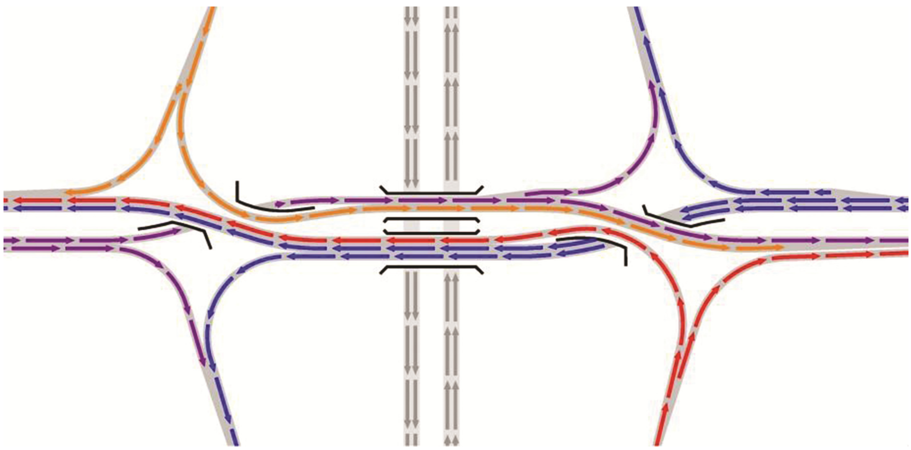

Fig. 4. Traffic paths through a double diamond interchange (Color figure online)

double diamond, the continuous flow intersection, a median U-turn, or a superstreet were designed to remove left turning traffic movements from where two streets crossed [30]. However, in doing so, some of these intersection geometries create extremely confusing paths and soundscapes for pedestrians who are blind. Some, like the diverging diamond, are solvable problems, given proper training and infrastructure (Fig. 4). Others, like the continuous flow intersection pose a greatly enhanced risk for pedestrians who are blind.

2.2 Developments in Using Technology to Create Smart Environments to Assist People Who Are Blind

Thus far, relatively low level innovations to the built environment have been used to try to solve accessibility issues for people who are blind. Audible beacons, raised crosswalks, and pedestrian channeling with fences can improve accessibility for pedestrians who are blind but these solutions tend to address specific issues at specific locations. In order to address systemic accessibility issues, more advanced technological solutions are being explored. These more technology based solutions also tend to be targeted at one element of transportation or mobility but are more able to be leveraged at a later date into something larger. There are three general classes into which current technologies can be placed: those that use technology to link blind pedestrians to intermediaries for help in navigating environments, those that attempt to enhance the amount of environmental information a blind pedestrian has access to, and those that create a platform in which the blind pedestrian interacts with the environment in a way that allows each to respond and adapt to the other.

An example of technology using intermediaries to help pedestrians who are blind to navigate environments is AIRA. In this system, a person who is blind wears a pair of eyeglasses outfitted with Google Glass or Vuzix. When the user requires information or assistance, they tap on the glasses to activate the system and a live, trained AIRA agent links in with the user. The agent is able to locate the user on their computer and also is able to see what is in the user's environment through a camera on the glasses. The user and agent converse and the agent gives the user necessary information which might include describing the environment, looking up transit information, plotting ideal routes to destinations, or even suggesting local restaurants. The agent stays on the line with the user as long as necessary until the user no longer needs the agent's services. Currently AIRA has 20 trained agents and has interacted with a select number of beta test individuals who are blind in cities across the United States. There are also other systems using a similar paradigm, such as a tele-guidance navigation system in Finland [31] and a remote guidance system developed at Brunel University in the UK [32]. Other similar systems use combinations of GPS, GIS, Digital Maps, Bluetooth, voice/video links through internet and GSM connections, digital web cams [33–36].

The development of smartphones, especially in combination with GPS, has allowed an explosion of apps designed to enhance environmental information available to pedestrians who are blind. Some, such as Tap Tap See and LookTel are not directly related to navigation but allow a person who is blind to be able to know more precisely what is in the environment around them. Tap Tap See takes a picture with the smartphone's camera, processes the picture, then speaks what is in the picture. Apps designed to enhance access to navigational information by people who are blind generally use some combination of Google maps, Apple maps, OpenStreetMaps, and GPS to provide location information. Different applications offer different options or user portals. Examples of these apps include:

- Blindsquare (uses data from Foursquare, OpenStreetMap, and Apple Maps to note current location, plan routes, link to transit apps, notes locations of interest, and explore maps),
- Sendero GPS Look Around (announces heading and cross streets, points of interest, voice over for Google maps),
- iMove (saves waypoints and links them to alerts and user recorded sounds),
- The Seeing Assistant Move (based on OpenStreetMaps, notes current location, plan routes, notes locations of interest, controlled by voice),
- Sendero Seeing Eye GPS (fully accessible turn by turn GPS app),
- City Lights (vibrates 3 times whenever near a traffic light),
- Smart Ride (transit directions, real time predications, and transportation routes),
- ViaOpta Nav (uses Apple Maps and Google Maps, GPS app that includes searches for accessibility information such as tactile paving and audible traffic signals),
- Ariadne GPS (notes current location, saves waypoints, explores maps),
- Microsoft soundscapes (provide 3D audio to traveler including turn by turn directions, and information about nearby items, points of interest, and obstacles).

There is also a range of standalone GPS based devices such as the Trekker Breeze, the Trekker Maestro, the Kapten, or the Braillenote GPS that are designed to provide travel information to people who are blind. While the Trekker series of GPS units enjoyed success within the blindness community, they are no longer being offered and even products still produced such as the Kapten, the Braillenote GPS, (see Fig. 5) are being replaced in user's life by smartphone based applications or other technologies that incorporate more features or link to other systems. Integrated systems such as Cydalion combine a smartphone, acoustic feedback, and vibrotactile feedback (through a vest for Cydalion) to provide warning of environmental obstacles.

The development of devices to aid people who are blind has a long history of devices not accepted by end users. However, the increasing precision of GPS technologies and the ease of having a range of digital tools on a smartphone has increased the chance that a person will have access to a tool that they find useful. The drawback in this recent plethora of applications and devices geared toward people who are blind is that it is difficult for even beneficial tools to draw the interest they deserve.

Finally, there are systems being developed to leverage a range of technologies embedded in the built environment to allow for interaction between the environment and the traveler. In 2016, 78 medium sized cities in the United States responded to the Department of Transportation's Smart City Challenge [37]. In this competition, cities developed proposals to create systems to make transportation safer, easier, and more reliable. Some common mobility challenges seen through the proposals include connecting underserved populations to transit from the first and last mile of their routes, coordinating systems, optimizing transport of goods, increasing parking and payment efficiency, limiting climate impact, and optimizing traffic flow [38]. The 7 finalists

Fig. 5. Images of the Braillenote GPS from Humanware and the Kapten from Kapsys

chosen to work with the Department of Transportation to further their ideas included Austin, Columbus, Denver, Kansas City, Pittsburgh, Portland, and San Francisco. In most cases, the proposed systems involve increased access to people with disabilities, with several specifically addressing needs of people with visual impairments. By ensuring that all city inhabitants have easy access to and use of the proposed systems, a city stands a better chance of developing a system that will be accepted and effective.

In Helsinki and the West Midlands, UK, the Mobility-as-a-service Initiative demonstrates how the internet of things and other trends in urban travel might be combined to create a new form of travel system [39]. The initiative is envisaging a time when there is no private car ownership but instead all inhabitants of the city will combine public transportation (bus, train, metro), on demand services (Uber, Lyft), and dedicated mini buses to plan and travel routes. As seen in Fig. 6, building the proper supports in the infrastructure allows a traveler to use one interface to access the full range of transport options linked in one system to plan and complete routes in an optimal manner.

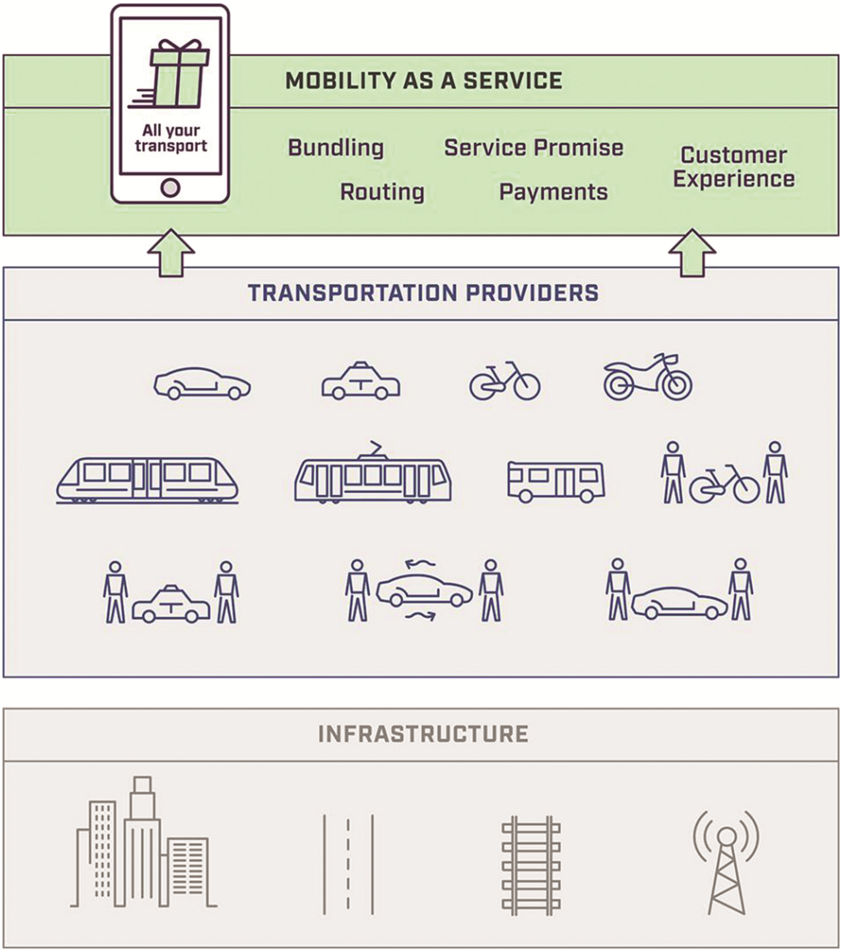

Fig. 6. Graphic of the mobility as a service system

Many proposals for developing smart city transportation include leveraging the internet of things, where the increasing number of elements in the built environment that have the ability to send and receive data allow for a broad network of digital connectedness. For example, there are several cities that are experimenting with some combination of beacons and smart signs so that any pedestrian, including those who are blind, can know when a bus or train will arrive, what route that bus or train is servicing, what the stops are when riding a transportation system, the layout of transit terminals, and a range of other useful pieces of travel information. As cities begin to put in place streetlights, garbage cans, and traffic lights that can all be connected in a digital web, it will be easier to create smartphone applications accessible to all pedestrians that allow for precise location information and interaction with a transportation system that is always in motion. If an urban system has smart garbage cans, buses, light poles, and traffic signals (among other things), a pedestrian who is blind that is employing an app linked to that system will be able to know not only where they are within the urban landscape but what smart items are around them and the status of those items (such as whether a light is green or red). There is even a project investigating smart paint where crosswalk lines or paint at an intersection corner can be accessed to give location information to pedestrians with an applicable device [40]. Since the infrastructure of the built environment, principally the hardware and software associated with traffic control devices, are already more commonly communicating with a central transportation control hub, the foundation of such an integrated system is already being implemented. With these systems in place, and with the addition of vehicles that are more able to sense what is around them, it is a small step to include pedestrians into the mix. And for pedestrians who are blind, if the entire transportation or mobility infrastructure is designed to optimize use by all pedestrians and is designed for accessibility, then the days of designing tools only for people who are blind will be past and all pedestrians will be able to simply use the same systems and tools, no matter their physical abilities.

2.3 Autonomous Vehicles

Much has been made lately of the advent of autonomous vehicles. Google's autonomous vehicle has already logged more than 1,000,000 miles of autonomous driving on public roads. There are estimates that many auto manufacturers will have autonomous vehicles in production by 2020 [41]. Autonomous vehicles offer the promise of a scenario in which a pedestrian who is blind can simply order up a vehicle, which will drive up and take them where they want to go.

An extension of the kind of communication that an autonomous vehicle has with the environment through its sensors is vehicle-to-vehicle (V2V) or vehicle-to-infrastructure (V2I) communication. This sort of communication between an autonomous vehicle and the environment fits well into the Mobility As A Service system shown in Fig. 6. When vehicles communicate directly with other vehicles to optimize safety and with the road and built environment infrastructure to optimize efficiency, the entire mobility network theoretically operates better. In this type of scenario, a pedestrian, whether blind or sighted, who has a device on their person that communicates their location to the built environment infrastructure, can access information about their location, the state of the surrounding infrastructure (construction, traffic light status, traffic volume, bus schedules, etc.) and vehicles approaching that pedestrian will be able to take any action required to avoid collisions.

While technologies previously discussed in this article were generally designed to assist people who are blind in navigating the built environment, autonomous vehicles are a trend in the transportation arena that do not target people who are blind. As such, it is important that advocates for people who are blind are part of the design process so that any wholesale modifications to the travel environment are made with the needs and abilities of people who are blind in mind. In this regard, interfaces through which a person communicates with an autonomous vehicle need to be accessible to people who are blind. When smartphones were first introduced, the touch screen interface posed an accessibility issue for people who are blind. However, with the development of voice over software for touch screens and other innovative overlays, people who are blind can now use touch screens adeptly for most applications. A similar interface solution will need to be designed into autonomous vehicle interactions since it is likely that people who are blind will be using autonomous vehicles regularly.

Five levels of automation have been adopted by the National Highway Transportation Safety Administration when referring to autonomous vehicles [42]. These levels are:

- Level 0: No automation (human driver in control of driving task)
- Level 1: Driver assistance (vehicle systems assist in either steering or acceleration/deceleration only in reaction to environmental information)
- Level 2: Partial automation (vehicle systems assist in both steering and acceleration/deceleration in reaction to environmental information)
- Level 3: Conditional automation (vehicle systems perform all aspects of driving task with human driver always ready to intervene)
- Level 4: High automation (vehicle systems perform all aspects of driving task even if human driver does not intervene when requested)
- Level 5: Full automation (vehicle systems perform all aspects of driving task full time) [42].

Theoretically, a large number of autonomous vehicles operating even at level 1 would eliminate a third of the annual crashes and fatalities on U.S. roadways [42]. Reductions in congestion, energy use, carbon emissions, and cost are also theorized [42].

Autonomous vehicles, especially at level 5, hold the promise of opening up travel possibilities for people who are blind more than any other development in recent memory. If the theoretical models hold true, a person who is blind will be able to use their smartphone to call up a vehicle that will meet them at their residence. The vehicle will not be subject to the schedule of a driver or other passengers and so will be on time more often. This is already a huge benefit since many people who are blind use paratransit services for longer routes in a city and many paratransit operations are notorious for being late and requiring at least 24 h scheduling ahead of time. Some sort of system will need to be incorporated into the autonomous use system to ensure that a person who is blind is able to know when the vehicle has arrived and which vehicle is the one they ordered. Once in the vehicle, the person who is blind will be able to take advantage of travel applications or devices such as those discussed previously to monitor their location or view nearby points of interest as they travel in the vehicle. Single person autonomous vehicles will be able to be linked to mass transit systems so that a person who is blind could take a single person vehicle to a metro stop or train station to begin a longer trip.

Whether a short inner city trip or a longer trip between cities, if autonomous vehicles are an integral part of the design of an overall mobility system, then a person who is blind will be able to access all levels and portions of the transport system the same as a person who is sighted. Of course, there will always be a place for personal mobility training and use of low tech devices such as the long cane. Any level of technological advancement will get a person only so close to a destination, the final leg of a journey will always be a person traveling with their own set of skills to locate a final destination.

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